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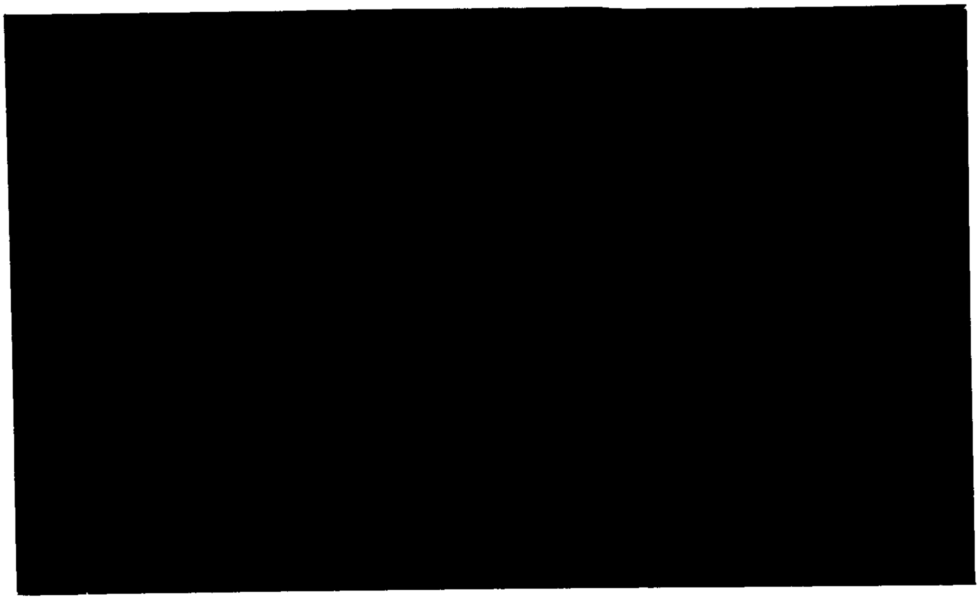

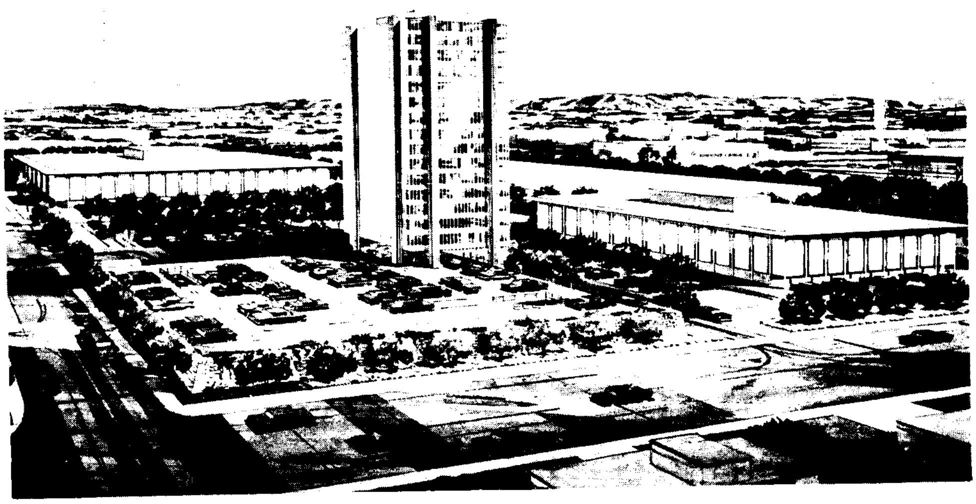

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Final Report

FEASIBILITY STUDIES OF PROMISING STABILITY AND GRAVITY (INCLUDING ZERO-G) EXPERIMENTS FOR MANNED ORBITING MISSIONS

Prepared for
Headquarters
National Aeronautics and Space Administration
Washington, D. C. 20546

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Prepared by
EOS Staff and Consultants

Under the supervision of

Austin D. McGuire

Austin D. McGuire
Office of the
Corporate Chief Scientist

Approved by

Henry L. Richter Jr.

Henry L. Richter, Jr.
Vice President
Manned Space Program Office

ELECTRO-OPTICAL SYSTEMS, INC. - PASADENA, CALIFORNIA
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1. INTRODUCTION

1.1 General

The present study of the feasibility of conducting some selected experiments in a manned orbiting research laboratory in the post-Apollo time period represents a portion of the planning effort required to define future NASA programs. The general question to which the results of the present study apply is: Assuming the feasibility of developing and operating an extensive manned orbiting space station, what scientific objectives can and should be accomplished by the station, and what special features should be provided in the station to accomplish the scientific objectives?

An early step in the planning of a research program is to identify the scientific objectives. The next step is to group scientific objectives by common features. The third step is to define the apparatus, procedures, measurements, required data, etc., to accomplish an objective or group of objectives, i.e., define "experiments". The next step is to compare the experiments against practical considerations such as equipment weight, power, flight system capability, costs, etc., and exercise judgment as to whether each experiment should be retained in the program. The practical considerations can often result in a modification of the scientific objectives chosen in the first step--that is, the planning process is iterative, having a feedback mechanism as represented by a simple diagram (Fig. 1-1).

Following the definition of a scientific program, the further steps in the overall planning cycle may proceed. Further steps include:

1. Weighing the estimated cost against the expected return from accomplishment of the program.

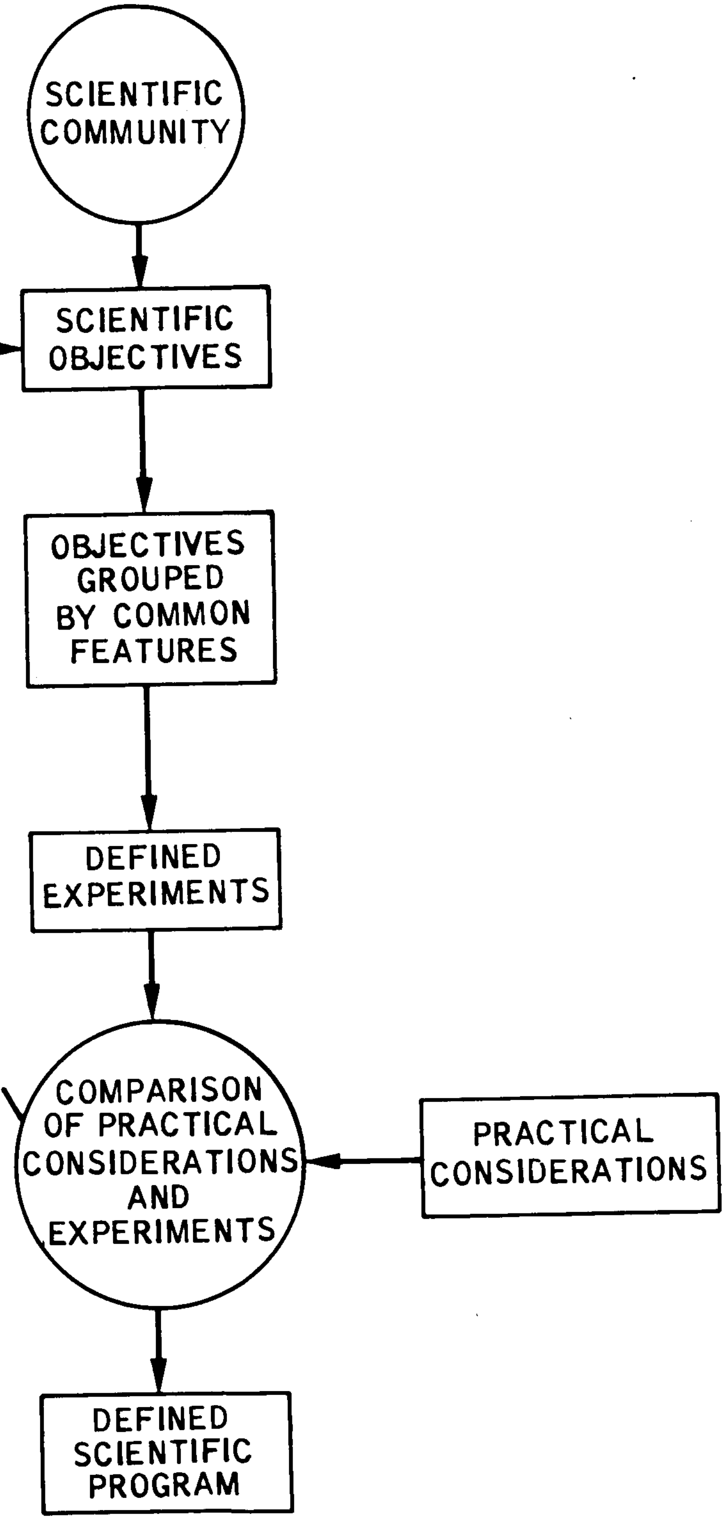

FIG. 1-1 EXPERIMENT SELECTION FLOW CHART

2. Weighing the costs and objectives of the manned orbiting station against the cost and objectives of other programs which might be initiated instead.
3. Weighing the political and public acceptance aspects of the program against costs and time scale.

The results of the present study effort are intended to provide guidance in the early planning phases of identification of some scientific objectives, grouping of the objectives by common features, and definition of "experiments". The present study is limited to consideration of those scientific disciplines in which the weightless environment of the spacecraft was most likely to be an important feature in the experimental procedure. Experiments involving measurements of the space environment, the earth's surface, or astronomical bodies are outside the present scope. The limited nature of the study prevents use of the present results alone in defining the complete scientific program for a manned orbiting station, or for serving as the sole basis for assessment of the scientific value of a proposed scientific program.

1.2 Technical Background

The success of early manned space flight programs - Mercury and Gemini - has led rapidly to the point where manned space flight activities represent approximately half of the total U. S. space effort. The present major single program is Apollo, with the objective of conducting a manned flight to the moon about 1970. Manned space flight programs being considered for the immediate post-Apollo time period, i.e., 1971 to 1976, fall into two general categories; namely, extensive operations on the moon and extensive operations in large manned orbiting space stations. While manned flight to Mars is continually being considered, the earliest reasonable date presently appears to be near the 1985 opportunity.

A portion of present NASA planning is aimed at the definition of several manned orbiting spacecraft concepts, including earth orbiting research laboratories, lunar orbiters, and planetary types, to follow the Apollo program. Utilization of the post-Apollo manned spacecraft to pursue studies in the space sciences is a major consideration in the planning, and spacecraft designed with the primary mission objective being that of providing the facility to conduct a research program are under consideration. Evaluation of the capability of personnel aboard a spacecraft to conduct scientific investigations is in progress, and planning of missions and of experiments to be conducted is going forward. Payloads and configurations of vehicles are being considered from the point of view of accommodating the scientific objectives of the missions.

1.3 Objectives and Scope of Present Study

1.3.1 General

The objectives of the present study were taken at four levels:

1. Identify and define essential and promising experiments to be conducted in a large post-Apollo manned spacecraft, considering primarily those in which the weightless environment is an important feature.
2. Evaluate the feasibility of conducting the identified experiments in a manned space station.
3. Identify the requirements of the experiments considered as to crew skills, space station stabilization, data acquisition and handling techniques, and apparatus weight, volume, and power.
4. Provide background material for two elements of the program plan which will be required to specify the scientific requirements of a post-Apollo manned space laboratory:

a. A scientific justification of the experiments to be conducted and a definite answer to the question why an experimental program should be prepared for a zero-G laboratory.

b. A summary of the expected capabilities and limitations of an orbital laboratory.

The scope within which the stated objectives were pursued was limited in four major directions:

1. Experiments which require or utilize the weightless environment in the spacecraft were emphasized.
2. The study was limited to three of the many areas of scientific discipline from which suggestions for experiments have arisen; i.e., gravitation, materials research, and biology.
3. Consideration of the general aspects of a manned space laboratory, such as total payload, tradeoff between scientific utilization and other utilizations, costs, etc., were outside the present scope.
4. The present effort was limited to a low level and did not include detailed design or prototype fabrication.

The scope of the present study, as limited with respect to each of the four objectives of the study, is further described in the following.

1.3.2 Identification of Experiments

In the identification of promising experiments to be conducted in a manned orbiting station, the scope of the present study was limited in two directions, that of the scientific disciplines considered for suggestions, and that of which features of the spacecraft environment were to be utilized to accomplish the experiments.

1.3.2.1 Scientific Discipline

Suggestions for experiments or series of experiments which require or utilize the unique features of the space station have arisen from many scientific disciplines. Examples are:

Optical Astronomy	Chemistry
Cosmic Ray Physics	Oceanography
Nuclear Physics	Aeronomy
Medicine	Fluid Dynamics
Space Environmental Physics	Solid-State Physics
Geophysics	Biophysics
Astrophysics	Biology
Meteorology	

The scope of the present study was limited to three areas of scientific discipline which have been chosen and identified as:

1. Gravitation and Stabilization
2. Materials Research
3. Biology

The scope of the study within each of the three areas of scientific discipline is discussed in detail herein. Consideration of measurements and experiments aimed at specific engineering and development goals were outside the present scope.

1.3.2.2 Spacecraft Environment

The four outstanding, unique features of the environment of a manned space station when considered as a scientific laboratory are:

1. The (approximately) weightless state of personnel, equipment, and apparatus within and near the laboratory.
2. A location outside the earth's atmosphere where radiation from space may be observed without atmospheric attenuation and refraction.

3. The unique capability to observe substantial portions of the surface of the earth and the near-earth environment repeatedly in short periods of time.
4. The availability of high vacuum with high pumping speed.

The present study has been mainly limited to consideration of those experiments which utilize or are enhanced by the weightless state within the laboratory (two exceptions are the meteoroid studies and crystallization studies which utilize, in addition, the vacuum environment).

1.3.3 Evaluation of Experiment Feasibility

In the evaluation of the feasibility of experiments identified, no limitation in scope was applied, except that of the inability to perform laboratory preprototype experimentation.

1.3.4 Specification of Apparatus and Spacecraft Requirements

Some of the gross features of a post-Apollo manned space vehicle which must be considered in formulation of a complete program plan are:

1. Total weight in orbit.
2. Payload weight for scientific programs.
3. Payload weight for other operational programs.
4. Payload weight for life support expendables, station keeping propellant, power generation, etc.
5. Crew complement of station as to total number, duty assignments, skills required, and duration of stay in orbit.
6. Resupply operational schedule of both personnel and apparatus to the station.
7. Total operational time in orbit of the station.
8. Contingency and alternate plans for reprogramming the later phases of the station operations on the basis of results and experience obtained in the earlier phases of the operation.

The scope of the present study is limited to a consideration of a few features of the spacecraft and mission profile which interface with, or influence that portion of the scientific research program studied. For each experiment considered as feasible for the research program, the following aspects have been estimated:

1. Crew skill and training required.
2. Crew manhours to accomplish the experiment.
3. Volume, weight, and power requirements of the apparatus to accomplish the experiment.
4. Requirements for stabilization of the apparatus while performing the experiment.
5. A preliminary, conceptual description of apparatus as it might be physically located within a spacecraft.
6. A preliminary, conceptual description of experimental procedures, data acquisition techniques, and data handling requirements for the experiments.

1.3.5 Presentation of Scientific Justification and Overall Summary

In preparing a scientific justification of an experimental program to be conducted in a zero-G laboratory and preparing an overall summary of the expected capabilities and limitations of an orbital laboratory, no limitations in scope were applied, except that of devoting a reasonable portion of the available effort to the task.

1.4 Organization of the Present Report

The method employed in pursuing the study is described in detail in Section 3 of the present report. Those experiments identified in the study and selected as being both feasible and appropriate for a manned space research program are described briefly in Section 4. The problems of integrating the apparatus into a spacecraft are discussed in Section 5, and the rationale and scientific motivation for an overall program is presented in Section 6. Sections 7, 8, and 9 are technical presentations of the scientific background and theoretical considerations for each of the three areas of scientific discipline considered. The technical considerations were formulated earliest in the study to identify the potential scientific objectives for the program, and the experiments selected for further consideration are described in the technical sections in terms of their scientific objectives and parameters to be measured.

2. SUMMARY AND RECOMMENDATIONS

2.1 General

Within the three areas of scientific discipline to which the present study is directed, a number of experiments and measurements have been identified which are of significant scientific value, and which require the environment of a manned orbiting space laboratory. From these, a specific set of the most significant experiments was adopted for planning purposes as constituting part of a program of scientific research to be conducted in a large, manned spacecraft utilized as a research laboratory in the 1971 to 1975 time period. The selected experiments were analyzed in sufficient detail to allow preliminary, conceptual specification of the apparatus requirements, data acquisition techniques, and specialized spacecraft interface requirements. The scientific rationale, or scientific justification, has been considered both for the individual experiments identified and for a program of scientific research to be conducted in a manned space laboratory.

2.2 Results

The six major results of the study are as follows:

1. The identification of some specific, feasible experiments in the scientific areas of gravitation, materials research, and biology.
2. The recognition that a manned orbiting laboratory should be provided with the capability of maintaining apparatus in a highly stabilized state to perform some of the experiments identified, i.e., the laboratory should include a platform which can be stabilized to about 10^{-6}G.
3. The preliminary definition, for planning purposes, of a program of research in materials and gravitational biology for a manned orbiting laboratory.

4. The determination that the expected capabilities of the orbiting laboratory are sufficient to allow performance of the identified experiments in an acceptable short time period.
5. The determination that the experiments identified are of significant scientific value, and the recommendation that: (1) experimentation in gravitational biology and gravitational experimentation in materials research receive further consideration in planning manned space research programs, and (2) that a complete program be prepared for a manned orbiting laboratory to allow assessment of costs of the program against expected returns.
6. The recognition that the needs of a research program will change during the course of the operational period of the laboratory, and that the apparatus and facilities of the laboratory must be designed to allow maximum utilization and operational flexibility for zero-G research.

Each of these six major results is discussed in turn in the paragraphs which follow. Some further results of a more detailed character are pointed out in the course of the discussions.

The Identification of Some Specific Experiments

The study effort resulted in the definition of a number of significant scientific objectives in each of the three areas of scientific discipline to which the study was directed. In the area of gravitational research, only two of the objectives identified -- those of measurement of solar oblateness and starlight bending by the sun -- lead to experiments which are appropriate for a manned orbiting laboratory. Experiments to accomplish other scientific objectives in the area of gravitation are more appropriate for spacecraft of a nature more specialized than a manned laboratory. The specific result of the gravitation portion of the study is that the manned space laboratory apparatus should include a small-aperture, wide-field-of-view telescope and a small, maneuverable, occulting satellite to accomplish the two objectives indicated.

In the other areas of scientific discipline, a much larger number of scientific objectives leading to experiments appropriate for a manned orbiting laboratory were identified. While the experiments have been grouped in different ways for the different portions of the study, a division into two groups seems most natural for purposes of overall program definition. The two groups are defined on the basis of the scientific training, background, and experience of the investigators who will perform the experiments. The category designated "gravitational research in materials" consists of the observation and measurement of the dynamic behavior of liquids, solids, and gases in the weightless environment, and the observation and measurement of the properties of unique materials produced by processes which require the weightless environment. The category designated "gravitational biology" consists of the observation and measurement of biological processes in the weightless state in biological systems ranging from microscopic forms to whole animals.

The Preliminary Definition of a Program of Gravitational Research in Materials and Gravitational Biology

Experiments to accomplish the specific objectives identified in the areas of gravitational research in materials and gravitational biology have been analyzed on the basis of other common features in addition to that of scientific discipline. Common requirements for spacecraft facilities, skills of crew members, mission profiles, data acquisition techniques, duration of the experiment, and stabilization requirements have been considered. The definition of the experiment was then modified so that the group of experimental procedures constitutes a balanced program. The experiments comprising the program are described in brief form in Section 4 and in more detail in Sections 8 and 9 and Appendix E. The program consisting of the specific set of experiments was adopted to serve as a basis for the remainder of the study, and as a possibly useful concept in further NASA planning.

The Determination That the Expected Capabilities of a Manned Orbiting Lab Can Easily Accommodate the Experimental Program Adopted

The apparatus, facilities, and crew skills required to perform the program adopted have been summarized. Arbitrarily assuming a 90-day operational period, it was found that 16 scientific personnel and nine spacecraft operating personnel could execute the entire program, and that total weight, power, and volume requirements are within the expected capability of a large post-Apollo manned spacecraft. The 90-day operational period is arbitrary, being chosen for illustrative purposes only. Assuming a longer operational period for the experiments adopted would result in a reduction of the crew and weight requirement. It is clear, however, that the program of gravitational research in materials and gravitational biology, as defined herein, will constitute a significant fraction of the total program.

Evaluation of the Scientific Value of the Program

The question central to the study was: "Why should an experimental program be prepared for a zero-G laboratory?" A discussion of the scientific value of each of the experiments adopted is presented in the detailed sections of the report. Each discussion consists of a presentation of the technical background relevant to the experiment and an explanation of the new scientific knowledge that potentially can be acquired by performing the experiments. The experiments adopted are clearly of significant scientific value since they will provide new knowledge which will constitute an advancement of present scientific frontiers in several directions. Because of the great scientific merit of the experiments identified and the high probability that data acquired in the early phases of the program will lead to the definition of additional scientific objectives, it is strongly recommended that experimentation in gravitational biology and gravitational research in the behavior and properties of materials receive high priority in the planning of manned space research programs for the large space laboratory. The subject of gravitational biology, in particular, is just beginning to receive wide and serious consideration by the scientific community, and it has great growth potential as a field of scientific activity.

In view of the scientific merit and growth potential of the limited program defined by the present study, it is strongly recommended that the planning of a space station be continued to allow assessment of the costs of the program defined. An assessment of cost against expected scientific return must be made at some future point in the planning, but a determination of the cost of the limited program defined cannot be made until the complete program for the manned space station has been defined and criteria established for assessment of the correct fraction of the total cost against portions of the program. At the present stage of planning for a manned orbiting laboratory, the answer to the central question is that a complete program for a manned orbiting laboratory should be defined to allow assessment of the costs of the program against the expected returns of the program.

The Recognition of the Need for Multiple Purpose Utilization and Operational Flexibility of the Laboratory Apparatus

Throughout the course of the study it has become increasingly clear that the needs, requirements, and objectives of the scientific research activity will continuously change during the course of the program. The set of scientific objectives adopted herein for present planning purposes is not the only set which could have been chosen. The experiments ultimately to be approved for the program are not presently identifiable, since they will probably arise in part from an analysis of data obtained from experiments performed on Gemini and Apollo-type missions. Other suggestions may be made by scientists who are presently too busily engaged in current research to participate in planning efforts. After the initiation of research activities in the space station, the analysis of data acquired in the early portion of the program is expected to suggest further scientific objectives and modifications to the experimental procedures in the later portion of the program. On the other hand, equipment procurement lead times indicate that initial design of spacecraft and apparatus must begin before the experiments planned for the Apollo program are completed. The clear conclusion is that a primary design criterion must be that of multipurpose utilization and operational flexibility in order to provide the highest probability that the apparatus and facilities for scientific utilization of the post-Apollo manned space laboratory will be adaptable to the changing needs of the research program.

Making maximum use of human intelligence and human manual operation of apparatus aboard the space laboratory is clearly the one outstanding criterion which will provide maximum multipurpose capability and operational flexibility. For many of the experiments, particularly in the biosciences, the best data acquisition mechanism is the judgment of the experienced scientist directly observing the specimen of interest in the weightless environment. In the matter of operation of equipment, a human is inferior to automatic, electro-optical-mechanical servo systems in the performance of any given single function. The scope and flexibility of the human operator, however, and the capacity of the human operator to adjust to unforeseen abnormalities in equipment function is unmatched by any automatic system. Many or all of the scientific objectives identified could be met with some degree of completeness by the use of automatic equipment in unmanned satellites. The automatic apparatus would be rather inflexible in its ability to adapt to the changing needs of the program, would provide considerably less complete data, and would be of lower reliability. While cost comparisons are always difficult, a cost effectiveness comparison might well favor the manned orbiting research laboratory over a series of automated satellites.

2.3 Recommendations

Four major recommendations resulting from the study are identified as follows:

1. Planning of programs of manned space research in materials and biology should continue, while consideration of the use of manned spacecraft for research into the phenomenon of gravitation should be deemphasized.
2. Feasibility studies to identify promising experiments should be undertaken in additional areas of research, as outlined in Section 6 herein.
3. It is timely to undertake the definition of a complete program of research and operations to be conducted over a 1 to 5 year period in a manned orbiting space station.
4. It is timely to undertake the preliminary design of some selected items of equipment required to perform the experiments identified.
5. In parallel with the effort to define a complete program, one or several alternate choices of spacecraft size, crew size, orbit elements, and mission duration should be adopted to allow an estimate of the cost of executing the program.

The following are recommendations of a more detailed character:

1. Further consideration of the use of manned spacecraft for research into the phenomenon of gravitation should be deemphasized until further results are available from experiments with unmanned vehicles, since it appears that experiments to achieve further understanding of the gravitational interaction (other than the making of measurements utilizing the techniques of optical astronomy) will not require manned spacecraft.
2. The measurement of starlight bending and solar oblateness should be classified as part of the manned astronomy program, since the techniques employed are those of optical astronomy.

The measurement of the bending of starlight by the sun should be performed as a manned space experiment using a telescope of specialized design and an occulting system. A measurement of solar oblateness should be performed with the same telescope, but the direct measurement of the effect of solar oblateness on the motion of a solar probe is a superior method of achieving the desired result and should be performed in addition to the optical measurement.

3. The center of mass of the spacecraft should be accessible for the location of an isolated platform to be used in experiments requiring intermittent short periods of highly stabilized conditions.
4. Detailed designs should be initiated for some particular items of equipment necessary to perform some of the experiments identified in the completed study. The items suggested are those which can be designed prior to a final choice of configuration and size of the manned orbiting research laboratory and whose design will provide interface information necessary for the determination of the characteristics of the spacecraft. Specific items of equipment include the following:
   a. A stabilized facility for general use within the spacecraft for those experiments which require extremely low acceleration.
   b. A solar furnace and associated control and mounting system for raising free-floating (or nearly free-floating) material samples to high temperature. The technique for using the solar furnace should be demonstrated in a vacuum chamber.
   c. A mass spectrometer for the analysis of micrometeoroid impact debris.
   d. Long-working-distance, dissecting stereomicroscope and integrated stereocamera unit for zero-G use.

e. General-purpose microscope and associated optical system for zero-G use.

f. A small maneuverable satellite (or satellites) to be controlled from the main spacecraft. Uses include occultation of the sun while acquiring data for the measurement of starlight bending, providing a highly stabilized region for long-duration exposure of living specimens, and transport of instruments for measurements of the space environment.

g. A small-aperture, wide-field-of-view telescope and stabilized mounting platform to perform the two measurements indicated previously.

h. An optical instrument with capability for densitometry, spectrophotometry, nephelometry, and light-scattering photometry.

i. Micromanipulators.

j. Microtomy equipment.

k. Life support provision for cultures and specimens.

l. Combination culture and observation vessel.

5. In addition to the specific items of apparatus which should be designed, some of the general facility work areas of a manned spacecraft should be laid out in detail to further define the interface requirements which will be imposed on the spacecraft, and to define the problems of adaptation of the equipment to use in zero-G. Facilities whose design should be initiated are enumerated:

   a. The isolated platform to be used within the spacecraft for experiments requiring intermittent short periods of highly stabilized conditions.

   b. Photographic processing facility.

   c. Facility for metallurgical analysis.

   d. Isotope handling facility.

   e. Wet laboratory facility.

   f. Histology laboratory facility.

   g. Small nonaquatic animal maintenance facility.

   h. Aquarium.

3. METHOD EMPLOYED IN THE PRESENT STUDY

3.1 General

Restated briefly, the objectives of the present study were:

1. The identification of promising experiments for a manned orbiting space laboratory.
2. The evaluation of the feasibility of the experiments identified.
3. The preparation of a summary of apparatus, crew, and spacecraft requirements to perform the experiments.
4. The presentation of the scientific justification for a manned space research program and an overall summary of the capabilities and limitations of a large manned space station.

The method used to accomplish these objectives has included the following:

1. Survey the three specified areas of scientific discipline to identify potential scientific objectives.
2. Apply selection criteria to the scientific objectives identified with respect to scientific value and practical feasibility of accomplishment of the scientific objectives in a manned orbiting laboratory.
3. Formulate a specific set of experiments to accomplish some of the scientific objectives identified, and to adopt a specific set of experiments for planning purposes as part of the scientific program of a manned orbiting laboratory.
4. Specify in a preliminary way the apparatus, crew skill, data handling, and spacecraft stabilization requirements of the set of experiments adopted.
5. Present the scientific justification of a research program for a manned space station.

3.2 Selection of Scientific Objectives

The general objective of a research program is the acquisition of new knowledge. Following a survey of physical phenomena and biological phenomena predicted to be observable in the spacecraft environment, but not observable on earth, specific examples of the behavior of matter and radiation were selected as the phenomena studied in the experiments. In formulating specific scientific objectives, the following four criteria of scientific merit were adopted:

1. That of performing a measurement or observation to confirm or deny the existence of an effect or phenomenon predicted by a theory based on extensive earlier experimental work.
2. That of establishing the truth or falsehood of an *ad hoc* hypothesis which may lead to a theory.
3. That of a desire to refine the accuracy of existing measurements of parameters which describe the physical behavior of matter.
4. That of performing measurements and observations in a regime, e.g., the weightless state, where no measurements have been performed before.

The theoretical and experimental background varies considerably in nature and degree of refinement among the three areas of scientific discipline. In the first area, that of gravitation, a rigid and mathematically precise theoretical framework exists as a guide. In the area of classical mechanics, no cases were identified in which observation of gravitational effect in a spacecraft would constitute an experiment satisfying any of the criteria of scientific merit. In the area of special relativity theory and relativistic gravitational theory, two specific observations appropriate for a manned space research program were identified. The detailed consideration given to the subject of gravitation is described in Section 7. In the area of materials research, two classes of theories have been formulated, namely, particle theories and continuum theories. No suitable scientific objectives were identified on the basis of particle theories since gravitational forces are extremely weak compared to electrostatic and nuclear forces among particles. In the area of behavior of continuous matter, many phenomena were identified in which the gravitational energy is comparable to other energies involved so that experimental objects in a weightless environment are predicted to exhibit previously unobserved behavior. The detailed scientific background for the materials experiments is reported in Section 8. In the third area of scientific discipline, that of biological research, the identification of scientific objectives has been based largely on the criterion of conducting a systematic exploration of the effect of weightlessness on biological processes. While the complexity of the life process precludes the formulation of a rigid theoretical framework embracing the entire subject, theoretical guidance is available within some subareas to indicate which phenomena may be expected to exhibit gravitational effects most readily. Biological processes were considered over a range defined largely on the basis of the size of the biological system, or subsystem, taken as the subject. A very extensive list of scientifically valuable experiments spanning the range of physical sizes from molecular behavior to sensory reactions in whole animals has been formulated and considered. The list of experiments and a discussion of those selected for detailed study is given in Section 9.

3.3 Formulation of Specific Set of Experiments to Consider as Part of a Program

From the possible scientific objectives identified, a specific set of experiments has been selected, and adopted for planning purposes, as constituting a portion of the research program to be conducted in a manned orbiting laboratory. The criteria used in formulating and adopting the experiments were:

1. The experiment will accomplish one or more of the scientific objectives identified.
2. The experiment either requires or is substantially facilitated by the presence on the spacecraft of personnel having extensive training and experience as scientific experimenters.

3. The experiment requires one or more of the unique features of the space laboratory environment.
4. The experiment is feasible in that suitable data can be acquired in a reasonable time; apparatus can be developed in a reasonable time; power, weight, and volume requirements are not prohibitive; etc.
5. Spacecraft requirements regarding stabilization, "stay time" in orbit, mission profile, etc., can be met.

A list and brief description of the specific experiments adopted are given in Section 4.

3.4 Preliminary Consideration of Spacecraft, Apparatus, and Crew Requirements

The specific set of experiments adopted was analyzed to determine the apparatus, crew, and spacecraft facility requirements. Sufficient study was devoted to the question of integrating the apparatus and facilities into a spacecraft to determine that no major problems in apparatus integration can be foreseen at present. Some tradeoffs to be made in choosing the configuration of the spacecraft for a manned space laboratory are identified.

Special attention has been given to understanding the gravitational environment within the spacecraft and to understanding the effect of the sun, moon, planets, and irregularities in the earth's gravitational field upon the gravitational environment in the neighborhood of the spacecraft. Some detailed calculations were performed as a basis for understanding the details of the gravitational environment and these are given in the appendixes.

3.5 Scientific Justification of a Research Program

The requirement to present scientific justification for a research program to be conducted in a manned space station has been addressed at two levels: (1) a scientific justification of the specific individual experiments adopted from within the scope of the present detailed study of experiments, and (2) a consideration of the justification of a total research program. The detailed rationale used in identifying the experiments as reported in Sections 7, 8, and 9 serves as scientific justification for the experiments considered. The more general question of justifying a scientific program is addressed in Section 6.

4. SPECIFIC EXPERIMENTS ADOPTED AS SUITABLE FOR A MANNED SPACE RESEARCH PROGRAM

On the basis of the theoretical and technical studies described in Sections 7, 8, and 9, and the selection criteria stated in Subsection 3.2, the following experiments have been adopted, for planning purposes, as constituting a portion of a research program to be carried out in a manned orbiting laboratory.

1. Measurement of the bending of starlight by the sun
2. Measurement of the solar oblateness
3. Mass spectrographic analysis of micrometeoroid impact debris
4. Formation of synthetic meteoroids
5. Formation of meteoroids from natural meteoritic material
6. Production of ultrapure materials
7. Crystallization studies
8. Study of a gas composed of macroscopic particles
9. Dynamic and static capillarity studies
10. Study of the dynamics of free liquid drops
11. Study of bubble formation in low-G
12. Study of critical-state behavior of fluids in low-G
13. Experimental embryology in low-G
14. Fundamental microbiology in low-G
15. Tropic responses and morphogenesis of plants in ultralow-G
16. Cell division and experimental cytobiology in low-G
17. Biological transport phenomena in low-G

A brief specification of the requirements to perform each of the experiments is given in Appendix E. A discussion of experiments considered, but not adopted as part of the program, appears in the technical sections 7, 8, and 9. The remainder of the present section is a brief, overall description of each of the experiments selected.

1. Measurement of the Bending of Starlight by the Sun

The objective of this experiment is to verify the general theory of relativity by a more precise measurement of the deflection of starlight by the gravitational field of the sun. The procedure is to photograph two different star fields on each of a series of photographic plates. One of the two star fields is a reference and calibration, the other is the star field at and near the sun's limb. The photographic plates are exposed through a 10-inch aperture, 5° field-of-view telescope mounted externally to the spacecraft and highly stabilized in pointing angle. The sun must be occulted by an opaque object external to the telescope. The telescope drift rate will be recorded. About 25 photographic plates are to be exposed and returned for processing and analysis on the ground. The plates are of larger than usual size (one to two meters on edge). The operators will manually change and package plates and will manually acquire the star fields and operate the occulting system. Other requirements are: about 600 watt-hours at 50 watts peak and 100 manhours of work performed by one astronaut with several months' training in the operation of the telescope.

2. Measurement of the Sun's Oblateness

The objective of this experiment is to verify the relativistic origin of the advance of the perihelion of Mercury by setting a limit to solar oblateness. Using the 10-inch aperture telescope referred to earlier, the sun will be photographed in several wavelengths and the exposed plates packaged for recovery. Plate development and data reduction are performed on the ground. Plates 20 cm on edge are required; 100 plates will be provided. About 500 watt-hours will be required at 50 watts peak. About 5 minutes per exposure is required. The same operator who makes the exposures for measurements of starlight bending by the sun can make the exposures for measurement of solar oblateness in about 50 hours.

3. Mass Spectrographic Analysis of Micrometeoroid Impact Debris

The objective of this experiment is to obtain a partial chemical analysis of micrometeorites with particular attention to the amounts and species of organic molecules. A target surface is erected outside the vehicle. Micrometeoroids impinge upon the target and vaporize. The vaporized meteoroid material enters the aperture of a mass spectrometer where the constituents of the meteoroid are analyzed. The spectrum of vapor detected from an individual impact can be recorded as a single photograph of an oscilloscope trace. About 60 recorded impacts per day are expected. Records will be kept of the times of occurrence of the recorded impacts. Data reduction will be done by the experimenter in the laboratory so that changes in the settings of the spectrometer controls may be made on the basis of the data obtained. Near-earth orbits are preferred - the target should not face the earth. About 120 watt-hours of energy will be used per day (about 11 kilowatt-hours total). The experiment will require about 4 hours per day of the time of one crew member with training as a laboratory experimenter and experience in the use of mass spectrometers. The apparatus will be erected by the experimenter in an extravehicular operation, will weigh about 20 pounds, and will require 3/4 ft^3 for storage.

4 and 5. Formation of Artificial Meteoroids from Synthetic and Natural Meteoritic Materials

The objectives of these experiments are to obtain and study samples of meteoroid-like material which has been formed under known and controlled conditions of vacuum and low gravity. Materials will be heated and fused in a solar furnace located external to the laboratory and allowed to cool radiatively. The resulting solid material will be analyzed metallographically and compared to natural meteorites. The distribution of physical forms and chemical compositions will be analyzed for the purpose of gaining further understanding of the conditions under which natural meteorites were formed. Data reduction and analysis will be performed in the space laboratory so that the conditions of later sample preparations may be modified as to sample size, heating and cooling rate, etc., on the basis of early results. The major apparatus consists of the solar furnace and associated sample handling system, external to the laboratory, and equipment for chemical and x-ray analysis in the space laboratory. Data will consist largely of photographs - including metallographic x-ray photographs. One astronaut/metallurgist with experience in meteorite analysis will be required about half-time for about 400 manhours total. About 1 kilowatt-hour per day (90 kWh total) will be required.

6 and 7. Crystallization Studies and Production of Ultrapure Materials

The objective of these experiments is to extend the technique of zone refining using the weightless environment to create ultrapure materials and crystals of size considerably larger than those available at present. Both metallic and nonmetallic samples will be suspended externally to the spacecraft. The solar furnace is used to form a molten zone which is moved across the sample. Temperatures are recorded versus time from a two-color pyrometer and thermocouples, and the process is recorded photographically. Analysis and data reduction will be performed in the space laboratory to provide guidance in the conduct of the experimental program. Crystallographic, x-ray diffraction, and spectroscopic analyses will be performed, and solid-state measurements will be performed. A wide variety of metallic and nonmetallic materials will be studied. About 400 watt-hours per day will be required. The experiments require a two-man research team, one man trained as a general laboratory experimenter and one as a metallurgist/crystallographer. The team will operate about 8 hours per day. A 200-mile orbit will provide acceptable vacuum, but in a 600-mile orbit the improved vacuum would allow some additional studies of the properties of clean surfaces of pure materials. Extravehicular activities will be required for erection of the solar furnace and some sample handling.

8. Study of a Gas Composed of Macroscopic Particles

The objective of the experiment is to observe the nonequilibrium behavior of a gas which is composed of particles sufficiently large as to be visible. A number of samples of particles ranging in size from a few to a few hundred thousandths of an inch are provided. Both spherical and nonspherical particles will be used. An appropriate number of particles (about 10^6) are placed in a container, and the equivalent temperature of the gas is raised by vibrating the walls of the container to impart kinetic energy to the particles. When the particles have filled the container, the vibration is stopped and the behavior of the gas is observed in stroboscopic light by two vidicons in stereoview. Data is stored on tape, transmitted to the ground for analysis, and results returned to the spacecraft to guide the subsequent course of the observations. The parameters to be controlled are the size, shape, density, and material of the particles. A search for the effects, if any, of electrostatic and magnetic fields must be carried out. One experimenter with a knowledge of gas dynamics will devote about 8 hours per day to the experiment. Accelerations at or below 10^{-4}G are required for the container. About 300 watt-hours per day are used. The container, vidicons, electronics, and samples weigh about 65 pounds.

9. Dynamic and Static Capillarity Studies

The objective of the experiment is to determine quantitatively the dependence of capillary flow on the properties of liquids and surfaces. Observations consist of photographing the motion of liquids in straight and helical transparent capillary tubes. A sequence of measurements will be performed using different liquids, different diameters of tubing, and different vapors above the liquid in the tubes. Static capillary forces will be measured by observing the value of gas pressure required to stop capillary flow. Wetting angles will be measured by photographing liquid drops in contact with flat surfaces in reduced gravity. The quantities measured will be flow rates, temperatures, pressures, and wetting angles. Data will be on photographic film and magnetic tape. Data reduction and analysis will be done in the space laboratory. About 45 kilowatt-hours total will be used at a peak rate of about 500 watts. One crew member, trained as a physicist and with experience in research in hydrodynamics, will perform the experiment, devoting about 4 hours per day. The apparatus and samples weigh about 200 pounds and occupy approximately 3 ft^3 of space. Stabilization to 10^{-4}G or less is required.

10. <u>Study of the Dynamics of Free Liquid Drops</u>

The purpose of the experiment is to study the oscillatory modes of free liquid drops and to study the interaction of two free droplets. Droplets of the selected liquid are placed in a chamber containing the selected ambient gas or vapor (buffer). The droplets are then perturbed either by gas jets or by acoustical vibration. The dynamics of the drops are then recorded by a movie camera. In some cases the drops will fragment. Collision and coalescence of droplets will also be recorded. The parameters to be varied are buffer material, temperature, pressure, type of liquid, and size of droplet. Measured quantities are amplitude, frequency, and mode of oscillation; damping rate; number and size of fragments; and two-drop impact parameter. Data reduction and analysis are performed in the space laboratory. About 180 kilowatt-hours will be used at a peak rate of 500 watts. One crew member with training as a physicist and experience in research in hydrodynamics will devote about 4 hours per day to the experiment. An acceleration level below 10^{-6}G should be achieved for the apparatus, although some results can be obtained at levels of 10^{-4}G. The apparatus and samples weigh approximately 50 pounds and occupy about 1 ft^3.

11. <u>Study of Bubble Formation in Low-G</u>

The objective of the experiment is to observe the dynamics of bubble growth and interface oscillations in a convection-free environment. Heat is applied to the liquid in two ways - by radiation and by conduction through a surface. Bubble formation can thus be made to take place at the surface and in the liquid bulk. Microphotography will be used to record the bubble formation and subsequent growth and dynamics. Observations will be made for different liquids, different processes, and different rates of heat input. Data will be recorded on film and magnetic tape. Data will be reduced and analyzed in the spacecraft. The chamber must be stabilized to 10^{-4}G. About 70 kilowatt-hours will be used at about 700 watts peak. One crew member with elementary knowledge of hydrodynamics and experience in general laboratory procedures will devote about two hours per day to the measurements. The apparatus and samples will weigh about 100 pounds and occupy about 3 ft^3.

12. Study of Critical-State Behavior in Low-G

The objective of the experiment is to determine the form of the coexistence curve in the vicinity of the critical point for single- and two-component fluids. The measurements are performed by recording the pressure and volume of a liquid held in thermal equilibrium. The container volume is varied, and the pressure recorded for each volume after thermal equilibrium has been established. The measurements are repeated for several different liquids and for a series of temperatures for each liquid. One crew member trained as a physicist and with experience in gas physics will devote 8 hours per day to the experiment. About 45 kilowatt-hours will be used at the rate of 500 watt-hours per day. The apparatus must be stabilized to 10^{-4}G. Total apparatus and sample weight is 25 pounds. Data will be reduced and analyzed in the spacecraft, and the program of measurements will depend strongly upon the early data and the judgment of the experimenter.

Experiments 13 through 17 constitute a program of research in gravitational biology. The experiments are to be performed by a group consisting of seven scientific investigators assisted by three highly skilled technicians. The allocation of scientific effort among the five biological experiments has been made flexible to permit modification and redirection of the experimental procedures based on early results obtained in orbit. The apparatus to perform the biological experiments weighs 3800 pounds. The biology program also makes extensive use of the general support facilities in the spacecraft, and requires the expenditure of about 1200 kilowatt-hours.

13. Experimental Embryology in Low-G

The objectives of the experiment are the determination and measurement of gravitational influence on such features of morphogenesis as cleavage, differentiation, induction and the formation and organization of tissues. The experimental technique involves fertilization of eggs, observation and manipulation of the developing embryos by a skilled embryologist, and recording, by photography and photomicrography, of critical stages and events during development. Specimens preserved in orbit at critical stages of development will be returned to the ground for future study. Major facilities and equipment considerations include the handling and processing of wet specimens and liquids, maintenance of specimens at temperature optima, and provision for microscopy and histology operations. Approximately 900 to 1700 hours of crew time will be required to accomplish the experiment during a 3-month period in orbit.

14. Fundamental Microbiological Processes in Low-G

The objectives of the experiment are: (1) general studies of the influence of gravitational forces on growth rate and mutation rate of microorganisms, and (2) studies of the sensitivity of induction and reversion of L forms and of lysogeny to gravitation. Standard bacteriological methods of batch and continuous culture will be modified as necessary to adapt them to the weightless laboratory. Measurements will be performed using standard optical, electrochemical, isotopic, and cytological techniques. The three principal equipment and facilities considerations involve the handling and preparation of wet cultures, the handling of radioisotopes, and the performance of various cytological procedures. As presently conceived, the experiment requires approximately 1250 manhours over a 3-month period for its accomplishment.

15. <u>Tropic Responses and Morphogenesis of Plants in Ultralow-G Environments</u>

The objective of the experiment is the determination and measurement of the effects of gravitational forces on the growth and development of plants. The three areas of special emphasis are early morphogenesis, mechanisms of perception of gravitational forces, and the coupling of geotropic and phototropic phenomena. The experimental techniques involve studies of both gross and microscopic morphology with photographic recording of significant observations, autoradiographic studies, and wet biochemical analysis. The most important equipment consideration connected with this experiment is the requirement for G-levels of 10^{-7} or less for periods exceeding 14 days. Other requirements include provisions for the handling of radioisotopes and a work station for wet chemistry and histological operations. It is estimated that 1400 to 2000 hours of scientific crew time over a period of 3 months will be required to fulfill the objectives of the experiment.

16. <u>Cell Division and Experimental Cytobiology in Low-G</u>

The objective of the experiment is the determination of the effect of gravity on mitosis, chromosomal morphology, DNA synthesis, the cyclical aspects of cell division, differentiation, and cellular metabolism. The experimental procedures involve use of <u>in vitro</u> cultures of various cells and tissues, and the use of protozoans and various eggs. Morphological observations will be recorded mainly on film. The physiological studies that employ isotopic labeling and other biochemical techniques will also utilize micromanipulation and microinjection of single cells. The principal hardware considerations imposed by the experiment center about a facility for wet chemistry and preparation of cultures and specimens and a facility for the handling of radioisotopes and preparation of autoradiographs. An allowance of 1100 to 1250 scientific manhours should be sufficient for performance of the studies and observations.

17. Biological Transport Phenomena in Low-G

The objective of the experiment is to determine whether gravitational forces cause alteration of biological transport phenomena. Study of both known and postulated transport mechanisms will seek to elucidate the role of gravitational forces in transport kinetics. The experimental techniques involve isotopic labeling and light-scattering photometry of bacterial cultures for uptake studies. Microscopy and photomicrography will be used for studies of phagocytosis pinocytosis, streaming, and cyclosis. *In vitro* studies of two-phase biochemical systems will also be utilized. The principal hardware requirements are connected with the handling of radioisotopes, histological and cytological specimens, and wet cultures and chemistry operations. It is estimated that approximately 780 manhours of scientific crew time would be required during a 3-month mission for performance of the experimental studies.

5. APPARATUS, CREW, SPACECRAFT, AND MISSION CONSIDERATIONS

5.1 Introduction and Summary

A summary has been made of the weight, volume, power, and personnel required to perform the specific experiments identified in the present study. Assuming arbitrarily that all of the experiments are to be performed in a single 90-day operating period, leads to an estimated total spacecraft crew requirement of 25 men, and an experimental apparatus and facilities weight requirement of about 25,000 pounds. The requirements are compatible with the expected capabilities of the largest spacecraft defined by previously completed engineering studies of manned space stations. If it were decided to construct a smaller station, the experiments defined herein can be conducted over a period longer than 90 days, assuming the use of a smaller crew and less apparatus. If the large station is available, the experiments can also be conducted over a period longer than 90 days, with some of the crew and equipment capability being simultaneously devoted to other programs. While some of the experiments identified would benefit from the harder vacuum available in far-earth orbit, the program described herein can be successfully executed in a 200 to 400-mile orbit.

Although it is too early to choose a size and configuration for the manned orbiting laboratory, some preliminary concepts for integrating laboratory apparatus into a spacecraft were prepared for the purpose of identifying possible future problems. No major difficulties in integrating the apparatus into a spacecraft are foreseen. Alternate configurations for the laboratory spacecraft are discussed for the purpose of pointing out some of the tradeoffs which must be made in choosing the ultimate configuration.

The requirements of the experiments identified in the present study offer some guidance in the development of a laboratory configuration.

However, the complete program should be defined, at least in a preliminary way, before the spacecraft configuration is finally optimized.

5.2 Method Used in Study

A brief systems engineering study was performed on the experiments adopted as forming part of the research program for a manned space laboratory. The factors considered were weight, volume, power requirements for apparatus, crew size and skills, spacecraft stabilization requirements, data requirements, etc. The study was performed for the purpose of identifying potential future problem areas in the design and mission planning of a manned orbiting scientific laboratory.

An integration study was performed by preparing a brief description of the specific experiments adopted (see Section 4 and Appendix E), and determining that the total requirements for all of the experiments did not exceed the expected limitations of a large manned orbiting spacecraft for post-Apollo time (post-1971). The expected spacecraft limitations were drawn from previously completed engineering studies of manned orbiting stations (MORL, LORL, MOSS, etc.).

Overall spacecraft configuration was considered from the two aspects of accommodating the requirements of the experimental apparatus and procedures, and accommodating the crew living space requirements. Factors affecting the gross configuration of the spacecraft were recognized to be:

1. The desirability of having the crew quarters portion of the spacecraft in rotation to provide a gravitational field.
2. The relationship between spacecraft dimensions and the gradient of the spin-induced gravitational field.
3. The recognition that future experience may indicate that a gravitational field in the spacecraft crew quarters is not necessary.
4. The mode of spacecraft stabilization to be employed (gravity gradient, active attitude control, or spin stabilization).

The requirements for stabilization of apparatus fall into five categories. Category I requirements are for a nominally stabilized environment at acceleration levels in the neighborhood of 10^{-3}G, but with vibration and random impulses such as would be generated by personnel motion and operation of machinery being tolerable. Category II requirements are for acceleration levels in the range from 10^{-3} to 10^{-7}G for operational time periods of a few minutes to a half-hour required to conduct an individual measurement, and with convenient access to the stabilized region by the operator between measurements. Category III requirements are for a region stabilized to a level of as low as 10^{-7}G for long periods of several days to several weeks, but with no requirement for access to the stabilized region over the time period that samples are being tested on the platform. Category IV requirements are for control and stability of angular degrees of freedom where stabilization of translational degrees is not required, and Category V requirements are for an environment in which samples are to be maintained in a gravitational field produced either by rotation of the spacecraft or by rotation in a centrifuge.

The apparatus required to perform each of the experiments has been considered in an attempt to identify possible installation problems to be encountered in a spacecraft from the point of view of satisfying the stabilization requirements. Figure 5-1 represents some of the equipment installed in a cylindrical section of a vehicle which is to be nominally stabilized as per Category I. A highly stabilized facility as per Category II should also be accessible within the spacecraft. The general problem of isolation of the highly stabilized facility is quite complex, and it is too early in the program to select a particular method of isolation of the platform (see Section 7).

To allow an assessment of total crew requirements, some assumption as to mission duration is necessary. Assuming that all of the experiments adopted are to be carried out in one 90-day operational period of the space station, the required crew is estimated to be nine

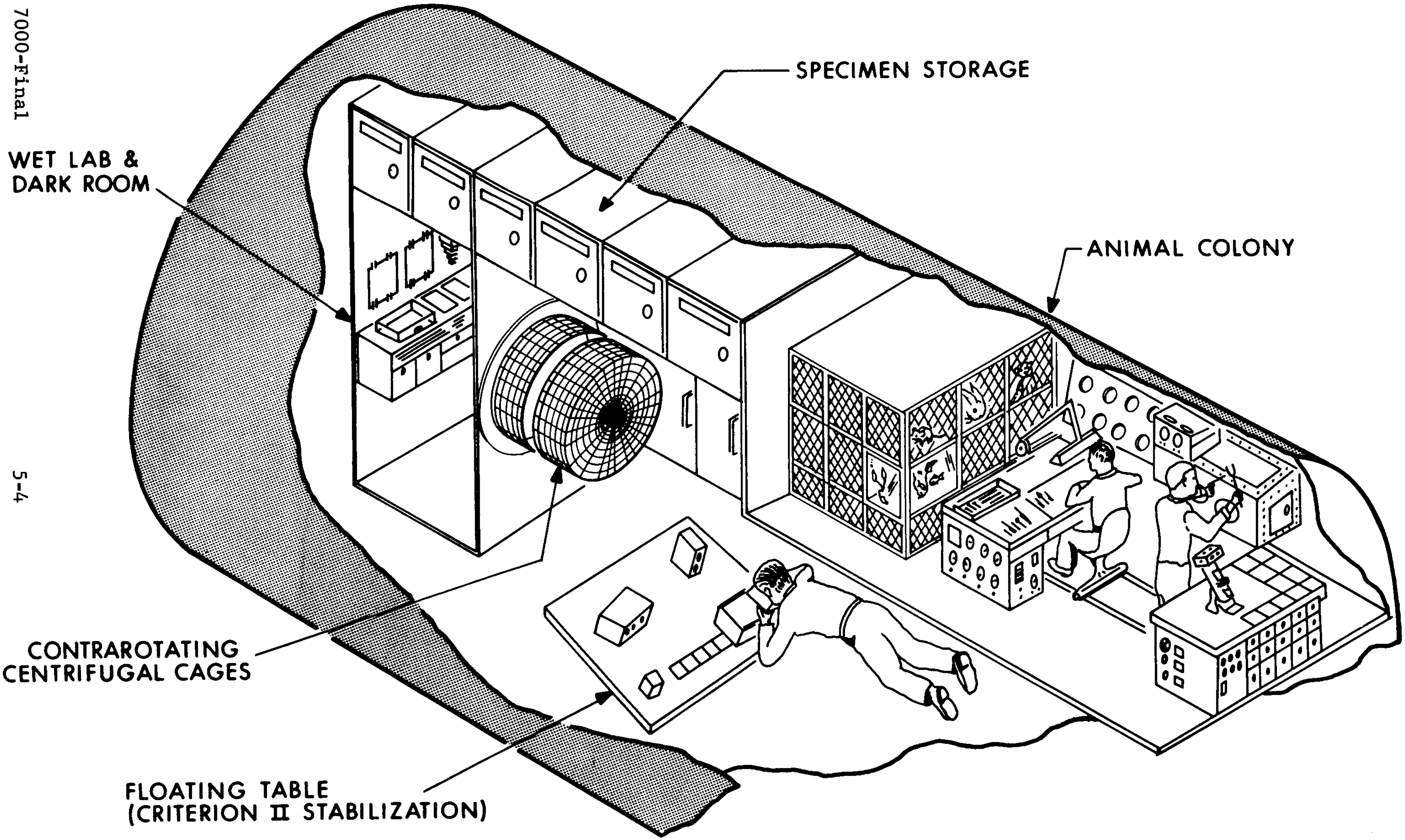

FIG. 5-1 BIOLOGICAL SCIENCES APPARATUS - CONCEPTUAL CONFIGURATION

pilot/astronauts and 16 scientific personnel, for a total crew of 25. When a complete program for the orbiting station is planned, it may be decided that the experiments identified by the present study should be performed over a time period longer than the 90 days considered, in which case the size of the crew can be reduced accordingly.

5.3 Requirements for Specific Experiments Adopted

Requirements for apparatus, facilities, and crew to perform the experiments adopted have been summarized in two categories: (1) the requirements for personnel and equipment which are used mainly in connection with one or a few of the experiments, and (2) the general research facilities which are utilized by many experiments. The experiment-peculiar requirements are summarized in Table 5-I, and the general experimental facility requirements are described in Table 5-II.

Table 5-I is a summary of the requirements for the individual experiments taken in part from the brief descriptions of experiments given in Appendix E. The weight of fuel cells and combustibles to generate the required power has been included, but the volume requirements do not include fuel cell volumes. The total weight of apparatus is slightly less than the sum of the entries in the table, since the telescope used for the starlight-bending experiment is the instrument used in the solar-oblateness measurement and has been included only once in the total. In addition to the 16-man scientific crew required to perform all the experiments in a single 90-day period, an estimated nine-man crew is required to operate and maintain the spacecraft proper, for a total crew estimate of 25 men.

In considering apparatus requirements, the experiments have been considered in four groups, based upon commonality of the laboratory procedures to be employed. The four groups are: (1) astronomical observations, (2) biological experiments, (3) physical science experiments, and (4) metallurgical experiments. The requirements for the astronomical observations are primarily the specialized telescope, one operator, and about 200 pounds of photographic plates. Some use of the

EXPERIMENT	WEIGHT (POUNDS)	VOLUME (FT^3)	ENERGY REQUIRED (90 DAY MISSION) Kw HR.	FUEL CELL WT. (POUNDS)	TOTAL WT. (POUNDS)
BENDING OF STARLIGHT	300	2.5	0.6	3.0	303
SUN'S OBLATENESS	300	2.5	0.5	3.0	303
CELL DIVISION & EXPERIMENTAL CYTOBIOLOGY	700	27.0	240	1190	1890
EXPERIMENTAL EMBRYOLOGY	850	24.0	230	1160	2010
TROPIC RESPONSES & MORPHOGENESIS OF PLANTS	1100	35.0	325	1620	2720
BIOLOGICAL TRANSPORT PHENOMENA	650	25.0	195	975	1625
FUNDAMENTAL MICROBIOLOGY	500	15.0	215	1080	1580
MACROGAS	65	2.0	27.0	135	200
OSCILLATIONS OF FREE LIQUID DROPS	50	1.5	180.0	900	950
BUBBLE FORMATION	100	4.0	68	338	438
CRITICAL - STATE BEHAVIOR	25	1.5	45.0	225	250
DYNAMIC & STATIC CAPILLARITY	200	5.0	45.0	225	425
ARTIFICIAL & NATURAL METEOROIDS	300	2.5	90.0	450	750
CRYSTALLIZATION & ULTRAPURE MATERIALS	90	3.0	36.0	180	270
MASS SPECTROGRAPHY	20	0.7	11	54	74
EXPERIMENT PECULIAR REQUIREMENTS					
TOTALS	5150	151.2 (1)	1708	8538 (2)	13688 (3)

TABLE 5-I

MMARY OF EXPERIMENT-PECULIAR REQUIREMENTS (NOT INCLUDING GENERAL EXPERIMENTAL FACILITIES)

CREW REQUIREMENTS (90 DAY MISSION)	STABILIZATION REQ'D (G's)	EVA REQUIRED	ORBIT REQUIREMENTS	COMMENTS
100 HOURS 0.5 ASTRONAUT	NO REQUIREMENTS	YES	BELOW RADIATION BELTS TO PREVENT FOGGING OF PHOTO PLATES (ie 300nml)	DRIFT RATE <0.02 SECONDS OF ARC PER 5 SECO EXPOSURE TIME. 200 POUNDS OF DATA TO BE RETURNED TO EART
50 HOURS 0.5 ASTRONAUT	NO REQUIREMENTS	YES	BELOW RADIATION BELTS (ie 300 nml)	TELESCOPE IS SAME AS THAT USED IN STARLIGH PHOTOGRAPHIC PLATE SIZE IS SMALLER 200
1100 HOURS 1.0 CYTOLOGIST 0.25 HISTOLOGIST 0.50 LAB. TECH.	10^{-3}	NO	NONE	RADIO-ISOTOPES WILL BE USED AND WILL REQUI WET LAB. ANALYSES WILL ALSO BE PERFORME 175 POUNDS OF DATA TO BE RETURNED TO EART
1000 HOURS 1.0 EMBRYOLOGIST 0.50 HISTOLOGIST 0.25 LAB. TECH.	10^{-3}	NO	NONE	WET LABORATORY ANALYSES WILL BE PERFORM LIVE ANIMALS WILL BE KEPT IN BOTH ZERO"G" A "G" ENVIRONMENT. 175 POUNDS OF DATA TO
1500 HOURS 1.0 BOTANIST 0.25 HISTOLOGIST 1.0 LAB TECH.	$2X10^{-7}$	YES	NONE	REGION III (ie SMALL MANEUVERABLE SATELLITE VERY LOW "G" EXPERIMENTS IS REQUIRED. RADIO-ISOTOPES WILL BE USED FOR AUTO-RADIO 100 POUNDS OF DATA TO BE RETURNED TO EART
780 HOURS 1.0 BIOCHEMIST 0.25 LAB. TECH.	10^{-3}	NO	NONE	RADIO-ISOTOPES WILL BE USED; REQUIRING SPEC HANDLING. 100 POUNDS OF DATA TO BE RETURNED TO EART
1200 HOURS 1.0 MICROBIOLOGIST 1.0 LAB. TECH.	RANGE 1.0 to 10^{-6}	NO	NONE	RADIO-ISOTOPES WILL BE USED REQUIRING SPEC HANDLING. WET LAB ANALYSES WILL BE PERF 130 POUNDS OF DATA TO BE RETURNED TO EART
900 HOURS 1.25 PHYSICIST	10^{-4}	NO	NONE	EXPERIMENTAL APPARATUS MUST BE ISOLATED VIBRATIONS IN THE RANGE 10 CPS TO 10 KCPS.
360 HOURS 0.5 PHYSICIST	10^{-5}	NO	NONE	EXPERIMENTAL APPARATUS MUST BE MECHANICA FROM SPACECRAFT. "G" LEVELS HIGHER THAN 10-
180 HOURS 0.25 PHYSICIST	10^{-4}	NO	NONE	DATA TO BE REDUCED IN SPACE WITH MINIMUM A DATA TO BE RETURNED TO EARTH
180 HOURS 0.25 PHYSICIST	10^{-4}	NO	NONE	DATA TO BE REDUCED IN SPACE WITH MINIMUM A DATA TO BE RETURNED TO EARTH.
180 HOURS 0.25 PHYSICIST	10^{-4}	NO	NONE	DATA TO BE REDUCED IN SPACE WITH MINIMUM A DATA TO BE RETURNED TO EARTH.
710 HOURS 1.0 METALLURGIST	10^{-4}	YES	EITHER SUN-SYNCHRON OR HIGH ALTITUDE ORBIT TO OBTAIN LONG LIGHT PERIODS (>4 HOURS)	THE POINTING ACCURACY OF THE SOLAR FUR IS ± 6 MINUTES OF ARC.
1400 HOURS 1.0 METALLURGIST 1.0 PHYSICIST	10^{-4}	YES	600 nmile MINIMUM ALTITUDE PREFERRED TO MINIMIZE SURFACE DEGRADATION	THE POINTING ACCURACY OF THE SOLAR FURNAC MINUTES OF ARC.
360 HOURS 0.5 PHYSICIST	NO REQUIREMENTS	YES	NEAR-EARTH TO MAXIMIZE METEOROID FLUX	SPECTROGRAPH MUST POINT AWAY FROM EARTH METEOROID FLUX IS UNIDIRECTIONAL, COMING F SPACE.
10000 HOURS 16 MEN (4)				

1 DOES NOT INCLUDE FUEL CELL VOLUME OF 75
2 INCLUDES CONVERTER, FUEL & TANKAGE
3 DOES NOT INCLUDE WT. OF MEN AND LIFE SUPP
4. DOES NOT INCLUDE CREW OF 9 MEN

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LY ISOLATED 5 CAN BE TOLERATED	BUT TEST DURATION WOULD BE SHORTENED. 10^{-3}g IS UPPER LIMIT.

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TABLE 5-II

GENERAL EXPERIMENTAL FACILITIES

	Weight	Volume
Experimental Chambers (biology)	730 lb	125 cu ft
Photographic Laboratory	1,000	168
Metallurgical Equipment	450	5
Miscellaneous (electronics, etc.)	4,000	130
Aquarium (including sea water)	4,000	60
Subtotal	10,180	488
Contingency (15%)	1,500	73
Total	11,680 lb	561 cu ft

spacecraft photographic facilities is required, but the bulk of the plates will be returned to earth for processing and analysis.

The specialized telescope with small aperture and wide field-of-view (utilized for the two measurements) requires stabilization only in the three angular degrees of freedom; i.e., according to stabilization Category IV. The telescope must be mounted on a stabilized platform which is, in turn, mounted to the spacecraft. The platform could be mounted either internally to the spacecraft in the Category I region, or external to the spacecraft. External mounting would place less severe limits on the permissible orientation and angular motion of the spacecraft while the telescope is in use. Internal mounting would require a window in the spacecraft but would greatly facilitate the problems of photographic plate handling. In the absence of the guidance required to allow plausible assumptions regarding the limits to be placed on spacecraft orientation while the telescope is in use, a choice between internal and external mounting cannot presently be made. The design of the mounting platform for the telescope and the plate handling technique to be employed will depend largely on the choice.

To possibly identify future major problems to be encountered in integration of apparatus into a spacecraft, some preliminary sketches were prepared to show how the apparatus for each of the major groups of experiments might be configured within an 18-foot-diameter cylinder. The cylindrical shape is arbitrary since it is too early to make a reasonable assumption regarding the shape which will ultimately be adopted for the spacecraft.

Figure 5-1 is a conceptual sketch of a possible configuration of the apparatus required for the metallurgical experiments. The solar furnace used to raise samples to high temperatures is shown mounted outside the spacecraft with samples being placed at the focal zone of the furnace either manually, during an extravehicular operation, or by manipulators which pass the samples through a lock near the furnace. To balance the radiation pressure and minimize the resulting acceleration of samples in the solar furnace, half of the incident radiation is focused on one side of the sample by a mirror and half is focused on the opposite side of the sample by a lens. The lens and mirror are mounted coaxially in a frame which is mounted on an external arm in an extravehicular operation after launch. The success to be expected in manual-visual tracking of the sun by the solar furnace and the success in manually-visually maintaining free-floating samples at the focal point are questionable but not beyond consideration. Solar sensors can be added to the solar furnace and servoed to propulsion jets so that automatic pointing can be achieved. A servo system utilizing magnetic restoring forces or gas jets to maintain samples at the focal zone could be provided if design study and prototype work should indicate that automatic control is required.

In addition to the experiment-peculiar requirements summarized in Table 5-I, the experiments will use the experimental facilities summarized in Table 5-II. If a configuration for the orbiting station is chosen in which a substantial fraction of the volume of the spacecraft is in rotation to provide an "artificial" gravitational field to facilitate routine living functions, some of the experimental facilities should be located in the rotating portion of the spacecraft. The handling of fluids in the photographic darkroom, and for some purposes in connection with the handling of biological samples, would be simplified by the presence of a gravitational field. Other of the facilities should be located in the nonrotating, low-G region of the spacecraft. Detailed specification of the facilities that should be located in the rotating region of the spacecraft does not seem indicated at the present stage of planning, since it is not now possible to make a reasonable assumption as to whether the spacecraft will or will not have an appreciable fraction of its volume in rotation.

Personnel requirements to conduct the experiments identified indicate that in addition to the 16 trained scientific personnel required to perform the experiments (Table 5-I), additional personnel are required to act as pilot and spacecraft maintenance and operational personnel. A minimum of three men per shift seems reasonable; one as pilot or general spacecraft commander and controller, and two to perform routine maintenance and surveillance functions. Three men per shift for three shifts per day gives a total estimate of nine for the required crew complement for spacecraft operations and maintenance, and a total estimated crew requirement of 25.

The total requirements for the partial experimental program considered are as follows:

	Weight	Volume
Experiment-Peculiar Requirements (Table 5-I)	13,688 lb	151 cu ft
Experimental Facilities Requirements (Table 5-II)	11,680 lb	561 cu ft
Total	25,368 lb	712 cu ft*

Total crew requirement for performance of all experiments in 90 days - 25 men (16 scientific personnel and 9 other).

* Does not include fuel cell and tank volumes.

As can be seen from Table 5-III, the requirements of the experiments considered can be accommodated within the weight, volume, and crew capabilities of the larger of the space stations defined by earlier engineering studies. The larger of the stations considered will sustain a 25-man crew and about 50,000 pounds of "systems", or experimental apparatus. Having completed the experiments identified in the first 90-day period, the crew can be rotated and replaced with personnel trained to carry out additional experiments or studies in the station during a subsequent operational period. Apparatus to replace some of the apparatus on the station also can be provided for use in subsequent operational periods.

TABLE 5-III

SOME PARAMETERS OF MANNED SPACE STATIONS
DEFINED BY PREVIOUSLY COMPLETED ENGINEERING STUDIES

	Title of Study		
	Large Orbiting Research Laboratory (LORL) (Lockheed-Calif.)	Manned Orbital Space Station (MOSS) (NAA, S&ID)	Manned Orbital Research Laboratory (MORL) (Douglas M&SSD)
Station Crew Size	24 nominal, 36 maximum	21	6
Station Operational Period	1 year to 5 years	1 year to 5 years	1 year to 2 years
Resupply Schedule Considered	12 men & 15,455 lb cargo per 90 days	6-8 week crew stay time. Resupply with either 3-man Apollo or modified 5-man Apollo	2 new crew & 4,000 lb per 45 days
Manhours for Experimental Program	--	--	45 manhours per day
Orbit Considered	260 naut mi, 29.5° incline	400 naut mi, between 40° N&S latitudes	200 naut mi, 28.72° incline
Gravitational Environment in Station	0.21G to 0.41G in radial modules of rotating station with a "zero-G" central capsule	0.39G maximum in rotating station	"zero-G" nonrotating station with centrifuge for crew conditioning

TABLE 5-III (contd)

SOME PARAMETERS OF MANNED SPACE STATIONS
DEFINED BY PREVIOUSLY COMPLETED ENGINEERING STUDIES

	Title of Study: Large Orbiting Research Laboratory (LORL) (Lockheed-Calif.)	Manned Orbital Space Station (MOSS) (NAA, S&ID)	Manned Orbital Research Laboratory (MORL) (Douglas M&SSD)
Station Weights	Structure 104,660 lb Systems 51,193 Propel. etc. 9,867 Expendables 81,780 Station Launch 247,500 lb	Structure 75,150 Equipment 63,450 Apollo Veh. 15,900 Apollo Escape System 5,800 Interstage 10,000 Launch Config. 170,300 lb	Total: 33,900 lb
Volume	Gross: 67,300 cu ft Module Floor Area: 3,160 sq ft	Total: 34,000 cu ft	Total: 9,118 cu ft
Power	Light: Av. 32 kW Peak 42 kW Dark: Av. 22 kW Peak 36 kW	16.2 kW	6.039 kW

5.4 Consideration of Spacecraft Configuration

Several engineering studies of manned space stations for post-Apollo time have been completed. Table 5-III is a short listing of some of the parameters of the stations as defined by the studies. Crew sizes considered range from six to 36 personnel aboard the space stations, operational periods of the stations range from 1 to 5 years, and station weights range from 40,000 pounds to 270,000 pounds. While the launch weight for the largest station included in the table is 247,500 pounds, the operational concept is to launch the station without the crew and some of the apparatus, and supply personnel and apparatus to the station via subsequent launches. Resupply schedules range from a few to a dozen personnel exchanged from earth to the station at the end of each 90-day period and from 8,000 pounds to 15,000 pounds of cargo in the same period. Orbits considered are from 200 to 400 nautical miles altitude.

In choosing a configuration for the space stations, it has been assumed in each case that the personnel in the station require access to a region in the station in which a substantial gravitational field is provided by rotating that part of the station. In one case, the configuration of the station is basically a cylinder which is not in rotation, but within the cylinder there is provided a centrifuge in which two crew members at a time may sit and experience a gravitational field as the centrifuge is operated. The operational procedure to be employed is for the personnel to function continually in the "zero-G" environment with occasional short periods spent on the centrifuge for "reconditioning", especially just prior to reentry from the station.

A configuration considered in another of the studies is to have the space station in rotation to provide a continuous gravitational field. Apparatus may be "free floated" at the center of mass of the system, of course, and the configuration is described as including a "zero-G" capsule consisting of the central module of the structure within which the center of mass of the vehicle is located. The parts of the structure located further from the center of the mass in radially extending modules and in modules arranged toroidally around the central module are utilized both as laboratory space and as crew living quarters. Gravitational fields ranging from 0.20 to 0.41 times earth gravity are presently envisioned for the noncentral modules. The presence of the gravitational field may prevent the onset of some undesired physical symptoms in the personnel, and will allow routine functions such as eating, sleeping, bathing, fluid handling, and recreational activities to be performed by familiar procedures. The general problem of fluid handling is, of course, greatly simplified by virtue of the presence of a gravitational field in much of the volume of the station.

The experiments adopted for detailed consideration in the present study require apparatus to be located in a low-G region of the spacecraft, i.e., in a region which is not in rotation. The experiments also require that some samples, particularly biological, be maintained in gravitational fields of a strength comparable to earth gravity. It seems desirable to provide crew living space in which a gravitational field is induced, if it is not too costly to do so. In establishing the spacecraft configuration to accommodate an experimental program, one problem is to determine the optimum ratio of nonrotation, or "low-G", volume to the rotating, or "artificial-G", volume. Since the experiments considered in detail in the present study represent only a portion of the experimental program which will ultimately be adopted for a manned space station, no quantitative determination should be attempted at present.

A related question is the tolerance of personnel to the gradients present in a gravitational field generated by the rotation of a structure of relatively small dimensions. By way of illustration, a 6-foot man standing on a platform that is rotating on a 12-foot radius would experience at the location of his head a gravitational field half the strength of the field at his feet. In moving about on the platform, particularly in performing motions in which he changes the distance of his head from the center of rotation, it is feared that the continually changing gravitational field experienced by the man might induce serious vestibular disturbances. Considerable experience must be acquired before the criteria for personnel utilization of modules having large gravitational field gradients can be formulated in detail.

To identify further the problem of choosing the optimum configuration of a space-station vehicle to accommodate a research program, four possible basic configurations are indicated in Fig. 5-2. Part A of Fig. 5-2 indicates a configuration in which a low-G volume is provided at the center of the structure and the volume to be used for crew living quarters and for some of the experimental work is located relatively far from the center of the structure to minimize the gravitational field gradient in the living and working space. Part B of the figure indicates an alternate concept in which the spacecraft consists of two coaxial cylinders, one rotating to provide an artificial-G environment and one stabilized and not rotating within which the low-G environment is available. Both of the configurations will have a total angular momentum by virtue of the rotational motion.

Part C of the figure indicates a spacecraft configuration in which the artificial-G region is divided into two parts, with one part on either side of the central nonrotating section. By rotating the two end sections in opposite directions at the appropriate relative angular velocities, the total angular momentum of the spacecraft can be made equal to zero. Part D of the figure indicates the concept of a single, nonrotating cylinder which may be provided, if necessary, with a personnel-conditioning centrifuge.

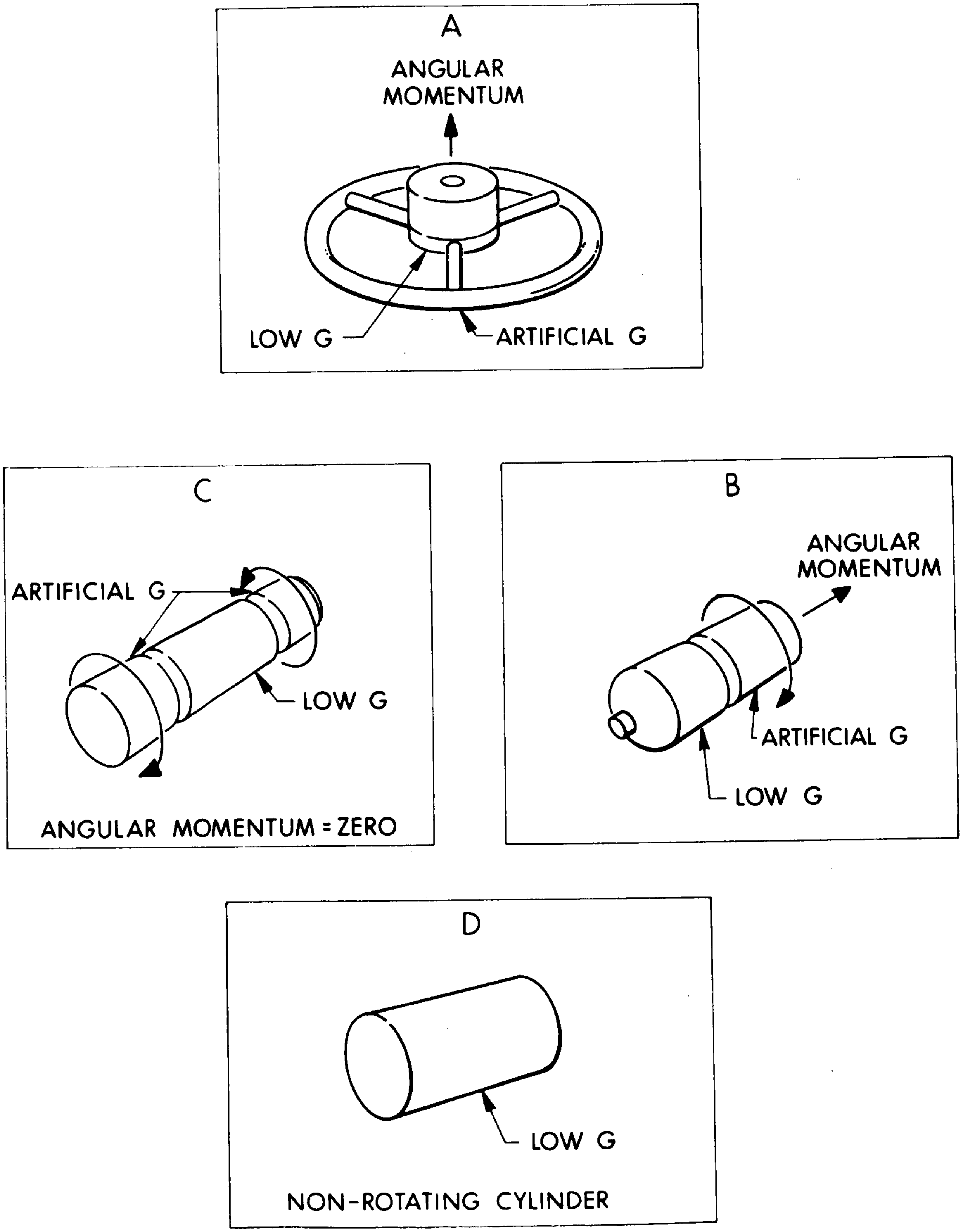

FIG. 5-2 POSSIBLE BASIC SPACECRAFT CONFIGURATIONS

A comparison may be made of the advantages and disadvantages of the four configurations. The large-diameter rotating structure, ("A" of Fig. 5-2), has the advantage of a relatively lower gravitational gradient in the working and living space, but has disadvantages in that the structure is large and must be either unfolded or assembled from a compact configuration required for launch, that the structure will be significantly heavier and more costly than other structures for the same volume, and that the spacecraft must necessarily have an appreciable angular momentum about its axis of symmetry. In the coaxial configuration, (designated as "B" in Fig. 5-2), the structure can be launched in the final configuration, obviating the necessity of unfolding or assembly. It also can be lighter and less costly for a given total volume than configuration "A". One major disadvantage of configuration "B" is the requirement for a rotating coupling or bearing between the two sections of the spacecraft. The design of a suitable coupling would be a major engineering undertaking. Another disadvantage is the problem of absorbing the angular momentum of a crewman as transfer is made from one section of the spacecraft to another. The spacecraft will also require a stabilization system to maintain the low-G section at zero angular velocity, or at the desired small angular velocity if gravity-gradient stabilized motion is desired. The spacecraft will have an appreciable angular momentum, as in the previous configuration. If gravity-gradient stabilization is desired for the nonrotating section, the angular momentum must be aligned precisely normal to the plane of the orbital motion, and a precise stabilization and control system will be required for this purpose.

The contrarotating configuration, (identified as "C") is comparable to configuration "B" with the additional disadvantage that two couplings are required instead of one. Since the total angular momentum of the spacecraft can be made to equal zero, the entire vehicle can be stablized and oriented more readily than the two considered previously, but the requirement for precise stabilization control will exist. If full advantage is to be taken of the contrarotation to achieve zero angular momentum, the rotating couplings must be of a more sophisticated design capable of rigidly transmitting torques normal to the symmetry axis.

Most advantageous mechanically is the simple, nonrotating cylindrical configuration indicated as "D" in Fig. 5-2. The simple configuration has the obvious advantages of being a lighter and less costly structure than any of the others, but it does not provide space in which a gravitational field exists. The experimental program requires samples maintained in gravitational fields, independent of the question of whether periodic conditioning of personnel by use of a centrifuge is sufficient. The spacecraft can be made to have zero total angular momentum by designing the required centrifuges with balanced contrarotating sections.

Underlying the problem of optimizing the configuration eventually to be adopted for a manned orbiting space station is the choice of the ratio of the stabilized, low-G volume to the volume of the rotating region containing a gravitational field, the questions of whether living quarters should be provided with artificial gravity, what the allowable value of the gradient should be, and whether periodic conditioning of personnel is sufficient and extended low-G living is not too uncomfortable. The present study of some specific experiments to be conducted in a manned space station has not provided any appreciable progress toward answering the questions concerning spacecraft configuration, but it has served to clarify the tradeoffs which must eventually be made.

6. DISCUSSION OF AN OVERALL PROGRAM

6.1 General

One objective of the present study is to provide background material for two elements of the program plan which will be required to specify the scientific requirements of a post-Apollo manned space laboratory:

1. A scientific justification for the experiments to be conducted and a definite answer to the question why an experimental program should be prepared for a zero-G laboratory.
2. A summary of the expected capabilities and limitations of an orbital laboratory.

Three subjects are to be addressed: (1) justification for a research program, (2) scientific justification for individual experiments selected for the program, and (3) a description of the capabilities of an orbiting laboratory. Because the three subjects clearly require consideration in somewhat different context, they are discussed separately in the present section. Some general background consideration also is presented.

6.2 Justification for a Manned Space Research Program

The scientific justification for a manned space research program is part of the more general question, "What is the justification, scientific and otherwise, for any research program?" A separate but related question is, "Having decided upon a given level of support for research activities, what criteria should be used in choosing the activities to be supported?" No simple or widely accepted answer to either question exists.

Scientific activities are often divided into the following three categories:

1. Basic research - effort that is motivated only by a desire to acquire new knowledge.
2. Applied research - effort that is motivated by a desire to achieve a practical application of technology to a need recognized at the outset of the research activity.
3. Development - effort that is undertaken to achieve and verify solutions to specific technical problems which have been identified in the course of generating new applications of technology.

Taking the term "support" to be more or less synonymous with the term "funding," the institutions for society's support of science can be identified in three categories:

1. Industrial (profit making) organizations
2. Government agencies
3. Educational and other nonprofit organizations

Considering the first point, it may be taken as an observed fact that society does support scientific research activities. Society does so because science contributes to some of the goals which the supporting society has chosen for itself. The social goals to which science contributes can be identified under four headings:

1. Science contributes to culture.
2. Science contributes to physical well-being (public health, military defense).
3. Science contributes to economic well-being.
4. Science is an essential element of education.

Table 6-I shows figures compiled by the National Science Foundation for 1962 (the latest year for which statistics are available). These figures indicate the relative amount of support provided by the three categories of supporting agencies to the three classes of scientific activities.

TABLE 6-I

RELATIVE LEVEL OF SUPPORT OF SCIENTIFIC ACTIVITIES
BY TYPE OF ACTIVITY AND FUNDING AGENCY
FOR FY 1962

Total = $14.7 Billion/Year

Type of Scientific Activity \ Category of Supporting Agency	Industry (percent)	Government (percent)	Educational (percent)	Total (percent)
Basic Research	2	7	1.5	10.5
Applied Research	6	15	1	22
Development	24	43	0.5	67.5
Total	32	65	3	100

To match the table against the four categories of motivation for society's support of research, industrial support (32 percent) is largely derived from a desire for economic return on investment and is synonymous with the motivation of achieving beneficial application to the economy and economic advancement of the society. Research sponsored by universities and other nonprofit organizations (3 percent) is motivated largely as a cultural activity and in support of education, but to some extent is undertaken in the hope of contributing to the physical well-being of society through public health and safety, and national defense. The government-sponsored activities (65 percent) are undertaken in support of each of the four social goals identified. Nearly all Federal funds allocated in support of research are administered by government agencies which are charged with a primary mission which is nonscientific in itself - military preparedness and operations, public health, education, welfare, etc. The nature of the research activities supported, quite naturally and understandably, is influenced strongly by the character of the primary mission of the government agency providing the support.

In summary, the U. S. is presently supporting research and development activities at the level of about $15 billion per year, or 3 percent of the Gross National Product. Of the $15 billion annually, 65 percent ($10 billion) is administered by the various agencies of the Federal government in widely diverse technical areas and with a wide diversity of motivations or "justifications". While 10 percent of all research and development activities is classified as "basic" research, 11 percent of government-sponsored activities (or 7 percent of the total R&D effort) is classified as basic.

While it seems clear that society believes that support of science is desirable because science contributes to the goals of society, and that the general level of support at 3 percent of the Gross National Product is reasonable, and that it is proper that a large fraction of the support be by public funds administered by government agencies, there is a very considerable lack of agreement as to which specific fields of science and specific projects within fields should be supported. At nearly all levels of scientific planning, in all fields of technical discipline, and across the spectrum from basic science to development work, a continuing decision-making and selection process is required to select among proposals competing for the available support. Probably no one feels that all decisions have been made correctly, either with regard to which proposals have been accepted or with respect to the level of support allocated to proposals after acceptance. At the same time, there does not seem to be any strong body of opinion favoring a major change in existing mechanisms for allocation of support to scientific activities.

The criteria used for selecting the research activities to be supported vary widely with the missions and objectives of the agency providing the support. Industrial organizations naturally favor activities which appear to offer the possibility of a financial return, while universities are more likely to favor proposals solely because of a widely accepted reputation for intellectual accomplishment on the part of the sponsor or sponsors. The criteria employed by government agencies vary widely with the agency, but generally a connection between the primary mission goals of the agency and the goals of the research activities sponsored is readily apparent.

To discuss justification of a major scientific research program to be carried out in a large post-Apollo manned spacecraft, some assumptions are made as to the nature and scope of the program:

1. The program will include basic scientific objectives, applied scientific objectives, and development activities.
2. The program will include objectives in many traditional scientific disciplines (astronomy, meteorology, etc.).
3. The program will be (predominantly) supported by an agency of the U. S. Government (NASA).
4. The program will be sufficiently large that competition for the available support will be felt both internally and externally by the sponsoring agency.

The first aspect of justification for the program concerns the relationship of the program to the major mission of the sponsoring agency. The second is whether competing programs of similar scope would better support the agency's mission. The third factor to be considered is whether programs of other agencies with other missions should be supported instead. A discussion of the third point is beyond the scope of this document.

The starting point is taken by recognizing the mission of NASA (as defined by the Congress) to be that of developing and utilizing the technological capabilities of the United States for space exploration and space operations. Support of space sciences is part of the stated mission. Achieving beneficial applications of space technology to the economy and to education is also part of the stated mission, while military application of space technology is not.

The single, major current program of NASA is Apollo, with the objective of a manned flight to the moon in 1970. Manned space flight activities presently represent about one-half of all NASA activities. Beyond Apollo, no future major objectives for NASA manned space flight programs have been announced. A recognized potential objective is that of conducting a manned flight to Mars at the 1985 opportunity.

In the immediate post-Apollo era, it is to be assumed that the technological and operational problems of maintaining men at high functional efficiency in space for periods in excess of 2 weeks will have been solved. In considering manned flight to Mars, the problems posed by considerably longer flight duration (perhaps 500 days) must be faced. A large orbiting spacecraft that is operational for several years immediately following Apollo seems clearly to be a most desirable facility in which to perform the applied scientific research and gain the operational experience necessary to maintain the national posture which will allow commitment to the objective of manned flight to Mars.

Considering a major post-Apollo manned space research program in light of the given NASA mission goals, the following "justification" is readily apparent:

1. The purely scientific activities of the program clearly accomplish the stated NASA mission objective of supporting and contributing to science generally.
2. A research program in which personnel are maintained in the near-earth space environment for extended periods is necessary to develop the capability for long-duration manned space flight, an objective clearly consistent with the stated mission of NASA.

It may be noted that extended operations on the lunar surface are being considered as the basis for formulating major manned space-flight programs for the post-Apollo time period. A major research program also can be conducted as one aspect of those extended lunar operations. A moon base would offer somewhat different, but clearly comparable, opportunity and facility for the conduct of research. A comparison of the two programs, extensive lunar operations and a large manned space station for the post-Apollo era, is beyond the present scope.

In summary, the question of justifying a research program for a large, manned post-Apollo space vehicle has been viewed in the context usually adopted when considering major allocations of public funds by agencies of the U. S. Government in support of scientific research and development activities. Within the usual context, the research program considered will clearly contribute to two important given mission goals of NASA, namely the support of basic science and the development of the capability for space operations.

6.3 Scientific Justification for Individual Experiments Selected for the Program

The criteria used in weighing the scientific justification for individual experiments to be included in a research program are obviously different from the criteria applicable to the question of justifying a major research program. As mentioned earlier, individual experiments fall into one of the three following categories:

1. Development work
2. Applied science
3. Basic science

The criteria used in further judging a particular experiment vary considerably from one category to the other.

6.3.1 Development Experiments

Development experiments are often tests of working-material systems which are conducted to observe the response of the systems to environmental factors or artificial stresses for the purpose of confirming that the system will operate as designed, or to quantitatively observe the performance of the system in the event that it does not operate as designed. The criteria for merit of development experiments are whether the system to be tested will be useful if it should be developed later, whether the test or development procedure will subject the system to stresses which bear a known relationship to the stresses under which the final product must function, and whether the departures from predicted operation during the test will be recorded in an interpretable way.

6.3.2 Applied Science

Applied scientific work is more difficult to discuss generally, since experiments may take a wide variety of forms with respect to objective and method employed. One class of experiments which would clearly fall under the heading of applied science would be a series of observations to determine the effects of drugs on the vestibular function of personnel in the weightless environment. The criteria for scientific justification of the measurements would be the degree to which the effects of the drugs to be used were presently understood, the degree to which side effects of the drugs were present or absent, the statistical validity of the results to be obtained, and the likelihood that results of the measurements might suggest some beneficial routine use of the drugs in future manned space flights to counteract some ill effects of the environment.

6.3.3 Basic Science

Basic scientific experiments are characterized in part by the absence of any foreseeable practical application of the results at the time of undertaking the experiments. The criterion for merit of an individual experiment is whether and to what extent the experiment will acquire new knowledge. Criteria for judging in advance the likelihood that a particular proposed experiment will acquire significant new knowledge, and how much, are only moderately well developed, but experiments which meet one of the four following criteria are generally accepted as being well conceived:

1. The experimental measurement will confirm or deny a prediction of a theory which rests on considerable prior experimental evidence.

2. The experimental measurement will confirm or deny a clear and unambiguous ad hoc hypothesis relating several previously known facts.
3. The experimental measurement will determine the magnitude or numerical value of a parameter or parameters of a theory where no doubt exists concerning the applicability of the theory, but where magnitudes of the constants are not known.
4. The experimental measurement constitutes the first observation in an environment or regime where no observations have been made before (i.e., exploration).

The experiments considered in depth in the present study have the common feature of being of a basic scientific character, and each was selected to satisfy one of the criteria stated. Details regarding the theories and hypotheses to be tested, the parameters to be measured, and the character of new environments and regimes to be explored by the individual experiments are described elsewhere in the three sections which discuss the experiments in each of the three areas of scientific discipline.

In summary, scientific justification for individual scientific experiments is to be discussed in a considerably different context than justification for an entire program. The criterion of merit for development-type experiments is often that of whether a valid test will be achieved; for applied science experiments, that of whether the results are likely to find application. For basic scientific experiments, the only criterion for merit is that of whether significant new knowledge is likely to be acquired. Four generally accepted criteria for the formulation of basic scientific experiments are stated, and these constitute the scientific justification for the experiments considered in depth in the present study.

6.4 Summary of the Expected Capabilities and Limitations of an Orbital Laboratory

The capabilities of a post-Apollo manned orbital laboratory are summarized in this subsection. For purposes of the summary, reference has been made to the several independent engineering studies of manned orbiting space stations for the post-Apollo period which have been made or are in progress. The manned orbiting stations considered in the studies vary as to size and complexity, and as to the scope of the operations which can be accommodated. A composite among the various space stations would be a system with characteristics in the following ranges:

1.	Crew size	6 to 35
2.	Weight in orbit	15,000 to 270,000 lbs
3.	Manhours per year for operational or experimental programs	5,000 to 20,000
4.	Operational period	1 to 5 years
5.	Annual resupply	5,000 to 20,000 lbs per year of apparatus

For the composite system placed in low-earth orbit, the expected capabilities are summarized as follows:

1. Utilitarian Functions
    - a. Military Surveillance
    - b. Meteorological Surveillance
    - c. Agricultural Surveillance
    - d. Oceanographic Surveillance
    - e. Assembly and Launch of Deep Space Vehicles
    - f. Communications

2. Development of Advanced Technology

    (in such areas as:)

    - a. Life support systems for extended-duration space flights
    - b. Operational experience with long-duration, manned space flight systems

c. Operational experience with assembly of deep-space craft in orbit

d. Development of space navigation and rendezvous techniques

e. Operational experience with the utilization of human operators for repair of spacecraft in flight

3. Applied Research in Support of Space Technology

(in such areas as:)

a. Space medicine for long-duration flights

b. Space navigation and rendezvous techniques

c. Solar weather prediction

d. Materials for space applications

e. Earth weather forecasting

f. Communications techniques

g. Meteoroid damage control

h. Hydraulics and fluid mechanics

i. Lubrication in the space environment

4. Basic Research

(in such areas as:)

a. Astronomy

(1) visible

(2) infrared

(3) ultraviolet

b. Cosmic ray physics

c. Space environmental physics

d. Nuclear physics

e. Chemistry

f. Physics of comets

g. Studies of meteoroids

h. Biology

i. Biophysics

j. Geophysics

k. Astrophysics

l. Meteorology

m. Oceanography

n. Aeronomy

o. Fluid dynamics

p. Solid-state physics

The present study is aimed primarily at the identification and definition of basic scientific experiments in three areas of basic science (gravitation, materials, and biology). The study is restricted to considering in depth those experiments identified which require or substantially benefit from the presence of men in the space station, and is directed to emphasize those experiments which utilize the weightless environment of the station. The specific capabilities of the crew and space station employed in each of the experiments considered in depth is described in Section 4.

6.5 Relation of Scientific Program to Other Considerations

The present feasibility study of some scientific experiments to be conducted in a manned orbiting station in the post-Apollo time period constitutes a small part of the planning required to allow a decision regarding the weight to be assigned to the scientific aspects of future manned space flight programs. As indicated, scientific motivation for space activities has decreased in relative importance from the primary incentive in the mid-1950's to perhaps third priority as of the mid-1960's. The immediate need clearly exists in the planning cycle to formulate a basis for weighing the costs of scientific activities against expected returns, and for identifying the scientific (versus engineering, development, etc.) portion of planned programs, to allow reasonable apportionment of the costs among the different aspects of a given program.*

Cost estimates for the manned orbiting stations (MOS), defined by previously completed engineering studies, are indicated in Fig. 6-1. The higher curve is a rough estimate for a station resembling the largest of those considered in the studies. This curve includes the larger estimate for costs of continuing resupply operations.

In considering costs versus scientific value of the station, an indication of the costs of the present level of research and development effort in the United States is presented. Of the \$1.5 billion expended in 1962, about two-thirds was provided by the Federal government. Assuming that research costs escalate at the same rate as the projected Gross National Product (4 percent/year), the costs of U. S. basic research beyond 1962 are projected.

The purely scientific value of a large orbiting station will certainly not be the sole justification for an expenditure of about half the anticipated total Federal funds for basic research. Definition of a complete program for a manned station and adoption of a set of criteria by which the overall size and cost of the station can be estimated are required to allow assessment of the costs of the program against the expected returns from the program.

Upon achieving the present major announced goal of the national space program - a manned lunar mission - the United States

*Disappointment has been expressed in some quarters that the scientific value of space programs has not been higher; "...I admit that I am among the persons (and I believe there are quite a few) who would consider it more valuable for us, and for the generations to come, to invent some experiment on gravitons and gravity waves (if they exist) than to send a man to the moon. The preference for the man on the moon is largely due to a naive concept of science, and also to the fact that it is easier by far to send a man to the moon than it is to invent some crucial experiment on gravitation." Prof. G. Bernardini, 1963 International Conference on Sector-Focused Cyclotrons, and Meson Factories, CERN, Geneva, Switzerland, April 23, 1963.

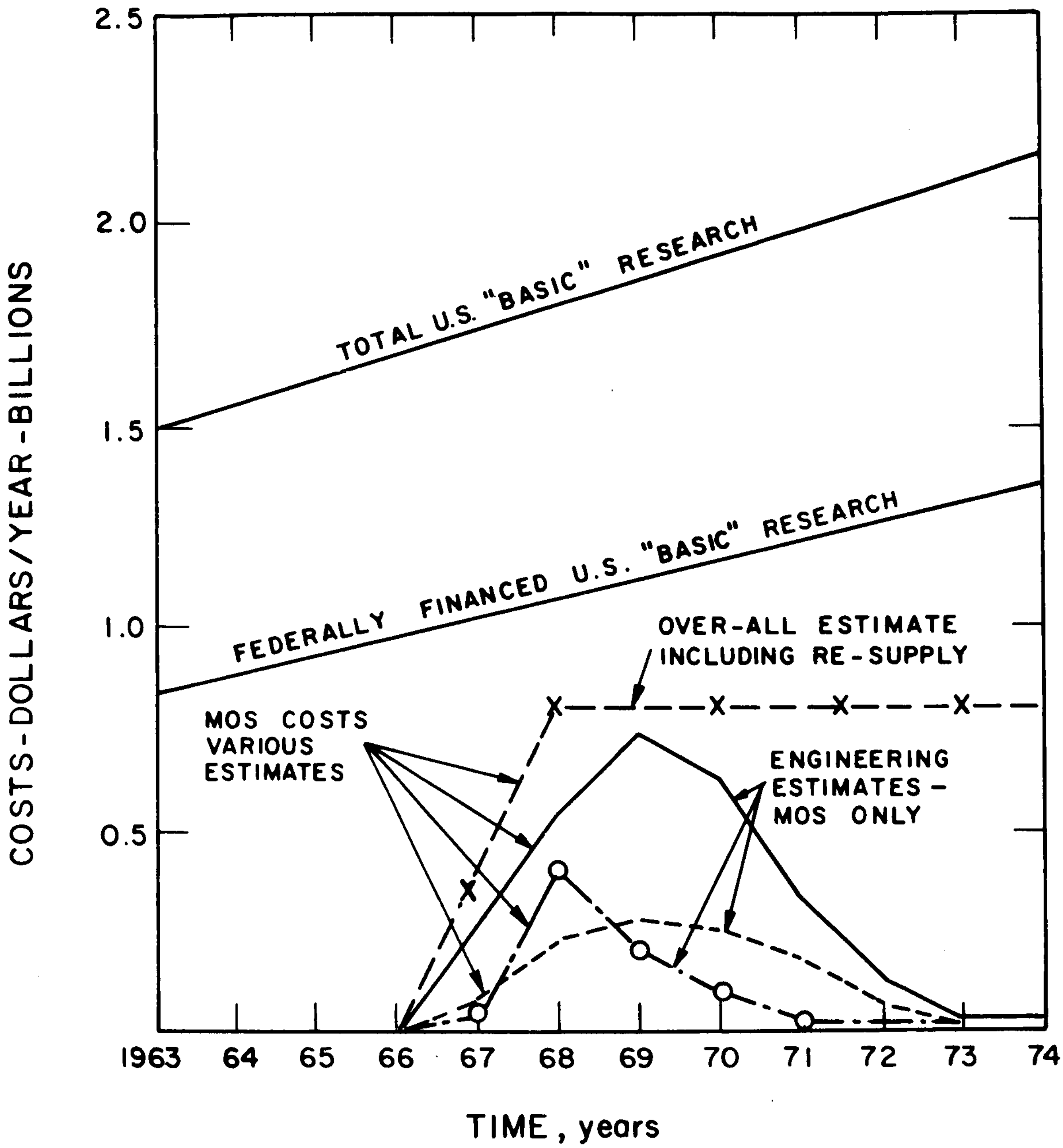

FIG. 6-1 COST ESTIMATES OF U.S. "BASIC" RESEARCH EFFORTS AND A MANNED ORBITING STATION

will in all likelihood choose further major goals for manned space flight programs. For example, extensive lunar exploration could be chosen as a major post-Apollo goal of manned space flight activities, and an extensive basic and applied research program could be incorporated into the lunar exploration operations. While a detailed comparison of the purposes and relative merits of a manned orbiting station versus a lunar exploration program is beyond the present scope, some major facets of the anticipated manned orbiting station which appear relevant are:

1. The large manned orbiting station provides an ideal laboratory for research on and development of life support systems and space-medical techniques for extended-duration life support.
2. The manned orbiting station will provide the operational experience necessary prior to a decision to undertake a Mars mission.
3. The military and economic motivation for manned orbiting stations may be significant.
4. A major scientific program can be executed.

Assignment of relative priorities among the several uses of the station will be required.

7. DETAILED CONSIDERATION OF GRAVITATION AND STABILIZATION

The gravitation and stabilization study consisted of the following two distinct phases:

1. Gravitation

   The identification and definition of experiments which would be feasibly performed in a manned orbiting laboratory to provide a more detailed scientific understanding of gravitational interactions.

2. Stabilization

   The examination of the engineering problem posed by the need to provide a well stabilized low-G environment for experiments like those described in this report.

The clear distinction between scientific and engineering questions is possible because of the very high degree of accuracy with which classical Newtonian mechanics predict the motions, under gravity, of non-relativistic systems such as spacecraft in earth orbit. No new concept of significance to spacecraft engineers is expected to result from the scientific program, nor is any engineering measurement likely to provide any new scientific concepts.

The methods and main conclusions of each of the two phases of the study are summarized in the following paragraphs.

7.1 Summary of the Gravitation Study

A thorough review of the scientific literature was conducted. The experiments discussed in the literature, as well as certain others, were analyzed to determine the feasibility of performing them in space and, in particular, in a manned spacecraft. Because of the advanced state of the science of gravity, only a few experiments of great difficulty are of interest. Of these, only two appear to be suitable for performance in manned spacecraft. The following scientific objectives were identified as being suitable for space experimentation:

1. Improvement of the measurement of the bending of starlight by the sun.
2. Measurement of the sun's oblateness.
3. Measurement of the precession of an orbiting torque-free gyroscope.
4. Measurement of the gravitational red-shift of an electromagnetic wave.
5. Measurement of the motion of a solar probe.
6. Detection of gravitational waves.

The first two objectives require the observation of the sun with a solar telescope from above the earth's atmosphere. Both measurements are appropriate for a manned orbiting laboratory. The telescope required must have a wide-field and a long focal length. The development of such a telescope is considered feasible, but the device would be large enough that it would be necessary to integrate the telescope design with the spacecraft design. Further work is needed to define the telescope design in view of the integration problem.

The next three objectives are only suitable for unmanned experimentation at the present time. The torque-free gyro experiment could perhaps be launched from a manned orbiting station, but it must remain undisturbed in orbit for a year or more. The other objectives require orbits which enter hostile regions of space.

The last objective, the detection of gravitational radiation, remains on the list because of its great scientific interest. No realizable detection apparatus has yet been invented which is likely to detect anything uniquely identifiable as gravitational radiation. An unsuccessful attempt to design such an experiment is described in this report.

A number of experiments were examined and were rejected, either because they were not of sufficient scientific interest, or because they were not feasible, or both. A list of these experiments and the reasons for their rejection is given in Table 7-I.

Four specific recommendations result from the study:

1. A suitable wide-field, long-focus solar telescope should be included in the instrument complement of a manned orbiting laboratory.
2. Development of an unmanned satellite to measure the gravitational red-shift should be considered.
3. Development of a close, unmanned solar probe should be considered.
4. A second-generation version of the unmanned torque-free gyro experiment presently under development at Stanford and Illinois should be examined at a later date to see if a manned laboratory could provide useful support.

The general conclusion of the study is as follows: No gravitational experiment of significant scientific interest which requires the facilities of a manned low-G laboratory has been proposed. The two telescope experiments which do appear attractive should properly be performed in an astronomical laboratory, not in a low-G laboratory. Engineering experiments, like those which might be performed with gravity-gradient instruments, should be considered separately as part of the engineering development program.

7.2 Summary of the Stabilization Study

Effort in the stabilization study was mainly directed at understanding two problems: (1) the determination of the relative motion of two objects placed in close orbits, and (2) the determination of the degree of isolation required between a manned spacecraft and an experimental volume whose maximum tolerable acceleration is specified. Although both of these problems are theoretically straightforward, it was felt that each must be thoroughly understood in a

TABLE 7-I

REJECTED EXPERIMENTS

Experiment No.	Title	Nature of Measurement	Scientific Interest (if feasible)	Feasibility Evaluation
1.	Low-G Geodetic Satellite	Improved determination of gravitational potential coefficients from orbit determination of low-G drag-cancelling satellite.	High	Not feasible. Drag is not a principal source of error in current measurements.
2.	Relativistic Precession of Earth Satellite	Observation of relativistic effects in an earth satellite orbit, using a low-G satellite to cancel drag.	Very High	Not feasible. Effect of smaller magnitude than the uncertainty in the precession produced by the earth's oblateness.
3.	Observation of Gravitational Waves from a Binary Star System	Construct tunable quadruple mass antenna in space. Measure output as a function of frequency in the frequency region corresponding to the period of known binary stars.	Very High	Not feasible because of a lack of sensitivity of any conceivable man-made antenna. No suitable star system appears to exist.
4.	Observation of Gravitational Waves from Periodic Sources Within the Solar System	Construct tunable quadruple mass antenna in space. Measure output as a function of frequency in the frequency region corresponding to the period of known binary stars.	Very High	Not feasible. The periods of motions within the solar system are all larger than the time required for light to travel across the solar system, so that only near-fields rather than true radiation can be observed.
5.	Improvement of the Value of the Gravitational Constant	A. Measure force between two known masses isolated in space.	Low	Not feasible. Ultimately the achievable accuracy depends on the knowledge of the force reference. The best-known force reference is the acceleration of gravity at the earth's surface.

TABLE 7-I (contd)

REJECTED EXPERIMENTS

Experiment No. Title	Nature of Measurement	Scientific Interest (if feasible)	Feasibility Evaluation
	B. Measure motion of two masses placed in space and allowed to orbit each other.	Low	Not feasible. Gravitational forces between any conceivable masses are negligible compared to other forces. An orbit near earth is not even stable because of the gravity gradient effect. Accuracy of position measurement required would be very high.
6. Neutrino Red-Shift	Observation of the neutrino Mossbauer effect as a function of G-level. No resonance can exist except in a very low-G environment.	Very High	Feasibility in doubt, because of a lack of data. Very difficult.

general way before specific hardware design is attempted. Hence, the work performed has been entirely analytical in character.

The conclusions of the study are as follows:

1. The relative motion of two objects placed in orbit near one another is not stable in general. In determining this motion between any two artificial objects of feasible size placed in earth orbit, the gravitational interaction between the two can be neglected compared to the interaction between them and the earth. Under these circumstances, the orbits have different periods unless their total energies are identical. If the total energies of the two orbits are equal, the separation of the two objects will oscillate in time unless the angular momentum vectors of the two orbits coincide exactly and the orbits are circular. The only configuration in which a finite relative separation is stable is that in which the two bodies follow the same circular orbit with at most a difference in phase. If the centers of mass of the two bodies coincide (one inside the other) constant zero separation is possible on an eccentric orbit, provided that equality between the energies and angular momenta obtains. It follows that in practice one or both objects must be propelled so that a constant relative separation can be maintained by a feedback loop. Fuel requirements can be minimized by intelligent design of the feedback loop and by placement of the experimental enclosure at the center of mass.

2. The degree of isolation required between the manned spacecraft and an experimental system evidently depends on the maximum acceleration which the experiment can tolerate. Perturbing accelerations fall into two main classes:

a. Quasi-state accelerations resulting from nongravitational forces applied to the main spacecraft or to the experimental system. Examples are: atmospheric drag, magnetic forces, radiation pressure, electric forces between spacecraft and enclosure.

b. Stochastic acceleration resulting from the motion of men or equipment, air currents, electromagnetic switching transients, and similar disturbances.

The magnitudes of some of these accelerations were estimated for a spacecraft and experimental system of a size considered feasible in an advanced mission. From these estimates it was concluded that the stochastic accelerations are far larger in magnitude than the quasi-static accelerations. Figure 7-1 shows the estimated ranges of maximum tolerable acceleration for which precautions must be taken to eliminate perturbing accelerations from the sources listed. Shielding of the experimental enclosure from air currents and electric and magnetic fields will ordinarily be required also. The degree of isolation required depends on the nature and mass of the materials used in the experimental system. At about 10^{-7}G, the laboratory enclosure must be orbited separately from the main spacecraft. At this point, precautions to eliminate electromagnetic and air current coupling certainly must be taken. Analysis discussed in detail in later sections of this report has shown that the maximum acceleration of such an isolated system may be held at 10^{-10}G if extreme care is exercised. Even if the acceleration of the center of mass of an enclosure is zero, the gravity gradient effect limits the dimensions of the enclosure over which a field of specified magnitude can be attained. The relation between the maximum radial diameter of the experimental volume and maximum tolerable acceleration is tabulated on the following text page.

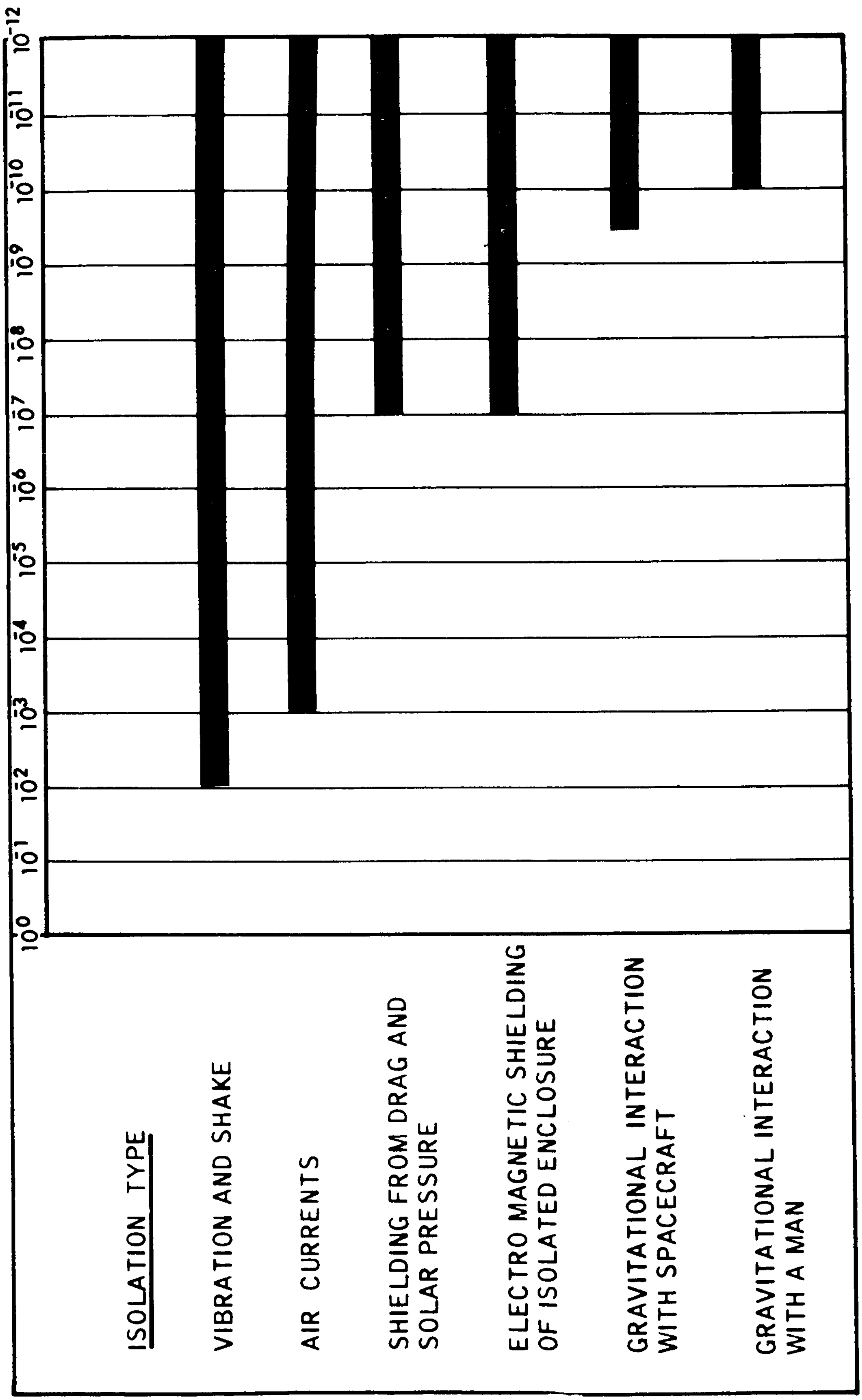

FIG. 7-1 MAXIMUM ACCEPTABLE ACCELERATION LEVEL - EARTH G

Maximum Tolerable Acceleration G's	Maximum Radial Diameter of Experimental Volume
10^{-6}	4.6 m
10^{-7}	4.6 cm
10^{-8}	4.6 cm
10^{-9}	4.6 mm
10^{-10}	0.46 mm

The dimensions of the enclosure normal to the orbital radius vector are limited by the existence of periodic terms in the gravity gradient tensor proportional to the eccentricity of the orbit. The ratio between the amplitudes of the main periodic term which is linear in the eccentricity and the radial gradient is 1/3e. If an upper limit for eccentricity in a near-earth orbit is taken as 0.03, the periodic transverse terms amount to only 1 percent of the radial term. Hence, the enclosure may be made at least an order of magnitude larger in the transverse than in the radial direction if the maximum acceptable acceleration is specified.

Comparison of the table above with Fig. 7-1 leads to the conclusion that the isolated enclosure required to eliminate external accelerations at the 10^{-7}G level need not have a useful radial dimension much larger than 50 cm. The transverse dimensions may be made larger if desired, up to 50 meters if the orbital eccentricity is about 0.03. If the enclosure is to be arbitrarily oriented, the maximum useful diameter is 50 cm. In practice, the need to eliminate electromagnetic acceleration dictates a design with a high degree of symmetry, so that the feasibility of constructing a very asymmetrically shaped enclosure has not been established.

In summary, isolation of experimental volumes from the main manned spacecraft is not necessary, if the acceptable maximum acceleration exceeds about $10^{-2}G$. An increasing degree of isolation is required in the range of 10^{-2} to 10^{-7} but, in principle, the control system reference can be the average acceleration of the spacecraft (assuming no continuous thrust is applied). At a level of $10^{-7}G$, the mean acceleration of the spacecraft is perturbed by external forces so that it is necessary to allow the experimental enclosure to orbit separately from the main spacecraft, continuously correcting the spacecraft orbit. These ranges of acceleration define the limits of Regions I, II, and III respectively. Minimum system complexity and minimum propellant use result if the isolated experimental volume (Region III) is placed at the center of mass of the main spacecraft, since an equilibrium configuration with both bodies in the same orbit then exists. Minimum gravitational interaction between the experimental enclosure and the spacecraft is also likely to occur at a position near the center of mass of the spacecraft. The maximum experimentally useful diameter of such an enclosure (excluding services) appears to be about 50 cm. If so, unless it proves feasible to build unsymmetrical enclosures, the dimension normal to the orbit radius can be considerably larger. The construction of such an enclosure to reach accelerating levels as low as $10^{-10}G$ has previously been studied in detail and appears feasible in principle.

Extreme low-G enclosures present serious problems to the instrument designer, who must devise power and data handling systems with no mechanical connection to the isolated enclosure, and with no moving parts or electromagnetic leakage fields.

Further work is required to define the nature of the problems encountered in the range 10^{-2} to $10^{-7}G$, when a continuous spectrum of isolation techniques is available. This problem, at present, appears to have higher priority than the development of a very low-G enclosure.

7.3 Consequences of Relativity Theory

7.3.1 Special Relativity

Gravitation is by far the weakest of the interactions between elementary particles. Still, the strength of the attraction between massive celestial objects is so great that it determines the structure of the entire universe. The need to explain the motions of the planets eventually gave rise to the classical mechanics of Galileo and Newton. For almost three centuries, this dynamical and gravitational theory satisfied the most rigorous experimental tests, with a degree of accuracy not yet surpassed in any field of physical science.

Successively more quantitative and detailed predictions were confirmed by experiment. By the end of the nineteenth century, many astronomers, physicists, and mathematicians accepted the Newtonian theory as though it were revealed truth rather than well-founded human conjecture. Their attitude was only reinforced by such events as the humiliation of the authoritarian philosopher Hegel, whose declaration that the perfection of the number seven implied the existence of only seven planets, preceded the discovery of the eighth, Neptune, by a matter of weeks. The embarrassment of Hegel was particularly complete because the discovery of Neptune was a spectacular triumph of the scientific method, for Neptune's position had been predicted from the measured perturbations of Uranus, using the Newtonian theory.

By the end of the nineteenth century, only a few small discrepancies remained to plague the empiricists. One such effect was the inexplicable residual advance of the perihelion of Mercury at the rate of 43 seconds of arc per century, after all known perturbations had been accounted for.

The theoreticians were concerned about an inconsistency, not between the Newtonian theory and numerology, but between the Newtonian mechanics and the electrodynamics of Maxwell. Certain terms in Maxwell's equations are required to predict the propagation of electromagnetic waves at the speed of light, a phenomenon first observed by Hertz and universally accepted soon thereafter. Yet, these same terms caused the Maxwellian equations to transform differently from the Newtonian equations where a transformation was made from a fixed frame of reference to a moving one. The experiment of Michelson and Morley, since repeated many times with greatly increased precision, showed essentially that Maxwell's equations were in fact correct in any frame, moving or not. Einstein's Special Theory of Relativity modified the Newtonian mechanical theory to make it consistent with electromagnetism. Although the Special Theory met with emotional opposition at first, its experimental support is now so overwhelming that its validity is universally accepted. The Special Theory is used daily at the engineering level in high-energy physics, where extreme relativistic effects are the rule rather than the exception.

The Special Theory alone says nothing in particular about gravitation. The motion of a particle can be computed using the Newtonian law of gravity and the relativistic equations of motion just as for any other force, such as the electromagnetic force. Relativistic corrections to observed planetary motions are exceedingly small. The Special Theory does predict the precession of the perihelion of Mercury, but the predicted effect is six times smaller than that observed.

7.3.2 General Relativity

Since the time of Galileo it has been known that objects of different mass fall with the same acceleration. This fact has now been experimentally confirmed with very great precision by Eötvös and Dicke. Newton took account of this empirical observation in his theory by making the gravitational force on an object proportional to its mass. It remained for Einstein to recognize the possible fundamental character of the observation: namely, that motion under gravity seems to depend on the properties of the space in which the objects move rather than on the properties of the objects themselves. Einstein's General Theory of Relativity - perhaps more properly called a relativistic theory of gravitation - correctly predicts the advance of the perihelion of Mercury as well as two effects since observed: the bending of starlight by the sun and an apparent reduction in the rate of a clock placed in a gravitational field. The theory is based on a minimum of assumptions, which are as follows:

1. The principle of the equivalence of gravitational and inertial mass just mentioned
2. The validity of Special Relativity as a limit in the absence of gravitational fields
3. The principle of relativity, requiring that the physical laws of nature should not depend on the description employed by an observer

If these assumptions are granted, Einstein's theory follows in an essentially unique way. Because each of these assumptions is independently supported by experience, the theory is an extremely natural one, but it has two features which cause difficulties that are practical in character. First, in nearly all experimental situations, the deviations from the predictions of Special Relativity are exceedingly small - at or below the threshold of observation. Second, the consequences of the General Theory in regions of large gravitational fields become difficult to understand because of the mathematical complexity of the theory. For many years gravitational researchers were preoccupied with these mathematical and cosmological questions, many of which are still unresolved. In the last decade, interest in the experimental examination of the various theories of relativity and gravitation has grown rapidly.

7.3.3 The Use of a Zero-G Laboratory

One purpose of the proposed zero-G laboratory program is to conduct research in the area of gravitation and stabilization. In this connection, two questions arise. First, how can the present understanding of gravitation be improved by experiments performed in space, and in a manned spacecraft in particular? Second, what engineering techniques are available to perform such experiments?

Any engineering application must be preceded by a verification of the scientific principles upon which the engineering practice depends. For centuries, engineering mechanics has been based upon the mechanics and gravitational theory of Newton. Recently, the modifications of the Newtonian theory by the Special Theory of Relativity have become important to engineers in certain fields. Still, in the field of space mechanics, relativistic effects can barely be observed, and so far have had no important engineering consequences.

It is concluded that although nearly all significant scientific investigations into the nature of gravity will involve the details of the relativistic theories, engineering efforts in space flight and space instrumentation will continue to be based on well-understood Newtonian principles. In the following sections, a brief review of the experimental foundations of theories of Newton and Einstein is presented to establish this conclusion. No attempt is made at a complete theoretical discussion since these are available in a number of excellent texts.

7.4 Review of Classical Theory and Its Experimental Support

The advances in scientific thought leading up to Newton form a dramatic sequence of ideas in the development of the classical theory of mechanics. The first idea, attributed to Ptolemy (circa 200 A.D.), was that the sun, moon, planets and stars described circular paths around the earth, and that the five known planets also moved in epicycles in addition to their earth-centered motion. This view persisted for nearly 12 centuries until Copernicus (1473-1543) put forth the bold hypothesis that the earth, moon, and planets revolved uniformly in circular paths about a central, stationary sun. Epicycles were still required, but their number was greatly reduced. It remained for Kepler (1571-1630) to finally dispense altogether with the artifice of epicycles. Based on the multitude of recorded planetary observations made by Tycho Brahe (1546-1601), Kepler was able to formulate his three laws of planetary motion. The first law, which states that the orbit of each planet is an ellipse with the sun at one of its foci, brought to an end the long-held theory of circular planetary orbits. The second and third laws state that the radius vector to a planet sweeps out equal areas in equal times, and that the period of a planet is proportional to the three-halves power of its mean distance from the sun. By means of these laws, it was finally possible to predict, with a high degree of accuracy, the positions of the earth and the five known planets. Small discrepancies between Kepler's laws and observed planetary motion were mostly attributed to inaccuracies in the methods of observation.

Kepler was the last of the mathematician-astronomers to be concerned merely with the kinematics of the solar system. Galileo Galilei (1564-1642), who generally is regarded as the father of experimental physics, was the first scientist to introduce the dynamic viewpoint in astronomy. As a result of his experiments with falling bodies, he proved not only that all objects fall to the earth with the same acceleration but also postulated that an undisturbed body continues to move uniformly in a straight line, or remains at rest. Prior to Galileo, the state of rest was considered the natural state, and motion was regarded as a forced state, so that the continued motion of a planet required an explanation. After Galileo, uniform motion was considered as natural as rest, whereas the change in motion demanded an explanation.

The conclusions reached by Galileo and his contemporaries, along with Kepler's laws of planetary motion, were finally consolidated and interpreted by Sir Isaac Newton (1642-1727). Newton's three laws of motion and his law of universal gravitation constitute the foundation of classical theoretical physics. In his laws of motion, Newton formally introduced the concept of force. The first law is a restatement of Galileo's postulate about the uniform motion, or state of rest, of an undisturbed body in the absence of an impressed force. In its simplest form, the second law states that the force acting on a body is proportional to its acceleration, where the constant of proportionality is the inertia of the body - mass being a measure of inertia. The second law defines the equation of motion of a body and forms the basis for celestial mechanics, while the third law states the equality of action and reaction. The first two laws are concerned with forces acting on a single body whereas the third law is concerned with the mutual forces between two bodies.

The original concept of force, as it appears in Newton's laws of motion, was that of actual physical contact between bodies, since this type of action was the most common to human experience. But the planets were known to move in curved paths around the sun, and, hence, were being continually accelerated so that, according to Newton's second law of motion, they must be continually acted on by force. Kepler had suspected that the sun was responsible for the planets' motion, but he never gave an interpretation to this motion. From Kepler's second law, Newton was able to show that the acceleration of a planet must be directed along a line passing through the center of the sun and, from Kepler's first law, he showed that this acceleration is inversely proportional to the square of the distance from the sun. From Kepler's third law, Newton showed that the undetermined factor contained in the acceleration is the same for all the planets, so that this factor must depend only on the sun. By introducing this acceleration into his second law of motion, Newton was able to conclude that the force exerted on the planet by the sun was directly proportional to the product of the two attracting masses and inversely proportional to the square of the distance between them. As an independent check on the inverse square aspect of his law, Newton computed the ratio of the moon's acceleration toward the earth to the acceleration of a body at the earth's surface. If the force which kept objects on the surface of the earth also kept the moon in its orbit, and if this force varied as $1/r^2$, then the square of the ratio of the moon's orbital radius to the earth's radius should coincide with the above computed ratio. Newton found that the two numbers differed by only one part in two hundred, or about 0.5 percent. The agreement was remarkable, and the difference explained by the fact that the values of the moon's orbital radius and earth's radius used by Newton were in error. Newton made the far-reaching generalization that the force of attraction, F, between any two particles of masses m_1 and m_2 separated by a distance, r, is

$$F \sim \frac{m_1 m_2}{r^2} = \frac{G\, m_1 m_2}{r^2} \tag{7.1}$$

where G is a proportionality constant. The fact that Cavendish, in 1798, was able to evaluate G by measuring the force of attraction between two lead spheres was further evidence of the omnipresence of gravitation. (The presently accepted value of G is $6.670 \pm 0.005 \times 10^{-11}$ $m^3/(kg\text{-}sec^2.)$ The most general shape that m_1 and m_2 may assume in Eq. 7.1 is a sphere, containing homogeneous, concentric layers, where r is the distance between the centers of the spheres. If the radii of the masses are negligible compared with r, then m_1 and m_2 may assume any shape. Thus, in computing the force of attraction between two planets, no account need be taken of their shape or structure, since the minimum distance separating them far exceeds their size.

By writing Newton's second law of motion for the two masses, m_1 and m_2, and letting the force acting on each mass be given by Eq. 7.1, it is possible to solve the two vector equations and obtain the relative motion of m_1 and m_2. The relative motion is an elliptical orbit, having the property described by Kepler's second law. The period, T, of the orbit is given by

$$T = \frac{2\pi\, a^{3/2}}{\left[G(m_1 + m_2) \right]^{1/2}} \qquad (7.2)$$

where a is one-half the sum of the minimum and maximum distances separating m_1 and m_2. Although Eq. 7.2 has the same form as Kepler's third law, it coincides with this law only if $m_1 \gg m_2$, since Kepler's three laws were written specifically for the sun (m_1) and any one of the planets (m_2). The constant of proportionality appearing in Kepler's third law is, therefore, $2\pi/(Gm_1)^{1/2}$. Thus, Kepler's three laws follow directly from Newton's second law of motion and his law of gravitation.

Equation 7.2 is useful in determining the sum of the masses of a two-body system, if their period of revolution, T, and their mean separation, a, are known. Such a system could be the sun and any one of the planets, or a planet and one of its satellites. The mass of the earth, however, can be determined uniquely, since, from Eq. 7.1, m_2 = mass of earth = $(r^2/G)\ (F/m_1)$, where r is the radius of the earth and $F/m_1 = g$ is the acceleration of a small mass, m_1, at the earth's surface.

Newton's law of gravitation, in conjunction with his second law of motion, has been completely successful in explaining or predicting a host of natural phenomena. The validity of the theory has been demonstrated both on the surface of the earth and in space - with the most dramatic verification occurring in space. In almost all cases, the discrepancies between theory and observation are too small to be recognized, and in all but a few cases where the two differ measurably, the difference is due either to the complexity of the problem and the difficulty of applying the theory, or to faulty observations. Several of the most important successes of the theory are described below.

7.4.1 Departure from Keplerian Ellipse

One of the earliest triumphs of the theory was an explanation of the small discrepancies between the observed motion of the planets and the motion predicted by Kepler's three laws. As the planets orbit the earth, the gravitational forces acting between them cause the planets to depart slightly from their Keplerian ellipses, and also cause their mean elliptical paths to change their shapes and their orientations in space. The former perturbations are called periodic, and the latter, secular. Both perturbations are cyclic in nature, the former having a period of a few hundred years and the latter a period of tens and hundreds of thousands of years. Employing Newton's theory, this irregular planetary motion was derived by Laplace and Lagrange (Refs. 7-1 and 7-2) almost two centuries ago.

7.4.2 Translational Motion of the Moon

As the moon orbits the earth, it is continually being perturbed by the sun and by the principal planets. As a result of these perturbations, the elements of the orbit undergo many subtle variations. The first complete analysis of the moon's motion, employing Newton's theory, was performed by Brown (Ref. 7-3), and the results of this analysis were later tabulated by Brown in his famous "Tables of the Motion of the Moon," (Ref. 7-4). The agreement with observation was perfect, except for an unexplainable variation in the moon's longitude of approximately 11 seconds of arc per 257 years. The discrepancy was finally resolved after it was discovered that this error in the moon's position could be explained by the random fluctuations in the earth's rotational rate. These fluctuations are believed to be caused by expansions and contractions of the earth, which alter the earth's radius by only a few feet.

7.4.3 Points of Libration

Although the problem of the relative motion of two isolated bodies, each attracted to the other according to Newton's theory, can be solved analytically, a general analytical solution cannot be similarly obtained for the problem of three or more isolated bodies. It is possible, however, to obtain special solutions for this problem, some of which were first obtained by Lagrange (Ref. 7-2). He found two possible equilibrium configurations of the three bodies. In one configuration, the three bodies lie along a straight line, and in the other, they lie at the vertices of an equilateral triangle. In either configuration, the bodies remain fixed relative to each other and the system rotates at a constant angular velocity about the common center of mass. The positions occupied by the three bodies are called points of libration. Within the last hundred years, a physical counterpart of the equilateral triangle configuration has been confirmed. Moving in Jupiter's orbit about the sun are two groups of asteroids occupying the two points equidistant from the sun and Jupiter. One group contains five asteroids and the other, six. The two groups are known as the Trojan group. The appearance of the asteroids at these two locations provides additional support for Newton's theory. The collinear configuration is one of unstable equilibrium, so that systems in that configuration are not observed.

7.4.4 Tidal Forces and Roché's Limit

One of the more common phenomena that can be explained by Newton's theory is that of the tides, which are caused by the greater force of attraction of the moon and sun on the parts of the earth nearest to them. These unequal forces are called tidal forces; they cause the oceans to move vertically relative to the land masses. As the earth rotates, the high water point moves horizontally across earth.

Another example of tidal forces can be found in the space around Saturn. Saturn has nine known satellites, in addition to its rings. The rings are now believed to consist of a swarm of individual particles, each particle describing a circular orbit about Saturn. The rings all lie in the plane of Saturn's equator and are approximately ten miles thick. On the basis of work done by Roché, the French mathematician, it is now believed that the rings are remnants of one or more large satellites that were torn apart by the tidal forces of Saturn. In 1850, Roché, employing Newton's theory, proved that a liquid satellite of any planet would be merely distorted by the tidal forces of the planet if the satellite were beyond a certain critical distance from the planet, but it would be torn apart by these forces if it approached within this distance. If the satellite and planet had the same density, Roché showed this critical distance to be 2.44 times the planet's radius. It is significant that the radius of the outer ring of Saturn is only 2.3 times the radius of Saturn, and the distance of the nearest known larger satellite to Saturn is 3.11 times the radius of the planet.

The tidal or gravity-gradient forces are of fundamental importance in the problem of stabilizing experiments in a low-G laboratory. The problem is discussed in detail in later sections.

7.4.5 Discovery of Neptune

A great triumph of Newton's theory of gravitation was the discovery of Neptune. After the accidental discovery of Uranus in 1781 by Herschel, it was found impossible to predict Uranus' orbit, even after taking into account the perturbations of Saturn and Jupiter. In 1845, the planet deviated by almost two minutes of arc from its calculated position. It appeared, then, that some unknown force must be perturbing Uranus. After a thorough investigation of the discrepancies in Uranus' motion, the French mathematician, Leverrier, also employing Newton's theory, predicted the location of the perturbing body, and, in 1846, it was found within one degree of the predicted point. The new planet was subsequently called Neptune.

7.4.6 Deep-Space Tracking

While a general analytical solution of the n-body problem cannot be obtained in terms of constants of motion, the solution for any given case can always be found by direct numerical integration of the equations of motion. The accuracy is then limited only by the computational errors and uncertainties in the knowledge of physical constants. A most dramatic verification of the accuracy of the classical dynamics is provided by the engineering application of the theory to the guidance and control of the lunar and planetary probes in the Ranger and Mariner series. Because of the extreme accuracy of the Doppler tracking system, small discrepancies in the motions at the level produced by present uncertainties in physical constants become obvious. The Newtonian mechanics holds down to the level at which the effect of solar pressure produces a measurable effect on the motion.

7.4.7 Outside the Solar System

The validity of Newton's theory outside the solar system is best demonstrated by the behavior of the visual stellar binary systems (double stars). More than 17,000 binary stars are catalogued, but the orbital characteristics of only a few hundred are accurately known. The orbital data reveal that Kepler's second law is obeyed and that the two stars describe elliptical orbits about the common center of mass, which lies at the focus of each ellipse. These observations imply, respectively, that the mutual force is centrally directed and that it also varies inversely with the square of the distance.

The total mass of a binary system can always be computed from Eq. 7.2, provided that T and a are known. If the position of the center of mass, relative to the two stars, can be accurately determined, then each mass can be evaluated separately.

Other possible examples of gravitational forces acting in the universe are the spherically shaped, globular star clusters and the densely populated central regions of the spiral nebulae (island universes). The thousands of stars in the globular clusters are apparently attracted to each other by gravitational forces, as are the vast multitude of stars in the centers of the spiral nebulae. Whether these forces vary as $1/r^2$ is not known.

In spite of the phenomenal success of Newton's gravitational theory, it fails to predict the advance in the perihelion of Mercury. The discrepancy between theory and observation is only 43 seconds of arc per century, and, although exceedingly small, it is quite observable.

7.5 Magnitude and Importance of Relativistic Effects

From the preceding discussion of the accuracy with which the classical Newtonian theory predicts gravitational effects on the astronomical scale it should be clear that relativistic effects, if present at all, must be extremely small. From the scientific point of view, accurate measurements of these small relativistic effects are extremely important, since their magnitudes are different in different theories. In particular, because general relativistic effects depend upon the presence of intense gravitational fields, no scientifically significant gravitational experiment can be performed in a truly zero-G environment. From an engineering point of view, these relativistic effects are so small as to be negligible, except in elementary-particle physics. To illustrate this argument, some order-of-magnitude calculations are presented to show the sizes of the effects being discussed.

7.5.1 Effects of Scientific Interest

In all practical calculations, the sizes of special relativistic and general relativistic effects relative to classical (Newtonian) effects are given by two dimensionless parameters. Special relativistic effects are, to a first order of approximation, proportional to the square of the ratio of the speed of an object to the speed of light. General relativistic effects are generally proportional (again to first order) to the ratio of the gravitational potential, Φ, to the square of the speed of light. In Tables 7-II and 7-III, values of these parameters in various experimental situations are given. Table 7-II pertains to special relativistic effects. Reference numbers, where given, apply to actual experiments or

TABLE 7-II

MAGNITUDES OF SOME SPECIAL RELATIVISTIC EFFECTS

Phenomenon Studied	Experimental Condition	Ref.	v^2/c^2	Nature and Magnitude of Effect	Feasibility of Observation
Time Dilation or Transverse Doppler Effect	Source and absorber mounted at center and on rim of a wheel 13.5 cm in diameter rotating at 30,000 rpm	Hay, et al., 1960	4.88×10^{-20}	Frequency shift of Mossbauer line in Fe^{57}: $\Delta\omega/\omega = 2.44\times10^{-20}$	Feasible
	Random thermal motion of atoms in a crystal lattice	Pound & Rebka, 1960a	8×10^{-13}	Difference in frequency between $0^{o}K$ and $273^{o}K$ $\Delta\omega/\omega \sim 4\times10^{-13}$	Feasible
	Oscillator carried by an earth satellite in a low orbit	Singer, 1956	7×10^{-10}	Frequency shift of oscillator (transverse Doppler term only) $\Delta\omega/\omega = 3.5\times10^{-10}$	Feasible
	Oscillator carried by a Venus probe at time of maximum velocity with respect to earth (assuming Hohmann transfer)		5.1×10^{-8}	Frequency shift of oscillator (transverse Doppler term only) $\Delta\omega/\omega = 2.6\times10^{-8}$	Feasible
	Change in lifetime of pi-meson with an energy of 1 GeV		0.985	Time dilation factor $\left(1 - \frac{v^2}{c^2}\right)^{-1/2} = 8.15$; Lifetime at rest 25.5 nsec at 1 GeV 207 nsec (1 nsec = 10^{-9} seconds)	Unavoidable

TABLE 7-III

MAGNITUDES OF SOME GENERAL RELATIVISTIC EFFECTS

Phenomenon Studied	Experimental Condition	Ref.	Φ/c^2	Nature and Magnitude of Effect	Feasibility of Observation
Gravitational Frequency Shift	Oscillator at surface of uranium ball, radius 1 meter, mass 82 metric tons		6.1×10^{-23}	$\Delta\omega/\omega = 6.1 \times 10^{-23}$	Impossible
	Mossbauer source and absorber separated by 22 meters in earth's field	Pound & Snider, 1964; Pound & Rebka, 1960b; Pound, 1961	2.4×10^{-15}	$\Delta\omega/\omega = 2.4 \times 10^{-15}$	Feasible
	Oscillator in an earth satellite in a high orbit	Singer, 1956	7×10^{-10}	$\Delta\omega/\omega = 7 \times 10^{-10}$	Feasible
	Shift of a line of the solar spectrum	Bertotti, et al, 1962	2×10^{-6}	$\Delta\omega/\omega = 2 \times 10^{-6}$	Marginal (masked by turbulence)
	Shift of a line of a white dwarf star	Bertotti, et al, 1962	$\sim 10^{-4}$	$\Delta\omega/\omega \sim 10^{-4}$	Marginal (systematic errors dominate)
	Possible shift of light from a neutron star		~ 1	$\Delta\omega/\omega \sim 1$	Unknown
Bending of Light	Bending by uranium ball, radius 1 meter, mass 82 metric tons		6.1×10^{-23}	Bending 5×10^{-17} seconds of arc	Impossible
	Bending by Jupiter	Einstein, 1916	1.8×10^{-8}	Bending 0.02 seconds of arc	Impossible

TABLE 7-III (contd)

Phenomenon Studied	Experimental Condition	Ref.	Φ/c^2	Nature and Magnitude of Effect	Feasibility of Observation
Bending of Light	Bending by the sun	Bertotti, et al., 1962	2.1×10^{-6}	Bending 1.75 seconds of arc	Marginal to Feasible
	Bending by a white dwarf star		$\sim 10^{-4}$	Bending ~ 100 seconds of arc	Unknown
	Bending by a neutron star		~ 1	Bending ~ 1 radian	Unknown
Precession of Planetary Orbit	Two uranium balls, each with radius 1 meter and mass of 82 metric tons, in near circular orbit at 10 meters separation		0.6×10^{-23}	Angular rate of precession 4×10^{-27} radians/sec, or 26×10^{-11} seconds of arc per millenium	Impossible
	Advance of the perihelion of Mercury	Bertotti, et al., 1962		Angular rate of precession 43 seconds of arc per century	Feasible
	Advance of perigee of earth satellite in 400-km orbit	Einstein, 1916	7×10^{-10}	Angular rate of precession 150 seconds of arc per year	Marginal to Impossible (masked by other effects)
	Two white dwarf stars, each of one solar mass, in orbit at separation of 10 earth radii		2.3×10^{-5}	Angular rate of precession 15 degrees per year	Unknown
Precession of a Torque-Free Gyroscope	Gyroscope in low-earth orbit	Schiff, 1960a, 1960b	7×10^{-10}	Angular rate of precession 7 seconds of arc per year	Marginal

calculations reported in the literature. These will be discussed in detail later. In the last column of both tables, an entry has been made to show whether observation of the relativistic effect by presently available techniques is considered feasible (error much less than unity), marginal (error of order unity), or impossible (effect masked by other effects or by instrumental errors).

Examination of Tables 7-II and 7-III shows that while special relativistic effects are large in particle physics, such effects are quite small in space applications where velocities are small compared to the speed of light. General relativistic effects are large only in regions of very intense gravitation, such as in the neighborhood of a white dwarf star, but they are very small on the earth and sun, and completely unobservable in the field of any conceivable man-made object.

7.5.2 Effects of Engineering Interest

If effects are so small as to be hardly observable, they are unlikely to be important for engineering purposes. Relativistic effects in the neighborhood of man-made structures are completely unmeasurable, although radar tracking accuracies may make it barely possible to observe certain relativistic effects in planetary and satellite motion (Ref. 7-5). It follows that conventional engineering mechanics based on the Newtonian laws, appropriately modified by the Special Theory of Relativity where necessary, will provide an adequate theoretical foundation for some time in the future. Although new and unsuspected applications of the Newtonian mechanics may be invented, the newness will reside in the application, not the theory.

A number of classical effects are of importance in the problem of stabilizing experimental equipment in a laboratory. Gravitational interaction between portions of the equipment is negligible, but the variation in gravitational and centrifugal force within the laboratory volume has profound implications in that only a restricted set of stable relative configurations exist for a pair of objects in orbit. Of even greater importance, is the need to isolate low-G experiments from shock vibration, air currents, and electric and magnetic fields. A detailed estimate of the magnitudes of such forces on a typical system is given in a later section.

7.6 Discussion of the Effects of General Relativity

Besides the three classic effects of General Relativity (the gravitational red shift, the bending of starlight, and the advance of the perihelion of Mercury) several other effects yet unobserved have been predicted. The theory predicts the existence of gravitational waves, which are expected to propagate at the speed of light (see, for example, Ref. 7-6). The axis of a spinning gyroscope placed on the surface of a rotating planet will precess at a rate proportional to the angular velocity of the planet. If the same gyroscope is placed in a satellite orbit, an additional precession proportional to the orbital frequency is predicted (Refs. 7-7 and 7-8). If natural or artificual planets are tracked with a suitable radar system, small relativistic effects should be observable (Ref. 7-5).

All of these effects, including the three classical ones, are small and difficult to observe. Relatively large relativistic effects are expected to occur in white dwarf stars and the hypothetical neutron stars because of their extremely intense gravitational fields. Prolonged observation of these stars from space, outside the curtain of the earth's atmosphere, will no doubt yield new and unexpected information. While there is some question whether quantum gravitational effects will be observed even on a neutron star (Ref. 7-9), it seems clear that such dense systems are the most likely place to find quantum effects if they exist.

Each of these effects are discussed in turn in the following subsections.

7.6.1 Gravitational Red Shift

Very early in Einstein's study of the gravitational phenomenon, he recognized that there must be a connection between gravitation and the behavior of light. A light quantum carries energy, in an amount proportional to its frequency. Einstein himself won the Nobel Prize by using this principle to explain the photoelectric effect.

If the quantum is absorbed by a material atom, that atom becomes heavier according to Special Relativity and the principle of equivalence of gravitational and inertial mass. The frequency (energy) of a photon must then change in propagating through a region of changing gravitational potential. Otherwise, one could, in principle, construct a device which produced energy (useful work) out of nothing, by allowing atoms to emit photons at low gravitational potential and absorb at high potential. The gravitational potential energy of the system would then increase indefinitely. If energy is to be conserved, the frequency of a photon must vary with gravitational potential according to the (approximate) relation:

$$\omega \left(1 + \frac{\Phi}{c^2}\right) = \text{constant},$$

where ω is the angular frequency of the photon, Φ is the gravitational potential, and c^2 is the square of the speed of light. The original argument is given by Einstein (Ref. 7-10). This simple argument does not depend on the full apparatus of the General Theory.

One must regard prediction of the red shift as a requirement to be placed on any successful theory, rather than as a unique prediction of the Einstein theory. Nevertheless, precise observation of the red shift is desirable to establish the class of theories which must be considered. This point has been discussed at some length by Schild (Refs. 7-11 and 7-13) and Dicke (Ref. 7-13). The effect was first observed as a shift of the spectral lines of the sun and other stars toward the red. Unfortunately, convective motion of the luminous shell or atmosphere gives rise to ordinary first-order Doppler shifts of the same general magnitude as the relativistic effect. Only near the limbs, where the radial motion is random, does the measured effect approach the predicted value. By observing the shift of sodium D1 absorption lines in the upper atmosphere of the sun, Brault (Ref. 7-14) has been able to measure a red shift of 1.05 ± 0.05 times the theoretical value. Other observational difficulties apply to measurements of the red shift of the light received from white dwarf stars (Ref. 7-15). The red shift is observed, but with rather large uncertainties.

A direct and convincing measurement of the red shift was performed by Pound and Rebka (Ref. 7-16) and later by Pound and Snider (Ref. 7-17), who used the 14.4 KeV Mössbauer line of Fe^{57} as a frequency standard to measure the magnitude of the shift caused by a 74-foot vertical separation in the earth's field. The ratio of the observed and predicted frequency shifts was found to be:

$$0.9970 \pm 0.0076.$$

Singer and Basov, et al., (Refs. 7-18 and 7-19) have proposed measuring the red shift by placing a stable maser oscillator in an earth satellite. A frequency shift between the orbiting oscillator and a similar oscillator on the ground is expected. If the frequency of the oscillator in space is ω, the frequency of the signal received on the ground when the orbit is circular will be shifted by the amount:

$$\frac{\Delta\omega}{\omega} = \frac{gR}{2c^2}\left[\frac{3}{2}\left(1 + \frac{h}{R}\right)^{-1} - 1\right]$$

where g is the acceleration due to gravity at the earth's radius R, c is the speed of light, and h is the altitude of the orbit above the earth's surface. The total frequency shift arises from two effects: (1) the special relativistic time dilation (transverse Doppler shift) resulting from the motion of the satellite, and (2) the position-dependent gravitational effect. Since the shift is small (at most 7 parts in 10^{10}) very stable oscillators are required, but maser frequency standards of substantially greater stability do exist.

Singer's experiment has been extensively analyzed in the literature. An exhaustive 33-page review and analysis has been made by Basov, et al. (Ref. 7-19).

The experimental difficulties in observing the gravitational frequency shift of an orbiting oscillator are two: (1) the reference oscillators must be extremely stable, and (2) the gravitational frequency shift must be disentangled from the far larger first-order Doppler shift arising from radial motion of the satellite. The observed shift beyond the first order is the sum of two effects: the second-order transverse Doppler shift arising from the relative motion of satellite and ground station, and the gravitational shift. The ground station sees a shift in the frequency of the orbiting oscillator by an amount given to first order in $1/c^2$ by

$$\Delta\omega_o = \omega_o \left[-1/2\ v^2/c^2 + \frac{\Delta\Phi}{c^2}\right]$$

while an observer moving with the satellite measures a shift of a ground-based oscillator of

$$\Delta\omega_g = \omega_g \left[-1/2\ v^2/c^2 - \frac{\Delta\Phi}{c^2}\right]$$

In these equations, v/c is the ratio of the relative speed of ground station and satellite to the speed of light, while $\Delta\Phi$ is the absolute value of the difference in gravitational potential. Singer's more precise treatment (Ref. 7-18) gives the same result, to first order.

If two such oscillators are used and the resulting measured shifts are telemetered and compared, the special-relativistic transverse Doppler shift and the gravitational shift can be independently measured:

$$-\frac{1}{2}\frac{v^2}{c^2} = \frac{1}{2}\left(\frac{\Delta\omega_o}{\omega_o} + \frac{\Delta\omega_g}{\omega_g}\right)$$

$$\frac{\Delta\Phi}{c^2} = \frac{1}{2}\left(\frac{\Delta\omega_o}{\omega_o} - \frac{\Delta\omega_g}{\omega_g}\right)$$

The above demonstration that the two effects can be separately measured contradicts statements made in the literature by authors who have not recognized the utility of the two-way frequency comparison. The magnitude of the shift is quite small, at best 7 parts in 10^{10}, when the satellite is at a very great distance. For a 400-km orbit, the gravitational shift is only about a sixteenth as large.

Maser oscillators having instabilities as small as one part in 10^{12} over the period of a year have been constructed and used in an experiment which confirms the hypothesis of Special Relativity (Ref. 7-20). With this stability, a measurement of the gravitational shift with an accuracy of about one part in 700 could, in principle, be performed. To attain the large shift required, a high eccentric orbit with low perigee and very high apogee (say 10 earth radii or more) is desirable, so that the full modulation of the received signal frequency can be observed during several orbits. Because of radiation hazards and the special nature of the orbit, the Singer experiment seems to be a natural candidate for a special-purpose unmanned satellite containing the stable oscillator and telemetry equipment together, perhaps, with equipment for observing the magnetic and radiation environment.

The actual observation of the shift is complicated by the existence of the first-order Doppler effect, and of the need to observe variations in the shift on a very eccentric orbit rather than the absolute shift which may be in error because of variation in the absolute frequency of the oscillator. Schemes for eliminating the first-order Doppler effect exist. The first such scheme, proposed by Badessa, et al. (Ref. 7-21), works as follows: The ground station sends at the frequency f. The frequency f' received by the satellite is slightly different, as a result of the first- and second-order Doppler effect and the red shift. This frequency is compared in the satellite with twice the nominal ground station frequency, to form a new frequency, $f'' = 2f - f'$, which is retransmitted to the ground. The signal received on the ground is again shifted to the frequency f'''. The frequency difference from f''' and the original frequency transmitted, f, is independent of the first-order Doppler shifts to third order, or one part in 10^{14}. The transmitter may be pulsed to avoid overloading the receiver with the transmitted signal.

A number of similar schemes have been examined by Basov, et al (Ref 7-19), in the review already referred to. It appears that an experiment of this type is quite feasible, but the effect observed from a 400-km manned laboratory orbit is much smaller than the potentially observable effect. Measurement of the effect in a manned laboratory will not be as justifiable as a measurement on a high trajectory like that of Ranger 1 and 2. On such a high trajectory, the attainable accuracy would be comparable to that achieved with far less means by Pound and Snider (Ref. 7-17).

The effect can also be observed if a stable oscillator is placed aboard a solar probe. The maximum gravitational frequency shift observable for a trajectory with a perihelion distance of 0.5 astronomical units is about 1 part in 10^8, which is about 14 times larger than the maximum effect observable in earth orbit. This experiment should also presumably be done in an unmanned spacecraft.

One concludes that red-shift experiments should be included in the unmanned space science program, and that accuracies comparable to those now attained are achievable using significantly different techniques.

7.6.2 Bending of Starlight

When light passes a body of mass M at a mean distance R, the angular deflection of the light, in radians, is

$$\theta = \frac{2GM}{Rc^2} (\alpha + \gamma)$$

where G is the universal constant of gravitation, c is the speed of light as usual, and α and γ are coefficients of the two lowest orders of relativistic effects (Ref. 7-22). The value of α must be +1 to produce agreement with the red shift. Einstein's General Theory of Relativity gives $\gamma = +1$, and predicts a numerical value of the deflection for a ray at grazing incidence is 1.75 seconds of arc.

Long ago, Newton calculated the deflection expected from his corpuscular theory of light, which depended upon the assumption that light rays consisted of streams of small corporeal particles moving at the speed of light. The same deflection was obtained by Einstein (Ref. 7-10), using the Special Theory of Relativity. The value obtained is half that predicted by the General Theory, so that an accurate measure of the bending of starlight provides a clear test of General Relativity. An opinion to the contrary was presented by Schiff (Ref. 7-23), but his argument does not seem to have been generally accepted (Refs. 7-11, 7-13, and 7-15).

The bending effect has been measured directly during six eclipses, by photographing the star field surrounding the sun. The positions of the stars were compared to their positions on another plate taken several months later when the sun had moved to a different place among the stars. Systematic errors in the measurements are a severe problem, and the values obtained by different experimenters differ from one another by more than the probable errors quoted. Still, the observed deflections, which range from about 1.4 to 2.7 seconds of arc, tend to agree with the relativistic predictions and are definitely in conflict with the Newtonian prediction. It follows that the value of α is quite well known from red-shift measurements, while the value of γ is known to about 20 percent. Bertotti, et al, (Ref. 7-15) have reviewed the current experimental situation in detail. Nothing can be added here to their rather complete summary.

Other experimental approaches have been suggested from time to time. One of the more obvious, and possibly more promising, techniques is that of putting a solar coronagraph in orbit, avoiding the great difficulties introduced by scattering and turbulence in the atmosphere as well as the rapid temperature variations which occur during an eclipse (Ref. 7-24). Such a coronagraph would be useful for other purposes. Subotowicz (Ref. 7-25) has proposed mounting a laser on an artificial planet occulted by the sun; his analysis shows that the laser beam is intense enough to be detected even in the presence of the sun's corona.

In units of the solar radius, the deflection of a ray passing at a distance R is given by

$$\theta = 1.75'' \frac{R_\odot}{R}$$

where $R_\odot$ is the solar radius and R is the closest distance from the ray to the center of the sun. This angle is comparable to those measured in parallax determinations. To achieve the maximum effect, one must observe the deflection of light passing as close to the sun as possible; but because of the brightness of the corona, observation at minimum distances less than 2 solar radii is not feasible. At this radius, the gravitational deflection is reduced to 0.875". The catalogued star positions are too inaccurate for comparison with eclipse measurements, so that it is necessary to compare the eclipse measurements with the sun-free star field observed with the same instrument at a different time.

The correction to the measured position for every exposure of a star field is slightly different, usually varying linearly from the plate center. Variation in the correction is caused by slightly different focal settings, emulsion warping or irregularities, temperature effects, and atmospheric turbulence. If the scale correction for a plate varies linearly, then the observed deflection is given by $\Delta r = A/r + Br$, where the first term is the relativistic effect and the second is the scale correction. Two graphs are presented (Fig. 7-2) which indicate typical discrepancies in starlight bending measurements. Quoted errors on $\delta\theta$ at $r = R_\odot$ are of the order of 0".1 to 0".2 second, while a comparison of the measurements suggests systematic errors of twice this amount. Very little information about the dependence of $\delta\theta$ upon r has been obtained. The experiment is of sufficient scientific importance that it should be repeated if a substantial improvement in the results can be made. Perhaps "substantial improvement" can be defined as (a) a reduction of measurement errors to the region 0".01 to 0".03 second, and (b) a measurement of the functional form of $\delta\theta(r)$.

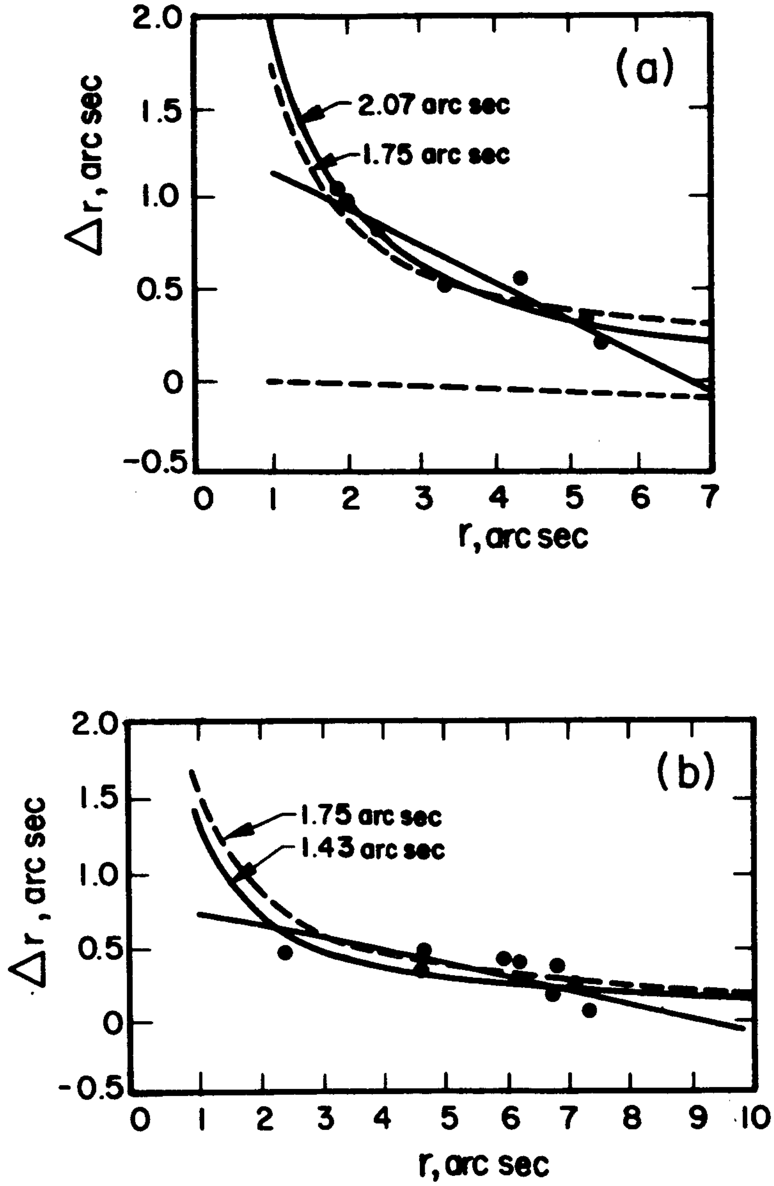

FIG. 7-2 OBSERVED PLATE DEFLECTION OF STAR IMAGE, Δr, AS A FUNCTION OF DISTANCE OF IMAGE, r, FROM SOLAR CENTER

From eclipse expedition of
(a) 29 May 1919 in Brazil, and
(b) 29 February 1952 in Sudan.
(Reproduced from Mikhailov (1959)).

An experienced eclipse observer, Von Klüber (Ref. 7-27), states that further observations are only justified if there is real progress in fulfilling the stringent eclipse measurement conditions.

Observation of the bending of starlight from space offers the following substantial advantages:

1. The deleterious effects of turbulence and scattering in the atmosphere are absent.
2. The experimental apparatus can be kept at constant temperature. (Temperatures on earth fall rapidly during an eclipse.)
3. A continuous series of plates can be taken as the sun moves among the stars. As a result of the bending effect, the stars would appear to move out of the way of the sun as it approached. Since the sun moves in the sky at the rate of a degree (or 4 solar radii) per day, plates taken over a 1-day period should show most of the effect. Experimental conditions must be held constant over this period.

Lillestrand (Ref. 7-28) has proposed an experiment which would more or less continuously monitor the angle between a star pair as one member approaches the sun. The experiment would be done either from an unmanned satellite in polar orbit or (with more difficulty) from a high-altitude balloon. Although the satellite version would be a "one-shot, one-star" affair, it might well attain the goals stated above and should be taken very seriously.

However, consideration is given here to the gains to be made in performing the classical experiment from a manned orbiting vehicle. To conduct the experiment, the scientists/astronauts would need to mask the sun by means of an occulting slave satellite located about 1/2 kilometer from the manned laboratory, in order to eliminate errors due to heat absorption in the apparatus. A sequence of exposures then could be made on one photographic plate. The sequence might be as follows: As the satellite emerges from the earth's shadow, a reference star field could be photographed; then a field centered about the sun; then fields centered at positions to the left and right of the sun over a total distance of 5 degrees (for comparison with plates made at earlier and later times); and, finally, the reference field again, displayed by a few minutes of arc in a known direction. The apparatus would then be covered until the procedure is repeated, on a different plate, after several more orbits. A number of plates would be taken during a period of about 1 week. The difficulty of the measurement must not be underestimated. The desired accuracy of 0".01 second corresponds to the angle subtended by a fruitfly 15 miles away!

The most serious limitations on the experiment arise from local dimensional stability problems on the photographic plates. Astronomers are normally limited by these effects to about 1μ position uncertainty. A smaller uncertainty seems unattainable.

7.6.2.1 Stars to be Used

The number of stars in the sky brighter than a visual magnitude, m, is approximately given by

$$N = 7.40 \times 10^{\frac{m}{2.15}}$$

Of the order of a hundred stars should be used. To find this many stars sufficiently close to the sun, one must go to the 9th or 10th magnitude. The time of year also must be chosen to optimize the number and distribution of the stars. From stellar parallax work, it is well known that angular separations can be accurately measured only for stars of similar brightness. Therefore, only stars within a magnitude or so of the limiting magnitude are useful (the sun's occultation of α Leo is probably not useful).

7.6.2.2 Telescope Aperture

The angular radius of a star's diffraction image is given by

$$\varphi = \frac{14''.1}{a} \text{ sec/cm}$$

where a is the aperture diameter in centimeters. If a photometric method of bisecting the image is used and if the emulsion is not too grainy, the center of the image can be determined to within 1/50 of the radius. For $\Delta\varphi = 0''.01$ second, one then obtains

$$a = 30 \text{ cm}.$$

In addition, it is desirable to observe stars as far into the solar corona as possible because of the hyperbolic radial dependence of the deflection angle. For a given focal length, the brightness of a star (energy per unit area on the plate) is directly proportional to the square of the aperture diameter while the corona brightness remains constant. Using the corona brightness figures quoted by Lillestrand (Ref. 7-28) for a sunspot maximum year and apertures of 10, 20, and 30 cm, the curves shown in Fig. 7-3 were obtained. These plots show the minimum distance from the sun at which a star of given magnitude is visible, defining this distance as that at which the stellar diffraction image is as bright as the corona on the plate. Because of the vagaries of the corona, these results are approximate but it is clear that, for this reason also, a 30 cm objective would be desirable.

It is necessary to photograph a field out to about 10 solar diameters, or 2.5 degrees on either side of the optic axis. The focal length necessary (to be discussed below) is such that a focal ratio of about f20 is required. Thus, an approximately f20 telescope with a field flat to 2.5 degrees off axis and a 30 cm aperture is required. Resolution should be to the diffraction limit and distortions should be low. It is understood that such a system can be built, either as a simple refractor or as a modified Cassegrainian system. Further details must be determined by instrument weight and size considerations, which have been deferred because the size appears sufficiently large that the telescope must be designed with a specific spacecraft in mind.

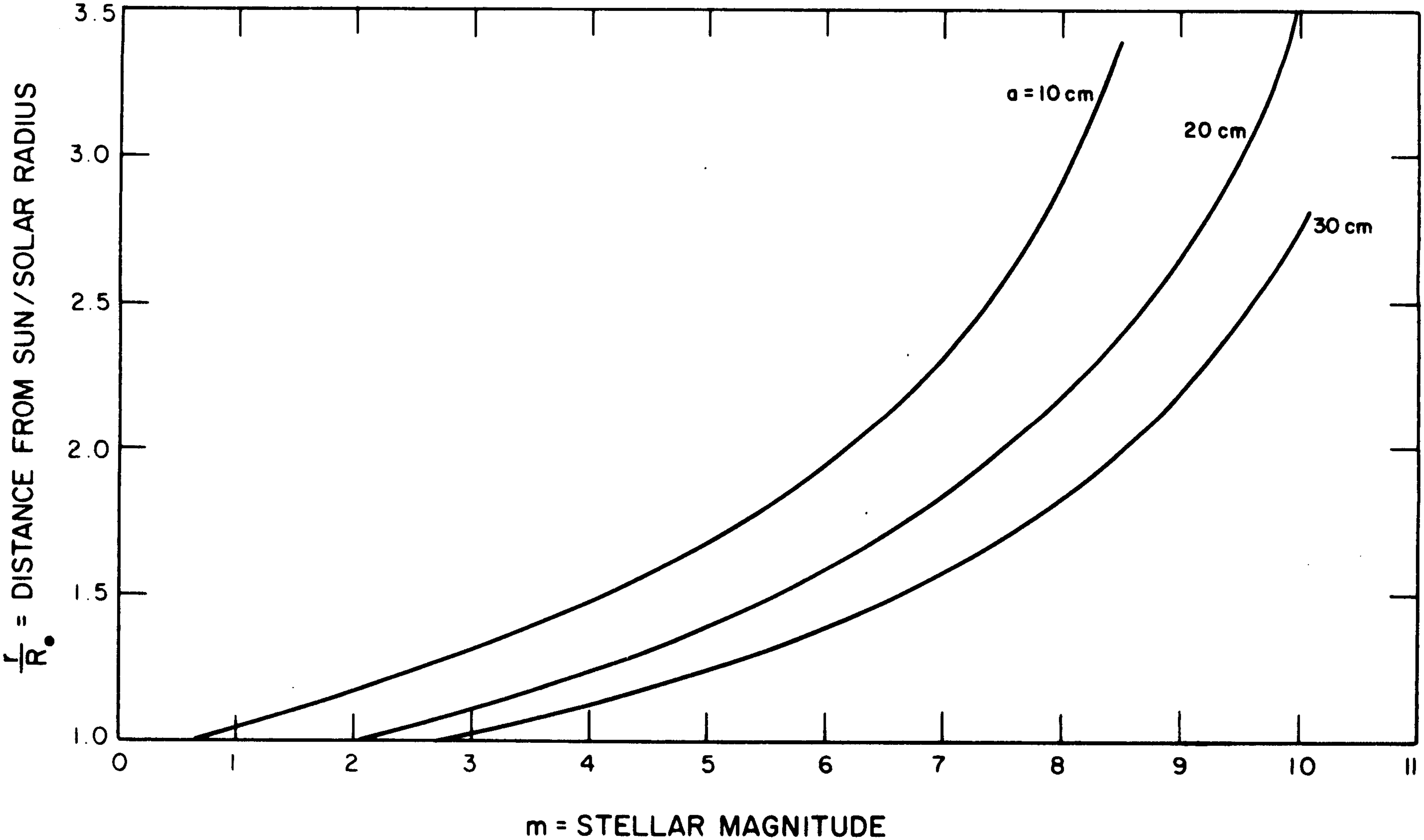

FIG. 7-3 DISTANCE FROM THE SUN AT WHICH THE STELLAR DIFFRACTION IMAGE IS AS THE CORONA

7.6.2.3 Focal Length

In determining the focal length of the telescope, one must compromise the uncertainties in image position with a practical upper limit on plate size; and, as mentioned earlier, the compromise is a serious one. In the first place, if one can believe a film position to within 1μ and insist that this correspond to 0".01 second, the focal length must be 20 m. A field of view of about 5 degrees (at least along the ecliptic) is required, so that plates 2 m square would be needed. As a reasonable compromise, one would use lm x lm plates, with an objective of 10 m focal length, and relax the error requirement to 0".02 second of arc.

7.6.2.4 Exposure Time and Stability Requirements

Assume that a star of magnitude, m, is photographed with a system of aperture, a, and focal length, f. Assume, also, an image F times larger than the diffraction image and negligible light loss in the optics. Then Poynting's vector on the image area is of magnitude

$$p = 1.473 \cdot 10^3 \frac{a^4}{f^2} \frac{1}{F^2} \cdot 10^{-0.4m} \text{ ergs/cm}^2 \text{ sec}$$

With typical parameters for this experiment,

$$p \sim 0.1 \text{ ergs/cm}^2 \text{ sec}$$

for a 10th magnitude star. Taking, for instance, Eastman Kodak's "Spectrum Analysis Plate No. 3" as typical, one finds that, for exposure to a density of 0.5 a 1-second exposure is necessary. Being more pessimistic, one might require a 5-second exposure. For a drift of less than 0".01 second during this time, telescope drift rates must not exceed 0".12 second/min.

7.6.2.5 Distance and Size of the Occulting Satellite

Let the occulting satellite have diameter, d, and be at a distance, s, from the laboratory. For an umbra of angular radius, θ_1, as seen from the aperture edge, and a penumbra of angular radius, θ_2, one obtains

$$d = a \frac{\theta_2 + \theta_1}{\theta_2 - \theta_1}$$

$$s = a \frac{1}{\theta_2 - \theta_1}$$

Placing the umbra at 1.1 solar radii and the penumbra at 1.3 solar radii, the experiment would require an occulting satellite 3.6 m in diameter, located 0.36 km from the laboratory.

7.6.2.6 Summary

A great improvement in the results of the classical bending-of-light-by-the-sun experiment appears possible (but difficult) by doing the experiment from a manned orbiting laboratory. It is suggested that the sun be eclipsed by an external occulting satellite about 3.6 m in diameter and 0.36 km distant from the laboratory. The telescope should have an aperture of about 30 cm and a focal length of 10 m, and a 5^{o} flat field. Plates 1m square are required. Multiple exposures, recording stars to about 10th magnitude, would require several seconds each. The maximum allowable angular slewing rate of the telescope during the exposure is 0".12 second of arc/minute, or 3.5×10^{-5} radians per second. It appears possible to measure the relative positions of individual stars to 0".02 second, or to about the level needed for highly significant results.

7.6.3 The Planetary Precession

The most striking confirmation of General Relativity is the very accurate prediction of the advance of the perihelion of Mercury (Ref. 7-15):

Experiment:	43.11 ±0.45	second of arc per century
Theory:	43.03	seconds of arc per century

The calculated effect is only 7 seconds of arc per century if only the dynamical corrections implied by the Special Theory of Relativity are used (Ref. 7-29). Unfortunately, the Special Theory of Relativity is not the only alternative theory. Theories exist which predict values for the bending of starlight and for the planetary precession only slightly different from the values obtained by Einstein.

While the numerical predictions of these theories differ only slightly from those of General Relativity, their conceptual foundations are very different. In particular, there are theories in which the universal constant of gravitation varies very slowly. The subject has been reviewed by Dicke (Ref. 7-30) and Brill (Ref. 7-15). In a special version of such a theory invented by Brans and Dicke, the light-bending and precession are given by

$$\text{Bending Angle} = \frac{3 + 2\omega}{4 + 2\omega} \times \text{Einstein Value}$$

$$\text{Precession Rate} = \frac{4 + 3\omega}{6 + 3\omega} \times \text{Einstein Value},$$

where ω is a positive parameter of the theory. If the value of ω is sufficiently large, the predictions of such a theory approach those of the Einstein theory, at least in these instances.

Because such theories have profound cosmological consequences and actually predict results close to those of General Relativity, further accurate tests of Relativity are of considerable scientific importance.

Full confidence in the measurement of the planetary precession depends on knowledge of the quadrupole moment of the sun's gravitational field. Because the sun rotates with a 27-day period, centrifugal force must lead to a small oblateness of the sun's figure, and hence to a value of the quadrupole moment which is different from zero. This question has been considered by Dicke, who concluded that an observed oblateness* of 5 parts in 10^5, corresponding to a difference in the angular diameter of about 0".1 second of arc, would cause an 8 percent discrepancy in the observed precession of the perihelion of Mercury. If the entire mass of the sun rotated with the same angular rate, the expected oblateness would only be about 10^{-5}, corresponding to a 1.6 percent discrepancy in the observed precession rate (Ref. 7-31). Dicke speculates that the core of the sun may rotate faster than the surface to produce an oblateness of 5×10^{-5}. He argues that the resulting discrepancy in the relativistic precession rate, of the order of 10 percent of the Einstein values, would indicate that the true theory might be one of the type mentioned above, such as the Brans-Dicke theory with the parameter ω approximately equal to +3.

Dicke has already initiated solar oblateness measurements at Princeton, using a rotating photoelectric detector. Accurate measurements of this type are very difficult because of atmospheric turbulence. Because of such difficulties, all that may be said at present (R. H. Dicke, private communication) is that it is unlikely that the solar oblateness exceeds 0".1 second of arc.

If a telescope properly designed for observation of the sun is available in space, the accuracy of this measurement can be greatly increased. The rotating detector used by Dicke is necessary principally to smooth out the atmospheric turbulence, and it is possible that direct measurement of the image of the sun on a photographic plate would be sufficiently accurate.

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*The oblateness is the difference of the polar and equatorial diameters divided by the equatorial diameter.

We shall assume that it is desirable to measure the solar oblateness with an accuracy of 3 parts in 10^6, corresponding to a difference in the polar and equatorial angular diameters of 0".005 second of arc. The residual systematic error caused by oblateness in the precession of the perihelion of Mercury would then be comparable to the error in the calculation of planetary perturbations. The principal experimental problem is to determine the position of the limb of the sun to this accuracy.

7.6.3.1 Aperture

It is evidently unnecessary to build a solar telescope capable of completely resolving such a small angle, which is fortunate, because the diameter of objective needed would be 25 meters. It is ordinarily feasible to measure the position of an edge with an rms error of about one tenth the width of the diffraction pattern. Somewhat more precise results can be obtained with a recording photometer. Assume that the total rms position error corresponding to this angle is σ. The error in the oblateness (single measurement) is then about $2\sigma/r_e$, where r_e is the equatorial diameter. If one takes 200 measurements, the residual error would be about the order of 0.01 times the half-width of the diffraction disc, implying that a 25-cm telescope, with a diffraction disc of radius 0".5 second of arc, would be adequate to achieve the desired accuracy.

The angular width of the diffraction disc corresponds to 50 microns displacement on the plate if the focal length is 5 m, implying that the individual measurements must be accurate to 5 microns, or thereabouts. Measuring microscopes with stages which repeat with an error of ±1 micron are commonly available, so that error of the measuring instrument is unimportant.

7.6.3.2 Image Size

The diameter of the solar image will be about 5 cm if the focal length is 5 m.

7.6.3.3 Exposure Time

R. F. Howard (private communication), of the Mt. Wilson staff, operates a solar telescope viewing the sun in green light with a band-pass filter of width = 250Å. Using Eastman F4 spectrographic plates (resolution 225 lines/mm--about what is needed here) and an f/60 lens, an exposure time of 0.2×10^{-3} second is required. With an f/20 lens, it is suggested that the exposure must be reduced by a factor of 9. Further attenuation of the solar light may be required.

7.6.3.4 Systematic Errors

To eliminate systematic distortion, photographs should be taken with the entire apparatus rotated 90^{o}. The rotation could be accomplished by rotating the entire spacecraft.

7.6.3.5 Summary

The minimum specifications of the telescope required to measure the solar oblateness to the limiting accuracy desired, (3 parts in 10^{6}), are:

1. Minimum Aperture: 25 cm
2. Focal Length: 5 m
3. Plate Size: 5 x 5 cm

These specifications are less stringent than those of the telescope required to perform the starlight bending experiment. If that telescope, with the same aperture and a focal length of 10 meters were used (f/40), the required exposure time, using a 250Å filter and Eastman F4 plates, is about 10^{-4} second.

It is concluded that such a measurement is feasible. The measurement may, however, be more easily performed by use of a rotating detector on an earlier spacecraft not capable of carrying such a large telescope.

7.6.3.6 Discussion

Several points regarding the telescope experiments should be made:

1. Neither experiment requires a low-G environment, except for telescope stabilization.
2. Both environments are astronomical observations, and spacecraft designed for astronomical observations will necessarily provide the well-stabilized platform for a large telescope.

Hence, these two experiments should be considered as part of the astronomy program, not of the low-G laboratory program.

A final point regarding the oblateness measurement must be made. A direct measure of the oblateness is only an indirect measure of the shape of the sun's gravitational field.

If a minor or artificial planet, having a very eccentric orbit, approached substantially closer to the sun than Mercury, and preferably having an orbit inclined at about 45 degrees to the sun's equatorial plane, the relativistic precession would be large. The oblateness effect vanishes at this inclination. These orbital specifications correspond to those of an out-of-the-ecliptic solar probe, a project which has been discussed from time to time. Precise radar tracking of such a probe, especially if it carried the precision oscillator used to measure the red shift, might well provide an accurate measure of the planetary precessions in a short time. An evaluation of this idea, however, is beyond the scope of the present contract.

Such an experiment is related to the radar time delay experiment proposed by I. I. Shapiro (Ref. 7-5). Measurement of the delay of a radar pulse reflected from Mercury or Venus constitutes a new test of general relativity. This ground-based experiment has been analyzed (independently of the present contract) and it has been found that it measures the same gravitational parameters as does the starlight bending experiment, but in a new combination. To be specific, the expression for arc length in a gravitational field in the neighborhood of a spherical object of mass M can be written as follows according to a procedure introduced by H. P. Robertson:

$$ds^2 = \left\{ [1 - 2\alpha\ r_o/r + 2\beta\ r_o^2/r^2 + \ldots]\ c^2dt^2 - (1 + 2\gamma\ r_o/r + \ldots)\ dr^2 \right.$$
$$\left. - r^2\ (d\theta^2 + \sin^2\theta\ d\phi^2) \right\}$$

where r, θ, and ϕ are the usual spherical polar coordinates and $r_o = GM/c^2$. Only the low-order terms, multiplied by the parameters α, β, and γ, are measured in any of the experiments. General relativity predicts the values $\alpha = \beta = \gamma = 1$. The three classical tests of relativity (red shift, starlight bending, and planetary precession) measure the following combinations of the parameters:

Red shift	α
Light bending	$\alpha + \gamma$
Planetary precession	$2\alpha(\alpha + \gamma) - \beta$

The Shapiro experiment measures the combination

$$(\alpha + \gamma)\ f_1 + \gamma f_2$$

where f_1 and f_2 are functions of the point on the orbit at which the time delay is measured. The function f_1 is larger than f_2, but the contribution of f_2 is typically 20 to 30 percent. It follows that the measurements proposed by Shapiro are indeed a new test of general relativity, in that the parameters α and γ can be independently measured. When the results are combined with the red-shift and precession experiments, which measure the indicated combinations of parameters to 1 percent or better, the parameter β can be evaluated.

Extended analyses of the experiment have recently been performed by Ross and Schiff (Ref. 7-32), as well as by Shapiro (Ref. 7-33). Both analyses confirm the importance of the experiment. Precise active tracking of an artificial solar satellite should provide the same or superior information. Studies of scientific merits of an unmanned solar probe should be pursued. An independent measurement of the solar oblateness is still desirable, but of lower priority.

7.6.4 Precession of a Torque-Free Gyroscope

As a consequence of General Relativity, a top or gyroscope placed either in orbit or on the earth's surface will very slowly precess. The precession rate is the sum of two terms; one of which is proportional to the earth's angular rate, while the other (far larger) is proportional to the orbital angular velocity. The respective magnitudes of the two terms are 0.2 and 7 seconds of arc per year (Refs. 7-7 and 7-8). Because of the extremely small magnitude of the effect, only the most sophisticated gyroscope can be used. It should be placed in orbit, not only to produce the larger of the two effects, but also to eliminate any bearing torques resulting from gravitational forces. Studies of the design of such a gyroscope, funded by NASA, are now being carried out by Stanford University and the Coordinated Sciences Laboratory of the University of Illinois.

The Stanford apparatus consists of a spinning quartz ball, polished as highly as possible, and covered with superconducting niobium. The spinning ball is electrically supported within a spherical enclosure. The direction of the spin is sensed by superconducting pickups sensitive to the magnetic field of the rotating sphere. A star tracker provides the reference.

A substantial correction is required for the proper motion of the star.

Present analyses indicate that isolation of the translational motion of the satellite from such nongravitational forces as drag and solar pressure is unnecessary. The effect of the gravity gradient is to place stringent limitations on the allowable deviation from spherical symmetry of the ball.

This apparatus cannot feasibly be operated within a manned space laboratory because of its extreme delicacy and the long time (months to years) required for the observation. However, launching or recovery from a manned spacecraft is feasible. A low-G environment in such a manned spacecraft would be useful for systems test. A fully meaningful test can be performed only if the level of acceleration inside the spacecraft is held comparable to that experienced by the gyro-bearing satellite in space; estimated at about 10^{-6}G. Means of achieving such low levels of acceleration for extended periods are discussed in the section on stabilization.

This experiment appears to be the only gravitational experiment which might conceivably require the facilities of the low-G laboratory. An extended discussion of apparatus is out of place in this report in view of the fact that the Stanford work is still in progress.

7.6.5 Gravitational Waves

Almost any relativistic theory predicts that gravitational waves exist and move with the speed of light. Such waves have never been observed, because their detection is exceedingly difficult. Different theories predict different kinds of wave phenomena. The Einstein theory predicts a tensor wave, which interacts with the moment of inertia of massive bodies. Theories of the Brans-Dicke type also predict the existence of scalar waves. Determination of the nature of the polarization of gravitational waves, once detected, would provide a most important indication of the nature of the gravitational interaction.

The tensor waves predicted by the General Theory of Relativity, if they exist, are expected to interact very weakly with matter. Such waves should be generated by changes in the moments of inertia of massive systems.

J. Weber (Ref. 7-34) has proposed using naturally resonant mechanical systems, such as the vibrational motion of earth and moon, as tuned detectors to look for gravitational waves at the resonant frequency of the detector. Use of the earth for this purpose is ruled out because of its high level of seismic activity. Because of the failure to complete the Ranger 3-4-5 mission, there is currently no information regarding seismic activity on the moon.

Weber and his associates at Maryland (Ref. 7-34) have constructed a mechanical detector resonant at 1657 cycles per second, with which they are attempting to observe high-frequency gravitational waves that might have been radiated during some cosmic catastrophe. A principal experimental problem is the identification of an observed oscillation with gravitational radiation, because the output of the detector is more or less constant, and the diurnal variation in the observed activity may be sociological rather than gravitational in origin.

To make the detection of gravitational radiation unambiguous, it is desirable to attempt to detect the frequency spectrum of radiation from a known source. For example, if it were possible to detect gravitational radiation having the same frequency as, and incident from the direction of, say, a known binary star system, an argument for the existence of gravitational radiation would be quite convincing. The mere existence of an output from a detection instrument without any knowledge of the source would prove nothing, unless it could be made absolutely certain that an observed signal could not be accounted for by an effect other than gravitational radiation.

Since gravitational waves have not been shown to exist, there are evident logical difficulties with such a procedure. For this reason we have examined an alternate approach, namely, that of constructing a feedback oscillator in space which can be tuned through the frequencies of known variable phenomena. Observation of identifiable peaks in the frequency spectrum of the output would confirm the existence of gravitational waves. Polarization states could be identified by changing the position of the device.

While the construction of such a device appears feasible (if expensive), it has been found that the waves radiated from known binary stars are not strong enough to be detected in a finite time. The description of the apparatus and the sensitivity analysis follows.

To fix ideas, consider two masses in free space uncoupled by any material object, but whose relative motions are sensed by an optical servo system. Assume that the masses are attitude-stabilized and equipped with proportional engines of low thrust. Assume that the thrust levels are controlled so that the masses attract each other, at least over a small interval in their separation, with a force proportional to their separation x. The equation of motion in one dimension relative to the common center of mass is

$$m\ddot{x} + 2R\dot{x} + kx = 0$$

where m is the reduced mass of the system (half the mass of either body, if they are identical), k is the spring constant determined by the gain of the servo loop, and R is the damping coefficient, determined by the bandwidth of the servo loop. The dot indicates time differentiation.

If R^2/m^2 is small compared to k/m, such a device forms an oscillator, with the period

$$T = 2\pi \sqrt{\frac{m}{k}}$$

and the damping time constant

$$t_d = m/R$$

The oscillations will be damped if R is positive, the desired condition if the device is to function as a receiving antenna.

The servo loop response time is of the order R/k. If the period is several hours, and the response time is a millisecond or less, the damping times are measured in the millions of hours.

Since the sensitivity of such a detector is directly proportional to its Q (the ratio of period/π to the damping time) it is clear that the attainable sensitivity is limited, at least in theory, only by the length of time available for observation.

According to Weber (Ref. 7-6), the absorption cross section at resonance for such an antenna averaged over all possible orientation is

$$S = \frac{15\pi G m Q_{in} \beta^2 r^2}{8 \omega c}$$

where

- G = the universal constant of gravitation, 6.67×10^{-11} m^3/kgm-sec^2
- m = the mass of one of the two masses comprising the oscillator
- Q = the oscillator quality factor
- ω = the frequency of the oscillators (and wave)
- c = the speed of light, 3×10^8 m/sec
- β = the propagation number ω/c
- r^2 = the mean-square separation of the masses

If one sets $Q = \frac{\omega\tau_d}{2}$, where τ_d = the damping time, the formula becomes ($\beta = \omega/c$)

$$S = \frac{15\pi}{16} G m \frac{\omega^2}{c^3} r^2 \tau_d$$

showing that the sensitivity, for given ω, increases with the damping time. We will later estimate the order of magnitude of S by assuming m = 1 metric ton (1000 kg), r = 100 meters, τ_d = 1000 hours. These parameters correspond to a very ambitious antenna used to detect radiation from a double star system with a period of observation of several thousand hours.

The noise power, according to Weber, is

$$P_{N1} = \frac{N\hbar\omega}{8\tau_a\,[e^{\hbar\omega/kT} - 1]} \approx \frac{NkT}{8T_a} \quad , \ \hbar\omega \ll kT$$

where

N = the receiver noise factors

$\hbar$ = Planck's constant over 2π

τ_a = the observing time

T = the antenna temperature

For the proposed system, take N as a free parameter, and choose

τ_a = 1000 hours = 3.6×10^6 sec

ω = 0.0628 sec^{-1}

$\hbar\omega$ = 0.4×10^{-16} eV

T = 3°K, so that

kT = 1/4000 eV, so that $kT \gg \hbar\omega$

The noise power depends only on the noise factor, antenna temperature, and averaging time and is, with the above parameters

$$P_N = 8N \times 10^{-12} \text{ eV/sec} = 1.3 \times 10^{-30} \text{ watts.}$$

The signal-to-noise ratio is

$$\frac{P_S}{P_N} = \frac{SI}{P_N}$$

where

S = the antenna cross section

I = the incident radiation flux (power per unit area)

It remains to estimate the radiation flux expected from sources. Binary star systems have been selected for detailed study, since some such systems are quite close and have relatively short periods.

The problem of gravitational radiation from point masses in Keplerian orbit has been discussed by Peter and Mathews (Refs. 7-35 and 7-36). For our purposes, this case is a sufficiently close approximation to a real binary star. Let us further assume a circular orbit. Then the power radiated into unit solid angle is given, after some arithmetic, by

$$\frac{d^2E}{dt\ d\Omega} = -0.7541 \times 10^{22} \left(\frac{1}{T}\right)^{10/3} \frac{M_1^{\ 2} M_2^{\ 2}}{(M_1 + M_2)^{2/3}} \ f(i) \text{ watts/sr}$$

where

T = the period of the system in days

$M_1(M_2)$ = the mass of star 1(2), in solar masses

i = inclination of the system to the plane of the sky, and

$f(i) = \frac{1}{4\pi} \frac{5}{16} (1 + 6 \cos^2 i + \cos^4 i)$

Such a system decays by gravitational radiation alone in a finite time; the separation becomes zero at T_c given by

$$T_c = 4.73 \cdot 10^{10} \ (T)^{8/3} \ \frac{(M_1 + M_2)^{1/3}}{M_1 M_2} \text{ years}$$

where T is the initial period in days.

Results for the total radiated power and lifetimes are given in Figs. 7-4 and 7-5. The chief moral is to be drawn from Fig. 7-5. Since we live in a universe characterized by a time scale of $\sim 2 \times 10^{10}$ years, systems whose lifetime is much less than 10^9 years or so will be quite rare. Thus, a binary star whose period is less than about half a day should be regarded as a curiosity, because it should long since have lost its energy by gravitational radiation.

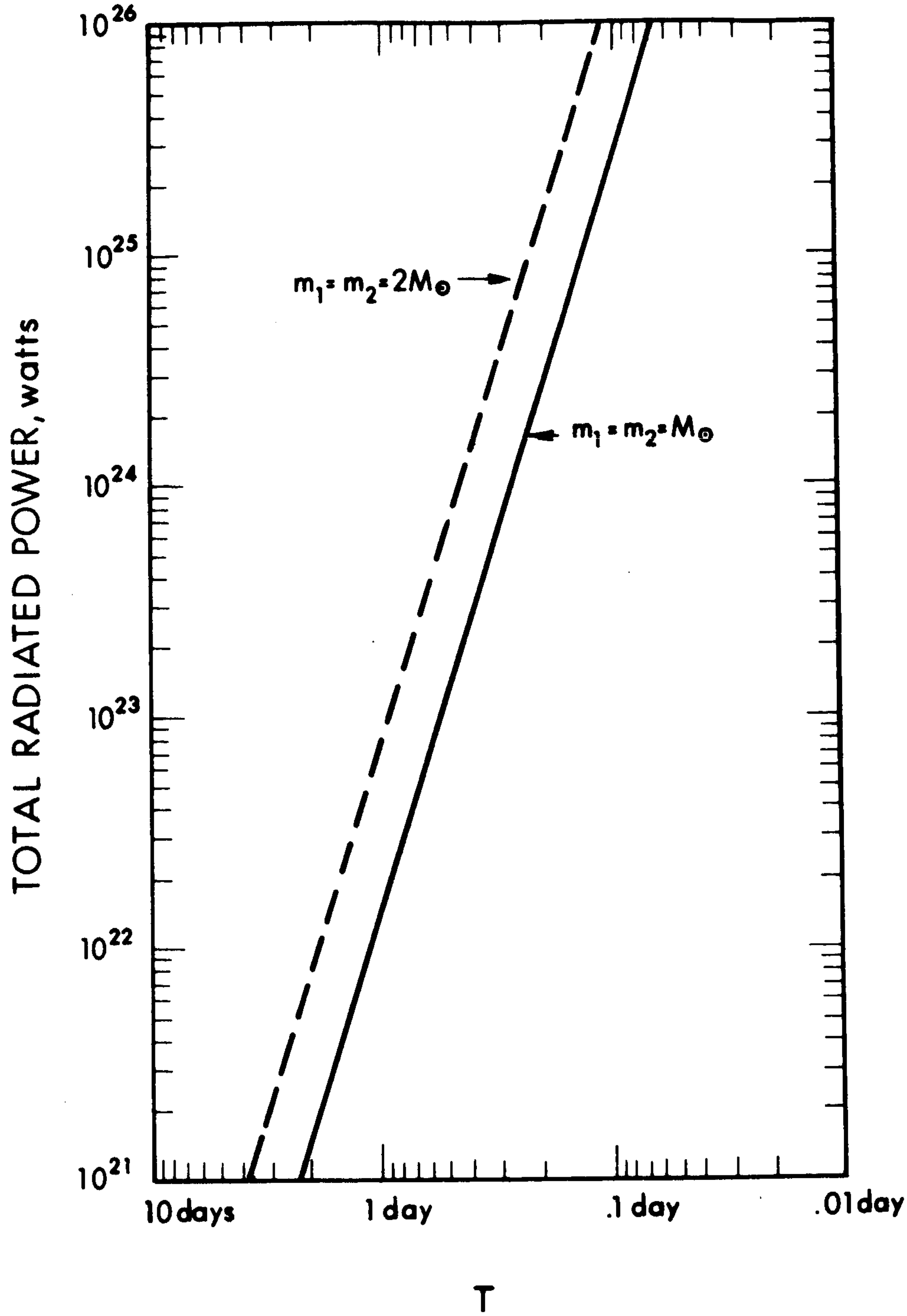

FIG. 7-4 TOTAL POWER RADIATED BY A BINARY STAR SYSTEM OF PERIOD T

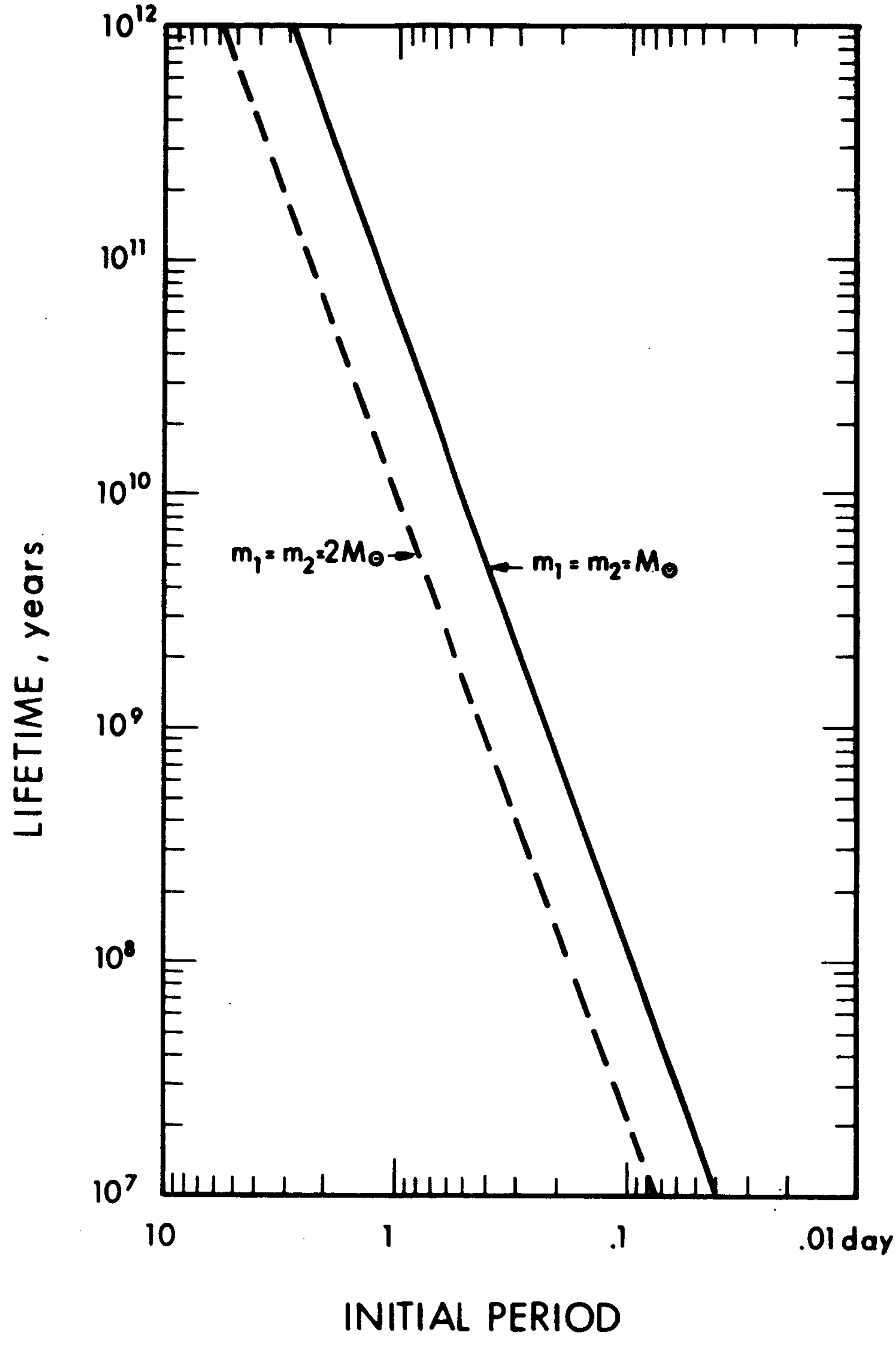

FIG. 7-5 LIFETIME OF BINARY STAR SYSTEM (POINT MASSES, CIRCULAR ORBIT)

Indeed, the shortest period binary known, D Q Her, has a period of $0^d.19$, apparently because $M_1 + M_2 \approx 10^{-2}$.

Objects which are short-lived on the cosmological time scale, such as OB aggregates like O Ori or the bright stars of the Pleiades, are usually associated with dusty or gaseous regions. One should not expect such phenomena close to the sun.

The sort of object discussed here is a binary system in which the components are almost or exactly touching. They perhaps share a common envelope. The structure of such systems is extensively discussed by Kopal and Struve (Refs. 7-37 and 7-38). About 20 percent of such objects are detectable as eclipsing binaries: Wolf-Rayet stars should perhaps be included also (Ref. 7-39).

Nine eclipsing binaries are known to exist within 30 psc of the sun. Their parameters are given in Table 7-IV. Most of the data is from Kopal.

HD 16157 is the closest such system known, being at a distance of $(0.083)^{-1} = 12$ psc. Many objects, at greater distances, have periods which range from about $0^d.25$ to $0^d.4$. This period seems to be an empirical limit, in agreement with the theoretical arguments given above.

The data indicate that one should expect about 50 close binary systems within about 30 psc of the sun. Ten of them might have periods of the order of a quarter day. None will have masses much larger than $M_\odot$ (they would be very bright otherwise). Moreover, for reasons of time scale, one should not expect objects of shorter periods.

Taking $T = 0^d.25$, a distance of 10 psc, $M_1 = M_2 = 1$, and $f(i) = \frac{1}{4\pi}$, one finds a graviton flux of 1.01×10^{-12} watts/m^2. The cross section of the proposed antenna is, with $\omega = 2\pi/T = 2.9 \times 10^{-4}$,

$$S = 6.1 \times 10^{-33} \text{ m}^2$$

TABLE 7-IV

NEARBY ECLIPSING VARIABLES

Object	Period	M_1	M_2	Parallax
β Aur	$3^d.960$	2.33	2.25	
i Boo	$0^d.268$	1.38	0.68	
R CMa	1.136	0.49	0.11	
YY Gem (Castor C)	0.814	0.64	0.64	0".072
VW Cep	0.278	1.44	0.47	
CrB	17.4			0".049
β Per (Algol)	2.867	5.2	1.0	
δ Cap				
HD 16157	1.5609			0".083

The received power is thus only 6×10^{-45} watts. 15 orders of magnitude less than the calculated noise power with unity noise factor.

It thus appears that there is small incentive to conduct a search for gravitational radiation from near binary stars since the power level of radiation from the stars is predicted to be greatly below the noise power for the most promising detection scheme considered. During the course of the present study, it has not been possible to discover a periodic system which radiates a detectable signal. Radiation from nearby objects in the solar system is ruled out since the time required for light to cross the solar system is much less than the periods of satellite systems. Hence, the fields detected are near-zone fields (ordinary inverse-square fields) not radiation fields.

An experiment of the type described does not appear feasible.

7.6.6 Discussion of Neutrino Resonant Absorption

An experiment to determine that neutrinos exhibit a gravitational red shift has been considered. The feasibility of conducting the experiment is presently in doubt and cannot be established without extensive laboratory work. The suggested experiment consists of observing that resonant absorption of mono-energetic neutrinos takes place in the low-G environment, although in a gravitational field the red shift of neutrino energy is sufficient to destroy the resonance. A discussion of the experiment is included here for reference in the event that the feasibility of the experiment becomes established at a later time.

The phenomenon of resonant absorption of gamma rays, also known as the Mössbauer effect after the discoverer, was first reported by Mössbauer in 1958 (Ref. 7-40), and confirmed in 1959. Since 1959, hundreds of experiments have been reported in which the Mössbauer resonant absorption of gamma rays was observed. An excellent general review of the subject was published by Frauenfelder in 1962 (Ref. 7-41). An extensive collection of references to the literature as of 1964 appears in the proceedings of the Third International Conference on the Mössbauer Effect.

The Mössbauer effect is observed as follows: A radioactive source of gamma rays and a gamma-ray detector are placed on opposite sides of a sample of material called the absorber (Fig. 7-6). Gamma rays emitted by the source enter the absorber and are either absorbed by the nuclei of the absorber or pass through and activate the detector. Scintillation detectors are commonly used with the amplitude of the pulses from individual gamma rays being used to select gamma rays in the appropriate energy range. Individual pulses from the detector are counted in an electronic device. A mechanical drive device is provided such that gamma rays may be counted when there is a relative linear velocity between the source and the absorber. Reciprocating motion of the source toward and away from the absorber is often used

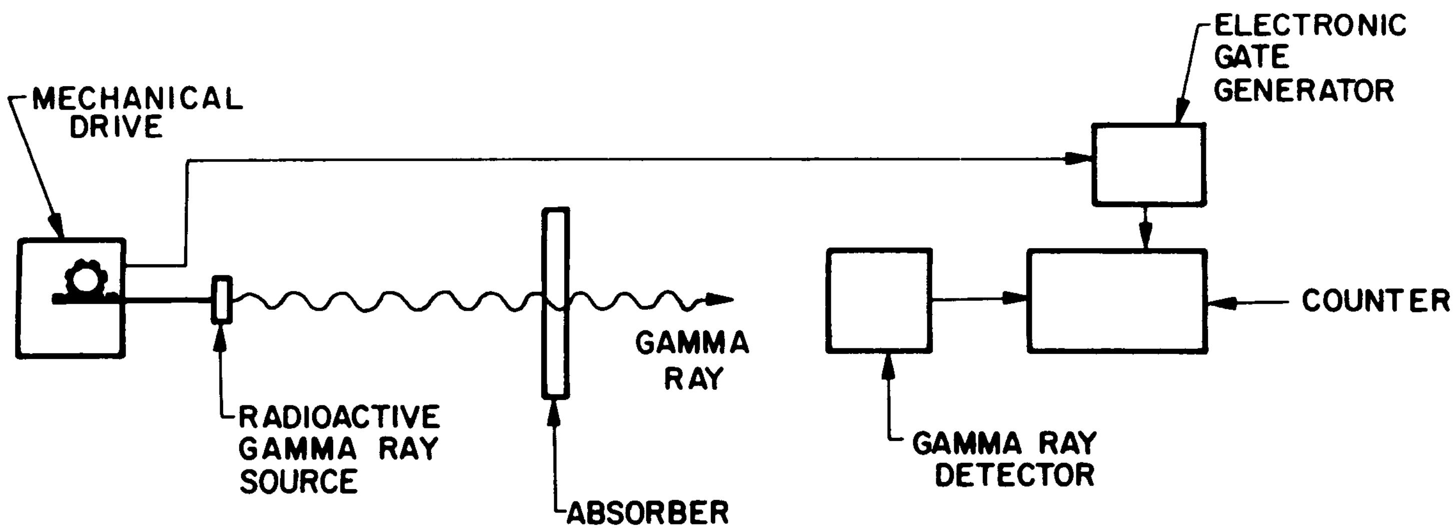

FIG. 7-6 EXPERIMENTAL ARRANGEMENT FOR OBSERVATION OF THE MOSSBAUER EFFECT

with an electronic gate circuit which allows detected gamma rays to be counted only on a portion of the mechanical motion cycle when the relative velocity between source and absorber lies in a narrow velocity interval.

Gamma rays are quanta of electromagnetic radiation emitted when a nucleus decays from an initial excited state to a final state of lower energy. For most cases of interest for Mössbauer experiments, the gamma-emitting nucleus is the daughter of a parent beta-active nuclide. While the mean life of the beta decay of the parent nucleus may have any value (seconds to years), the mean lives of the nuclear excited states which give rise to the gamma rays are typically in the range 10^{-10} to 10^{-12} sec. For the Mössbauer effect to be possible, the final state in the electromagnetic transition must be the stable ground state or at least a quite long-lived state of the nuclide, and the absorber must contain nuclei of the same isotope as the gamma-ray emitter. The commonly used decay scheme of Co^{57}, the beta decaying parent of Fe^{57}, the gamma-ray emitting daughter, is shown as Fig. 7-7. The Mössbauer effect on the 14.4 KeV gamma rays can be observed if the absorber contains Fe^{57}.

When a nucleus emits a gamma ray, the energy of the gamma ray will be less than the energy difference between the initial and final states if the nucleus is free to recoil. During the emission process from a free nucleus, the recoil velocity of the nucleus results in a Doppler shift of the gamma ray, and the nucleus receives an amount of energy equal to

$$R = \frac{P^2}{2M} = \frac{P^2}{2M} = \frac{E_\gamma^{\,2}}{2MC^2}$$

where R = Recoil energy of free nucleus

M = Mass of nucleus

P = Momentum of nucleus

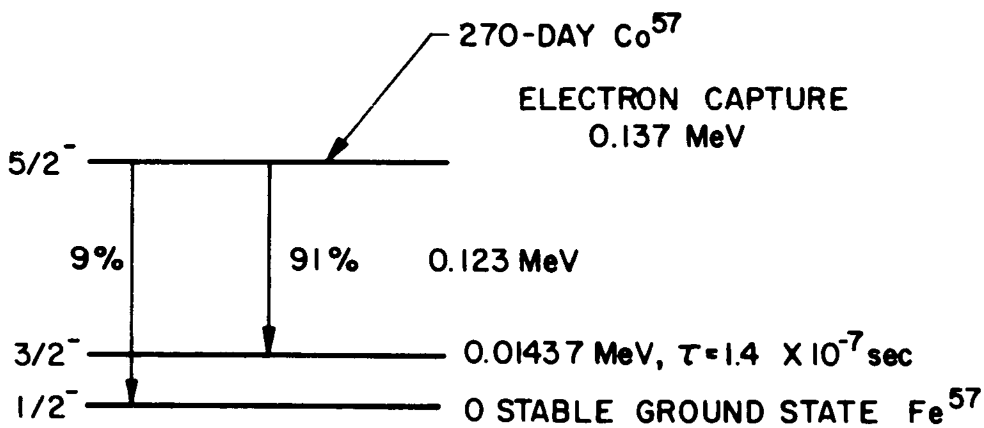

FIG. 7-7 DECAY SCHEME OF Co^{57}, THE BETA-ACTIVE PARENT NUCLIDE, AND Fe^{57}, THE GAMMA-RAY-EMITTING DAUGHTER NUCLIDE

p = Momentum of gamma ray

E_γ = Energy of gamma ray

C = Velocity of light

If the energy difference between the initial and final state of the free nucleus is E_r, energy conservation requires

$$E_\gamma = E_r - R$$

In passing through the absorber, the gamma ray impinges upon nuclei of the same nuclide as the emitter having the excited state at an energy E_r above the ground state. For free target nuclei, resonance absorption can occur if the gamma-ray energy is equal to the energy difference plus the energy required for the recoil of the target atom, i.e., for gamma rays of energy $E_r + R$. The term "resonant absorption" describes the inverse of the emission process in which the gamma-ray energy is converted back into nuclear excitation energy. The inverse process will occur readily when the gamma ray is "tuned" to the absorber, i.e., when the gamma-ray energy is precisely correct, and will occur less readily for gamma rays of different energies. The rate at which radiation is absorbed by nuclei is customarily described by the apparent size of the nuclei as viewed by the radiation, i.e., the absorption cross section per nucleus, commonly expressed in cm^2. For gamma rays of wavelength λ, the absorption cross section at resonance is very nearly equal to λ^2. As a function of energy, the absorption cross section varies as the familiar resonance curve, namely

$$\sigma_{abs(E)} = \frac{2I_B + 1}{2I_A + 1} \lambda^2 \frac{\Gamma \Gamma_\gamma}{4[E - (E_r + R)]^2 + \Gamma^2}$$

where $\sigma_{abs(E)}$ = Gamma ray absorption cross section (cm^2)

I_A = Spin of ground state

I_B = Spin of excited state

λ = Wavelength of gamma-ray photon

Γ = Total width of the excited level

Γ_γ = Partial width of the excited level due to the gamma-ray transition probability

E = Energy of the gamma ray

E_r = Energy difference between the two levels

R = Recoil energy required by the target nucleus

For the case of an excited state which decays only by electromagnetic transition to a stable ground state, the total level width is due to the gamma width Γ_γ. In the case of Fe^{57}, the emitting level is further broadened by the competing transition to the intermediate level. The level width is related to the transition probability per unit time - the inverse of the mean life - by the uncertainty relation

$$\Gamma \tau = \bar{h}$$

where Γ = Level width in electron volts

τ = Level mean life-sec.

$\bar{h}$ = $1/2\pi$ x Planck's constant = 6.58×10^{-16} eV-sec.

The gamma-ray absorption cross section versus energy, then, has a strong maximum at the resonant energy $E_r + R$, the width of the resonance, Γ, being a property of the nuclear excited state.

Prior to Mössbauer's original work, attempts to achieve resonant absorption had been made by supplying the required energy deficit, 2R, by Doppler shifting the emitted gamma rays by virtue of using sources moving at high velocities with respect to the absorber. Not much success was achieved. Mössbauer's original experiment was a demonstration of a technique by which the nuclear recoil energy, R, is reduced to zero for both emitter and absorber. By having both the emitting and absorbing nuclei bound in crystal lattices, and by cooling the crystals to temperatures well below the Debye temperature, θ, for the crystals, it was shown that, in a substantial fraction of emissions and absorptions, the recoil momentum was absorbed by the crystal as a whole with the emitting and absorbing nuclei remaining bound in the crystal during the event. When the recoiling mass is set equal to the mass of an entire crystal, the recoil energy is zero for practical purposes. For the "recoilless" events, the large resonance cross section is observed for a fraction of the gamma rays with zero relative velocity between the source and absorber. The demonstration that resonance absorption is taking place consists in observing the counting rate of transmitted gamma rays (Fig. 7-6) as a linear velocity is imparted to the source and, hence, Doppler energy shift is imparted to the gamma rays. Results are plotted as counting rate versus linear velocity. Figure 7-8 is from Mössbauer's original data for the 129 KeV gamma ray of Ir^{191}. Note that a source velocity of only 2 cm/sec is sufficient to Doppler shift the gamma rays off resonance.

One particularly interesting application of the Mössbauer effect is the measurement of the gravitational red shift (and blue shift) of gamma rays by Pound and Rebka (Ref. 7-42) and later by Pound and Snider (Ref. 7-17). In the Pound/Rebka experiment, the source and absorber were separated by a vertical distance of 23 meters. It was observed that Mössbauer resonance occurred for a different relative source-absorber velocity when the source was at the top of the 23-meter path and the absorber at the bottom than when the source and absorber were interchanged. Attributing the difference in the required Doppler shift to the assumption that the gamma-ray energy changes by an amount equal to the change in gravitational potential energy of the gamma rays gave agreement with the observations within the experimental error reported as 0.8 percent. The experiment is taken as a direct observation and measurement of the gravitational red shift.

The red shift of gamma rays resulting from placing a Mössbauer emitter-absorber in an accelerated system has been measured

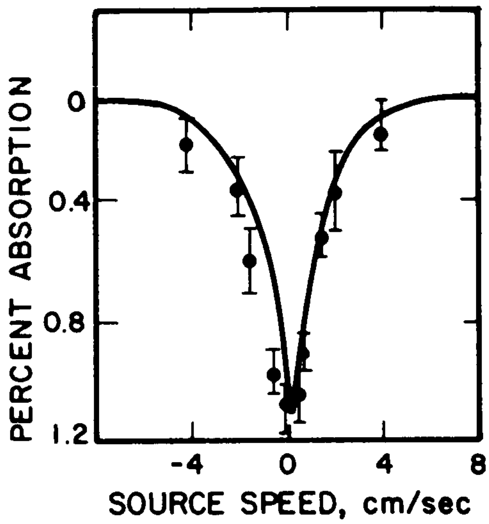

FIG. 7-8 THE RELATIVE INTENSITY OF 129 KeV GAMMA-RAYS FROM Ir^{191} TRANSMITTED BY AN Ir ABSORBER AS A FUNCTION OF SOURCE SPEED (Data from (Ref. 7-43)

(Ref. 7-44). The source was placed at the center of a turn-table and the absorber, in the shape of a hoop, was placed at the edge of the table. As the rotational speed of the table was increased (up to 30,000 rpm), the gamma rays suffered an increasing red shift in moving from the center to the edge of the turntable. Experimental results agree well with prediction, and are consistent with the hypothesis of the principle of equivalence of a gravitational field and an acceleration of the reference system. The reader with a deeper interest in the subject of the Mössbauer effect for gamma rays is referred to the original literature, especially Frauenfelder (Ref. 7-41), Bearden (Ref. 7-45), and references contained therein.

Analogous to the emission of the zero-rest-mass gamma ray in the electromagnetic transition between nuclear states, massless particles are emitted in transitions governed by the weak interaction. The best example of the weak interaction is perhaps the beta decay of the free neutron into a proton, an electron, and an anti-neutrino

$$n \rightarrow p + e^- + \tilde{\nu}_e$$

The subscript e is now commonly used to indicate the neutrinos associated with the weak interactions of electrons (the subscript μ is used to indicate neutrinos arising from weak interactions of mu-mesons). The existence of the neutrino as a massless particle resulting from the beta decay process was first postulated by Pauli in 1930 (Ref. 7-45), and a quantitative theory of the beta decay process with the neutrino taken into account was developed by Fermi in 1934 (Ref. 7-47). The free anti-neutrinos from beta decay of fission products were observed outside a high-power reactor shield to induce the process which was the inverse of that in which they were created, i.e., inverse beta decay.

$$\tilde{\nu}_e + p \rightarrow n + e^+$$

with a cross section of 10^{-43} cm^2 consistent with the prediction of the modern theory (Refs. 7-48 and 7-49). The hydrogen nuclei present in 1000 pounds of water provided the target protons in the apparatus. Interactions were observed at the rate of about one per hour.

Their small cross section makes neutrinos very difficult to detect. A neutrino below the threshold in energy for inversion of any beta decay process may not interact with matter at all, or may have only a very small cross section for scattering electrons. Energy transport from within dense, hot stars is probably largely via the neutrino flux, so that a presently interesting measurement would be a measure of the cross section for neutrino-electron scattering.

It was pointed out by Nagle and reported by Visscher in 1959 (Ref. 7-50), that if the conditions necessary to achieve Mössbauer resonant scattering of ν_e could be achieved, neutrinos would be absorbed with the large resonant cross section of the order of λ^2. For 100 KeV neutrinos, the resonant absorption cross section would be about 10^{-25} cm^2, which is nine orders of magnitude larger than in the nonresonant absorption of fission product neutrinos in hydrogen, and is large enough that an appreciable probability for absorption can be achieved with an absorber thickness on the order of a centimeter. To obtain mono-energetic neutrinos, Visscher suggests the use of an isotope which undergoes K-capture, i.e., the absorption of a K electron by the nucleus with the energy difference between initial and final state being carried away by a neutrino. The resulting neutrinos are then mono-energetic to a degree determined by the natural linewidth, or lifetime, of the excited state, and/or the energy distribution of the captured electrons.

To resonantly absorb the neutrinos, an absorber crystal must be prepared with vacancies available to the electron to be created in the inverse K capture, and the final electron state must have the same energy as the state of the initial electron which underwent capture. K shell electron capture will not produce neutrinos which can be resonantly absorbed since, in the target atom, the exclusion principle will prevent the product electron from entering the already full K shell. Secondly, if the mean life of the electron capture process is, say 10 days, the width of the neutrino energy distribution is narrower than in the typical gamma-ray case by a factor of 10^{17}. The width of the neutrino energy distribution will be

$$\Gamma = \hbar/\tau = 8 \times 10^{-22} \text{ eV for } \tau = 10 \text{ days.}$$

One implication of the extreme sharpness of the resonance, recognized from experience with gamma rays, is that even thermal vibrations would introduce sufficient random motion between source and absorber to destroy the resonance. A second implication is that the red shift predicted (but not yet observed) for neutrinos in a terrestrial laboratory will destroy the resonance if there is a vertical displacement of the absorbing atom with respect to the emitting atom by as much as 10^{-8} cm (1Å).

Visscher has made suggestions to overcome all of the above difficulties. It is doubtful that his suggestion of placing a cryostat in free-fall is a practical method for overcoming the gravitational effect, however. His suggestions for overcoming the electronic and accoustical vibration difficulties, while certainly requiring an experimental verification, appear to be practical. Visscher's suggested method is described briefly here.

An element A which undergoes electron capture to form the ground state of element B is selected. A crystal of element B is prepared. One half of the crystal is doped with element A as an impurity to the amount of perhaps 0.1 percent. The neutrinos of interest are those emitted not by K-electron capture but by the capture of outer electrons from discrete levels in the vicinity of the impurity site. For the target B atom, in reverting back to an A atom by neutrino capture, the outer levels in the vicinity of the (about to be created) impurity site will be empty. Visscher has calculated that if the emitter and absorber are parts of the same crystal, so that phonons can be propagated from one to the other without attenuation, the Doppler shift of neutrinos due to relative motion of source and absorber will not destroy the resonance. If the temperature of the crystal is maintained well below the Debye temperature, θ, the probability of recoilless absorption is

$$e^{-3R/2K\theta}$$

where

$R = E_\nu{}^2/2MC^2$ is the classical recoil energy

θ = Debye temperature

K = Boltzmann's constant

Thus the absorption cross section is

$$\sigma = 1/2\, \sigma_o e^{-3R/\theta}$$

where

$$\sigma_o = 2\, \lambda^2\, g\, \Gamma_o/\Gamma_{tot}$$

λ = neutrino wavelength

g = statistical factor

Γ_o = partial width for capture of an outermost conduction electron

Γ_{tot} = total capture width

for E_ν about 100 KeV and z about 80, σ is about 10^{-25} cm^2.

Visscher suggested the use of Dy^{159}, which electron captures to Tb^{159} with a mean life of 134 days, sometimes emitting a 58 KeV gamma ray. The branching through the gamma activity is important since the gamma activity may then be used to detect the Dy^{159} created in the initially "clean" end of the crystal. The Dy^{159}

should be diffused into one end of a Tb crystal containing some Tb^{159}. It is not completely clear that Dy^{159} is a favorable case since neither the neutrino energy nor the branching ratio to the ground state is known.

The role of gravity in the measurement can be readily understood. It is hypothesized that neutrinos undergo a gravitational red shift identical to that for photons. As mentioned above, the neutrino energy linewidth is about 10^{-22} eV for τ = 100 days, and a vertical displacement in a field of 1 G of 10^{-8} cm produces a gravitational shift of 10^{-22} eV. Thus, in a terrestrial laboratory, only the target atoms in a horizontal slice of the crystal 10^{-8} cm thick could serve as potential target atoms.

Considering the experiment to be conducted in an orbiting laboratory, a gravitational field of 10^{-8}G will be required to allow a 1-cm vertical thickness of the crystal to participate in the absorption. It is doubtful that a field of 10^{-8}G could be obtained in the free-falling cryostat suggested by Visscher for the time required and with a practical design.

The experiment considered for the zero-G laboratory consists of maintaining the prepared Tb crystal at 10^{-8}G for a period of 10 to 30 days, and then analyzing the initially undoped end of the crystal for Dy^{159} activity. If a 50-gm crystal of Tb^{159} with one half doped with 0.1 percent of Dy^{159} were kept at liquid helium temperature and at 10^{-8}G for 15 days and then cut apart, the initially pure Tb half should be emitting gamma-rays at the rate of 100/sec if the following conditions obtain:

1. The branching ratio is 50 percent,
2. The neutrino energy is 100 KeV,
3. The Debye temperature is 300°K,

and 4. The principle of equivalence applies to neutrinos.

7.6.7 Measurement of the Universal Constant of Gravitation

The universal constant of gravitation, G, is unique among the constants of physics in that it never occurs in measurable combination with other fundamental constants. Although it occurs in every gravitational force expression, it is always multiplied by a mass. For example, the product of $M_{\odot}G$, where $M_{\odot}$ is the solar mass, is known extremely well in astronomical units, very well in light-seconds as a result of the measurements of the radar range of Venus, and quite well in laboratory units, a principal error being the small uncertainty in the speed of light.

The value of G can be measured accurately only if gravitational forces resulting from different configurations of masses are compared; the values of the masses and distances involved being known in laboratory units. To perform the comparison, it is necessary to have access to a reference force or torque which does not depend directly on G and which is stable to the required accuracy.

The definitive measurement of G was performed by P. R. Heyl and P. Chrzanowski at the National Bureau of Standards in 1942. They obtained the value

$$G = (6.673 \pm 0.003) \times 10^{-8} \text{ dynes-cm}^2\text{-G}^{-2}$$

which compared well with the still-accepted value of $(6.67 \pm 0.005) \times 10^{-8}$ dynes-cm^2-G^{-2} obtained by Heyl in 1930. The experiment was performed using a torsion balance consisting of two 87-gram platinum balls held 20 cm apart by an aluminum tube supported, in turn, by a tungsten lamp filament about one mil in diameter and about a meter long. The measured quantities were the periods of oscillation when two 66-kg steel cylinders were placed along the equilibrium position of the balance and at right angles to it. Large differences (of the order of 700 seconds out of 2500) were observed. The gravitational constant is then determined by

$$\frac{GK}{I} = (2\pi)^2 \left[\frac{1}{T_1^2} - \frac{1}{T_2^2} \right]$$

where K is a constant depending on the masses and geometrical factors, and I is the moment of inertia of the balance arm and balls.

The torsion constant of the wire cancels out of the above expression, but one must recognize that the experiment depends entirely on the stability and linearity of the torsion fiber, which provides the reference torque in this experiment. The experimental error quoted arises almost entirely from systematic differences observed when two different fibers were used. The tension applied to the wire was the weight of the balance and its platinum balls, and was, of course, as stable as the acceleration of gravity normally is in the location of the test (Washington, D. C.). The acceleration of gravity can be independently measured with a pendulum in laboratory units, to an accuracy approaching one part per million.

It is unlikely that any other reference force can be measured to this accuracy. For example, measurements of magnetic force depend on measurements of current, which, in turn, depend ultimately on either the gravitational force or on the less accurate electrochemical measurements which can be uncertain to a few parts in 10^5. One concludes that the value of G is not likely to be improved by measurements in a spacecraft, where the stable reference force is not available. Improvement is more likely to result from an improvement in the stability of the intermediate reference (the torsion fiber).

One occasionally hears the suggestion that the universal constant of gravitation might be measured by placing two known masses M_1 and M_2 in orbit about one another and observing their relative motion, using Kepler's second law:

$$T^2 = \frac{a^3}{G(M_1 + M_2)}$$

A 100-kg ball of uranium has a radius of 23 cm. If two such balls were placed in orbit with a semimajor axis of 1 meter, the period, T, would be 7.74×10^4 seconds, or $0^d.32$. To limit the relative error in G to one part in 2×10^4 (a factor of 10 better than at present), the tolerable measurement errors are:

Period:	0.5×10^{-4}	(1.3 sec)
Mass:	10^{-4}	(10 grams)
Semimajor axis:	0.3×10^{-4}	(30 microns or about 0.001 inch)

The measurements of time and mass are simple, but the distance measurement evidently requires the greatest care. The gravitational force between the two objects is:

$$F_g = \frac{G M_1 M_2}{r^2} = 6.67 \times 10^{-7} \text{ newtons}$$

The solar pressure of 4.5×10^{-6} newtons/m^2 at the distance of the earth leads to a force on each half (assumed nonreflecting) of 0.72×10^{-6} newtons, an order of magnitude larger. Other forces, from drag, cosmic dust, the solar wind, and the magnetic field in space are also present and are much larger than the force of 3×10^{-11} newtons which one seeks to measure.

Such an experiment is, in any case, impossible in low-earth orbit, because the gravity gradient will separate the two bodies unless very stringent conditions are met. For a rigorous justification of this statement, one may appeal to the knowledge of the properties of the restricted problem of three bodies.

Assume that two massive bodies rotate about one another in a circular orbit with angular frequency ω, while a small test body moves in their common field. The equation of motion of the small body, expressed in a coordinate system with its origin the center of mass and rotating at the frequency ω, is

$$\ddot{r} + \overline{\omega} \times (\overline{\omega} \times \overline{r}) + 2\overline{\omega} \times \dot{\overline{r}} = \frac{\mu_1 \overline{r}_1}{r_1^3} + \frac{\mu_2 \overline{r}_2}{r_2^3}$$

where $\bar{r}$, $\bar{r}_1$, and $\bar{r}_2$ are the vectors from the small body to the center of mass and to the other two bodies of masses μ_1/G and μ_2/G, respectively.

The motion is conservative, since the centrifugal acceleration can be derived from a conservative potential $\frac{1}{2}\left[(\bar{\omega} \times \bar{r})^2 - \omega^2 \bar{r}\right]$, while the Coriolis acceleration, $\bar{\omega} \times \dot{\bar{r}}$, does no work, having precisely the same form as the acceleration of a charged particle in a uniform magnetic field. The scalar potential function is, in the plane $\omega \cdot r = 0$

$$V = \frac{\mu_1}{r_1} + \frac{\mu_2}{r_2} + \frac{1}{2}\omega^2 r^2$$

The equipotentials of this function determine the boundaries of the motion of the small particle since, for a given total energy, the particle can never enter a region in which the potential energy is greater than the total energy. This argument shows that the periodic orbits are possibly sufficiently near either massive body, between the body and the collinear libration points which are saddle points in the potential surface. If the particle is given a greater energy, it can escape from the neighborhood of one body and orbit both, or escape from both. It can also execute stable motions in the neighborhood of one of the Trojan points, at the vertex of an equilateral triangle whose other vertices are at the centers of the two massive bodies.

The critical argument is the following one: suppose that one massive body is the earth, and that the other is a massive test object (a few hundred kilograms, say). Then it is easy to see that the entire region of periodic orbits about the test object must lie inside the test object because of the finite density of materials, unless the orbit is very high (several earth radii). It is, therefore, impossible to orbit two objects about one another in close orbit about a third, even neglecting the nongravitational perturbations (such as drag) which are larger than the gravitational forces in any case. If the two test objects are of comparable mass, the argument is simply more complicated, but the conclusion is the same.

To derive the condition, it is sufficient to calculate the positions of the collinear liberation points, since orbits closer to the test mass are stable.

The gravitational and centrifugal accelerations balance at the libration point:

$$\omega^2 r = \pm \frac{\mu_1}{r_1^2} + \frac{\mu_2}{r_2^2}$$

Assume $\mu_1 \ll \mu_2$, so that the center of mass is located at the center of the mass μ_2/G. Then $r = S \pm r_1$, and $r_2 = S \pm \Delta r$, where S is the separation of the two massive bodies. Then, to first order in r,

$$\omega^2\left(S \pm r_1\right) \approx \frac{\mu_1}{r_1^2} + \frac{\mu_2}{S^2}\left(1 \pm 2\frac{r_1}{S}\right)$$

Now, $\omega^2 S = \frac{\mu_2}{S^2}$, since the two massive bodies are in orbit about one another. Hence, we obtain;

$$\pm\omega^2 r_1 \approx \frac{\mu_1}{r_1^2} \pm 2\frac{\mu_2}{S^2}\frac{r_1}{S} \approx \pm\frac{\mu_1}{r_1^2} \pm 2\omega^2 r_1$$

We conclude that, to first order in r_1/S,

$$r_1^3 = \frac{\mu_1}{3\omega^2} = \frac{1}{3}\frac{\mu_1}{\mu_2}S^3$$

if $\mu_1 \ll \mu_2$, $r_1 \ll S$. Now we assume that the two masses μ_1/G and μ_2/G are spherical with average densities ρ_1 and ρ_2, and radii R_1 and R_2, respectively. We obtain

$$\left(\frac{r_1}{R_1}\right)^3 = \frac{1}{3}\frac{\rho_1}{\rho_2}\frac{S^3}{R_2^3}$$

It follows at once that, if $\rho_1 = \rho_2$, $r_1 \geq R_1$ only if $S > 3\sqrt{3}\,R_2$ or 1.44 R_2, so that a small object will orbit a larger one only if the orbital altitude exceeds 2800 km. If the orbiting mass is uranium, with density 19.5 compared to the earth's 5.6, it is barely possible for two objects to orbit one another in low orbit about another object. In a 400 km orbit, all stable orbits lie within a shell whose thickness is only 12 percent of the radius of the uranium sphere. The configuration is almost unstable and will be destroyed by the slightest perturbation. A large stable region is not attained until the orbiting bodies are several earth radii distant.

7.6.8 Improved Measurement of the Earth's Gravitational Field Satellite by Means of a Zero-G Satellite

The use of earth satellites for obtaining measurements of the gravitational figure of the earth is an advanced art. The procedure consists essentially of a least squares determination of the harmonic coefficients in the earth's gravitational potential from tracking data furnished by precise observations of many satellites during many orbits. Many terms in the expansion are now known, including 13th, 14th, and 15th azimuthal harmonic coefficients which are important because of a resonance between the length of the day and the period of a low satellite orbit.

Many people have suggested the use of a so-called zero-G satellite for improving such measurements. Such a satellite could conceivably be launched from a manned orbiting laboratory. Such a satellite consists of an isolated central ball surrounded by a shield which does not touch it. The externally orbiting shield carries propulsion which is used to keep it in a fixed position relative to the ball, with the ball at its center. The development of such a device is under way at Stanford, where work has been done by R. H. Cannon (Ref. 7-51), De Bra (private communication), and B. Lange (Ref. 7-52). The construction of such a device to reach accelerative levels of 10^{-10} g seems quite feasible. We have drawn heavily on Lange's work in discussing the question of stabilization of equipment inside an orbiting laboratory.

The most recent measurements of the earths gravitational field were reported at the Second International Symposium on The Use of Artificial Satellites for Geodesy, held in Athens, Greece, in March, 1965. From the review article by W. A. Kaula and the detailed solution of R. J. Anderle presented at that conference, it is concluded that the present knowledge of the figure of the earth is sufficient to predict the orbits of earth satellites to within the errors arising from the small uncertainty in station locations and from noise in the tracking instruments. Solutions obtained from lower satellite orbits agree well with measurements on 24-hour satellites, indicating that drag on the lower orbits does not introduce a substantial error into the computations. It follows that there appears to be little justification for the employment of a zero-G satellite to cancel drag in order to improve the accuracy of geodetic measurements. Such a conclusion has also been reached at Stanford University, where work on zero-G satellites is primarily motivated by a desire to measure the drag and other nongravitational perturbations.

One may also consider the measurement of the relativistic precession of a zero-G satellite orbit per revolution. The rate of advance of perihelion

$$\frac{d\theta}{dn} = \frac{6\pi}{c^2} \frac{GM}{a(1 - e^2)} = \frac{6\pi}{c^2} \frac{gR_o^2}{p} = \frac{6\pi}{c^2} \frac{v^2}{c^2} \left(\frac{1 - e}{1 + 3}\right)$$

where

- G = the universal instant of gravitation
- M = the earth's mass
- a = the semimajor axis
- e = the eccentricity
- p = the semilatus rectum
- g = the acceleration of gravity at the earth's surface
- R_o = the earth's radius
- v = the circular velocity for an orbit of the same energy (major axis)

Neglecting e compared to unity, and putting v equal to the circular velocity for a 400 km earth orbit (7.65 km/sec), the rate is

$$\frac{d\theta}{dn} = 4.8 \times 10^{-9} \text{ radians/revolution}$$

$$= 2.2 \times 10^{-4} \text{ seconds of arc/revolution}$$

$$= 4.3 \times 10^{-6} \text{ degrees per day.}$$

This rate is completely masked by the error in the rate of several degrees per day predicted from the oblateness of the earth. Because the dependence of the two effects on orbit parameters is different, it might still be possible to disentangle the two effects if there were not so many larger terms in the earth's potential. In view of the fact that a good fit is obtained without the relative term, down to the noise level expected from station errors, the prospects for a precise measurement of the relativistic effect are rather dim.

7.7 Stabilization

It has been shown above that all practical engineering questions related to guidance and control of spacecraft or the stabilization of experimental apparatus can be answered by the nonrelativistic mechanics of Newton. In the present report, preliminary conclusions are presented regarding the principal engineering problems of the low-G orbiting laboratory.

The perturbing accelerations on the spacecraft, or on an apparatus located in it, are conveniently divided into three groups:

1. Perturbations from internal nongravitational forces, such as electrostatic forces or reactions from the motion of men or apparatus
2. Perturbations from external nongravitational forces such as drag and solar pressure
3. Perturbations from tidal (gravity-gradient) forces

Estimates presented below indicate that as a result of the motion of men and equipment, the manned laboratory spacecraft will be subject to impulsive accelerations, randomly oriented, of magnitudes of 10^{-2} G or more. While most experiments, particularly preliminary ones, may be performed in this environment, it seems clear that precise equipment must be isolated from the main spacecraft, essentially in a separately-orbited enclosure. One may now ask, "What control must be applied to the spacecraft to keep the separate enclosure in or near the spacecraft (that is, at constant relative position), given the maximum tolerable acceleration as a parameter?

The main features of the control scheme are easy to derive. In principle, external nongravitational forces may be cancelled on the average, by applying propulsion to the spacecraft. It is shown below that atmospheric drag is the largest such force, and propulsion requirements are simply those required to keep the spacecraft in orbit for an extended period. The calculation depends on the details of the spacecraft's configuration and mission. An estimate is given below.

Forces of the second type produce a direct perturbation of the motion of the laboratory enclosure. If the relative positions of spacecraft and laboratory are held fixed by a control loop, the two objects accelerate together at the rate given by the force per unit mass of the enclosure. To see this, let us write the equations of motion of the enclosure and spacecraft:

$$m_s \ddot{\vec{r}}_s = \vec{F}_s + \vec{F}_{se} + m_s \vec{G}_s + m_s \vec{G}_{se} + \vec{P}$$

$$m_e \ddot{\vec{r}}_e = \vec{F}_e - \vec{F}_{se} + m_e \vec{G}_e - m_e \vec{G}_{se}$$

where

m_s = spacecraft mass

m_e = enclosure mass

$\ddot{r}_s$ = acceleration of the spacecraft

$\ddot{r}_e$ = acceleration of the enclosure

$\vec{F}_s$ = external nongravitational force applied to the spacecraft

$\vec{F}_e$ = nongravitational force applied to the enclosure

$\vec{F}_{se}$ = mutual nongravitational force between spacecraft and enclosure

$m_s \vec{G}_s$ = external gravitational force applied to the spacecraft

$m_e \vec{G}_e$ = external gravitational force applied to the enclosure

$\vec{G}_{se}$ = mutual gravitational acceleration of spacecraft and enclosure

$\vec{P}$ = propulsion force applied to the spacecraft

If we choose $\vec{P}$ to null the relative acceleration of spacecraft and enclosure, using a position servo for example, we find after setting $\ddot{r}_s - \ddot{r}_e = 0$, and substituting the value of P back, that

$$\ddot{\vec{r}}_s = \ddot{\vec{r}}_e = \frac{\vec{F}_e}{mc} - \frac{\vec{F}_{se}}{me} - (\vec{G}_s - \vec{G}_e) - \vec{G}_{se}$$

The term may be interpreted as the acceleration of the ball caused by external forces, forces between ball and spacecraft, gravity-gradient forces, and gravitational forces between spacecraft and enclosure. The applied acceleration can be sensed by an accelerometer, but the gravitational accelerations cannot be. In principle, although perhaps not in practice, it is possible to add a second servo to eliminate the sensed forces by applying forces to the enclosure (i.e., by deliberately modifying F_{se} to cancel F_e). The motion will then be purely gravitational. It is also necessary to prevent rotation of the enclosure in inertial space, so that an attitude servo is also required.

This short theoretical analysis indicates the nature of the required control scheme, which in principle must contain three (vector) feedback paths. The variables measured and controlled are listed in Table 7-V.

7.7.1 Internal Perturbations

Perturbations from the motions of the crew and of spacecraft equipment (e.g., guidance, ventilation, and refrigeration equipment) are by far the largest forces with which one must deal. Estimates have been made of the magnitude of the accelerations applied to a spacecraft with a mass of 10 metric tons (22,000 pounds) from three typical sources listed in Table 7-VI.

This analysis leads to the conclusion that the impulsive acceleration from shocks and vibration are relatively large. It is possible to show quantitatively that if reasonable care is taken, electrostatic and magnetic forces produce accelerations many order of magnitude less. The analysis is presented in detail in another section on the engineering design of a low-G enclosure. It is concluded that isolation of an experimental system from the manned environment becomes important at a level of about 10^{-2} G.

TABLE 7-V

STABILIZATION CONTROL

Effect to be Nulled	Measured Variable	Controlled Variable	Possible Activator
Acceleration of space-craft relative to enclosure and resulting from forces on space-craft only	Relative position (and velocity) of spacecraft and enclosure	Spacecraft acceleration	Propulsion jets
Absolute acceleration of enclosure	Acceleration of enclosure	Mutual force between spacecraft and enclosure	Electrostatic force, radiation pressure, magnetic force
Rotation of enclosure in intertial space	Angular position of enclosure with respect to the stars	Torque between enclo-sure and spacecraft	Electrostatic force, radiation pressure, magnetic force

TABLE 7-VI

SOME TYPICAL "NOISE" ACCELERATIONS

	Estimated Peak Source Acceleration (G)	Estimated Peak Spacecraft Acceleration (G)
Man (80 kg) rising 2 feet in 1 second	1[a]	8×10^{-3}
Vibration of 400 cps motor with 5 kg armature 0.01 mm off balance	6.4	3×10^{-3}
Air current from passage of a man close to a 100-kg experimental object.		10^{-3}[b]
Operation of gass reaction jets, assuming 10% duty cycle and 10% unbalance of two jets capable of holding spacecraft in 1-degree, 2-minute limit cycle. Spacecraft radius of gyration, 2 meters	1	10^{-6}

[a]Calculated by assuming a variation in position of the form $x = x_o/2\ (1-\cos\omega t)$.

[b]Assuming a mass of 100 gms of air is given a momentum of 0.1 newtons-sec, absorbed by the experimental system in 0.1 sec.

7.7.2 Nongravitational Perturbations

There are a number of nongravitational forces acting on an orbiting satellite. Most are very small. Assuming that a servo is used to cancel such forces on the average, it is only necessary to take account of the largest forces to estimate the G-level at which such control must be applied and the propulsion requirements

The accelerations from drag and solar pressure have been estimated assuming the following parameters of the manned spacecraft:

1. Mass 10^4 kg
2. Typical cross section 25 m
3. Typical diameter 5 m
4. Circular orbit altitude 400 km

The estimated accelerations are given in Table 7-VII together with the value of the gravity gradient for comparison. It is interesting to note that the accelerations from drag and solar pressure differ by only a factor of three, while the gravity-gradient acceleration between two objects 1 meter apart is larger than either.

TABLE 7-VII

SOME TYPICAL PERTURBATIONS

Estimated Effect	Magnitude of Effect	Special Assumptions
Atmospheric drag acceleration	8×10^{-8} G	Drag Coefficient, 2.0 Air Density, 6.5×10^{-12} kg/m^3
Acceleration of solar pressure	2.4×10^{-8} G	Solar constant, 1.4 kW/m^2 (spacecraft is a perfect reflector)
Gravity gradient acceleration	1.4×10^{-7} G/m	Circular orbit. See Appendix A for details of the gravity gradient acceleration on elliptic orbits.

Cancellation of these forces implies a continuous thrust of about 10^{-2} newtons, or 0.2×10^{-2} pounds. Such a thrust is attainable with an ion engine. Assuming a specific impulse of 2×10^3 seconds, 16 kg of propellant are required per year. A gas-jet system with an I_{sp} of 50 seconds would require 40 times as much fuel, or 640 kg. Fuel consumption rises rapidly in lower orbits.

7.7.3 Gravitational Forces

The sensed acceleration of a body-fixed accelerometer is zero only at the center of mass of the spacecraft. Other parts of the spacecraft experience gravitational forces, which are cancelled by internal stresses.

As explained in an earlier subsection, a large object can be torn apart by these stresses. In 1850, Roché showed that a satellite composed of a perfect fluid of the same density as a central attracting body would be torn apart if the radius of the orbit was near than 2.44 times the radius of the central body. In 1856, Maxwell concluded that the rings of Saturn must be composed of small independent particles, since the motion of a solid or fluid ring would be unstable. In 1947, H. S. Jeffreys (Ref. 7-53) showed that a satellite composed of ordinary rock would be torn apart in a close approach to the earth if it were larger than about 300 km in diameter.

The tidal stresses in spacecraft or in objects found inside spacecraft are hardly large enough to damage them. Still, tidal forces impose a lower limit on the levels of gravitational acceleration attainable in an experimental enclosure of given size.

The tidal forces also impose restrictions on the number and location of the very low-G experimental stations in a given spacecraft.

The gravity gradient results in differences in orbit parameters which can produce large separations in a single orbit. Suppose two objects are launched into orbit with the same velocity but with a small difference in altitude. Then, the higher object has a longer orbital period. In each revolution, the distance between the objects measured along the circumference of the orbit increases by

$$R\Delta\theta \approx 6\pi\Delta r$$

where Δr is the initial difference in altitude. This relation implies that two objects, initially 1 meter apart, separate by 19 meters per revolution, or by about 12.5 meters per hour, or 3 mm per second. At this rate, a free floating specimen located 1 meter from the center of mass of the spacecraft would remain for only 30 milliseconds in the 100-micron field of a high-power microscope mounted in the spacecraft.

Provided that the fields of the spacecraft itself are negligible, the optimum location for the low-G enclosure is at the center of mass of the spacecraft. If the orbits are not circular, the relative separation of two bodies displaced in phase in an elliptic orbit varies, since the rate of change of angle varies according to the law of areas:

$$r^2\theta = h = \text{constant}$$

Thus, in general, two objects can move with constant separation only if the separation is zero, so that their centers of mass coincide. Since it has been shown that gravity gradient accelerations are large compared to the drag acceleration if the centers of mass of spacecraft and enclosure are separated by several meters, it becomes clear that, in general, the propellant required to keep the spacecraft near an isolated enclosure will be substantial unless the enclosure is located at the center of mass. If modulation of the separation between an external enclosure and spacecraft is acceptable, servo control must be applied to the spacecraft to keep it in an orbit of the same period as that of the enclosure. It is clear that in practice only one such completely isolated enclosure may be used with a given spacecraft for long periods of time, since, in general, two or more enclosures would tend to drift apart. As was shown previously, no tendency of the enclosures to hold conveniently together as a result of their mutual gravitational interaction can be expected in low orbits. A single enclosure may as well be placed at the center of mass.

The spacecraft can be placed in orbit as a single enclosure by an initial maneuver, but subsequent control is required to cancel the accelerations of nongravitational forces as discussed above. In general, the center of mass of the spacecraft and the center of gravitational force do not coincide unless the spacecraft mass is symmetrically distributed about the center of mass. The enclosure tends to fall toward the center of force, but this mutual motion of spacecraft and enclosure cannot be sensed by the loop which controls the absolute acceleration of the enclosure. The controls operate to keep the relative position of spacecraft and enclosure constant, so that the spacecraft accelerates at the same rate that the enclosure falls. The practical consequence is a very small, but continuous, change in the spacecraft orbit.

The actual magnitude of the acceleration toward the center of force of the spacecraft is, of course, very small. This acceleration can be written

$$a = \beta \frac{GM}{R^2}$$

where M is the mass of the spacecraft, R is a typical radius, and β is a parameter less than one which depends on the degree of symmetry (it is zero if the spacecraft mass distribution is perfectly symmetric). With $G = 6.67 \times 10^{-11}$, $m^3 - kg^{-1}\ sec^{-2}$, $M = 10^4$ kg, $R = 2$ m, and $\beta = 0.1$; we obtain $a = 1.7 \times 10^{-8}$ cm/sec^2, or 1.7×10^{-9} G. Under this acceleration, the free floating specimen would remain in the field of the microscope for several minutes, even if the microscope were rigidly attached to the spacecraft. A complete analysis of the gravity gradient terms and of the motion in the gradient field is given in Appendix A.

These considerations indicate that the gravity gradient forces impose major constraints on the design of experimental enclosures which contain systems in which ready access or continuous monitoring is desired.

7.7.4 Engineering Discussion

The acceleration estimates given in the previous sections lead the conclusion that three ranges of acceleration level exist, requiring different engineering approaches to the stabilization problem. The maximum tolerable accelerations for each of these regions were given in Table 7-IV. In the second region (10^{-2} to 10^{-7} G), it is important to isolate the laboratory enclosure from the shock and vibration of the spacecraft, but it is unnecessary to attempt to cancel drag and solar pressure, and other nongravitational forces applied to the spacecraft. Hence, the stabilization control required is a very low-pass filter, which may be a simple mechanical filter at the upper end of the acceleration range. At the lower end, the enclosure may be allowed to float within the spacecraft, provided that very weak forces are applied to it to keep it from drifting to the walls. The servo which applies such forces must have a sufficiently slow response to filter vibration and shock.

An even better reference may be provided if a zero-G satellite is constructed within the main spacecraft to serve either as a laboratory enclosure in its own right or as a gravitational acceleration reference.

If accelerations of the experimental volume of less than 10^{-4} G or so are desired, the position reference must be the position of the enclosure, and propulsion must be applied to the spacecraft. Attitude control, using the fixed stars as a reference, must be used. Nongravitational forces between the spacecraft and the enclosure and between the enclosure and the external environment must be meticulously eliminated. In his paper on the drag-free satellite, B. Lange (Ref. 7-52) has estimated some of these forces for a satellite whose central isolated body is a copper ball with a radius of 2 cm. He concluded that the largest source of error, of order 10^{-11} G, resulted from gravitational interaction between the ball and the spacecraft. The satellite presently under design at Stanford uses a central ball of silicon, doped to provide an optimum conductivity. If Lange's analysis is extended to a larger body which is to be an isolated laboratory enclosure, several features of the analysis are different:

1. The size of the enclosure will be much larger: typically 1 m in diameter.
2. The average density of the enclosure will be lower.
3. The gravitational field of the ball may be asymmetrical.
4. The magnetic moment of the enclosure may be much larger, both because it may contain electric circuits and because it may necessarily contain materials of high susceptibility or even slight residual magnetism.
5. The motion of men and equipment in the main spacecraft may change the forces on the central enclosure in a relatively uncontrollable way.

Lange's discussion will not be repeated here, but we shall present some computations, in tabular form, indicating the forces which might be experienced by a carefully designed internal laboratory enclosure. We assume the parameters of the main laboratory and internal enclosure listed in Table 7-VIII. The calculations of the perturbing forces are given in Table 7-IX. From this table we see that the gravitational perturbation between the spacecraft and the central body are larger, by about a factor 10, than they are in the small unmanned satellite studied by Lange. Nongravitational forces, however, are in general smaller, mainly as a result of the larger size of the apparatus. We conclude, tentatively, that it is feasible to construct an isolated enclosure inside a manned spacecraft whose acceleration differs from that of an ideal isolated point mass by not much more than 10^{-10} G. This conclusion may be modified if a previously overlooked interaction mechanism is discovered. It is considered rather unlikely that the lower limit of 10^{-10}G can easily be reduced by much more than an order of magnitude.

To minimize the propulsion requirements, it is obviously desirable to locate the laboratory enclosure within the spacecraft at the center of mass, so that there will be no average gravity-gradient acceleration.

The motion of such a centrally located, separately orbiting object may be used as an acceleration reference for other less critical experimental enclosures located elsewhere in the laboratory spacecraft, perhaps using an optical system to compare the positions. In such a system, the sensed accelerations experienced by the second slave enclosure is equal to the gravity-gradient acceleration.

In the current work, detailed systems studies have been avoided in favor of the foregoing analysis, which has been aimed at acquiring the intuitive understanding of the engineering problem necessary for intelligent design.

It is recommended that further detailed analysis of feasible stabilization systems be performed, provided there is sufficient interest in the scientific program to warrant engineering support studies at this time.

In particular, the methods of isolation to be used in the acceleration region between 10^{-2} and 10^{-6} or 10^{-7}G should be studied in detail to delineate the ranges in which various isolation techniques are applicable.

TABLE 7-VIII

PERTURBATIONS ON LABORATORY ENCLOSURE

Effect	Perturbing Force	Relation	Special Assumptions	Typical Accelerations in Earth G's	Comments
1.	Vehicle gravity	$f = 2K_2 \frac{G_{ms}}{d_1^2}\left(\frac{r_{ZB}}{d_1}\right)$	Refer to Lange (Ref. 7-52) $k_2 = \frac{1}{344}$, $\frac{r_{ZB}}{d_1} \lesssim 0.1$	$1.6 \cdot 10^{-10}$	Order of magnitude larger than case computed by Lange
2.	Effect of a man 2.5 m from ball	$f = \frac{M_m G}{r^2}$	r - 2.5 m'	$9 \cdot 10^{-11}$	Almost as large as (1)
3.	Leakage electric field in cavity	$f = \frac{3\epsilon_o V_B E}{g_c \rho_m R_B^2}$	$V_B = 0.1V$ $E = 0.1$ V/m	4×10^{-15}	Far smaller than effect computed by Lange because of larger ball, in spite of lower density of central enclosure
4.	Electric Image attraction of central enclosure on spacecraft	$f = \frac{3\epsilon_o V_B^2}{g_e \rho_m R_B d_1^2}\left(\frac{r_Q}{d_1^9}\right)^3$	$\left(\frac{r_Q}{d_1}\right) = 0.1$	3×10^{-15}	smaller as a result of increased size of enclosure
5.	Induced magnetic moment: interaction with spacecraft	$f = \frac{3\chi_m M_{HS}^2}{4\pi^2 \mu_o d^7 \rho_m}$	$\chi_m = 3 \cdot 10^{-4}$ $M_{HS}/\mu_o = 10$ amp-m^2 $d = 2$ m	7×10^{-15}	Smaller as a result of increased separation of dipoles, in spite of increased susceptibility and moment
6.	Radiation force from optical sensor and internal telemetry	$f = \frac{W}{M_{BC}}$	$W = 10^{-9}$ watts	7×10^{-21}	Enough power for a real-time video channel

TABLE 7-II

ASSUMED PARAMETER

Parameter	Symbol (Notation of Lange)	Assumed Magnitude
Spacecraft mass	M_s	10 metric tons (10^4 kg)
Spacecraft outer radius (typical)	d_2	5 meters
Spacecraft inner radius (typical)	d_1	0.5 meters
Spacecraft magnetic moment	M_{HS}	$10\mu_o$ amp-m^2
Mass of man	M_M	80 kg
Mass of laboratory enclosure (with equipment)	M_B	50 kg
Radius of laboratory enclosure	r_B	0.5 m
Permanent magnetic moment of laboratory enclosure	M_{HB}	10^{-8} μ_o amp-m^2
Susceptibility of enclosure	χ_m	$3 \cdot 10^{-4}$
Mean displacement of enclosure from zero-self gravity-point	r_{ZB}	
Acceleration of ball	f	-

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8. DETAILED CONSIDERATION OF MATERIALS RESEARCH

8.1 Introduction

Within the second area of scientific discipline considered in the present study, that of materials research, the objectives were to identify important phenomena and effects which can be understood more completely by investigations carried out in a manned orbiting laboratory. After identification of phenomena and effects of interest, further goals of the study were to define specific scientific objectives and to formulate experiments to accomplish those objectives.

The materials research portion of the study consisted of the following:

1. A general review of past theoretical and experimental work in relevant technical subjects.
2. Selection of phenomena in and properties of solids, liquids, and gases which are sensitive to unique features of the spacecraft environment, namely weightlessness or vacuum, or both.
3. Formulation of a specific set of scientific objectives which potentially can be accomplished in a manned orbiting space station.
4. Formulation of a specific set of experiments to accomplish the objectives identified.
5. Preliminary specifications of the apparatus, weight, power, volume, crew skills, and crew time required to perform the experiments.

The experiments chosen for detailed consideration are representative of the spectrum of technical subjects embraced by the general field of materials research and serve, for planning purposes, to define the general types of apparatus and procedures to be employed.

8.2 Method Used in the Study

The method used in the study was first to consider the features of the manned orbiting spacecraft to be utilized as a laboratory to carry out a research program in the 1970 to 1975 time frame. The unique features of the laboratory, from the point of view of materials research, may be enumerated as follows:

1. The presence of trained personnel at the site of the experimental apparatus.
2. The weightless (or nearly weightless) environment within and near the laboratory.
3. The availability of "good" vacuum with high pumping speed at the laboratory.

For purposes of the present study, the designation "materials research" was interpreted in the broadest sense to encompass research in the physical and chemical properties of matter in all states of aggregation. While no rigid theoretical framework embraces all of the subjects considered, guidance obtained from a review of past theoretical work was used to formulate the scientific objectives.

Theories of the structure and behavior of matter fall into two recognizable categories; particle theories and continuum theories. Particle theories describe the behavior of one or a few interacting particles in terms of particle properties such as mass, electrostatic charge, magnetic moment, angular momentum or spin, scattering cross section, ionization cross section, etc. Continuum theories describe the behavior of aggregations of large numbers of particles in terms of bulk properties of matter such as mass density, charge density, electric and magnetic susceptibility, pressure, temperature, volume, heat conductivity, surface tension, viscosity, work function, etc.

A review of particle theories was conducted in an attempt to identify types of particle interactions which are influenced to a measurable extent by the gravitational energy of the particles in the earth's gravitational field. One clear example, that of the resonant absorption of monoenergetic neutrinos in a crystal at low temperature, was identified. In principle, observation of resonant absorption of neutrinos in a crystal in a low gravitational field constitutes an experimental verification that the principle of equivalence applies to weakly interacting particles, namely neutrinos. As discussed in Subsection 8.4, the feasibility of the experiment is doubtful, and detailed consideration of the experiment in the latter phase of the study was not justified. No other examples of particle interactions sensitive to energies as small as that of the gravitational interaction were identified.

Considering the possibility of utilizing the vacuum environment of the spacecraft as a tool in the study of particle interaction did not lead to any useful conclusions. While vacuum techniques are employed in the course of most experiments in which interactions of particles are observed, no case was identified in which the vacuum systems possible in an orbiting laboratory offered any significant advantage over vacuum systems available in terrestrial laboratories.

In reviewing the theories of the behavior of solids, liquids, and gases, i.e., the theories of the behavior of aggregations of very large numbers of particles, several examples were found in which a unique feature or combination of unique features of the space laboratory is predicted to cause or allow behavior significantly different than any exhibited in the earth environment.

In many instances, weightlessness is the feature of the laboratory environment which gives rise to or permits the phenomenon or effect of interest. In the case of meteoroid formation studies, crystallization studies, and the production of ultrapure materials, both the weightless environment and the high-quality vacuum available in the space laboratory are features necessary to the conduct of the experiments.

A gas composed of macroscopic particles is an example of a system which exhibits scientifically interesting behavior in a weightless environment. In the space laboratory, a collection of particles large enough to be visible can be expected to behave as a gas with an atmospheric scale height that is large compared to the dimensions of the container enclosing the gas.

Observation of the behavior of the "macrogas" to compare the observed behavior with that predicted by theory constitutes a portion of the program identified by the present study. In particular, the motion of the individual particles in the gas can be observed as a function of time following preparation of the gas sample in a highly nonequilibrium configuration, and the flow of thermal energy from the macro regime to the micro regime via inelastic collisions.

Another example of fluid behavior which is governed by specific energies comparable to gravitational energies, and which thus exhibits markedly different behavior in a low-G environment from that at the earth's surface, is the capillary flow of liquids. In the low-gravity environment, fluid motion due to capillary forces is expected to occur with appreciable velocities. A systematic determination of the dependence of the parameters governing capillary forces upon fluid velocity for a series of liquids has been identified as a significant and feasible experiment for the space laboratory.

The specific experiments adopted in the area of materials research are discussed in turn in the remainder of the present section from the point of view of scientific rationale. A brief statement of objectives, crew requirements, and apparatus is included in Section 4.

8.3 Results of the Study

8.3.1 General

Midway in the course of the materials research portion of the study program, a definite set of scientific objectives were identified and adopted for planning purposes as the objectives of experiments. In one case, that of observation of the red shift of neutrinos, the feasibility of the experiment required to accomplish the objective is doubtful, and the experiment is not included as part of the program planning. To accomplish the other scientific objectives identified, 11 experiments have been formulated. These experiments are discussed in the remainder of the present section where emphasis is placed on the scientific and technical rationale used in the formulation of the experiments. The discussions are intended to clarify the scientific "justifications" for including the experiments in a research program.

8.3.2 Meteoroid Experiments

The only samples of extraterrestrial matter available for examination on earth are meteorites and (possibly) tektites. It is probable that the origin of meteorites and tektites is in some way connected with the origin of the solar system. An understanding of the mechanisms by which the wide variety of meteorites and tektites were formed should, therefore, be of considerable value in the study of the solar system and other space science problems, including the origin of the elements and the composition of planets and interplanetary dust. A good summary of information regarding meteorites and tektites is given by Mason, Curator of Geology and Mineralogy, American Museum of Natural History, 1962 (Ref. 8-1). The most recent ideas on the origin of meteorites are discussed by E. Anders, Professor of Chemistry, University of Chicago, 1964 (Ref. 8-2).

Although there exists considerable literature on the origin of meteorites and their relationship to the solar system, it is recognized that much more information is needed to permit the formulation of a definitive theory for the origin of meteorites and tektites. Some critical data can be obtained by simple experiments in a manned space laboratory.

Ideal investigations would consist of observing physical characteristics of meteoroid-building materials during partial and total fusion under the vacuum and subgravity conditions of space. Such experiments would provide useful information on how finely divided, partially molten, or molten protometeorite and prototektite materials would cohere under various conditions of temperature, water content, and subgravity. In addition, molten silicates could be heated to temperatures high enough to facilitate evaporation and redeposition on cool surfaces consisting of a variety of materials (including meteorite surfaces of various smoothness and mineralogical composition) to ascertain whether accumulation centers are of some consequence in determining mineralogical composition or crystallographic and physical structures of chondrites. Information of this type may be of considerable consequence in understanding the processes involved in the formation of chondrites.

Probably the most difficult but most important experiments involve meteoritic material collected in space. Such material would be devoid of terrestrial contamination. The chondrites, which constitute over 90 percent of meteorite falls, are the most suspect of having been altered after entering the earth's atmosphere. They are friable and contain oxidized iron and hydrated minerals such as serpentine and chlorite.

The carbonaceous chondrites are particularly suspect of contamination. They contain organic matter and fossil-like elements which are thought to be biogenic. They also contain hydrated minerals and carbonates. It would be extremely important to determine whether the water, carbon dioxide, and organic compounds can be obtained from meteoritic samples which are free of contamination due to contact with the earth's atmosphere and/or surface by pyrolysis.

Although the carbonaceous chondrites number comparatively few meteorites, they occupy an extremely significant place in meteorite research because of the peculiarities of their mineralogical and chemical composition, especially the presence of hydrated minerals and organic compounds. All of the known carbonaceous chondrites were seen to fall and were picked up shortly afterwards; otherwise, it is doubtful that they would survive for any length of time, since they are very friable and contain water-soluble compounds. Even if they did survive it would require an experienced collector to recognize them as meteorites.

The first meteorite of this type fell at Alais in France on March 15, 1806. When it was sent to Berzelius for chemical analysis, he expressed doubt that it was a meteorite, since its composition was so remarkably different from all other meteorites known up to that time. A second one fell at Cold Bokkeveld in South Africa in 1838. Altogether, only some 15 meteorites of this type are now known. Carbonaceous chondrites are nowhere clearly defined, but they can certainly be readily distinguished from all other meteorites by their peculiar characteristics - dull black color, friability, generally low density, and an absence or paucity of free nickel-iron.

In 1956, H. B. Wiik chemically analyzed 11 of the carbonaceous chondrites and took the analyses of three others from the literature. He showed that they could be divided into three subgroups, according to the mean values of certain constituents, as follows:

	SiO_2	MgO	C	H_2O	S
Type I	22.56	15.21	3.54	20.08	10.32
Type II	27.57	19.18	2.46	13.35	5.41
Type III	33.58	23.74	0.46	0.99	3.78

These three subgroups have characteristic physical and mineralogical differences. Type I carbonaceous chondrites have notably low density ($\sim$ 2.2), are largely made up of amorphous hydrated silicates, are strongly magnetic (apparently from finely-divided iron-nickel spinel), and contain much of their sulphur as water-soluble sulphate. Those of the second type have densities ranging from 2.5 to 2.9, are largely made up of serpentine (hydrated magnesium-iron silicate), are weakly or nonmagnetic, and contain much of their sulphur in the free state. Type III carbonaceous chondrites have densities ranging from 3.4 to 3.5, and are largely made up of olivine, with accessory pigeonite (a calcium-poor monoclinic pyroxene).

Types I and II are never found as large stones (presumably because of their friability), the largest being the Mighei stone, which weighed about 8 kg. The carbonaceous chondrites are coated with a black, fusion crust which is normally somewhat thicker than that found on other stony meteorites. The interior is dark grey to black in color; sometimes with a greenish tinge. Type I carbonaceous chondrites contain no chondrules (an awkward contradiction); Type II contain chondrules which vary from one meteorite to another in size, abundance, and perfection in form. These chondrules are composed of olivine (forsterite) and enstatite or clinoenstatite. Trace amounts of nickel-iron also occur in some specimens.

Knowledge of the chemical composition of the carbonaceous chondrites is largely due to the work of Wiik, although the earlier analyses also provide much useful information. Wiik reported figures for C and loss on ignition, commenting that the latter figure was total loss on ignition minus H_2O, C, and S, and was an approximate measure of the amount of organic compounds. The chemical analysis of carbonaceous chondrites presents some almost insoluble problems. Wiik made a noteworthy contribution when he recalculated his analyses of the carbonaceous chondrites on the basis of atomic percentages of water, carbon, oxygen, and sulphur. The differences between the various types then disappear, and it is seen that they have essentially the same composition for the major elements - Fe, Ni, Co, Si, Ti, Al, Mn, Mg, Ca, Na, K, P, and Cr - and they all belong to the "high-iron group" of Urey and Craig.

Measurements of the content of minor and trace elements in the carbonaceous chondrites show that, for many of these elements, the abundances are the same as in the common chondrites. However, for a few of them - Bi, Pb, Tl, Hg, I, Te, and Cd - the abundance in the carbonaceous chondrites is an order of magnitude or more higher than in the normal chondrites, and is consistent with the estimated cosmic abundance of these elements. The carbonaceous chondrites also show an abnormally high content of the inert gases, especially xenon.

The occurrence of organic compounds in carbonaceous chondrites was noted as long ago as 1833, when Berzelius analyzed the Alais meteorite. A considerable number of papers describing such occurrences was published before 1900. It has been shown that some of the organic compounds can be extracted from the carbonaceous chondrites by sublimation or by solvents such as alcohol, ether, or benzene. The amount of extractable compounds is generally small (seldom more than 1 percent of the meteorite) and with the minute amounts available, little identification of the actual compounds was possible by the classical techniques available in the 19th century. Nevertheless, this early work showed the presence of solid hydrocarbons; compounds containing C, H, and O; and compounds containing C, H, and S.

In recent years, the nature of the organic material in these rare meteorites has been the subject of renewed interest and investigation. The results have been summarized by Briggs and Mamikunian (Ref. 8-3). Of the total organic matter, they comment that only about 25 percent has been extracted and only about 5 percent chemically characterized. Of this 5 percent, most is a complex mixture of hydroxylated aromatic acids together with various hydrocarbons of the paraffin, naphthene, and aromatic series. Small amounts of amino acids, sugars, and fatty acids also are present. Most of the organic matter, however, is a black, insoluble, and nonvolatile material which is probably a mixture of high-molecular-weight aromatic and hydrocarbon polymers.

Nagy, Department of Chemistry, University of California, Meinschein, of Eastern Standard Service Organization, and Hennessy, Fordham University (Ref. 8-4) have examined, with the mass spectrograph, organic compounds from the Orgueil meteorite and have identified a number of paraffinoid hydrocarbon molecules in the C_{15}-C_{30} range, with peaks at C_{18} and C_{23}. They find a good correlation with the pattern of distribution of these hydrocarbons and that observed in material of biological origin such as in butter and in recent marine sediments. Claus, NYU Medical Center, and Nagy (Ref. 8-5) have presented evidence for the presence of fossil micro-organisms in the Orgueil and Ivuna stones.

The origin of these organic compounds is, of course, a question of extreme importance. Nagy and his coworkers believe that their observations indicate that the material is of biological origin; that there is living matter at the place where the Orgueil meteorite originated. In this they agree with the opinions of some of the early workers. On the other hand, Berzelius commented in 1833 that the presence of these organic compounds in carbonaceous chondrites does not justify the conclusion that living matter existed where these meteorites originated. Mueller (Ref. 8-6) pointed out the significance of the fact that the extracts from the Cold Bokkeveld meteorite showed no measurable optical rotation, whereas the earth's biologically formed organic compounds invariably show optical rotation. He writes, "In the light of modern organic chemical experience, there seems to be no great difficulty in accounting for a nonbiological origin of the organic substances. The existence of CH, CN, and similar radicals in atmospheres of comets has been proved spectroscopically. It is reasonable to conjecture that under conditions of varying illumination and temperature, a proportion of the constituents of such an atmosphere would polymerize into complex molecules." Such synthesis of complex organic compounds from methane, ammonia, and water has been demonstrated experimentally.

The following classes of materials have been selected as the subject of experiments to be conducted in the manned orbiting laboratory:

1. True meteorites
2. Artificial meteorites
3. Meteoroids

In the first class are samples of natural meteorites selected for reduced-G research in connection with their representative (or perhaps anomalous) compositions and structures. The materials of the second class are substances detected in true meteorites or those inferred from theoretical considerations to be present in meteorites at some time in their history. The main objective of experiments on these materials is to synthesize meteorite compositions and structures for study under controlled conditions. The experiments with materials of the first two classes are primarily mineralogical and metallurgical studies regarding the influence of reduced-G conditions on material transport and crystallization processes. There is a clear relationship between these experiments and the experiments in the crystallization and interface studies. Apparatus and facilities undoubtedly will be similar and the experimental techniques will require the same type of crew skills.

It is intended that the meteoroids, the third class of materials listed above, will be collected by devices in or on the laboratory so that uncontaminated samples can be obtained for compositional analysis. A major objective of experiments with these materials is to resolve some of the questions that have been raised regarding the biogenic character of meteorite constituents. While the capture of meteorites intact in the orbiting laboratory would allow careful analysis of natural meteoric material, the high velocities of meteorites appear to make the approach impractical. The approach adopted is that of examining with a mass spectrometer the products of micrometeoroid impact on a clean, outgassed surface.

8.3.2.1 Mass Spectrographic Analysis of Micrometeoroid Debris

The instrument contemplated for *in situ* analysis of meteoroids consists essentially of a target plate and mass spectrometer. Geometric arrangement of these components will permit vaporized particle constituents, resulting from meteoroid impact with the target, to be sampled and analyzed by the mass spectrometer. In the case of a manned flight laboratory, the mass spectrogram will be available immediately to the crew so that appropriate modification to experimental procedures can be made.

Of the 700 or so meteorites that have been collected after having been seen to fall, only about 15 are carbonaceous chondrites. It is likely, though, that the true abundance of carbonaceous chondrites may be considerably greater since they are very difficult to recognize and often are quickly destroyed by weathering. Hence this ratio, which shall be adopted here, should be considered as a minimum.

The average cumulative mass distribution curve for micrometeoroids is given in Fig. 8-1. With reference to this figure, it is observed that a target area of 10 sq cm will result in approximately 500 impacts per hour of particles whose mass is 10^{-10} grams or larger. Using the ratio 20/700 for carbonaceous particles, we can expect a minimum of 14 hydrocarbon analyses per hour.

It should be noted that this calculation is based on data for the near-earth space environment. For interplanetary flights in deep space, the result may be reduced by a factor of 10^4 or greater.

It is worthwhile at this point to demonstrate that the meteoroid will completely vaporize as a result of hypervelocity impact with the instrument target plate. Since the heat of vaporization of iron is many times that of the hydrocarbon constituents, that element is selected for a worst-case analysis.

Iron has a melting point of 1535°C and boils at 3000°C. Its specific heat is 0.16 at 1000°C, hence the heat of vaporization is approximately 480 cal/gm or very nearly 2×10^6 joules/kg. The energy E of a meteoroid is given by

$$E = 1/2\ MV^2 \text{ joules}$$

or

$$E/M = 1/2\ V^2 \text{ joules/kg}$$

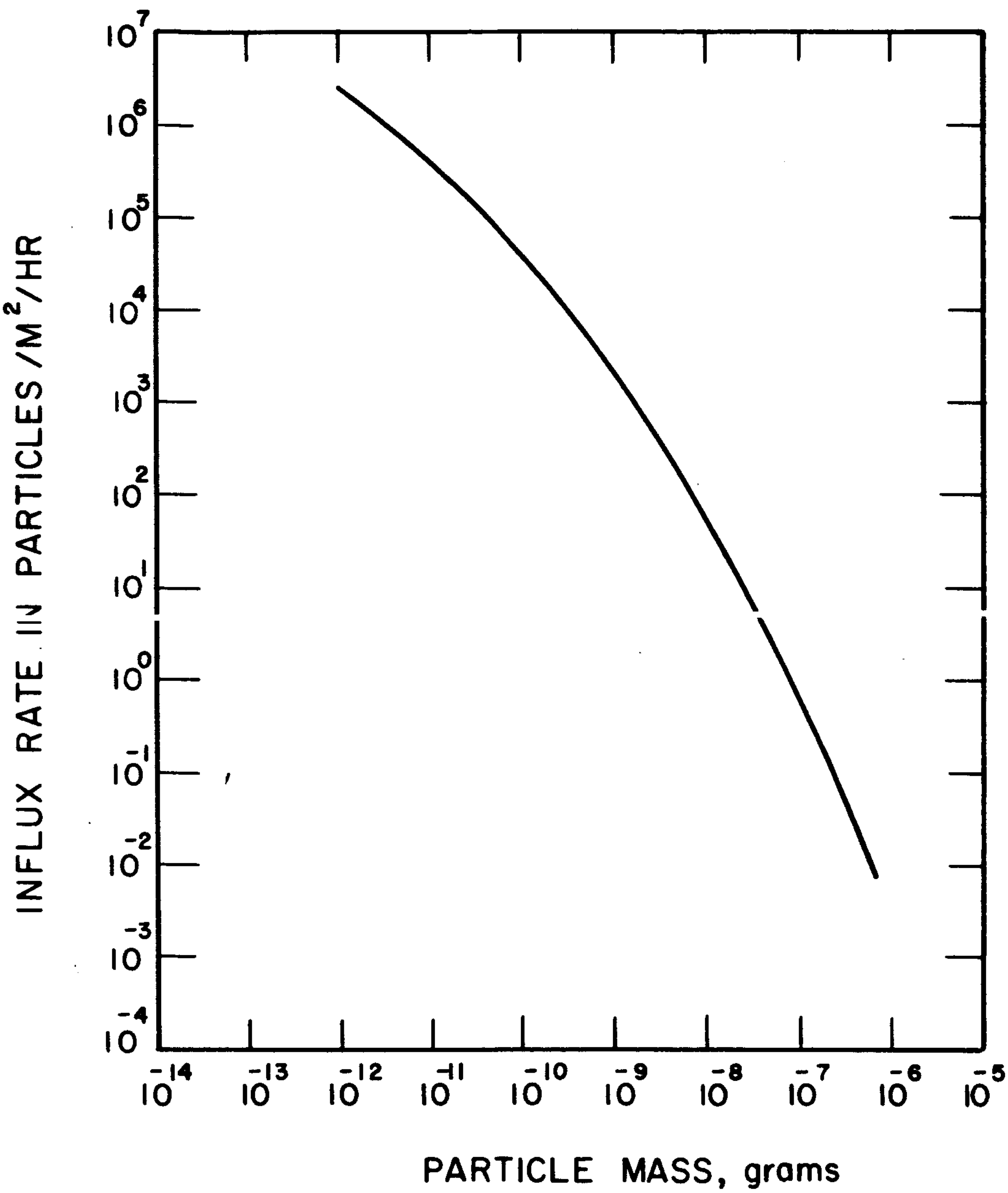


FIG. 8-1 AVERAGE CUMULATIVE-MASS DISTRIBUTION OF MICROMETEOROIDS

Particle speed lies in the range from 10 km/sec to 70 km/sec. For an average speed of 30 km/sec, we have

$$E/M = 1/2(30 \times 10^3)^2 = 450 \times 10^6 \text{ joules/kg}$$

which is $450 \times 10^6/2 \times 10^6$ or 225 times the energy actually required for vaporization.

It should be pointed out that the energy released at impact is insufficient for constituent ionization, and electron bombardment must be utilized in the mass spectrometer.

Many different types of mass spectrometers are available for adaption to space flight instrumentation. These include magnetic deflection, cycloidal focusing, Bennett RF, the Omegatron, and time-of-flight mass spectrometers. Certain aspects of the time-of-flight mass spectrometer make it especially attractive for this application. It is a lightweight, rugged instrument with reported resolution as high as 1 part in 1000 at all masses. The device has been used with good results in meteorite studies at California Institute of Technology.

In the nonmagnetic time-of-flight mass spectrometer, both the electron beam and ion beam are pulsed and all ions with the same charge receive the same energy. The ion bunch created at the beginning of each cycle is accelerated into field-free drift space between the source and the detector. Since these ions have a mass-dependent velocity, the lightest ions reach the detector first and are followed in succession by ions of heavier mass. Since no mass scanning is used, the ion signal amplifier needs a wide bandwidth to avoid widening the individual ion peaks and thereby reducing resolution. An ion selector grid system may be placed near the detector. The grid is excited once during each cycle, and only those ions gaining this extra energy can pass a repeller grid--thus eliminating the wide bandwidth requirements on the amplifier.

A conceptual design of the flight analyzer is given in Fig. 8-2. The target plate consists of a hemispherical shell of hardened steel. The cylindrical time-of-flight analyzer is positioned on a radius in such manner that the ion source is approximately in the center of the shell. A rigid boom from the spacecraft supports the device and permits a 2π-steradian field of view.

It is estimated that the flight instrument will require 30 watts of electrical power and the total weight is approximately 20 lbs.

8.3.2.2 Formation of Synthetic Meteoroids

The experiment involving the formation of synthetic meteoroids consists of heating and melting materials in the space environment outside the laboratory utilizing the solar furnace as a heat source. The solar furnace is to be employed for several experiments and is described in some detail in Subsection 8.3.3. In the synthetic meteoroid experiment, the materials are placed in the focal zone of the furnace. The materials are to be powders and fused, or partially fused, materials having a chemical composition and mixture similar to that of chondrites or protochondrites. The behavior of the materials as melting and solidification occur is to be observed from within the spacecraft. Both visual and photographic observations will be made through an appropriate optical system. An extensive sequence of different chemical composition and physical forms of the starting material are to be heated, with the material composition and heating and cooling rates for each experiment to be programmed manually and visually by the experimenter on the basis of results obtained from earlier experiments in the sequence.

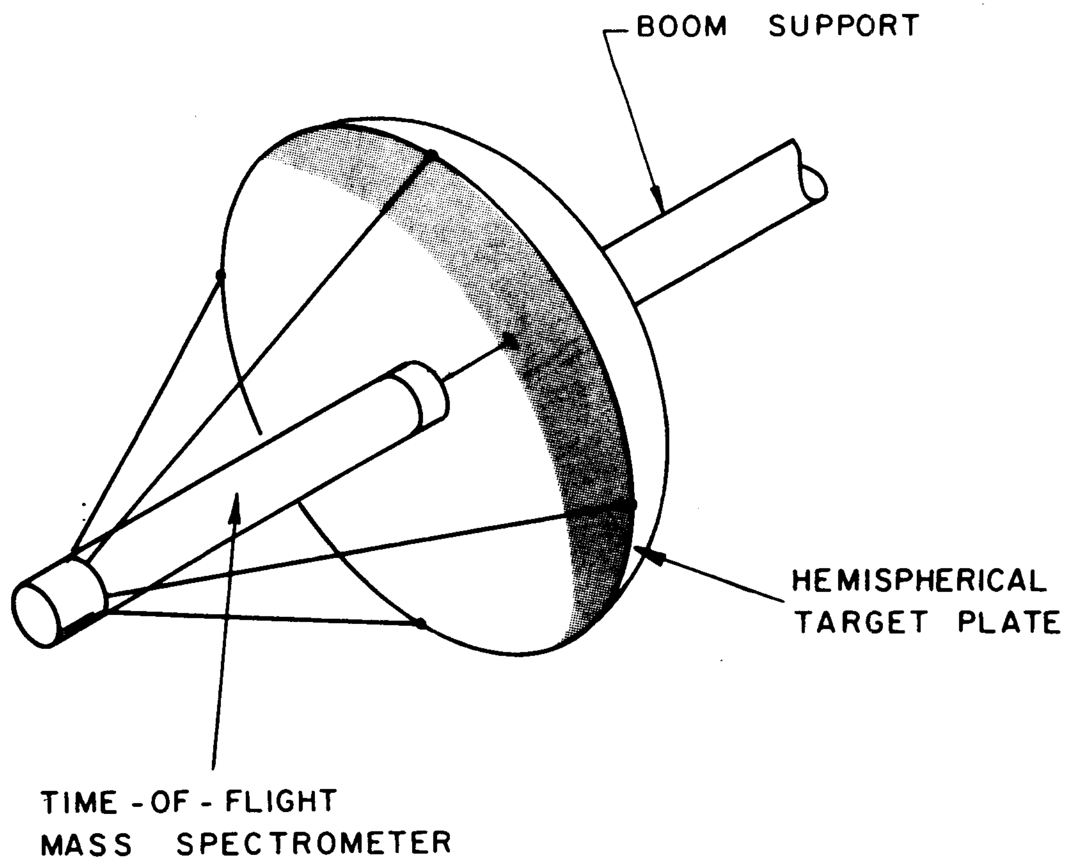


FIG. 8-2 CONCEPTUAL DESIGN OF FLIGHT ANALYZER

The objective of the sequence of measurements is to gain an understanding of the effects of chemical composition, physical form, and temperature-time profile on the final physical form of the synthetic "meteoroids" produced. The process must be guided by the judgment of the skilled observer based upon his direct observation of the object of the experiment in situ, since quantitative measurements to be used in programming the experiment are difficult to identify. Some facets of the expected behavior of the synthetic meteorite are listed below:

1. The tendency of fine particles to adhere into globules on heating and cooling.
2. The types of resulting crystalline structures.
3. The degree to which the synthetic meteorites are similar and dissimilar to natural meteorites.
4. Observation of the tendency (or lack of the tendency) for globules to form and break away from the molten samples.
5. Determination of differences between the composition of the globules and the composition of the parent sample.

8.3.2.3 Formation of Meteoroids from Natural Meteoric Material

After completing a number of experiments in which synthetic materials have been melted and cooled, the process is to be repeated with samples of natural meteorites carried aloft in the space laboratory. As before, the judgment and experience of the observer are of primary importance guiding the experiment and acquiring data. Some exemplary questions to be answered by observations taken during the experiment include the following:

1. How long can the meteorite be maintained in a molten state in low gravity before gross changes in its composition are evident?
2. Will the molten material, when cooled rapidly, form the chondrule type of structure?
3. Are the natural chondrites an assemblage resulting from rapid heating and cooling of powders that contain water (Fredrikson and Ringwood, Ref. 8-7)?
4. Does the glass matrix of a chondrite melt first and then resolidify as a glass matrix upon cooling?

Considerable experience and background data can and must be obtained in earth laboratories in preparation for the meteorite experiments. In earth laboratories, the low gravitational field cannot be achieved, of course, but experience with melting meteoroid-like materials by solar radiation can be acquired to provide guidance in the detailed planning of the experimental procedure.

8.3.3 Crystallization Studies and Production of Ultrapure Materials

The relation among the bulk properties of solids and liquids, i.e., the equation of state, is not expected to be measurably different for samples in the weightless environment than for samples at the earth's surface. Since the energies represented by the gravitational attraction of the earth on individual particles in a liquid or solid is small compared to the forces of chemical and crystal binding, and properties such as density, thermal and electrical conductivity, compressibility, specific heat, etc., are affected to a negligible degree by gravity. The free energies involved in phase transition are also large compared to gravitational energies, and no observable differences in phase transition processes in the weightless environment as opposed to those occurring in the terrestrial gravitational environment are expected.

In considering the behavior of liquids, and in particular the interaction of liquid surfaces with solid surfaces, the interaction energies controlling some processes are comparable to terrestrial gravitational energies. As a result, some processes are possible in the weightless state which are not possible in the earth's gravitational field. Crystallization taking place at a liquid-solid interface has been recognized as a process which will be modified by a change in the gravitational field. Two series of procedures to utilize low-gravity behavior of the crystallization process have been identified as experiments for the space laboratory. These are described in the following subsections.

8.3.3.1 The Production of Ultrapure Materials

In earth-G environments, one must either use a crucible to contain the material during zone refining or use a floating-zone procedure (Ref. 8-8). The presence of the crucible limits the purity of the material since it eventually acts as a contaminant as the purity of the material increases. For high-melting-temperature materials and certain reactive chemical compounds, no suitable crucible materials are known to exist that do not react with the molten material. The use of the floating-zone procedure for zone refining, which consists of placing a vertical bar of the material in a heat source to melt a small zone and slowly moving the molten zone up or down the rod, is severely limited by (1) the size of molten zone that is stable and (2) contamination from the atmosphere and from heated surfaces of the auxiliary apparatus. Theoretical analysis of the zone stability shows that the maximum zone length increases linearly with radius for small radii and approaches a constant limiting value for large radii (Ref. 8-9). Maximum zone length decreases as $(\gamma/\rho g)^{1/2}$ where γ is the liquid-vapor interfacial energy and ρ is the liquid density. These are the constraints imposed upon earth-based zone purification experiments and there is little doubt that they limit purification capabilities.

One task of zone refining experiments in a zero-G environment would be the preparation of ultrapure standards that would subsequently be used for sophisticated solid-state property measurements. In particular, such highly purified materials should allow unique investigations to be made of their electronic properties. One such property - the "Fermi Surface" - is discussed here.

The electron theory of metals has been developed to the state where a detailed knowledge of the Fermi surface for monovalent and polyvalent metals is needed to assess the present level of understanding of this complicated yet important subject. The main experimental observations of interest are cyclotron resonance, high-field magnetoresistance, and the de Haas-van Alphen effect.

Cyclotron resonance in metals allows one to look at closed orbits of electrons corresponding to external positions of a repeated Fermi surface. When the shape of the Fermi surface has been found by other methods, the cyclotron frequencies provide the gradients of the electron energy in phase space (wave number) near the Fermi surface. Band structure calculations can provide estimates of the cyclotron resonance frequency that can be checked in detail by experiment (giving a check on band structure calculations). High-field magnetoresistance studies are capable of great use in the detection and analysis of multiply-connected Fermi surfaces and the establishment of their general topology. By studying the de Haas-van Alphen effect, the Fermi surface can be "charted". The period of oscillation gives directly a simple geometrical parameter of the surface--the maximum or minimum cross-connected area of the Fermi surface normal to the magnetic field. By making measurements of all orientations of the crystal relative to the magnetic field, one can construct the Fermi surface almost exactly.

In ordinary metals at room temperature these effects cannot be observed. The relaxation time, τ, of an electron due to scattering by impurities and lattice vibrations under such conditions is about 10^{-14} seconds and we would need to apply enormous magnetic fields (cyclotron frequency in the optical range) to see a whole cycle between collisions. However, by using an extremely pure specimen and by going to very low temperatures, fields in the 10^4-oersted range will give cyclotron frequencies in the microwave range which can be readily studied.

Considerable value would be gained by mapping out the Fermi surface for all metals and, in particular, those that are considered to be the simplest metals, i.e., Na, Li, K, etc. (Ref. 8-10). If theoretical models are to fit any system, they should do so best of all for the alkali metals. However, because of the reactivity of these metals with oxygen and with most crucible materials that contain them, little progress has been made with respect to their purification. In space, these limitations can be overcome and the metals can be purified. Subsequent to such purification, single crystals could be grown for electrical studies. A brief discussion of the technical aspects of zone refining is given later in this section.

A second category of materials preparation that is advantageously conducted in space is the melting of macroscopic samples of reactive materials. There, the melting of relatively large quantities of a material without crucible contamination is perfectly feasible. Such processing allows the purification of a wide variety of materials (metals, semiconductors, insulators, etc.) and the preparation of alloys of such materials. Should evaporation of a constituent prove a problem, a blanket of pure argon could be used to inhibit the evaporation. A magnetic "bottle" produced by an electromagnetic coil could be readily used to position samples in an argon-filled container. In the zero-G environment, the melting and processing of high-melting-temperature compounds, or particularly reactive chemical compounds like the fluorides, (cryolite, for example) becomes a reality. The latter class of materials is almost impossible to process in the earth environment. Examples of particular materials are: (a) Metals (Na, Li, K, Be, Ti, Mo, Nb, W, etc.) and (b) Non-metals (III-V compounds, borides, carbides, fluorides, aluminates, etc.).

A technique which makes possible the production of high-purity metals and semiconductors is that of zone refining. The process depends on the fact that impurities are more soluble in the liquid phase of certain materials than in their solid phase.

The equilibrium distribution coefficient (k_o) is defined as the ratio of concentration of the impurity in the solid versus the concentration in the liquid at the same temperature $(C_s/C_l)_T$. This ratio may be determined from the phase diagram by observing the intersection of the isotherm with the solidus and liquidus lines (Fig. 8-3). The equilibrium distribution coefficient is rarely observed in practice since it requires an extremely low rate of freezing. While, ideally, the distribution coefficient should be constant, it often depends upon impurity concentration. When impurity addition raises the melting point of the solution, $k_o > 1$; when impurity addition decreases the melting point of the solution, $k_o < 1$. The latter condition is more often met in the laboratory.

In the floating-zone method, a liquid zone is created by heating a small portion of a bar and then allowing this molten zone to traverse the bar at a relatively slow speed. If k_o is

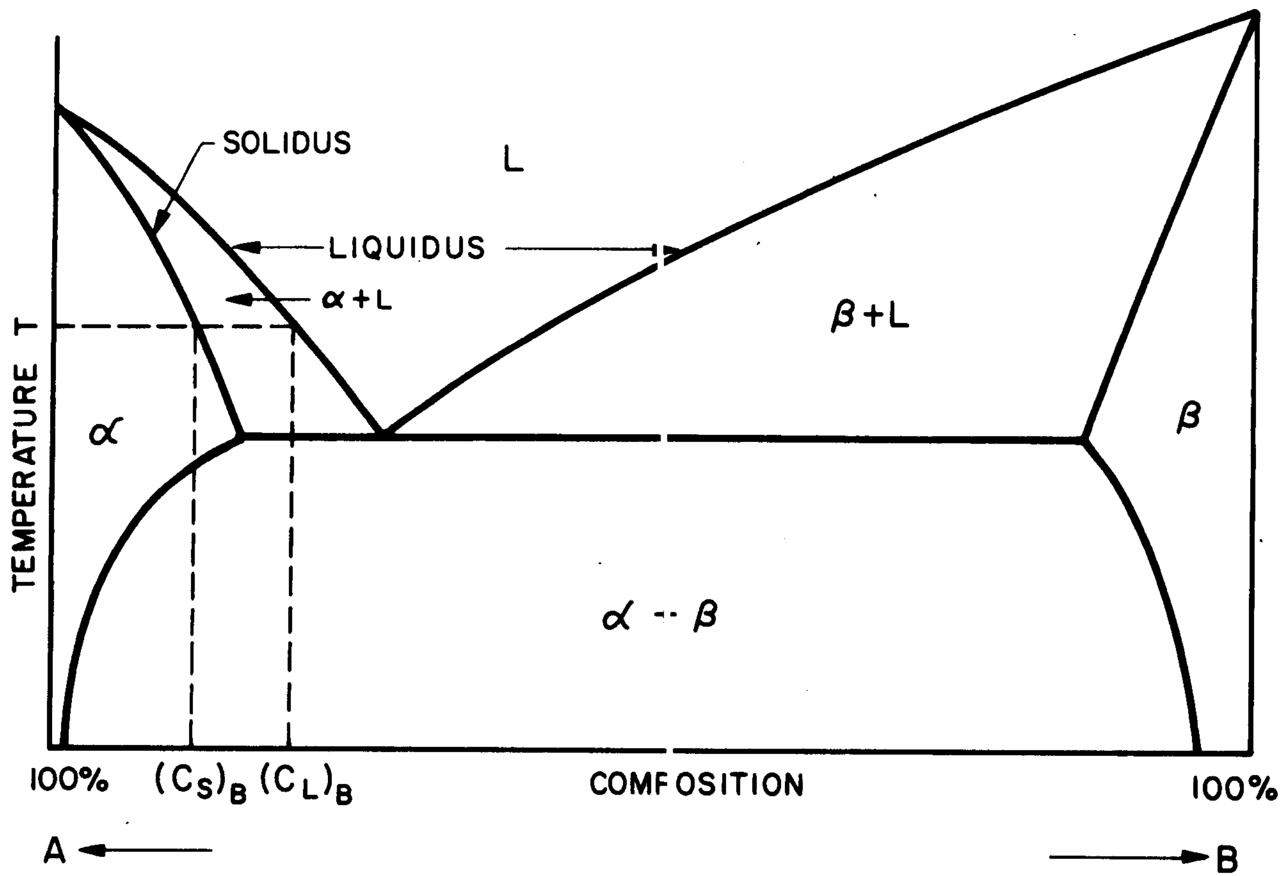


FIG. 8-3 PHASE DIAGRAM SHOWING METHODS OF OBTAINING $k_o = C_s/C_1 > 1$

smaller than unity, the impurities tend to be rejected from the growing interphase into the liquid zone. As the molten zone travels along the bar, the impurity concentration in the melt continually increases with time if near-equilibrium conditions are maintained. In that case, the impurity concentration throughout the liquid zone is reasonably constant with position (Fig. 8-4) and a good ratio of purification will obtain in accordance with

$$C = kC_o (1 - n)^{k-1}$$

where C is the concentration of impurities in the solid after a fraction n of the total liquid has solidified; C_o is the original mean impurity concentration; and k is the effective distribution coefficient. The smaller the distribution coefficient, the more effective the purification by zone melting. Thus, for a distribution coefficient $k = 0.01$, the solute concentration C at the halfway point of the crystal will be 0.02 of the starting concentration (C_o). Likewise, purification may be achieved by utilizing a large effective distribution coefficient. In this case, the molten zone rejects the impurity into the solid and the purest material solidifies last and the last 30 percent of the crystal will achieve a purification factor (C/C_o) of 0.04 for a distribution coefficient of $k = 5$. The concentration profile in such a crystal is rather steep throughout, which makes this process considerably less attractive. As impurity is rejected from the interface of the growing crystal (in the case of $k < 1$), relatively high concentration builds up in the liquid immediately adjoining (Fig. 8-4). The impurities in this layer can either be incorporated in the growing crystal or diffused into the liquid zone. With convective or magnetic stirring, the bulk of the liquid zone will exhibit uniform concentration. In this way, a concentration buildup occurs near the solid-liquid interface until a steady state is reached where impurity buildup

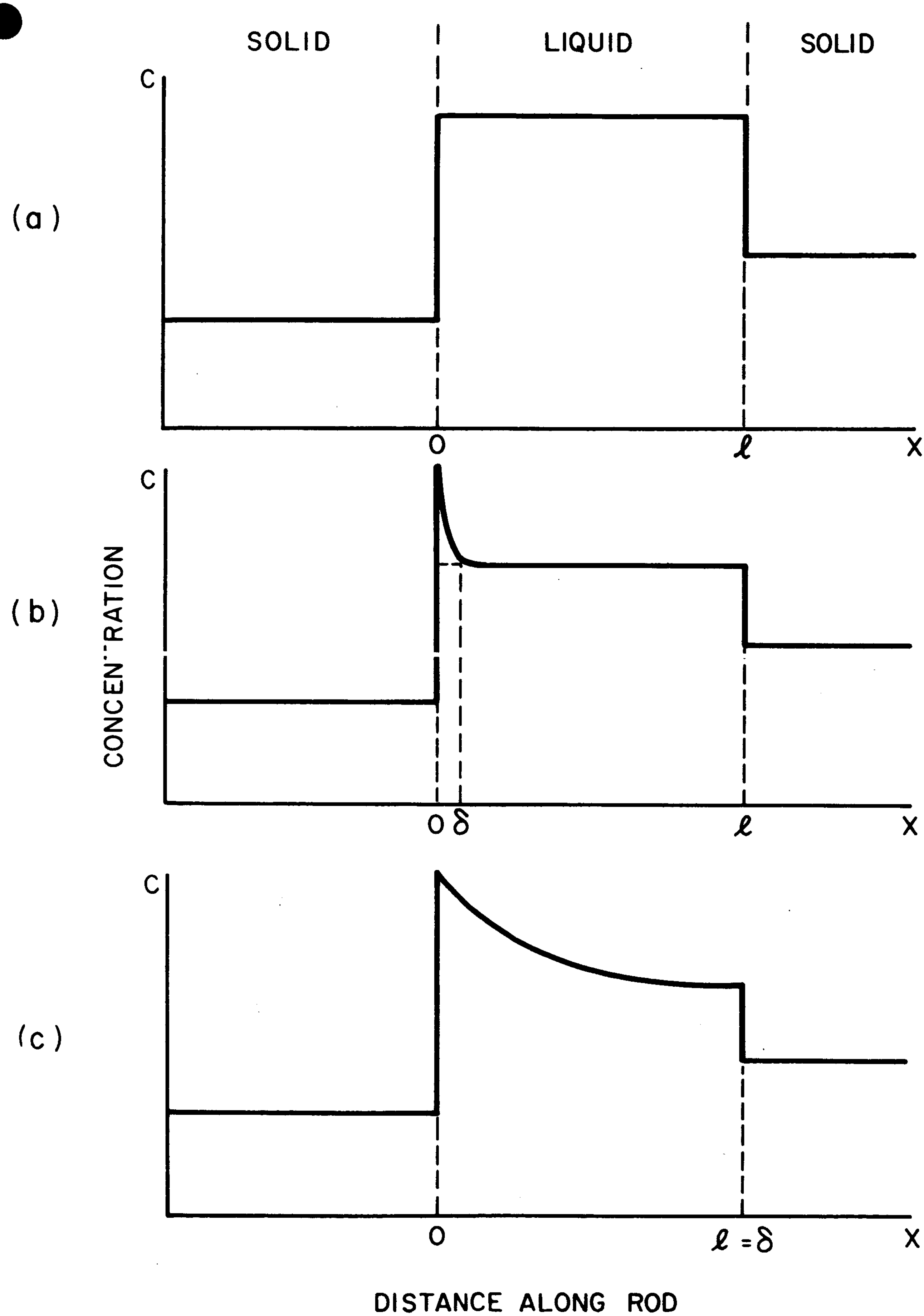


FIG. 8-4 CONCENTRATION PROFILE IN THE VICINITY OF THE MOLTEN ZONE (For K > 1)

(a) Equilibrium freezing (b) Normal freezing (stirred)
(c) "0" G freezing (no stirring or convection) 1 = length of molten zone

is balanced by diffusion mixing and incorporation in the solid. Solid-state diffusion, that is impurity removal by diffusion into the solid interface, is also possible; however, it is expected to be insignificant at common rates of zone movement and compared to liquid diffusion.

Burton, Prim, and Slichter (Ref. 8-11) have developed a theory for the effective distribution coefficient. These authors conclude that

$$k = \frac{k_o}{k_o + (1 - k_o)\, e^{-f\delta/D}}$$

where f is the growth rate, δ is the thickness of the enriched layer (commonly referred to as the diffusion layer), and D is the diffusivity, which generally lies between 10^{-5} and 10^{-4} sq cm per second. The exponential $-f\delta/D$, often taken as the normalized growth velocity, is the predominant factor determining the effective distribution coefficient k. Delta (δ) is determined by the stirring action and may be as small as 10 microns, or, in the case of complete absence of stirring, may encompass the whole zone length (Fig. 8-4). Heating methods which do not in themselves provide stirring, and the absence of convective stirring, may be utilized for experimentation with δ and D. In Fig. 8-5 is shown a comparison of solute concentration profiles in the case of complete mixing in the liquid, curve A, and complete absence of mixing in which redistribution of the concentration occurs by liquid diffusion only, curve B. While the controlled absence of mixing can be instructive in determining growth parameters as suggested above, it obviously is not desirable from the standpoint of pure crystal fabrication.

In order to assess the role convection plays in crystallization, it will be necessary to provide information on mixing rates under known circumstances. It is suggested that a series of experiments be carried out which define mixing by inductive stirring in space (without convection) and that the resulting concentration profiles be compared with other samples in which convection was the only stirring

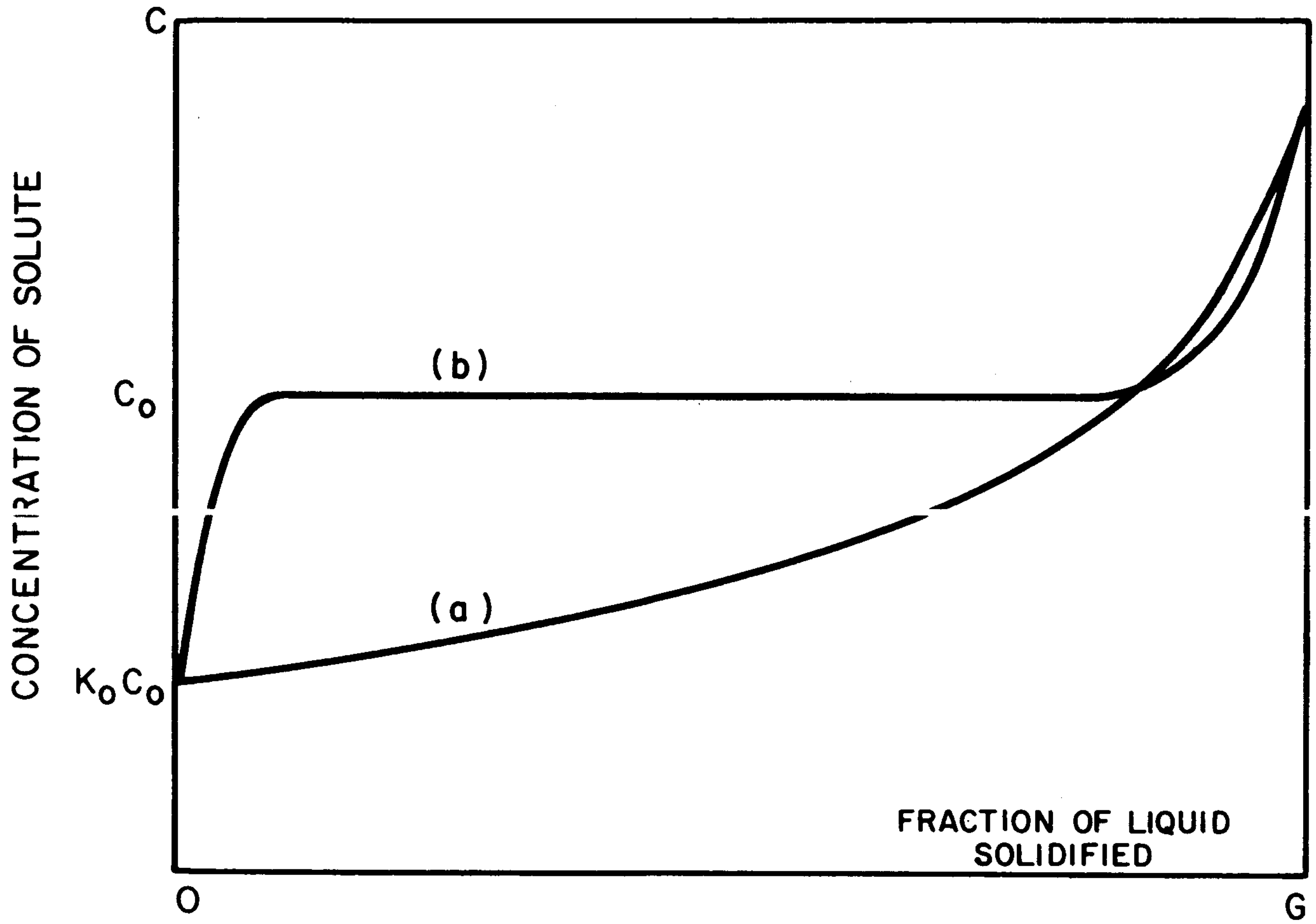


FIG. 8-5 CONCENTRATION OF SOLUTE AFTER FREEZING VERSUS FRACTION SOLIDIFIED FOR TWO CASES

(a) Complete liquid mixing (convection at 1 G)
(b) Diffusion-dominated distribution (0 G)
(After W. G. Pfann)

mechanism. The latter set of experiments would be done in an earth laboratory using electron-beam heating or radiant heating in order to prevent magnetic stirring. These experiments should be carried out with well known materials, such as silicon or germanium, with well known impurities, such as boron, phosphorus, arsenic, aluminum, and antimony. In addition to the use of different impurities with widely varying distribution coefficients, the zone length may be varied in order to increase the observed range of convection to the widest possible limits. The degree of magnetic stirring (space experiment) which yields identical results to the earth-prepared, convection-mixed crystals will allow a quantitative description of the role of convection in crystal growth.

It is well known that the advantages of zone melting are neutralized when dendritic growth takes place, probably trapping liquid pockets during solidification. Likewise, it has been shown that solidification does not always take place in an orderly way along a uniform flat surface. It is proposed to study the effect of a zero-G environment on decanted growth surfaces grown on earth and in space under as near identical conditions as possible.

The influences of zero-G environment in the production of crystal imperfections and defects produced by the floating zone method should be investigated also.

The major item of apparatus required to conduct crystallization experiments is a solar furnace designed to provide temperatures up to 3000°C by concentrating solar radiation onto the solid samples to be melted. A sketch of the apparatus is shown in Section 5. The apparatus is mounted externally to the spacecraft, and samples of materials are placed in the focal zone of the concentrator by the astronaut. An operator inside the spacecraft observes the samples visually and manually tracks the solar furnace and controls the shutter to accomplish either the zone refinement of a sample clamped into the solar furnace or the melting and solidification of free-floating samples in the case of meteorites or emulsion melting experiments, as discussed later in this section. After melting and cooling, samples are returned to the space laboratory for analysis. They also may be sealed in vacuum containers for return to earth for analysis. The space laboratory will contain apparatus to (1) measure the physical properties of the specimens, such as hardness, tensile strength, ductility, malleability, and (2) to measure crystalline properties by x-ray and electron diffraction techniques. Spectroscopic analysis also will be performed to determine sample purity.

In the studies of ultrapure materials, a standard material such as silicon should be adopted and a number of samples prepared and measured to establish the degree of purity achievable in the laboratory. Hall-effect measurements and resistivity measurements will serve as means for determining the purity achievable, and the electrical properties of pure silicon are of interest in their own right. For metallic samples, more sophisticated measurements, such as measurement of the Fermi surface, become interesting, since the results of Fermi surface measurements are highly sensitive to impurities in the material. Measurements such as the de Haas-van Alphen effect in pure materials are of great interest, but they require elaborate equipment such as magnets, cryogenic systems, and microwave apparatus in the 1000 Mc range. These measurements, therefore, should be performed on earth after recovery of the samples. In the earth laboratory, Fermi surface measurements of an uncontaminated sample can be achieved if suitable care is exercised in packaging the samples for return to earth.

8.3.3.2 Crystallization Studies

The basic procedure in experiments classified as crystallization studies is the same as that of the pure materials experiments, namely the heating and solidification of samples placed in the solar furnace and subsequent measurements of properties of the recovered samples in the space and earth laboratories. Within the limited effort of the present study, possibilities for the production of new materials and analysis of new properties of materials have not been completely analyzed. The number of samples carried into space in the laboratory and the level of effort devoted to the crystallization portion of the program should be adjusted to complement other space station activities.

Some specific samples of experiments to be included are the formation of alloys of invincible metals, formation of metal-nonmetal composite materials, and metal-organic solid emulsions. The low-gravity and high-temperature environments available in the space station are used in these experiments to form the materials. Since gravitational forces are nearly negligible, buoyant forces are absent in the molten samples, thus allowing the formation of emulsions of invincible materials which after solidification, can be conveniently studied.

The absence of convection currents in the weightless environment leads to another type of crystallization experiment. Single or multiple-phase liquid samples will not be influenced by convection currents during solidification and resulting crystals may exhibit properties different from those of crystals formed in a gravitational field.

Natural convection, multiphase suspension experiments, the alloying process, capillary effects, and vacuum considerations are discussed in Appendix D to serve as a guide for further effort in identifying other materials and combinations of materials of interest in the study of crystallization phenomena in reduced gravity.

8.3.4 Study of a Gas Composed of Macroscopic Particles

The kinetic theory of gases has been very successfully used in predicting macroscopic properties from various models of gas molecules and molecular interactions. Extensive calculations have been performed considering gas molecules as hard spheres, as more complicated structures having internal degrees of freedom, and as particles having interaction potentials of various forms. Real gases behave very nearly as the perfect gas when the density of the sample is low enough that the mean separation between molecules is large compared to the molecular dimensions.

In a planetary atmosphere, the behavior of a perfect gas is strongly influenced by gravitational forces. In particular, the density of an idealized, isothermal atmosphere varies exponentially with altitude according to the well-known barometric equation

$$n = n_o \exp(-mg^z/kT)$$

where n is the number density, z is the altitude, k is Boltzmann's constant, T is the (isothermal) gas temperature, g is the acceleration of gravity, and m is the mass of the gas molecules. The quantity kT/mg has the dimensions of length, and is equal to about 9 km for air at the earth's surface. It has been recognized that in the low gravitational field of the space laboratory, an assembly of macroscopic particles can be expected to behave as a perfect gas and have a scale height that is large compared to macroscopic dimensions. The mass of individual particles can be made large enough that the particles are directly visible, allowing detailed observation of the behavior of the "macrogas". The proposed experiment consists of preparing a macrogas sample in the space laboratory environment and observing individual particle motions in equilibrium and nonequilibrium conditions for a wide range of densities and equivalent temperatures of the gas, and for various types and shapes of particles. The higher density regime in which the gas behavior is expected to depart radically from the perfect gas law and where condensation or "crystallization" of particles may occur is of particular interest.

The apparatus needed to conduct the experiment consists of a cubical chamber about 5 inches on an edge. Particles are placed in the chamber and raised to a high equivalent temperature, either by vibrating the walls of the chamber or by shaking the chamber to impart kinetic energy to the particles. The chamber is then allowed to float freely in the laboratory and photographic records are made by a camera and stereoscopic viewing system which permits observation of the gas through a transparent face of the chamber. Periods of "free float" will be in the range of several minutes. The observations will be repeated periodically with different types and sizes of particles and with different numbers of particles placed in the container; the choice of materials for later observations being based on the judgment of the operator and his experience with earlier observations.

The earlier observations in the experiment will be directed toward verifying the fact that macroscopic particles will behave nominally as a perfect gas. A parametric design study included herein indicates that initial particles should have a diameter of 5 mils, a mass of 10 μgrams, an rms velocity of 6 cm/sec, and a density of $10^3/cm^3$. A chamber acceleration level of 10^{-5}G is low enough to provide a scale height for the macrogas that is large compared to the chamber dimensions. The rate of energy loss in the gas particles, i.e., the rate of loss of average kinetic energy per particle, is of particular interest and will be determined from the photographic records. The rate at which heat energy is transferred to the container walls and to the particles by inelastic collisions is not predictable from theory without detailed measurements of the properties of the materials to be used.

Subsequent observations will be made of the behavior of the gas in a regime where the particle density has been increased until the assembly of particles ceases to behave like a perfect gas.

Aggregation or condensation of the particles may be observable at higher particle densities in a way that is analogous to condensation and crystallization as the macrogas "cools". Here the behavior is more difficult to predict theoretically, and theoretical analysis of the results obtained will be a challenging task.

In the remainder of the present section, some background discussion of the theoretical basis for the experiment is given. As indicated in the section on experiment design parameters, measurement of the equation of state of the rare macrogas is interesting and practical to perform. In particular, the virial coefficients of the gas will be determined for comparison with theory.

8.3.4.1 Some Properties of a Gas Composed of Neutral Particulate Matter

A considerable portion of the molecular theorv of gases and liquids is devoted to the properties of gases composed of hypothetical molecules that are rigid and have simple shapes such as spheres, cubes, cylinders, ellipsoids, etc. (Refs. 8-12 through 8-16). The theories of these gases admittedly are restricted in the application to real gases; nevertheless, because they can be rigorously developed, they are useful for comparisons with approximate theories and serve as check points in limiting cases.

Despite the simplifications afforded the theory by molecular models, however, calculations are limited to properties of model gases at low to moderate densities. The reason for this is the exceedingly complex nature of the higher-order terms which become important in the virial equation of state as density is increased. For rigid-sphere molecules, the virial coefficients up to the fifth have been calculated and the equation of state is

$$p/nkT = 1 + an + (5/8)\ a^2n^2 + 0.2869\ a^3n^3 + (0.115 \pm 0.005)\ a^4n^4$$

where $a = (2/3)\pi\sigma^3$; σ is the sphere diameter. If it is assumed that the maximum density of the gas is that of a hexagonal, close-packed crystal composed of spheres of diameter σ, then the equation of state can be expressed

$$p/nkT = 1 + 2.97\alpha + 5.50\alpha^2 + 7.49\alpha^3 + 8.90\alpha^4$$

where $\alpha = n/n(\max)$ with

$$n(\max) = \sqrt{2}/\sigma^3$$

From this expression, it is readily determined that for densities less than about 1 percent of maximum, only the first two terms on the right side need be considered. When the density approaches 20 percent of maximum or more, all five terms become important. At still higher densities, all terms become comparable in magnitude and additional terms are needed for accurate calculations.

8.3.4.2 Macrogas Experiment Parametric Design

Three dimensionless parameters determine the design of the macrogas apparatus. They are the virial parameter ϵ,

$$\epsilon = d/\lambda = \tau_o/t_o \tag{8-1}$$

the smoothness parameter θ,

$$\theta = \lambda/L = t_o/T_o \tag{8-2}$$

and the gravitational parameter δ,

$$\delta = mgL/kT' \tag{8-3}$$

In the above equations, d is the range of intermolecular forces (that is, the diameter of the spheres), λ is the mean free path of the macromolecules, τ_o the interaction time, t_o the mean time between collisions, L is a characteristic dimension of the apparatus (assumed below to be the edge of a cubical container), T_o a characteristic time for macroscopic effects such as establishment of a flow pattern, m is the particle mass, g the effective gravitational acceleration (presumably about 10^{-5} g_o or 10^{-2} cm sec^{-2}), k is Boltzmann's constant 1.37×10^{-16} erg deg^{-1}, and T' is the effective (kinetic) temperature.

Since the collision cross section for spheres of diameter d is πd^2, N such spheres in volume L^3 have Maxwell mean free path

$$\lambda = L^3/\sqrt{2}\ \pi N d^2 \tag{8-4}$$

if their distribution function is of Maxwell-Boltzmann form. Therefore

$$\epsilon = \sqrt{2}\ \pi N\ (d/L)^3 \tag{8-5}$$

$$\theta = (L/d)^2/\sqrt{2}\ \pi N \tag{8-6}$$

whence

$$L = d/\epsilon\theta \tag{8-7}$$

$$N = 1/\sqrt{2}\ \pi\epsilon^2\theta^3 \tag{8-8}$$

Thus, the number of spheres required for the macrogas is determined directly by ϵ and θ, as is the ratio of apparatus dimension to particle diameter. Since

$$3KT' = m\,v^2 \tag{8-9}$$

the rms speed of the macromolecules is

$$v = (3gL/\delta)^{1/2} = (3gd/\delta\epsilon\theta)^{1/2} \qquad (8\text{-}10)$$

Hence, the time scales for the macrogas experiment are

$$\tau_o = d/v = (d\delta\epsilon\theta/3g)^{1/2} \qquad (8\text{-}11)$$

$$t_o = \lambda/v = (d\delta\theta/3g\epsilon)^{1/2} \qquad (8\text{-}12)$$

$$T_o = L/v = (d\delta/3g\epsilon\theta)^{1/2} \qquad (8\text{-}13)$$

If photographic observation of the macrogas is employed, each exposure should be long compared to τ_o but less than t_o. The total observation period should be greater than T_o if macroscopic changes are to be noted.

If the macromolecules are made of a material of mass density ρ, the mass of each is

$$m = \pi d^3 \rho/6 \qquad (8\text{-}14)$$

and the required kinetic temperature is, therefore,

$$T' = \pi d^4 \rho g/6k\delta\epsilon\theta \qquad (8\text{-}15)$$

which corresponds to a mean kinetic energy per particle of

$$u = mv^2/2 = \pi d^4 \rho g/4\delta\epsilon\theta \qquad (8\text{-}16)$$

If all this energy were converted to heat (rather than unrelieved strain energy of deformation) by the inelasticity of collisions among macromolecules, the rise in real (thermodynamic) temperature of a macromolecule would be

$$\Delta T = u/mc = v^2/2c \qquad (8\text{-}17)$$

The specific heat c may be estimated as

$$c = \frac{6 \text{ cal}}{\text{mol deg}} \times \frac{4.18 \times 10^{7} \text{ erg}}{\text{cal}} \times \frac{1 \text{ mol}}{\text{A gm}} \tag{8-18}$$

where A is the gram molecular weight of the material. Then

$$\Delta T = 6 \times 10^{-9} \, gda/\delta\epsilon\theta \tag{8-19}$$

In order to choose ϵ, θ, and δ intelligently, and thereby determine the properties of the macrogas apparatus, we must consider their physical significance.

The first parameter, ϵ, measures the fraction of the time that a molecule is interacting with another. It thus determines the significance of correlations (two-body or higher-order distribution functions) in the statistical description of the system. Indeed, Bogoliubov claims that when the Boltzmann equation (for the single-particle distribution) is used instead of more elaborate members of the BBGKY hierarchy, the error is of order ϵ. It would be of substantial scientific interest to use a macrogas to study the higher order corrections predicted by the BBGKY hierarchy, since these are still somewhat controversial, but by the same token, it is desirable first to establish the validity of the macrogas concept without equivocation. We should therefore compare our observations with Boltzmann theory and regard ϵ as a measure of error in that theory.

If we make fluid-flow measurements (e.g., permitting the macrogas to expand, or comparing pressure levels and flow rates at various positions relative to the boundaries), we may compare them to the Euler equations (which are of zero-order in θ) and regard θ as the error in our theory, or to the Navier-Stokes equation (error θ^2) or even to the Burnett equations (error θ^3). It seems practical to include transport phenomena at the level of

Navier-Stokes theory where necessary, so that θ^2 may be regarded as a fair measure of error.

The significance of δ was discussed in the second quarterly report (EOS Report 7000-Q-2).

As a first test of the macrogas concept we therefore suggest setting

$$\epsilon = 0.01, \theta = 0.1, \delta = 0.01 \tag{8-20}$$

so that all theoretical errors will be of order 1 percent. The number of macromolecules required is then

$$N = 2.25 \times 10^6 \tag{8-21}$$

If, as a preliminary survey of commercial suppliers indicates, 5-mil steel spheres are the best available macromolecules, we have

$$d = 1.27 \times 10^{-2} \text{ cm} \tag{8-22}$$

whence

$$L = 12.7 \text{ cm} \tag{8-23}$$

For

$$g \approx 10^{-5} g_o \approx 10^{-2} \text{ cm sec}^{-2} \tag{8-24}$$

the rms speed becomes

$$v = 6.2 \text{ cm/sec} \tag{8-25}$$

which makes the time scales

$$\tau_o = 2 \text{ msec} \tag{8-26}$$

$$t_o = 0.2 \text{ sec} \tag{8-27}$$

$$T_o = 2 \text{ sec} \tag{8-28}$$

The mean free path is

$$\lambda = \theta L = 1.27 \text{ cm} \tag{8-29}$$

for molecules on molecules, and

$$\lambda_v = 4\lambda \approx 5 \text{ cm} \tag{8-30}$$

for photons on molecules (i.e., we can see 5 cm into the macrogas).

If the density of the material from which the macromolecules are fabricated is of order 10 gm cm^{-3}, then the mass of each is about

$$m = 1.0 \times 10^{-5} \text{ gm} = 10 \ \mu g \tag{8-31}$$

which implies a total mass

$$M = Nm = 23 \text{ gm} \tag{8-32}$$

The mean kinetic energy per particle is

$$u = 1.9 \times 10^{-4} \text{ erg} \tag{8-33}$$

corresponding to an effective temperature

$$T' = 9 \times 10^{11} \text{ deg} \tag{8-34}$$

and a total energy

$$U = Nu = 430 \text{ erg} \tag{8-35}$$

Conversion of this energy to heat would yield a real temperature increase of only about

$$\Delta T = 7.5 \times 10^{-6} \text{ deg} \tag{8-36}$$

even for A = 100.

In conclusion, it may be noted that the pressure of the macrogas under the above conditions should be found to be

$$p = NkT'/L^3 = \rho gd/6\sqrt{2}\ \delta\theta = 0.15 \text{ dyne cm}^{-2} \tag{8-37}$$

If this is to be detected by the acceleration of a free diaphragm, the surface density of the diaphragm must be no more than

$$\sigma = p/100\ g = 0.15 \text{ gm cm}^{-2} \tag{8-38}$$

if the resultant acceleration is to be 100 times the irreducible G-level. This can be achieved with a metal foil 6 mils thick. The above pressure results from a flux of macromolecules

$$\phi = N\ v/4.3L^3 = 1.6 \times 10^3 \text{ cm}^{-2} \text{ sec}^{-1} \tag{8-39}$$

striking the walls. The flux is small enough to suggest the use of a miniature microphone for measurement of pressure produced by impacts.

8.3.4.3 Effects of Interparticle Forces

In the molecular theory of gases and liquids, the term "hard-sphere" is used to designate the two-body intermolecular potential function, P(z), with the form

$$P(z) = 0 \qquad z > \sigma$$
$$= \infty \qquad z < \sigma$$

where z is the center-to-center distance between molecules and σ is the molecular diameter. In the sense of this definition, macroscopic particles are not true hard-spheres since they are subject to interparticle cohesive and gravitational forces. The potential function depends on z for $z > \sigma$. Under certain conditions, the energies associated with these interactions can be several orders of magnitude greater than thermal energies and completely dominate the macrogas behavior.

The cohesive forces between particles arise from atomic or molecular interactions at the particle surfaces and tend to make contacting surfaces of two particles weld together. The effects of these interactions are difficult to assess in advance since they vary widely from one material to another and are exceedingly dependent on the degree to which the surfaces are covered by adsorbed gases or combined chemically with foreign substances. Moreover, because they are short-range forces, any atomic-scale roughness of the surfaces which prevents intimate contact will diminish their effectiveness.

An upper limit on the energy involved in cohesive interactions can be estimated by taking the product of the surface energy per unit area and the areas of two spheres which are within interacting range of each other when the spheres are in contact, assuming the surfaces of the spheres are smooth. If the range of interaction is taken to be 1×10^{-8} cm, the energy of the interaction is

$$E = (1 \times 10^{-8}) \pi \sigma \epsilon$$

where ϵ is the surface energy of the material. For particles with 200 micron diameter having $\epsilon = 10^2$ ergs/cm^2,

$$E = 6.28 \times 10^{-8} \text{ ergs}$$

At normal temperatures, this energy is several orders of magnitude greater than kT; the particles would tend to aggregate and the macrogas would be completely condensed. It is emphasized that this calculation represents an approximate upper limit, however, because of the effects of adsorption and surface roughness. At the present time, an unequivocal assessment of the cohesive properties of these particles can be gained only by experiment.

The gravitational force between particles fortunately is not subject to the same degree of uncertainty and a relatively rigorous analysis of gravitational effects can be carried out. Consider a macrogas contained in an isothermal cavity formed by plane, parallel walls at $x = + W/2$ and $- W/2$. The gravitational potential, $\varphi(x)$, and particle number density, $n(x)$, are related by Poisson's equation

$$d^2\varphi/dx^2 = 4\pi\gamma m n(x) \qquad (8\text{-}40)$$

and the Boltzmann relation

$$n(x) = n_o \exp\left[-m(\varphi - \varphi_o)/kT\right] \qquad (8\text{-}41)$$

In these equations, γ is the gravitational constant, m is the particle mass, n_o is the particle number density in the center plane of the cavity at $x = 0$, φ_o is the gravitational potential at $x = 0$, k is Boltzmann's constant, and T is the cavity temperature. Substituting Eq. 8-40 into Eq. 8-41

$$\psi = m\varphi/kT \qquad (8\text{-}42)$$

$$\psi_o = m\varphi_o/kT \qquad (8\text{-}43)$$

and

$$\eta = (x/\lambda_g) \exp(\psi_o/2) \tag{8-44}$$

Poisson's equation can be written in the form,

$$d^2\psi/d\eta^2 = \exp(-\psi) \tag{8-45}$$

Integrating Eq. 8-45 twice with the condition

$$d\psi/d\eta = 0$$

at x = 0, and returning to the original parameters, we have

$$n(x) = n_o \operatorname{sech}^2 (x/\lambda_g \sqrt{2}) \tag{8-46}$$

and

$$\varphi(x) = \varphi_o + (kT/m) \ln [\cosh^2 (x/\lambda_g \sqrt{2})] \tag{8-47}$$

for the variation of number density and gravitational potential within the cavity.

The parameter, λ_g, which appears in Eq. 8-44 and in the solutions (Eqs. 8-46 and 8-47) has dimensions of length and is given by

$$\lambda_g = (kT/4\pi\gamma m^2 n_o)^{1/2}$$

Since this length is completely analogous to the characteristic length, the Debye wavelength, which appears in the corresponding electrostatic problem, it is appropriate to call λ_g the Debye gravitational wavelength.

As an illustrative example of distribution of particles described by Eq. 8-46, consider a macrogas composed of 100-micron particles with a material density of 1 gm/cm^3 contained in a

4-cm wide cavity at 300^{o}K. When the number density, n_o, is 10^6 particles/cm^3, the Debye gravitational wavelength is 0.424 cm. If the number of particles in the cavity is decreased so that $n_o = 10^5$ particles/cm^3, $\lambda_g = 1.34$ cm, and at $n_o = 10^4$ particles/cm^3, $\lambda_g = 4.24$ cm. In Figure 8-6, the normalized number density distribution, $n(x)/n_o$, is plotted versus position in the cavity for these three values of λ_g.

The tendency for the macrogas particles to aggregate or condense is clearly in evidence in these curves. At the center of the cavity, the particle number density for curve A ($n_o = 10^6$ particles/cm^3) is approaching the maximum sphere-packing density, n_o (max) calculated for a hexagonal close-packed lattice. The ratios, n_o/n_o (max), are stated in the caption of the figure.

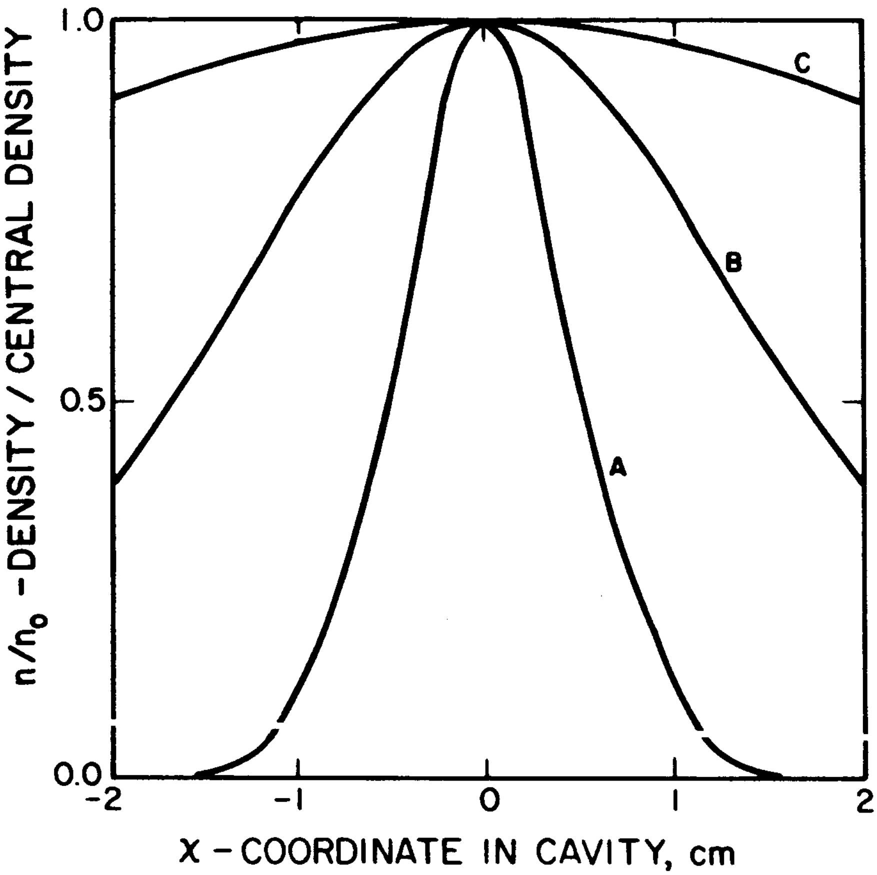
The significance of the Debye gravitational wavelength also is indicated qualitatively by the shape of the curves. It will be noted that the macrogas becomes more uniformly distributed throughout the volume as the central density is decreased, or, in other words, as the Debye wavelength is increased. Using Eq. 8-46, it can be shown that the condition for uniformity is

$$\lambda_g \gg W$$

In the case shown in curve C, the width of the cavity is comparable to λ_g and the number density variation is approximately 10 percent.

8.3.4.4 Properties of a Gas Composed of Ferromagnetic Particulate Matter

It is well known that a magnetically polarizable fluid is influenced by a nonuniform magnetic field. The fluid mechanics and thermodynamics of incompressible ferromagnetic fluids in the presence of a nonuniform magnetic field has recently been studied analytically (Ref. 8-17) and a method of electric power generation based on these principles has been proposed (Ref. 8-18).



A $n_o = 10^6$, $n_o/n_o(max) = \sqrt{2} = 0.707$

B $n_o = 10^5$, $n_o/n_o(max) = 7.07 \cdot 10^{-2}$

C $n_o = 10^4$, $n_o/n_o(max) = 7.07 \cdot 10^{-3}$

FIG. 8-6 NORMALIZED DENSITY DISTRIBUTION IN A 4 cm WIDE CAVITY

In a terrestrial laboratory, to study the interaction of various ferromagnetic particles with a magnetic field, a carrier fluid must be used. Typical ferromagnetic fluids which have been studied to date consist of a colloidal dispersion of ferrite particles in an organic liquid (Ref. 8-17). Ferrite particles suspended in gases could also be studied although this apparently has not been done to date. The results of experiments will obviously depend on the properties of the carrier fluid and it is possible that the influence of the carrier fluid could sometimes make the interpretation of the results difficult.

In a zero-gravity environment, however, no carrier gas is required. Therefore, the results of a zero-gravity experiment in which macroscopic ferromagnetic particles interact with a magnetic field will depend only on the properties of the particles. Relatively large particles could be used, thus greatly facilitating flow visualization. The use of large ferromagnetic particles would also make possible the study of the forces between the particles.

8.3.4.5 Particle Availability

Six suppliers of small particles have been contacted and, to date, four have replied. The information received indicates that it will be difficult at this time to acquire particles with diameters less than about 150 microns if uniformity in shape and dimension is required. For diameters exceeding about 150 microns, however, spherical particles can be supplied in a variety of materials ranging from high-density, hard metals and compounds to low-density synthetic materials. These particles can be made uniform in diameter within 2 percent and spherical within 0.2 percent.

It is assumed that particle uniformity is essential if the results of the macrogas experiments are to be quantitative and meaningful comparisons with theory. It is conceivable that a theory can be formulated which includes effects of nonuniformity but the prospect of performing macrogas experiments for comparisons with such a theory is not attractive. A theory of nonuniform particulate gases must include size and shape distributions which adds complexity in analysis and which ultimately must be determined by experimental classification of hundreds or thousands of particles. Moreover, in the absence of the symmetry of spherical particles and the loss of this symmetry for simplifying calculations, much of the motivation for theoretical investigations of model gases is lost.

8.3.5 Liquid/Vapor/Solid Interface Studies

In the weightless environment of a spacecraft, two types of fluid behavior can be observed which are ordinarily masked by gravitational forces. One type is the gross motion of fluids due to surface tension forces; the other is condensation and vaporization in the absence of convection currents. Four fluid mechanics experiments have been identified - two experiments to observe each of the two types of fluid motion in the weightless state. The phenomena observed are:

1. Gross flow of fluids due to capillary forces.
2. Oscillatory motion of fluids with surface tension as the restoring force.
3. The bubble-forming vaporization process in the absence of convection currents in the liquid phase.
4. The droplet-forming condensation process in the absence of convection currents in the gas phase.

The four experiments are discussed in the paragraphs which follow.

8.3.5.1 Dynamic and Static Capillarity Studies

These studies comprise a series of measurements of flow produced by capillary forces acting upon a contained volume of liquid in the absence of a gravitational field. It has been observed in zero-G drop tower experiments that liquids flow at a reduced rate from that predicted from analytical studies of capillary flow. The cause of this reduced flow rate may be either or both of the following:

1. Unknown viscous forces existing in the boundary layer between the liquid and the wall (capillary layer).
2. A different value for the surface tension coefficient for moving fluid as opposed to static fluid.

In the capillary studies, several liquids of different viscosity will be allowed to flow in response to capillary forces in tubes of various sizes and materials. From the data taken on dynamic and static experiments, new mathematical models can be considered to explain the nature of capillary flow and additional experiments over desirable ranges of significant parameters will be performed to verify or select the theory most consistent with observed data.

Experimental Design

The design parameters for the capillary studies can be determined by writing down the equation of motion for the capillary flow. Figure 8-7 shows a vessel containing the capillarity flow liquid. The liquid flows through a connecting capillary. The meniscus is brought to rest at x_o, by air pressure or other means, and is then released. The motion is observed.

The reservoir is a right cylinder of area A_2 and is filled to a depth X_{02} (ideal case because in zero-G the fluid would flow under surface tension forces). The capillary tube is of radius A_1, the contact angles in the reservoir and capillary are θ_2 and θ_1, respectively. The surface tension of the liquid is S. The dynamical equation is formed by summing the surface tension forces both at the capillary and reservoir surfaces (in the proper sense) and equating this to the sum of the mass-acceleration products for both the fluid in the reservoir and the capillary. This becomes:

$$2\pi r_1 S_1 \cos\theta_1 \left[1 - \sqrt{\frac{A_2}{A_1}\,\frac{S_2}{S_1}\,\frac{\cos\theta_2}{\cos\theta_1}}\,\right] = \tag{8-48}$$

$$\frac{1}{2}\left[M_{01}\left(1 + \frac{X_{02}}{X_{01}}\right) + \rho\, A_1 X_1 \left(1 - \frac{A_1}{A_2}\right)\right]\ddot{X}_1$$

If the surface tension in the reservoir is neglected along with the effect of the motion of the reservoir fluid, the following equation results:

$$2\pi r_1 S_1 \cos\theta_1 = \frac{1}{2}\left[M_{01} + \rho\, A_1 X_1\right]\ddot{X}_1 \tag{8-49}$$

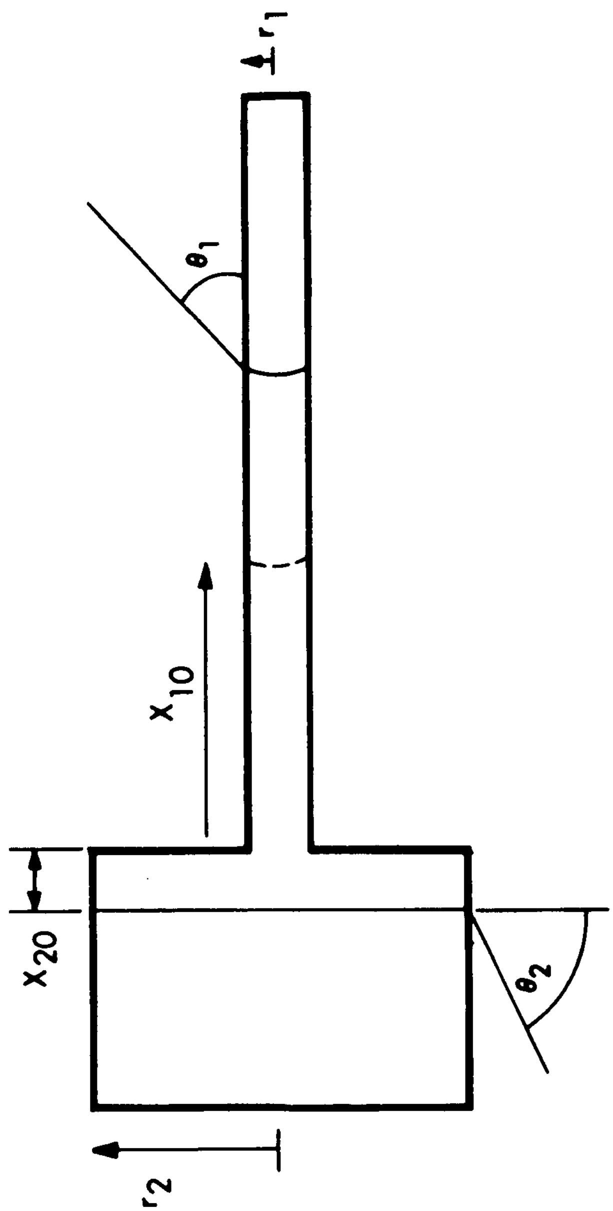


FIG. 8-7 CAPILLARY FLOW APPARATUS

This form would be nearly correct if the experiment were designed so that certain terms are made negligible in Eq. 8-48. An experiment designed in such a way that Eq. 8-49 holds is desirable so that the capillary flow will not require special analyses to take into account the effect of the reservoir. Thus, to satisfy this condition, the following features must be designed into the experiment:

1. $\check{X}_{02} \leq 0.01\ \check{X}_{01}$
2. $r_2 \geq 10\ r_1$
3. $\cos\theta_2 \leq 0.1\ \cos\theta_1$

Putting in convenient numbers:

$$\text{for } X_{01} = 1 \text{ meter}$$

$$X_{02} = 1 \text{ cm}$$

$$\text{for } r_1 = 0.5 \text{ cm}$$

$$r_2 = 5 \text{ cm}$$

$$\text{for a Pyrex-water system } \cos\theta_1 \approx 1 = 10 \cos\theta_2$$

$$\theta_2 \simeq 85^{\circ}$$

Generally θ_2 should be close to 90° unless θ_1 is close to zero, such as for water in a Pyrex capillary. For θ_1 not close to zero, θ_2 should be 90°. This may be accomplished by mating the reservoir with a silvered internal surface when water is used as the fluid.

A variety of liquids having a wide range in surface tension, molecular structure, density, and viscosity will be tested. At least 20 liquids will be required, including water, mercury, glycerol, and ethyl alcohol. Measurements will be made in tubes of diameters varying from 0.1 mm to 10 cm at temperatures varying from above the freezing point to below the boiling point of the liquid and over a range of pressures. The apparatus will consist of an enclosed, shock-mounted box containing a reservoir to which capillary tubes of various sizes may be connected. The reservoir and open end of the capillaries are connected to a common pressure control, permitting liquid flow under a zero pressure differential. Thus, the flow is strictly capillary.

The weight of the test system is 200 pounds and will occupy a volume of 5 cubic feet. Timing devices and photographic equipment will be required. The experimenter will set up the experiment, attaching the capillary to the reservoir, fill the reservoir, and pressurize the capillary to start the initial flow at zero velocity. The desired pressure and temperature will be set and the capillary pressurization released to permit fluid flow. Motion pictures will record the progress of the liquid column and the timer. The pictures shall have sufficient resolution to discern the shape of the meniscus. The conditions or materials will be changed periodically in the course of the measurements.

8.3.5.2 Study of the Dynamics of Free Liquid Drops

The purpose and objectives of this experiment include the following:

1. Study the dynamics of freely suspended liquid drops; including oscillatory modes, stability conditions, fission and fragmentation modes, surface wave phenomena, viscosity damping and drop formation, when the drops are subjected to surface and volume perturbations arising from external and coalescence forces.
2. Perform a kinetic study of the effect of miscibility on drop dynamics resulting in the coalescence of drops of different species.
3. Investigate the barocapillary effect which occurs when the gravitational self energy is on the order of the capillary energy.

4. Study the Kapitza instability. This is a wave motion due to surface tension which is assumed to result from an instability of the original flow that sets in at comparatively low Reynolds numbers.

Liquid-drop dynamics are of major significance in various fields; for example, the behavior of liquid propellants in space and surface-wave phenomena. The results of these studies should yield definitive tests of analytical techniques for treating stable and unstable fluid dynamics under simple boundary conditions (no boundary layers) with large perturbations. Miscibility studies, likewise, would be conceivably related to the problem of propellants in tanks. Such studies would provide correlation with the modes of motion predicted by the liquid-drop model of the atomic nucleus. The following points of analogy may be drawn between the liquid drop and the nucleus: the density of a liquid drop is almost independent of its size, so that the radius R of a liquid drop is proportional to the cube root of the number A of molecules. The energy necessary to evaporate the drop completely into well-separated molecules is approximately proportional to the number A (this is analogous to the binding energy of a nucleus). The morphology of tektites could also be studied with liquid drops.

Kapitza instability has been observed when a thin layer of viscous fluid flows down a vertical wall, but this effect cannot be conveniently observed in an earth laboratory when spherical drops are involved. It would be interesting to observe this phenomenon on spherical drops so as to relate it to the surface waves postulated by nuclear theory. The formation of ullages in liquids has been investigated under zero-G conditions at the NASA Lewis Research Center drop tower and at other laboratories, but these studies are severely handicapped by the short period of time during which zero G can be achieved. The study of liquid-drop dynamics has been thoroughly investigated theoretically by many workers, including Lord Rayleigh (Ref. 8-19). Experimental studies have also been made, but the accuracy of these is hampered by the fact that the drop must be suspended at some point in an earth laboratory. The point of support induces large distortions in small drops, while large drops, due to their weight, cannot be supported and, hence, cannot be studied. The barocapillary effect has not been observed in an earth laboratory for the same reason. Miscibility studies can be crudely approximated on earth by suspending one liquid in another, but these studies are limited to low impact velocities and do not accurately represent spherical drop collision dynamics.

Experimental Procedure. The parameters relevant to drop dynamics are the surface coordinates as functions of time. If we choose a spherical coordinate system (r, θ, ϕ), the variable to be observed is $r(\theta, \phi, t)$. The expected variations in r range from the smallest to the largest radii of the drops, i.e., in the range of 1 to 100 mm. Liquid drops of varying sizes, surface tensions, viscosities, and densities will be freely suspended in a stabilized spacecraft. Synchronized stereoscopic cameras oriented at angles so as to observe the full surface of a suspended drop will be used to observe the oscillations and fission resulting from induced perturbations and collisions. Small gas jets will be used to manipulate the drops, produce collisions, and induce large transient surface perturbations. In order to induce rapid oscillations, acoustic excitation will be employed.

Surface displacements of acoustically excited drop oscillations are to be measured by means of high-speed photography. The required time resolution of the cameras is on the order of 10^{-4} sec (10,000 frames/sec). In order to determine surface displacements accurately, the spatial resolution of the cameras must be approximately 0.001D (D = drop diameter). Electronic measurements are not made in this experiment; only an electrically driven camera and a source of illumination are involved.

All the relevant data is recorded on film. The film record will contain information concerning the spatial and velocity components of centers of mass of the drops and the position and velocity components of the drop surfaces. This film record will be analyzed by digital computer, in exactly the same manner that bubble chamber data is analyzed in high-energy nuclear physics. The data, thus reduced, will then be compared with theoretically predicted results.

This experiment may be performed anywhere within the spacecraft which affords sufficient room for manual operations. There are no special requirements on attitude control. To begin the experiment, the astronaut ejects drops into the chamber, and, by means of fluid jets, positions the drops for collision studies or surface perturbations. At the onset of collision or forced surface perturbation, the high-speed camera is activated. This procedure is repeated until several camera sequences of surface perturbation and collision observations have been made for a particular liquid species. The astronaut then simultaneously activates the acoustic wave generator and camera. Several camera runs of 500 msec each are made in this manner. When this sequence of operations is complete, the chamber is cleaned, another species of liquid drops introduced, and the entire process is repeated. At least five species should be studied. The time requirements for each cycle will be approximately 20 minutes. There are no special requirements for stability or pointing accuracy.

Calculation of G Requirements. According to Rayleigh (Ref. 8-20), small oscillations of a liquid drop about a spherical equilibrium configuration obey the dispersion relation

$$\omega^2 = n(n-1)(n+2)\alpha/\rho a^3 \qquad (8\text{-}50)$$

where ω is the angular frequency, n the mode number, α the surface tension, ρ the mass density, and a the equilibrium radius. If the density ρ' of the surrounding gas is nonnegligible, the quantity $n\rho'/(n + 1)$ must be added to ρ (Ref. 8-21). (Equation 8-50 holds for cylindrically symmetric -- zonal -- modes only. An equivalent formula for sectoral or tesseral modes is not at hand at the moment.) On the other hand, the dispersion relation for free-surface oscillations of a semi-infinite liquid under combined surface-tension and gravitational influence is (Ref. 8-22)

$$\omega^2 = \alpha k^3/\rho + gk \tag{8-51}$$

with k the wave number $k = 2\pi/\lambda$. If we make the obvious identification of wavelength on the spherical drop

$$\lambda = 2\pi a/n \tag{8-52}$$

then

$$k = n/a \tag{8-53}$$

and the right side of Eq. 8-50 is well-approximated by the first term on the right of Eq. 8-51, the difference being that between n^3 and $n(n - 1)(n + 2)$. These two expressions are identical for $n = 2$ (the lowest order mode on the drop) and, as is intuitively obvious, for $n \rightarrow \infty$, with the greatest fractional deviation (scarcely over 10 percent) coming at $n = 4$. We therefore base our analysis of G-level requirements for the oscillating drop experiment on Eq. 8-51, rather than on the equation recently derived by Seitz (Ref. 8-23).

$$\omega^2 = \alpha n(n - 1)(n + 2)/\rho a^3 + h(\rho g) \tag{8-54}$$

in which $h(\rho g)$ is known only to be a function of the gravitational force density alone, and is otherwise undetermined.

We propose to determine α from Eq. 8-50, by measuring ω and α, but assert that the relative error ϵ in α due to neglect of g is the same as the relative error which would be made in calculating ω^2 from Eq. 8-51 with neglect of the second term, that is

$$\epsilon \geq \frac{g\rho}{\alpha k^2} \approx \frac{g\rho a^2}{\alpha n^2} \tag{8-55}$$

so that the G-level required is

$$g \leq (4\alpha/\rho a^2)\,\epsilon \tag{8-56}$$

There is, of course, a second limitation on G-level, namely that the drop not "fall" to any boundary of the apparatus during the time required to perform the experiment. It is this which probably makes it impractical to eliminate the effect of G on earth, by measuring the frequencies of two modes for a single drop and cancelling $h(\rho g)$ between the two evaluations of Eq. 8-54.

We can expect the measurement to be complicated by mode-mixing, but both the performance and the interpretation of the measurements will be simplified if we excite the oscillations by means of a variable-frequency driving force. One could either tune the driving frequency for minimum shimmer (due to transient modes) on a particular drop, or sweep the driving frequency slowly and measure the radii of drops which exhibit standing waves of a recognizable pattern for each frequency. The choice between these techniques would be related to the number of drops under simultaneous observation. In either case, the driving force could be provided by acoustic waves in the surrounding gases, (although the coupling efficiency would be small for drop radii, very small compared to wavelength in the gas phase); or by an electric field. Use of a uniform electric field is predicated on the assumption that the drops consist of a polarizable fluid. Alternatively, the drops could carry a small charge and the field would be made spatially nonuniform; but, again, this leads to small coupling efficiency.

Sommerfield (Ref. 8-22) pointed out that the most accurate way to measure surface tension is to measure the wavelength of standing capillary waves excited by a tuning fork, since elevation measurements in capillary tubes are inaccurate because of impurities on the tube walls. (He also pointed out that the oscillating drop problem cannot be solved exactly when gravity is included, which accounts for the indirect method of estimation used here).

Another calculation by Rayleigh (Ref. 8-19) gives the dispersion relation for a drop which carries total electric charge q (in esu) on its surface as

$$\omega^2 = \frac{n(n-1)}{\rho a^3}\left[(n+2)\alpha - \frac{q^2}{4\pi a^3}\right] \tag{8-57}$$

so that the spherical form is stable for all displacements if

$$q^2 < 16\pi a^3 \alpha \tag{8-58}$$

but unstable for any integral $n \geq 2$ such that

$$n < (q^2/4\pi a^3 \alpha) - 2 \tag{8-59}$$

Neglect of g will introduce the same fractional error in the value of q^2 for marginal stability as in the value measured for α. However, another question which Eq. 8-57 raises is, how nearly neutral must the drops be before it buys us anything (in precision measurement of α) to have g very small? Assuming again that the gravity term which should be added to Eq. 8-57--if we knew how to do it--is the same as in Eq. 8-51), the comparison is

$$\frac{n(n - 1)}{4\pi\rho a^6} q^2 \approx g \frac{n}{a} \tag{8-60}$$

or

$$q < [4\pi\rho a^5 g/n]^{1/2} \tag{8-61}$$

In terms of the relative error in α, this is

$$q < [16\pi a^3 \alpha\epsilon/n]^{1/2} \tag{8-62}$$

or a maximum allowable potential (esu)

$$V = [16\pi a\alpha\epsilon/n]^{1/2} \tag{8-63}$$

If, for example, $a = 0.05$ cm (1-mm-diameter water drops) $n = 2$ and $\epsilon = 10^{-6}$, in which case

$$\omega/2\pi \approx 350 \text{ cps} \tag{8-64}$$

the G-level required is

$$g \leq 0.13 \text{ cm sec}^{-2} = 1.3 \times 10^{-4} g_o \tag{8-65}$$

and the maximum permissible droplet potential is

$$V = 0.013 \text{ esu} = 4 \text{ volts} \tag{8-66}$$

To produce fission, a charge of

$$q_o = 0.7 \text{ esu} \tag{8-67}$$

is required, which the (isolated) droplet will hold at a potential of

$$V_o = 14 \text{ esu} = 4200 \text{ volts} \tag{8-68}$$

This last expression comes from Eq. 8-58 and $V = q/a$, so that the general expression for maximum stable potential is

$$V_o = \sqrt{16\pi a \alpha} \text{ (esu)} \tag{8-69}$$

Oscillating Drop Experiment. The following is a description of an experimental apparatus to perform a zero-G liquid-drop oscillation experiment. The liquid drops are enclosed in a chamber 12 inches on edge. Two adjacent sides of the chamber are transparent to allow for optical viewing. Provision is made for the injection of several types of gases and for the control of the pressure. An injector is provided for the liquid. A 90° stereo optical system is used for viewing the droplets.

A single-frame Fastex camera is used to record the surface waveforms. A strobe light is slaved to the oscillator and phase-shift knob. Frequency and clock time are displayed.

The frequency range is from 10 cycles to 10 kilocycles per second. The drop size will range from 5 millimeters to 0.01 millimeters. Water droplets will be observed initially in equilibrium with air and vapor. Then salts and organic compounds in a water droplet will be observed. Measurements will be made on Q to separate viscosity and surface tension effects. Observations will show surface interaction with vapor.

8.3.5.3 Study of Bubble Formation in Low g

The purpose of this study is to perform experiments on the growth of nucleated bubbles in a zero-G gravitational environment so that bubble growth may be observed in a size regime not accessible in a ground-based laboratory. The growth of a bubble is influenced by motions induced by buoyant forces in a one-G environment after growing to a large radius. This influence is illustrated by the following analytical results.

The ratio of inertial force to buoyant force in the presence of bubble growth is called the Froude number, F_r. This number depends upon the specific heat, latent heat, and thermal diffusivity of the liquid as well as variables such as the bubble radius, local acceleration, pressure, and superheat of the liquid. For water with a superheat of 16^oF and a pressure of 15 psia, the expression for the Froude number is

$$F_r = 5.66 \times 10^{-3} R^{-3} (a/g)^{-1}$$

where R is the bubble radius in inches and (a/g) is the ratio of the local acceleration of gravity to that at the earth's surface (or G's). For example, a bubble, 5 mils in radius, in a one-G field will have a Froude number of 45,300. Thus, the growth of the bubble is overwhelmingly controlled by inertial forces, and a zero-G environment is not required. However, a bubble 1 inch in diameter has a Froude number of 5.66×10^{-3} and the growth of such a bubble is influenced primarily by buoyant forces. To study the growth of this bubble with negligible buoyancy present, an experiment would have to be performed in a G-field of about 10^{-4}, which would result in a Froude number of 57.

A relationship can be plotted between bubble radius and local G such that the Froude number is above some "acceptable" number. See Fig. 8-8 which is plotted for an F_r of 56.6.

The magnitude of what is "acceptable" depends, in part, upon the results of the experiment. Thus, the presence of an experimenter in the zero-G laboratory is desirable for the purpose of

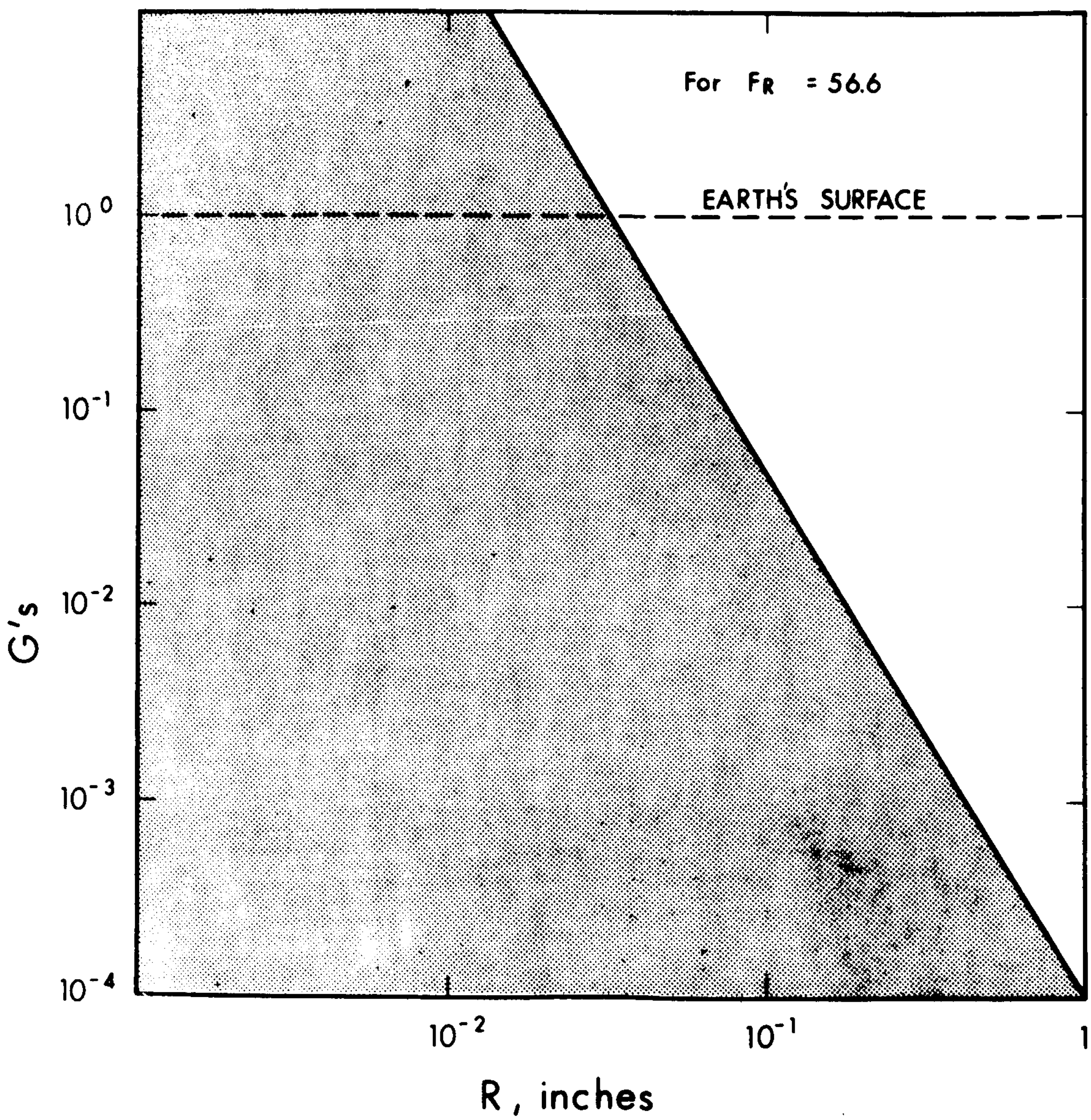


FIG. 8-8 BUBBLE RADIUS VERSUS LOCAL G

exercising judgment as to the required F_r, hence, G-level for the experiment as a result of the observed behavior of the bubble.

It should be noted at this point that, although convection will play a part in effecting bubble growth, it will be a small effect compared to buoyancy.

The study of bubbles in a low-g environment can be carried out in a vessel completely filled with a liquid. A provision is required for maintaining a constant hydrostatic pressure in the liquid. The vessel is thermally shielded and shock mounted to control the superheat level and eliminate perturbing motion of the liquid.

A camera is placed at a viewpoint to record the growth of bubbles. The time rate of growth is obtained for a widely varying set of values of superheat temperature and pressure. Several kinds of liquids and mixtures having different thermal diffusivity, density, specific heat, latent heat of vaporization, and viscosity will be studied. The liquids will include water, alcohol, glycerine, and 20 to 30 others.

The apparatus will consist of a chamber 4 inches on edge with a viewing port located on one of the surfaces. It will weigh about 3 pounds at the most, filled. The chamber will be thermally insulated to minimize the power required to sustain a constant temperature; however, 300 watts of power will be required to warm the chamber initially within half an hour. The experimenter must be an astronaut/physicist.

8.3.5.4 Study of Critical-State Behavior of Fluids in Low-G

There is considerable discrepancy in the experimental data and theories as to the form of an isotherm in the region of the critical point. Besides contamination, gravity plays an important role in observing experimental data. The reason for this is that, ideally, a gas achieves an infinite compressibility at the critical point. In a practical case, a gas in a vertical tube will compress substantially under the influence of gravity and this will result in a gradient of density along the tube. In this condition, one has to choose a single value for the density of the system so that a point (P, ρ) can be recorded on the isotherm. This is accomplished by a technique presented in Ref. 8-24. The technique, which is a monatomically decreasing function of the length of the container, is limited in accuracy. The performance of the experiments to determine the form of isotherms near the critical isotherm could be done more accurately and easily in a zero-G laboratory.

The measurement of critical isotherms for mixtures in a gravitational field is even more difficult. The effect of gravity is to produce a concentration gradient as indicated in the following discussion.

The flux, F, of one component of concentration, C, in a binary mixture is given by

$$F = -D(T) [\partial\mu/\partial C)_T \nabla C + Kg] \qquad (8\text{-}70)$$

where μ is the chemical potential, g is the acceleration of gravity, D(T) is the binary diffusion constant and is nonvanishing at the critical point, and K is a constant which measures the difference between the densities of the two components. The flux vanishes at equilibrium by definition, and $(\partial\mu/\partial C)_T$ vanishes at the critical point. Under these circumstances

$$0 = -D [0 \times \nabla \times C + Kg] \qquad (8\text{-}71)$$

Since g and D are nonzero,

$$0 \times \nabla C + Kg = 0 \qquad (8\text{-}72)$$

If K is nonzero for two components of different density, then ∇C must become larger near the critical point. Thus, to eliminate the concentration gradient when equilibrium is reached, a zero-G environment is required.

The study of critical behavior of one or two component substances can be performed in a container with viewing ports and temperature-pressure controls. In a one-G experiment, the critical state is observed by noting the disappearance of the meniscus. For zero-G experiments, it would be observed by the disappearance of the liquid-vapor interface located near the center of the container for liquids that wet it. The reappearance of a liquid-vapor interface would be an interesting phenomenon to observe because gravity is not present. Gravity, in conjunction with the high compressibility, would condense the liquid in the lower portion of the vessel. The behavior of the liquid-vapor interface would be recorded by cinematography. Pressure, temperature, and density measurements would be recorded and the coexistence curves plotted.

The interest in these curves arises from their form in the critical-point region. Are the curves quadrates, cubic, or flat? To what degree are data on mixtures obscured by gravitational forces?

Liquids such as water, glycerol, and sulfur hexafluoride will be used in one component test. Alcohol-water mixtures and others will be used as binary systems. The relative densities will be varied.

The experimenter should be an astronaut/ physicist with considerable experience in equation-of-state research.

8.4 Summary and Recommendations

The previous portions of this section have described a set of materials experiments to be performed in a zero-G laboratory. The primary factor in the choice of these particular experiments was the availability of a very low-G environment which would allow the observation and recording of data which could not be obtained in an earth-based facility.

The information presented on these experiments is meant to act as a guideline for the design of a space laboratory which will not only provide the requirements for the performance of such investigations, but will also enable the most optimum use of the equipment designed for use in a space laboratory.

As discussed in Section 2 of this report, it became quite evident during this study that the sole emphasis of the zero-G environment greatly restricted the scope of the study. Furthermore, it was clear that there were other aspects of the space environment which could be utilized in the performance of many other experiments and which would enable useful investigations into other fields. With this in mind, in addition to the results of the studies of the experiments presented in this section, the following is a summary of the recommendations resulting from the study of materials experiments.

With regard to the set of experiments described in this section, it is recommended that the design of the experiments be carried into the preliminary stage such that sufficient information may be obtained to enable a conceptual design of an overall spacecraft system. During this effort, greater attention must be given to the placement of the apparatus in relation to the spacecraft components and further details on the structure of the experiment should be developed. The needs of the crew also should be further emphasized, since the performance of these experiments requires a relatively long time period when there would be a fairly substantial interface between the systems which support the experimenter as he is doing his investigation and those which maintain him in space.

Other aspects of the space environment should be considered in the choice of experiments. The fact that an extremely high and well-controlled vacuum is obtainable without the use of vacuum pumps is very important. Two areas of materials studies which are of great interest from this viewpoint are surface physics and surface chemistry. Most surface physics experiments are limited by the extent of the vacuum system available and the background contaminants produced by the vacuum pumping equipment. As a result, the surfaces are generally limited with respect to the degree of purity obtainable. Furthermore, the time of experimentation is limited to the time it takes to build up an appreciable fraction of a monolayer after the surface has been flashed. Studies of surfaces of materials (both refractory and non-refractory) could be carried out on a large scale in such a space station.

Another field of interest is plasma physics. The vastness of space provides an extremely large vacuum system in which an almost limitless plasma can be created by a plasma generator. The behavior of such plasmas cannot be studied effectively in a vacuum chamber of finite dimensions.

The above-mentioned investigations are but two of the more obvious uses which could be made of the space environment from a space laboratory. There are, however, a number of other investigations which could be carried out; for example, probing the atmosphere with charged particle beams, the use of plasmas as an antenna in space, the performance of experiments related to phenomena occurring in the comet nucleus or tail, the effect of beaming charged particles to other satellites.

In addition, there are a variety of experiments which could be performed on the ground in preparation for the performance of the identified experiments in space. For example, the behavior of molten metals in a vacuum may be investigated before such studies are attempted in space. Furthermore, some of the devices specified in materials space experiments (such as a solar furnace) should be tested in a vacuum chamber to identify problems in the use of such instruments.

It is further recommended that development programs on specific instruments which would be used in these experiments should be initiated. One such instrument is the solar furnace. Another is the mass spectrometer which would be used in the meteoroid studies. Facility design studies should be performed on a facility for metallurgical analysis and a photographic processing facility for use in the space laboratory.

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9. DETAILED CONSIDERATION OF BIOSCIENCES

9.1 Introduction and Summary

The advent of manned orbiting research laboratories will afford the opportunity to initiate a coordinated attack on many problems in the basic biosciences. Frequent flights by large laboratory vehicles will make possible the direct access of the bioscientist to the specimens of interest in the unique environment of space. The development of a rationale and detailed guidelines for a coordinated program of basic research in the biosciences is therefore presently of high priority in the manned space laboratory planning effort.

In this study a program of research in the basic biosciences utilizing the unique features of a manned spacecraft equipped as a research laboratory is discussed. The discussion is presented in the form of a set of specific experiments which can be performed aboard a manned orbiting research station. The assumptions, constraints, and scientific motivation used to develop a rationale for the selection of specific experiments are discussed. The specific experiments are identified and described. The general requirements of apparatus and facilities to conduct the experiments are discussed, and the role of the astronaut-scientist is defined. The type and importance of results to be derived from the program are discussed.

The most important feature of the space environment from the point of view of the biologist is the phenomenon of weightlessness. Clearly, the development of life forms on earth has been profoundly influenced by the earth's gravity. Therefore, the various fields and subfields of the life sciences were reviewed for the purpose of identifying areas of meaningful experimentation for performance in an orbiting scientific laboratory. The following were selected as constituting a suitable prototype program of gravitational biology.

Experiments involving basic elements of the life process:

Biological Transport Phenomena

An investigation of the effects of gravitational forces upon the means by which the individual existence of the fundamental unit of life is sustained.

Cell Division and Cytobiology

Cell division and the synthesis of protoplasm are the basic mechanisms in the propagation of life and the source from which the sustained flow of biological continuity derives.

Experiments involving the three "kingdoms" of living things:

Micro-organisms

Investigation of phenomena involved in growth, mutation, synthetic activity, and morphology with respect to gravity.

Animals

Investigation of the role of gravitational forces in embryological differentiation and early morphogenesis.

Plants

Study of the mechanisms by which gravity plays a controlling part in tropic responses and morphogenesis of plants.

It is from a consideration of the present problems of biological science and consideration of the problems of spacecraft and equipment design that a rationale for the details of a space bioscience program has been developed. It is hoped that the impetus supplied by such a rationale and by the new tools inherent in the space environment will enable us to delve more deeply into the fundamentals of the life process and allow us to prepare experiments in the absence of a gravitational field which will illuminate basic aspects of the life process. It is to this end that the bioscience portion of this study program has been dedicated.

9.2 Background and Objectives

The existence of life is a fact of the most fundamental interest to intelligent living beings. At the same time, due to the complexity of the physical processes involved in the sustained flow of biological continuity, many aspects of this subject are very incompletely understood. Much of man's quest for knowledge in the sciences can be related to his desire to understand himself and his interaction with the forces and entities making up the world around him. The more easily measurable physical sciences have enjoyed a quicker progression through observation, experiment, and development of comprehensive theories than have the biological sciences. Because of this, it is quite natural that the space environment was investigated with probing instruments prior to man entering space himself.

In conceptual design, space probe instrumentation is in general not complex and, initially, the space research program concerned itself with measurements of the properties of the environment with instruments which could be carried on the available vehicles. Hence, it is not surprising that a rather small portion of the research effort to date has been devoted to the biological sciences. We are excluding from consideration here, of course, those very carefully conceived and executed measurements of a biomedical nature necessary to a solution of the engineering problems of life support. We are pointing instead to the more fundamental types of experiments in which the principal tool in data acquisition is direct visual observation of the biological specimen by the trained observer.

Some simple bioscience experiments have already appeared in the program, but to date the study of the effects of the space environment on biological systems has been largely limited by the need to recover the samples for direct visual observation on the ground. For the vast majority of vehicles launched to date, recovery was not planned or attempted. Now, however, the space research program is reaching a level of maturity which calls for the initiation of an extensive program of research in the biosciences utilizing the space environment to maximum advantage.

The achievement of spacecraft capabilities of a high order makes feasible the development of manned space bioscience laboratories in which we are able to bring together simultaneously the appropriate specimens, the physical environment, the scientific investigator, and a sufficient complement of equipment. In this way, the highly fruitful biological research techniques involving direct observation and manipulation of the sample by the trained scientist can be utilized. In unmanned satellites we have the necessary physical environment and often the appropriate experimental samples and specimens, but frequently are unable to get desired data due to the absence of experienced scientists in the spacecraft. In the various manned programs to date, we have had the necessary physical environment but there has been room for few appropriate experimental samples or specimens, and the astronauts chosen thus far have not been selected from the community of experienced bioscientists. In none of the programs to date has it been possible to include an amount of equipment which would allow retrieval of more than a small fraction of the potential scientific information contained in the experiment. The principal objective of the orbiting bioscience research laboratory concept set forth in this study is to draw four essential elements together into a meaningful program for bioscience experimentation as indicated in Fig. 9-1.

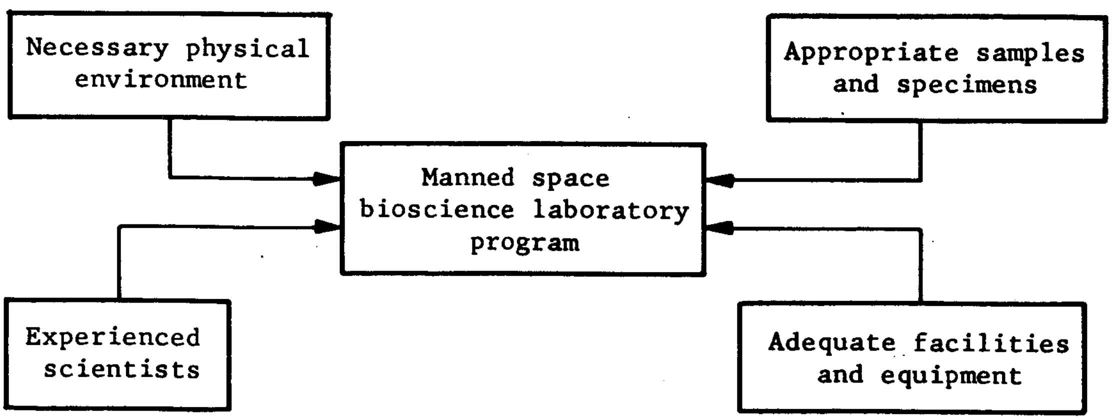


FIG. 9-1 ELEMENTS OF BIOSCIENCE LABORATORY PROGRAM

As previously stated, the principal objective of the bioscience portion of the study was to derive a concrete and well defined approach to the development of a bioscience program and associated experimental capability for a manned orbiting research station sufficient for use as a guide in future planning. The first objective of the study effort was the identification of a roster of potential experiments from which to select a set constituting a hypothetical bioscience program for a nominal mission. The next objective was the selection and organization of a set of experiments into a scientifically meaningful program. The third objective was the selection of universal and widely adaptable equipment to enable the experimenters to carry out a wide range of bioscience experiments in a highly compact laboratory aboard the spacecraft. The laboratory apparatus compatible with and functional in a spacecraft will, ultimately, of course, require a carefully planned engineering-design effort. Consideration of laboratory tools for use in the space environment in turn led to the next main objective of the study effort which was to define the research facilities which should be provided to biological scientists aboard the spacecraft. The design and definition effort was concerned with:

1. Experimental samples and specimens
2. Experimental apparatus
3. Work areas and spacecraft facilities
4. The scientific investigator
5. Data acquisition elements

Subsidiary objectives included analysis of crew requirements and data management. A further objective of the study was analysis of the interfaces between the experiment and the spacecraft including preliminary definition of weight, volume, and power requirements. The final item of desiderata was a set of recommendations based on the results of the rest of the study.

9.3 Method Used in the Study

The approach utilized in this study to determine the kind of biological experimentation one would wish to perform in a large sophisticated manned space laboratory consisted of the following steps:

1. Possible experiments were identified and categorized.
2. Individual experiments were grouped into study areas based upon various commonalities.
3. A prototype mission was assumed.
4. Selection and definition of specific studies suitable to such a mission was performed.
5. The selected experimental studies were organized into a hypothetical program of gravitational bioscience experimentation.
6. The facility and equipment requirements imposed on the system by this hypothetical program were determined and analyzed.

Details of the techniques used in these various steps are discussed below. For planning purposes, a mission of 90 days nominal duration in near earth orbit (ca. 200 n. mi) was assumed in step 3.

9.3.1 Identification of Potential Experiments and Studies

Because the biological sciences are concerned with chemical-physical-electrical systems of tremendous complexity, complete quantitative theories and models useful in guiding the search for significant experiments are not yet as available as in the physical sciences. Because of this relative paucity of mathematical type techniques to facilitate correlation of scattered observations and yield predictions of unobserved phenomena, the planning of biological experimentation is, of necessity, heavily dependent on the individual understanding and insight of highly trained and skilled investigators. Guidance from the scientific community in identifying significant biological experiments has resulted in an extensive list of recommended experiments and measurements to be performed in an orbiting laboratory.

A number of methods have been utilized in identifying areas of scientific interest in space bioscience experimentation. Among these has been the guidance provided by (1) distinguished elements of the scientific community such as the National Academy of Sciences, Space Science Board, (2) contacts with individual scientists, particularly those whose research programs seem especially fruitful and appropriate, (3) survey and analysis of the many suggestions which have been presented from time to time in the literature, and (4) analysis of convergences among many lines of current research and the synthesis of critical experimental approaches which would interrelate isolated natural phenomena.

A large number of suggested experiments were drawn from many sources within the bioscientific community. Some of the scientists consulted had considerable background in space experimentation and weightlessness research, while others had no prior experience in this field. Such a diverse group of sources was utilized to obtain as broad a cross section of current bioscience interests and activities as possible. It was fully recognized that as originally conceived by some of the individual scientists, some suggested experiments would not be suitable for the type of program of concern in this study. Therefore a set of ground rules was formulated to guide the acceptance of experiments for inclusion in the list of candidates for further evaluation. The following factors were considered to be minimum necessary properties:

1. The experiment has definite scientific purpose in that a prediction or hypothesis is to be tested.
2. The experiment provides information of value to future scientific investigations.
3. The experiment requires the presence of experienced scientists at the site of the experiment in the spacecraft.

4. The experiment cannot be performed on earth because of (1) uniqueness of the space environment; (2) potential invalidation of results because of transit of samples back to earth; or (3) requirement for cumulative environmental effects over prolonged time periods, too impractical for earth-based simulation.

Those experiments accepted for further consideration in accordance with these criteria are listed in Subsection 9.4.1 by the title under which they were originally proposed.

Since more than 400 experiment suggestions were accepted as candidates for further consideration in the study, it was necessary to make a preliminary division into the following four subject areas:

1.	Biosciences	(172 suggested experiments)
2.	Biomedicine	(139 suggested experiments)
3.	Bioengineering	(9 suggested experiments)
4.	Behavioral Biology	(87 suggested experiments)

Bioscience encompasses those experiments which deal with phenomena that are basic to life processes in both plant and animal kingdoms as well as in the realm of microbiology. In a sense, bioscience experiments may be said to deal with nonapplied studies of form and nonconscious functions of living things. The general ground rules for bioscience experiments are: (1) man is not the subject of the experiment, (2) the experiment is done to understand the course or end result of a life process rather than to gain knowledge for application to a particular engineering design purpose and (3) the experiment is not concerned with the life process because of its effect on conscious activities of the living system in question. Bioscience studies deal with phenomena at the physico-chemical, subcellular, cellular, tissue, organ, organ system and organism levels of biological organization. Some of the major areas of current interest are biophysics, biochemistry, physiology, morphology, genetics and bacteriology.

The biomedical experiment suggestions adhere to the following ground rules: (1) only those experiments exploiting the unique features of the space environment; and (2) only those experiments utilizing man as a subject are considered. The areas of responsibility are: (1) health and safety; (2) physiological reactions; and (3) certain psychological effects. The interests of space medicine may be described as being presently directed toward the identification, elucidation, anticipation, and correction of deteriorative changes in the human body during prolonged space flight. The following major biomedical areas have been identified: (1) neurological, (2) cardiovascular, (3) respiratory physiology, (4) cardio-respiratory dynamics, (5) metabolic, (6) endocrine, and (7) hematological. Consideration of the problems of current interest in space medicine has, in many cases, been helpful in selecting experiments for the basic bioscience program.

Bioengineering experiments are concerned with acquisition of a particular item of biological knowledge which has a definite and more or less immediate engineering application. The bioengineering experiments suggested in this study deal with problems connected with the development of advanced life support systems. The applicable ground rules here are: (1) the experiment must require the unique properties of the space environment for satisfactory performance and (2) there must be a definite engineering design application for the knowledge gained in the course of the experiment.

Behavioral biology is concerned with the conscious functions of animals, including man, and with the underlying etiology mediating a particular condition or response. Studies falling within this area generally deal with aspects of psychology, neurology, psychophysiology, sensory and motor functions. It will be noted that similarly titled experiments are found in both the biomedical and behavioral categories. Those experiments falling in the biomedicine area involve man as the subject and are basically physiological or pathological in nature while those in the behavioral biology group utilize various animals possessing conscious functions and cover a broader range of approaches than the biomedical group.

The rationale used in selecting experiments for consideration in the study has been based on the premise that the proposed program of scientific research is to be conducted in the post-Apollo time period when the biological requirements of man in space for a duration of several weeks will be well understood, but when the longer term effects of weightlessness will not have been experimentally investigated. It has also been assumed that the experiments identified are to be performed as parts of a coordinated program conducted in an orbiting laboratory by trained scientists.

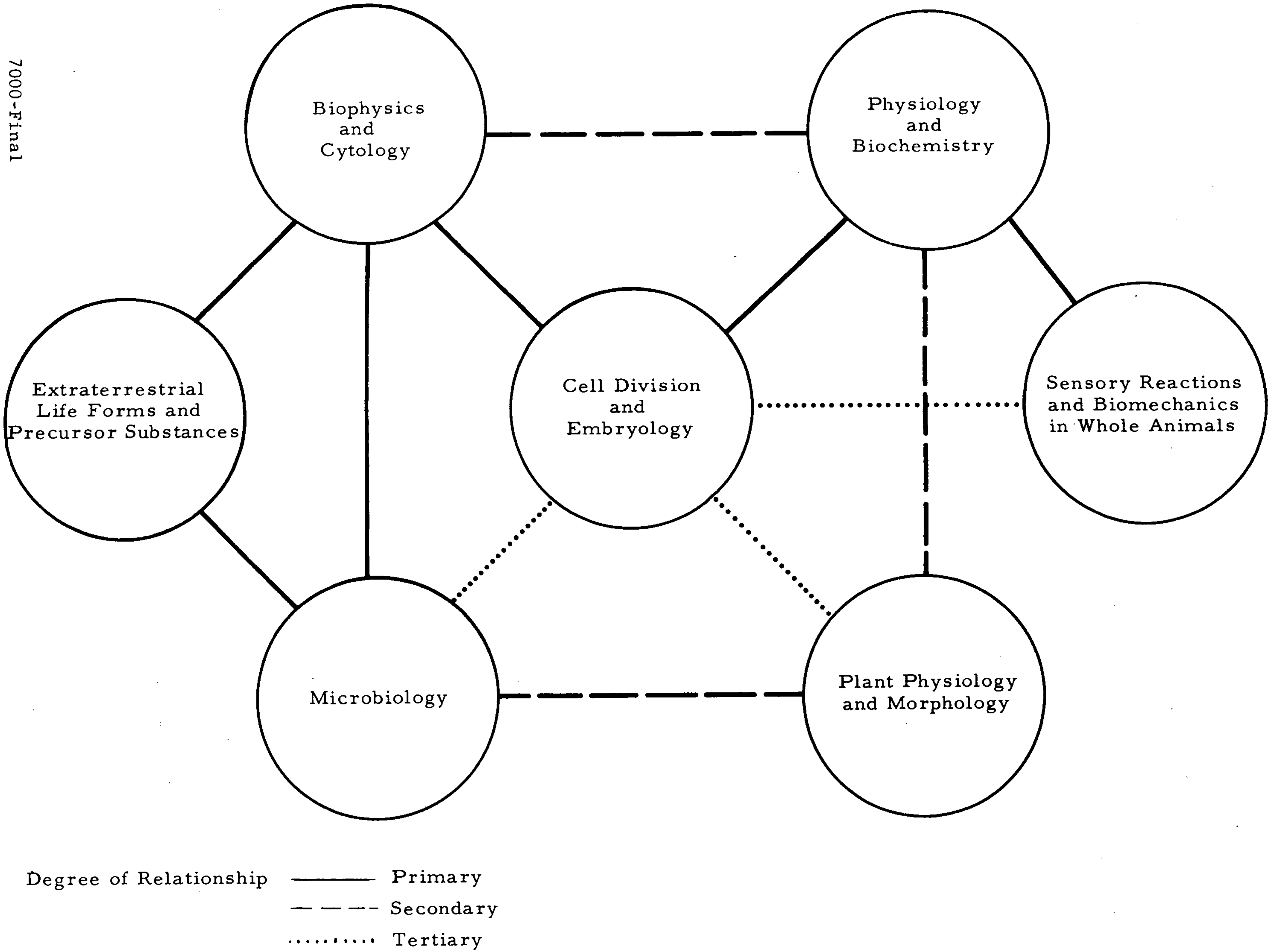
9.3.2 Organization of Individual Experiments into Study Areas

The bioscience experiments suggested have been grouped into the following seven areas:

1. Search for extraterrestrial life and precursor substances
2. Biophysics, cytology and cell physiology
3. Microbiology
4. Cell division and embryology
5. Plant physiology
6. Physiology and biochemistry
7. Sensory reactions and biomechanics studies in whole animals

These seven areas encompass the full spectrum of biological organization and complexity from large molecules through cells, tissues, and organs to whole organisms. The interrelationships of these areas are illustrated in Fig.9-2. As we move from left to right across the chart, it can be seen that the equipment required to perform experiments in these areas increases in size and complexity while the experimental techniques become progressively more complicated and lengthy. Hence, it is logical to consider performing experiments in the areas towards the lefthand side of the chart at an earlier point in the program than those on the righthand side.

FIG. 9-2 INTERRELATIONSHIP OF BIOSCIENCE STUDY AREAS



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Presented below are a few scientific experiments typical of each of the above seven areas. These lists are not intended to be either complete or exhaustive but to indicate something of the general nature of experiments which can be considered representative of these areas.

Extraterrestrial Life Forms and Precursor Substances

Determination of existence
Life chemistry studies
Morphological studies
Propagation and culture studies

Biophysics and Cytology

Cell membrane studies
Cytoplasmic motion and mechanics
Virus replication
Biological transport

Cell Division and Embryology

Meiosis
Mitosis and cytokinetic studies
Differentiation and organization
Tissue formation and maturation

Physiology and Biochemistry

Calcium metabolism
Nitrogen metabolism
Endocrine function
Hemochemistry

Microbiology

Growth rate and metabolite transport
Induction and reversion phenomena
Mutation studies
Immunological studies

Plant Morphology and Physiology

Gravotropism and gravophobism

Morphogenesis

Auxotrophic phenomena

Sensory Phenomena and Biomechanics

Static and motor reflexes

Kinematic reflexes

Hemodynamics

9.3.3 Selection and Definition of Specific Experimental Studies

Since the number of ideas for experimental work gleaned from the above-mentioned sources was very large, it was necessary to establish selection criteria for deciding which specific experiments should receive detailed consideration for a Manned Space Laboratory program. These criteria fall into two basic groups, the first of which examines the scientific merit of a proposed experiment while the second group is concerned with the appropriateness of the experiment for inclusion in the Manned Space Laboratory program. Scientific considerations include: (1) Is there a valid scientific rationale? and (2) Does the experiment make a significant contribution to the state of scientific knowledge in some particular field or area? Program-related criteria include: (1) Are the environmental parameters required by the experiment available within the system concept? (2) Will it be possible to include appropriate scientific manpower within the vehicle to accomplish the experiment, and (3) Will the equipment and facilities required for the performance of the experiment be compatible with the program concept?

There are many ways of defining a group of experiments which require a more sophisticated space laboratory than is possible to build into current programs. For example, one could approach the problem in the following way:

1. Define a set consisting of <u>all possible</u> biological experiments
2. Define a subset consisting of those which should be done in the space environment
3. Define a sub-subset which has not already been done or cannot be done in some existing program with current vehicles

Clearly, however, with the above technique, there is little possibility of <u>ever</u> completing step 1, much less advancing beyond it.

Another approach is to take as a set all of the experiments which at one time or another have been proposed for various space laboratory research programs and eliminate those which we can afford to <u>not</u> do at all. Of those remaining, we may further eliminate those experiments which we can afford to do in the milieu available to us in unmanned or early manned vehicles. We can, in this way, define a group of experiments which <u>must</u> be done. However, the very assertiveness of this approach may well result in excessive rigidity of the program plan. (Some tendency to this can be seen in the exobiology program.)

A rather different approach to the problem can be made in one of the two following ways. The first involves establishing several definite criteria and immediately eliminating from further consideration any proposed experiment which does not simultaneously meet all of them. There is a great danger here of rejecting genuinely critical and significant experiments due to imperfections or misconceptions in the set of criteria. The second way involves utilization of the same set of criteria as guidelines for the "invention" of suitable experiments. The main hazard here is that of creating experiments which in fact meet a large number of elaborate criteria but will not contribute to the store of scientific knowledge.

Throughout this study, an attempt has been made to pursue a somewhat intermediate course and elements of each of the above approaches have been used in arriving at a set of what are believed to be reasonable criteria. At the same time, it is important to remember that these criteria, as is the case with any set of practical rules, are merely guidelines and if too slavishly followed can accomplish as much harm as good.

First among the criteria is scientific merit. Second, the proposed experiment must engender a very high degree of interest within the scientific community since the principal raison d'être for a space laboratory and its experiments is to serve the interests and needs of science and scientists. As an example, general cosmology is of great interest to perhaps 98 percent of all scientists while middle invertebrate taxonomy can excite perhaps a few dozen.

The third selection criterion concerns the degree of dependence of the experiment upon the parameters of physical environment which can be uniquely provided by a space laboratory. There are only two which can be positively identified at the moment. One is, of course, weightlessness, and the other is extremely energetic radiation. Certainly short periods of weightlessness have been produced in parabolic aircraft flights and acceleration as low as 10^{-2} to 10^{-3}G is probably obtainable with current spacecraft designs. But at least one biological experiment suggested would probably require about 10^{-7}G to ensure a meaningful result. While it is true that most radiation encountered in space can be duplicated in the laboratory, the cosmic radiation does have a component with energies as great as 10^{19} eV per particle. However, there have been no bioscience experiments actively proposed which require such energies.

The hard vacuum of space is another environmental feature which has often been mentioned as having potentially great use. While pressures as low as 10^{-9} torr can probably be attained and extremely high pumping speeds are inherent, the two places in which we contemplate use of this capability are operation of lyophilyzers and electron microscopes.

The fourth criterion evaluates the flight durations required by the proposed experiment. When the required flight time is 30-60 days or less, the experiment can frequently be done more economically in simpler space laboratories with shorter mission times than those envisioned in this report. None of the systems currently planned seem to offer much possibility of maintaining environmental parameters (such as acceleration forces) to very close tolerances for periods in excess of a few days to a few weeks.

A fifth criterion concerns the requirement for space laboratory facilities possessing sophistication or special features considerably beyond those which can be achieved with any existing or currently planned system. For example, experiments have been suggested which require very large laboratory work spaces or such facilities and equipment as several large centrifuges or free-floating platforms.

The sixth item which we utilize as a selection or guidance criterion attempts to assess the baseline data requirements of proposed experiments. Not infrequently we have found that proposed experiments whose other characteristics recommend them highly are lacking in baseline data to an extent that prevents further planning pending ground-based and/or simpler space-based investigation to elucidate areas of uncertainty. If historical experience is a valid guide, we may expect some of these earlier experiments to extract all of the information there is to be obtained from a given line of investigation and, hence, eliminate the experiment from the advanced program. In other cases, the early experiments may, in fact, yield no information, in which case there will be no indication that the experiment is worth doing in a more sophisticated way. Some proposed lines of investigation have not yet had the benefit of critical ground-based experiments upon which to make a reasonably firm decision to include or exclude them in the plans for an advanced space laboratory. All that can be done for the present is to tentatively retain them as excellent candidates for further consideration and suggest critical ground-based and simple space-based experiments which will provide the required inputs to a future decision.

The seventh item evaluates the requirement for direct participation of trained scientific investigators at the site of the experiment in orbit. Some of the more important reasons for placing an experienced scientist in the space bioscience laboratory are listed below.

CAPABILITIES OF THE BIOSCIENTIST IN SPACE

Sensory	Particularly, discernment of fine detail and patterns in fragmentary data
Manipulative	Ability to perform extremely diverse and complex mechanical functions where each action may depend on the unpredictable outcome of the last one
Intellectual	Ability to evaluate data of great complexity
	Highly selective, flexible, and extensive memory
	Ability to deal effectively with unforeseen situations
	Capacity for combining inductive and deductive reasoning
	Ability to make judgments
Communicatory	Unique ability to extract and communicate significant information from large quantities of data

In biology, more than any other science, the experimenter functions as a trained observer; hence, the ability to discern fine details and recognize patterns, particularly in fragmentary or incomplete data is of paramount importance. Man's manipulative abilities are rather well known, and, whenever man is compared with the machine for the performance of any single, simple task, the machine almost invariably appears much more attractive from the standpoint of weight, volume, power, etc. However, when one considers highly complex and diverse functions, particularly where reasoning of an inductive nature must be used between manipulations, it becomes apparent that it may be beyond the competence of modern technology to create a machine capable of performing all of the many tasks which man, the trained scientist, is capable of performing. Only a few of the more important, intellectual capabilities of the trained scientist have been listed and need not be dwelled upon at length, since much information is already available concerning these. It is interesting to note with regard to communication, however, that the trained and experienced investigator has a very unique ability to communicate extremely large quantities of data in very few words, depending, of course, upon circumstances. A typical example would be where an experimenter in space says, "This experiment turned out just like the last one except for the final step where there was a 5-percent change in response." Such a statement communicates volumes of information and yet emphasizes for immediate understanding only that small portion which is significant. It is also interesting to note that years of scientific training and experience incur no weight and power penalties; hence, as an analytical computer, a sensor, and a data communicator, the skilled scientist has excellent cost effectiveness. In the event that man's participation is found to be unnecessary, the experiment may be recommended for an advanced biosatellite or other program.

Finally, upon passing the screening procedure an experiment is defined in depth and a detailed experiment plan is prepared. The accompanying flow diagram (Fig. 9-3) illustrates the method of screening experiments using the criteria developed from the above considerations.

Each of the experiments chosen for the bioscience program was developed and the detailed definition prepared in accordance with the following:

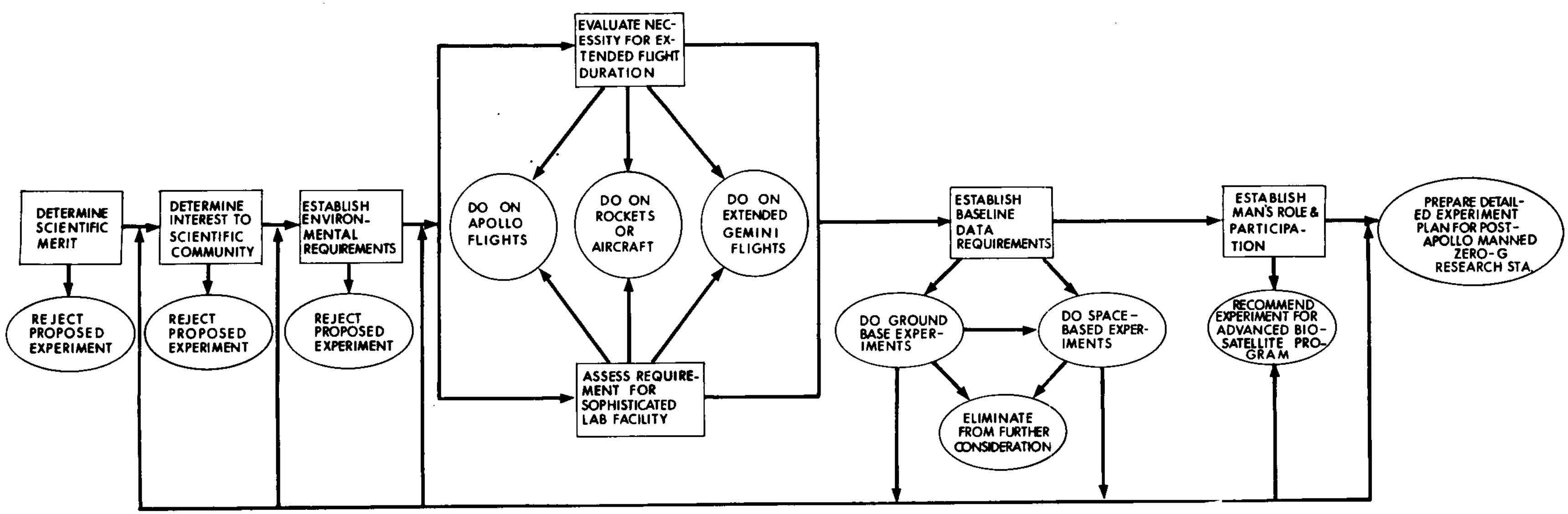


FIG. 9-3 EXPERIMENT EVALUATION FLOW CHART

- Objective of the experiment
- Technical rationale
  - Scientific background
    - theoretical
    - experimental
  - Scientific justification
  - Practical justification
- Feasibility
- Method
- Requirements
  - Instrumentation and apparatus
  - Spacecraft facilities
  - Scientific crew
  - Information handling and data management

9.3.4 Analysis of Engineering Requirements Imposed by the Scientific Program

Since orbiting bioscience laboratories must be equipped with the necessary apparatus to perform experiments and collect data, a versatile laboratory concept was established which contained the basic pieces of equipment necessary to perform a wide assortment of probable biological experiments. In addition, the laboratory was made flexible enough to permit inclusion of specialized apparatus as needed for particular experiments.

The hardware and equipment requirements of a bioscience experimentation program are conveniently divided into four major areas. The physical facilities include workspace, utilities and housekeeping items. Instrumentation deals with items which are directly involved in the data collection process as differentiated from apparatus which encompasses items involved in the storage, maintenance, manipulation and handling of specimens. Finally, we have information handling and data processing equipment which is involved in analysis, transmission and storage of data rather than in actual data collection. Examples of items included in each of these categories are summarized below:

PHYSICAL FACILITIES

- work spaces
- storage provisions
- general utilities
- waste disposal

INSTRUMENTATION

- cell counters
- microscopes
- radiation counters
- spectrophotometers
- oscillographs
- polarographs

APPARATUS

- culture vessels
- small centrifuges
- incubators
- pipettes and fluid transfer devices
- micromanipulators
- special light sources

INFORMATION HANDLING AND DATA PROCESSING AND STORAGE EQUIPMENT

- small computers
- telemeters
- television links
- film processing
- lyophilizer
- freezer
- re-enterable data cassettes
- tape recorders

The hardware definition and design effort, in addition to utilizing existing descriptions of experimental equipment, analyzed new experiments and experimental approaches to better determine the complement of basic equipment for the bioscience laboratory program. The study effort has identified specialized pieces of laboratory equipment, and developed in considerable detail the concept of a versatile laboratory, composed of apparatus with flexible multi-purpose accessories that could be interchanged during the flight to accommodate changes in the planned experiments.

The hardware analysis and definition effort was designed to develop:

1. A list of the apparatus required for each experiment in the planned program.
2. Recommendations for the development and flight qualifications of specific pieces of laboratory apparatus.
3. Preliminary specifications for recommended apparatus.
4. Recommendations for the development of techniques to handle samples in orbital laboratory.

While definition and analysis of the experiments was the primary objective of the study effort, analysis of the operation of the laboratory and the hardware interfaces between the laboratory and spacecraft was also conducted. In addition, other interface areas such as data handling and electrical power were considered. The above considerations resulted in the generation of recommendations regarding the design of the spacecraft, installation of laboratory equipment, and interfaces where the spacecraft subsystems provide services essential to the operation of the laboratory.

Equipment may be expected to change as recommended experiments change, and capabilities of the spacecraft and crew are better defined. The rationale for any practical space bioscience laboratory must accommodate the continually changing needs of the program since the pace of scientific discovery is such that experiments may be expected to change up to the time of launch. The equipment must also be sufficiently versatile to permit experimental approaches to be changed in space in instances where redirection of the course of the experiment is indicated due to unexpected results in the early stages.

9.4 Results of the Study

The results of the study consist of essentially three parts — identification, analysis, and integration. First, a large group of potential experiments (listed in Subsection 9.4.1) were identified. Then selection criteria were formulated to aid in the analysis of these experiments for various features of interest. Five experiment areas were established and a detailed scientific rationale was developed for each of them as a guide to further planning. The separate experiments within these five areas were integrated into a hypothetical program of bioscience experimentation suitable for an assumed mission of 90 days duration in near-earth orbit.

The second phase of the study effort was concerned with identification and analysis of the instrumentation, apparatus, facility, crew, and data requirements of each of the various experiments. More than 50 major items of equipment and apparatus required by the experiments have been identified and analyzed (Subsection 9.4.4). In addition, 14 major specialized facility items are identified and analyzed (Subsection 9.4.5). In this way, it has been possible to define a specific set of apparatus and facilities suitable for performing a program of bioscience experiments. It is interesting to note that although only five comprehensive experiments were used to generate the list of facility and instrumentation requirements, these items, when brought together in a suitable configuration, constitute a remarkably complete and well-equipped biological research laboratory.

Finally, the equipment and facilities are integrated, together with crew and data considerations, into a hypothetical experimental program suitable for the assumed mission. This hypothetical program, in turn, enables one to identify the interfaces between the bioscience experimental program and the overall system concept and to define requirements imposed by the bioscience program on vehicle design.

It is recognized that the requirements of a program change rapidly both before and after its formal initiation and that the specific experiments in this study are only hypothetical. The examples utilized, however, serve to point out with great clarity two points:

1. The urgent need for immediate efforts to accomplish the timely development of necessary baseline data
2. The absolute necessity of proper planning for multipurpose utilization of apparatus and facilities

Perhaps the most significant result of this study effort is the recognition and illumination of the emergence of gravitational biology as a major scientific discipline. In time, gravitational biology will grow from its present embryonic state into a fully developed discipline in much the same manner as marine biology and aerobiology.

9.4.1 Identification of Areas of Scientific Interest

Utilizing the techniques discussed in Subsection 9.3.1, a list of more than 1200 experiment suggestions was compiled. After a preliminary screening, which required that an experiment, in order to receive continued consideration, must (1) test a definite scientific hypothesis, (2) provide information of definite future value, (3) require the presence in orbit of experienced scientists, and (4) require an environmental parameter unique to orbital flight, 407 experiments were selected for detailed examination and consideration. As discussed previously, the 407 experiments were divided into four main groups: bioscience, biomedicine, bioengineering, and behavioral biology.

The experiment suggestions contained in each of these categories are enumerated below. It should be recognized that the experiments are listed essentially by unaltered titles and, hence, overlapping ideas and partial or complete duplications will be noted in some instances. This fact is not surprising since, if a particular idea is of great scientific interest, it is reasonable to expect that it will be mentioned independently by at least several scientists. Therefore, it is possible to gain an insight, albeit an imperfect one, into the degree of interest in various subject areas by merely scanning the lists of suggested experiments for repetitive ideas.

9.4.1.1 Biosciences

Analysis of prebiotic chemical compounds of extraterrestrial origin

The effects of high-energy particulate radiation on selected materials — particularly, organic compounds

Origin of biochemical compounds

Analysis of living material collected from space environment

Soft capture and identification of spaceborne micro-organisms

Collecting and sampling of micro-organisms in near-earth orbits

Survival of organisms in the space environment at orbital altitudes

The effect of the space environment on spores and micro-organisms

Survival of organisms exposed to space environment at manned orbiting altitude

Micro-organism exposure to space environment

Microflora of the human skin

Independent and synergistic effects of zero-gravity and radiation upon the growth rate and mutation rate of bacteria

Effects on growth rate of *E. coli*

Growth rate and mutation rate of micro-organisms in zero-G

Genetic drift in bacterial populations grown for many generations in zero-G

Lysogeny

Lysogenicity in bacteria propagated in zero-G

Induction and reversion of L-forms of bacteria

CO_2 evolution and aeration in bacterial cultures

Biological effects of weightlessness as a factor in gas-liquid separation in metabolites of micro-organisms

Bacterial protein synthesis

Phage production

Kinetics of phage growth

Virus and phage replication

Modification of phage production in *E. coli*

Modification of phage produced in bacteria *E. coli*

Genetics

Genetic effects in micro-organisms

Gene mutations caused by long-duration space flight

Changes in sex distribution of offspring conceived, developed, and born in the weightless state

Genetic and hereditary effects in zero and partial G

Mutation rate

Alterations of life cycles under conditions of weightlessness

Life cycle of *Drosophila*

Biochemical phenomena

Lipase activity

Rate of enzyme synthesis in space

DNA recombination

The effect of weightlessness on the replication and recombination of DNA

Effects of space flight on cerebral neuronal and glial chemistry

The effect of weightlessness on cerebral, neuronal and glial chemistry

Biological and chemical properties of mineralized tissue

The independent and synergistic effects of zero gravity and radiation upon the transport of material across the cell membrane

Convective and diffusive biological transport during weightlessness

Biological transport

The effects of zero gravity at the subcellular level

Morphological changes at the cellular and subcellular level during exposure to prolonged weightlessness

Microscopic studies of individual cells and their inclusions in the space environment

Cytological phenomena

Microscopic studies of individual cells

Mitosis/division cycle/DNA synthesis

Mitosis

Cell division

Effects of weightlessness on meiosis

Meiosis and maturation of gametes

The effects of radiation and a gravity-free environment in space, on cell division and growth

Effects of space flight on morphology and growth of micro-organisms and animal tissue cells

The synergistic effects of radiation in zero-G on cell division and growth

The effect of long-term weightlessness on cellular metabolism

Cellular physiology

The effects of zero-gravity on paramecia and hela cells

The effects of zero-gravity on tissue culture cells

Effect of weightlessness on dividing human cells in culture

Human mitotic cells in culture

Monocyte formation

Movement within cells

Cyclosis and streaming phenomena

Phagocytosis and pinocytosis in cells grown in zero-G

The effects of weightlessness on protozoa (1) synchronous division of nuclei (2) digestion, (3) growth (4) metabolism

Locomotory movement of protozoa

Locomotion in protozoans

The effects of zero gravity on ciliates

Tissue regeneration

Wound healing in zero-G

Limb regeneration during weightlessness

Study of tissue regeneration and wound healing during space flight

Study of tissue regeneration and wound healing during weightlessness

Tissue regeneration and wound healing during weightlessness

Liver regeneration (mitosis) at zero-G

Histological changes of various tissues

Embryology at zero-G

Embryology

Fertilization anomalies in zero-G

The effects of zero-gravity on the development of newly fertilized frog or chicken eggs

Effects of zero-gravity on the fertilization and development of various types of eggs

Embryological growth and differentiation

Maturation

The independent and synergistic effects of radiation and zero-gravity on differentiation in the flour beetle (Tribolium)

Posture of small animals

Spatial orientation and righting effects

Behavior and posture of mobile animals

Undirected sensory reactions

Directed sensory reactions

Postural reactions in reduced gravity

Orthokinesis and klinokinesis

Static and motor reflexes of higher animals

Kinematic reflexes in the weightless environment

Biorhythms in the primate

Cellular rhythms

Studies of metabolic rhythms

Circadian rhythms in small animals

Effects of weightlessness on the relationship between hibernation and biological clocks

Circadian rhythm during orbiting flight

Circadian leaf rhythms

Eclosion rhythms in Drosophila

Effect of reduced gravity on circadian rhythms in fungi

Circadian rhythms during prolonged orbital flight

The effect of reduced gravity on the coupling of orientation and the time sense

The effect of gravitational fields on the growth and development of plants

Growth patterns of plants in the weightless environment

Orientation of plants

Effects of weightlessness on plant morphology, seeds, culture, and leafy plants

The effect of weightlessness on plant morphogenesis

Germination, seedling development, and histological and morphological plant studies during zero-G

Phototropism in plants held at zero-G

Phototropism

Geotropism in plants held at zero-G

Geotropism in plants

Rhetropism in plants

Thigmotropism in plants

Traumatotropism in plants

Galvanotropism in plants

Chemotropism in plants

Hydrotropism in plants

Photosynthesis and plant physiology

A study of photosynthetic action spectra during exposure of alga cultures to true space illumination

Plant physiology

The effect of auxin on plant development in the absence of gravity

Influence of gravitational fields on plant metabolism

Growth and sporulation of fungi

Modifications of growth rate and development due to weightlessness

Evaluation of significance of possible circulatory changes

Zero-G exploration of the functional integrity of the cardiovascular system

Cardiovascular and hemodynamic functions

Study of blood flow in the weightless environment

Effects of weightlessness on cardiovascular and respiratory functions

The effects of weightlessness on the cardiovascular and respiratory systems

Pulmonary blood flow during weightlessness

Respiration problems in orbital vehicles

Gravity dependency of bronchial cilia

Digestive function

Metabolic adaptation to zero-G appropriate dietaries

Experiments with autonomic drugs

The synergistic effect of weightlessness and ionizing radiation on mineral metabolism

Mineral metabolism under the stress of weightlessness and ionizing radiations

Long-term osteoporosis studies

The effect of weightlessness on renal metabolism

Kidney function

Modification of kidney function and water balance due to weightlessness effects on endocrine factors

Kidneys and genito-urinary accessory organs

Endocrine gland function

Steroid and catecholamine levels as a function of weightlessness

Electrocardiographic studies of zero-G effects on the myocardium

Studies of zero-G effects on the nervous component of the cardiac control mechanism

Electroencephalographic studies

Monitoring of electrophysiological performance of the nervous system by neuromyography

Monitoring of neurophysiological, physiological, and performance functions in the primate under prolonged weightlessness

Biopotentials of neural tissues in extended weightlessness

Changes in vestibular nerve activity and vestibular mebry in fractional g loads and prolonged zero-G

The function and dysfunction of the gravity-sensitive organ in zero-G

Effects of weightlessness on the behavior of statocyst-bearing organisms

Senescence phenomena in zero-G

Antibody formation

Effect of weightlessness on immune defenses against pathogenic agent

Effects of weightlessness on immune defenses

Functional and morphological responses to the spacecraft environment by rodents

Effects of weightlessness on gross body composition of the rat

Effects of the space environment on the feeding, survival, and reproduction of Daphinia pulex

Respiratory movements in Amblystoma in a zero-G field

Experimental analysis of animal adjustment in various degrees of gravitational force

Discrimination and communication of animals under zero-G conditions

Long-term animal exposure

9.4.1.2 Biomedicine

General physical examination

Body mass

Exercise test

Voiding evaluation

Body temperature

Body temperature - thermometers or thermistors

Mucosal integrity evaluation

Urine and fecal occult hemorrhage

Incisional healing and bleeding time

Skin thickness

Joint motion range

Vestibular reaction

Bromsulphalein liver function test

Determination of long-term zero-gravity effects on man

Evaluation on conditioning devices and techniques

Liver size

Retinal examination

Centrifuge test

Gas formation and passage

Incidence of aerotitis media

Effects of weightlessness on cardiovascular, respiratory system, renal metabolism and behavioral observations in the primate

Evaluation of changes in microbiological flora of multiman crews during prolonged space flight

Bacteria smears and cultures

Microflora of the astronaut

Long-term occupancy of sealed microenvironments

Respiratory rate

Respiratory volume

Expiratory-inspiratory force

End expiratory pCO_2 & pO_2

Diffusion - end-tidal O_2 and CO_2 measurements

Oxygen uptake and carbon dioxide production

Pulmonary function--various spirometry studies

Cardiopulmonary symptoms

Cardiorespiratory functions of man during prolonged space flight

Pulmonary pathology and heart size

Adaptive cardiovascular responses during prolonged weightlessness

Cardiovascular dynamics in extended zero-G

Blood pressure

Blood pressure - sphygmomanometer (manual or automatic)

Venous pressure & circulation time

Pulse wave velocity

Pulse rate

Heart rate - pulse or cardiotachometer

Blood volume

Blood volume - dye dilution techniques

Venous distension

Capillary morphology

Cerebral blood flow

Cardiac electrical activity & state

Electrical activity of heart - electrocardiography

Cardiac output & heart movement

Cardiac output - indirect Fisk or vibrocardiograph

Peripheral assistance - cardiac output and blood pressure relationship

Heart sounds

Phonocardiography during long stay times in weightless environment

Ballistocardiography during weightlessness

Comparison of the usefulness of the ballistocardiograph and the vibrocardiograph

Evoked electromyography during weightlessness

Muscle activity and state

Muscle activity and contraction sequence - electromyograms

Muscle size

Muscle function

Muscle tone and strength - dynamometry

Glomerular filtration test

Tubular excretion test

Tubular reabsorption test

Capillary fragility

Urinalysis

Urine catecholamine

Urinary albumin

Urine 17, keto-steroids

Urine bilirubin

Urine and fecal nitrogen

Blood and urine analysis - specified determinations

Blood, salivary, and urine delayed analysis

Blood and urine creatinine

Blood and urine chloride

Blood and urine sugar

Glucose tolerance

Blood and urine potassium and sodium

Blood enzyme activity

Hemotological functions of man during prolonged weightless flight

Blood coagulation time

Prothrombin time

Blood osmolarity

Venous pCO_2, pO_2, pH

Complete blood cell count

Eosinophil count

Red blood cell mass

Red blood cell survival

Oxygen uptake by red blood cells

RBC uptake I_{125}

Blood bilirubin

Blood catecholamine

Blood alkaline phosphate

Blood - urea nitrogen

Blood ATP

Hemoglobin and hematocrit

Blood 17, keto-steroids

Stress hormones - 17 keto-steroids, SGOT, catecholamines

Blood plasma protein fractionation

Calcium balance study

Calcium mobilization - blood and urine Ca and PO_4 studies

Kidney & bladder stone formation

Condition of bone - specialized x-ray techniques

Bone density

Disuse atrophy - protein balance studies

Endocrine functions of man during prolonged space flight

Hormone, mineral, and water metabolism

Fluid intake and output evaluation

Total body water

Bowel function evaluation and stool characteristics

Eating habits evaluation

GI absorption test

Absorption - food intake, and fecal analysis

Protein assimilation test

Utilization - food intake, fecal analysis, and urinalysis

Energy requirements

Gastrointestinal tract motility

Pressures and movements of digestive tract - intraluminal transensor

Metabolic functions of man during prolonged space flight

Metabolic rate - oxygen uptake

Nausea - regurgitation evaluation

Hearing

Visual fields evaluation

Color vision evaluation

Visual illusion evaluation

Visual activity, depth perception & accommodation

Reflex response & clonus evaluation

Brain blood flow - rheoencephalogram

State of arousal

Cortical activity

Brain electrical activity - electroencephalogram

Autonomic hyperactivity

Evaluation of superficial sensation

Studies of the galvanic skin response in long-term zero-G

The pathophysiological effects of weightlessness on primates with initial attention to the roles of vestibular organs

The effects of drugs on behavior in space flight

Circadian rhythms in man

9.4.1.3 Bioengineering

Activated sludge in waste management

Zero-G growth chamber

Investigation and analysis of biotic components for life support and ecological systems

Ventilation of respired gases in manned space enclosures

The effects of high vacuum and radiation on bacteria; the effectiveness of various sterilizing agents on organisms in a space environment

The effects of high energy particulate radiation on selected bacterials in particular organic compounds

Biological monitoring of all life-support systems

Biological and chemical decontamination

Toxicological studies of respiratory gases in manned spacecraft

9.4.1.4 Behavioral Biology

Psychophysical effects in the weightless environment

Neurological functions of man during prolonged space flight

An analysis of space-induced neurological phenomena

Monitoring of neurophysiological and performance functions in the primate under prolonged weightlessness

Behavioral observations in the primate

Crew performance potential in the orbital environment

Altered performance baselines during extended weightless flights

Crew performance in orbital and re-entry operations

Study of crew performance and relationships in space

Astronaut in-flight performance

Determination of extent to which man's behavioral responses are predictable with respect to long-duration spaceflight

Emotional measures - standardized tests and interview

Social measures - social distance scales

Attitudinal measures - standardized tests and interview

Motivation evaluation - printed tests materials, ground interviews

Retention of skills learned during weightlessness under conditions of increased acceleration and gravity

Retention of learned skills

Cognitive skills evaluation

Inductive reasoning

Computation

Learned procedure

Learning behavior

Perceptual set

Cue abstraction

Decision making

Evaluation of decision-making processes - responses to mission alternatives

Evaluation of problem-solving processes - printed materials

Problem solving

Association

Drifts in sensory baselines induced by long-term weightlessness

Time perception

Olfaction

Speech & speech perception

Verbal performance - ground and crew monitoring

Effect of weightlessness on auditory discrimination in threshold

Tone pattern discrimination

Tone audition

Sound localization

The fine structure of oculogravic phenomena during prolonged weightlessness

Oculogyral, oculogravic, oculoagravic illusions

Visual orientation - mystagmus tests and axis judgment

Pattern recognition - printed materials

Color discrimination - printed materials

Visual field - visual perimeter

Acuity - eye charts and similar visual stimuli

The effect of long-term weightlessness on visual acuity

The effect of zero-G on visual acuity and depth perception

Near depth perception

Distant static depth perception

Dynamic depth perception

Visual resolution of detail

Brightness detection/discrimination

Color detection/discrimination

Peripheral visual/detection/discrimination

Complex pattern discrimination

Detection of heat/cold

Pain detection

Texture discrimination

Detection of light touch

Vibration detection/discrimination

Kinesthetic phenomena during prolonged weightlessness

Proprioception

Effects of weightlessness on postural mechanisms

Postural reflexes during weightlessness

Modification of reflexes during long-duration exposure to subgravity

Locomotor mechanics in zero-G

Positioning response adaptation during extended weightlessness

Position and orientation judgment

Rotary acceleration judgment

Spatial orientation mechanisms

Cross-hair placement - navigation or star-sighting equipment

Tracking - integrated in rendezvous and docking (control display) system

Visual-motor tracking

Arm/hand/finger reaction time & speed control

Arm/hand/finger manipulation

Muscular coordination - monitoring by crew members or TV-to-ground

Hand-eye coordination - perceptual motor apparatus

Reaction time - switch positioning

Steadiness - special apparatus

Movement discrimination - control displacement

Reach discrimination - control location

Mass handling

Control of force

Force discrimination - weights, inertia, or variable bungee

Detection/discrimination of force against limb

Detection/discrimination of linear & angular acceleration

Plasticity in human sensorimotor control

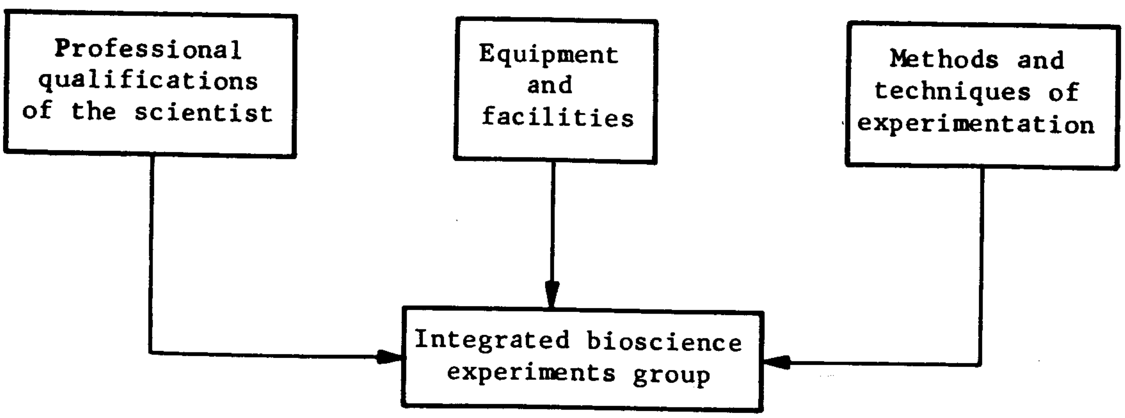
The effects of drugs on mammalian behavior in space flight

9.4.2 Scientific Areas Selected for Detailed Study

Due to the very large number of interesting experiments which were suggested, a decision was made to concentrate on only one of the four areas of (1) bioscience, (2) biomedicine, (3) bioengineering and (4) behavioral biology established during the preliminary screening process. Bioscience was selected as the area for consideration for two reasons. First, it has received less attention than have the other three in the space program thus far. Second, this area is more vitally concerned with basic or fundamental problems than are the other three and, hence, it is important to a greater cross section of the scientific community.

The effort and attention of the study was further concentrated and focused on the more basic areas of bioscience as delineated earlier on the chart in Subsection 9.3.2. Two experiment areas were selected from the cell division and embryology category and one experiment each from the categories of biophysics and cytology, plant morphology and physiology, and microbiology.

In this way, on a given mission, a group of scientists with complementary backgrounds utilizing similar experimental techniques and methods and a relatively small amount of multipurpose equipment and similar facility items would be able to perform a substantial number of related experiments. This relationship between tasks, men, and equipment is shown in the diagram below.



In order to establish a program covering the widest possible range of interests, attention was directed to the nature of the life process and to the diversity of living things. The experiment areas selected as embodying the life process were (1) biological transport - the means by which the life of the cell is sustained and (2) cell division - the mechanism by which life is propagated. Experiment areas encompassing the spectrum of life forms were based on Haekel's concept of three kingdoms: Protista or micro-organisms, Animalia, and Plantae. In each of these three areas, the major emphasis was placed on investigation of the gravitational determination of development, growth, and form.

The extensive list of suggested bioscience experiments presented in Subsection 9.4.1.1 was subjected to the screening and selection process described in Subsection 9.3.2. In addition, numerous discussions with working scientists in the various areas covered by the experiments were of immense help in further refining the original concepts of these experiments. The overall evaluation process, of course, resulted in the deletion of a number of the experiments suggested previously. Many of these were, in themselves, good experiments but were held to be beyond the scope of this study. For example, most of the suggested work on physiology and sensory-motor mechanisms was deleted, not because it was of lesser importance than other areas, but because it was organismal in level of organization and somewhat biomedical in ultimate orientation.

The experiment suggestions which were retained were completely revised and somewhat reoriented. Several were combined with others when it appeared that the original suggestions were, in reality, only separate aspects of a single larger subject area. In the present report, detailed discussions of five such experimental areas are presented.

9.4.2.1 Biological Transport

It seems apparent that a study of the effects of zero-G upon cellular transport phenomena would be of considerable importance since, if weightlessness affects any one of these processes, the overall metabolism of the cell may be severely affected. The modern biological transport hypothesis encompasses a number of mechanisms by which substances cross cell membranes. These may be placed in the following categories: (1) simple diffusion, (2) solvent drag, (3) diffusion restricted by membrane charge, (4) diffusion restricted by a lipid barrier, (5) facilitated diffusion, (6) exchange diffusion, (7) active carrier, (8) pinocytosis and phagocytosis.

It is apparent from the above that the different modes of biological transport involve processes such as diffusion, solvation, thermal agitation, electrochemical gradient, exchange diffusion and energy-yielding reactions. The kinetics of the particular transport process occurring at the cell membrane may be the rate-determining factor. An alteration of any flow system in the transport mechanism of living cells may have profound effects on a unicellular or multicellular system. Microconvectional instabilities have been described in which droplets of liquid form under diffusion and gravity effects and result in material transport. Such effects, if they are truly gravity-dependent, may be so subtle that long-term zero-G flight may be required to demonstrate a gross effect.

9.4.2.2 Cell Division and Experimental Cytobiology

The behavior of the chromosomes and other cellular constituents in both mitosis and meiosis during prolonged zero-G flights is of basic interest, and studies of these processes in the orbiting laboratory will help to answer many of the questions which have been raised regarding the influence of gravity on the basic mechanism of biological continuity. Recent space-flight studies have observed the occurrence of chromosomal aberrations and the fact that zero-G enhances cell development.

The object of this study would be (1) to examine the mitotic process, particularly with respect to chromosomal aberrations, and (2) compare cell division and DNA synthesis at zero-G and one-G.

9.4.2.3 Fundamental Microbiological Processes

Bacteria seem to be a particularly suitable biological system for experimental observation and determination of the gravity dependence of growth rate and mutation rate. There are a number of advantages in studying bacteria. In particular, bacteria have a relatively short generation time (on the order of minutes) so one is able to deal with large populations and many successive generations. Furthermore, bacteria are easy to handle. Finally, bacteria have been thoroughly studied in the laboratory. Growth rate can conveniently be measured by determination of optical density or light scattering of the culture as a function of time.

Russian studies reported in the literature have revealed no significant biological or hereditary peculiarities in micro-organisms exposed to zero-G for 24 hours, but examination of large bacterial populations for spontaneous mutation and other genetic changes should be conducted after longer exposure. In addition to longer zero-G flights, a statistical analysis of the mutation rate should be made. Mutation rate determination of auxotrophic (biochemical) mutants is the easiest and by far the most extensively studied; however, the other types of mutants are also of interest.

9.4.2.4 Experimental Embryology

It has been postulated that embryological development of many oviparous forms would be markedly influenced by a zero-G condition. The gravity-controlled gradient of yolk deposits in the oocyte and developing embryo partially determines which portions of the organism will be ectoderm and which will be mesoderm or entoderm. These, in turn, determine the position and type of organs to be formed. Since gravity controls the yolk platelet distribution in the oocyte, it is also thought to create a concentration gradient of chemical agents which determine the genetic fate of the presumptive ectodermal and mesodermal regions. Cleavage, under normal gravity conditions, always begins at the dorsal pole, where the population of yolk platelets is most sparse. At zero gravity, the first few cleavages may occur at any point on the surface of the fertilized egg. This might lead to the formation of daughter cells of unequal sizes and, subsequently, abnormal development. Embryological studies in zero-G will greatly enhance our knowledge of the mechanisms by which basic physical forces have mediated or modified the evolution of living things.

9.4.2.5 Tropic Responses and Morphogenesis of Plants

It is of major scientific importance to know if zero-G conditions cause grossly abnormal development of the mitotic figures and various aspects of early developmental morphology in plants.

Characteristically, roots show a positive geotropic response and stems a negative geotropic response. Roots are usually negatively phototropic and the leaves and stems are usually positively phototropic.

The mechanism of perception of the phototropic stimulus involves a pigment, whereas the transmission of the stimulus involves the movement of auxins. The method of perception of the geotropic stimulus is believed to be cell inclusions, but the transmission of the geotropic stimulus also involves the movement of auxins.

A geotropic response will not occur in the absence of auxins. If a root is kept in the dark, no auxins appear and there is a failure of geotropic response. The role of auxins at one-G is fairly well known but the role of light and gravity in the growth response of plants needs further elucidation. Study of the behavior of illuminated roots and stems and the movement of auxins at zero-G with variations of direction of illumination will contribute to a better understanding of geotropism and phototropism in plant growth and morphology.

An additional experiment which received early consideration involved study of the influence of gravitational variations on biological rhythms, in particular circadian and circumsynodical rhythms. This subject would seem to be a good candidate for investigation in an advanced zero-G laboratory since the gravitational variation between antipodal points along the earth-sun line due to the influence of the sun is of the order of 1.3×10^{-6}g while the variation due to the influence of the moon is about 3×10^{-6}g. Further evaluation in the light of ground-based data which does not presently seem to exist would be required, however, before a firm decision could be made regarding this potential experiment.

The experiments enumerated above by no means constitute a complete list of experiments that should be incorporated in a manned space laboratory. It will be noted that the bulk of the experiments mentioned deal with cells and fundamental tissues, with their functions and organization, and with certain biochemical and cytological phenomena. Not mentioned were the host of experiments at the complex tissue, organ, organ system, and organism levels of biological organization. It is felt that the experiments included in the above list would be highly desirable for inclusion in the earliest phases of the program and would be followed in logical sequence by others of a more complex and sophisticated nature.

9.4.3 Definition of Selected Experimental Studies

Details of the five experiment areas selected as representing a suitable hypothetical program are presented in the following paragraphs. A treatment sufficiently detailed to satisfy a specialist in any one of these areas must, of course, occupy several volumes. The information offered is, therefore, in the form of a summary of those points most pertinent to the establishment, for planning purposes, of a feasible program of scientific research for an advanced manned space laboratory.

9.4.3.1 Biological Transport Phenomena

Objective

Investigation of the biophysics and chemistry of biological transport phenomena to determine the role of gravity in:

1. Ordinary diffusion mechanisms
2. Restricted and facilitated diffusion
3. Carrier processes
4. Engulfment processes

Other studies in the weightless environment will provide tests of the validity of certain hypotheses, possible identification of additional mechanisms, and a determination of the magnitude of gravitational factors in transport kinetics.

Scientific Background

Any hypothesis of biological transport involves a theory of cell permeability. There have been two schools of thought on the theory of cell permeability: (1) sorption theory and (2) membrane theory. The sorption theory states that the cell permeability and its functional changes are determined by the properties of the protoplasm, rather than the cell membrane. It excludes the possibility of the preexistence of the resting potential. The rejection of the preexistence of resting potentials has led many investigators to question the reliability of the experimental results, thus causing investigators to adopt the membrane theory in its various modifications. According to the membrane theory, the preexistence of the resting potential is indisputable and forms the basis for a number of assumptions associated with the problem of cell permeability. The membrane theory of cell permeability, accepted in various forms by many physiologists, biochemists, and biophysicists, states that enzymes and catalytic carriers in the membrane can bring about the active transport of substances against their concentration gradient.

Modern biological transport theories which, on the basis of experimental evidence, are accepted by most modern workers, encompass a number of mechanisms by which substances cross cell membranes. These fall into the following categories:

1. Simple diffusion - an example is the diffusion of water into and out of most tissue cells
2. Solvent drag - frequently used example is thiourea movement in association with osmotic water flow in the toad skin
3. Diffusion restricted by membrane charge - chloride ions, for example, are permitted to flow through positively charged aqueous channels which exclude cations
4. Diffusion restricted by a lipid barrier - experimental evidence correlates the lipid-water coefficients with membrane-penetration rates in many nonelectrolytes
5. Facilitated diffusion (or mediated transport) - the most studied case is glucose transport in erythrocytes
6. Exchange diffusion - according to this concept, the carrier can cross the membrane only in a complexed form
7. Active carrier transport - the participation of an energy-yielding reaction is required to enable the cell to accumulate metabolites, to excrete unwanted substances, to develop membrane potentials, and to maintain a normal cell volume

8. Pinocytosis and phagocytosis - according to these concepts, the cell membrane develops invaginations, thus pinching off engulfed substances as intracellular vesicles. Pinocytosis engulfs smaller molecular aggregates than does phagocytosis.

It is apparent from the above that the different modes of biological transport involve processes such as diffusion, solvation, thermal agitation, electrochemical gradient, exchange diffusion, and energy-yielding reactions. The kinetics of the particular transport process occurring at the cell membrane may be the rate-determining factor.

Movement of cytoplasm within the cells of plants and animals is a commonly known phenomenon. Diffusion is too slow a process to be the transport mechanism for solutes from one part of a cell to another, and active cytoplasmic movement provides a rapid transport mechanism. Two types of cytoplasmic movement which appear to function as mechanisms of biological transport within cells are amoeboid movement and protoplasmic streaming.

Amoeboid movement is a form of protoplasmic motion accompanied by changes in cell shape, by the extension of pseudopods, and often by progressive motion. This type of movement is characteristic of a number of types of cells, particularly of certain protozoa. Amoeboid motion is generally believed to proceed according to the following scheme. The peripheral cytoplasm, which is in a gelated condition, will revert in a local area to the sol state, allowing the cytoplasm to flow outward as a lobe known as a pseudopodium.

Streaming may proceed in a fixed path and may be rapid enough for direct microscopic observation. Cyclosis, which is essentially a flow of cytoplasm around the vacuoles of some types of plant cells, is of this type. Although cyclosis was first described by Corti in 1774, research spanning nearly 200 years has, as yet, failed to successfully produce a theory to completely explain the phenomenon. Some workers have invoked electric or electromagnetic forces, while others have studied streaming in a magnetic field. Perhaps the most interesting result obtained to date is the fact that electrical currents as small as 3×10^{-8} amperes have caused temporary cessation of cyclosis. In other cells, streaming may be slow and may be more of a churning than a fixed-path current. Churning-type movement is readily observed in tissue cultures of fibroblasts. The effects on streaming of a variety of environmental factors have been examined, but the molecular mechanisms remain unknown.

Scientific Justification

A great deal of knowledge has been amassed in recent years regarding the basic elements of the life process. As one of these basic elements, biological transport represents the means by which the individual existence of the fundamental unit of life is sustained. Much information has been obtained which bears on a wide range of physical and chemical problems involved in biological transport processes since the advent of (1) sophisticated modern optical and electronic instrumentation, (2) radioisotopically labelled compounds and (3) electron micrography of ultrathin tissue sections.

Transmembranal transport is the mechanism by which all nutrients pass into and all wastes pass out of the cell. Hence, any force which might control or alter the nature or function of the membrane requires investigation. In like manner, because cytoplasmic movement is important in the transport of solutes within the cell and as a means of locomotion in many unicellular forms, a study of the influence of gravity upon the mechanisms and rates of various types of cytoplasmic flow is important. Two types of cytoplasmic movement which appear to be particularly interesting for such a study are ameboid movement and cyclosis.

Since so many of the transport processes involve fluid mechanics and chemical kinetics considerations, and in view of the fact that gravitational effects in these areas can be analyzed in mathematical detail, it is believed that zero-G studies in these areas will contribute to a significantly deeper understanding of the transport process generally.

Because the entire well-being of the organism depends so completely upon them, a better understanding of the physico-chemical processes underlying transport phenomena is required for the development of predictive theories which will support work being done in other areas.

Practical Justification

It is apparent that a study of the effects of zero-G upon cellular transport phenomena is of considerable practical importance since, if weightlessness effects any one of the above mentioned processes, the overall metabolism of the cell may be affected.

Method

Biological transport studies may employ either resting cells (that is, cells which are metabolically active but not multiplying) or cells harvested from exponentially growing cultures, and may conduct uptake studies during subsequent one- or two-generation development in a suitable medium. A large number of micro-organisms and the uptake of various compounds have been investigated. Some classical studies have used yeast cells and *Escherichia coli*. A study involving a strain of yeast demonstrated the transport of nonfermentable sugar across the yeast cell membrane. It was shown that sorbose and alpha-methyl-D-glucoside-D-Mannoside were not absorbed. The uptake characteristics may vary from one strain of yeast to another. It is important, therefore, to conduct controls on the ground. Another test examines uptake of Mn^{2+}, amino acids, and carbohydrate by *E. coli*, utilizing radioisotopically labeled compounds.

Exponentially growing cells are harvested, washed, and resuspended in a suitable buffer solution containing the substance under investigation. The mixture is incubated for a period of time, filtered through a Millipore filter, and the radioactivity of the filter pad holding the micro-organisms then is measured.

Phagocytosis and pinocytosis are similar in their process of imbibing droplets of liquid or particulate matter by an invagination of the cell membrane which is then pinched off as an intracellular vesicle. Pinocytosis differs from phagocytosis in the nature and size of the material that is taken in by the cell. Phagocytosis engulfs solid material while pinocytosis is a process of "drinking" by cells. These processes are well demonstrated by phase contrast study of *Amoeba proteus*. In addition, monocytes may also be used for study. Few difficulties are anticipated in the experimental procedure. The equipment required will consist of small culture vessels and a suitable microscope for making observations with perhaps the addition of the necessary apparatus for time-lapse photography. Aeration of the micro-organism cultures can be readily accomplished through a polyethylene membrane in the vessels, since the oxygen requirements of the culture will be quite small. Further details of the experimental procedures required to study phagocytosis and pinocytosis will be specified at a later time.

Although biological transport is discussed above in reference to micro-organisms, the uptake of ions and metabolites by erythrocytes and tissue cells may be affected differently. An alteration of any flow-system in the transport mechanism of living cells may have profound effects upon a unicellular or multicellular system. Zero-G studies in man, animal, and other biological systems have demonstrated the occurrence of physiological and cellular variations. However, the observed changes are not specifically attributable to the weightless condition. One extremely promising approach deals with the role of gravity forces in producing instabilities in fluid convectional flow. Microconvectional instability has been observed in which droplets of liquid form under diffusion and gravity effects and result in material transport. The process has been demonstrated in a stable-layered flow system and used to transport lysozyme rapidly from one layer to another. It is suggested that this transport mechanism may have considerable biological significance. Such effects, if they are truly gravity-dependent, may be so subtle that long-term zero-G flight may be required to demonstrate a gross effect. The cells of choice for study are erythrocytes and/or animal tissue cells. The cells should be grown in an appropriate medium under suitable conditions and the uptake studies performed with radioisotopically labeled compounds. After exposure to the compound or ion in question, the cells may be collected on a Millipore filter and the radioactivity measured.

In a study of cyclosis, or protoplasmic streaming, the cell of choice would be obtained from the common alga *Nitella*. In view of its remarkable sensitivity to electrical effects, *Nitella* would seem to be a particularly interesting type of cell to use in zero-G investigations of cyclosis.

Culture of *Nitella* in the orbiting laboratory can be accomplished in vessels similar to those utilized in other experiments. The only difficulty may be in transferring cells of this aquatic plant from the culture vessel to the microscope examination chamber without introducing droplets of fluid into the cabin atmosphere.

Lipase action requires that the enzyme react with the substrate at an oil-water interface. It can also react at a water/solid interface; for example, an aqueous suspension of fluorescein diacetate. Kinetic studies under zero-gravity conditions may yield data demonstrating the effects of zero-gravity upon macromolecular reactions. Its stability in aqueous solutions and at elevated temperature makes lipase an attractive system to study. In addition, it is capable of hydrolyzing the acetate moiety of fluorescein diacetate. The resulting water-soluble fluorescein is readily visible and can be measured on a spectrophotometer. An oil emulsion and suspension of fluorescein diacetate in a suitable buffer are reacted separately with a solution of lipase. Samples are removed for the determination of hydrolytic products at predetermined time intervals.

Instrumentation and Apparatus Required

The following pieces of equipment will be required to accomplish the various tasks in the above experiment:

1. Light-scattering photometer
2. Optical densitometer
3. Compound microscope with phase-contrast optics and photomicrography attachments
4. Movie camera with time-lapse capability
5. Plate camera
6. Polarograph
7. Spectrophotometer
8. Centrifuges at various G levels for controls
9. Fluid-transfer equipment
10. Radiation counters
11. Isotope-handling equipment
12. Dissecting microscope
13. Special filter apparatus
14. Specimen culture vessels
15. Refrigerator
16. Electron microscope (tentative)
17. Incubators
18. Automatic cell counters

Spacecraft Facility Requirements

The following have been definitely identified as requirements but should not be construed as a complete listing:

1. Isotope laboratory
2. Cytology and histology facility
3. Instrumentation bench
4. Microscopy and photography bench
5. A very small animal maintenance station

Scientific Crew Requirements

One full-time biochemist-biophysicist assisted by a 1/4-time wet lab technician will be sufficient to accomplish the experiment.

Estimated Data Output

20,000 feet of strip-chart records

30 lab notebooks

400 hours of magnetic instrumentation tape.

9.4.3.2 Cell Division and Experimental Cytobiology

Objective

Investigation of the effects of gravitational forces on (1) the mitotic apparatus and process, particularly with respect to chromosomal aberrations and (2) the cell-division cycle and DNA synthesis. A corollary investigation will determine the role of gravity in cellular differentiation and the metabolic aspects of cell growth and division.

Scientific Background

In the process of cell division, there occurs a period of DNA synthesis, followed by a subsequent division of DNA material and cell, resulting in two diploid cells. Mitosis, or the division process proper, occupies a fairly small fraction of the total division cycle. The mitotic process itself is divided into four stages, namely: prophase, metaphase, anaphase, and telophase. The rest of the division cycle is referred to as interphase and is divisible into three periods. The first of these is the post-mitotic period followed by a period of active DNA synthesis, after which there is a premitotic period before the next division. During the premitotic, mitotic, and post-mitotic periods, no DNA synthesis occurs. The entire division cycle and its various phases typically occur in a characteristic amount of time, depending upon the species and a complex of environmental factors.

Scientific Justification

Cell division and the synthesis of genetic material is the source from which the sustained flow of biological continuity derives. Studies of these processes, which are the basic mechanisms in the propagation of life, are of fundamental interest and importance in the biological sciences.

Clearly, the development of life forms on earth has been strongly influenced by the earth's gravity. At the same time, the diversity of living things is a result of cellular differentiation. Therefore, the behavior of the chromosomes and other cellular constituents in the synthesis and division of the basic materials of life is, without doubt, the most uniquely basic subject in biology. Experimentation in the weightless environment of space will provide a unique opportunity to seek answers to several of the problems central to this subject.

Practical Justification

In spite of the unforeseen difficulties which may arise in the interpretation of results, considerable insight into the long-term zero-G effects upon man can be gained from studies at a cellular level. Some considerations which indicate the advantages of studying processes at the cellular level are: (1) animal, and in particular, human, cells can be propagated in vitro; (2) cells can be observed and photographed during the study; (3) cells can be chemically fixed at appropriate stages for further observations, e.g., electron microscopic or cytochemical examination; and (4) tissue culture requires comparatively very little space. However, such experiments will require a scientist to be highly experienced in working with tissue culture, phase-contrast microscopy, and histological techniques.

Russian space flight studies have observed the occurrence of chromosomal aberrations and the fact that zero-G enhances cell development. The fact that accelerated cell development is, in part, analogous to cancer cell growth has important implications and, therefore, warrants a thorough investigation in this respect. Furthermore, if cell development is accelerated, there may be a consequent increase in metabolism during long space flights.

Feasibility

The feasibility of experimentation of the kind used in these studies is very high since most of the apparatus is of small size, light weight, and modest power requirements. The various specimens, while somewhat delicate, have requirements which can be readily met in the design of the spacecraft. In addition, a very large number of excellent experimental techniques now exist so the program would be able to utilize but would not be dependent upon major technological breakthroughs.

Method

Virtually all of the various experimental operations and observations contemplated here utilize some form of tissue culture or cell culture. The major problem is selection of the best and most useful from among the vast array of excellent techniques which currently exist in the field.

Certain specimens particularly recommend themselves and have tentatively been selected for some phases of the experiment. Cell strains with a diploid karyotype, such as strain-L mouse cells and the Don strain of Chinese hamster lung, are especially well suited to the study of mitosis, division cycle, and DNA synthesis. Chick fibroblast is also useful in many studies. Human placental cells are included because of their excellent growth characteristics. HeLa cells have been extensively studied and are, hence, perhaps the most useful heteroploid strain. Protozoans, because of their size and the ease with which they may be manipulated and injected, will be utilized extensively in many of the studies. Sea urchin eggs, because of the vast amount of work done with them, will also fill a prominent role.

Some of the methods and procedures which follow are planned for use in initial portions of the experiment with other types to be selected subsequently. Tritium labeled thymidine will be employed to follow the mitotic process by means of autoradiography. Observations will be made of the influence of gravitational forces on chromosomal distribution in the presence and absence of inert cellular inclusions. Studies will be conducted of the effects of distributions and gradients of inert inclusions on the mitotic apparatus, particularly in relation to the functional mechanics of the spindle fibers and time sequence of events.

Studies also will be made of the effects of zero-G on spindle orientation in appropriate specimens. While the preponderance of animal tissues do not exhibit this condition, the distal portions of rapidly growing plant roots show very strict orientation of mitotic spindles. This study would examine the relative influences of physical forces and biochemical mediators as well as coupling phenomena in order to better understand the significance and effects of spindle orientation on growth and form. In addition, observations would be made concerning the effect of intracellular chemical concentrations and gradients on cell division and the mitotic apparatus.

It will be extremely important to control variables such as vibration, thermal energies, electromagnetic energies, particulate radiation, and acceleration-deceleration effects. Ground-based controls should be exposed to as nearly identical an environmental regime as is possible to minimize uncertainties in the results.

Instrumentation and Apparatus Required

The following list covers the major items required in the initial phases of the experiment:

1. Compound microscope with multiple beamsplitter, phase-contrast optics, cinecamera attachments, plate camera attachments, and video camera
2. Long-working-distance, stereoscopic, "dissecting" type microscope with stereocamera attachment
3. Movie camera with shutter-speed control for time-lapse photography
4. Plate camera
5. Roll-film camera
6. Video camera
7. Stereo camera
8. Micromanipulators (preferably of the Ellis piezoelectric type)
9. Incubators and other special thermal environment chambers
10. Isotopic tracer equipment
11. Ultraviolet and fluorescence microscopy equipment
12. Special zero-G culture vessels for propagation of specimens
13. Tape recorder for dictating notes while making observations
14. Centrifuges for control samples
15. Lead (or other dense material) "safes" for radiation protection of specimens
16. Automatic cell counters
17. Scanning microscope

18. Optical densitometers
19. Centrifuge for gas-liquid phase separation
20. Ultrasonic generator and special transducers
21. Special light sources
22. Freezer
23. Lyophilizer
24. Refrigerator

Spacecraft Facility Requirements

This experiment imposes relatively modest requirements on spacecraft design insofar as workspace and utilities are concerned. The following features will be required:

1. "Wet lab" for culture preparation and general chemistry operations
2. Photographic processing facility
3. Instrumentation bench (may be located in wet lab area)
4. Isotope and autoradiograph lab and darkroom

Minimum useful G levels have not yet been established. Very long flight durations will greatly enhance the meaningfulness of the data due to the opportunity to propagate cultures for many cell generations.

Scientific Crew Requirement

One combination cytologist - cell physiologist with 1/4-time assistance of a histologist, plus a 1/2 to 3/4-time wet lab technician will be adequate to perform the experiment.

Estimated Data Output

1 million frames of 16 mm film
10,000 frames of 35 mm roll film
35 hours of magnetic tape
15 lab notebooks
1000 feet of strip-chart paper
500 histological slides
250 radioautographs

9.4.3.3 Fundamental Microbiological Processes

Objective

The objective of this experiment is to investigate the following four aspects of the microbiological life process as they relate to gravitational forces:

1. Determination of the growth rate in a weightless environment.
2. Study of the mutation rate due to zero-G acting alone and synergistically with radiation.
3. Elucidation of the induction and reversion of L-forms of bacteria (with the consequences to long-term zero-G operations forming a subsidiary portion of the study).
4. A study to investigate the effects of prolonged weightlessness and radiation individually and synergistically on the lysogenic processes in bacteria.

Scientific Background

Microbiology is the study of life processes in unicellular organisms. Several microbiological processes which may exhibit a dependence upon the strength of the gravitational field have been considered and are discussed below.

It is not necessary to present a discussion of the scientific background of microbiological growth and mutation studies since these subjects are well covered in any good textbook.

L-forms of bacteria are aberrant forms of bacteria which lack cell walls. They may be isolated from diseased tissue or may be inducted by subjecting normal bacteria to adverse conditions. For example, chemical induction can be achieved through the addition of penicillin, antiserum, or bovine serum. Very similar to the L-forms, though considered different by some investigators, are the pleuropneumonia organisms (PPO) and pleuropneumonia-like organisms (PPLO) which have been placed in the family Mycoplasmataceae. The organisms are pleomorphic, soft, and fragile, and are either pathogenic or saprophytic. Another feature of both the L-forms, and PPO and PPLO, is their ability to form filterable elementary bodies.

The classification of the L-form and Mycoplasma is, at present, a matter of conjecture. Some workers believe the two forms of bacteria to be quite dissimilar and that they should, therefore, be placed in two distinctly different groups. Other workers are of the opinion that the wide variation in nutrition requirements, osmotic changes, chemical compositions, and enzymatic activity could be attributable to strain differences, and hold that the key to establishing the similarity or distinction of L-forms and Mycoplasma appears to lie in the enveloping membrane, and urge that more strains of both types of organisms be examined by physical, chemical, and immunochemical techniques.

The role of the L-forms in nature is controversial. One point of view regards the L-form as a normal phase in a life cycle, whereas another point of view regards the L-form as a response to a harmful environmental influence. The fact that L-forms can be produced by (1) aging, (2) induction by penicillin, and (3) induction by antiserum and complement, and by bovine sera and/or glycine, inclines one toward the latter hypothesis. L-forms have been isolated from animal and human blood and tissue. L-forms obtained from group A Streptococcus and its isolation from tissue indicates that the body may harbor the L-forms. L-forms are insensitive to antibiotics and are seemingly nonpathogenic. Patients receiving penicillin for streptococcal infection are known to experience a recurrence of streptococcal infection when penicillin treatment is terminated, thus suggesting the formation of L-forms upon treatment and a reversion to the normal form upon removal of penicillin. In addition, coagulase-positive staphylococcal strains, when grown in the presence of penicillin G and/or its synthetic analogues, have been reported to produce L-forms. The above organisms in their natural state are pathogenic; however, their L-forms are seemingly nonpathogenic.

It has been suggested that subcutaneous pustules may be an example of L-form reversion to the normal pathogenic form.

The phenomenon of lysogeny has played a central role in the study of bacteriophage. Lysogeny is the production of lysis and refers to the propensity of bacterial strains to produce a bacteriophage capable of lysing other bacterial strains. Lysogeny is a genetic phenomenon which can be acquired by infection with a virus.

The following properties are characteristic of lysogeny:

1. In a lysogenic culture lysogenesis is a property of every cell and every spore.
2. Bacteria of a lysogenic culture generally absorb the mature phage produced by the culture, but are not damaged by it.
3. Lysis of lysogenic bacteria by enzymes, by other phages, or by mechanical means does not liberate mature phage particles. The intracellular phage in lysogenic bacteria is noninfectious; it is prophage.
4. Infection of a susceptible bacterial culture by a temperate phage may result in the conversion of a considerable proportion of the bacterial cells to the lysogenic condition, potentially capable of liberating the same kind of phage that was used to infect them.
5. Lysogenic bacteria can multiply without liberating mature phage and can undergo many cell divisions in the absence of external phage without losing the lysogenic propensity.
6. Lysis of single lysogenic bacterial cells - either spontaneously or after a characteristic latent period following induction - is accompanied by the release of many mature phage particles. Lysogeny is potentially lethal to the bacterial cells.

The Russians have reported that the lysogenic bacteria, Escherichia coli K-12 (λ), responded to the action of very low doses of ionizing radiation, as low as 0.3-0.5 r. This is the first biological system reported to respond demonstrably to such low levels of radiation.

Scientific Justification

Bacteria seem to be a particularly suitable biological system for experimental observation of the gravity dependence of growth rate. There are a number of advantages in studying bacteria. In particular, bacteria have a relatively short generation time, so one is able to deal with large populations; they are easy to handle; and they have been thoroughly studied in the laboratory. The biological growth rate may be expected to depend upon the gravitational field. It would not be surprising to observe a decrease in the growth rate in zero-G since nutrient availability and waste elimination processes at the cellular level are probably somewhat impeded. The extent of the reduction remains speculative at present.

The Russians have attempted to determine the causes of germ cell mortality in Drosophila following space flight and also the effects of space flight on microspores of Tradescantia paludosa. In unmanned Russian spacecraft, bacterial cultures maintained in the weightless state for up to 24 hours displayed no significant biological or hereditary peculiarities. No specific effects were discussed in the available reports. However, related studies indicated that the genetic mechanism may be affected by weightlessness.

Since the Russian studies revealed no significant biological or hereditary peculiarities in micro-organisms exposed to zero-G for 24 hours, examination of large bacterial populations for growth characteristics and spontaneous mutation and other genetic changes should be conducted after longer exposure. In addition to longer zero-G flights, a statistical analysis of the mutation rate should be made.

The behavior of L-forms *in vitro* and/or *in vivo* under prolonged zero-G conditions may reveal interesting data on growth rate and pathogenicity and, in addition, may elucidate the nature of the role of L-forms.

Study of lysogenecity provides an opportunity to study the behavior of certain macromolecular phenomena in a very simple living system. The observation of effects of physical forces such as g forces will be made easier since lysogeny involves destruction of the integrity of the cell membrane, gross changes in the character of the protoplasm, and release of "macromolecules" with molecular weight of the order of 2×10^8, radii in the neighborhood of 0.04 microns and densities in the vicinity of 1.5. Other interesting aspects of this study include the genetic property of the phage and the similarity in the relationship between virology and genetics.

Practical Justification

Studies of micro-organisms in the weightless environment contribute very directly to our understanding of the factors governing the evolution of life in nonterrestrial as well as terrestrial environments. In addition, these studies should provide basic information on the relationship between man and microbiological forms which may find direct application to the engineering of life support systems for space flights of longer duration.

Feasibility

Microbiological studies have extremely high feasibility for performance in the space environment because so much valuable data can be obtained with a relatively small volume of compact equipment and uncomplicated manipulative techniques.

Method

Escherichia coli strain B is a particularly suitable strain for study in a space laboratory since it can be grown easily in a chemically defined medium or a complex mixture of organic nutrients such as amino acids, vitamins, etc. Furthermore, the culture medium may have a wide range in composition and concentration. E. coli can be grown in a chemically defined medium contained in either a chemostat or a container specially constructed for use under zero-G conditions. The commonly used device known as a chemostat (which may be described as a continuous fermentation system) will, of course, require adaptation for space use. Stirring and aeration must be accomplished in zero-G. It may be more desirable to grow the organism under anaerobic conditions, in which case the nutrient medium need not be agitated or aerated. Some development work will be required to determine a suitable method for growing E. coli in the zero-G environment.

Growth rate is measured by optical density determinations of the bacterial suspension as a function of time. It is important that the suspension be homogeneous at the time of optical density reading. Sampling from the chemostats without disturbing the mixture may not yield representative samples, particularly if the mixture is not homogeneous. An alternative method is to use replicate sets of tubes containing growing bacterial cultures which are sacrificed at the predetermined time.

A standard method for determining mutation rates of bacterial suspensions should be adopted for use both in flight and in supporting ground work. In flight, the bacterial suspensions will be taken from growth vessels at various times and should be allowed to propagate for as many generations as possible. Mutation rate determination for auxotrophic (biochemical) mutants is probably the easiest and by far the most extensively studied; however, the other types of mutants also are of interest. The calculations of mutation rate under ideal conditions requires the fulfillment of at least three conditions. First, a large population should be surveyed. Second, there should be an insignificant rate of back mutation, i.e., less than the experimental error of counting (or else there should be an accurate measure of back mutation). Third, the mutant and parent types should be able to coexist equally.

A suitable method for determining mutation rates utilizes the following:

1. Small and equal quantities of inocula which are transferred to a series of tubes containing only a small volume of nutrient broth.
2. The tubes are incubated until growth is completed, whereupon the number of organisms within each culture is determined by some convenient means (Coulter Counter or standard plate count).
3. The contents of each tube are then transferred to a selective and/or differential medium on which mutants will be distinguishable from the parent type.
4. Mutation rates are calculated from the percentage of tubes showing the absence of mutants and the average number of bacteria present in the tubes in the following way:

Let p_o represent the fraction of tube cultures in which no mutants appear, N the average number of bacteria in the cultures at time t when the contents of the tube were transferred to the selective medium and ln natural logarithms, then

$$\frac{-\ln p_o/N}{t}$$ is an estimate of the number of mutations per bacterium per unit time

$$\frac{-\ln p_o}{N}$$ is an estimate of the number of mutations per bacterium per division

$$\frac{-(\ln 2)(\ln p_o)}{N}$$ is an estimate of the number of mutations per bacterium per division cycle

In the above method, a small amount of inoculum is employed to seed each of the tubes in the series in order to reduce the chance for accidentally including a mutant in the inocula.

Since the method provides an estimate of the number of cultures which show mutants, the addition of a mutant to any tube in the series would bias the estimate of the mutation rate and yield a value higher than the true one. The purpose in using only a small amount of medium (0.1 to 1 ml.) in each culture tube is to avoid the possibility of mutation occurring in all or most of the tubes, a likelihood which is increased with an increase in total population (absolute number of organisms in a tube).

From the nature of the method it is obvious that the reliability of the estimate of the number of mutations is increased by employing a larger number of tubes. In this regard, the statistical problems of the method are similar to any method of estimate based on a most probable number determination. A further limitation is the ability to observe experimentally all of the mutations which do occur.

The production of L-forms may be initiated by the presence in the media of salts, amino acids, sera, antibiotics, etc. For example, L-forms of a number of bacteria, some of which include Salmonella, Shigella, Flavobacterium Haemophilus, Enterobacterium, gram-positive spore-formers, and Streptobacillus, have been induced by penicillin. The suitable concentrations have to be found by trial, and a procedure suitable for every organism must be resolved independently. In most cases, frequent transfers of the transformed growth from the initiating medium are required for the establishment of L-forms.

The L-form growth and/or morphology cannot be demonstrated in the visual bacteriological smear preparation. Special techniques have been developed for the demonstration of L-colonies. For example, the agar fixation technique of Kleineberger Nobel is especially useful for the demonstration of L-colonies and bacterial growth. The method essentially involves (1) incubation of inoculated agar on a sterile coverslip, (2) fixation with Bouin's fixative and removal of agar, (3) washing and staining with Giemsa solution (1:50) and, (4) microscopic examination. The phase-contrast microscope may be used to follow the growth of the L-forms.

Lysogeny studies routinely utilize the agar layer method for plating bacterial viruses to estimate the numbers of phage particles and/or lysogenic bacteria. The method essentially involves the following: a mixture of host bacteria and phage particles of appropriate numbers mixed in a small volume of warm 0.7-percent agar is poured over a surface of an ordinary agar plate and allowed to harden. The plate is then incubated and the bacteria will grow as tiny subsurface colonies and receive nutrient from the deep agar layer of 1.5-percent agar. The plaques, which constitute phage infection, appear as clear holes in the opaque layer of bacterial growth. The dark field colony counter is a good device for data collection and observation.

Instrumentation and Apparatus Required

The following items comprise the bulk of the major equipment required by the experiment:

1. Automatic cell counters
2. Light-scattering photometer
3. Optical densitometer
4. Automatic plate-scanning counter
5. Spectrophotometer
6. Polarograph
7. Special culture-observation vessels
8. Special filter apparatus
9. Fluid transfer equipment
10. Refrigerator
11. Freezer
12. Centrifuges for control specimens
13. Centrifuges for solid-liquid-gas phase separations
14. Ultrasonic generator and transducers

15. Electron microscope
16. Compound microscope with complete phase-contrast, dark-field and polarizing optics
17. Incubators
18. Ultraviolet and fluorescence microscopy equipment
19. Thermal environment chambers
20. Special zero-G culture vessels
21. Roll-film camera with special closeup attachments
22. Lead "safes" for radiation protection of sensitive control specimens and seed cultures
23. Tape recorder
24. Time-lapse camera with beamsplitter and closeup optics for recording progress of plate cultures
25. Special light sources
26. Lyophilizer
27. Dark-field colony counter

Spacecraft Facility Requirements

As currently conceived, the above experiment will have a requirement for the following:

1. A microscopy and photographic work station
2. An instrumentation bench and work station
3. Cytology laboratory facilities
4. A "wet lab" area for culture preparation and maintenance
5. Limited photography processing facilities
6. Sterilization facility

Scientific Crew Requirement

One microbiologist assisted by a full-time chemical-bacteriological technician will be adequate to perform the study.

Estimated Data Output

30 lab notebooks

5000 feet of strip-chart records

200 hours of magnetic tape

2500 cytologic preparations

200 vials of lyophilized specimens

9.4.3.4 Experimental Embryology

Objective

These studies will investigate the role played by gravity in the development of metazoans. Among the developmental features of interest are cleavage, subsequent differentiation of the basic germ layers, and tissues. The exact mechanisms by which gravity can act as a primary inductor will be investigated. In order to determine the significance of gravitational forces in the evolution of higher animals, the morphogenesis and development in organisms representing a variety of embryological modes will be investigated.

Scientific Background

Through many years of study, the details of normal embryology of an enormous variety of organisms has been elucidated. In addition, through experimentation and studies of abnormal development, some of the causal mechanisms of development have become well understood. One of the most interesting and fundamental sets of principles thus derived is that which is commonly referred to as the "rules of cleavage" which state that:

1. The mitotic spindle is centered in the cytoplasmic mass of the cell but may or may not be centered in the cell as a whole, depending upon the amount and distribution of yolk or other inert material present.
2. The orientation of a cleavage spindle is determined by the longest axis of the cell's cytoplasmic mass.

3. The plane of cleavage lies at right angles to the spindle and hence to the long axis of the cytoplasmic mass.
4. The rate of cleavage is directly proportional to the concentration of the cytoplasm (or inversely related to the concentration of yolk).

These rules, though not yet properly tested under the appropriate conditions, are believed to hold for zero-G since no theoretical arguments have been advanced challenging their validity.

It has been postulated that embryological development of many oviparous forms would be markedly influenced by a zero-gravity condition. The gravity-controlled gradient of yolk material and inert cellular inclusions in the oocyte and developing embryo holds great significance for the entire course of development of the individual, especially in eggs with any appreciable amount of yolk, since at early cleavage stages the developmental fates of future tissues are largely determined. The differentiation of tissues, in turn, determines the position and type of organs to be formed. It is not known at what point in development gravity ceases to play a major role in the induction and differentiation of many animals.

Scientific Justification

Understanding the role played by the fundamental physical forces in the evolution and development of different kinds of living organisms is one of the cornerstones of natural science and is, by itself, sufficient justification for undertaking this experiment. In addition, important insights may be gained into the possible evolution and development of living organisms in extraterrestrial locations with gravitational environments very different from our own.

Practical Justification

A potentially important practical justification involves the possibility of transport, propagation and culture of a wide assortment of living organisms on extended space flights for a variety of reasons including use as a food source. Due to the nature of their embryological development, many of these species would probably be highly susceptible to developmental abnormalities in zero-G environments. It is important, therefore, to determine the kind and extent of these abnormalities as well as their practical consequences.

Feasibility

There are no known phenomena or reasons which would limit the feasibility of an experiment of the kind contemplated here.

Method

Since there are many aspects of embryological development that should be examined, it will be necessary to utilize a variety of species representing the various characteristics of interest. Among the features of greatest initial interest are:

1. Studies of spiral and radial cleavage
2. Comparison of mosaic and regulative development
3. Use of typical miolecithal, medialecithal, and megalecithal eggs as well as intermediate cases to establish developmental patterns based on variable amounts of yolk and other inert material
4. Investigation of holoblastic and meroblastic cleavage patterns

The following chart shows the distribution of the above embryological characteristics among a variety of specimen types which are suitable for use in this study:

Phylogenetic Group	Cleavage Pattern		Type of Egg			Development Type		Cleavage Type	
	Radial	Spiral	Miolecithal	Medialecithal	Megalecithal	Mosaic	Regulative	Holoblastic	Meroblastic
Coelenterates			+				+	+	
Ctenophores						+		+	
Annelids		+		+		+		+	
Arthropods		+			+				
Molluscs		+		+		+			
Echinoderms	+		+				+		
Tunicates	+					+			
Fish	+				+				
Amphibia	+			+			+		
Reptiles	+				+				+
Birds	+				+				+

The exact species selected for each portion of the experiment will, of course, depend upon a number of factors, but in general they will be species which have been extensively studied previously on the ground.

It will be noted that the development of most of the groups listed takes place in an aqueous environment. Practically all of the rest, mainly bird and reptile eggs, have a common requirement for an atmospheric environment. Thus, essentially only two main kinds of experimental procedures and apparatus should suffice for culture and observation of specimens.

The following are some of the planned initial studies. These early observations will utilize amphibian material since the abnormal as well as the normal embryonic development of the amphibian has been so thoroughly studied. Any deviation from the norm in embryos developing in a zero-gravity laboratory would, therefore, be readily detectable.

1. A study to determine the site of origin of cytokinesis in the fertilized oocyte. The appearance of the first three or four cleavages are observed with a hand lens or a simple dissecting microscope. Under conditions of zero-gravity, the yolk platelets should be rather equally distributed instead of showing the normal gradient. The first two cleavages, under normal gravity conditions, are meridional, always beginning at the dorsal pole where the population of yolk platelets is most sparse. At zero-gravity, the first few cleavages might occur at any point on the surface of the fertilized egg. This might lead to the formation of unequal sizes of daughter cells and, subsequently, abnormal development.
2. A study to determine the relative effect of gravitational forces at different stages of development. Frog eggs are fertilized in both the ground and the gravity-free laboratories. The rate of development of those fertilized on the ground are controlled by thermal methods. By maintaining experimental specimens in centrifuges, zero-gravity is imposed at certain critical stages of development, e.g., invagination of the dorsal lip of the blastopore, formation of the neural plate, induction and differentiation of the lens of the eye, etc. The developing embryos are photographed in life and then fixed for subsequent sectioning procedures.
3. A study of the influence of yolk distribution on gene action and differentiation. Oogenesis is allowed to take place in zero-G in female frogs which are then induced to ovulate by pituitary-extract injections. The eggs are fertilized, and then as the developing embryos reach the

blastula, gastrula, and later stages, they are examined, harvested from their gelatinous matrix, photographed, and fixed for subsequent histological examination. Sections from the blastula stage would show the relative amount and position of the yolk-laden, enlarged entodermal cells in contrast to the smaller ectodermal and mesodermal elements. Gastrulation is normally characterized by an invasion of mesodermal cells to line the blastocoele. Zero gravity may markedly alter this procedure as a result of abnormal genefunction during the formation of the mesoderm. Evidence of inhibition of gene action would be refined, with the use of antinomycin D and puromycin in subsequent tests, as guided by the results of the initial observations. Other experimental procedures will utilize sea urchin eggs, some of which will be injected with a quantity of inert particles in order to contrast miolecithal with pseudo-medialecithal zygotes from the same parent. Controls would be run at several G levels in centrifuges. This technique would require ground studies to develop adequate baseline data. Recent evidence showing hormone-induced puffing of insect salivary gland chromosomes has confirmed the hypothesis that genotypic expression can be mediated by chemically activating genetic loci. Since gravity controls the yolk platelet distribution in the oocyte, it is also thought to create a concentration gradient of chemical agents which determine the genetic fate of the presumptive ectodermal and mesodermal regions. Experiments under conditions of zero-gravity would test this hypothesis.

The above is but a small sample of the many interesting studies to be done in the course of a major embryology experiment in an advanced zero-G laboratory. Others to be defined subsequently will round out the plan for fulfilling the complex of experimental objectives.

Instrumentation and Apparatus Required

1. Illuminated magnifiers
2. Dissecting stereomicroscope with stereocamera attachment
3. Movie camera with time-lapse capabilities and special lenses for extreme closeup work
4. Roll-film camera
5. Video camera with special closeup lenses
6. Micromanipulators
7. Special combination culture-observation vessels
8. Special life-support units for maintaining culture vessels within optimum range
9. Incubators and thermal and humidity control chambers
10. Automatic cell counters
11. Centrifuges for control specimens
12. Tape recorder
13. Ultrasonic generator and special transducers
14. Freezer
15. Refrigerators
16. Special filters and fluid handling devices
17. Aquaria and holding tanks
18. Compound microscope with attachments for photomicrography

Spacecraft Facility Requirements

The facilities currently anticipated as firm requirements consist of:

1. An animal maintenance area for invertebrates and poikilothermic vertebrates
2. A histology laboratory area
3. Microscopy and photographic work bench
4. Film processing facility
5. Small wet lab area

Scientific Crew Requirement

It is anticipated that one embryologist could adequately perform all of the necessary studies and observations involved in this experiment if he were supported by the 1/2-time effort of a histologist. It would be better, however, to have two embryologists, one with a strong anatomical background and the other with heavier emphasis upon physiological embryology. Ideally, they should also be supported by an animal maintenance technician as well as a wet lab technician. These latter two functions, however, should not require more than 1 hour per day.

Estimated Data Output

2 million frames of 16 mm film

10,000 frames of 35 mm roll film

50 hours of voice-recording tape

1200 histologic slides

10 lab notebooks

250 vials of fixed specimens

9.4.3.5 Tropic Responses and Morphogenesis of Plants

Objective

The purpose of this study is to investigate the role played by gravity in the growth and development of plants. Included are the following:

1. Investigation of the mechanisms by which the gravitational stimulus is perceived and geotropism initiated
2. Investigation of the mechanisms involved in coupling between geotropic and phototropic phenomena
3. Investigation of the nature and sensitivity of the morphogenetic process to extremely low levels of gravitational force

Scientific Background

The mechanism of perception of the phototropic stimulus in plants involves a pigment, while the perception of the geotropic stimulus is believed to involve cell inclusions. In both cases, the site of action is by movement of small quantities of indolacetic acid (auxin). The classical experiment material for the study of growth responses in plants is the coleoptile, the small, green, hollow sheath within which the seedling of grass emerges. It has been shown that the extreme tip of the coleoptile perceives the stimulus of the light but the mechanism of movement occurs in the region of cell extension some distance from the tip. The perception of gravity occurs at the tip of the root but the region of response is once again the area in which cells elongate.

The tip of the coleoptile produces a small amount of auxin which is transmitted down the stem to stimulate the elongating cells to grow. In response to unilateral illumination, the distribution of the auxins is changed to produce the asymmetric growth that actually occurs.

A geotropic response will not occur in the absence of auxins. If a root is kept in the dark, no auxins appear and there is a failure of geotropic response. However, due to the inability to conduct experiments in the absence of gravity, it has not been possible to do the reciprocal study, namely, a determination of whether the phototropic response fails in the absence of gravity.

Scientific Justification

This experiment involves principles which form one of the cornerstones of botanical science, a better understanding of which will give deeper insights into the evolution of higher plants, not only on this planet but possibly in extraterrestrial environments as well. It is virtually impossible to carry out this line of investigation except in a very sophisticated space vehicle since the evidence accumulated by various workers mostly in the past 5 years indicates geotropic responses at as little as a few times 10^{-6} G.

Practical Justification

There is a growing body of opinion which holds that long-term space flights will very likely utilize higher plants (particularly broad-leaved varieties) in their closed ecological systems. It is, therefore, important to ascertain whether zero-G adversely influences normal growth, development, and health of such plants and, if so, what remedial measures can be employed as correctives.

Feasibility

There are no currently known problem areas which would render such an experiment infeasible. As far as is known, existing technology can be applied in a straightforward manner.

Method

Initially, Avena is the test species of choice because of the extensive past work with it. However, as baseline data are obtained in the earlier phases of the experiment, it will become possible to plan work with various monocots and dicots as well as other types of material such as stem cuttings, etc. The first phases of the experiment would utilize suitably fortified agar as a growth medium. In later phases, however, it will be necessary to employ additional culture techniques, some of which will require considerable ground-based development.

Much development needs to be done in the area of auxin assay methods. Conventional techniques, although relatively simple and straightforward, require the use of flammable or toxic solvents, both of which constitute unacceptable hazards in a space vehicle. Hence, if no better method can be developed, it will be necessary to return frozen or lyophilized material to the ground for assay.

A variety of methods will be utilized for maintaining groups of control samples, including centrifuges operating at several G levels, ground-based samples, and clinostats. By comparing the controls from the centrifuges with those from the ground, it should be possible to ascertain whether there are qualitative differences between rotationally generated acceleration and that due to gravity. By maintaining some control samples in clinostats, it will be possible to verify the validity of the extensive work done on the ground with these instruments.

As currently envisioned, the experiment will also make use of isotopically labeled substances to trace the course of material transport within the specimen.

Instrumentation and Apparatus Required

The following is a semicomplete list of the major items of equipment needed in the experiment:

1. Centrifuges for maintaining controls at several different G levels
2. Clinostats
3. Time-lapse and single-frame cameras and backdrop measurement grids
4. Special controlled-illumination equipment
5. Isotope-handling equipment and radiation counters
6. Lyophilizer and freezers
7. Freezing microtome
8. Radioautography equipment

Spacecraft Facility Requirements

In addition to a wet lab for propagating specimens, darkrooms will be required to conduct those portions of the experiment dealing with phototropism. As currently conceived, the experiment will require provision within the laboratory of acceleration levels of 10^{-7} G or less for as long as 2 to 4 months at a time. A photographic darkroom will be required for a limited amount of film processing. A histological and cytochemical laboratory is extremely desirable, if not mandatory.

Scientific Crew Requirement

One scientist trained in both morphological and functional botany could conceivably perform the experiment. However, a better arrangement would be a plant morphologist and a plant physiologist, both with extensive training in cytology, histology, biochemistry, and biophysics. In addition, a 1/4-time histologist and a full-time wet lab technician trained in radioisotope methodology should be included.

Estimated Data Output

20,000 frames of 16 mm film

10,000 frames of 35 mm film

1000 histologic preparations and radioautographs

20 lab notebooks

9.4.4 Analysis of Instrumentation and Apparatus Requirements

The apparatus to be used in an orbital lab must be planned several years in advance of the flight, but the experiments to be performed with the apparatus may not be significant at flight time if they are planned too far in advance. Furthermore, an experiment which appeared significant early in the flight may have to be changed during the flight because of new findings in the early phases of the experiment. It is important that the apparatus be designed for greatest possible flexibility so that changed or new experiments can be accommodated.

The absence of gravity poses challenging problems in handling biological specimens. Fluids are difficult to contain and difficult to transfer. Aquaria and culture vessels must be designed not only to contain specimens but also to provide for oxygen in zero-G. Preparation of such everyday materials as microscrope slides and agar cultures will require new techniques. Several important new pieces of apparatus for handling biological specimens must be designed and developed.

Processes which require special attention include the transfer and mixing of fluids. To transfer a fluid from one container to another, or to mix two fluids, the fluid must be accelerated. If zero acceleration of the fluid is a necessary condition for a meaningful experiment, it may not be possible to transfer the fluid without destroying the meaning of the experiment and mixing may be necessarily limited to diffusion. These constraints must be considered in the design of experiments that are dependent on zero-g. For example, a device has been considered which would transfer the fluid by moving the container while the fluid remains stationary; however, viscous forces complicate the problem.

Similar pieces of apparatus, such as aquaria and microscopes, are called for in different experiments. Since the greatest part of the weight or bulk of the experimental payload will be apparatus rather than samples, considerable savings in bulk can be realized by using the same apparatus to perform several different experiments. One question that needs to be explored in much greater detail is: "What groups of different experiments can most effectively be performed with one set of apparatus?"

Most of the required instruments do not exist as space-qualified models. They will require a period of development and test before they can be successfully operated on the zero-G laboratory. Because of the long lead times needed for development, test, and procurement of operational models, specifications for the instrumentation should be prepared and development effort should begin at the earliest possible date.

A large number of instruments and pieces of apparatus have been identified for use with the five prototype experiments discussed in the previous sections. Table 9-I lists the instruments and identifies the experiments with which they are associated. It also indicates the facility in which instruments will be located and the region of the spacecraft in which they will be used. Insofar as possible, sizes have been given for the various pieces of apparatus. In cases where it was not possible to give estimated dimensions, approximate volumes have been listed. In the case of items such as freezers, refrigerators, etc., it has not been possible to determine exact dimensions or volume requirements.

The instrumentation and apparatus fall into three general categories. The first of these is defined as items which are primarily concerned with the performance of observations and the collection of experimental data. The second category includes apparatus such as microtomes, phase-separation centrifuges, etc., utilized in the performance of routine laboratory operations. The third category of equipment encompasses items devoted primarily to storage and maintenance of specimens in a prescribed environment.

TABLE 9-I

INSTRUMENTATION AND APPARATUS REQUIREMENTS

Instrument	Experiments					Size Inches			Region of Location	Associated with Facility
	I	II	III	IV	V	h	w	d		
Spectrophotometer				+	+	5	8	15	I	1, 7
Optical densitometer	+			+	+	4	2	8	I	1, 7
Light scattering photometer				+	+	6	20	12	I	1, 7
Automatic plate scanning counter					+	9	8	8	I	1, 3
Automatic cell counters	+	+		+	+	12	8	10	I	1, 7
Dark field colony counter					+				I	3
Polarograph				+	+	14	9	12	I	1, 7
Compound microscope	+	+	+	+	+	12	6	8	I & II	3,4,9
Multiple beamsplitter	+									
Phase contrast optics	+			+	+					
Interference optics				+						
Polarizing optics					+					
Dark field optics					+	3	6	12		
Cinecamera attachments	+	+								
Plate camera attachments	+	+	+							
Roll film camera attachments		+	+							
Video camera attachments	+	+								
Ultraviolet and fluorescence microscopy equipment	+				+				I & II	3, 4
Scanning microscope	+					12	8	10	I	3
Long-working distance, steroscopic, "dissecting" type microscope with stereo-camera attachment	+	+		+		12	6	8	I & II	1,3,4
Electron microscope (tentative) DELETED				+	+	-	-	-	-	-
Illuminated magnifiers		+				Various			I & II	

TABLE 9-I (contd)

INSTRUMENTATION AND APPARATUS REQUIREMENTS

Instrument	Experiments					Size Inches			Region of Location	Associated with Facility
	I	II	III	IV	V	h	w	d		
Special light sources and controlled illumination equipment	+		+		+	Various			I,II & III	1 thru 14
Movie camera	+	+	+	+	+	6	3	12	I & II	3,4,5,6
Single frame and time lapse capability	+	+	+	+	+					
Optics for extreme close-up work		+			+					
Beamsplitter					+					
Plate camera	+			+		5	6	8	I & II	3,4,5,6
Roll film camera	+	+			+	4	6	7	I	3, 5
Stereocamera	+	+				4	6	5	I,II & III	5,6,14
Video camera	+	+				6	14	4	I & II	3,4,6,6
Microscope adapters		+				2	2	3		
Special close-up optics		+				2	2	8		
Tape recorder	+	+			+	22	5	13	I	7
Micromanipulators (preferably of the Ellis piezoelectric type)	+	+				8	6	12	I	7
Ultrasonic generator and special transducers	+	+			+	4	4	6	I	1
Freezing microtome			+			5	4	6	I	9
Rotary microtome						7	6	9	I	9
Isotope handling equipment			+	+		2	1/2 ft^3		I	11
Isotope tracer equipment	+		+			2	ft^3		I	11, 7
Radiation counters			+	+		1	1/2 ft^3		I	11, 7
Radioautography equipment			+				1/2 ft^3		I	12 <u>or</u> 9, 10

TABLE 9-I (contd)

INSTRUMENTATION AND APPARATUS REQUIREMENTS

Instrument	Experiments					Size Inches			Region of Location	Associated with Facility
	I	II	III	IV	V	h	w	d		
Lead (or other dense material) "safes" for radiation protection of sensitive control specimens and seed cultures	+				+	1 1/2 ft³			I	
Freezers	+	+	+		+				I	
Refrigerators	+	+		+	+				I	
Lyophilizer	+		+		+				I	1 or 9
Incubators	+	+		+	+				I,II or III	
Thermal and humidity control chambers		+							I,II or III	
Special thermal environment chambers	+				+				I	
Specimen culture vessels				+					I,II & III	
Aquaria and holding tanks		+							I	13
Special zero-G culture vessels for propagation of specimens, e.g., chemostats	+				+				I	1
Special combination culture-observation vessels		+			+				I,II & III	
Special life support units for maintaining culture vessels within optimum range		+							I,II & III	
Fluid transfer devices and fluid handling equipment		+		+	+				I & II	1,3,4,9,10,11,13
Special filter apparatus		+		+	+				I	1

TABLE 9-I (contd)

INSTRUMENTATION AND APPARATUS REQUIREMENTS

Instrument	Experiments					Size Inches			Region of Location	Associated with Facility
	I	II	III	IV	V	h	w	d		
Centrifuges for solid-liquid-gas phase separations	+				+				I	1
Centrifuges for maintaining controls at different G levels	+	+	+	+	+				I	
Clinostats			+						I & III	14

At first glance, it appears that, in many cases, several of the instruments mentioned could be combined into a single, general-purpose instrument. A case in point would be the possibility of combining the spectrophotometer, optical densitometer, and light-scattering photometer into a single, all-purpose instrument. However, consideration of the requirements of the individual experiments indicates that a single instrument might not be wholly adequate to serve the needs of the total experimental program. As a matter of fact, depending on whether a single, multipurpose instrument could be developed, it may be necessary to plan on providing two spectrophotometers, two optical densitometers, and a light-scattering photometer; each item set up to handle a certain portion of the experimental program.

This situation is perhaps even better illustrated in the case of microscopes. At first, it would appear that a single microscope, fitted with an all-purpose mechanical system and various sets of optics which could be easily attached as needed, would best serve the requirements of the program. This approach to the problem, however, reflects past experience with space experimentation in which weight and volume considerations were the dominant factors. A realistic projection of those facilities which should be provided in future programs shows that scientific requirements will become the dominant factor and engineering parameters will occupy a subsidiary role. At the present time, estimates based on preliminary time utilization data indicate that more than one compound microscope should be available in the spacecraft. A minimum of two stereoscopic dissecting-type microscopes also should be provided. There is a distinct possibility that these requirements would increase even further as more extensive and numerous experimental procedures are planned.

In the following paragraphs, individual instruments are discussed one at a time in order to identify various functional requirements and special features that may be required.

Spectrophotometer

The spectrophotometer should have capability for operating in both the visible and infrared regions of the spectrum. It is not known at this time whether capability will be required in the ultraviolet region, but further analysis of the experimental techniques is expected to clarify this point. The spectrophotometer should be of the scanning type, i.e., one which is capable of scanning across a suitable portion of the spectrum and recording absorption as a function of wavelength on a strip-chart recorder or X-Y plotter. The assumption that all of these various capabilities can be incorporated in a single instrument is based on the concept of interchangeable elements such as prisms, cams, photomultipliers, monochromator gratings, etc. If time-line analysis were to demonstrate that such a concept were not feasible, it would be necessary to provide two separate instruments; one for the visible portion of the spectrum and the other for the infrared. A third might conceivably be needed for the ultraviolet portion.

Optical Densitometer

In reality, the optical densitometer is a simplified special case of the spectrophotometer. However, present estimates of time utilization of these two instruments indicate that it may be desirable to maintain them as separate entities. It may prove to be desirable to give the optical densitometer broader capabilities, and use it as a spectrophotometer for certain specialized tasks.

Light-Scattering Photometer

As in the case of the optical densitometer, the light-scattering photometer is essentially a special case of the spectrophotometer. In this instrument, the photomultiplier tube, instead of being fixed along the same axis as the light source and the sample cell, is attached to a mount which rotates about the sample cell and measures the amount of light that is scattered at various angles by the particles in suspension within the cell. Once again, there is no reason why the light-scattering photometer could not be given broader capabilities and become more of a general-purpose instrument.

Automatic Plate-Scanning Counter

This instrument utilizes mechanical traverse of either the optical detector or the plate itself as a scanning mechanism. This device materially reduces the amount of scientist time required to obtain data from several of the experiments. It may also be desirable to employ a similar technique for counting colonies in roll tubes.

Dark-Field Colony Counter

The dark-field colony counter is an additional aid in the study of bacterial colonies. It is used in much the same manner as the ordinary dark-field microscope.

Polarograph

Electrochemical studies utilizing the polarograph will be a key feature of the experiment on biological transport and the experiment dealing with microbiological processes. Considerable development work would probably be required to adapt polarography for use in the space environment. Some of these adaptations would include conversion from rotating to vibrating electrodes, sealed sample chambers, and miniaturization of much of the mechanical and all of the electronic portion of the equipment. These efforts, however, will be well justified because electrochemical techniques have been one of the most powerful tools available for studies of biological transport phenomena since, with them, it is possible in a very short period of time to ascertain the nature, rate, and reaction kinetics of biochemical processes.

Compound Microscope

The compound microscope is without question the single most universal instrument encountered in the biological sciences. In recent years, there has been a tremendous proliferation of special-purpose optics for the compound microscope. The improved techniques of microscopy made possible by special optics have even further enhanced the importance of this instrument. At the present time, analysis of various experiments and the time utilization predicted for microscopes indicates that there will be several compound microscopes located in different facilities within the spacecraft.

One of the accessories that will be utilized extensively with at least two of the microscopes is a multiple beam-splitter assembly which enables the scientist to observe the sample and simultaneously take photographs of important observations and events. In this way it would also be possible to provide a video link to earth so that the scientist in orbit could collaborate in real time with his ground-based colleagues and, thereby, enhance the scientific value of the experiment. The standard set of optics for use with microscopes will be apochromatic objectives and suitable compendating oculars.

In addition to these, however, there will be many specialized sets of optics; among these will be phase-contrast optics which are used for observation of living material (since there are virtually no color differences in the various constituents of the cellular plasma, it is necessary to use phase-contrast optics to observe the differences in refractive indices of the various cellular constituents and, thereby, view the living system in the vital state).

Interference and polarizing optics are used in the analysis of inclusion bodies (particularly crystals) in various living and histologically prepared preparations. Dark-field optics are used primarily in work with bacteria and in other microbiological studies where it is necessary to determine the presence of extremely small particles which are somewhat below the resolving power of normal light-field optics.

Naturally, attachments will be provided for adapting movie cameras, time-lapse, plate and roll-film cameras, as well as video cameras, to the microscope. Complete and rapid interchangeability of the various optical systems and attachments mentioned is certainly an important requirement in order to achieve maximum flexibility and utilization of equipment.

Ultraviolet and Fluorescence Microscopy Equipment

At the present time, it seems likely that ultraviolet and fluorescence microscopy will be done with a separate microscope. It is possible, however, that suitable optics could be designed for use with the standard compound microscope contemplated for other purposes.

Scanning Microscope

The scanning microscope might take the form of a separate instrument or, alternatively, it could be an automatically traversing mechanical stage arrangement for the regular compound microscope.

Long-Working-Distance Stereoscopic Microscope

The dissecting-type, or long-working-distance stereoscopic microscope, is a most useful tool in observing three-dimensional aspects of larger specimens such as embryological material. This microscope should be provided with a suitable stereo camera attachment in order to make permanent records of observations which, by virtue of their three-dimensional effect, will convey great amounts of information.

Electron Microscope

The question of whether to provide an electron microscope and plan for its use in orbit has received extensive consideration. At present, no justification has been found for inclusion of such an instrument in the program. Therefore, this item has been deleted from the list of recommended equipment.

Illuminated Magnifiers

These units will combine a small hand-held magnifier with a self-contained light source as a convenient tool for making brief periodic checks on the state of various experimental specimens.

Special Light Sources

These light sources are associated with photography, microscopy, and certain aspects of various experiments such as the provision of controlled illumination in plant growth.

Movie Cameras

It is anticipated that several movie cameras will be required due to time utilization considerations. Each of them should have the capability for time-lapse work, as well as either turret or interchangeable optics to permit closeup and wide-angle work. A beamsplitter should be provided to allow an instrument panel to be photographed on the same frame of film as the specimen, thereby recording key data relating to the particular observation.

Plate Camera

The plate camera will be used principally in conjunction with photomicrography. It may also be used as needed for work where extremely fine details are required in the photographs.

Roll-Film Cameras

It is expected that the roll-film cameras will be the general-purpose photographic recording device of choice for use in recording many of the observations made in connection with the various experiments.

Stereo Camera

The stereo camera will be used principally in conjunction with the long-working-distance stereoscopic microscope. It may also be used in certain other cases independently of a microscope, as, for example, in connection with plant growth experiments.

Video Camera

A video camera should certainly be included to provide a capability for collaboration with ground-based scientists. It is felt that providing this capability in the bioscience program will multiply its usefulness severalfold.

Tape Recorders

Tape recorders will be included to allow for dictation of comments while the scientist is actually observing the specimens. There will also be instrumentation-type recorders associated with various items of equipment which have outputs suitable for this method of data storage.

Micromanipulators

Certain aspects of the experiments on cell division and embryology will require the use of micromanipulators to perform operations on individual cells. The instrument of choice is the Ellis piezoelectric-type micromanipulator. This instrument eliminates the time lags, poor tracking, and numerous other difficulties of hydraulic, thermal, and mechanical types of manipulators.

Ultrasonic Generator

The ultrasonic generator and special transducers will be utilized for disruption of cell walls in various portions of the experiments requiring the use of this technique.

Microtomes

The freezing and rotary microtomes will be located in the histology facility and will be used for preparing thin tissue sections as needed for the preparation of histological specimens and for certain biochemical studies.

Isotope Handling and Tracer Equipment

These items are at present not well identified but will be dealt with in more detail as the detailed analysis of prototype experiments continues. The same holds true in the case of radiation counters and radioautography equipment.

Radiation Shielding

Safes for the protection of sensitive control specimens and seed cultures might be made of lead, but perhaps a better material would be depleted uranium. It is currently estimated that perhaps 1-1/2 cubic feet of contained volume would satisfy the requirements specimen storage. This volume, incidentally, includes provision for the storage of the various isotopes that will be used in the laboratory.

Lyophilizer

The lyophilizer will be utilized in the preparation of freeze-dried material for storage prior to return to earth.

Refrigerators, Freezers, Incubators, and Other Thermal Control Equipment

The exact requirements, including numbers, sizes, and temperatures, have not as yet been determined in detail for these items of equipment.

Centrifuges and Clinostats

The detailed requirements for centrifuges will become better known as the detailed analyses of the various experiments continue. Clinostats are included merely as a means of validating earlier ground-based work.

Numerous items of equipment which have not been mentioned here will certainly be present in the orbiting laboratory. Many of the routine supplies relating to the various experiments have not been discussed in detail, since they are included in the weight and volume estimates of the experiment-peculiar equipment. Typically, these items would include such things as culture tubes, dissecting forceps, etc.

9.4.5 Analysis of Facility Requirements

The spacecraft facilities required by a bioscience research program can be broken down into two main areas which may be called "general facility requirements" and "specialized facility requirements". Under the heading of general facility requirements are such standard considerations as sufficient work space, common utilities, adequate provision for locating and mounting various items of equipment, and suitable environmental control provisions. Specialized facility requirements are those elements which have associated with them some unusual burden on the design or operation of the system. Thus far, 14 such separate specialized facilities have been identified and are summarized in Table 9-II.

A well-designed and properly equipped wet lab area will certainly be required, since there will be a good deal of wet chemistry culture preparation, periodic maintenance of cultures, and a number of analytical and measurement operations including various chemical analyses, preparation of samples for spectrophotometry, and various other determinations. In addition, any solutions necessary for photographic processing and for the histological and cytochemical laboratory will probably be made up in this area. These other facilities may then, in a sense, be regarded as subsidiaries of the wet lab area and will, in fact, be located immediately adjacent to it in Region I of the spacecraft. Here, the requirements for stability are moderate, since many of the biological specimens, at this point, will either be in a biologically inactive state prior to the initiation of an experiment or will be material which has been fixed after completion of a phase of one of the experiments and is ready for histological or other examination. Other experimental material in Region I will have requirements for modest degrees of stability as mentioned earlier. As currently envisioned, the liquid-handling area of the wet lab will be essentially a six-sided box (closely resembling a standard glove box minus the gloves) five walls of which will be lined with cellulose

TABLE 9-II

SPACECRAFT FACILITY REQUIREMENTS

	Required by Experiments					Region of Location			Utilities Required					
	I	II	III	IV	V	I	II	III	Water Supply	Liquid Waste Removal	Special Atmosphere Control	Electrical Supply	Compressed Gas or Air	Vacuum
1. "Wet lab" for culture preparation and maintenance and general chemistry operations	+	+	+	+	+	+			+	+	+	+	+	+
2. Sterilization facility					+	+				+	+	+		
3. Microscopy work station		+		+	+	+						+		+
4. Microscopy bench							+	+				+		
5. Photography work station		+		+	+	+						+		
6. Photography bench								+	+			+		
7. Instrumentation work station	+			+	+	+						+		
8. Instrumentation bench or rack							+	+				+		
9. Histology, cytology, and cytochemical laboratory facility		+	+	+	+	+			+	+	+	+		+
10. Photographic darkroom and film processing facilities	+	+	+		+	+			+	+		+		
11. Isotope handling facility	+			+		+			+	+	+	+		+
12. Limited autoradiography facility	+					+						+		
13. An animal maintenance area for invertebrates, poikilothermic vertebrates, and a very small maintenance station for mammalian specimens		+		+			+		+	+	+	+	+	
14. "Darkbox" facilities for phototropism experiments			+				+	+				+	+	

material, resembling thick blotting paper, that will serve to control liquid spills by absorbing the liquid and retaining it by capillarity. The sixth side will contain a window panel and a panel with suitable openings for easy access. The openings will be fitted with suitable covers to contain any floating droplets when the facility is not in use.

Also located immediately adjacent to the wet lab will be a small sterilization facility for insuring the sterility of tissue culture media and cultures prepared for the microbiological work. At the present time, it seems feasible to plan on dry-heat sterilization utilizing a small oven for certain instruments and equipment, as well as a small autoclave-type unit which will provide wet-heat sterilization for those items not tolerating dry-heat methods. In addition, there probably will be provision for ultraviolet sterilization of plastics and other materials readily damaged by heat. The sterilization facility can probably be designed to occupy a space no greater than 2 to 2-1/2 cubic feet; however, it is called out as a major specialized facility because of the extensive power and/or heat requirement and the attendant burden on the thermal control system which will be engendered by requirements for waste heat rejection.

The requirement for a photographic darkroom and film processing facility is somewhat uncertain at the moment, since (1) it may be possible to make all photographs required for use in orbit in the bioscience experiments by a dry development technique such as the polaroid process, and (2) it is not known whether to plan on a bioscience program and an astronomy program being conducted in the course of the same mission. Analysis of an astronomy program would almost certainly reveal whether a photographic processing facility would be planned for the spacecraft. If it is possible to acquire sufficient photographs by dry development techniques, the design of the spacecraft will be materially simplified by the elimination of the photographic darkroom and film processing facility. At the moment, however, a major area of uncertainty also exists with respect to detailed knowledge of the requirement for photographs to be used in orbit for reprogramming the course of experiments and planning the day-to-day activities in the experimental program. The major difficulty in designing a film processing facility for use in the weightless environment is the necessity for handling large quantities of fluids in a darkroom where it is not possible to keep track of fluid droplets that may escape and, hence, contaminate the environment control system.

The histology and cytochemical laboratory facility poses problems that are somewhat similar to the wet lab and darkroom in regard to fluid management. These problems are further compounded by the fact that many of the solvents used are extremely volatile and/or very toxic and, hence, a histology facility throws an enormous burden on the environmental control system design. If routine histological procedures are to be used in a closed ecological system such as will be employed in a manned orbiting station, a specialized fume hood incorporating catalytic burners, adsorbent filters, and other such devices will be a mandatory requirement. To the writer's knowledge, no adequate attempts have yet been made to analyze in any detail the requirements of such a space environment fume hood. It is true that many of the standard histological and cytochemical techniques could be drastically revised in order to eliminate from the experimental program hazardous solvents and chemicals with high vapor pressures or high toxicities.

The isotope handling facility also will be located adjacent to the wet lab area. As currently planned, it will have provision for storing and handling 3 to 5 millicuries of such isotopes as carbon 14, sulphur 35, and phosphorus 32. Since it is of paramount importance to control radioactive contamination of the spacecraft, particularly the environmental control system, the isotope handling facility probably will be designed along the same lines as a standard glove box. Laminar, recirculating air flow equipment and a special sequential filter will be used to insure the removal of all droplets, dust, aerosols, and contaminated gases from the air stream before it is allowed to return to the main environmental control system. To minimize the possibility of contaminating any area of the spacecraft other than the isotope handling facility, all fluid-transfer operations involving radioactive material will be conducted within the isotope handling facility, and isotopes will be introduced into the vessels containing the specimens which will then be sealed before being returned to open laboratory areas. At the moment, it is virtually certain that the isotope handling facility should be located in Region I of the spacecraft, with transfer of specimens and their containers to Regions II and III. The ultimate decision will depend upon an evaluation of the possible requirement for keeping the specimens continuously in a quite low level of G at the time of isotopic treatment or whether it may be possible to remove them for brief periods to a less well stabilized area in the spacecraft.

Three different locations have been considered for the autoradiography facility:

1. It could be located in conjunction with the isotope handling facility.
2. It might be associated with the histology facility.
3. It could be placed within the photographic darkroom facility.

The latter, at first glance, seems the most likely location, since it is necessary to work with unexposed film and apply the film over histological sections of the specimens. However, more detailed analysis suggests that if it is possible to perform such operations on the ground without seriously hindering the experiment, this would be the method of choice. Alternatively, the operations could be split between the histology facility and the darkroom, if a darkroom is included. Hence, the requirement for a separate facility of this sort remains an open question for the moment.

The darkbox facilities for the phototropism experiments involve some rather peculiar and difficult requirements in that it has been demonstrated that the phototropic response can be induced by between 10 and 100 photons. Thus, it may be seen that there is a very stringent requirement for maintaining absolute darkness during the transfer of various experimental samples into and out of these facilities. In view of the stringency of these requirements, it becomes obvious that there will be very serious design constraints on all openings and access provisions connected with the darkbox facilities.

The animal maintenance area is currently envisioned as occupying approximately 15 square feet of floor space based on rat- and mouse-size specimens. The size of the area would be increased materially if larger mammalian specimens are found to be required. While it is desirable to keep the required number of warm-blooded animals to a minimum, certainly some will be necessary and, hence, provision must be made for them. If one were to contemplate experiments with whole-animal physiology, it is very likely that animals such as dogs, cats, rabbits, and small primates will be required. As indicated elsewhere, a number of invertebrate species will be utilized and many of them will be aquatic. There will also be various poikilothermic vertebrates such as amphibians. Current thinking indicates that these animals would be stored in the required numbers in sealed, circulating, aquatic microenvironments which have provisions for removal of specimens in the required numbers without excess loss of fluids, etc.

It will be noted that microscopy, photography, and instrumentation capabilities are currently provided in more than one region of the vehicle. This does not indicate that there is a total overlap or even significant duplication of facilities in each of the various regions, but rather that certain items of equipment are required for actual observations and measurements in Region II or III and that provision has been made for locating a particular item of equipment in Region II or III as required by the experiment being conducted at a particular time. A microscopy facility, for example, is located in conjunction with the histology facility on a permanent basis, and microscopy equipment and mounting provisions are located in Region II on an ad hoc basis where changes in the experimental samples are being studied under very low-G conditions.

9.4.6 Analysis of Scientific Crew Requirements

9.4.6.1 Personnel Background Requirements and Assignments

An important consideration influencing the choice of experiments for the proposed program is the role to be played by man as an experimenter in a space laboratory. As previously mentioned, biological experiments in space research have not been numerous to date; the reason being the difficulty or impossibility of automating the experimental arrangement for making measurements in which the skilled observer is such a basic element in the data system. The proposed program is strongly influenced by the fact that it permits the observer and the subject to exist simultaneously in the space environment.

A point worthy of note in any discussion of space experimentation is that man always has a role and is perforce always a participant in each experiment. In the simplest case, man designs the experiment in such a way that he may remain on the ground and receive data from the experiment through a communications link, and perhaps, perform remotely a few simple functions such as starting, stopping, or making rudimentary adjustments via a radio command link. In the intermediate case, man functions primarily as an observer directly at the site of the phenomena under examination or at the point in space from which they may be most advantageously observed. He also may perform simple tasks such as operating cameras or operating simple mechanical or electronic controls. Man has performed such intermediate functions in Project Mercury by making observations and photographs of the phenomena of zodiacal light and the occultation of stars. In the ideal case, man is at the site of the experiment and makes use of as many of his diverse capabilities as possible, not only to observe and perform numerous and complex manipulations but also to reduce and correlate data, exercise judgment and inductive reasoning, and thereby modify, in-flight, the future course of the experiment.

In most cases where the effectiveness of man in performing a single simple function has been compared with the effectiveness of an automatic instrument, man has been shown to be decidedly inferior. This situation is rapidly reversed, however, as either the number of functions to be performed or their complexity is increased. Suffice to say that building an automatic system to provide the required number and diversity of motions and delicate controls together with a continuous reprogramming capability so necessary to the manipulation of biological materials is probably far beyond the competence of current technology.

As one begins to design spaceborne experiments such as those discussed in this report, it becomes readily apparent that the presence of man is a vital necessity. This requirement can be demonstrated by simply cataloging the many sensory, actuatory, and data processing functions required and establishing the weight, volume, and power demands assignable to each function.

Among man's most useful attributes for performing scientific experiments in space are the following:

1. His sensory capabilities; particularly the visual sense which is capable of discerning extremely fine detail and detecting patterns even in very fragmentary presentations.
2. His extreme flexibility in performing mechanical functions; particularly in complex manipulations where each succeeding step may require reference to the inductive reasoning process.
3. His unique ability to communicate vast amounts of information in a few words. (For example, he can say, "This experiment turned out just like the last one," and convey several hours worth of information in a few seconds.)
4. His intellectual capabilities which include:
   a. The ability to evaluate data of great complexity
   b. A highly selective, flexible, and extensive memory
   c. The capacity to deal effectively with unforeseen situations

d. The capacity for combining inductive and deductive reasoning

e. The ability to make judgments

The philosophy adopted by this study, based on the above considerations, is to utilize the astronaut-scientist in the performance of all operations for which he is physically and mentally qualified. In this way, it will be possible to maximize the number and complexity of the experiments by minimizing the amount of equipment required to perform them.

As an illustration of the application of this philosophy, an experimental technique may be cited which is of more than mere hypothetical significance. An embryological experiment of the most compelling interest involves post-cleavage separation of the blastomeres. The technique by which this is accomplished was developed during the series of experiments for which Hans Spemann received the Nobel Prize. The method involves the use of two loops (or a noose) made of the finest obtainable hair to tease apart and separate, without damage to either cell, the blastomeres following first, or in some cases second or third, cleavage. The number and diversity of motions and fineness of control required to accomplish this operation can best be appreciated by those who have attempted it. Designing and building an automatic instrument to perform this task is beyond the capability of present technology. In addition, the weight, volume, and power requirements of such a device would almost certainly border on the absurd. Yet in the hands of a skilled embryologist, a few simple items of equipment can yield an entirely satisfactory result in a few minutes time. When one considers the large number, wide variety, and complex nature of experiments which would take full advantage of the opportunities afforded by an orbiting laboratory, it becomes apparent that utilization of man to the utmost degree is a mandatory requirement.

It is recommended that the individuals selected to implement and perform the bioscience experiments be, first and foremost, men of outstanding research abilities. Personal traits, such as imagination, curiosity, and inclination, should be carefully considered in the selection of scientist-astronauts. The purpose of the training each man receives should be to render him knowledgeable over a wide variety of biological fields. This would involve individual training programs, the details of which would be based initially on the man's knowledge when he comes into the program. Biologists possessing broad interests and training are definitely necessary, especially during the early missions of such a program. More specialization may be practical in later missions when larger scientific crew complements may be possible.

Based upon the hypothetical or prototype mission formulated in the current study, the following crew requirements are recommended:

Biological Transport Phenomena

One full-time biochemist-biophysicist assisted by a 1/4-time wet lab technician will be sufficient to accomplish the experiment.

Cell Division and Experimental Cytobiology

One combination cytologist - cell physiologist with the 1/4-time assistance of a histologist, plus a 1/2- to 3/4-time wet lab technician will be adequate to perform the experiment.

Fundamental Microbiological Processes

One microbiologist assisted by a full-time chemical-bacteriological technician will be adequate to perform the study.

Experimental Embryology

It is anticipated that one embryologist could adequately perform all of the necessary studies and observations involved in this experiment if he were supported by the 1/2-time effort of a histologist. It would be better, however, to have two embryologists, one with a strong anatomical background and the other with heavier emphasis on physiological embryology. Ideally, they should be supported by an animal maintenance technician and a wet lab technician. These latter two functions, however, should not require more than 1 hour per day.

Tropic Responses and Morphogenesis in Plants

One scientist trained in both morphological and functional botany could conceivably perform the experiment. However, a better arrangement would be a plant morphologist and a plant physiologist both with extensive training in cytology, histology, biochemistry, and biophysics. In addition, a 1/4-time histologist and a full-time wet lab technician trained in radioisotope methodology should be included.

It is recommended that the scientists in the space laboratory be essentially free to run the experiment as they see fit, based on immediate reaction to developments, rather than by adherence to a predetermined experimental plan. It is virtually impossible to predict the exact effects of conditions of low gravity, and experiments will be far more meaningful if investigative lines respond to experimental results as they develop. The training and insight required of each orbiting scientist give assurances that he would be capable of modifying an experimental approach in the most meaningful direction. To use such creative individuals as mere automatons would be wasteful and would probably thwart the entire experimental program.

The team of responsible scientists monitoring the experiments from the earth and supervising the control groups in each experiment should support, collaborate with, and advise the orbiting scientists to the maximum practicable extent. It is recommended that this team of scientists be composed of individuals most responsible for formulation of the basic experimental program, specialists in fields most pertinent to the investigation, and contemporaries of the orbiting scientists. One important criterion that should be used in the selection of the individual orbiting scientist should be a past harmonious relationship with the individuals of the ground-based advisory group.

9.4.6.2 Manpower Requirements

Based on a 90-day mission of 8-hour days and 6-day weeks, the scientific personnel time estimates shown in Table 9-III will be required to accomplish the objectives of the experimental program.

TABLE 9-III

SCIENTIFIC MANHOUR REQUIREMENTS

	Principal Scientist	Supporting Scientist	Technician	Total
Biological Transport Phenomena	624		156	780
Cell Division and Experimental Cytobiology	624	156	312-468	1092-1248
Fundamental Microbiological Processes	624		624	1248
Experimental Embryology	624-1248	312	156	936-1716
Tropic Responses and Morphogenesis in Plants	624-1248	156	624	1404-2028
Total Scientific Manhours	3120-4468	624	1862-2018	5606-7110

9.4.7 Analysis of Scientific Data Management Requirements

9.4.7.1 Data Analysis Techniques

Bioscience experiments present a real challenge in data handling because of the varied outputs and the skill levels required to analyze them. In some cases, the output is produced by a qualitative observation of an event; for example, observing the orientation of the third cleavage plane in an embryo developing in the absence of gravity. In other cases, the observation is highly quantitative and requires chemical analysis; for example, in the extraction of auxins.

In only a few cases, such as counting with radioactive tracers, does an experiment produce an electrical output that is directly transmittable as a digital or analog signal. Accordingly, much of the data that will be required to correlate observations of experimental samples with ground-based controls must be converted, at the lab site, from qualitative terms to something transmittable.

The severity of the data handling problem can be reduced by limiting the transmission of photographic material and by transporting specimens to the ground. A professional observer on the zero-G laboratory can make observations, do on-board analysis, and draw conclusions, thereby further reducing the requirements for the transmission of data to the ground. Only results and supporting data may need to be transmitted. To achieve this goal, a high level of professional competence would be required, and it is not anticipated that an astronaut would be capable of such judgment without extensive recent experience as a practicing scientist. A topic which requires serious consideration, therefore, is the orbital flight of high-caliber professional scientists in several fields of biology.

There are, however, alternatives to intensive on-board analysis. One alternative is real-time TV to the ground or, still better, a two-way TV link. The use of such equipment would permit scientists on the ground to observe experiments on the zero-G laboratory, make judgments, and collaborate with the scientist in the laboratory in modifying the experimental procedure or redirecting the course of experiment. Although real-time TV is highly desirable for some experiments, it may not be practically realizable to the extent desired. During the near future, the only tracking and telemetry stations to be in communication with IMCC in Houston, Texas, on wideband links are Guaymas, Mexico, and Cape Kennedy, Florida. These stations may provide a capability for real-time TV during 10 to 15 minutes per orbit for six orbits a day. More real-time TV would be possible with either a net of wideband ground links or a communications satellite system. The net of wideband ground links is not planned, but the communications satellite network will probably be in an advanced operational status by the time the zero-G lab is in use. Positive steps should be taken to provide a full-time wideband link between the zero-G lab and IMCC, via communications satellite, to permit real-time TV.

Photography will be more useful than TV in certain cases where very high resolution is required, as in some microscope work, and in other cases where a high framing rate is not required (such as observing growth or slow movements). Photography, however, presents severe problems in the handling of film. Either the film must be developed on board and photos carried or telemetered to the earth, or exposed film must be stored in the orbiting lab and transported to the ground for development. The transportation to the ground of film and photos prior to the return of the laboratory personnel is expensive in both time and money and should be avoided if possible. Work should be done to provide good workable solutions to the photography problem.

Besides film, other items must be returned to the ground. Samples from some experiments may require analyses of such complexity that they cannot be conducted in the laboratory. On-board analysis would require not simply a high level of training, but rather a skill level developed only through a lifetime of professional growth. Unless scientists of such stature can spend time on the zero-G lab, samples must be returned to the earth for analysis. The return of samples to the earth is a formidable problem. The sample must be stored and maintained within narrow environmental limits both aboard the zero-G lab and after recovery on the ground. Frozen samples must be preserved during reentry and recovery. After landing, there must be a way of recovering the sample and delivering it, still frozen or refrigerated, to the scientist who will analyze it. This task, although costly and time consuming, must be reduced to a normal operating procedure if a series of zero-G experiments is to return such samples for ground analysis.

Continuing efforts are required to develop trustworthy criteria for deciding whether to perform on-board analysis of the samples from any experiment or return the samples to the ground for analysis. The criteria should be based on technological feasibility within reasonable costs. Because of the different kinds of analysis and different skills required, the decision must be made independently for each experiment.

All the experiments recommended will involve the simultaneous observation of earth-based control groups. Ground-based groups of plants, animals, and chemicals must be treated in exactly the same manner as the corresponding orbiting experimental groups. It becomes necessary, therefore, that all significant changes in the orbital experiments be relayed to earth without delay, so that the control groups may be similarly treated.

9.4.7.2 Summary of Measurements and Data Format

Biological Transport Phenomena

Measurements will consist principally of electrical and optical measurements and isotopic counting. The data generated will be recorded on 20,000 feet of strip-chart records, as written data in 30 lab notebooks, and on 400 hours of magnetic tape.

Cell Division and Experimental Cytobiology

Direct observations and photographs will be used in collection of morphological data. Approximately one million frames of 16 mm film plus 10,000 frames of 35 mm film will be required.

Physiological data will utilize optical and electrical measurements which will be read out directly or recorded by means of film, magnetic tape, strip-chart recordings, and written records. These records will occupy 35 hours of magnetic tape, 15 lab notebooks and 1000 feet of strip-chart paper. There will be about 500 histological preparations and 250 radioautographs.

Fundamental Microbiological Processes

Measurements will be made by standard isotopic, electrochemical, optical, and cytologic preparations. Lyophilized specimens will be returned from orbit. Data will be recorded in the form of 30 lab notebooks of written records, 5000 feet of strip charts and 200 hours of magnetic tape containing records of optical, electrochemical, electrical and isotopic measurements. In addition, 2500 cytologic preparations and 200 vials of lyophilized specimens will be returned to the ground.

Experimental Embryology

Measurements will consist mainly of direct observation, study of histologic preparations and photographs. Data to be accumulated for return consist principally of 2 million frames of 16 mm film and 10,000 frames of 35 mm film. Also included are 10 lab notebooks of written data and 50 hours of voice recordings on magnetic tape. In addition, 1200 histological preparations and 250 vials of preserved specimens will be returned to the ground.

Tropic Responses and Morphogenesis in Plants

Measurements will be made regarding both gross and microscopic morphological parameters by making photographs, radioautographs, histologic preparations. Wet chemistry will be used in conjunction with electrical and optical measurements for physiological data. Approximately 20,000 frames of 16 mm film will be required for time lapse photographs and 10,000 frames of 35 mm roll film for nonperiodic records. Histologic and autoradiographic preparations will number 1000, while 20 lab notebooks will be utilized to record the optical and electrical measurements utilized in the physiological and the remainder of the morphological studies.

A summary estimate of the data volume expected is shown in Table 9-IV.

9.4.8 Identification of Interfaces for Laboratory Conceptual Design

The principal interface of the bioscience research program with the vehicle and system involves the gravitational stability of the laboratory. The significance of the stabilization requirement is exemplified by assessing the G-levels probable on other vehicles. The information currently available indicates the Apollo Applications Laboratory will probably operate at 10^{-2} G in general and perhaps 10^{-3} G under the best conditions. Similarly, the Biosatellite is supposed to be capable of maintaining 10^{-4} G and of achieving 10^{-5} G under optimum conditions. By contrast, some of the experiments contemplated in this study require less than 10^{-6} G and probably as low as 10^{-7} G. The other interfaces are of a more routine nature and are summarized only briefly here since they are dealt with more extensively elsewhere in the report.

It is important to be able to predict the degree of stabilization required for the bioscience experiments. Although the orbital laboratory is nominally at zero-G, there are actually small accelerations caused by air drag on the outside of the spacecraft, gravity gradients, and some much smaller forces such as electromagnetic forces and solar pressure. Furthermore, there are accelerations, shock and vibration caused by movement of the crew, machinery on the spacecraft, and attitude control impulses. Because of these

TABLE 9-IV

SUMMARY OF ESTIMATED DATA VOLUME

Experiment	Lab Notebooks (each)	Strip Charts (feet)	Magnetic Tape (hours)	16 mm Film (frames)	35 mm Film (frames)	Histological and Cytological Slides (each)	Autoradiographs (each)	Preserved Specimens Lyophilized or in Fixative (vials)	Frozen Specimens (vials)
1. Biological Transport Phenomena	30	20,000	400						
2. Cell Division and Cytobiology	15	1,000	35	10^6	10,000	500	250		
3. Microbiological Processes	30	5,000	200			2500		200	
4. Experimental Embryology	10		50	2×10^6	10,000	1200		250	
5. Tropic Responses and Morphogenesis in Plants	20			2×10^4	10,000	1000	300	200	100
TOTAL	105	26,000	685	3.02×10^6	30,000	5200	550	650	100

accelerations and vibrations it is not possible to achieve true zero-G. It is possible to achieve a controlled amount of acceleration on the order of 10^{-4}G to 10^{-7}G.

The first question which must be answered is: "Can zero-G bioscience experiments produce meaningful results at accelerations as high as 10^{-6}G?" Experiments performed with clinostats have indicated that certain plant preparations may respond to accelerations of this magnitude or smaller (Ref. 9-1). However, many biological processes could be markedly changed as soon as surface tension forces become much larger than gravity forces. For example, the third cleavage after fertilization of amphibian eggs on the ground leaves more yolk in the lower cells (macromeres) than in the upper cells (micromeres). At what smaller value of G would cellular forces predominate to make this division so nearly equal that no difference could be observed? Perhaps there can be no satisfactory answer to this question until the experiment is repeated at a series of different G values.

In bioscience it has been extremely difficult to make accurate predictions of the effects on a subject of various quantities of stimuli. The experimental procedure has often required measurement of the response to a large range of stimuli. In the orbital laboratory, it would be desirable to be able to produce a controlled range of accelerations. It is not possible to say definitely at this time what limits this range of acceleration should take. Regardless of what practical range is selected, scientists may wonder what effects might be observed outside that range. A practical range for early missions seems to be 10^{-6}G (obtainable on stable platforms) up to one G (achieved on a small centrifuge, or several small centrifuges designed to operate at various ranges of angular acceleration). Accelerations higher than one G could easily be achieved on a small centrifuge, but they can be achieved on the ground and may not be justified in space, except perhaps as controls for detecting the effects of parameters other than G.

As discussed elsewhere in this report, the concept of a station having separate regions of varying degrees and durations of stabilization has been strongly influenced by the requirement for providing facilities and equipment which tend to inherently reduce the stability of the spacecraft. Hence, facilities and equipment that are not directly involved with observation or work with living specimens or samples have, in general, been located in Region I, the area of minimum stability. Also located in this area will be experiments and specimens having moderate requirements for low-G over periods of long duration and those requiring laboratory equipment and facilities too extensive to be located in Regions II or III. The facilities and instruments necessary to those portions of the experimental program requiring greater levels of stability for periods of moderate duration and frequent ready access by the experimenters have been located in Region II. The instruments and facilities involved with portions of the program having the most stringent requirements for stability and long-term ultralow-G have been located in Region III.

At present, it would be best to plan an orbital laboratory in which controlled values of G could be produced. During this study, attempts have been made to define the ranges of G through which each experiment should be performed. Because of the empirical nature of bioscience, however, it is not probable that one can identify with any great exactitude the specific values of G where significant effects can be observed until actual experiments have been performed in space.

None of the experiments, as currently conceived, require any particular spacecraft orientation. Unless one or more special requirements, such as solar illumination of plants, etc., are generated at some time in the future, it is not likely that this will become a system interface consideration. The estimated stabilization requirements of the experiments are summarized below.

Summary of Spacecraft Stabilization Requirements

Biological Transport Phenomena

Stability of between 10^{-3} and 10^{-4} will be sufficient for all anticipated experimental runs. Duration of this stability requirement will probably not exceed 1 hour at a time.

Cell Division and Experimental Cytobiology

Stabilization of the order of 10^{-3}G is believed to be adequate for all parts of this experiment.

Fundamental Microbiological Processes

Some studies will require performance in Region II of the spacecraft. The majority, however, can be accomplished satisfactorily, it is presently thought, in Region I. Most of the observations will not require lengthy sequences of preparatory exposure to zero-G.

Experimental Embryology

Accelerations of 10^{-3} and less are thought to be adequate for this experiment at the present time. Hence, Region I of the spacecraft should satisfy this requirement. It is not currently thought that any observations will need to be made in the regime provided by Region II; however, this might be changed based on early results in orbit.

Tropic Responses and Morphogenesis in Plants

Predictions and conclusions based on recent laboratory work with plants indicate sensitivity to gravitational forces as low as 2 x 10^{-6}G. Certain of the studies contemplated for performance in Region III are thought to require 10^{-7}G for a period of 45 days.

Summary of Experiment/Spacecraft Interfaces

Biological Transport Phenomena

Management of wet lab operations, waste handling and isotope utilization.

Cell Division and Experimental Cytobiology

Management of waste handling, specimen maintenance, toxic vapors, wet lab operations.

Fundamental Microbiological Processes

Management of wet chemistry operations, toxic vapors, and waste handling.

Experimental Embryology

Specimen maintenance, wet lab operations, waste management, and the toxic hazards of the histological operations.

Tropic Responses and Morphogenesis in Plants

The problems connected with the degree of stabilization required for acquisition of meaningful measurements are the paramount interface. A secondary problem is the requirement for voluminous thermal-humidity environment chambers.

Weight, Volume and Special Requirements

Biological Transport Phenomena

Weight of experiment-peculiar equipment is approximately 650 pounds. Volume of experiment-peculiar equipment is estimated at 25 cubic feet.

Cell Division and Experimental Cytobiology

Weight of experiment-peculiar equipment is estimated at 700 pounds. Volume of the equipment peculiar to this experiment is estimated at 27 cubic feet.

Fundamental Microbiological Processes

Weight of experiment-peculiar equipment is estimated at 500 pounds. Volume of experiment-unique items is estimated at 15 cubic feet.

Experimental Embryology

It is currently estimated the experiment-peculiar equipment will weigh, in the aggregate, approximately 850 pounds. Experiment-peculiar equipment is estimated to occupy approximately 24 cubic feet. A two-way TV link would be desirable.

Tropic Responses and Morphogenesis of Plants

Estimated weight of experiment-peculiar items is 1100 pounds. Estimated volume of experiment-peculiar items is 35 cubic feet.

Power Requirements Summary

Biological Transport Phenomena

Estimated power consumption is 150 to 200 watts continuous for approximately 8 hours each day plus 5 square-wave peaks of 300 watts for 10 minutes duration. Specimen environmental maintenance equipment, etc., will require an estimated additional 350 watts average power.

Cell Division and Experimental Cytobiology

150 watts continuous for 8 hours each day plus 450 watts continuous throughout the mission for environmental control of specimens in storage, etc.

Fundamental Microbiological Processes

Power principally for incubators, freezers, refrigerators, etc., is estimated at 400 watts average. An additional 200 watts continuous for 5 or 6 hours per day is required for microscopy and lab operations.

Experimental Embryology

The power required will be associated with the light sources for microscopy and photography and with the freezers, refrigerators, and thermal environment chambers for specimens. The lights will probably require 150 watts continuously for 6 hours each day. Other equipment will require an average power of 500 watts.

Tropic Responses and Morphogenesis in Plants

Microscopy and photography are expected to consume 200 watts continuously for 8 hours and 50 square-wave peaks of 500 watts and 20 seconds duration daily, plus a requirement of 650 watts average for specimen environment chambers.

Summary of Environmental Requirements

Biological Transport Phenomena

Shirt-sleeve environment should be entirely satisfactory for the experimental materials and procedures.

Cell Division and Experimental Cytobiology

Shirt-sleeve environment is acceptable for all laboratory operations. Specimens will be stored and maintained in appropriate micro-environments such as refrigerators, incubators, etc.

Fundamental Microbiological Processes

Shirt-sleeve environment will be adequate except for those specimens requiring incubation or refrigeration.

Experimental Embryology

Shirt-sleeve environment will be adequate for lab operations. Most specimen storage will be in specially controlled micro-environments.

Tropic Responses and Morphogenesis in Plants

Shirt-sleeve environment will probably be acceptable for most specimens, assuming cabin pressure is not too far reduced. Some, if not all, specimens will be maintained in specially controlled humidity conditions.

9.5 Recommendations

The recommendations presented here are based on a long-range view of the space research program and its potential for meaningful contributions to science and technology. Implementation of these recommendations would constitute early building blocks in the foundation of a comprehensive program in gravitational biology.

9.5.1 General

The Space Science Board of the National Academy of Sciences (Statement on National Goals in Space 1971-1985; October 24, 1964) recommended the assignment of high priority to the solution of biomedical-bioengineering problems and to the search for extraterrestrial life or possible precursors. The Academy specifically identified the exploration of Mars as the outstanding goal, and pointed to the importance of those tasks required to develop the capability of man to undertake long journeys in space. The Academy quite understandably stressed the enormous scientific interest in a search for present or past life forms on Mars, and expressed the view that the discovery of Martian life might well rank as the most important outcome of space research in our generation.

A different view has been taken by other distinguished scientists involved in governmental planning activities. Some have recently deplored the lunar and Martian exploration programs as having scant scientific content. Their recommendation was for a program utilizing the space environment as a tool in performing controlled scientific experiments. One of the key areas stressed as warranting intensive effort was study of the nature, origin, and evolution of life forms and living systems.

These two divergent suggestions can be summarized briefly as favoring exploration on the one hand and controlled experimentation on the other. An example of the possible results which might be expected from each may be drawn from historical evidence. The first Antarctic expeditions and much of the basic research into the way certain classes of organic molecules react and couple took place during the same period. The Antarctic exploration produced many exciting scientific discoveries in spite of great difficulties and hardship. By contrast, the controlled experiments in polymer chemistry, though not so exciting or well publicized at the time, provided the world with synthetic fibers and modern plastics.

What should be the rationale used in developing plans for the first phase of a long-range program of biological research in space? How greatly should the early biological research program be slanted toward experimentation most likely to yield data useful in the solution of immediate engineering problems in life support? How can space research activities be best coordinated with biological studies in progress and planned within the government, university, and industrial research community? Since the space biology research programs of the next decade will be but a fraction of the total national effort in the life sciences, what are the outstanding, unique contributions to be made by space bioscience in the manned orbiting laboratory to the overall advance of knowledge in the life sciences?

There is, of course, no simply stated, single answer to the questions raised. However, the analysis performed in this study has shown that the maximum advantage should be taken of the opportunity to study and observe the response of living organisms to the space environment. It is recommended that the following statement of purpose be adopted for the proposed manned space laboratory biological research program:

1. To investigate the role of the environment in establishing and maintaining the normal organization of living systems.
2. To investigate fundamental biological processes and forms of life as they may develop in or adapt to extraterrestrial conditions.

Biological systems employed should encompass the entire range of living things.

Another major aspect of space bioscience research involves the assembly of many separate considerations into a meaningful and integrated program. Among the various tasks inherent in the effort are mission planning, resupply logistics, on-board task analysis, sources and generation of extraneous disturbing forces, number of specialists needed, consequences of incapacitation of a key crew member, consequences of failure of major equipment items, etc. While attention has been devoted to selected areas, it has not been possible to cover them all or in great depth in the present report. It is recommended that further study be performed in these areas.

9.5.2 Long-Range Scientific Studies

It is recommended that serious attention be focused on gravitational biology which is now being recognized as a major scientific discipline currently in the embryonic stage. A corollary recommendation concerns studies leading to the development of a more complete theoretical framework for the biosciences. The conclusions based on analysis and the intuitive impressions gained in the course of this study indicate three areas in particular as holding great promise of significant immediate results if properly investigated. These areas are:

1. Biophysics — especially physico-chemical surface phenomena and fluid dynamics studies. Some of the work of Mel exemplifies the type of studies envisioned.
2. Animal embryology and morphogenesis — some work in this area is already being performed in the space program, but not, however, the more subtle and sophisticated experiments which will provide deep insight into the consequences of gravity in the evolution of life forms.

3. Plant morphology and physiology — some of the best pioneering work concerning gravitational influence on form and function in plants is contained in the experiments of Gordon (Ref. 9-1). This work should be expanded and extended to include consideration of evolutionary implications.

In all of these studies, a continuing effort is required to construct theories interrelating known facts and observations. These theories will, in turn, lead to the generation of hypotheses that may be tested by experiments, thus supplying further observations. By maximum utilization of theoretical guidance, research in gravitational biology in the space program will be conducted in a more systematic and fruitful way.

An additional point of concern centers around the current state of background knowledge and experiment planning activities. The development of criteria for making meaningful evaluations and selecting appropriate experiments and research areas is rendered extremely difficult by the absence of good information (or, indeed, in many cases, any information at all) as to what kind and quality of baseline data may be expected from current and planned programs. For example, several of the experiments mentioned in the report are regarded by the scientific community generally as being fascinating experiments of potentially great significance. It is recommended, therefore, that simple versions of these experiments be performed in earlier, less sophisticated vehicles to develop baseline data for the detailed planning of the sophisticated experiments analyzed and discussed in this study.

Advantage must be taken and utilization made of other environmental factors. In addition to weightlessness, the effects of the reduced and changing magnetic field, cosmic radiation, and the absence of or change in the diurnal cycle should be considered, both individually and in combination to ascertain possible synergistic effects.

The current study has investigated selected portions of an overall program. One of the firm conclusions reached is that certain corollary studies must now be initiated to complete the program planning effort.

9.5.3 Program and Scientific Equipment Development

The operation of a space bioscience laboratory will involve many people and pieces of equipment both on the ground and in orbit. It is a complex task and should receive serious consideration at the earliest possible date to assure that equipment is developed and personnel are trained to accomplish the mission in the most effective way. This study should produce the following components for planning the operation:

1. Experiment Sequential Plan. A method must be established by which the principal steps in each experiment may be identified and their chronological order and expected duration analyzed. Possible steps include devising some significant experiments, conducting preliminary ground work, and planning flight tests. If the experiment involves steps with complex interrelationships and alternatives, a PERT or Planalog chart may be utilized to show the steps and their time relationships.
2. Flight Operations Plan. From the viewpoint of the bioscience laboratory, potential problems in prelaunch, launch support, orbital operations, ground support of orbital operations, and post-flight operations must be identified, and courses of action to achieve solutions to the problems must be recommended.

   A tentative list of ground equipment should be prepared and recommendations for development of equipment should be presented where necessary.

Preliminary specifications for recommended ground equipment should be prepared if the equipment is not in the current inventory, under development, or in current plans for the program time period.

3. Crew Requirements. The study must consider crew requirements and relate them to existing NASA astronaut training programs. For these experiments professional bioscientists will be required. The nature of the experiments will require expert experimenters who have extensive experience with similar experiments on the ground. It must be possible to identify, select and flight-train this type of experimenter in time for the first phase of the program.

Planning and analysis efforts should also consider and integrate the following:

1. Projected flight schedules
2. Projected vehicle development schedules
3. Projected booster availability
4. Operational constraints
5. Sequencing of experimental program
6. System interface requirements

Several facility and equipment items requiring further immediate consideration have been identified. It is recommended that because of the long lead times involved in the development of some of these items, preliminary design effort should be undertaken promptly. These items must all achieve both reliability and convenience of operation in the weightless environment. These items include the following:

1. Photographic processing equipment and facilities
2. Isotope handling facilities
3. Facilities and equipment for wet laboratory operations
4. Facilities and equipment for orbital histology, including a fume hood for the management of the many toxic and hazardous vapors

5. Microtomy equipment
6. Micromanipulators
7. Combined life support and observation provisions for cultures and specimens
8. Special long-working-distance stereo-microscope with integrated stereo-camera unit
9. Versatile compound microscope with provisions for a wide range of interchangeable optics and mechanical accessories
10. An optical instrument combining the capability for densitometry, spectrophotometry, nephelometry, and light-scattering photometry

Attacking some of the problems connected with design of such a selection of apparatus for use in bioscience experimentation will serve to clarify and define many of the spacecraft interfaces.

9.5.4 Academic-Government-Industry Interface and Communications

The biological measurements and experiments adopted as comprising a bioscience program for planning purposes must be considered as tentative. As planning proceeds, it is hoped that a large number of additional experiments will be suggested by scientists too busily engaged in other research activities to participate in planning efforts at this time. At present, however, the most creative minds in the bioscientific community cannot be induced to concern themselves seriously with the details of planning experiments which may be conducted sometime in the far future. This is in large part a function of the unfamiliarity of the bioscientific community with long-lead-time development problems involving the commitment of resources on an extremely large scale. At the same time, interest in the general subject of the effects of weightlessness on biological processes is high among bioscientists. The experiments selected by this study are sufficient to define a worthwhile bioscience program for present planning purposes, and to indicate that, once the planning is sufficiently firm to speak of scheduling firm design efforts, considerably more detail can be developed rapidly for the bioscience research activities.

A further problem area requiring serious immediate consideration involves the selection of scientists for orbital participation in the program. The special training required of astronauts for performance of the suggested experiments indicates that prior training and prior interest should be the main consideration in the selection of scientist-astronauts. The first criterion in selecting such personnel should not be age and physical characteristics, but inclination, interest, and training. While specific training can be suggested, it is hard to specify that quality of general curiosity which will be essential in a man who for the first time examines a new realm of nature. The importance of suitable physical standards should, of course, not be neglected, but it may be possible or even necessary to compromise on many physical qualifications in order to obtain the best-qualified men for the research program.

Finally, consideration must be given to achieving the broadest possible participation in the program in terms of both contributory inputs and dissemination and utilization of the outputs. The space bioscience program to date has been criticized as having insufficient participation and representation of the biological community and inadequate communication with working bioscientists. A recommended approach to the problem of communication is depicted in Fig. 9-4.

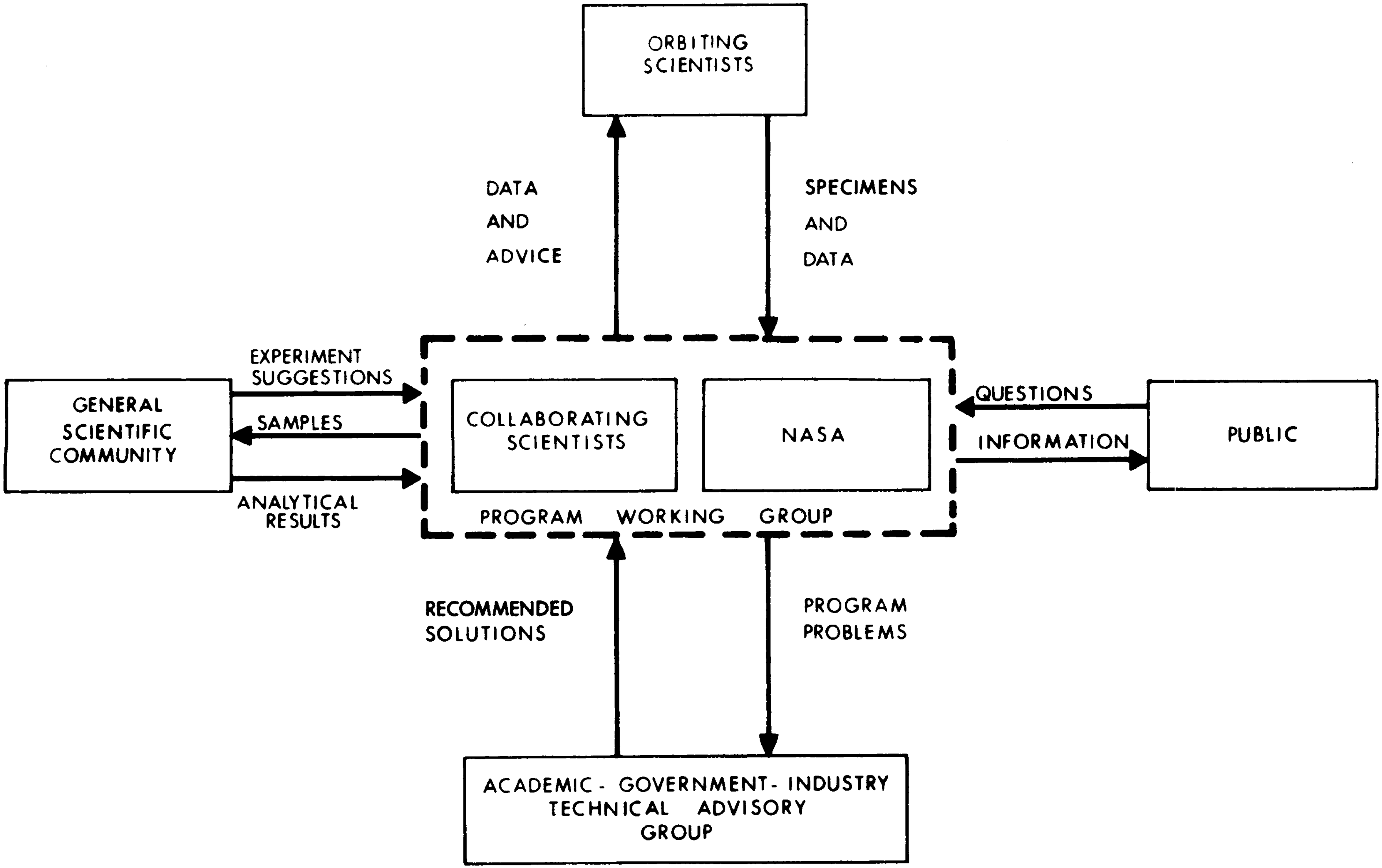


FIG. 9-4 PROPOSED LINES OF COMMUNICATION

REFERENCE
Section 9

9-1 S. A. Gordon, Proc. 24th Annual Biol. Colloq. (April 1963)

APPENDIX A

THE STATICS AND DYNAMICS OF A MATERIAL SYSTEM CONTAINED WITHIN AN ORBITING VEHICLE

APPENDIX A

THE STATICS AND DYNAMICS OF A MATERIAL SYSTEM CONTAINED WITHIN AN ORBITING VEHICLE

1. INTRODUCTION

Problems involving the statics and dynamics of a "material particle" within an orbiting vehicle have been treated in the literature for some special situations. To the extent that an actual material system within the vehicle can be idealized as a "very small" rigid body, the description of relative motion (or absence of it) developed for the "particle" should suffice.

However, if one wishes to look more deeply into the force fields within and relative motion of internal systems which are nonrigid continua, a more general viewpoint must be taken. This is especially true if one wishes to search for lower bounds on theoretically realizable "zero-G" conditions which might exist over an experimental domain of reasonable size within the orbiting vehicle, when a part of this domain is occupied by a material continuum. (Most experiments are done "on something", other than free space.)

This note reviews the pertinent dynamical equations for the "material particle", then proceeds to consider the corresponding analytical description for a continuum.

2. STATICS AND DYNAMICS OF A MATERIAL PARTICLE

In [1]*, the force on a material particle constrained to remain at a fixed location within the body of an orbiting vehicle was derived. Denote by $\underline{\rho}$ the location of a field point within the vehicle relative to a base point rigidly embedded therein, and by $\underline{\rho}_{cm}$ the location of the instantaneous center of mass of the system (consisting of the vehicle of mass M' together with a material point mass m at the field point) with respect to the same base point. Suppose that the force per unit mass from the external gravitational field is a point function $\underline{g}(P)$ (where P is any point in the neighborhood of the vehicle), that the value of this field is $\underline{g}_o$ at the base point, and that its gradient evaluated at the base point is the dyadic Φ. Denote by $\underline{F}$ the force on the mass particle by the rest of the vehicle, by $\underline{f}_1$ and $\underline{f}_2$ the non-gravitational external forces on the material particle and on the complete vehicle-particle system, respectively. Put $M = m + M'$ and $\underline{x} = \underline{\rho} - \underline{\rho}_{cm}$. Then from [1],

$$\frac{1}{m}\underline{F} = \ddot{\underline{x}} - x \cdot \Phi + \underline{f} + \ldots \tag{1}$$

where $\underline{f} = \underline{f}_2 - \underline{f}_1$ and the dots represent higher order terms in the expansion of $\underline{g}$ about the base point. The size of these neglected terms is discussed in Appendix B.

In component form relative to an arbitrary basis, Eq. 1 becomes

$$\frac{1}{m} F^k = (\ddot{\underline{x}})^k - x^p \Phi_p^k + f^k \tag{2}$$

when the higher derivatives of the gravitational field are discarded.

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*Numbers in brackets refer to references listed at the end of the appendixes.

Equation 1 or 2 gives the force exerted by the vehicle on the material particle. In particular, if this force is just sufficient to hold the apparent derivatives of $\underline{\rho}$ equal to zero -- i.e., the derivatives $\overset{\circ}{\underline{\rho}}$ and $\overset{\circ\circ}{\underline{\rho}}$ with respect to an observer fixed in an axis frame $\{\underline{e}_k\}$ rigidly embedded in the rotating vehicle -- then $\underline{F}$ is related to the output of a body-mounted proof-mass type accelerometer "located at" $\underline{\rho}$. In this case,

$$\frac{1}{m}\underline{F} = -\overset{\circ\circ}{\underline{\rho}}_{cm} - 2\underline{\omega} \times \overset{\circ}{\underline{\rho}}_{cm} + \dot{\underline{\omega}} \times \underline{x} + \underline{\omega} \times (\underline{\omega} \times \underline{x}) - \underline{x} \cdot \Phi + \underline{f} \tag{3}$$

where $\overset{\circ}{\underline{\rho}}_{cm}$, $\overset{\circ\circ}{\underline{\rho}}_{cm}$ are apparent derivatives of $\underline{\rho}_{cm}$ in the $\{\underline{e}^k\}$ frame and $\underline{\omega}$ is the angular velocity of the frame in inertial space. In component form,

$$\begin{aligned}\frac{1}{m} F^k = &- \ddot{\rho}^k_{cm} - 2\, \epsilon_{pqr}\, \delta^{kp}\, \omega^q\, \dot{\rho}^r_{cm} + \epsilon_{pqr}\, \delta^{kp}\, \dot{\omega}^q\, x^r + \\ &\omega^k\, \omega^p\, x^q\, \delta_{pq} - x^k\, \omega^p\, \omega^q\, \delta_{pq} - x^p\, \Phi^k_p + f^k\end{aligned} \tag{4}$$

Although the derivation of an accelerometer output was the motivation of [1], Eq. 3 or 4 suffices as a basis for the statics of any material particle in a space vehicle. An especially important form of Eq. 4 occurs when the center of mass of the main vehicle remains stationary itself with respect to the vehicle, so that $\dot{\rho}^k_{cm} = \ddot{\rho}^k_{cm} = 0$ and one obtains

$$\frac{1}{m} F^k = \delta^{kp}\, \epsilon_{pqr}\, \dot{\omega}^q\, x^r + \omega^p\, \omega^q\, x^s\, (\delta^k_p\, \delta_{qs} - \delta^k_s\, \delta_{pq}) - x^p\, \Phi^k_p + f^k \tag{5}$$

Equation 5 was given in essence by Synge in 1959 [2] in connection with the behavior of a pendulum in a satellite (the practical considerations for which had already been discussed in [3]). However, he applied it only in the static case to find equilibrium orientations of the pendulum within a rigid vehicle on a circular orbit, putting $f^k = 0$, $\omega^k = \omega_o \Theta_2^k$, $\Phi_p^k = \omega_o^2 (3 \Theta_3^k \Theta_3^q \delta_{pg} - \delta_p^k)$. Here, the orbital angular velocity ω_o is assumed constant, and Θ_p^k denotes the direction cosine between the k^{th} body axis and the p^{th} orbit axis $\underline{\xi}^p$, $\underline{\xi}^3$ being the local outward vertical and ξ^2 being the normal to the orbit plane. The constraint force $\underline{F}$ is taken along the line of the pendulum, $F^k = - \lambda (x^k - x_o^k)$ where $\underline{x}_o$ is the $\underline{x}$ -value at the pendulum suspension point and λ is the tension which becomes a Lagrange multiplier of the problem. Under these assumptions, Eq. 5 reduces to

$$(\Theta_2^k \Theta_2^p - 3 \Theta_3^k \Theta_3^p) \delta_{pg} x^q = - \frac{\lambda \delta_q^k}{m \omega_o^2} (x^q - x_o^q) \qquad (6)$$

Actually Synge assumed the pendulum suspension was at the center of mass so that $\underline{x}_o \equiv 0$. Equation 6 is in the form of a standard eigenvalue problem. The simplest way to visualize the solution is to assume that the vehicle itself is oriented precisely with the ξ-frame, so that $\Theta_p^k = \delta_p^k$, so that the eigenvalues are $\frac{\lambda}{m \omega_o^2} = 0, -1, 3$ and the corresponding eigenvectors are $\{\pm\ell, 0, 0\}$, $\{0 \pm\ell, 0\}$, $\{0, 0, \pm\ell\}$ (recalling the constraint $|\underline{x} - \underline{x}_o| = \ell$, the pendulum length). In other words, the equilibrium orientations are fore or aft, left or right, up or down in the cabin. The case where the vehicle is aligned arbitrarily is best considered by introducing the coordinates x'^s of the point with respect to the ξ-frame, by putting $x^q = x'^s \Theta_p^q \delta_s^p$ into Eq. 6. It is easy to see that the same eigenvalues exist and that the eigenvectors themselves are the same, except now they refer to the ξ-frame rather than the body frame. Thus, the physical interpretation of the equilibrium orientations also remain the same.

The dynamics of a particle inside or near a spacecraft, in the sense of motion with respect to the craft, has been considered for special situations by several authors. In 1958, Hord [4] discussed the relative motion with application to the problem of terminal approach of one vehicle to another (both on "free fall" trajectories). In this case, there is no force on the "particle" (approaching vehicle) physically applied by the "target", so that F^k in Eq. 4 is zero. However, f^k generally is not, since propulsive forces may act on either vehicle during the approach. In effect, then, Hord began with the vector equation $\ddot{\underline{x}} = \underline{x} \cdot \Phi - \underline{f}$. He determined the magnitude and direction of the force $\underline{x} \cdot \Phi$ for special relative positions, considered a specific terminal guidance law which made $\underline{f}$ proportional to the unit vector along $\underline{x}$, and analyzed the latter neglecting the gravity gradient acceleration. Hence, except to conform Eq. 4 for a specific situation, his work has no direct application to the behavior of nonpropelled "floating" subsystems of the vehicle.

Some rather similar results are surveyed in [5]. Note that Eq. 1 can be solved completely in a certain case. Consider a free-floating particle (so $F^k = 0$) on which no nongravitational force acts, and assume that the vehicle itself is also free of nongravitational force so that $f^k = 0$. The frame $\{\underline{e}_k\}$ discussed previously in obtaining Eq. 4 from Eq. 1 was specified for simplicity to be rigidly bound to the vehicle. Actually, however, there is no loss in generality if it is interpreted as any rotating frame, provided the ω^k components are the components of angular velocity of that frame resolved into that frame itself, and the $\underline{x}$ and its apparent derivatives are also resolved into components with respect to this general rotating frame. In particular, the frame can be chosen as the orbit frame $\{\underline{\xi}_k\}$. Assume that the orbit is plane (a good but not perfect approximation) though not necessarily circular, so that $\underline{\omega} = \omega_o(t)\, \underline{\xi}_2$, $\Phi = \frac{\mu}{r^3}(-\underline{\xi}_1 \underline{\xi}_1 - \underline{\xi}_2 \underline{\xi}_2 + 2\underline{\xi}_3 \underline{\xi}_3) = \Phi_{pq}\, \underline{\xi}_p \underline{\xi}_q$, where μ is the gravitational constant of the attracting body and r is the radial distance of the center of mass of the orbiting system from it. Equation 2 reduces to

$$\ddot{x}^k + 2\,\omega_o\, \delta^{kp}\, \epsilon_{2qp}\, \dot{x}^p + \dot{\omega}_o\, \delta^{kp}\, \epsilon_{2qp}\, x^q + \omega_o^2\, (\delta^{k2}\, x^2 - x^k) + x^p\, \Phi_{pq}\, \delta^{kq} = 0 \qquad (7)$$

If, further, it is assumed that ω_o is constant, then Eq. 7 can be expanded into

$$\ddot{x}^1 + 2\omega_o \dot{x}^3 = 0 \tag{8a}$$

$$\ddot{x}^2 + \omega_o^2 x^2 = 0 \tag{8b}$$

$$\ddot{x}^3 - 2\omega_o \dot{x}^1 - 3\omega_o^2 x^3 = 0 \tag{8c}$$

whose solutions are

$$x^2 = \frac{\dot{x}_o^2}{\omega_o} \sin\omega_o t + x_o^2 \cos\omega_o t \tag{9a}$$

$$\begin{aligned} x^1 &= x_o^1 + \dot{x}_o^1 t - 2 \frac{\dot{x}_o^3}{\omega_o}(1 - \cos\omega_o t) \\ &\quad - \frac{2}{\omega_o} (2 \dot{x}_o^1 + 3\omega_o x_o^3) (\omega_o t - \sin\omega_o t) \end{aligned} \tag{9b}$$

$$x^3 = x_o^3 \cos\omega_o t + \frac{\dot{x}_o^3}{\omega_o} \sin\omega_o t + \frac{2}{\omega_o} (\dot{x}_o^1 + 2\omega_o x_o^3) (1 - \cos\omega_o t) \tag{9c}$$

where the subscript o refers to the state at t = 0. Equations 9 are plotted in Figs. 1, 2, and 3 for an orbital altitude of 400 km (orbital period = 92.66 minutes, $\omega_o = 1.13 \times 10^{-3}$ rad/sec) and initial conditions of $x_{10} = x_{20} = x_{30}$, $\dot{x}_{10} = \dot{x}_{20} = \dot{x}_{30} = 0$.

These equations are given in several of the references cited in [5]. No attempt has been made to trace their origin. They state that a free particle moves in an approximately cycloidal pattern about the composite center of mass, with the axis of the cycloid parallel to the ξ^1-axis, meanwhile executing simple harmonic motion in and out of the plane of the orbit. Both the latter and the cycloidal motion have a period equal to that of the orbit.

The treatments discussed above were rather limited in generality, though the approach culminating in Eqs. 8 and 9 has the advantage of providing considerable insight into the relative motion. However, Lur'e more recently [6] has given an almost completely general solution

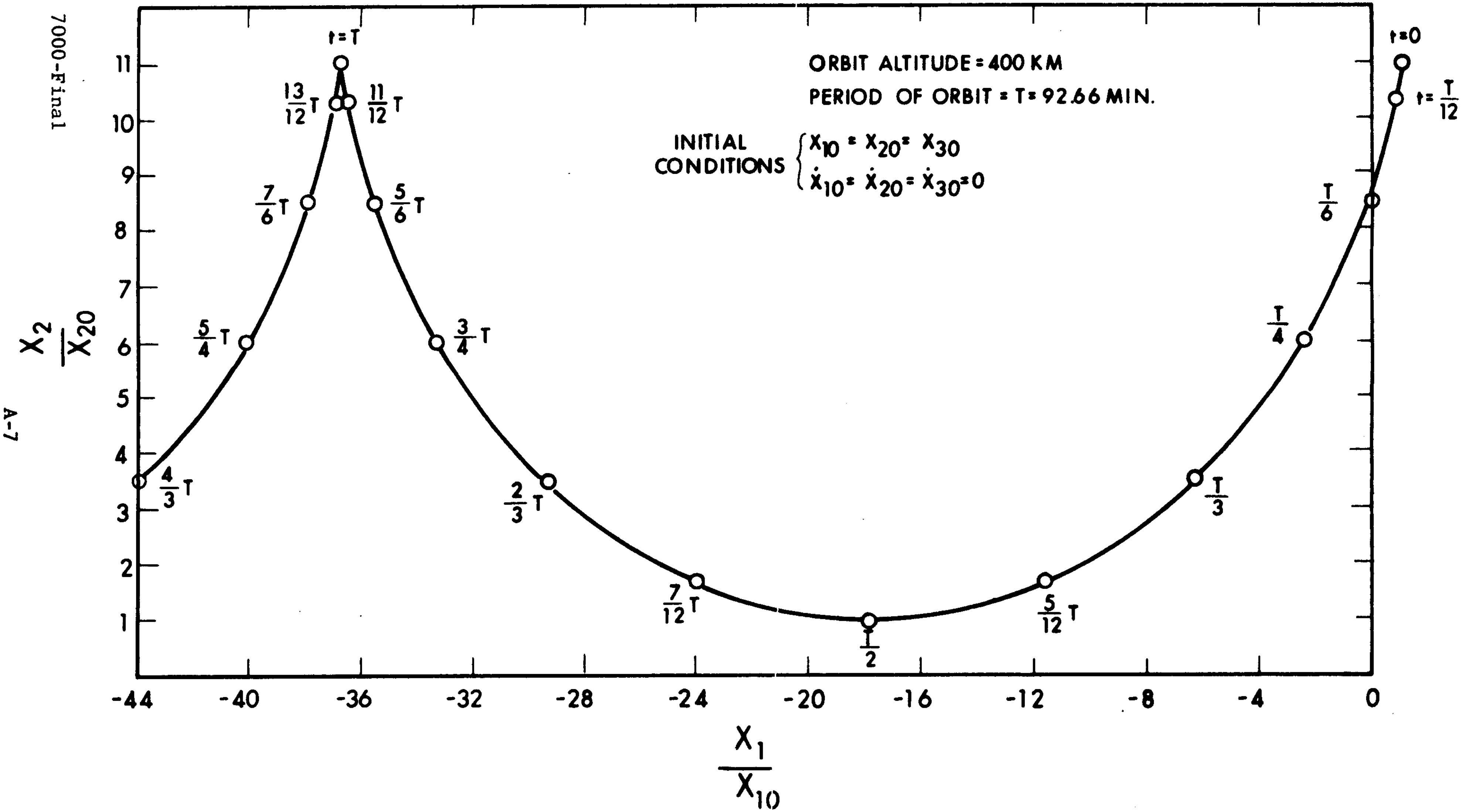

FIG. 1 MOTION OF FREE PARTICLE IN $x_1 x_2$ PLANE

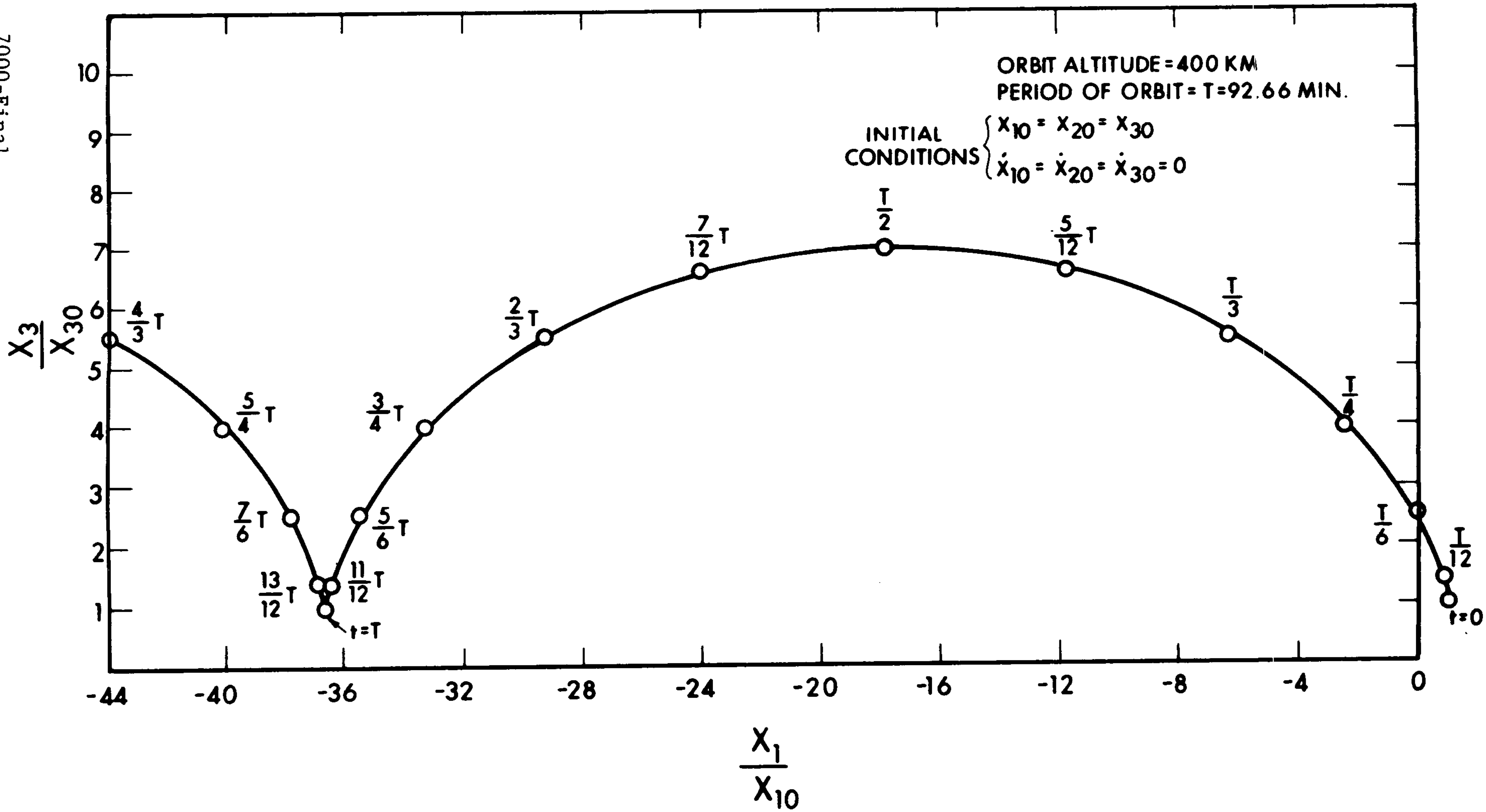

FIG. 2 MOTION OF FREE PARTICLE IN x_1x_3 PLANE

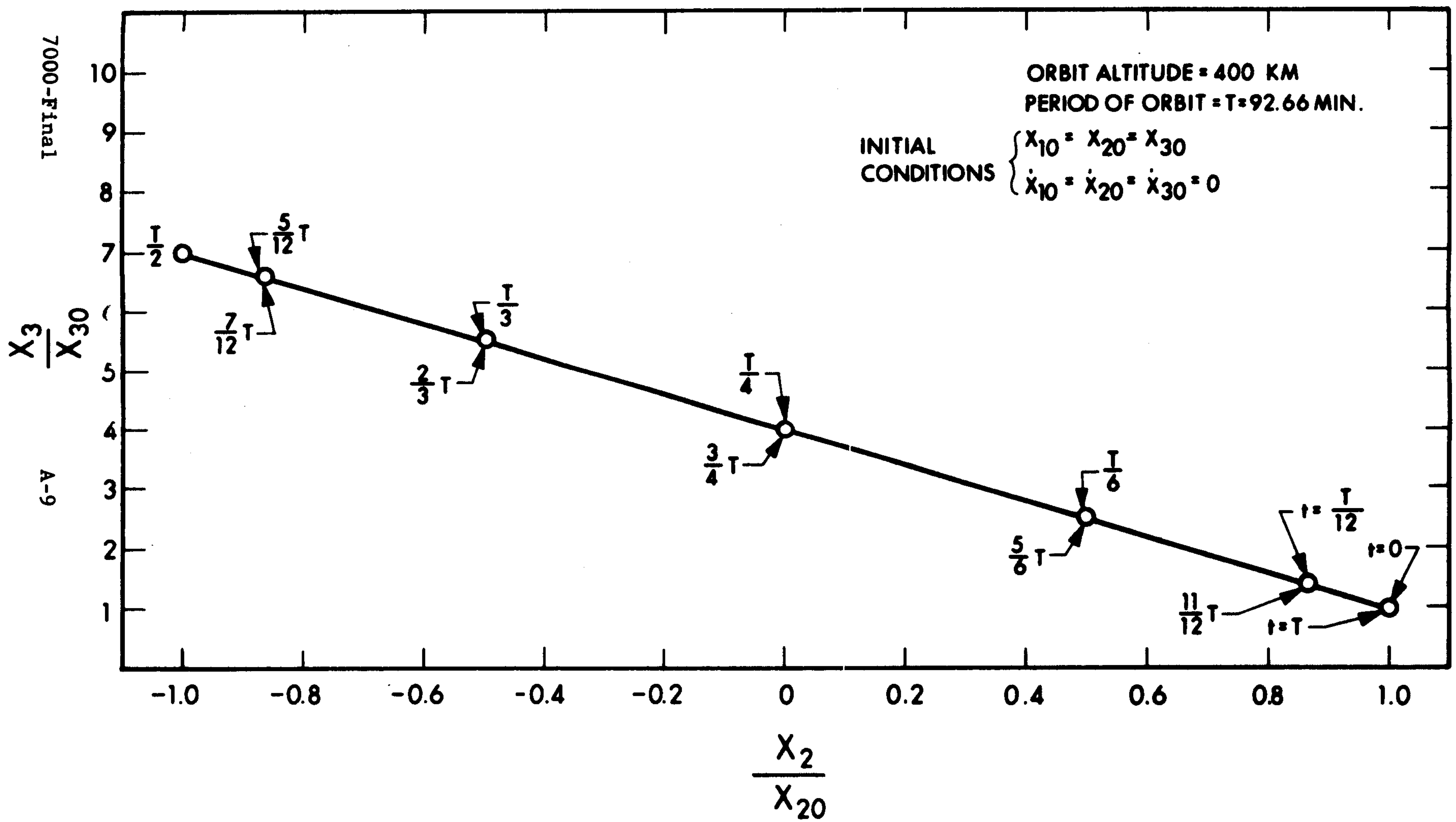

FIG. 3 MOTION OF FREE PARTICLE IN x_2x_3 PLANE

to the linearized problem of relative motion characterized by Hord's vector equation (i.e., Eq. 1 with $\underline{F} = 0$). Arbitrary orbit eccentricity is permitted, the only restriction being that during the solution time of interest the vehicle orbit is indeed a two-body orbit. He defines a set of six vector functions $\underline{q}_s(t)$ and their derivatives $\dot{\underline{q}}_s(t)$ (given explicitly in Appendix C to this work) in terms of which he writes

$$\underline{x} = \sum_{s=1}^{6} C_s \underline{q}_s, \quad \dot{\underline{x}} = \sum_{s=1}^{6} C_s \dot{\underline{q}}_s(t) \tag{10}$$

as solutions to the homogeneous equation ($\underline{f} = 0$).

The constants C_s are to be determined by the initial relative motion of the particle, which Lur'e always takes as a state of zero relative velocity. The base vectors in terms of which he expresses the $\underline{q}_s$ are precisely the $\{\underline{\xi}_k\}$ discussed previously, but it is simple enough to translate the motion into a vehicle-fixed frame if the angular motion of the latter is known. He gives explicit forms of the simplified results for several special cases, including the circular orbit and a variety of assumptions concerning $\underline{\omega}$.

Since the problem is a linear one, the solution of the nonhomogeneous case ($\underline{f} \neq 0$) can be obtained from the homogeneous solution by quadrature. Lur'e does this in general terms, and considers explicitly the case of aerodynamic force.

In summary, questions of the statics and dynamics of a material particle within a space system can be considered settled to the following extent:

1. If the particle is rigidly bound to the vehicle, the constraint force can be found when the vehicle angular velocity and center of mass behavior are known. (Eqs. 4, 5)
2. If the particle is free of the vehicle, its relative motion can be found completely in a reference frame $\{\underline{\xi}_k\}$ related to the orbit, provided only that the vehicle itself describes two-body motion about the central body. (Eq. 10 and Appendix C)

3. If the particle is nonrigidly attached to the vehicle, the only treatment seems to be that of Synge (for the specific case of an internal pendulum under quite specialized conditions). For this category of situations, the problem cannot be considered solved.

It should not need emphasizing that these remarks are only within the framework of the <u>linearized</u> equations of relative motion (Eq. 1 and the others derived from it). No investigations seem to have been published which include higher order terms in the expansion of the gravity function about $\underline{x} = 0$. (However, see Appendix B.)

3. CONSTRAINED INTERNAL MOTION OF PARTICLE

If neither $\overset{\circ}{\underline{\rho}} = 0$ nor $\underline{F} = 0$, it must be presumed that the particle is free to move within the vehicle but that it is subject to some interaction force which depends on its internal position. In particular, mutual gravitational attraction between vehicle and particle is of this class. Since this interaction force reacts back upon the vehicle itself, Eq. 1 for the particle must in this case be supplemented by the dynamical equations for the vehicle, and these equations must be solved simultaneously. If the particle mass is very small, the coupling between these equations will be very weak, to be sure, and may be negligible in practice. However, it is necessary to investigate the matter by formulating the dynamical basis properly.

Denote by $\underline{r} = \underline{r}(t)$ the location of the vehicle base point with respect to an inertial frame of reference. Denote by $\underline{H}$ the angular momentum of the main body of the vehicle, not including the internal material system, with respect to the center of mass of the vehicle alone. Also, let $\underline{L}$ be the torque of external effects on the main body with respect to the same point. Using other symbols in the sense specified previously, the dynamical equations of the system can be written as Eq. 1 plus

$$\ddot{\underline{r}} + \ddot{\underline{\rho}}_{cm} = \underline{g}_o + \underline{\rho}_{cm} \cdot \Phi + \dots + \underline{f}_2 \tag{11}$$

$$\frac{d\underline{H}}{dt} = \underline{L} + \frac{M}{M'} (\underline{\rho}_{cm} - \underline{\rho}) \times \underline{F} \tag{12}$$

(One merely writes the equations of translation and rotation for the main body and particle separately, then translates them into present notation. The particle is assumed to have no rotational inertia, so no rotational equation is written for it.)

It is more convenient to reexpress Eq. 12 in terms of angular momentum and torque with respect to the fixed base point, since the center of mass with respect to which they now are defined generally moves with respect to the main vehicle body frame. For this purpose define: J, the inertia dyadic of the main vehicle (not including the material particle) calculated with respect to the base point and not necessarily constant if the main body is nonrigid or contains other moving parts; $\underline{\omega}$, the angular velocity of the main body in inertial space (not simply of an arbitrary basis $\{\underline{e}_k\}$ as in Eq. 3 et seq.); $\underline{h}$, the angular momentum about the base point from any nonrigid character of the main body, i.e.

$$\underline{h} = \int_{B_1} \underline{\rho}' \times \overset{o}{\underline{\rho}}' \, dm \tag{13}$$

where $\underline{\rho}'$ locates a point of the main body with respect to the base point, $\overset{o}{\underline{\rho}}'$ denotes an apparent time derivative as before, and the integral is carried out over the material system which constitutes the main body; $\underline{L}^*$, the torque of external forces calculated with respect to the base point (including any body couples which do not arise from external forces). It actually is more convenient to subdivide $\underline{L}^*$ further into $\underline{h}$, the contribution from nongravitational effects, plus a gravity torque as

$$\begin{aligned} \underline{L}^* &= \underline{h} + \int_{B_1} \underline{\rho}'' \times (\underline{g}_o + \underline{\rho}'' \cdot \Phi) \, dm \\ &= \underline{h} + M' \underline{\rho}_{cm} \times \underline{g}_o + \int_{B_1} \underline{\rho}'' \times \frac{\mu}{r^3} (- E + 3\underline{\xi}_3\underline{\xi}_3) \cdot \underline{\rho}'' \, dm \\ &= \underline{h} + M' \underline{\rho}_{cm} \times g_o + \frac{3\mu}{r^3} \underline{\xi}_3 \times J \cdot \underline{\xi}_3 \end{aligned} \tag{14}$$

In these terms and in view of Eq. 14, Eq. 12 takes the form

$$\frac{d}{dt}(J \cdot \underline{\omega} + \underline{h}) + M' \boldsymbol{\rho}_{cm} \times \ddot{\boldsymbol{\rho}}_{cm} = \underline{\ell} - \frac{m\mu}{r^3} \boldsymbol{\rho}_{cm} \times \boldsymbol{\rho}$$

$$+ \frac{3\mu}{r^3} \boldsymbol{\xi}_3 \times [J + M \boldsymbol{\rho}_{cm} (\boldsymbol{\rho}_{cm} - \frac{m}{M} \boldsymbol{\rho})] \cdot \boldsymbol{\xi}_3$$

$$- \boldsymbol{\rho}_{cm} \times (M \underline{f}_2 - m \underline{f}_1) + \frac{M}{M'} (\boldsymbol{\rho}_{cm} - \boldsymbol{\rho}) \times \underline{F} \qquad (15)$$

The three equations, Eqs. 1, 11, and 15 are to be considered a simultaneous set for the three vector unknowns, $\underline{r}$, $\boldsymbol{\rho}$, and $\underline{\omega}$. It is assumed, of course, that $\underline{F}$ is specified in some way, as are all of the external nongravitational forces and torques. The variables, $\underline{h}$ and $\boldsymbol{\rho}_{cm}$ may seem to present some difficulty. The latter, of course, is given by

$$M \boldsymbol{\rho}_{cm} = m\boldsymbol{\rho} + \int_{B_1} \boldsymbol{\rho}' \, dm \qquad (16)$$

so that the problem is in the evaluation of the integrals over B_1 in Eqs. 13 and 16. There are two possibilities. If the structure of the main vehicle is prescribed, i.e., known purely as a time function (and, in particular, if the structure is constant so that $\underline{h} = 0$), then both integrals are compatible from independently given data and do not add any unknowns to the dynamical equations. On the other hand, if the structure of the main body is time-variable in some other way (e.g., if it is a flexible continuum whose motions are themselves excited by $\underline{\omega}$), then it is necessary to adjoin other dynamical equations to the set to make the problem determinant.

Subsequent remarks are limited to the case of a fixed structure of the main body, since the other cases are too broad for inclusion here. If the structure does not vary with time, it follows that

$\int_{B_1} \underline{\rho}' \, dm$ is constant, in which case there is no special reason for choosing the base point anywhere but at the main vehicle center of mass, so that this latter integral is zero. In this case, the equations take the particularly though still widely applicable simple form

$$\underline{\rho}'' + \frac{\mu}{r^3} \underline{\rho} \cdot (E - 3\underline{\xi}_3\underline{\xi}_3) = \frac{1}{M'} \underline{F} - \frac{M}{M'} \underline{f} \tag{17a}$$

$$\ddot{\underline{r}} = \underline{g}_o + \frac{1}{M'} (M \underline{f}_2 - m \underline{f}_1 - \frac{m_r}{M} \underline{F}) \tag{17b}$$

$$J \cdot \dot{\underline{\omega}} + \underline{\omega} \times J \cdot \underline{\omega} = \underline{h} + \frac{3\mu}{r^3} \underline{\xi}_3 \times (J + \frac{m_r m}{M} \underline{\rho}\,\underline{\rho}) \cdot \underline{\xi}_3$$

$$- \underline{\rho} \times [(1 + \frac{m_r}{M'}) \underline{F} + m_r \underline{f}_1] \tag{17c}$$

where m_r is the reduced mass $mM'/M \approx m$. The first of these is in the same general form as Eq. 1, so that all of the previous discussion of that equation and its alternative forms still applies. In Eq. 17b, the combination $M \underline{f}_2 - m \underline{f}_1$ is (returning to basic definitions) simply the nongravitational force on the main vehicle not including the proof mass.

4. FUNDAMENTAL EQUATIONS OF CONTINUUM MECHANICS

Consider a material system B enclosed by surface S (B to be identified with the orbiting vehicle including its "subsidiary" material system F), and let $B' \subseteq B$ be any material subset of B enclosed within surface S'. The following quantities are defined over B. Let $\underline{f}_E + \underline{f}_M$ and $\underline{\ell}$ be fields of "assigned forces" and "assigned couples" respectively in the sense of Truesdale and Toupin ([7], p. 537). Specifically, $\underline{f}_E$ and $\underline{f}_M$ are respectively the fields of extrinsic and mutual forces per unit mass, while $\underline{\ell}$ represents couples per unit mass from non-Newtonian forces. Let $\underline{t}_{(n)}$ and $\underline{m}_{(n)}$ respectively represent fields of stress vectors and couple stresses on the surface S'. Define position vectors of points as shown in Fig. 4, and refer axial torque and angular momentum vectors to the base point BP selected arbitrarily within B'. Provided only that the force and couple fields are limited to integrable functions (excluding concentrated loads unless the integrals are appropriately generalized to Lebesgue-Stieltjes integrals), one may write the dynamical equations of the continuum in integral form, following ([7], p. 537), as

$$\frac{d}{dt}\int_{B'} \dot{\underline{r}}\, dm = \int_{B'} (\underline{f}_E + \underline{f}_M)\, dm + \int_{S'} \underline{t}_{(n)}\, da \tag{18}$$

$$\frac{d}{dt}\int_{B'} \underline{\rho} \times \dot{\underline{r}}\, dm = \int_{B'} [\underline{\ell} + \underline{\rho} \times (\underline{f}_E + \underline{f}_M]\, dm + \int_{S'} [\underline{m}_{(n)} + \underline{\rho} \times \underline{t}_{(n)}]\, da \tag{19}$$

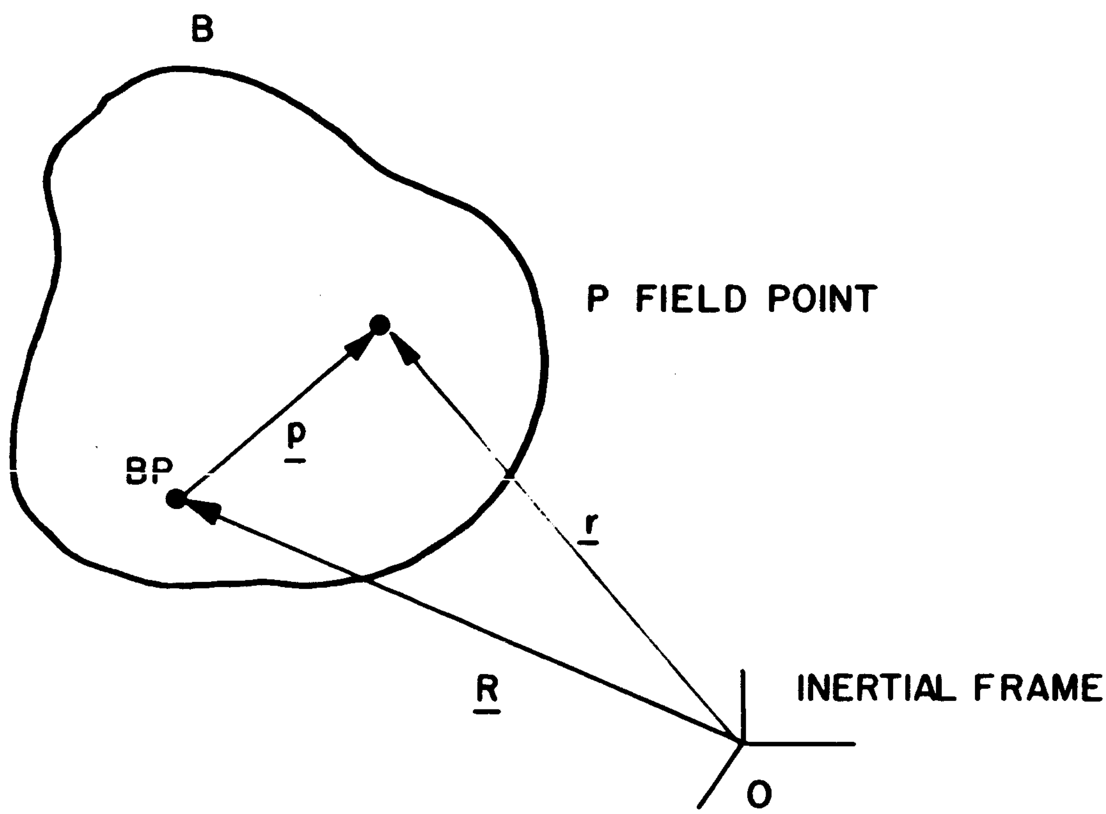

FIG. 4

As in ([7], p. 543), introduce stress tensor t^{km} and a tensor m^{kqp} (skew-symmetric in the first two indices) such that on any surface element whose unit normal vector is* n_m, one has $t^k_{(n)} = t^{km} n_m$ and $m^{kq}_{(n)} = m^{kqp} n_p$. Here $m^{kq}_{(n)}$ is the skew-symmetric tensor formed from vector $m^k_{(n)}$ (i.e., $m^{kq}_{(n)} = \epsilon^{kqp} \delta_{ps} m^s_{(n)}$). In these forms, Eqs. 18 and 19 can be recast as

$$\frac{d}{dt} \int_{B'} \dot{r}^k \, dm = \int_{B'} (f^k_E + f^k_M) \, dm + \int_{S'} t^{kp} \, da_p \tag{20}$$

$$\begin{aligned} \frac{d}{dt} \int_{B'} \rho^{[k} \dot{r}^{p]} \, dm &= \int_{B'} [\ell^{kp} + \rho^{[k}(f_E + f_M)^{p]} \, dm \\ &+ \int_{S'} (m^{kpq} + \rho^{[k} t^{p]q}) \, da_q \end{aligned} \tag{21}$$

Let δ be the density point function for the material system, and suppose that t^{km} and m^{kpq} are continuously differentiable and that $\delta\ddot{r}^k$, $\delta(f_E + f_M)^k$ and $\delta\ell^{kp}$ are continuous. From a known integral theorem,** necessary and sufficient conditions for the balance of linear and angular momentum follow as the differential equations

$$\begin{aligned} \delta \, (\ddot{R}^k + \ddot{\rho}^k) &= t^{km}, m + \delta \, (f^k_E + f^k_M) \\ m^{kpq}, q + \delta \, h^{kp} &= t^{[kp]} \end{aligned} \tag{22}$$

These are called by Truesdale and Toupin the "fundamental equations of continuum mechanics"; the first is also called "Cauchy's first law of motion".

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*Component forms are used hereafter.

**Based on the fact that Eqs. 20 and 21 hold for arbitrary $B' \subseteq B$. (see ([6], pp. 468, 545).

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APPENDIX B

THE GRAVITATIONAL ENVIRONMENT WITHIN AN EARTH SATELLITE

by

Robert E. Roberson

ABSTRACT

A model is developed for the gravitational environment caused by external fields at points away from the center of mass of an earth satellite. It is shown that: 1) the fields of sun, moon and planets can be neglected relative to that of the earth; 2) quadratic terms in the displacement from the center of mass generally can be ignored, but for certain exceptional cases when they are included they can be based purely on the inverse square attraction of the earth; 3) the linear gravity gradient terms from the earth can be obtained to considerably better than one part in 10^3 by keeping only the $C_{2,0}$ asphericity terms. By far the largest part of the gravitational environment is a constant term of magnitude 0.31353×10^{-6} $(r_0/a)^3$ earth "G" per meter of displacement away from the center of the earth. Asphericity modifies this by not more than about 0.5 percent. For orbits with eccentricity $e \leq 0.03$, a first harmonic of orbital frequency occurs with an amplitude below 10 percent of the constant value. No other harmonics should have an amplitude more than a small fraction of 1 percent of that constant.

APPENDIX B

THE GRAVITATIONAL ENVIRONMENT WITHIN AN EARTH SATELLITE

1. INTRODUCTION

One of the best-known phenomena of space flight is the apparent weightlessness of objects inside a vehicle which is freely following its natural gravitational trajectory. The effect can be described in more precise terms as follows. Suppose that a material particle is situated at a point P which is the center of mass of a space vehicle. Suppose further that both vehicle and particle are acted upon only by the gravitational field force of an external mass distribution.* Then, aside from the effects of the mutual interaction force between vehicle and particle, P is an equilibrium position of the particle. No effective external force acts to make the particle drift away from P.

A second property is perhaps less widely recognized, although there is a substantial body of literature based on it. Again leaving aside mutual interaction forces, if the material particle is located anywhere within the vehicle except at P, an effective external force generally does act upon it and causes it to drift within the vehicle. The appearance of this force often is characterized as the "gravity gradient effect" because it depends on gravitational field differences between point P (the center of mass) and other points P' within the vehicle.

Although the calculation of the force gradient tensor has an established place in the astronautical literature, there seems to have been no systematic exploration of the complete gravitational environment within a space vehicle, especially an earth satellite. The detailed nature of the internal field becomes very important in attempting to define the lower limits of a "gravity-free" environment within a vehicle such as an orbiting laboratory, and to determine essential

*This qualification can be replaced by a weaker one in terms of specific forces from all sources, but only the gravitational effects are considered here.

gravitational periodicities under these circumstances. This Appendix concerns such questions.

Numerical results are given from which a model of the internal gravitational environment (created by <u>external</u> fields) may be selected at any prescribed G-level.* It should be understood clearly that the apparent forces arising from spacecraft rotation are not considered. Coriolis and centripetal effects fall out automatically from the dynamical description of the motion of the particle as seen by a spacecraft-fixed observer. This topic is developed elsewhere.

2. APPROACH AND BASIC RELATIONS

The total gravitational potential $U(P')$ at any point P' in the neighborhood of the vehicle** P is a sum of functions $U_{B_i}(P')$, each of which corresponds to a particular material body B_i contributing to the gravitational field at P'. Because the potentials are additive we may consider the gravitational force field from each body separately and later add the results. Let r, θ, λ be spherical coordinates which describe the field point P' with respect to the center of mass of an arbitrary one of the attracting bodies, say B_i. In this development θ is geographic latitude (not co-latitude as in a common convention for spherical coordinates) and λ is geographic longitude measured positively "eastward" from Greenwich.

It is well known that the gravitational potential of an arbitrary mass distribution can be written as an infinite sum of spherical harmonics. A canonical form adopted in 1961 by the International Astronomical Union for the field of the earth is

$$U_{\oplus} = \mu \left[\frac{1}{r} + \sum_{n=2}^{\infty} \sum_{m=0}^{n} \frac{r_o^n}{r^{n+1}} P_n^m (\sin\theta)(C_{n,m} \cos m\lambda + S_{n,m} \sin m\lambda) \right] \qquad (1)$$

where r_o is the equatorial radius, P_n^m is the associated Legendre function, and $C_{n,m}$ and $S_{n,m}$ are to be considered empirical constants of

*Earth "G"s are used here, with a standard value of 9.80 m/sec^2.
**Specifically, P is the center of mass of the system consisting of the vehicle and the material particle.

TABLE 1

CONSTANTS OF ATTRACTING BODIES*

Body	μ (km^3/sec^2)	Minimum R(10^8 km)	Upper Bound μ/R^2 (Earth "G")
Sun	1.325×10^{11}	1.469	0.627×10^{-3}
Moon	4.890×10^{3}	0.3564×10^{-2}	0.393×10^{-5}
Earth	3.986009×10^{5}	—	—
Mercury	2.165×10^{4}	0.7718	0.371×10^{-9}
Venus	3.244×10^{5}	0.3810	22.8×10^{-9}
Mars	4.291×10^{4}	0.5449	1.48×10^{-9}
Jupiter	1.265×10^{8}	5.877	37.4×10^{-9}
Saturn	3.788×10^{7}	11.94	2.71×10^{-9}
Uranus	5.794×10^{6}	25.79	0.0890×10^{-9}
Neptune	6.860×10^{6}	43.00	0.0379×10^{-9}
Pluto	3.312×10^{5}	42.84	0.0018×10^{-9}

*Except for the Earth, all data here and following are from [3]. For the Earth, however, [1] and [2] are used.

the body. It is assumed here that an analogous form is used for all attracting bodies of interest: the earth, the moon, the sun, the planets. In each case, of course, the gravitational constant μ, the radius r_o and the asphericity constants $C_{n,m}$, $S_{n,m}$ are to be those which pertain to the body in question. The constants with which we are concerned here, other than asphericity coefficients, are given in Table 1. The constants $C_{n,m}$, $S_{n,m}$ given by Anderle [2] are summarized in Table 2.

It will be found later as numerical results are developed that even the inverse square contributions of bodies other than the earth to the gravity differences between points P' and P are extremely small. They exceed 10^{-18} G per meter only for the sun and moon. Hence it is pointless to explore the asphericity effects of these bodies, which are still one or more orders of magnitude smaller. The largest oblateness encountered is that of Saturn (1/9.5), corresponding to a $C_{2,0}$ of the order of 2×10^{-2}. The selenopotential constants are not yet well known, but Ref. 3 gives a value of 6.27×10^{-4} for the "dynamical flattening" which implies a value of $C_{2,0}$ in the approximate range $(10^{-4}, 2 \times 10^{-4})$. If Eq. 1 is differentiated with respect to r one finds that the $C_{2,0}$ term contributes about $\left| 3/2\ C_{2,0}(r_o/r)^2\ (3 \sin^2\theta-1) \right|$ relative to the inverse square effect for the same body. Using the estimate above for $C_{2,0}$, r_o = 1738 km, $r \geq$ 356,400 km and observing that θ is not large, this relative error cannot exceed about 10^{-8} with respect to the inverse square force of the moon on the satellite. This may be magnified by a factor of two in calculating the gradient effects, but since the gravity difference from the inverse square effect itself will be seen to be only 2×10^{-14} G per meter, the additional factor of 10^{-8} brings it well below the smallest terms considered in this work. (An arbitrary cutoff at 10^{-20} G has been chosen.) We conclude that no asphericity terms except those of the earth need be considered.

Let us denote any inverse square field effect by the prescript o, and any asphericity effect by the prescript *. In view of the remarks

TABLE 2

EARTH'S GRAVITY COEFFICIENTS (AFTER ANDERLE*)
(All Coefficients Times 10^{-6})

n	m	$C_{n,m}$	$S_{n,m}$	$(C_{n,m}^2 + S_{n,m}^2)^{1/2}$
2	0	-1084.7	-	1084.7
2	1	0.3	0.08	0.085
2	2	1.59	-0.098	1.62
3	0	2.6	-	2.6
3	1	3.29	0.41	3.32
3	2	0.33	-0.31	0.46
3	3	0.081	0.24	0.25
4	0	1.5	-	1.5
4	1	-0.47	-0.55	0.72
4	2	0.060	0.15	0.16
4	3	0.0616	-0.015	0.063
4	4	-0.0087	-0.0072	0.011
5	0	0.2	-	0.2
5	1	0.03	-0.11	0.11
5	2	0.10	-0.053	0.11
5	3	-0.012	4.8×10^{-3}	1.3×10^{-2}
5	4	-0.43×10^{-3}	1.2×10^{-4}	5.7×10^{-4}
5	5	0.16×10^{-5}	-1.5×10^{-5}	1.5×10^{-5}
6	0	-0.79	-	0.79
6	1	-0.07	0.15	0.16
6	2	1.6×10^{-2}	-5.5×10^{-2}	5.7×10^{-2}
6	3	-3×10^{-4}	-1.6×10^{-3}	1.6×10^{-3}
6	4	-7.2×10^{-4}	-2.3×10^{-4}	7.6×10^{-4}
6	5	-7×10^{-5}	-6.4×10^{-4}	6.4×10^{-4}
6	6	-7.4×10^{-5}	-8.3×10^{-5}	1.0×10^{-4}
7	0	0.43	-	0.43
7	1	2×10^{-2}	6×10^{-2}	6×10^{-2}
7	2	3.5×10^{-2}	-2×10^{-2}	4×10^{-2}
7	3	4.5×10^{-3}	6×10^{-4}	4.6×10^{-3}
7	4	-0.99×10^{-3}	-5×10^{-4}	1.1×10^{-3}
7	5	2×10^{-5}	7×10^{-6}	2×10^{-5}
7	6	-3.3×10^{-5}	-1.7×10^{-5}	3.7×10^{-5}
13	13	-1×10^{-14}	2×10^{-14}	2×10^{-14}
15	13	-1×10^{-15}	-1×10^{-15}	1×10^{-15}
15	14	3×10^{-17}	-8×10^{-17}	9×10^{-17}

*His $\bar{C}_{n,m}$ is related to $C_{n,m}$ by $C_{n,m} = [(n-m)!\ (2n+1)K/(n+m)!]^{1/2}\ \bar{C}_{n,m}$ and similarly for $S_{n,m}$, where K=1 if m=0, K=2 if m≠0. (This relationship is misprinted in the preprint version of [2].)

above, the total field at the vehicle can be described to the desired accuracy by a potential function of the form

$$U = {}^{o}U_{\oplus} + {}^{*}U_{\oplus} + \sum_i {}^{o}U_{B_i} \tag{2}$$

where the summation is carried out over all bodies other than the earth and where each ${}^{o}U$ term has the general form

$${}^{o}U = \mu/r \tag{3}$$

(The μ-value and the significance of r change from term to term, of course.)

Suppose that any particular potential term in Eq. 2 is expressed in terms of the independent variables r, θ, λ that are spherical coordinates for the gravitating center under consideration. These may be designated by coordinates y^1, y^2, y^3, and the specific potential function may be denoted simply by ${}'U$, understanding that this may be ${}^{o}U_{\oplus}$ or ${}^{*}U_{\oplus}$ or any of the ${}^{o}U_{B_i}$. One may form the covariant components ${}'g_{\alpha}(P)$ of the gravitational field evaluated at point P by*

$${}'g_{\alpha} = \partial_{\alpha}{}'U \tag{4}$$

Consider a nearby point P' whose coordinates are $y^{\alpha} + dy^{\alpha}$. Then,

$${}'g_{\alpha}(P') = {}'g_{\alpha}(P) + {}'g_{\alpha,\beta}dy^{\beta} + \tfrac{1}{2}{}'g_{\alpha,\beta\gamma}dy^{\beta}dy^{\gamma} + \ldots . \tag{5}$$

where the comma denotes covariant differentiation and all covariant derivatives are evaluated at P. The total field vector is of the form ${}'\underline{g}(P') = {}'g_{\alpha}(P')\ {}'\underline{e}^{\alpha}$ when constructed from the covariant components ${}'g_{\alpha}$ given by Eq. 5, but the vectors ${}'\underline{e}^{\alpha}$ here are <u>not</u> orthonormal.

Orthonormal vectors are ${}'\underline{E}^1 = {}'\underline{e}^1$, ${}'\underline{E}^2 = r\ {}'\underline{e}^2$, ${}'\underline{E}^3 = r\cos\theta\ {}'\underline{e}^3$, whence

$${}'\underline{g}(P') = {}'g_1(P')\,{}'\underline{E}^1 + \frac{1}{r}\,{}'g_2(P')\,{}'\underline{E}^2 + \frac{1}{r\cos\theta}\,{}'g_3(P')\,{}'\underline{E}^3 \tag{6}$$

---

*Greek suffices and indices have range 1,2,3 throughout, and the summation convention is used. The notation $\partial_{\alpha} = \partial/\partial y^{\alpha}$ is Schouten's.

Further, suppose now that $\{\underline{E}^{\alpha}\}$ is the corresponding orthonormal set defined by the spherical coordinate curves for the earth itself, and that the $\{{}'\underline{E}^{\alpha}\}$ for any other body are related thereto by ${}'\underline{E}^{\alpha} = {}'a^{\alpha}_{\beta}\underline{E}^{\beta}$. The matrix $\|{}'a^{\alpha}_{\beta}\|$ of the tensor components ${}'a^{\alpha}_{\beta}$ is the direction cosine (rotation) matrix which relates the two orthonormal frames. Recognizing that the prime may designate the earth (symbol ⊕) or any of the bodies B_i, the total gravitational field vector at P' may be written

$$\underline{g}(P') = \left[\left({}^{\oplus}\underline{g} \cdot \underline{E}^{\beta}\right)\delta_{\beta\alpha} + \sum_i \left({}^{B_i}\underline{g} \cdot {}^{B_i}\underline{E}^{\beta}\right)\delta_{\beta\gamma}\ {}^{B_i}a^{\gamma}_{\alpha}\right]\underline{E}^{\alpha} \tag{7}$$

The components $\underline{g}(P') \cdot \underline{E}^{\alpha}$ are of interest in some applications, but our main interest here is in the field strength $g(P') = [\underline{g}(P') \cdot \underline{g}(P')]^{\frac{1}{2}}$. Using Eq. 7, one has

$$\begin{aligned}
|g(P')|^2 &= \delta^{\alpha\lambda}({}^{\oplus}\underline{g} \cdot \underline{E}^{\beta})({}^{\oplus}\underline{g} \cdot \underline{E}^{\gamma})\delta_{\beta\alpha}\ \delta_{\gamma\lambda} \\
&\quad + 2({}^{\oplus}\underline{g} \cdot \underline{E}^{\beta})\delta_{\beta\alpha} \sum_i \left({}^{B_i}\underline{g} \cdot {}^{B_i}\underline{E}^{\delta}\right)\delta_{\delta\gamma}\ {}^{B_i}a^{\gamma}_{\lambda}\ \delta^{\alpha\lambda} \\
&\quad + \sum_{i,j} \left({}^{B_i}\underline{g} \cdot {}^{B_i}\underline{E}^{\beta}\right)\left({}^{B_j}\underline{g} \cdot {}^{B_j}\underline{E}^{\delta}\right)\delta_{\beta\gamma}\ \delta_{\delta\rho}\ {}^{B_i}a^{\gamma}_{\alpha}\ {}^{B_j}a^{\rho}_{\lambda}\ \delta^{\alpha\lambda} \\
&= {}^{\oplus}g^{\beta\gamma}\ {}^{\oplus}g_{\beta}(P')\ {}^{\oplus}g_{\gamma}(P') \\
&\quad + 2\sum_i({}^{\oplus}\underline{g} \cdot \underline{E}^{\beta})\left({}^{B_i}\underline{g} \cdot {}^{B_i}\underline{E}^{\gamma}\right){}^{B_i}a_{\beta\gamma} \\
&\quad + \sum_{i,j} \left({}^{B_i}\underline{g} \cdot {}^{B_i}\underline{E}^{\beta}\right)\left({}^{B_j}\underline{g} \cdot {}^{B_j}\underline{E}^{\gamma}\right){}^{B_i}a_{\lambda\beta}\ {}^{B_j}a_{\mu\gamma}\ \delta^{\lambda\mu}
\end{aligned} \tag{8}$$

where ${}^{\oplus}g^{\beta\gamma}$ is the metric tensor for the earth's spherical coordinate system and ${}^{B_i}a_{\beta\gamma} = {}^{B_i}a^{\rho}_{\beta}\delta_{\rho\gamma}$.

From Eq. 8 the exact field magnitude at P' can be calculated: in conjunction with Eqs. 5 and 6, it can be expressed in terms of the various covariant field components at the nearby point P. But the result clearly depends on the exact configuration of all the celestial bodies with respect to the earth through the rotation tensors ${}^{B_i}a_{\alpha\beta}$. The approach here is to seek a more general statement independent of the details of the planetary configurations. In particular, upper and lower bounds for the difference $|\Delta g| = |g(P') - g(P)|$ will be sought.

3. BOUNDS ON $|\Delta g|$

By straightforward manipulation it is evident that $\Delta g = g(P') - g(P) = \Gamma/[g(P) + g'(P)] = \Gamma/[2g(P) + \Delta g]$ where Γ has been used for brevity for the expression $|g(P')|^2$. Thus, $(\Delta g)^2 + 2g(P)\Delta g - \Gamma = 0$ and $\Delta g = -g(P) + \sqrt{|g(P)^2 + \Gamma}$. Because g(P) is field magnitude, it is positive. In the neighborhood of $\Gamma = 0$, this result can be written

$$|\Delta g| = \kappa |\Gamma| / 2g(P) \tag{9}$$

where the factor κ is very close to unity. Some values of κ are:

Γ	κ
$10^{-2}\ g^2$	0.99712
$-10^{-2}\ g^2$	1.002512
$10^{-3}\ g^2$	0.99976
$-10^{-3}\ g^2$	1.00026

Since Γ can be expected to be still much smaller in practice a good estimate can be made with $\kappa = 1$. The bounds developed later can be made rigorously correct by using some κ_{max} or κ_{min} in Eq. 9, corresponding respectively to the upper and lower bounds found to exist on Γ. This should be an unnecessary refinement for most purposes.

In order to bound $|\Gamma|$, introduce $\Delta' g_\alpha$ for the difference $'g_\alpha(P') - 'g_\alpha(P)$ for each effect separately. Then Eq. 8 becomes

$$
\begin{aligned}
|g(P')|^2 &= {}^{\oplus}g^{\beta\gamma}\left[{}^{\oplus}g_\beta(P) + \Delta^{\oplus}g_\beta\right]\left[{}^{\oplus}g_\gamma(P) + \Delta^{\oplus}g_\gamma\right] \\
&\quad + 2\sum_i\left[{}^{\oplus}\underline{g}(P) + \Delta^{\oplus}\underline{g}\right]\cdot\underline{E}^\beta\left[{}^{B_i}\underline{g}(P) + \Delta\,{}^{B_i}\underline{g}\right]\cdot{}^{B_i}\underline{E}^\gamma\,{}^{B_i}a_{\beta\gamma} \\
&\quad + \sum_{i,j}\left[{}^{B_i}\underline{g}(P) + \Delta\,{}^{B_i}\underline{g}\right]\cdot{}^{B_i}\underline{E}^\beta\left[{}^{B_j}\underline{g}(P) + \Delta\,{}^{B_j}\underline{g}\right]\cdot{}^{B_j}\underline{E}^\gamma\,{}^{B_i}a_{\lambda\beta}\,{}^{B_j}a_{\mu\gamma}\,\delta^{\lambda\mu} \\
&= |g(P)|^2 + 2\,{}^{\oplus}g^{\beta\gamma}\,{}^{\oplus}g_\beta(P)\Delta^{\oplus}g_\gamma + |\Delta^{\oplus}g|^2 \\
&\quad + 2\sum_i\left[{}^{\oplus}\underline{g}(P)\cdot\underline{E}^\beta\right]\left[\Delta\,{}^{B_i}\underline{g}\cdot{}^{B_i}\underline{E}^\gamma\right]{}^{B_i}a_{\beta\gamma} \\
&\quad + 2\sum_i\left[{}^{B_i}\underline{g}(P)\cdot{}^{B_i}\underline{E}^\gamma\right]\left[\Delta^{\oplus}\underline{g}\cdot\underline{E}^\beta\right]{}^{B_i}a_{\beta\gamma} \\
&\quad + 2\sum_i\left[\Delta^{\oplus}\underline{g}\cdot\underline{E}^\beta\right]\left[\Delta\,{}^{B_i}\underline{g}\cdot{}^{B_i}\underline{E}^\gamma\right]{}^{B_i}a_{\beta\gamma} \\
&\quad + 2\sum_{i,j}\left[{}^{B_i}\underline{g}(P)\cdot{}^{B_i}\underline{E}^\beta\right]\left[\Delta\,{}^{B_j}\underline{g}\cdot{}^{B_j}\underline{E}^\gamma\right]{}^{B_i}a_{\lambda\beta}\,{}^{B_j}a_{\mu\gamma}\,\delta^{\lambda\mu} \\
&\quad + \sum_{i,j}\left[\Delta\,{}^{B_i}\underline{g}\cdot{}^{B_i}\underline{E}^\beta\right]\left[\Delta\,{}^{B_j}\underline{g}\cdot{}^{B_j}\underline{E}^\gamma\right]{}^{B_i}a_{\lambda\beta}\,{}^{B_j}a_{\mu\gamma}\,\delta^{\lambda\mu}
\end{aligned}
$$

Since $\left| {}^{B_i}a_{\alpha\beta} \right| \leq 1$, it follows that

$$2\left[{}^{\oplus}g(P) - \sum_i {}^{B_i}g(P)\right]\left[\left|\Delta^{\oplus}g\right| - \sum_i \left|\Delta^{B_i}g\right|\right] + \left[\left|\Delta^{\oplus}g\right|^2 - \sum_i \left|\Delta^{B_i}g\right|^2\right]$$

$$\leq \left|\, \left|g(P')\right|^2 - \left|g(P)\right|^2 \right|$$

$$\leq 2\left[{}^{\oplus}g(P) + \sum_i {}^{B_i}g(P)\right]\left[\left|\Delta^{\oplus}g\right| - \sum_i \left|\Delta^{B_i}g\right|\right]$$

$$+ \left[\left|\Delta^{\oplus}g\right|^2 + \sum_i \left|\Delta^{B_i}g\right|^2\right] \qquad (10)$$

Anticipating that the earth's field strength is the dominant effect, Eq. 10 shows that $|\Gamma|$ has bounds of the form

$$2\,{}^{\oplus}g(P)\left|\Delta^{\oplus}g\right| - \epsilon_1 \leq |\Gamma| \leq 2\,{}^{\oplus}g(P)\left|\Delta^{\oplus}g\right| + \epsilon_2$$

where ϵ_1 and ϵ_2 are small; hence to a good approximation, $|\Delta g| \approx \left|\Delta^{\oplus}g\right|$. This, of course, is what would be inferred at the outset under an <u>ab initio</u> postulate that all fields but those of the earth are negligible. We do not wish to assume this, but rather to establish it by a careful numerical investigation of the other terms in Eq. 10.

Before turning to the detailed developments under assumptions of inverse square fields and aspherical potentials, it is important to have an expression for the magnitudes $\Delta' g$ that appear in Eq. 10 for the various attracting sources. If ${}'g^{\alpha\beta}$ is the metric for the spherical coordinate system centered at the body characterized by the prime,

$$\left|{}'g(P')\right|^2 \equiv {}'g^{\alpha\beta}\left[{}'g_{\alpha}(P) + \Delta' g_{\alpha}\right]\left[{}'g_{\beta}(P) + \Delta' g_{\beta}\right]$$
$$= \left|{}'g(P)\right|^2 + 2\,{}'g^{\alpha\beta}\,{}'g_{\alpha}(P)\,\Delta' g_{\beta} + \left|\Delta' g\right|^2$$

from which

$$'g(P') = 'g(P)\left[1 + \frac{'g^{\alpha\beta}\ 'g_\alpha(P)\ \Delta' g_\beta}{|\ 'g(P)|^2} + \frac{'g^{\beta[\delta}\ 'g^{\alpha]\gamma}\ 'g_\alpha(P)\ 'g_\gamma(P)\ \Delta' g_\beta\ \Delta' g_\gamma}{|\ 'g(P)|^4} + \ldots\right]$$

and

$$\Delta' g = \frac{'g^{\alpha\beta}\ 'g_\alpha(P)\ \Delta' g_\beta}{g(P)} + \frac{'g^{\beta[\delta}\ 'g^{\alpha]\gamma}\ 'g_\alpha(P)\ 'g_\beta(P)\ \Delta' g_\beta\ \Delta' g_\gamma}{|g(P)|^3} + \ldots \qquad (11)$$

4. INVERSE SQUARE FIELDS

For a potential function of the type given by Eq. 3, it is a detail to show that the only non-zero first and second covariant derivatives are

$$\begin{array}{lll} {}^o g_{1,1} = 2\mu/r^3 & {}^o g_{2,2} = -\mu/r & {}^o g_{3,3} = -\mu \cos^2\theta/r \\ {}^o g_{1,11} = -6\mu/r^4 & {}^o g_{2,12} = 3\mu/r^2 & {}^o g_{3,13} = 3\mu \cos^2\theta/r^2 \\ {}^o g_{1,22} = 3\mu/r^2 & {}^o g_{2,21} = 3\mu/r^2 & {}^o g_{3,31} = 3\mu \cos^2\theta/r^2 \\ {}^o g_{1,33} = 3\mu \cos^2\theta/r^2 & & \end{array}$$

from which

$${}^o g_1(P') = \frac{-\mu}{r^2} + \frac{2\mu}{r^3}\, dr + \frac{1}{2}\left(-\frac{6\mu}{r^4}\, dr dr + \frac{3\mu}{r^2}\, d\theta d\theta + \frac{3\mu \cos^2\theta}{r^2}\, d\lambda d\lambda\right) + \ldots \qquad (12a)$$

$${}^o g_2(P') = -\frac{\mu}{\gamma}\, d\theta + \frac{3\mu}{r^2}\, dr d\theta + \ldots \qquad (12b)$$

$$^{o}g_3(P') = -\frac{\mu}{r}\cos^2\theta\, d\lambda + \frac{3\mu}{r^2}\cos^2\theta\, drd\lambda + \ldots. \tag{12c}$$

If x^1, x^2, x^3 denote rectangular cartesian coordinates measured along the tangents to the r, θ, λ coordinate curves at P, the differentials are related by $dx^1 = dr$, $dx^2 = rd\theta$, $dx^3 = r\cos\theta\, d\lambda$. In terms of the rectangular coordinate differentials the covariant components of the gravitational field become

$$^{o}g_1(P') = \frac{-\mu}{r^2}\left[1 - 2\frac{dx^1}{r} + \frac{3}{2r^2}\left(-2dx^1dx^1 + dx^2dx^2 + dx^3dx^3\right) + \ldots.\right] \tag{13a}$$

$$^{o}g_2(P') = \frac{-\mu}{r}\left[\frac{dx^2}{r} - \frac{3}{r^2}dx^1dx^2 + \ldots.\right] \tag{13b}$$

$$^{o}g_3(P') = \frac{-\mu\cos\theta}{r}\left[\frac{dx^3}{r} - \frac{3}{r^2}dx^1dx^3 + \ldots.\right] \tag{13c}$$

From these, it follows in turn using Eq. 11 that

$$\Delta^{o}g = \frac{\mu}{r^2}\left[-2\frac{dx^1}{r} + \frac{1}{r^2}\left(3dx^1dx^1 - dx^2dx^2 - dx^3dx^3\right) + \ldots.\right] \tag{14}$$

The first term in Eq. 14 is the usual "gravity gradient" effect. The quadratic terms in dx^α might be termed a "second gradient" effect. It invariably is truncated in applications, but here the validity of the truncation is to be investigated. The higher order covariant derivatives could have been added without serious formal difficulty, although it is somewhat tedious. It is evident that the next terms will be of the order of $(dx/r)^3$.

Now, on the basis of Eq. 14, consider how $\Delta^{o}g$ depends on time. Denote by $\underline{R}$ the vector from the center of the earth to the attracting body and by $\underline{\rho}$ the vector from the center of the earth to the satellite. Suppose that $\underline{R}$ makes an angle α with the plane of the satellite orbit and that its projection in this plane makes an angle β with the peri-apsis: then it is easy to prove that $r = [\rho^2+R^2-2\rho R \cos\alpha \cos(\varphi-\beta)]^{\frac{1}{2}}$ where φ is the angular advance of the satellite from peri-apsis. The actual angles α,β are not hard to determine given a specific satellite orbit inclination and ascending node, and a date from which the right ascension and declination of moon, sun and planets can be calculated. But for present purposes this is not really necessary: it is important only that the changes in α and β have very low frequency compared with the satellite orbital angular frequency n so that they are substantially constant during an orbit. We are interested more in bounding the coefficients of certain terms than in computing their values for a very specific configuration of celestial bodies.

The functions needed for Eq. 14 are r^{-3} and r^{-4}. If $\rho/R \ll 1$,

$$\frac{1}{r^3} = \frac{1}{R^3}\left[1 + 3\zeta \frac{\rho}{R} + \frac{3}{2}(5\zeta^2 - 1) \frac{\rho^2}{R^2} + 0(\rho^3/R^3)\right] \tag{15a}$$

$$\frac{1}{r^4} = \frac{1}{R^4}\left[1 + 4\zeta \frac{\rho}{R} + 2(6\zeta^2 - 1) \frac{\rho^2}{R^2} + 0(\rho^3/R^3)\right] \tag{15b}$$

where $\zeta = \cos\alpha \cos(\varphi-\beta)$. Let e be the eccentricity of the orbit and a be its major semi-axis. Then well-known formulas give

$$\frac{\rho}{a} \cos\varphi = -\frac{3}{2} e + \cos nt + \frac{e}{2} \cos 2nt + 0(e^2)$$

$$\frac{\rho}{a} \sin\varphi = \sin nt + \frac{e}{2} \sin 2nt + 0(e^2)$$

$$\frac{\rho^2}{a^2} = 1 - 2e \cos nt + 0(e^2)$$

whence

$$\frac{1}{r^3} = \frac{1}{R^3}\Big[k_{30} + k_{31} \cos(nt - \gamma_{31})$$

$$+ k_{32} \cos(2nt - \gamma_{32}) + k_{33} \cos(3nt - \gamma_{33}) + \dots\Big] \tag{16a}$$

$$\frac{1}{r^4} = \frac{1}{R^4}\Big[k_{40} + k_{41}\cos(nt - \gamma_{41}) + k_{42}\cos(2nt - \gamma_{42})$$

$$+ k_{43}\cos(3nt - \gamma_{43}) + \dots\Big] , \qquad (16b)$$

where

$$k_{30} = 1 - \frac{9}{2}\frac{ae}{R}\cos\alpha\cos\beta + \left(\frac{5}{2}\cos^2\alpha - 1\right)\frac{3a^2}{2R^2}$$

$$k_{31} = \left|\frac{3a}{R}\cos\alpha + \frac{3a^2e}{R^2}\left[\cos\beta\left(1 - \frac{5}{2}\cos^2\alpha\right) + \frac{15}{4}\cos^2\alpha\cos 3\beta\right]\right|$$

$$k_{32} = \left|\frac{3a}{2R}\cos\alpha\left(e^2 + 5\frac{ae}{R}\cos\alpha\cos\beta + \frac{25}{4}\frac{a^2}{R^2}\cos^2\alpha\right)^{\frac{1}{2}}\right|$$

$$k_{33} = \left|\frac{15}{4}\frac{a^2e}{R^2}\cos^2\alpha\right|$$

$$k_{40} = 1 - 6\frac{ae}{R}\cos\alpha\cos\beta + (3\cos^2\alpha - 1)\frac{2a^2}{R^2}$$

$$k_{41} = \left|\frac{4a}{R}\cos\alpha + \frac{4a^2e}{R^2}\left[\cos\beta(1 - 3\cos^2\alpha) - \frac{9}{2}\cos^2\alpha\cos 3\beta\right]\right|$$

$$k_{42} = \left|\frac{4a}{R}\cos\alpha\left(e^2 + 6\frac{ae}{R}\cos\alpha\cos\beta + 9\frac{a^2}{R^2}\cos^2\alpha\right)^{\frac{1}{2}}\right|$$

$$k_{43} = \left|6\frac{a^2e}{R^2}\cos^2\alpha\right| ,$$

all plus terms of the order of e^2 and $(a/R)^3$. The phase angles γ are not important for present purposes.

It is clear that bounds are

$$|k_{30}| \le 1 + \frac{9ae}{2R} + \frac{9a^2}{4R^2}\ , \qquad |k_{40}| \le 1 + \frac{6ae}{R} + \frac{4a^2}{R^2}$$

$$|k_{31}| \le \frac{3a}{R}\left(1 + \frac{21ae}{4R}\right)\ , \qquad |k_{41}| \le \frac{4a}{R}\left(1 + \frac{13ae}{2R}\right)$$

$$|k_{32}| \le \frac{3a}{2R}\left(e + \frac{5a}{2R}\right)\ , \qquad |k_{42}| \le \frac{4a}{R}\left(e + \frac{3a}{R}\right)$$

$$|k_{33}| \le \frac{15a^2e}{4R^2}\ , \qquad |k_{43}| \le \frac{6a^2e}{R^2}$$

to within terms of the order of e^2, $(a/R)^3$.

If r^{-3} and r^{-4} from Eq. 16 are used in Eq. 14, one finds that $\Delta^o g$ has the general form

$$\Delta^o g = \frac{\mu}{R^2}\left[k_o + k_1 \cos(nt - \gamma_1) + k_2 \cos(2nt - \gamma_2) + k_3 \cos(3nt - \gamma_3) + \ldots.\right] \tag{17}$$

where

$$k_o = -2k_{30}\frac{dx^1}{R} + \frac{k_{40}}{R^2}\left(3dx^1dx^1 - dx^2dx^2 - dx^3dx^3\right) + \ldots. \tag{18a}$$

$$|k_1| \le 2|k_{31}|\left|\frac{ax^1}{R}\right| + \frac{|k_{41}|}{R^2}\left|3dx^1dx^1 - dx^2dx^2 - dx^3dx^3\right| + \ldots. \tag{18b}$$

$$|k_2| \le 2|k_{32}|\left|\frac{dx^1}{R}\right| + \frac{|k_{42}|}{R^2}\left|3dx^1dx^1 - dx^2dx^2 - dx^3dx^3\right| + \ldots. \tag{18c}$$

$$|k_3| \le 2|k_{33}|\left|\frac{dx^1}{R}\right| + \frac{|k_{43}|}{R^2}\left|3dx^1dx^1 - dx^2dx^2 - dx^3dx^3\right| + \ldots. \tag{18d}$$

Now the neglected terms are those of the order of $(dx^\alpha/R)^3$. These results, recall, apply when the attracting body is much further from the earth than the satellite itself is.

For the attraction of the earth, we have simply $r \equiv \rho$, whence

$$\frac{1}{r^3} = \frac{1}{a^3}\left[\left(1 + \frac{3}{2}e^2 + \frac{15}{8}e^4 + \ldots\right) + \left(3e + \frac{27}{8}e^3 + \ldots\right)\cos nt\right.$$

$$+ \left(\frac{9}{2}e^2 + \frac{7}{2}e^4 + \ldots\right)\cos 2nt + \left(\frac{53}{8}e^3 + \ldots\right)\cos 3nt$$

$$\left. + \left(\frac{231}{24}e^4 + \ldots\right)\cos 4nt + 0(e^5)\right] \tag{19a}$$

$$\frac{1}{r^4} = \frac{1}{a^4}\left[\left(1 + 3e^2 + \frac{45}{8}e^4 + \ldots\right) + \left(4e + \frac{17}{2}e^3 + \ldots\right)\cos nt\right.$$

$$+ \left(7e^2 + \frac{67}{6}e^4 + \ldots\right)\cos 2nt + \left(\frac{23}{2}e^3 + \ldots\right)\cos 3nt$$

$$\left. + \left(\frac{115}{12}e^4 + \ldots\right)\cos 4nt + 0(e^5)\right] \tag{19b}$$

These results can be used in Eq. 13 to give ${}^{o}g_{\alpha}(P')$. However, it is preferable to consider the asphericity contribution ${}^{*}g_{\alpha}(P')$ as well before making the substitution.

5. CONTRIBUTION OF EARTH'S ASPHERICITY

At this point we have $|\Delta g| = |\overset{\oplus}{\Delta} g|$, if we anticipate the numerical results of the next section, and also have $\overset{\oplus}{\Delta} g$ expressed in general by Eq. 11. Further, for the inverse square part of the earth's field, Eq. 14 holds. It now is a question of deriving the analog of Eq. 14 when the complete potential function of Eq. 1 is used.

Note first that the "second gradient" effect for the earth, calculated by Eq. 14 for the inverse square field alone, does not exceed the order of 3dx/2r times the first order term in dx, or about

$1/4 \times 10^{-6}$ per meter of dx for a close orbit. It is shown in the next section that this is about 1/16 the size of the uncertainty in μ/r_e^2 caused by present lack of precision in our knowledge of these constants μ, r_e. It follows that one would have to be at least 16 meters from the center of mass of the orbiting vehicle before the quadratic term in dx could become as large as the uncertainty in the basic field itself. One concludes that for most purposes there is little point in including the "second gradient" term from the standpoint of either absolute or relative error. On the other hand, for a "vehicle" some hundreds of meters in extent, one may wish to keep it. The important consideration for our immediate purpose, however, is the fact that asphericity changes the picture obtained on a purely inverse square basis only by about one part in 10^3 (the ratio of the $C_{2,0}$ term in Eq. 1 to unity). Hence, one has the positive conclusion that for any vehicles of foreseeable size one does not have to examine the asphericity contribution to the "second gradient" (and, indeed, probably does not need to consider this order of effect at all). In the sequel only the first order terms in dx are considered in the expansion of ${}^{\oplus}g_{\alpha}(P')$ obtained from the complete potential function of Eq. 1.

As before, ${}^{\oplus}g_{\alpha} = \partial_{\alpha} U_{\oplus}$. Then, (omitting henceforth the $\oplus$ prescript for brevity)

$$g_{1,1} = \frac{\partial g_1}{\partial r} \qquad g_{2,1} = \frac{\partial g_2}{\partial r} - \frac{1}{r} g_2 \qquad g_{3,1} = \frac{\partial g_3}{\partial r} - \frac{1}{r} g_3$$

$$g_{1,2} = \frac{\partial g_1}{\partial \theta} - \frac{1}{r} g_2 \qquad g_{2,2} = \frac{\partial g_2}{\partial \theta} - r g_1 \qquad g_{3,2} = \frac{\partial g_3}{\partial \theta} + \tan\theta \, g_3$$

$$g_{1,3} = \frac{\partial g_1}{\partial \lambda} - \frac{1}{r} g_3 \qquad g_{2,3} = \frac{\partial g_2}{\partial \lambda} + \tan\theta g_3 \qquad g_{3,3} = \frac{\partial g_3}{\partial \lambda} + r \cos^2\theta \, g_1$$

and from Eq. 11,

$$\Delta g = \frac{\left(g_1\, g_{1,\alpha} + \frac{1}{r^2}\, g_2\, g_{2,\alpha} + \frac{1}{r^2 \cos^2\theta}\, g_3\, g_{3,\alpha}\right) dy^\alpha}{\left(g_1\, g_1 + \frac{1}{r^2}\, g_2\, g_2 + \frac{1}{r^2 \cos^2\theta}\, g_3\, g_3\right)} \tag{20}$$

It is entirely straightforward but tedious and unrewarding to work out the coefficients of dy^α in Eq. 20 in literal terms. If a result accurate to much better than a part in 10^3 is desired it is best obtained by purely numerical methods with the aid of a digital computer. However, we may note that the coefficient $C_{2,0}$ dominates all others in $U_\oplus$, and that it is about 10^{-3} times the unit coefficient of $1/r$. It is quite practical to evaluate Eq. 20 explicitly for the truncated potential function

$$U_\oplus \approx \mu \left[\frac{1}{r} + \frac{r_o^2}{2r^3}\; C_{2,0}(3\, \sin^2\theta - 1) \right] \tag{21}$$

and to expect the neglected terms to be of the order of 10^{-6} relative to unity (see Table 2).

From Eq. 21, the only non-zero g_α and $g_{\alpha,\beta}$ are

$$g_1 = \frac{-\mu}{r^2} \left[1 - \frac{3\, C_{2,0}}{2} \left(\frac{r_o}{r}\right)^2 (3\, \sin^2\theta - 1) \right]$$

$$g_2 = \frac{3\mu r_o^2}{2r^3}\, C_{2,0}\, \sin 2\theta$$

$$g_{1,1} = \frac{2\mu}{r^3} \left[1 + 3\, C_{2,0} \left(\frac{r_o}{r}\right)^2 (3\, \sin^2\theta - 1) \right]$$

$$g_{1,2} = g_{2,1} = -\frac{6\mu r_o^2}{r^4}\; C_{2,0}\, \sin 2\theta$$

$$g_{2,2} = \frac{-\mu}{r} \left[1 - \frac{3\, C_{2,0}}{2} \left(\frac{r_o}{r}\right)^2 (3 - 7\, \sin^2\theta) \right]$$

$$g_{3,3} = \frac{-\mu}{r} \cos^2\theta \left[1 + \frac{3\ C_{2,0}}{2}\left(\frac{r_o}{r}\right)^2 (3 \sin^2\theta - 1)\right]$$

from which

$$\overset{\oplus}{\Delta} g = \frac{\mu}{r^2}\left\{- 2 \frac{dx^1}{r}\left[1 + \frac{9\ C_{2,0}}{2}\left(\frac{r_o}{r}\right)^2 (3 \sin^2\theta - 1)\right]\right.$$

$$\left. + \frac{dx^2}{r}\left[\frac{9\ C_{2,0}}{2}\left(\frac{r_o}{r}\right)^2 \sin2\theta\right]\right\} \qquad (22)$$

(Squares of $C_{2,0}$ have been dropped as consistent with the neglect of higher terms in the potential function.) This is to be compared with Eq. 14 for the inverse square part of $U_\oplus$ alone. Equation 22 has been derived neglecting terms of the order of 10^{-6} relative to unity, but since a number of them having this magnitude have been neglected it is not possible to state that Eq. 22 is valid to a part in 10^6. However, a safe statement seems to be that the error is considerably less than a part in 10^3.

The $\overset{\oplus}{\Delta} g$ given by Eq. 22 can be decomposed further into harmonics in orbital frequency by means of Eq. 19 and the relations $\sin\theta = \sin i \sin u$ and $u = n(t - t_o) + 0(e)$, where i is the orbit inclination, u is the angular advance from the ascending node, and t_o is the time of ascending node passage (recalling $t = 0$ is at perigee). Terms of the order of e^3 and $eC_{2,0}$ are dropped, which is numerically consistent with previous approximations when eccentricity is limited to 0.03 as it is for purposes of subsequent calculations. It is necessary to expand $\sin2\theta$ in a Fourier series, which can be written

$$\sin2\theta = \frac{4}{\pi} \sin i \sum_{m=1}^{\infty} A_m \sin(2m - 1)\ n(t - t_o) \qquad (23a)$$

with $A_m = I_{2m-2} - I_{2m}$ and

$$I_{2m} = \int_o^{\pi/2} \sqrt{1 - \sin^2 i \sin^2 x}\ \cos2mx\ dx \qquad (23b)$$

If desired, the A_m can be expressed by straightforward transformations in terms of the complete elliptic integrals of the first and second kind, $K = K(\sin i)$ and $E = E(\sin i)$ respectively. For example,

$$A_1 = \frac{2}{3}\left[\cot^2 i\ K - (\csc^2 i - 2)E\right] \tag{24a}$$

$$A_2 = \frac{2}{15}\left[(8\csc^2 i + 1)\cot^2 i\ (K - E) - (4\csc^2 i - 1)E\right] \tag{24b}$$

The result is

$$\overset{\oplus}{\Delta} g = G_o + G_{11}\cos nt + G_{12}\sin n(t - t_o) + G_{21}\cos 2nt + G_{22}\sin 2n(t - t_o)$$

$$+ \sum_{\substack{m=3 \\ (\text{odd})}}^{\infty} G_m \sin mn(t - t_o) \tag{25a}$$

with

$$G_o = \frac{-2\mu\ dx^1}{a^3}\left[1 + \frac{3}{2}e^2 + \frac{9\ C_{2,0}}{4}\left(\frac{r_o}{a}\right)^2 (3\sin^2 i - 2)\right] \tag{25b}$$

$$G_{11} = \frac{-2\mu\ dx^1}{a^3}(3e) \tag{25c}$$

$$G_{12} = \frac{\mu\ dx^2}{a^3}\ \frac{9\ C_{2,0}}{2}\left(\frac{r_o}{a}\right)^2 \frac{4A_1\ \sin i}{\pi} \tag{25d}$$

$$G_{21} = \frac{-2\mu\ dx^1}{a^3}\left(\frac{9e^2}{2}\right) \tag{25e}$$

$$G_{22} = \frac{2\mu\ dx^1}{a^3}\ \frac{27\ C_{2,0}}{4}\left(\frac{r_o}{a}\right)^2 \sin^2 i \tag{25f}$$

$$G_n = \frac{\mu\ dx^2}{a^3}\ \frac{9\ C_{2,0}}{2}\left(\frac{r_o}{a}\right)^2 \frac{4}{\pi}\ \frac{A_{n+1}}{2}\ \sin i \qquad (n = 3, 5, 7, \ldots .) \tag{25g}$$

These expressions provide a basis for computing Δg to as high an accuracy as is justified at present. For "extreme" distances from the center of mass, the quadratic terms from Eq. 14 may be added to G_o.

6. SOME NUMERICAL RESULTS

The results calculated below are for a satellite in a 500 km orbit (a = 6878 km) whose eccentricity does not exceed 0.03. The qualitative conclusions are generally valid for any "near earth" satellite on an orbit of modest eccentricity.

Table 3 gives some upper bounds on the coefficients k_o, k_1, k_2, k_3 which appear in Eq. 17, for the sun, moon, and all planets excepting earth. The purpose here is to find the degree to which the "second gradient" terms (quadratic in dx^α) must be retained in computing $\Delta' g$ for these bodies. In order to exaggerate the effects of quadratic relative to linear terms the computation has been based on a per kilometer displacement from the vehicle center of mass rather than the more usual per meter. The positive conclusion that one draws from these results is that truncation at the ordinary gravity gradient term is valid for all of these bodies, with a relative error no greater than about 1 part in 10^7, except for the moon where the relative error is about 1 in 10^4. On a per meter basis (rather than per km), the relative error drops in all cases by another factor of 10^3.

On the basis that the "second gradient" is ignored, Table 4 combines the k-values of Table 3 with the basic attractions μ/r^2 from Table 1 to give the Δg per meter for sun, moon and all planets except earth itself, including a distinction among harmonics at orbital frequency. Recall that these are upper bounds computed for the closest approach of earth to each body separately: thus the expected value for an arbitrary planetary configuration would be much smaller in the case of the planets. Even without this observation it is evident that the sun and moon effects dominate this class, that these are of

TABLE 3

UPPER BOUNDS ON COEFFICIENTS k_0, k_1, k_2, k_3

(Cols. A are contributions from gradient per km of $|dx^\alpha|$; Cols. B are contributions from "second gradient" per km^2 of $|dx^\alpha \, dx^\beta|$)

	k_0		k_1		k_2		k_3	
Body	(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
Sun	1.34×10^{-8}	1.39×10^{-16}	1.91×10^{-12}	2.6×10^{-20}	2.9×10^{-14}	---	1.7×10^{-18}	---
Moon	5.62×10^{-6}	2.36×10^{-10}	3.25×10^{-6}	1.5×10^{-10}	4.88×10^{-8}	3.1×10^{-12}	1.2×10^{-9}	5.3×10^{-14}
Mercury	2.60×10^{-8}	5.04×10^{-16}	6.86×10^{-12}	1.8×10^{-19}	1.03×10^{-13}	---	1.5×10^{-14}	---
Venus	5.24×10^{-8}	2.07×10^{-15}	2.85×10^{-11}	1.5×10^{-18}	4.3×10^{-13}	3.1×10^{-20}	1.0×10^{-16}	---
Mars	3.66×10^{-8}	1.01×10^{-15}	1.39×10^{-11}	5.1×10^{-19}	2.1×10^{-13}	---	3.3×10^{-17}	---
Jupiter	3.46×10^{-9}	0.87×10^{-17}	1.20×10^{-12}	---	1.8×10^{-14}	---	2.6×10^{-20}	---
Saturn	1.68×10^{-9}	2.1×10^{-18}	2.90×10^{-14}	---	4.4×10^{-16}	---	---	---
Uranus	0.776×10^{-9}	4.5×10^{-19}	0.62×10^{-14}	---	0.93×10^{-16}	---	---	---
Neptune	0.466×10^{-9}	1.6×10^{-19}	0.22×10^{-14}	---	0.33×10^{-16}	---	---	---
Pluto	0.434×10^{-9}	1.6×10^{-19}	0.23×10^{-14}	---	0.34×10^{-16}	---	---	---

(Terms omitted are less than 10^{-20})

TABLE 4

Δg FROM THE INVERSE SQUARE ATTRACTION OF VARIOUS BODIES
(all in earth G per meter of $|dx^{\alpha}|$)

		Harmonics of Orbital Frequency		
Body	Mean	First	Second	Third
Sun	0.853×10^{-14}	1.2×10^{-18}	---	---
Moon	2.21×10^{-14}	1.28×10^{-14}	1.9×10^{-16}	0.47×10^{-17}
Mercury	0.96×10^{-20}	---	---	---
Venus	1.20×10^{-18}	---	---	---
Mars	5.4×10^{-20}	---	---	---
Jupiter	1.3×10^{-19}	---	---	---
Saturn	---	---	---	---
Uranus	---	---	---	---
Neptune	---	---	---	---
Pluto	---	---	---	---

(Terms omitted are less than 10^{-20})

comparable magnitudes with the moon somewhat greater, and that only the first harmonic at orbital frequency (from lunar effects) is of any consequence relative to the constant level.

But now compare these results with the Δg calculated from Eq. 14 for the earth. Kaula [2] gives for the gravitational constant and radius of the earth the values $\mu = 3.986009 \pm 0.000006 \times 10^{14}$ m^3/sec^2 and $r_o = 6378153 \pm 8$ m. These imply $\mu/r_o^2 = 9.798250(1 \pm 4 \times 10^{-6})$ m/sec^2, from which it follows that at 500 km, $\Delta g = 0.264 \times 10^{-6}$ g/m with a relative error of 4 parts in 10^6 merely because of the uncertainty in our present knowledge of earth constants. In other words, if we desire an <u>absolute</u> calculation of gravitational field differences at P' and P, the maximum contributions of sun and moon (and <u>a forteriori</u> other bodies) are well below current uncertainty in values of μ and r_e for the earth. Although at some future time one may need to take account of these other bodies, we conclude that an adequate model for the gravitational field within the vehicle need include only the effects of the earth. (Note that these calculations validate the remarks following Eq. 10.)

Under these conditions, Δg is given to considerably better than one part in 10^3 by Eq. 25. Note that the coefficient $2\mu/r_o^3$ has the numerical value 0.31353×10^{-6} G per meter. The dominant part of Δg is simply the constant part

$$G_o = - 0.31353 \times 10^{-6}(r_o/a)^3 \left[1 + \frac{3}{2} e^2 + 0(C_{2,0})\right]$$

where the $C_{2,0}$ term contributes no more than 0.00488 for any inclination. The first harmonic G_{11} term is again the same coefficient, now suppressed by $(r_o/a)^3(3e)$ so that its value is not more than 9 percent of the constant value for eccentricities $e \leq 0.03$. Both second harmonic terms are less than 1 percent of the constant value. The odd harmonics from Eqs. 25d and g depend on orbit inclination, but should be at most of the order of 0.3 percent of the constant value. Note, however, that these latter are caused by displacements dx^2 in the latitude direction from the center of mass rather than dx^1, radial displacements, as the other terms are.

On the basis of the calculations in this section, one may draw certain conclusions regarding a realistic model for the gravitational environment at points away from the center of mass of an earth satellite. These conclusions are summarized in detail in the abstract, and it is redundant to repeat them here.

REFERENCES TO APPENDIX B

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APPENDIX C
THE LUR'E FUNCTIONS

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THE LUR'E FUNCTIONS

The functions $q_s(t)$ discussed in connection with Eq. 10 of Appendix A which are linearly independent particular solutions of the vector equation $\ddot{\underline{x}} - \underline{x} \cdot \Phi = 0$, are defined by Lur'e in [1] as follows: Let r(t) be the orbit radius, $\varphi(t)$ be the angular advance in orbit from perigee, e be eccentricity, a be the semimajor axis, n be the orbit angular frequency (for a circular orbit equal to the w_o used in the text of the present work). Also, define $\{\xi_k\}$ as in this work: ξ_3 outward geocentric radius unit vector, ξ_2 normal to orbit plane, ξ_1 in the "forward" sense, so that $\{\xi_k\}$ is an orthonormal set. Then, according to Lur'e,

$$q_1 = \left[\frac{r}{a} - \frac{3n(t - t_o)}{2\sqrt{1 - e^2}} e \sin\varphi\right] \xi_3 - \left[\frac{3n(t - t_o)}{2\sqrt{1 - e^2}} (1 + e \cos\varphi)\right] \xi_1 \tag{1}$$

$$q_2 = - \cos\varphi\, \xi_3 + \frac{2 + e \cos\varphi}{1 + e \cos\varphi} \sin\varphi\, \xi_1 \tag{2}$$

$$q_3 = \sin\varphi\, \xi_3 + \frac{2 + e \cos\varphi}{1 + e \cos\varphi} \cos\varphi\, \xi_1 \tag{3}$$

$$q_4 = \frac{r}{a} \xi_1 \tag{4}$$

$$q_5 = \frac{r}{a} \cos\varphi\, \xi_2 \tag{5}$$

$$q_6 = \frac{r}{a} \sin\varphi\, \xi_2 \tag{6}$$

$$\dot{q}_1 = -n\left\{\left[\frac{e\sin\varphi}{2\sqrt{1-e^2}} - \frac{3n(t-t_o)}{2}\frac{a^2}{r^2}\right]\xi_3 + \frac{1+e\cos\varphi}{2\sqrt{1-e^2}}\xi_1\right\} \tag{7}$$

$$\dot{q}_2 = \frac{na}{r\sqrt{1-e^2}}\left(-\sin\varphi\,\xi_3 + \frac{e+\cos\varphi}{1+e\cos\varphi}\xi_1\right) \tag{8}$$

$$\dot{q}_3 = \frac{-na}{r\sqrt{1-e^2}}\left(\cos\varphi\,\xi_3 + \frac{\sin\varphi}{1+e\cos\varphi}\xi_1\right) \tag{9}$$

$$\dot{q}_4 = \frac{n}{\sqrt{1-e^2}}\left[(1+e\cos\varphi)\,\xi_3 + e\sin\varphi\,\xi_1\right] \tag{10}$$

$$\dot{q}_5 = \frac{-n}{\sqrt{1-e^2}}\sin\varphi\,\xi_2 \tag{11}$$

$$\dot{q}_6 = \frac{n}{\sqrt{1-e^2}}(e+\cos\varphi)\,\xi_2 \tag{12}$$

REFERENCES TO APPENDIX C

1. Lur'e, A. I., "Free Fall of a Material Particle in a Satellite Cabin," JAMM, 27, No. 1 (1963) pp. 1-9

APPENDIX D

BACKGROUND MATERIAL FOR CRYSTALLIZATION STUDIES

APPENDIX D

BACKGROUND MATERIAL FOR CRYSTALLIZATION STUDIES

1. NATURAL CONVECTION

Natural convection may occur in a liquid or a gas whenever the density distribution is such that fluid motion will allow the less dense volumes of fluid to move to a higher altitude. Convection can be driven by temperature distributions or by chemical inhomogeneities in the fluid. For example, a fluid between two horizontal parallel plates with the top plate hotter than the bottom plate will be quiescent. However, if the bottom plate is made sufficiently hotter than the top plate, convection currents will be set up in the fluid. If one were to consider an experiment in which a slab of molten metal 1 centimeter thick is placed on a horizontal plate heated to just above its melting point from below, and cooled by radiation to a low-temperature sink at the upper surface, the convective heat transport is found to be 3 to 4 times larger than the conduction heat transport. The comparison of the conduction and convection heat transport is given in this section for molybdenum and germanium. The pertinent results from Subsection 8.3.3 are given in Table D-I.

The presence of natural convection in earth-bound experiments is advantageous in certain instances when it is desired to enhance mass or heat transport. However, it is a serious disadvantage if one wishes to study the electromigration of certain solutes, in particular pure solvent materials; i.e., the enhanced migration rate of elements due to the application of electric field (Ref. D-1). The presence of fluid convection tends to homogenize the liquid, nullifying the effects of electromigration. A second consequence of fluid motion arises as a result of the mechanical force it applies to growing crystals; this

TABLE D-I

COMPARISON OF HEAT FLOW DUE TO CONDUCTION AND CONVECTION

Quantity	Symbol	Material Molybdenum	Germanium
Temperature drop across sample (^{o}K)	T_o-T_s	10	3
Conduction heat flow ($watts/cm^2$)	P_D	15	1.4
Convection heat flow ($watts/cm^2$)	P_V	63	4.9
Radiation heat flow (total) ($watts/cm^2$)	P_R	78	6.3

causes deformation and fragmentation of the crystals (Ref. D-2). This phenomenon is likely to be of considerable importance in ingots and castings; however, it is difficult to evaluate unless experiments in a convection-free situation can be conducted. The space laboratory provides the proper environment for such experiments.

1.1 Heat Flow by Conduction and Convection

Consider a specimen slab of molybdenum or germanium 1 centimeter thick on top of a horizontal hot plate which is at a temperature T_o. Natural convection will occur in the specimen because gravity is present and the temperature of the specimen decreases with height. Accordingly, the power conducted, P_D, plus the power convected, P_V, is equal to the power radiated from the upper figure, P_R, as given in Eq. 1.

$$P_D + P_V = P_R \tag{1}$$

An estimate of the relative importance of conduction versus convection is obtained by comparing the amount of power convected and conducted.

Thus we are going to evaluate P_D relative to P_V. The amount of heat P_D conducted through the specimen is given by

$$P_D = 4.185\ K \left(\frac{T_o - T_s}{\ell}\right)$$
$$= D \cdot (T_o - T_s) \tag{2}$$

which is the familiar conduction equation for conduction of heat through a solid or liquid of thickness ℓ with a temperature difference $T_o - T_s$ and having a conductivity K. Here, T_s is the temperature, unknown at the moment, of the specimen surface. The amount of heat, P_V, transported by convection through the specimen is given by

$$P_V = 4.185 \left(\frac{K}{\ell}\right) \left(\frac{ga\rho^2 C^2_{sp}\ell^3}{K^2}\right)^{1/4} \left(\frac{K}{\eta C_{sp}}\right)^{1/4} (T_o - T_s)^{5/4}$$
$$= V \cdot (T_o - T_s)^{5/4} \tag{3}$$

Equation 3 is the convection equation for convection of heat by matter flow away from a flat plane upward according to dimensional analysis (Refs. D-3, D-4, D-5). Finally, Eq. 4 is the radiation equation into space, that is, the Stefan-Boltzmann equation. The power radiated is given by Eq. 4.

$$P_R = 5.67 \times 10^{-12}\ \epsilon\ T_s^{\ 4}$$
$$= R \cdot T_s^{\ 4} \tag{4}$$

The various quantities from Eqs. 2, 3, and 4 and their magnitudes for molybdenum and germanium, are listed in Table D-II. Substituting the constants of Table D-II in Eqs. 2 through 4 results in the values for D, V, and R tabulated in Table D-III. Substituting Eqs. 2, 3, and 4 into Eq. 1 results in a transcendental equation in the unknown T_s. Solution of this equation for molybdenum and for germanium results in the following values for the power transmitted by convection and conduction given in Table D-IV.

It is seen that, for both molybdenum and germanium, the convection heat flow is comparable and larger in fact, by a factor of four, than the conduction-heat flow. Rather than being concerned with the numerical values, note only that the convection heat flow is significant and comparable to the conduction heat flow. Note also a 10-degree drop across the molybdenum liquid and a 3-degree drop across the germanium liquid.

1.2 Multiphase Suspension Experiments

Metallurgists have been restricted in the use of certain metals in the creation of improved materials as a natural result of the immiscibility which exists between a considerable number of the elements when in a liquid state. Present day metallurgy, therefore, is devoted primarily to those few common metals whose characteristics may be altered by mutual alloying. Recently, materials of unique characteristics have been produced from two or more immiscible elements by the use of powder metallurgy techniques. Powder metallurgical methods, however, cannot be utilized to produce true metal emulsions, since the process of recrystallization which occurs upon sintering, results in a grain structure considerably larger than the colloidal particles existing within the phase of an emulsion. In a weightless environment, true metal colloid systems might be produced by the intimate mixing of immiscible metals, followed by rapid cooling to retain the separate phases as a stable suspension. The possibility of creating metal emulsions, therefore, opens a new door to materials

TABLE D-II

CONSTANTS FOR EQS. 2 TO 4

Quantity	Symbol	Material: Molybdenum	Germanium
Thermal conductivity (cal/cm · ^{o}K)	K	0.346	0.11
Thickness of sample (cm)	ℓ	1	1
Gravitational acceleration (cm/sec^2)	g	980	980
Temp. coeff. of density change of fluid (^{o}K)$^{-1}$	a	2.2×10^{-5}	2.25×10^{-5}
Mass density of fluid (gm/cm^3)	ρ	9	5.5
Specific heat capacity at constant pressure (cal/gm)	C_{sp}	6.5×10^{-2}	7.4×10^{-2}
Coeff. of viscosity (gm/sec · cm)	η	$\sim 10^{-2}$	$\sim 10^{-2}$
Total normal emissivity	ϵ	0.2	0.5
Heat source temp. ~ melting temp. (^{o}K)	T_o	2,900	1,232

TABLE D-III

COMPUTED COEFFICIENTS FOR EQS. 2 TO 4

Quantity	Material: Molybdenum	Germanium
D	1.45	0.46
V	3.43	1.19
R	1.13×10^{-12}	2.83×10^{-12}

TABLE D-IV

COMPARISON—CONDUCTION, CONVECTION HEAT FLOW

Quantity	Symbol	Material: Molybdenum	Germanium
Temperature drop across sample (^{o}K)	$T_o - T_s$	10	3
Conduction heat flow (watts/cm^2)	P_D	15	1.4
Convection heat flow (watts/cm^2)	P_V	63	4.9
Radiation heat flow (total) (watts/cm^2)	P_R	78	6.3

research through the utilization of an increased number of elements to produce material of improved and unique properties. Research to the present has indicated the potential of systems capable of utilizing extremely fine dispersions of one phase in another phase. For example, present-day superalloys utilize the effects of a fine dispersion within the slip planes of a crystalline refractory alloy, unique magnetic properties become apparent when ferromagnetic materials are extremely finely divided, superstrength materials utilize dispersions of ceramic fiber within a metal matrix, etc. The possibility of creating emulsions between phases in a weightless environment would allow the production of new families of materials consisting of the following:

1. Metal - metal systems
2. Metal - inorganic
3. Metal - organic

1.2.1 Metal - Metal Systems

Well dispersed emulsions of metallic elements immiscible in the liquid state should be produced in zero-G environment by violent agitation of a liquid mixture of the respective elements. A solid-state emulsion is produced from the liquid by rapid cooling. A number of useful products might be produced from such emulsions. Among these are the following:

1. Spherical powders of great uniformity.
2. Materials exhibiting extremely low coefficients of friction.
3. Reactions of emulsions between elements exhibiting varying physical characteristics will provide materials of tailored characteristics in such properties as:
    a. Thermal conductivity
    b. Thermal expansion
    c. Electrical resistivity
    d. Density

Table D-V lists the metal systems exhibiting immiscibility gaps in the liquid state. The Mott number, used to predict the miscibility of two elements, is discussed in Subsection 1.3.

1.2.2 Metal - Inorganic Systems

Recent research has demonstrated the production of superstrength composite materials exhibiting a high strength-to-weight ratio through encapsulation of small-diameter, high-strength filaments within a metal matrix. Present methods for the production of such materials are very tedious, as a result of the problems encountered in encapsulating the ceramic fibers within a metal matrix. Composite materials presently available are limited to a narrow choice of matrix and fiber combinations.

The production of these superstrength composite materials might be greatly simplified if the high-strength ceramic fibers were simultaneously produced as fibers while being distributed within the melt. In a zero-G environment, glass-like ceramic materials might be melted in a molten metal bath and dispersed as an emulsion of high-strength fibers within the metal by agitation.

Such composite materials might be tailored to exhibit physical properties not now obtainable in any presently available material.

1.2.3 Metal - Organic Systems

Emulsion between low-melting-point metals and organic materials might readily be produced in an environment of zero-G. Such materials would be expected to exhibit properties unlike either of the starting constituents. Possible uses for such materials are as follows:

1. Radiation shielding
2. Lubricants
3. Heat transfer media
4. Propellants

TABLE D-V

SYSTEMS EXHIBITING IMMISCIBILITY GAPS
(Mott number in parentheses)*

Ag-Cr	(5.4, 2.88)
Ag-Mn	(-2.03, 0.09)
Ag-Ni	(00)
Ag-S	(-0.04)
Ag-Se	(1.18)
Ag-Te	(8.56)
Ag-U	(4.09)
Al-Bi	(10.6)
Al-Cd	(160.8)
Al-Ir	(21.2)
Al-K	(11.2)
Al-Na	(6.1)
Al-Pb	(7.4)
Al-S	(-0.04)
Al-Tl	(4.2)
As-Tl	(-2.40)
Bi-Co	(530)
Bi-Cr	(19.2)
Bi-Fe	(3297)
Bi-Ga	(5.07)
Bi-Mn	(130, 6.7)
Bi-Si	(888)
Bi-U	(11431)
Bi-Zn	(0.22)
Ca-Cd	(-0.15)
Ca-Na	(1.96)
Cd-Ga	(82.9)
Cd-K	(1.23)
Ce-Mn	(0.42, 0.18)
Co-Pd	(286)
Co-Se	(5.47)
Cr-Cu	(-1.69, -0.29)
Cr-Pb	(56.5, 18.0)
Cr-S	(0.01, 0.75)
Cr-Sn	(1764, 22.3)
Cu-Pb	(00)
Cu-S	(0.06)
Cu-Se	(4.37)
Cu-Te	(25.3)
Cu-Tl	(165)
Cu-U	(2.02)
Fe-Pb	(996)
Fe-Sn	(66.5)
Ga-Hg	(9.41)
Ga-Pb	(3.34)
Ga-Tl	(1.90)
K-Pb	(1.09)
K-Zn	(3.24)
La-Mn	(1.14, 0.42)
Li-Na	(120)
Mn-Na	(3.50, 1.45)
Mg-U	(2.01)
Mn-Pb	(70.0, 5.98)
Mn-S	(-0.07, -0.39)
Mn-Tl	(18.6, 9.96)
Na-Zn	(1.13)
Ni-Pb	(00)
Ni-Tl	(276)
P-Pt	(1.05)
P-Sn	(1.8, 1.3)
P-Tl	(16.5)
Pb-Se	(-0.12)
Pb-U	(157)
Pb-Zn	(-0.13)
S-Sb	(2.44)
S-Sn	(0.26, 0.06)
S-Tl	(1.82)
Sb-Se	(-0.72)
Se-Sn	(0.08, 0.60)
Th-U	(0.33)
Tl-Zn	(-0.07)
U-Zn	(3.77)

Note: Two Mott values given where a constituent has two valence states.

*The Mott number is defined in Subsection 1.3

1.3 The Hume-Rothery and Mott Rules for Alloying

A number of theories have been developed in attempting to predict the metallurgical behavior of elements in binary alloy systems (Ref. D-6). One of these theories is that of Hume-Rothery and involves the percentage differences between solvent and solute radii. The Hume-Rothery size factor has been quite useful in predicting solid solubility relationships. The radius ratio, defined as $R_{solute}/R_{solvent}$, can easily be converted to the percentage difference between radii by evaluation of the ratio:

$$\frac{R_{solvent} - R_{solute}}{R_{solvent}}$$

and, if it is greater than 1.000, subtract 1.000 and multiply by 100; or, if the ratio is less than 1.000, subtract it from 1.000 and multiply by 100.

The Hume-Rothery rule states that solid solubility in a binary system is unlikely if the percentage difference between radii is greater than 15 percent.

Another useful theory in predicting alloying behavior is that of Mott. Mott suggested that some of the discrepancies of other alloying theories might be accounted for by the tendency toward compound formation as the result of a large electronegativity difference between elements. The Mott bonding number, K, is defined as

$$K = \frac{Hf - 2RT}{23060(\Delta E_n)^2} = \frac{Hf - 1184}{23060(\Delta E_n)^2}$$

where Hf stands for Hildebrand factor.

$$Hf = 1/2\ (V_{solute} + V_{solvent})\ (\delta_{solute} - \delta_{solvent})^2$$

where V is the atomic volume, and δ is the Hildebrand solubility parameter for the element. In the Mott equation, R is the gas constant (1.987 cal/mole-deg), T the temperature considered (298°K), and ΔE_n the difference in electronegativities of the solute and solvent elements. In this expression, Mott used $23060(\Delta E_n)^2$ as an approximation to the binding energy (in cal/g-mole) per bond between elements.

The electronegativity difference is defines as

$$\Delta E_n = E_{n\ \mathrm{solvent}} - E_{n\ \mathrm{solute}}$$

After consideration of 529 binary systems, Mott concluded that if $K \geq 2$ the metals should be completely miscible, whereas if $K \geq 6$ some immiscibility should occur. In the range of K from 2 to 6, the incidence of immiscibility also depends upon relative atomic sizes. Mott attempted to discern a general guide to this influence by plotting K against the percentage difference in atomic radii. This plot is shown in Fig. D-1 (Ref. D-6). The points plotted in the figure represent experimental data from which the miscible-immiscible boundary was determined.

1.4 Experiments on Materials in the Absence of Gravitational Body Forces

In a terrestrial laboratory, structural defects may be introduced into a solid if the solid bears its own weight during manipulation and handling. Special precautions must be taken when experimenting with unusually low-strength materials, especially when the properties of interest are structure-sensitive. This problem will be minimized in a zero-G laboratory. In the absence of gravitational body forces, experimentation on materials could be carried out without the need for specimen support.

1.4.1 Capillarity Effects

In the discussion of zone refining (see text) it was noted that the gravitational body force on the liquid zone will disrupt

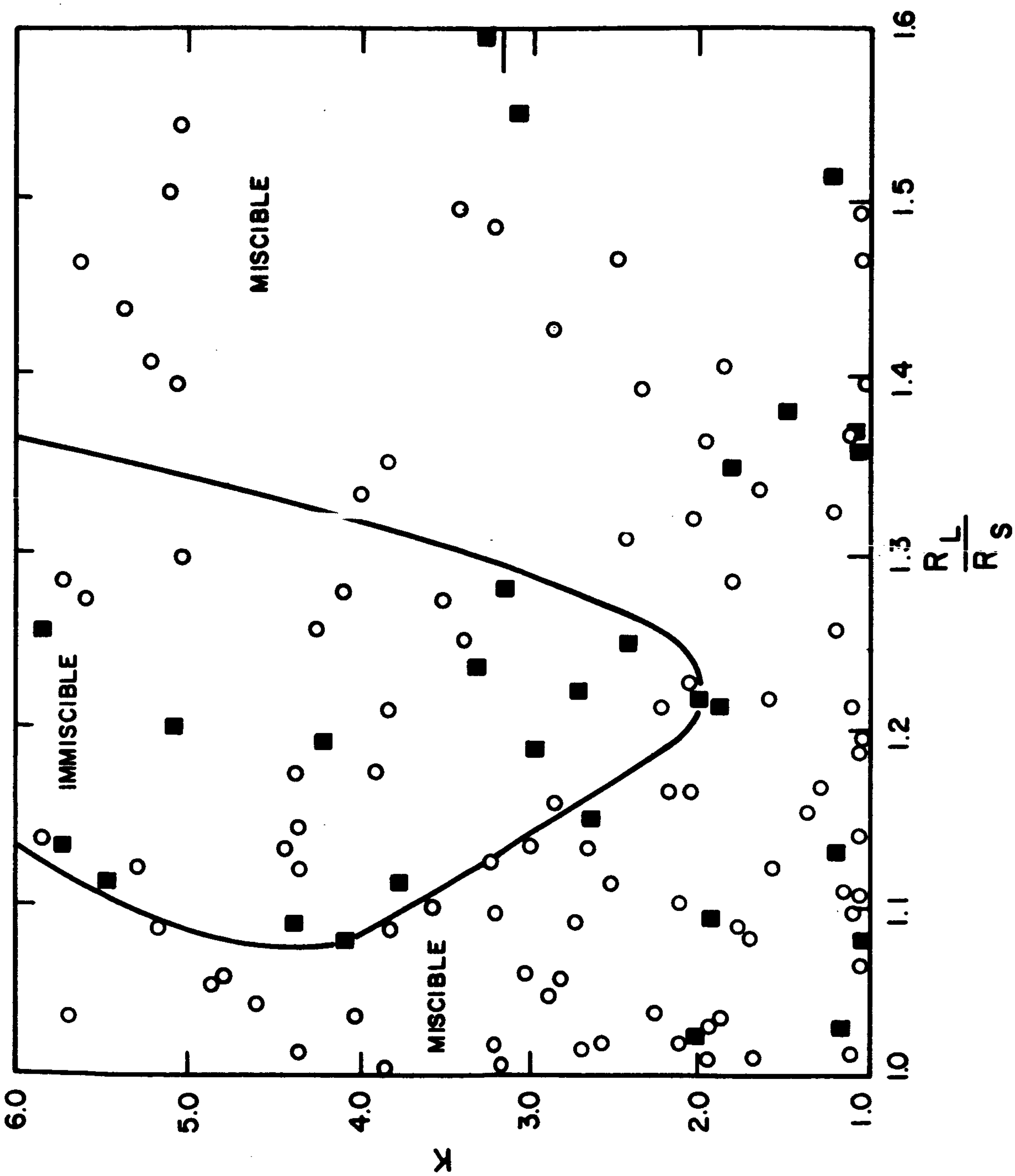

FIG. D-1 MOTT NUMBER K AS A FUNCTION OF THE RADIUS RATIO, FOR $1 \le K \le 6$

the zone if its length is increased beyond a limit. Since this type of constraint is expected when gravitational and capillary or surface tension forces are balanced, experiments and processes depending on this balance are being examined during the program. At this time, there are two cases (in addition to zone refining) of interest: (1) crystal growth by the Czochralski method, and (2) web formation between pulled dendrites.

In the Czochralski technique of crystal growing, a seed crystal is slowly removed from a melt maintained at a temperature somewhat above the melting point of the material (Refs. D-7 and D-8). As material from the melt freezes at the liquid-solid interface, the seed crystal is pulled away from the melt, drawing a solid crystal with it. The interface is slightly above the level of the melt and surface tension must balance the weight of the liquid contained between the interface and the melt to preserve continuity in the growth process. On the basis of a simple, but reasonable, model, Pohl (Ref. D-9) showed that the radius of the crystal is proportional to $2\gamma/\rho g$ for a given growth velocity and temperature difference between the freezing interfaces and melt.

Web formation is another facet of crystal growth from the melt. In pulling dendritic ribbons of semiconductors from a melt, it was often observed that two ribbons would grow side by side with a sheet of molten material held between them by surface tension. While at first this was considered a nuisance by workers primarily interested in studying ribbon formation, it was soon recognized as a possible technique for growing sheets of semiconductor material. Extremely long, continuous sheets of germanium and silicon, up to 2 cm wide and 750 microns thick, were subsequently grown. The sheets were single-crystal in structure, had low dislocation density, and their surfaces were of sufficiently good quality to permit immediate use in semiconductor devices (Ref. D-10).

Both of these processes are limited in terrestrial laboratories by the need to balance gravitational body forces by capillary forces. Under reduced-G conditions, this limitation is absent or, at least, reduced and the processes could be nearly universally applied to all substances without regard to surface tension. An intriguing possibility is the production of thick metal sheets, especially if their quality is comparable to the quality attainable with semiconductors.

2. EXPERIMENT DESIGN CONSIDERATIONS

Since a vacuum environment is as necessary as the low-G environment to perform the studies outlined, consideration has been given to defining the requirement for the vacuum. The "space vacuum" can be utilized directly or as a "pump" to evacuate a chamber located within the spacecraft. Presented below are some considerations of factors governing apparatus design for the crystallization and meteorite experiments discussed in the text.

One of the main considerations in the design of vacuum systems for research with materials is the cleanliness of the vacuum environment. A "clean" vacuum means that the flux intensities (particles per unit area per unit time) of the gaseous or vapor species within the vacuum that can affect the material under study are sufficiently small that the contact of these species with the material in the time duration of the experiment is negligible. Vacuum cleanliness as so defined is, of course, a relative matter since, in many cases, the ambient gases and vapors have no influence on the material.

However, when the experiments involve surface phenomena or when the materials are reactive, the gas and vapor constituents of the vacuum, their partial pressures, and their sources in the vacuum chamber are a special concern. Since the purity of materials is one of the main points of emphasis in the zero-G crystallization studies, the degree of vacuum cleanliness required to maintain or improve material purity will be the prime consideration in vacuum system design and usage.

Frequently it is not possible to state in advance the maximum flux intensities that can be tolerated. If a particle reacts chemically with a surface and the compound formed is very volatile, a higher flux intensity may be acceptable than in a case where the particle diffuses into the material and is retained as an impurity. Information on specific behavior of this sort is not always available. When planning an experiment, however, the chemical interactions between the material under study and the anticipated vacuum gases and vapors should be investigated whenever possible.

In the absence of specific information it is best to assume that every particle that strikes a material surface reacts in a detrimental way. Then, if N_m is the maximum acceptable number of impacts (or reactions), the acceptable flux level, Z_m, on a surface area of the sample, A, and the time duration of the experiment, t_e, are related simply by

$$Z_m - N_m/At_e \tag{5}$$

This means of estimating acceptable flux levels can be used either when the flux is directional or isotropic. The latter is the case when a sample is located in a uniform gaseous environment. The kinetic theory expression for the flux intensity of particles in an isotropic gas,

$$Z = p/(2\pi mkT)^{1/2} \ , \tag{6a}$$

$$= Kp \tag{6b}$$

can be used to relate the maximum flux to a maximum partial pressure. If, for example, the gas is molecular hydrogen, Z_m in molecules/cm^2•sec is

$$Z_m = 15 \cdot 10^{20} \ p_m$$

for p in torr. The coefficient $K = (2\pi mkT)^{-1/2}$ for several common residual gases of vacuum systems is tabulated in Table D-VI for $T = 273^\circ K$.

TABLE D-VI

FLUX INTENSITIES PER TORR FOR

SEVERAL COMMON GASES AND VAPORS AT $T = 273^\circ K$

(After Dushman and Lafferty, Ref. D-11)

Atomic or Molecular Species	$K \times 10^{-20}$
H_2	15.0
He	10.6
CH_4	5.31
H_2O	5.01
CO, N_2	4.02
O_2	3.76
$C\,C\ell_4$	1.71

An approximate value for N_m/A that is useful for estimation is 10^{12} reactions per unit area. This number is obtained by assuming that an acceptable level of contamination is one reaction for every 100 surface atoms and noting that a typical crystal surface has the order of 10^{14} atoms per unit area of surface. Using this value of N_m/A, we have, combining Eqs. 5 and 6b,

$$P_m = 10^{12}/Kt_e \tag{7}$$

for the relationship between the time duration of an experiment and the maximum acceptable partial pressure. Thus, in the example of molecular hydrogen considered above

$$P_m = 10^{12}/(15 \cdot 10^{20})\ t_e$$

$$= 6.7 \cdot 10^{-10}/t_e$$

If an experiment is to be run for 10 seconds, under the conditions stated, the maximum acceptable partial pressure of molecular hydrogen is $6.7 \cdot 10^{-11}$ torr. For the same experiment duration, the maximum partial pressure of water vapor is $2 \cdot 10^{-10}$ torr (see Table D-VI).

As an illustrative example of the type of calculation one might carry out in planning an experiment, consider a hypothetical material with a molecular weight of 100 and a density of 10 gms/cm^3. If the sample of this material has a radius of one centimeter, the total number of atoms, N, in the sample is

$$\begin{aligned} N &= (4\pi/3)\ (r^3\ \rho\ N_A\ /\ M) \\ &= (4\pi/3)\ (1)^3\ (10)\ (6 \cdot 10^{23})/100 \\ &= 2.5 \cdot 10^{23} \text{ atoms} \end{aligned} \tag{8}$$

In Eq. 8, r is the sample radius, ρ is the material density, M is the molecular weight, and N_A is Avogadro's number. If, during the time of the experiment, it is required that the increase in volume impurity content of the sample is less than 1 impurity per 10^6 atoms of the sample then

$$N_m = 2.5 \cdot 10^{17} \text{ impurity atoms}$$

and

$$N_m / A = 2.5 \cdot 10^{17}/4\pi$$

$$= 2.0 \cdot 10^{16} \text{ impurity atoms/cm}^2 \text{ of surface}$$

Using Eq. 5

$$Z_m = (2.0 \cdot 10^{16})/t_e$$

For an experiment that will take 10^3 seconds (about 17 minutes), the maximum Z_m acceptable is

$$Z_m = 2.0 \cdot 10^{13} \text{ molecules/cm}^2 \text{ sec}$$

Using Eq. 6b and Table D-VI to relate this flux intensity to pressure, we find that the maximum acceptable partial pressure of molecular oxygen is $5.3 \cdot 10^{-8}$ torr.

In this example, the acceptable impurity content was calculated on the basis of the total number of atoms in the whole sample. Had the surface impurity content been the important criterion, the maximum partial pressure of oxygen, calculated with Eq. 7, is $2.7 \cdot 10^{-11}$ torr. This is three orders of magnitude lower than the acceptable pressure calculated for volume impurity content and illustrates why researchers in surface physics and chemistry demand very high-quality vacuum systems.

In these examples, it has been assumed that no information is available on the interactions that take place between the residual vacuum gases and the sample of material under study. The acceptable partial pressures, which fall in the range from 10^{-11} to 10^{-7} torr, thus represent minimum values. It is possible that the requirements could be much less severe and higher pressures could be tolerated.

Nevertheless, partial pressures in this range are achieved routinely with modern vacuum techniques and should be the objective of any vacuum system design for experiments with pure materials.

To assess the vacuum conditions in space in the light of these requirements, consider the atmosphere of the earth at altitudes above 100 km. In Table D-VII, several relevant parameters are tabulated for altitudes between 100 km and 2000 km. The data are taken from a model earth atmosphere (Ref. D-12) for a period of maximum sunspot activity.* The details of the model and their experimental and theoretical justifications are discussed by Johnson (Ref. D-12) and will not be explored here. Of special interest to this discussion are the mean molecular weights (the third column of Table D-VII) and the pressures (fourth and fifth columns).

The variation in mean molecular weight with altitude reflects a variation in atmospheric composition. At altitudes below 100 km, the composition is reasonably constant with sea-level fractions of diatomic molecular nitrogen and oxygen. Above 100 km, the dissociation of these constituents reduces the mean molecular weight and, above 500 km, the constituents are mainly atomic. From more detailed data presented by Johnson, the concentrations of N_2 and N are approximately equal at 500 km whereas the concentration of O exceeds that of O_2 by over two orders of magnitude. Moreover, at this altitude, the concentration of O accounts for over 90 percent of the total concentration. At 2000 km, the predominant constituent of importance is atomic hydrogen; O and N concentrations are lower by more than one order of magnitude and the concentration of any diatomic molecule of these elements is completely negligible.

The major concern regarding the constituents and their atomic or molecular state is their chemical reactivity; for, as stated earlier

* The difference between maximum and minimum activity periods involves, at most, one order of magnitude in pressure. For this discussion, this difference is unimportant.

TABLE D-VII

ATMOSPHERIC PARAMETERS AS A FUNCTION OF ALTITUDE

(Sunspot Maximum)

Altitude (km)	Temperature (^{o}K)	Mean Molecular Weight	Pressure (dynes/cm^2)	Pressure (torr)
100	208	27.8	$1.74 \cdot 10^{-1}$	$1.31 \cdot 10^{-4}$
200	1230	22.0	$1.95 \cdot 10^{-3}$	$1.46 \cdot 10^{-6}$
300	1455	19.1	$3.60 \cdot 10^{-4}$	$2.70 \cdot 10^{-7}$
400	1500	17.5	$9.80 \cdot 10^{-5}$	$7.35 \cdot 10^{-8}$
500	1500	16.6	$2.90 \cdot 10^{-5}$	$2.18 \cdot 10^{-8}$
600	1500	16.3	$1.00 \cdot 10^{-5}$	$7.50 \cdot 10^{-9}$
700	1500	16.9	$3.50 \cdot 10^{-6}$	$2.63 \cdot 10^{-9}$
800	1500	16.0	$1.32 \cdot 10^{-6}$	$9.90 \cdot 10^{-10}$
900	1500	15.8	$4.90 \cdot 10^{-7}$	$3.68 \cdot 10^{-10}$
1000	1500	15.7	$1.90 \cdot 10^{-7}$	$1.43 \cdot 10^{-10}$
2000	1500	1.8	$9.5 \cdot 10^{-10}$	$7.13 \cdot 10^{-13}$

in the definition of a "clean" vacuum, the requirements on the partial pressures of flux intensities of residual gases in a vacuum environment must include a consideration of the chemical influences of the gases on the material under study. Atomic oxygen, nitrogen, and hydrogen are generally much more reactive than their molecular counterparts and it is reasonable to assume that, for most materials, an impact of one of these atomic species with a surface results in a "detrimental reaction".

Since, in the discussion of acceptable intensities and pressures, reaction on impact was assumed, the pressures shown in Table D-VII for altitudes exceeding 400 km are in the range regarded as acceptable for experiments sensitive to volume impurities. For experiments in surface phenomena, the altitude should exceed 1000 km. In Table D-VIII, the flux intensities calculated with Eq. 6a and the data of Table D-VII are shown. The flux intensity at 500 km is a flux primarily composed of atomic oxygen and, at 2000 km, the flux is atomic hydrogen. If N_m/A for a surface experiment is taken to be 10^{12}, the experimental time before contamination exceeds one percent will be impractically short at 500 km, but at 1000 km, it will exceed 30 seconds. This time is probably an absolute minimum.

For the flux intensities displayed in Table D-VIII, it is assumed that the sample is at zero velocity or a velocity small compared with atomic thermal velocities. In an orbiting vehicle, the vehicle velocity will exceed mean thermal velocities and the flux intensities incident on a sample outside the vehicle will be governed mainly by the rate at which the vehicle sweeps through the gas. At 1000 km, the orbital velocity is approximately $7 \cdot 10^5$ cm/sec and the flux intensity due to this velocity is about 20 times the thermal flux intensity. At 2000 km, the ratio is smaller - about 10. This factor effectively decreases the available experiment time, or, alternately, decreases the acceptable pressure, by the same factor. However, the flux due to orbital motion is directional and can be removed by suitable

TABLE D-VIII

INCIDENT FLUX INTENSITY AS A FUNCTION OF ALTITUDE

Altitude (km)	Z (particles/cm^2 sec)
100	$6.04 \cdot 10^{16}$
200	$3.13 \cdot 10^{14}$
300	$5.70 \cdot 10^{13}$
400	$1.60 \cdot 10^{13}$
500	$4.85 \cdot 10^{12}$
600	$1.69 \cdot 10^{12}$
700	$5.94 \cdot 10^{11}$
800	$2.25 \cdot 10^{11}$
900	$8.40 \cdot 10^{10}$
1000	$3.27 \cdot 10^{10}$
2000	$4.82 \cdot 10^{8}$

shielding. Shielding can reduce also the thermal flux and should be considered in optimizing apparatus design.

There are other sources of gases and vapors that affect the local vacuum environment of an orbiting laboratory. At low altitudes (< 400 km), sputtering of the vehicle and sample by energetic atmosphere particles may be serious. At higher altitudes, sputtering can occur by solar corpuscular radiation. Solar radiation, however, is directional and time dependent. A reliable estimate of secondary particle flux intensities has not been made.

Outgassing of the laboratory vehicle can produce gas and vapor flux intensities of magnitude comparable to those due to thermal energy and the vehicle velocity discussed above. These fluxes will depend on time and the distance between the vehicle and experiment. The outgassing properties of materials have been examined for several conventional materials used in the construction of vacuum systems by Dayton and outgassing rates for more than 100 materials are tabulated (Ref. D-13). Since the outgassing flux intensity will decrease approximately as the inverse square of the distance from the source, the placement of sensitive surfaces far from sources will markedly reduce contamination to acceptable levels.

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APPENDIX E

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORMS
FOR THE SPECIFIC EXPERIMENTS ADOPTED

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-1

1. TITLE: Bending of Starlight by the Sun

2. OBJECTIVE:

To verify the general theory of relativity by measuring the deflection of starlight by the sun's gravitational field.

3. EXPERIMENTAL PROCEDURE:

Utilizing 10" aperture, wide-field telescope, photograph two different star fields on each of a series of photographic plates. One of the two star fields is a reference and calibration. The other is the star field near and at the sun's limb. The sun must be occulted by an opaque object external to the telescope. Exposed plates will be packaged and recovered for processing and analysis on ground.

4. MEASUREMENTS AND DATA:

Photographs of star fields on special photographic plates. Record of drift rate of telescope.

5. a. DATA FORMAT:

Photographs of star fields. Visual readout of drift rate.

b. ESTIMATED BULK OF DATA:

25 photographic plates and containers (200 lbs., 2 cubic feet).

c. DATA REDUCTION:

Photographic processing and analysis performed on ground.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

6. MAJOR APPARATUS AND FACILITIES:

Ten-inch telescope - 5° field of view, attitude control for telescope, stabilization sensing equipment.

7. POWER REQUIREMENTS: (90-Day Mission)

Fifty watts continuous while exposures are being made. (About 600 watt-hours total.)

8. CREW REQUIREMENTS:

One astronaut with about 2 months training in the operation of the telescope

9. MANHOURS REQUIRED:

100 hours (including setup and checkout of the telescope)

10. ORBIT REQUIREMENTS:

Below radiation belt

11. SPACECRAFT ORIENTATION AND STABILIZATION:

Telescope must be pointed to 2 sec of arc, and must be stabilized to an angular drift rate less than 0.02 sec of arc per sec of time during the 5 sec of time exposures. Spacecraft must be oriented with axis of telescope mount within 30° of normal to the ecliptic plane.

12. ENVIRONMENTAL REQUIREMENTS:

None

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

13. EXPERIMENT/SPACECRAFT INTERFACES:

Telescope is mounted external to spacecraft and requires extra-vehicular activity to perform the experiment.

14. COMMENTS:

None

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-2

1. TITLE: Measurements of the Sun's Oblateness

2. OBJECTIVE:

To verify the relativistic origin of the advance of the perihelion of Mercury by setting a limit to solar oblateness.

3. EXPERIMENTAL PROCEDURE:

Utilizing the 10" aperture telescope, photograph the sun in several wavelengths and package exposed plates for recovery. Data reduction to be performed on ground.

4. MEASUREMENTS AND DATA:

Photographs of solar disk on special photographic plates.

5. a. DATA FORMAT:

Photographs of solar disk in various wavelengths.

b. ESTIMATED BULK OF DATA:

100 exposed photographic plates, 20 cm x 20 cm x 2 mm. Weight about 100 lbs., volume about 1 cubic foot (including containers).

c. DATA REDUCTION:

Analysis of plates on the ground.

6. MAJOR APPARATUS AND FACILITIES:

The 10" aperture optical telescope as used for the starlight bending measurement with the smaller-area plates substituted.

7. POWER REQUIREMENTS: (90-Day Mission)

50 watts continuous while exposures are being made. (About 5 min/exposure - 500 watt-hours total.)

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

8. CREW REQUIREMENTS:

One astronaut with about 2 months training in operation of the telescope.

9. MANHOURS REQUIRED:

50 hours total

10. ORBIT REQUIREMENTS:

Below radiation belt

11. SPACECRAFT ORIENTATION AND STABILIZATION:

Spacecraft must be oriented with the axis of the telescope mount within 30^{o} of the normal to the ecliptic plane.

12. ENVIRONMENTAL REQUIREMENTS:

Not applicable

13. EXPERIMENT/SPACECRAFT INTERFACES:

Erection of telescope by astronaut outside the vehicle. Changing of photographic plates by extravehicular activity. Attitude control of spacecraft.

14. COMMENTS:

Epicentered, gimballed, external mounting of telescope prevents coupling of torque to telescope from angular or translational motions of spacecraft.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-3

1. TITLE: Mass Spectrographic Analysis of Micrometeoroid Impact Debris

2. OBJECTIVE:

To capture and analyze in situ micrometeoroids to detect carbonaceous matter as evidence of extraterrestrial life.

3. EXPERIMENTAL PROCEDURE:

A target surface will be erected outside the vehicle. Micrometeoroids impinge upon the target and vaporize as a result of high-energy impact. The vaporized meteoroid material will enter the aperture of a mass spectrometer where the constituents of the meteoroid will be analyzed. Special attention will be given to the amount and species of the carbonaceous molecules. The experimenter will analyze the data of numerous events and attempt to conclude the composition of the pre-impact meteoroid material. Record shall be kept of the temporal distribution of various types of meteoroids.

4. MEASUREMENTS AND DATA:

Mass Spectrometer

Time

5. a. DATA FORMAT:

Clock

Polaroid pictures of scope face

b. ESTIMATED BULK OF DATA:

14 analyses/hour

56 pictures/day

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

c. DATA REDUCTION:

Onboard by experimenters

6. MAJOR APPARATUS AND FACILITIES:

Time-of-flight mass spectrometer

Clock

Scope

Polaroid camera

7. POWER REQUIREMENTS: (90-Day Mission)

120 watt-hours/day, total 10.8 KWH

8. CREW REQUIREMENTS:

Astronaut/mass spectroscopist (physicist)

9. MANHOURS REQUIRED:

4 hours/day

10. ORBIT REQUIREMENTS:

Near-earth orbits are required because the flux of meteoroids is concentrated by a factor of 10^4 times the flux in interplanetary space.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

None, except that the target should not face toward the earth.

12. ENVIRONMENTAL REQUIREMENTS:

Not applicable

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

13. EXPERIMENT/SPACECRAFT INTERFACES:

Extravehicular activity required for erection of analyzer. Analyzer must be pointed away from earth.

14. COMMENTS:

20 lbs total weight

0.7 ft^3

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-4 & E-5

1. TITLE: Formation of Artificial Meteoroids from Synthetic and Natural Meteoritic Materials

2. OBJECTIVE:

To obtain samples of meteoroid-like material formed under known and controlled conditions of vacuum and zero-G.

3. EXPERIMENTAL PROCEDURE:

Materials will be fused in a solar furnace array placed outside the laboratory and then allowed to cool radiatively and crystallize. The crystal structure shall be compared metallographically to natural meteorites. The distribution and type of compounds shall be analyzed.

4. MEASUREMENTS AND DATA:

Crystallographic plates

Chemical and mass spectrometry analysis

X-ray photographs

5. a. DATA FORMAT:

Dry-process photographs, chemical data (lab notebooks), recorder charts from mass spectrometer.

b. ESTIMATED BULK OF DATA:

2 metallographic photographs/sample

2 x-ray photos/sample

10 lbs total

c. DATA REDUCTION:

Analysis of photographs and records. Communications with ground personnel. Selection of subsequent samples on basis of continuing evaluations of results.

6. MAJOR APPARATUS AND FACILITIES:

Metallograph

X-ray machine

Solar furnace

Still cameras

Chemical lab and mass spectrograph

7. POWER REQUIREMENTS:

1 KWH/day, or about 90 KWH total

8. CREW REQUIREMENTS:

One astronaut/metallurgist with experience in meteorite analysis - half time.

9. MANHOURS REQUIRED:

5 hrs/day - 400 hrs total

10. ORBIT REQUIREMENTS:

An orbit that maximizes the ratio of light-to-dark time is desirable because of the time required to melt the sample and attain equilibrium. A 30° inclined orbit usually attained has a light time of approximately 1 hour at low orbital altitudes. This time is not enough to properly perform the experiment but long light periods can be attained at low altitudes if the proper inclination, such as a sun synchronous orbit, is chosen. Another way to obtain long light periods is to use very high altitudes such as 13,000 miles.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

The spacecraft should have the capability of maneuvering so as to keep the axis of the solar furnace mount to within 30° of the normal to the ecliptic plane. The solar furnace can have the capability of either being manually aimed by the astronaut or it can incorporate an attitude control system to maintain automatic pointing to within the desired requirements of 6 minutes of arc. It may also be possible to use the spacecraft to aim the furnace to the required pointing accuracy.

12. ENVIRONMENTAL REQUIREMENTS:

Solar furnace will be mounted external to spacecraft and far enough away to cool radiatively to space.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

13. EXPERIMENT/SPACECRAFT INTERFACES:

Airlock will be required to provide access to solar furnace for placing and removing specimens. The pointing of the solar furnace is directly tied into the attitude of the entire spacecraft.

14. COMMENTS:

The solar furnace will probably be erected by man after ejection into orbit.

The pointing accuracy of the solar collector should be within ±6 minutes of arc.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-6 & E-7

1. TITLE: Crystallization Studies and Production of Ultrapure Materials

2. OBJECTIVE:

To extend the techniques of zone refining in a zero-G field to enable the creation of ultrapure materials and crystals of sizes considerably larger than possible in a one-G field. To observe the formation of polycrystalline structure in a zero-G field.

3. EXPERIMENTAL PROCEDURE:

A sample (metallic or nonmetallic) suspended in space external to the vehicle. It is melted by a solar furnace. The sample is allowed to recrystallize in a controlled fashion. A two-color pyrometer, thermocouples, and a clock will be used to record the temperature-versus-time data. Motion pictures will be taken of the crystallization process. The crystallographic and x-ray diffraction, electron diffraction, and spectroscopic analyses, and solid-state measurements will be carried out.

A series of experiments will be performed on several samples and with various cooling rates. Data will be compared with those for samples produced in ground facilities.

4. MEASUREMENTS AND DATA:

Temperature

Time

Crystallographic properties

X-ray diffraction pattern

Electron diffraction pattern

Spectroscopic properties

Solid state measurements; i.e., resistivity, densities, specific heat, etc.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

5. a. DATA FORMAT:

Photos

Meter readings

Strip charts

b. ESTIMATED BULK OF DATA:

One sample/day

c. DATA REDUCTION:

Onboard, except for diffraction experiments which are telemetered to ground

6. MAJOR APPARATUS AND FACILITIES:

Clock

Crystallograph

X-ray diffraction apparatus

Electron diffraction apparatus

Spectroscope

Solid-state instruments

Two-color pyrometer

7. POWER REQUIREMENTS: (90-Day Mission)

500 watts for 8 hours/day, 400 watt-hours/day

36 KWH total energy required

8. CREW REQUIREMENTS:

Two-man team - 1 trained as metallurgist/crystallographer, the other trained as general experimental physicist.

9. MANHOURS REQUIRED:

8 hours/day

10. ORBIT REQUIREMENTS:

Approximately 200 mi. (except that surface measurements will be degraded unless about 600 mi. altitude is achieved).

11. SPACECRAFT ORIENTATION AND STABILIZATION:

Maneuvered such that solar furnace can be pointed at sun to accuracy of 6 minutes of arc.

12. ENVIRONMENTAL REQUIREMENTS:

10^{-4}G

13. EXPERIMENT/SPACECRAFT INTERFACES:

    Erection of solar furnace

    Placing sample in furnace

14. COMMENTS:

    90 lbs

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-8

1. TITLE: Study of a Gas Composed of Macroscopic Particles

2. OBJECTIVE:

   Observe the nonequilibrium behavior of a gas composed of macroscopic particles.

3. EXPERIMENTAL PROCEDURE:

   A box is filled partially with small spherical particles. The walls are vibrated by acoustical transducers causing the particles to distribute throughout the box with a distribution of kinetic energy. The position and velocities of the particles are recorded stroboscopically by stereo vidicons. The data is stored on tape, transmitted to the ground for reduction, and then returned to the spacecraft for evaluation. The state of the macrogas is then altered and another measurement is recorded.

   REPEAT WITH A SERIES OF DIFFERENT SIZES AND SHAPES OF PARTICLES.

4. MEASUREMENTS AND DATA:

   Velocity distribution of spheres in macrogas as a function of macrogas density, pressure, and equivalent temperature.

5. a. DATA FORMAT:

   Stereo vidicon pictures stored on tape and film.

   b. ESTIMATED BULK OF DATA:

   80 pictures/experiment, 100 experiments/day.

   c. DATA REDUCTION:

   On ground by telemetry link.

6. MAJOR APPARATUS AND FACILITIES:

13 cm Cubical Box	5	lbs
2 Vidicons	10	lbs
Amplifiers	5	lbs
Top	30	lbs

Timer	3	lbs
Oscillator	1	lb
Steel Spheres (5 mil)	0.05	lb
TOTAL	65	lbs

7. POWER REQUIREMENTS: (90-Day Mission)

3 watt-hrs/experiment, 300 watt-hrs/day (100 experiments/day), or 27 KWH total.

8. CREW REQUIREMENTS:

One astronaut/physicist with experience in gas dynamics experimentation.

9. MANHOURS REQUIRED:

5 minutes/experiment at 100 experiments/day, approximately 10 hours per day.

10. ORBIT REQUIREMENTS:

None

11. SPACECRAFT ORIENTATION AND STABILIZATION:

None

12. ENVIRONMENTAL REQUIREMENTS:

Acceleration level 10^{-4}G, shirt-sleeve environment

13. EXPERIMENT/SPACECRAFT INTERFACES:

Vibration isolation from 10 cps to 10 kcps

14. COMMENTS:

Many preliminary experiments will be performed to determine the validity of the model by correlating data with that predicted by theory. Then the experiments will be extended into the study of gas states and adequately (high density) covered by theory.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-9

1. TITLE: Dynamic and Static Capillarity Studies

2. OBJECTIVE:

Determine quantitatively the dependence of capillary flow on the properties of liquids and surfaces.

3. EXPERIMENTAL PROCEDURE:

Measure flow rate due to capillary forces by photography of liquids in motion in helical, transparent capillary tubes. A sequence of measurements will be performed using different liquids, different diameters of tubing, and different vapors above the liquid in the tubes. Static capillary forces will be measured by observing the value of gas pressure required to stop capillary flow in the tubes. Wetting angles will be measured by photographing liquid drops in contact with flat surfaces in reduced gravity.

4. MEASUREMENTS AND DATA:

Measure flow rates, temperatures, forces, pressure, wetting angle.

5. a. DATA FORMAT:

Photography of flow of droplets on plate. Data tabulation of pressure required to stop capillary flow. Temperature readout. Pictures and instrumentation readout on magnetic tape.

b. ESTIMATED BULK OF DATA:

5000 ft of 16 mm film

1 roll (2000 ft) of magnetic tape

50 rolls of 35 mm film (still)

c. DATA REDUCTION:

Film processing and data reduction by the experimenter in space to provide guidance for selection of subsequent experimenter arrangements and procedures.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

6. MAJOR APPARATUS AND FACILITIES

Liquid storage chambers (1 ft^3)

Pressure, temperature instruments

Camera equipment (movie and still)

Helical tubes of various sizes

7. POWER REQUIREMENTS: (90-Day Mission)

500 watts for lighting, instruments, and camera operation. 500 watt-hr/experiment, or 45 KWH total.

8. CREW REQUIREMENTS:

One astronaut/physicist with experience in hydrostatics and hydrodynamics.

9. MANHOURS REQUIRED:

One hr/experiment/day

10. ORBIT REQUIREMENTS:

None

11. SPACECRAFT ORIENTATION AND STABILIZATION:

None

12. ENVIRONMENTAL REQUIREMENTS:

10^{-4}G acceleration level, self-contained environment

13. EXPERIMENT/SPACECRAFT INTERFACES:

None

14. COMMENTS:

Total weight = 200 lbs

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-10

1. TITLE: Study of Dynamics of Free Liquid Drops

2. OBJECTIVE:

To study the oscillatory modes of free liquid drops as well as the interaction of two free droplets.

3. EXPERIMENTAL PROCEDURE:

The experimenter will place a droplet of a given substance and radius in a chamber containing a given medium (buffer). The drop is then perturbed by either gas jets or acoustical vibration. The drop dynamics are recorded by a movie camera. In some experiments the perturbation of the drop will be sufficient to cause drop fragmentation. Similar observations will be made on the interaction and coalescence of droplets. Observations to be made as a function of buffer, temperature, pressure, and type of liquid.

4. MEASUREMENTS AND DATA:

Amplitude and frequency
Mode of oscillation
Oscillation damping rate
Number and size of fragments
Two-drop impact parameters

5. a. DATA FORMAT:

Pictures of drops, frequency indicator, and elapsed-time clock.

b. ESTIMATED BULK OF DATA:

5000 ft 16 mm film.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

c. DATA REDUCTION:

Processing of film in lab and examination of film in order to determine the modifications in experiment required.

6. MAJOR APPARATUS AND FACILITIES:

Chamber (1 ft^3)

Drop injector

Motion picture camera (high-speed) (1000 frames/sec)

Darkroom (automatic) (wet photo lab)

Pressure and temperature recorders

7. POWER REQUIREMENTS: (90-Day Mission)

2000 watt-hours/experiment, or 180 KWH total

8. CREW REQUIREMENTS:

One astronaut/physicist with experience in hydrostatics and hydrodynamics.

9. MANHOURS REQUIRED:

4 hours/experiment/day

10. ORBIT REQUIREMENTS:

None

11. SPACECRAFT ORIENTATION AND STABILIZATION:

None

12. ENVIRONMENTAL REQUIREMENTS:

Acceleration $\leq 10^{-6}$G. Apparatus will be self-contained and isolated from laboratory environment.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

13. EXPERIMENT/SPACECRAFT INTERFACES:

Mechanical isolation of experimental apparatus to eliminate unwanted perturbation.

14. COMMENTS:

50 lbs total for all equipment exclusive of wet lab.

Acceleration levels greater than 10^{-6}G can be tolerated but duration of test would be shorter. 10^{-4} to 10^{-3} is the practical upper limit for acceleration levels.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-11

1. TITLE: Study of Bubble Formation in Low-G

2. OBJECTIVE:

To observe the dynamics of bubble growth and interface oscillations in a convection-free environment.

3. EXPERIMENTAL PROCEDURE:

Heat is applied to the liquid by a surface in contact with the liquid and separately by radiation. By these two techniques, bubble formation in the liquid bulk can be differentiated from formation at a surface. The procedure requires the heating of the liquid to sufficient temperatures to initiate boiling. Microphotography will be used to observe the initial formation and the subsequent growth and dynamics. Either direct or shadowgraph photography can be employed. The heating cycle and photography duration will be determined by the astronaut. He will also repeat the experiment at different pressures and with different liquids.

4. MEASUREMENTS AND DATA:

Temperature and pressure will be controlled and monitored. Photographs will be taken of the boiler.

5. a. DATA FORMAT:

All data will be recorded on the film and magnetic tape.

b. ESTIMATED BULK OF DATA:

5000 ft of 16 mm film

2000 ft of magnetic tape

c. DATA REDUCTION:

Data will be reduced in space in order to perform immediate modifications to experimental procedure.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

6. MAJOR APPARATUS AND FACILITIES:

Chamber with viewing and illumination window (1 ft^3)

Heat lamps and a resistance-heater surface

Thermocouples, pressure gages

Optical system for shadow photography

Motion picture camera (high-speed)

100 lbs at 5 ft^3

7. POWER REQUIREMENTS: (90-Day Mission)

750 watt-hours/experiment, or 67.5 KWH total.

8. CREW REQUIREMENTS:

Elementary knowledge of experimental principles, procedures, and expected phenomena.

9. MANHOURS REQUIRED:

1/2 hour/experiment/day.

10. ORBIT REQUIREMENTS:

None

11. SPACECRAFT ORIENTATION AND STABILIZATION:

None

12. ENVIRONMENTAL REQUIREMENTS:

10^{-4}G acceleration acceptable. Self-contained.

13. EXPERIMENT/SPACECRAFT INTERFACES:

None

14. COMMENTS:

100 lbs total weight.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-12

1. TITLE: Study of Critical-State Behavior of Fluids in Low-G

2. OBJECTIVE:

Determine the form of the coexistence curve in the vicinity of the critical point for single and for two-component fluids.

3. EXPERIMENTAL PROCEDURE:

A liquid is placed in a chamber. The chamber volume is changed and the corresponding pressure recorded for several fixed values of temperature in the region of the critical point. Care must be taken to allow the fluid to reach equilibrium before a measurement is recorded. This may take up to 15 minutes for each data point. A set of isotherms is recorded and the coexistence curve is then determined. The experiment is repeated with another liquid or a mixture of two liquids.

4. MEASUREMENTS AND DATA:

Pressure

Temperature

Volume

35 mm photographs

5. a. DATA FORMAT:

Photograph of chamber and instrumentation in same photo (split-beam photography).

b. ESTIMATED BULK OF DATA:

500 ft of 35 mm film.

c. DATA REDUCTION:

Data to be reduced in space in order to perform immediate modifications.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

6. MAJOR APPARATUS AND FACILITIES:

   Chamber 4" x 4" x 4" (adjustable volume)

   35 mm camera and flash

   Temperature control

   Pressure transducer

7. POWER REQUIREMENTS: (90-Day Mission)

   500 watt-hours, 45 KWH total

8. CREW REQUIREMENTS:

   One astronaut/physicist with experience in gas physics

9. MANHOURS REQUIRED:

   8 manhours/day

10. ORBIT REQUIREMENTS:

    None

11. SPACECRAFT ORIENTATION AND STABILIZATION:

    None

12. ENVIRONMENTAL REQUIREMENTS:

    10^{-4} G acceleration is acceptable. Self-contained environment.

13. EXPERIMENT/SPACECRAFT INTERFACES:

    None

14. COMMENTS:

    Total weight: 25 lbs

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-13

1. TITLE: Experimental Embryology in Low-G

2. OBJECTIVE:

Determination and measurement of gravitational processes in the several developmental modes and patterns occurring in the animal kingdom. Such features of embryological morphogenesis as cleavage, differentiation, induction, and formation and organization of tissues will be studied.

3. EXPERIMENTAL PROCEDURE:

In general, the techniques to be used will involve transporting into orbit a variety of unfertilized eggs stored at low temperatures, fertilizing as needed, observation of the course of development, photography and photomicrography of critical stages and events, removal of representative specimens at these times for later histologic study and, finally, return to the ground of living specimens for long-term study of the adult forms. In some cases, adult animals such as frogs or salamanders will be transported into orbit in order to study oogenesis and determine if eggs developed at zero-g and at one-g have differing embryological details. The experiment will utilize small vessels which may be taken to the required facility at a particular stage of the procedure. Approximately 6 hours occupancy of a microscopy work station and a photography work station will be required each day. The longest single series of observations will probably not extend beyond 90 days from the onset of first cleavage.

4. MEASUREMENTS AND DATA:

Measurements will consist mainly of direct observation, study of histologic preparations and photographs.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

5. a. DATA FORMAT:

Data to be accumulated for return is principally film, but also includes records of direct observation as well as histologic preparations and preserved specimens.

b. ESTIMATED BULK OF DATA:

2 million frames of 16 mm film

10,000 frames of 35 mm roll film

50 hours of voice recording tape

1200 histologic slides and 10 lab notebooks

c. DATA REDUCTION:

All data reduction will be accomplished on the ground.

6. MAJOR APPARATUS AND FACILITIES:

Facilities consist of:

general lab area

animal maintenance area

histology lab

microscopy and photography facilities

wet lab

film processing lab (tentative)

Instrumentation and apparatus required:

Illuminated magnifiers

Dissecting stereo microscope with stereocamera attachment

Movie camera with time-lapse capabilities and special lenses for extreme close-up work

Roll film camera

Video camera with special close-up lenses

Micromanipulators

Special combination culture-observation vessels

Special life support units for maintaining culture vessels with optimum range

Incubators and thermal and humidity control chambers
Automatic cell counters
Centrifuges for control specimens
Tape recorder
Ultrasonic generator and special transducers
Freezer
Refrigerators
Special filters and fluid handling devices
Aquaria and holding tanks
Compound microscope with attachments for photomicrography

7. POWER REQUIREMENTS: (90-Day Mission)

The power required will be associated with the light sources for microscopy and photography and with the freezers, refrigerators, and specimen thermal environment chambers. The lights will probably require 90 watts continuously for 6 hours each day. Other equipment will require an average power of 85 watts. 232 KWH total energy required.

8. CREW REQUIREMENTS:

It is anticipated that one embryologist could adequately perform all of the necessary studies and observations involved in this experiment if he were supported by the half-time effort of a histologist. It would be better, however, to have two embryologists, one with a strong anatomical background and the other with heavier emphasis upon physiological embryology. Ideally, they should also be supported by an animal maintenance technician and a wet lab technician. These latter two functions, however, should not require more than 1 hour per day.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

9. MANHOURS REQUIRED:

Based on 3-month stays in orbit consisting of 8-hour days, 6-day weeks; 624 to 1248 hours of embryologist time plus 312 hours of histologist time and 156 hours of animal maintenance and lab technician time for a total of 936 to 1716 hours of orbital time.

10. ORBIT REQUIREMENTS:

There are no special orbit requirements.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

No special orientation of the spacecraft is necessary. Accelerations of 10^{-3} and less are thought to be adequate for this experiment at the present time. Hence, Region I of the spacecraft should satisfy this requirement. It is not currently thought that any observations will need to be made in the regime provided by Region II; however, this might be changed based on early results in orbit.

12. ENVIRONMENTAL REQUIREMENTS:

Shirt-sleeve environment will be adequate for lab operations. Most specimen storage will be in specially controlled micro-environments.

13. EXPERIMENT/SPACECRAFT INTERFACES:

Specimen maintenance, wet lab operations, waste management, and the toxic hazards of the histological operations.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM (contd)

14. COMMENTS:

It is currently estimated that the experiment-peculiar equipment, i.e., equipment used in common with no other experiment, will weigh, in the aggregate, approximately 850 lbs. Experiment-peculiar equipment is estimated to occupy approximately 24 cubic feet.

A two-way video link would be desirable.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-14

1. TITLE: Fundamental Microbiological Processes in Low-G

2. OBJECTIVE:

Determination of the extent of gravitational influence on the growth rate and mutation rate of microorganisms. The sensitivity of induction and reversion of L-forms and lysogeny to gravitational forces will be measured.

3. EXPERIMENTAL PROCEDURE:

Standard bacteriological methods employing batch and continuous culture will be utilized. Parameters of interest will be measured by standard optical, electrochemical, isotopic, and cytological techniques.

Most operations will be carried out in the web lab area. A few procedures will utilize the isotope handling facility and histology lab.

4. MEASUREMENTS AND DATA:

Measurements will be made by standard isotopic electrochemical, optical, and cytologic preparations. Also lyophilized specimens will be returned from orbit.

5. a. DATA FORMAT:

Data will be generated as written and strip-chart records of optical and electrochemical measures,as well as isotopic and certain electrical measures,will be recorded on magnetic tape. Cytologic preparations and lyophilized specimens will be returned to the ground.

b. ESTIMATED BULK OF DATA:

30 lab notebooks

5000 feet of strip-chart records

200 hours of magnetic tape

2500 cytologic preparations

200 vials of lyophilized specimens

c. c. DATA REDUCTION:

All data reduction will be performed on the ground.

6. MAJOR APPARATUS AND FACILITIES:

Facilities required are:

- A microscopy and photography work station
- An instrumentation bench and work station
- Cytology laboratory facilities
- A "wet lab" area for culture preparation and maintenance
- Limited photography processing facilities
- Sterilization facility

Instrumentation and apparatus include:

- Automatic cell counters
- Light-scattering photometer
- Optical densitometer
- Automatic plate-scanning counter
- Spectrophotometer
- Polarograph
- Special culture-observation vessels
- Special filter apparatus
- Fluid transfer equipment
- Refrigerator
- Freezer
- Centrifuges for control specimens
- Centrifuges for solid-liquid-gas phase separations
- Ultrasonic generator and transducers
- Electron microscope
- Compound microscope with complete phase contrast, dark field, and polarizing optics
- Incubators
- Ultraviolet and fluorescence microscopy equipment
- Thermal environment chambers
- Special zero-G culture vessels

Roll-film camera with special close-up attachments

Lead "safes" for radiation protection of sensitive control specimens and seed cultures

Tape recorder

Time-lapse camera with beamsplitter and close-up optics for recording progress of plate cultures

Special light sources

Lyophilizer

Dark-field colony counter

7. POWER REQUIREMENTS: (90-Day Mission)

Power principally for incubators, freezers, refrigerators, etc., is estimated at 70 watts average. An additional 120 watts continuous for 5-6 hours per day is required for microscopy and lab operations. 216 KWH total energy required.

8. CREW REQUIREMENTS:

One microbiologist assisted by a full-time chemical-bacteriological technician will be adequate to perform the study.

9. MANHOURS REQUIRED:

Based on 3-month tours of nominal 8-hour days, 6-day weeks; 624 hours of scientist and 624 hours of technician time will be required for a total of 1248 man hours of orbital experimenter time.

10. ORBIT REQUIREMENTS:

There are no special orbit requirements.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

No special spacecraft orientation is required. Some studies will require performance in Region II of the spacecraft. The majority, however, can be accomplished satisfactorily, it is presently thought, in Region I. Most of the observations will not require lengthy sequences of preparatory exposure to zero-G.

12. ENVIRONMENTAL REQUIREMENTS:

Normal shirt-sleeve environment will be adequate except for those specimens requiring incubation or refrigeration.

13. EXPERIMENT/SPACECRAFT INTERFACES:

Management of wet chemistry operations, toxic vapors, and waste handling.

14. COMMENTS:

Weight of experiment-peculiar equipment is estimated at 500 lbs. Volume of experiment-unique items is estimated at 15 cu ft.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-15

1. TITLE: Tropic Responses and Morphogenesis of Plants in Ultralow-G Environments

2. OBJECTIVE:

Determine the effects on the growth and development of plants caused by gravitational forces. Particular aspects to be studied are coupling of geotropism and phototropism, morphogenetic sensitivity to gravity, and mechanisms of perception of gravity forces.

3. EXPERIMENTAL PROCEDURE:

Four types of observations will be made in the course of the experiment. The first involves taking photographs of developing seedlings against a background grid to record independently and concurrently the effects of gravity and light. The second utilizes autoradiographic methods of localizing chemical inductors and their sites of action. The third involves wet biochemical analysis of various tissue and fluid samples from plant material. The fourth utilizes histological examination of both tissue specimens and whole developing seedlings and cuttings for determination of the course of morphogenetic phenomena. Much of the work encompassed in this experiment will be performed in special environmental chambers located in the general laboratory area of the spacecraft. In addition, some of the observations will be made in Regions II and III. Some of the observations will require use of microscopy and photography work stations, while other observations and procedures will take place in the wet lab, isotope handling, and histology lab facilities.

4. MEASUREMENTS AND DATA:

Measurements will be made regarding both gross and microscopic morphological parameters by making photographs, radioautographs, and histologic preparations. Wet chemistry will be used in conjunction with electrical and optical measurements for physiological data.

5. a. ESTIMATED BULK OF DATA:

Film for time-lapse records and roll film for nonperiodic records. Histologic and radioautographic preparations as well as records of optical and electrical measurements will be utilized for the physiological and the remainder of the morphologic studies.

b. DATA FORMAT:

20,000 frames of 16 mm film

10,000 frames of 35 mm film

1000 histologic preparations and radioautographs

20 laboratory notebooks

c. DATA REDUCTION:

Data reduction will be performed on the ground.

6. MAJOR APPARATUS AND FACILITIES:

In addition to a "wet lab" for propagating specimens, dark rooms will be required to conduct the portions of the experiment dealing with phototropism. As currently conceived, the experiment will require provision within the laboratory for acceleration levels of 10^{-7}G or less for as long as 2-4 months at a time. A photographic darkroom will be required for a limited amount of film processing and a histological and cytochemical laboratory is extremely desirable, if not mandatory.

Instrumentation and apparatus required included:

Centrifuges for maintaining controls at several different G levels

Clinostats

Time-lapse and single-frame cameras and backdrop measurement grids

Special controlled-illumination equipment

Isotope-handling equipment and radiation counters

Lyophilizer and freezers

Freezing microtome

Radioautography equipment

7. POWER REQUIREMENTS: (90-Day Mission)

Microscopy and photography are expected to consume 200 watts continuously for 8 hours, and 50 square-wave peaks of 300 watts and 20 seconds duration daily, plus a requirement of 110 watts average for specimen environment chambers. 324 KWH total energy required.

8. CREW REQUIREMENTS:

One scientist trained in both morphological and functional botany could conceivably perform the experiment. However, a better arrangement would include a plant morphologist and a plant physiologist both with extensive training in cytology, histology, biochemistry, and biophysics. In addition, a 1/4-time histologist and a full-time wet lab technician trained in radioisotope methodology should be included.

9. MANHOURS REQUIRED:

Based on a 3-month mission with 8-hour days, and 6-day weeks; 624 - 1248 hours of botanical scientist time plus 156 hours of supporting scientist and 624 hours of technician time, for a total of 1404 - 2028 hours of orbital experimenter time.

10. ORBIT REQUIREMENTS:

No special orbit is required.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

No special spacecraft orientation is required. Predictions and conclusions based on recent laboratory work with plants indicate sensitivity to gravitational forces as low as 2×10^{-6}G. Certain of the studies contemplated for performance in Region III are thought to require 10^{-7}G for a period of 45 days.

12. ENVIRONMENTAL REQUIREMENTS:

Normal shirt-sleeve environment will probably be acceptable for most specimens assuming cabin pressure is not too far reduced. Some specimens will be maintained in thermal-humidity cabinets.

13. EXPERIMENT/SPACECRAFT INTERFACES:

The problems connected with the degree of stabilization required for acquisition of meaningful measurements are the paramount interface. A secondary problem is the requirement for large thermal-humidity environment chambers.

14. COMMENTS:

Estimated weight of experiment-peculiar items is 1100 pounds. Estimated volume of experiment-peculiar items is 35 cu ft.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-16

1. TITLE: Cell Division and Experimental Cytobiology in Low-G
2. OBJECTIVE:

Study of the influence of gravity on mitosis, chromosomal morphology, DNA synthesis, and cyclical aspects of cell division. Other studies include measurement of gravitational effects on differentiation and metabolic processes.

3. EXPERIMENTAL PROCEDURE:

The principal experimental technique utilized is the culture of various cells and tissues as well as the use of protozoans and sea urchin eggs. Morphological studies will rely heavily on photographic recording of data while physiological studies will employ isotopic labeling and other biochemical methods. In some cases, micromanipulation of portions of cells will be utilized, as will micro-injection of various materials into single cells.

4. MEASUREMENTS AND DATA:

Direct observations and photographs will be used in the collection of morphological data. Physiological data will utilize optical and electrical measurements which will be read out directly or recorded.

5. a. DATA FORMAT:

Film, magnetic tape, strip-chart recordings and written records. There will be a few histological preparations and radio-autographs.

b. ESTIMATED BULK OF DATA:

1 million frames of 16 mm film
10,000 frames of 35 mm roll film
35 hours of magnetic tape
Lab notebooks
1000 feet of strip-chart paper
500 histologic slides
250 radioautographs

c. DATA REDUCTION:

Data reduction will be performed on the ground.

6. MAJOR APPARATUS AND FACILITIES:

Principal facility requirements are as follows:

"Wet Lab" for culture preparation and general chemistry operations

Photographic processing facility

Instrumentation bench (may be located in wet lab area)

Isotope and autoradiograph lab and darkroom

Instrumentation and apparatus includes:

Compound microscope with multiple beamsplitter, phase-contrast optics, cinecamera attachments, plate camera attachments, and video camera

Long-working-distance, stereoscopic, "dissecting" type microscope with stereocamera attachment

Movie camera with shutter-speed control for time-lapse photography

Plate camera

Roll-film camera

Video camera

Stereo camera

Micromanipulators (Ellis piezoelectric type)

Incubators and other special thermal environment chambers

Isotopic tracer equipment

Ultraviolet and fluorescence microscopy equipment

Special zero-G culture vessels for propagation of specimens

Tape recorder for dictating notes while making observations

Centrifuges for control samples

Lead (or other dense material) "safes" for radiation protection of specimens

Automatic cell counters

Scanning microscope

Optical densitometers

Centrifuge for gas-liquid phase separation

Ultrasonic generation and special transducers

Special light sources

Freezer

Lyophilizer

Refrigerator

7. POWER REQUIREMENTS: (90-Day Mission)

90 watts continuous for 8 hours each day plus 80 watts continuous throughout the mission for environmental control of specimens in storage, etc. 238 KWH total energy required.

8. CREW REQUIREMENTS:

One combination cytologist - cell physiologist with the 1/4-time assistance of a histologist, plus a 1/2 to 3/4-time wet lab technician will be adequate to perform the experiment.

9. MANHOURS REQUIRED:

Based on a 3-month mission of 8-hour days, 6-day weeks; 624 hours of principal scientist time, plus 156 hours of supporting scientist time and 312 to 468 hours of technician time are required for a total requirement of 1092 - 1248 manhours in orbit for performance of this experiment.

10. ORBIT REQUIREMENTS:

No special orbit is required.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

No special orientation is required. Stabilization in the region of 10^{-3}G and better is believed adequate for all parts of this experiment.

12. ENVIRONMENTAL REQUIREMENTS:

Regular shirt-sleeve environment is acceptable for all laboratory operations. Specimens will be stored and maintained in appropriate micro-environments such as refrigerators, incubators, etc.

13. EXPERIMENT/SPACECRAFT INTERFACES:

Management of waste handling, specimen maintenance, toxic vapors, wet lab operations

14. COMMENTS:

Weight of experiment-peculiar equipment is estimated at 700 lbs. Volume of the equipment peculiar to this experiment is estimated at 27 cubic feet.

EXPERIMENT IDENTIFICATION AND DESCRIPTION FORM

E-17

1. TITLE: Biological Transport Phenomena in Low-G

2. OBJECTIVE:

Determine whether the influence of gravitational forces on biophysical and chemical systems cause alteration of biological transport phenomena. Studies of both known and postulated mechanisms will investigate gravitational factors in transport kinetics.

3. EXPERIMENTAL PROCEDURE:

Uptake studies will be performed by utilizing isotopic labeling and light-scattering photometry on bacterial cell cultures. Phagocytosis and pinocytosis are conveniently investigated using protozoans and tissue culture cells. Monocytes are also very good material for these studies. Time-lapse photomicrography will be the most valuable data-gathering technique. Fluid flow, especially as it is involved in such phenomena as streaming and cyclosis, will form a central part of the investigations. Direct observation and time-lapse photomicrography will again be used to obtain the data. In vitro studies of biochemical systems such as two-phase (or more) enzyme-substrate reactions will be accomplished for the most part with optical or electrical instrumentation such as spectrophotometers, polarographs, and fluorimeters.

4. MEASUREMENTS AND DATA:

Measurements will consist principally of electrical and optical measurements, strip-chart records, isotopic counting, written data in lab notebooks, and magnetic tape.

5. a. DATA FORMAT:

Written and strip-chart records, and magnetic tape

b. ESTIMATED BULK OF DATA:

20,000 feet of strip-chart records

30 lab notebooks

400 hours of magnetic instrumentation tape

c. DATA REDUCTION:

All data reduction will be performed on the ground.

6. MAJOR APPARATUS AND FACILITIES:

Facilities required are:

Isotope laboratory

Cytology and histology facility

Instrumentation bench

Microscopy and photography bench

A very small animal maintenance station

Instrumentation and apparatus include:

Light-scattering photometer

Optical densitometer

Compound microscope with phase-contrast optics and photomicrography attachments

Movie camera with time-lapse capability

Plate camera

Polarograph

Spectrophotometer

Centrifuges at various G levels for controls

Fluid transfer equipment

Radiation counters

Isotope handling equipment

Dissecting microscope

Special filter apparatus

Specimen culture vessels

Refrigerator

Electron microscope (tentative)

Incubators

Automatic cell counters

7. POWER REQUIREMENTS: (90-Day Mission)

Estimated power consumption is 120 watts continuous for approximately 8 hours each day, plus 5 square-wave peaks of 180 watts for 10 minutes duration. Specimen environmental maintenance equipment, etc., will require an estimated additional 50 watts average power. 195 KWH total energy required.

8. CREW REQUIREMENTS:

One full-time biochemist-biophysicist assisted by a 1/4-time wet lab technician will be sufficient to accomplish the experiment.

9. MANHOURS REQUIRED:

Based on 8 hours per day, 6 days per week, and 3-month tours in orbit; 624 hours of scientist time and 156 hours of technician time would be required for a total requirement of 780 man hours of orbital experimental time.

10. ORBIT REQUIREMENTS:

There are no special orbit requirements.

11. SPACECRAFT ORIENTATION AND STABILIZATION:

No special spacecraft orientation is required. Stability of between 10^{-3} and 10^{-4} will be sufficient for all anticipated experimental runs. Duration of this stability requirement will probably not exceed 1 hour at a time.

12. ENVIRONMENTAL REQUIREMENTS:

Regular shirt-sleeve environment should be entirely satisfactory for the experimental materials and procedures.

13. EXPERIMENT/SPACECRAFT INTERFACES:

Management of web lab operations, waste handling, and isotope utilization.

14. COMMENTS:

Weight of experiment-peculiar equipment is approximately 650 lbs. Volume of experiment-peculiar equipment is estimated at 25 cubic feet.