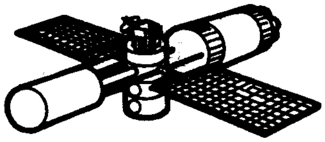
NV

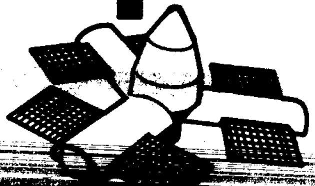
2gb MSC-EA-R-66-1,
Vol. ii END

3 PRELIMINARY TECHNICAL DATA FOR EARTH ORBITING SPACE STATION, 2#

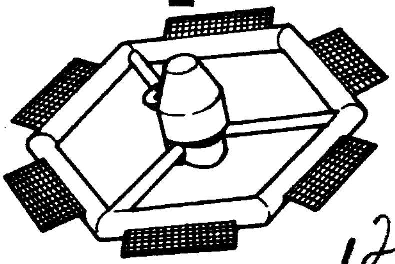


7 STANDARDS AND CRITERIA 9

VOLUME II; 2#



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
Houston 3



9 NOVEMBER 7, 1966 10

126 pages

FACILITY FORM 602

N67-27653	
(ACCESSION NUMBER)	(THRU)
1/126RS	1
(PAGES)	(CODE)
2gH TMX-59700 21B	31
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

Rq/43834A

PREFACE

This document, Volume II of IV, contains the Manned Spacecraft Center's technical data on Standards and Criteria for the Earth Orbital Manned Space Station Study. The data is concerned with the human factors, environment, logistics, and crew operations. This data is submitted in response to a NASA Headquarters' initiated study which includes requirements data from Langley Research Center, and experiment integration data from Marshall Space Flight Center. The complete integrated study will include the data from all three Centers.

The contributions of the various organizations within the Manned Spacecraft Center are acknowledged at the beginning of each section. Some of the data within these sections may differ slightly from the summary document since the summary presents the technical data in an integrated form. Any design philosophy presented in this volume represents the judgement of the contributing organization and has not necessarily been approved for the final study.

LIST OF VOLUMES

EARTH ORBITING SPACE STATION

Volume Number	Title
I	Summary Report - Preliminary Technical Data for Earth Orbiting Space Station
II	Technical Data - Standards and Criteria for Earth Orbiting Space Station
III	Technical Data - Systems for Earth Orbiting Space Station
IV	Technical Data - Configurations, Integration, and Weights for Earth Orbiting Space Station

TABLE OF CONTENTS

EARTH ORBITING SPACE STATION

STANDARDS AND CRITERIA

Section Subject

1.0 Medical Requirements
1.1 Acceleration Forces
1.2 Acoustics (Noise) and Vibration
1.3 Atmosphere
1.4 Crew Complement and Medical Care
1.5 Microbiology
1.6 Nutrition
1.7 Personal Hygiene
1.8 Thermal
1.9 Volume
1.10 Waste Management
1.11 Water Management

2.0 Habitability
2.1 Background
2.2 Area Requirements
2.2.1 Private Crew Quarters
2.2.2 Wardroom and Food Preparation Area
2.2.3 Exercise Area
2.2.4 Hygienic Facilities
2.2.5 Sick Bay
2.2.6 Command Station
2.3 Summary

3.0 Artificial Gravity
3.1 Background
3.2 Artificial Gravity Environment
3.3 Human Factors Design Considerations
3.4 Summary

4.0 Logistics
4.1 Configuration Implications
4.2 Logistics Requirements for Space Station Experiments
4.3 Logistics Requirements for Space Station Orbit Maintenance and Stabilization
4.4 Logistics Requirements for Space Station Housekeeping
4.5 Weight Estimates for Housekeeping Logistics and Stabilization Requirements

5.0 Crew Operations and Training
5.1 Space Station Crew Operations
5.2 Crew Training

TABLE OF CONTENTS (Continued)

Section	Subject
6.0	Environment Criteria
6.1	Meteoroid Protection
6.1.1	Damage Criterion
6.1.2	Comparison of Meteoroid Environments for Space Station and Mars Mission
6.2	Radiation Environment
6.2.1	Environment Definition
6.2.2	Dose Estimates for Proposed Space Station Missions
6.2.3	Space Station Application
6.2.4	Concluding Remarks

LIST OF FIGURES

EARTH ORBITING SPACE STATION

STANDARDS AND CRITERIA

Number Title

2.1 Living Space Per Man (Volume)
2.2 Living Space Per Man (Area)
2.3 Total Habitable Living Volume
2.4 Private Crew Quarters

3.1 Interior of Slow Rotation Room (SRR) at Pensacola
3.2 Manned Revolving Space Station Simulator (MRSSS) Complex
3.3 SRR and MRSSS Comparison
3.4 Geometry of a Rotating Body
3.5 Forces Due to Radial Movement
3.6 Total Force Reaction Angle
3.7 Centrifugal Force Variation
3.8 Coriolis Force Variation
3.9 Forces Due to Tangential Movement
3.10 Resultant Force Variation
3.11 Forces Due to Parallel Movement
3.12 Gravity Gradient Effects
3.13 Gravity Gradient Variation
3.14 Anatomy of the Vestibular System
3.15 Human Factors Design Envelope

4.1 9-Man Space Station Resupply Requirements
4.2 24-Man Space Station Resupply Requirements

5.1 Study Methodology - Functional Analysis

6.1 Meteoroid Flux Model
6.2 Meteoroid Shielding Weight Required for Space Station
6.3 Probability of Encounter for Threshold Mass for an Exposure Area-Time Product of 10^4 ft^2-Years
6.4 Interplanetary Meteoroid Model
6.5 Electron Map
6.6 Proton Map
6.7 Zone Protected from Radiation Due to Solar Flare Particle Events
6.8 Earth's Magnetosphere
6.9 Shield Weight Vs Radiation Dose - 30° and 60° Inclinations
6.10 Probability or Fraction of Time That Flux Exceeds J_1.
6.11 Synchronous Orbit Dose from Trapped Electrons - One Year Mission, Average Dose
6.12 Dose Probability
6.13 Dose Probabilities for 360 Day Mission - Solar Maximum
6.14 Dose Probabilities for 360 Day Mission - Solar Minimum

LIST OF FIGURES (Continued)

Number Title

6.15 Shield Weight Versus Radiation Dose for Polar Orbit and .01 Probability

6.16 Dose Versus Thickness at Synchronous Orbit for a Large Solar Flare Particle Event

LIST OF TABLES

EARTH ORBITING SPACE STATION

STANDARDS AND CRITERIA

Number	Title
4.1	Weight - Spare Components - 9 and 24 Man Crews - One Year
4.2	Weight - Tankage - 9 and 24 Man Crews
4.3	Weight - Expendables - 9 and 24 Man Crews

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 1.0

MEDICAL REQUIREMENTS

MEDICAL RESEARCH AND OPERATIONS DIRECTORATE

MANNED SPACECRAFT CENTER

1.0 MEDICAL REQUIREMENTS FOR AN EARTH ORBITING SPACE STATION

In setting forth requirements for space station design it is first necessary to establish a set of assumptions or postulates regarding the objectives and scope of the space station which the proposed criteria would serve. The first section of this report describes the purposes and objectives which would be assigned to a manned orbiting space station at this time. The assumptions regarding design set forth in this section of the report represent the concepts which seem most logical and reasonable to the MSC Medical Directorate for the design of a space station which could accomplish the desired scientific and technological objectives.

The fundamental premise upon which these design criteria are based is that this manned space station should enable scientists to identify and evaluate the biomedical significance of selected unique features of the space environment. The essential attribute of space that we would endeavor to evaluate through the use of an orbiting space station is the null-gravity state. Other environmental variables should be controlled as close to "earth normal" conditions as possible.

Other assumptions upon which these design criteria are based are listed below.

The laboratory will have an orbital life of 2 to 5 years.

The laboratory will have resupply and crew rotation capabilities.
    Revisitation intervals of 3 or 6 months.

The crew structure includes:
    Operation personnel
    Scientific personnel

The crew size shall not be less than 9 and shall not exceed 15 persons.

Separate living and laboratory spaces are to be provided.

1.1 ACCELERATION FORCES

Consideration must be accorded to acceleration forces experienced during launch, reentry, and orbital phases.

It is postulated that the station itself will be launched in an unmanned status and will be peopled by means of "shuttle" resupply flights utilizing spacecraft similar to the Apollo Command and Service Modules. Furthermore, it is postulated that the resupply missions will assume as much as possible the aura of routine operations. Hence, either land landing at an established base or pin-point water landings will be necessary to eliminate the need for deployment of large recovery forces. Optimally, the reentry g pulses, landing impact forces, and launch g forces should not exceed those commonly experienced during travel by commercial aircraft. However, energy requirement for achieving orbit as well as energy dissipation requirements for return to the Earth's surface probably preclude these goals.

Available data indicate that the potential occupants of a space station will not be adversely affected by the launch accelerations proposed for Apollo missions.

The reentry acceleration forces proposed for Apollo missions are also considered reasonable and not likely to severely influence the results of scientific studies. However, the majority of impact data is based upon subjective endpoints. Hence, the establishment of objective criteria is necessary before the effects of these forces can be adequately described.

Since the study of man under conditions of weightlessness constitutes the prime objective of biomedical research in an orbiting laboratory, a "zero g" laboratory is mandatory; this includes living quarters as well as experimental spaces in order that the adaptive mechanisms can achieve new steady state functioning levels in response to "zero g". On the other hand, despite the best efforts to make all other variables equivalent to those of Earth's environment, control groups of human beings should be studied simultaneously within the station. These control groups must experience all other conditions except weightlessness to the same degree as the "experimental zero g" group. Furthermore, our primary standard is man in Earth's environment (those ambient conditions prevalent in Earth-based biomedical research laboratories); hence, the appropriate variable isolation requires a control group under space station environmental conditions with the exclusion of weightlessness. Therefore, both a "zero g" laboratory complete with living quarters and a 1 g laboratory complete with living quarters are requisite for conclusively establishing the effects of weightlessness on man.

A 1 g area allows the utilization of many well established laboratory research techniques and methodologies which would not be otherwise appropriate. Additionally, the accomplishment of operational and maintenance tasks without the necessity of special tool and technique developments as well as extensive training (which would be required for "zero g" or "sub 1 g" acceleration force fields) can be achieved.

The creation of a 1 g acceleration force field has inherent problems which must be studied in detail to avoid compromising biomedical studies. Two such factors are the head-to-foot gravity gradient and the neurophysiological disturbances resulting from Coriolis forces. Current ground-based studies have not produced the necessary information which establishes the acceptable limits for these factors and thereby prevents setting forth specific requirements such as the minimum radius for rotation and the maximum angular velocities. These areas are of recurrent interest whenever artificial gravitational forces are considered and should therefore be accorded high priority for concentrated study efforts.

1.2 ACOUSTICS (NOISE) AND VIBRATION

Requirements in these areas should consider two mission operational phases, launch and orbit.

Launch requirements dictate that neither vibration nor noise interfere with performance capabilities or communication. Generally, the Apollo specifications for launch vibration limits are adequate. Nominally, noise should not exceed 125 db for a period of 30 seconds and should be less than 115 db if the duration is for 300 seconds. The Apollo specifications for speech interference are considered adequate.

During the orbital phase, vibration should be below the level of perception. Noise levels must not interfere with voice communication and must not constitute a chronic annoyance factor. Limitation of total white noise levels to 75 db (with a 50 db limit from 600 to 4800 cps) in laboratory spaces and 50 db in living quarters should approach these goals.

1.3 ATMOSPHERE

Ideally, the atmosphere should be identical to that of Earth, i.e., 14.7 psia pressure, 78.084 percent nitrogen, 20.9476 percent oxygen, and 0.9684 percent rare gases. This rare gas portion is comprised of 16 components, 6 of which do not vary significantly, and 10 of which show significant variation from time to time as well as place to place on the Earth's surface, and indeed some may well be undesirable contaminants. Furthermore, argon comprises 0.934 percent and carbon dioxide 0.0314 percent of the total atmosphere. This leaves only 0.003 percent of the total atmosphere for distribution among the remaining 14 rare gas components. In consideration of the complexity and increased loss of reliability imposed by the continual monitoring and control, an atmosphere (which is not entirely constant from time to time and from place to place on the Earth) composed of all the Earth's atmospheric components is not recommended. Since the physiological significance of the rare gases in Earth's atmosphere is not known, it is, however, important to isolate these variables.

The atmosphere must yield a calculated alveolar oxygen partial pressure of 105 mm Hg (21 percent oxygen at 14.7 psia). The carbon dioxide content should ideally not exceed that of Earth's atmosphere (0.0314 percent) and certainly should be maintained at levels less than 3.8 mm Hg absolute (0.5 percent at 14.7 psia).

Water vapor must be kept at levels which preclude discomfort by loss of evaporation cooling, i.e., a muggy, humid environment. Hence, total water vapor should be restricted between 10 mm Hg and 18 mm Hg with a relative humidity restriction which is discussed with other thermal requirements.

The maintenance of the atmosphere within a closed system requires appropriate surveillance and control. Two major types of contamination may be expected: aerosols (particulate matter and liquid droplets) and gases.

Aerosols may best be removed by filtration techniques. Removal of particles greater than 0.3 microns in size with 95 to 97 percent effectiveness is within the present state of the art and is considered adequate for this aspect of atmospheric contaminant control.

Gaseous contaminants arise from three major sources: those present as impurities in the atmospheric gas supplies, those contributed by offgassing of spacecraft materials, and those contributed by offgassing from the biological occupants whether they be human beings, experimental animals and plants, or uncontrolled growths of micro-organisms.

Control of contaminants from gas supplies is best obtained by appropriate quality control and quality assurance of procurement sources.

Control of spacecraft materials offgassing is also best accomplished by source control. Hence, a formalized management of selection or rejection of spacecraft materials based upon toxicological requirements as well as engineering requirements is essential for the prevention of atmospheric pollution.

The establishment of permissible materials and quantities of materials requires the development of predictive models which are based upon the basic kinetics of materials offgassing.

Control of biological offgassing contaminants will of necessity have to be accomplished by removal. The principal human offgassing products are carbon dioxide, carbon monoxide, water, hydrogen, methane, and ammonia. Other contaminants which are highly objectionable to the olfactory senses include skatols and indols. Catalytic burners are effective for scrubbing the hydrocarbons and oxidizing carbon monoxide, however, catalytic burners are not without their problems. These systems become explosive if sufficient amounts of hydrogen are present and certain fluorohydrocarbons are degraded by catalytic burners to agents more toxic than their precursors.

Carbon dioxide and water require scrubbing systems other than catalytic burners.

Monitoring of oxygen, nitrogen, carbon dioxide, and water should be continuous with automatic limit alarms. Logging should be by automatic printout at least four times each day. Additionally, all values which depart from nominal should be automatically recorded.

Sampling for trace contaminants should be at intervals no greater than two hours initially and at increased intervals later. Analysis sensitivity should be 1 ppm for individual substances and 10 ppm for total hydrocarbons.

Consideration of dysbarism is paramount when the possibility of changes in total pressure exists. Hence, airlock capabilities are required for EVA activities and either 3 to 4 hours of denitrogenation if 3.5 psia, 100 percent oxygen suit atmospheres are to be used, or else a 7 psia, mixed gas (oxygen 44 percent, nitrogen 56 percent) suit atmosphere would be required.

Recommended requirements for space station atmospheres are summarized below.

Pressure	14.7 psia
Composition	
Oxygen	21 percent
Nitrogen	79 percent
Contaminant Criteria	
Carbon Dioxide	0.5 percent
Carbon Monoxide	
Nominal	10 ppm
Maximum	25 ppm
Water Vapor Pressure	
Minimum	10 mm Hg absolute
Maximum	18 mm Hg absolute
Hydrocarbons	
Total	100 ppm
Individual Gas	1.0 ppm
Ozone	0.1 ppm
Aerosols	
Maximum Size	0.3 micron
Concentration	To be established

Materials Offgassing Products	Toxicologically allowable levels and criteria to be established.

1.4 CREW COMPLEMENT AND MEDICAL CARE

As crew size and mission duration increase, the implications of optimum medical and physiological selection criteria also take on added importance. An ideal selection program would enable management to obtain a crew each of whose members would successfully complete any required training and would perform throughout the mission duration at a high level of efficiency. The state-of-the-art falls far short of this ideal objective but certain principles have been established largely through empirical observations on group performance in isolated working environments such as polar expedition, submarine crews, mountain climbing expeditions, etc. Paying due attention to these principles should enhance the probability of mission success while total disregard for them would almost surely result in serious mission degradation or failure due to human inadequacies within the crew. Selection must be made not only on the basis of individual qualification of crew members, but also with a view toward the ability of each crew member to work effectively and harmoniously with the entire crew.

The exact number of people who comprise the crew depends upon task analysis much more than on medical or physiological considerations. If the number selected is too small in relation to the tasks associated with the mission, the probability of operator error becomes great. If the station is designed as a large complex community, the logistics of resupply become the limiting constraint and medical evacuation of sick and injured personnel along with medical resupply logistics must be considered. A crew of between 9 and 15 personnel appears to be a good compromise from the standpoint of avoiding undue complexity due to medical support requirements and yet obtaining valid data on the physiological adaptation of man in the spaceflight environment.

The medical criteria which have been established for selection of military aviators are generally appropriate for selection of space station crew members. Requirement for visual acuity and certain other pilot-related physical characteristics such as rapid reaction time and eye-hand coordination skill would be relaxed for scientist and technician crew members who are not required to control or maneuver the spacecraft. Adaptation of existing military and civil aviation medical standards rather than development of new physical criteria for selection of space station crew members should prove sufficient for the establishment of medical selection criteria. Applied research and development is indicated, however, in the area of psychological aptitude for space flight among scientists and technicians who have not already been preselected through the process of becoming professional pilots. While gross personality characteristics which would render candidate crew members unsuited for space station assignment can be identified using currently available techniques, the only satisfactory test of crew compatibility is to assemble a full candidate crew and observe the crew members during a prolonged period of living and working together under conditions as nearly representative of the actual mission situation as is practicable. Under conditions of enforced continuous close association, subtle individual characteristics become major factors in successful interpersonal relationships and concealed idiosyncrasies emerge which degrade and in some instances have destroyed the functional integrity of the entire crew. It is considered mandatory that careful attention be paid to timing and structuring the training program to allow for the demonstration of crew compatibility and to permit the replacement of individual crew members who do not fit into the group successfully as time goes by. Motivation, discipline, command structure, training, and individual intelligence of the crew are all important factors. Demonstrated crew compatibility ranks along with all of these in contributing toward mission success.

The presence of a physician as a biomedical scientist on the crew is recommended. This man would have primary responsibility for the proper conduct of the in-flight biomedical research program and should materially enhance the overall probability of mission success by furnishing in-flight medical support to the crew. A physician backed up by systems designed in accordance with optimum human engineering and preventive medicine practices and appropriate medical support of the crew through their preflight training period should be able to manage all of the medical problems which would arise in the course of a three-month to one-year orbital mission with relatively simple on-board equipment and treatment capability. This capability should include facilities and supplies adequate for the diagnoses and treatment of infectious diseases, simple fractures, minor surgical emergencies, and the initial care and stabilization of severely injured crewmen to prepare them for evacuation to ground-based medical facilities.

A designated medical treatment area will be required. This area does not have to be solely utilized for medical examination and treatment and would probably serve a dual function as part of the biomedical research laboratory capability that would be required in any case. The required examination area or cubical should be at least 9' x 7' x $6\frac{1}{2}$' in volume and should encompass an examination table, provisions for private interviewing, record keeping capability, and small lockers for records, instruments, and medical supplies. A clinical laboratory capability should be built into the space station laboratory space with provisions for sterilization of utensils and instruments, microscopic examination of biological specimens, incubation of bacterial cultures and the preparation and storage of samples for later shipment to Earth. A "field type" X-ray capability is required. Units exist and are flight qualifiable which weigh less than 100 pounds including shielding and image processing provisions. The volume required for storage of additional medical supplies including medications, dressing material, minor surgical instruments, splints, and casting material is estimated at 75 cubic feet. Bulk medical supplies could be packaged in lockers or other modular units and maintained in storage space within the space station with small packages being withdrawn from the bulk lockers and moved to storage cupboards in the treatment area as required.

A medical holding facility or "sick bay" is required for isolation and treatment of patients who may acquire infectious disease during the course of the mission. Since provision for individual privacy is highly recommended in the crew quarters, designation of a two-bed room or two single-bed rooms as dictated by overall design considerations is proposed. Early detection of a case of contagious disease among the crew would give rise to the possibility of isolating the carrier of the infection from the remaining crew members and avoiding spread of the infection throughout the crew. Rigorous quarantine measures are not recommended because the cost in terms of equipment and procedural complexity appears, in our judgment, to far outweigh the probable contribution of such attempts to mission success. Attempting to establish strict quarantine in the face of the close constant contact between crewmembers would probably be futile. It is recommended that provision be made for bacteriological filtering of atmosphere exhausted from the "sick bay" room. No other special provisions for isolation or unique construction of the bedrooms designated as "sick bay" are necessary.

Initial requirements regarding the crew and medical care are listed below.

- Selection and training
    - Initial selection for aptitude and compatibility
    - Early assembly of full crew
    - Realistic working relationship maintained to identify interpersonal problems
    - Physical and psychological standards for non-pilot crew members require development

- Medical care
    - Physician on crew
    - Examination and treatment area - 9' x 7' x 6.5' minimum
    - Drug and equipment storage space - 75 cubic feet

X-ray capability
Utensil and instrument sterilization capability
"Sick room" features included in crew quarters - two-bed capacity

1.5 MICROBIOLOGY

The occurrence of an infectious disease during a prolonged space mission must be avoided by adequate preventative and surveillance methods. The origin of such disease could be from one of several sources: first, from an incipient disease carried on board the spacecraft by a crew member; second, by some alteration in the microflora generated by the prolonged isolation; third, by the mutation of the spacecraft microflora. In addition, the state of disease resistance of the spacecraft crews may be altered due to lack of contact with the large variety of microorganisms that the terrestrial environment provides. All of these possibilities have their foundation in sound experimental data.

A program of prevention calls for a spacecraft design that in basic construction permits good general hygiene. It further calls for an environmental control system that offers a measure of control over the bacterial aerosols present in the atmosphere. This does not imply a provision for sterilizing either atmosphere or spacecraft components, but does require control methods that will insure a spacecraft whose biological environment is optimal for both man and mission.

A control program must provide for monitoring both the quantitative and qualitative aspects of the microflora. Only in this manner can the compatibility of this complex relationship of man, his supporting engineering systems, and the microbial environment be insured.

Even if conducted successfully, the state of disease resistance of the crew member remains relatively uncertain because no reliable operational procedure exists at this time to assay this area. On-board medical experiments should further define this state of resistance.

A summary of these requirements follows.

Total viable micro-organisms in ambient air must be less than 20/cubic foot of air

E.C.S. must have provision for removal of micro-organisms on a continuous basis

Material capable of freely supporting microbial growth should not be utilized in spacecraft construction

Development of techniques for monitoring flora of spacecraft and occupants

Twice weekly flora assessment of spacecraft hardware microflora and occupant flora

Daily aerosol data to include:
- a. Particle profile (concentration and size)
- b. Total viable organisms
- c. Total particles with viable organisms

(Above to be from at least three sampling points within laboratory)

1.6 NUTRITION

Evidence exists supporting the premise that on extended duration space flights, the psychologic response to the form (i.e., type) of food may be a major factor in the success (performance) of the mission. To be eaten, food must be acceptable, and this has little relation to the nutritional composition and value of the food. A food such as a liquid formula can be found acceptable under experimental or clinical conditions but not necessarily under practical operational conditions, and this may well be attributed to the fact that motivation and not acceptability is often being measured under the former conditions. Therefore, for a space station, it is recommended that a variety of familiar foods be provided which allow for individual hunger and satiety patterns. The study of the psychophysiology of monotonous diets should definitely be considered as an inflight experiment on the space station.

Dietary regimens should be tailored closely to the metabolic pattern of the individual astronauts. The individual variability of metabolic patterns for given dietary regimens will need to be established with reasonable degrees of precision if this goal is to be realized. The commonly accepted caloric value for sedentary idle living is 93 $W^{(3/4)}$, where W equals body weight in kilograms. This is 32 kcals/kg. of body weight or 2280 kcal/day for a 70 kg. man. Although by ground-based standards this is one and one third (1 1/3) times basal, it is recommended as the base maintenance requirement for space flight. This base figure is compatible with the calculated Gemini V and VII requirement of 2010 to 2219 kcal/day respectively. The caloric costs for zero g tasks on these Gemini missions were minimal due to cramped quarters and no extravehicular (EVA) or rendezvous activity. Ground-based data indicates a 15 to 30 percent increase above base will be required for simple frictionless environment tasks. Also some food residue (plate waste) is expected. Assuming crew activity on a space station would include: sleep (8 hrs/day); off duty (6 hrs/day); normal shirtsleeve duty (8 hrs/day) and excercise or pressurized suit activity (2 hrs/day), 2800 kcal/man-day would only allow 250-300 kcals per man-day as extra calories above base maintenance requirements, primarily expected to be expended during a 2-hour period of moderate to hard work. Therefore, 2800 kcals/man-day is the minimal total daily caloric expenditure for calculating food provisioning requirements.

The most realistic available data indicates that the diet should have the following distribution of calories:

15 percent protein calories
33 percent fat calories
52 percent carbohydrate calories

Utilizing semipurified ingredients this diet cannot weigh less than 592 grams (1.30 lbs.) in an ashless, dry form. Utilizing food sources processed as follows: 75 percent dried foods (rehydratable and bites); 15 percent heat processed flexible pouch foods; and 10 percent frozen foods, the diet <u>without</u> packaging would weigh at least 705 grams and probably 770 grams (water, ash, and fiber included). Allowing 20 percent additional for packaging and dispensing devices (assuming a 100 lb., $10'^3$ galley with food resupply no more often than every three months), 910 grams (2.0 lbs.) of food per man-day must be allowed to provide 2800 kcal/man-day. Total volume allowance for packaged food should be 250 cubic inches per man-day.

The galley, operable in both zero g and gravity states, would include a heat exchanger or thermoelectric water heater and cooler; a thermoelectric freezer and oven; preparation and eating trays; and interchangeable modules for food and waste. The volume of this system would be approximately 90 cubic feet for a 10-man crew. Only the modules would be interchanged on resupply. The integrated food concept and galley must be developed, but many of the subsystems are currently within the state-of-the-art.

The feeding system must be compatible with the periodic collection of food and water consumption data and other nutritional-physiology experiment requirements.

In summary, the requirements are as follows:

2800 calories per man per day

2 pounds per man per day

250 cubic inches per man per day

Utilize galley for food preparation in bulk
    Oven, chiller, freezer capability

Foods to be combination of
  Precooked packaged food
  Rehydratable foods

Food service to be adapted to both the null-gravity and one g environments

Develop acceptable simplified null-gravity eating techniques

Develop galley concept

Develop improved food concepts

Periodic food and water intake data

Daily weight

Ancillary, periodic, gastroenterology/nutrition data

1.7 PERSONAL HYGIENE

There is no documented evidence as to any health problems resulting from failure to bathe. Frequent bathing is recommended for social purposes since body odors are repugnant to the senses. Due to these social aspects, people have become indoctrinated into the need for frequent and routine body cleansing procedures. Even though bathing may not be a serious consideration in physical health, it is reasonable to believe that bathing will be both fatigue reducing and mentally hygienic for spacecraft crews.

The washing and frequent changing of clothing is very important in personal hygiene. Clothing serves a multi-purpose within the parameters of personal hygiene in serving as a cleansing agent over a large area of the body due to contact with the skin. Much of the skins excreta (cellular debris, hair, sweat, etc.) is transferred from the body to the clothing which thus becomes a good transport agent for body waste to a disposal point. Therefore, it becomes a necessity on prolonged space missions that facilities be present to insure frequent changing and laundering of clothing.

On space missions exceeding thirty days in duration, shaving of the beard and trimming of the hair must be considered for aesthetic reasons. Problems encountered in space missions due to this procedure have already produced shaving instruments suitable for short duration missions.

There have been many routines proposed for personal hygiene procedures during space missions, including,also,suggested hardware. It would appear to be a case of adapting existing and/or suggested procedures and hardware to the assigned task.

In summary, personal hygiene requirements are as follows:

- Handwashing and whole body washing capability
- Clothes washing capability
- Oral hygiene station
- Shaving, haircutting capability
- Develop simplified washing capability (zero and one g compatible)
- Establish personal hygiene and oral hygiene criteria
- Develop inflight clothes washing capability
- Develop inflight haircutting capability

1.8 THERMAL

Thermal regulation is of utmost importance in long-duration missions. Departure from operationally oriented tasks introduces a variety of activities, each of which may, for optimal performance, require a different thermal environment. Hence, the need for controllable temperature and humidity environments exists. Studies on comfort zones indicate that for most of the anticipated space laboratory activities, the temperature should be adjustable between 65°F and 80°F with an accuracy of ± 3°F at any selected temperature within this range. The transcompartment temperature gradient should not exceed 5°F. Humidity control is required in parallel with temperature to permit selection of the optimal temperature/humidity ratio for comfort. The absolute water content should not be less than 10 mm Hg nor exceed 18 mm Hg water vapor pressure. Even with these limits, it is necessary (to prevent a saturated atmosphere) to limit the maximum relative humidity to 80.

Experience has indicated that an air velocity of at least 15 ft/minute is necessary to maintain comfort.

The thermal control system must be capable of absorbing heat pulses produced by periods of physical activity. Although definite criteria depend upon firmly established activity routines, it would not be expected that any one individual would produce more than 4800 BTU/hr for longer than a 10-minute period, nor that more than four individuals would be engaged simultaneously in such strenuous activity; furthermore, the occurrence of such heat pulses would probably not occur more often than once within a two-hour period.

Adequate thermal control is of importance not only from the standpoint of man's performance, but also from the standpoint of increased requirements for expendables.

Established requirements are tabulated below.

Temperature	
Controllable Range	65°F to 80°F
Control Accuracy	± 3
Transcompartment Gradient	5°F maximum
Water Vapor	10 to 18 mm Hg (80% R.H.)
Air Velocity	15 cu ft/minute minimum

1.9 VOLUME

The specification of minimum volume requirements sufficient to sustain a group of people in a high state of operational efficiency over a prolonged time appears to be beyond the present state-of-the-art. As in the case of crew selection, a few empirical guidelines and general principles have been identified which are worthy of careful attention in the design of a facility for long-term habitability. In general, when people are thrown together in a confined isolated situation, their ability to get along and continue to operate effectively is dependent upon the satisfaction of what appear to be basic drives for occasional privacy and a modicum of individual control over space where personal belongings may be stored. In addition, experience has shown that the more clearly a division of functional utilization can be engineered into the habitable space in confining vehicles, the better they can be tolerated by personnel for long time durations. We would, therefore, strongly recommend that living quarters be distinct from working quarters in the station and that living quarters include individual or two-man bedrooms, individual personal storage space, a galley and group dining area and, if possible, an additional area designated for lounging, reading, group conversation, etc. Functional division of the work space depends upon maintenance requirements and scientific objectives around which the laboratory is designed. Living quarters for part of the crew complement are required in the 0 g portion of the station and, in a large sense, these could be construed as laboratory area; however, the term "laboratory area" is generally meant to refer to space in which scientific tests or measurements are conducted by personnel during the on-duty portion of the work/rest cycle. Our recommendations regarding establishment of habitable volume requirements are listed in summary below:

Living Volume Minimum
- 350 Ft^3
- Individual sleep quarters
- Individual personal lockers
- Galley and dining volume

Laboratory Volume
- Establish laboratory requirements
- Establish utilization of laboratory space
- Establish requirements commonality

1.10 WASTE MANAGEMENT

For the purposes of this discussion, waste management encompasses the collection, sampling, if required, treatment or processing and disposal of all body wastes, specifically, urine, semen, feces, vomitus, mucous, hair, nails, and food residue. The requirements for personal hygiene equipment are described elsewhere, but it is anticipated that in some instances the personal hygiene system will be a part of, or will otherwise utilize ancillary components of the waste management system for the disposal of consumable personal hygiene items and wash and laundry water.

A wide variety of collection systems have been developed to prototype state, but an optimal system has been constrained by space, weight, and power allowances. The aesthetic collection of urine and feces requires that the design of the equipment be versatile enough to accommodate the other body wastes and that the design of the equipment be based on normal human physiology principles and familiar habits. No direct contact between man and the collection equipment, such as condoms or adhesive devices, should be involved. The fecal/urine system should be compatible with the disposal of all other body wastes and food residue, although separate or ancillary collection devices operational in zero g are required to collect nails and hair. The simplest system would involve performing these latter functions in a vacuum cleaner (i.e., debris trap) enclosure.

Provisions for the continuous or periodic and accurate (± 3 percent) measurement of urine and fecal mass and/or volume is required for experimental and biomedical monitoring purposes. The capability for periodic sampling for later ground-based analyses should be available. The system must provide adequate sample identification for biomedical monitoring or experiment requirements. Ground-based data on the major nutrient balance contributions of hair and nails indicates that these parameters are insignificent. However, hair and nails are a potentially simple source of material for ascertaining protein (amino acid) and trace mineral status. This concept needs substantial ground based examination to determine its suitability and reliability, but once established, only periodic samples would be needed to monitor nutrient status.

As a general rule, a waste management system capable of adequately treating feces, will, in all probability, be adequate for the remaining waste components. One fecal/urine collection device and associated equipment should not require more than 5 cubic feet. One unit for each to 8 crew members is recommended. Power requirement is estimated at 10 watt-hours per man-day. The mass or volume measurement device should be in the vicinity of the collector and dryer (described below).

A waste management system must provide for the prevention of the buildup of toxic gases, odors and/or micro-organisms. For example, the latrine area must (1) be physically isolated from living quarters; (2) must be interconnected with the environmental control system for the isolation of odor, gas and aerosol from the remainder of the space station; (3) remove odor from the latrine area within five (5) minutes.

The waste management system must minimize space contamination. There are several methods of treating or processing body waste. Storage of wet feces by holding in sterilizable pressure tanks or freezing is not practical because as much as a ton of wet feces could be collected in a two-year ten-man mission. However, short term storage of body waste in accumulator tanks, allowing waste to be processed or regenerated at a uniform and predetermined time, regardless of the rates at which they are excreted by the crew members should be considered for (1) water reclamation devices, and (2) the experiments involving bioregeneration of waste to usable food and water.

Storage of body waste in a dry state has received considerable emphasis and offers some distinct advantages to biomedical monitoring and experiment programs. Because of its simplicity and versatility, it is the method of choice at this time. The decomposition of waste is prevented when moisture is removed. Vapor distallation methods are less complex and require less power than freeze drying systems but both utilize the vacuum of space. A vapor distillation dryer would require 4.0 cubic feet of space for a 5 to 8 man crew. One dryer unit in proximity to each collection device is recommended. Power or waste heat to provide 100°F to the dryer would be required. The same unit would be modified to provide reclaimed water (see Water narrative). The ultimate disposal of body wastes not required for experiment or biomedical monitoring purposes could be incineration. Waste produced by a 10-man crew would require an incinerator weighing 75 pounds.

Other advanced waste management systems such as wet oxidation, electrolytic waste treatment and biological waste treatment should be considered as experimental devices for evaluation on the space station. There currently exists no qualified waste management system which meets all the medical requirements. Prototype systems do exist which could evolve into the required equipment. Zero g and long-term ground-based functional verification testing of all hardware is required.

Requirements for a waste management system are summarized below.

Aesthetically acceptable collection system
    E.g., no condom, elastic, or adhesive devices required for nominal use

Provisions for periodic, accurate (± 3%) measurement of mass and/or volume of body waste

Prevention of buildup of toxic gases, odors, and/or microorganisms
    E.g., 1) Latrine area must be physically isolated from living quarters
    2) Latrine area environmental control system must be capable of isolating odor, gas, and aerosol from remainder of laboratory
    3) Any odor following latrine use must be removed within five minutes

Develop systems for collection and disposal of keratinized waste, i.e., hair, finger nails

Systems for disposal of food residue, fecal and urine solids, etc. Such systems should minimize space contamination

Periodic samples, properly identified from selected crew members

Periodic recording of urine and fecal output by selected subjects

1.11 WATER MANAGEMENT

It is an established metabolic standard to allow one (1) ml of water for every calorie of energy expended. Since the latter is variable,but for design purposes 2800 kcals/man-day is recommended, 2800-2950 ml (6.5 lbs.) of potable water/man-day must be allowed.

For long-duration missions in excess of 45 days, minimal personal hygiene concepts (i.e., three (3) wet wipes/day plus one dry utility towel per day and one toothbrush) becomes unsatisfactory since the flora of pathogens on the skin reach potentially hazardous levels in particular in the groin, the feet, and the armpits. In addition, desquamation is substantial at 14 days. Therefore, water for washing the total body area or parts thereof (sponge bath) at least once per week is believed necessary to assure physiological and esthetic requirements and to accomplish preventive medicine procedures on a routine basis. The minimal allowance should be 900 ml (2 lbs) per man-day for personal hygiene water.

Current ground-based potability standards are those established by the USPHS (1962); however, all aerospace biomedical scientists agree that these standards are not only incomplete but impractical for space use. The current Gemini potability standard is sterile deionized water; however, on no flight to date has sterile water been provided. The water being loaded is sterile but spacecraft components are not and therefore a limit based upon practical experience has been utilized. Water potability standards are needed which can be applied to space vehicles, in particular on-board reclamation systems. The hardware must be processed during development (e.g., internal plating of lines and containers with silver) to include bacteriocidal and/or bacteriostatic properties. A requirement for the reclamation of sterile, low conductivity, neutral pH water should be imposed on the contractor. However, the development of practical operational potability standards is mandatory. These standards must be compatible with the development of simple and reliable microbiological and chemical techniques to monitor potability of water at frequent intervals during flight. Crew observations of odor, taste, etc., should be included. The adequacy and efficiency of the inflight monitoring equipment must be validated in both ground-based and inflight studies. These studies must be an integral part of the evaluation of advanced reclamation techniques. In the interim, it is recommended that vapor distillation or similar equipment be employed which utilizes bacterial filters in the recovery of water and that further, a sterilization unit be developed to assure potability until confidence in less complicated procedures can be increased and reliability proven over extended duration in both ground-based and inflight studies.

In summary, the water requirements are given below.

6.5 pounds per man per day (potable water)

2 pounds per man per day (hygiene)

Develop potability standards for selected system

Develop microbiologic and chemical techniques for potability monitoring

Provision for periodic determination of water intake on selected subjects

Records of monitoring instrumentation readout and crew observation on odor, taste, etc., of water

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 2.0

HABITABILITY

ADVANCED SPACECRAFT TECHNOLOGY DIVISION

ENGINEERING AND DEVELOPMENT DIRECTORATE

MANNED SPACECRAFT CENTER

2.0 HABITABILITY

Operation of an orbiting space station for a prolonged period of time will depend upon the ability of each crewman to perform the tasks assigned to him. For short duration missions, man will tolerate fairly primitive environmental situations as long as the physiological essentials are provided. However, long duration missions require the consideration of the human factors that are disregarded in short duration missions. System design utilizing habitability as the unifying concept will not only insure performance but will maintain crew morale.

Habitability requirements in this paper have been narrowed to include only the volume considerations for the crew. These considerations include areas required for work, sleep, personal hygiene, exercise, and other crew functions. The volume required for life support consumables, crew furnishings, and other equipment, and the unfilled volume lost in corners, narrow spaces, etc. is not considered.

2.1 BACKGROUND

One of the major factors of interest in space cabin design is the suitability of a particular configuration for extended habitation (i.e., the volume requirements). Various individuals and groups have conducted extensive surveys to determine and evaluate the volumetric requirements associated with long duration missions. Since there is a minimum amount of data available, the majority of the writers in this area have based their work on earth operations. The volumes provided to date in the Mercury, Gemini, and Apollo spacecraft have only considered relatively short mission times (i.e., up to 14 days). Therefore, the applicability of these volumetric data to a spacecraft design for a long-duration mission is questionable. The longer the mission, the more essential the provisions for habitation become. "Public opinion concerning space flight would no doubt be less favorable if approximately 50 percent of all astronauts suffered major psychological and physiological symptoms during every long-duration space flight. An expert's advice, explaining that the symptoms were due to the spacecraft design, would not be heeded; nor would it help if it were explained that a man on the ground exposed to the same constraints would suffer identical symptoms."[1] Therefore, the level of habitability designed into the system must be commensurate with the full range of anticipated mission durations.

A brief review of confining systems is presented by Congdon.[2] This review included; an investigation of the U. S. Navy shipboard habitability standards, a review of literature on civil defense fallout shelter designs and design standards, a review of several laboratory facilities which have been used in confinement and habitability studies in support of the U. S. space efforts, and U. S. prison design standards.

a. Navy Habitability Standards[3]

The author felt that the figures obtained from these standards are not to be considered highly applicable to a space station design, since it is virtually impossible to determine the availability of the total usable volume. For example, there is no information regarding the availability of areas of the ship in which the crew spend much of their time; such as, stations, watch standing areas, recreational areas, etc.

b. Civil Defense Shelters[4]

Civil defense shelters are highly confining systems, however, they do not require a high degree of proficient activity. Therefore, the applicability is questionable.

c. Research Vehicles

The special purpose research vehicles, used in the exploration both of extreme ocean depths and atmospheric heights, were among the most confining systems found. In both cases, design emphasis was placed on minimizing the size of the vehicles. Although the volumes used in these vehicles represent some practical limit of minimum volume, these is little applicability to the space station design. Missions durations are very short and activities tended to be very restricted in variety.

d. Confinement and Habitability Research Chamber

Confinement and habitability research chambers which have been used specifically in the study of the space habitability problems were surveyed and only two of these chambers have been utilized for tests of greater than 30 days in length.

Chamber	Confinement Period (Days)	Est. Total Volume (Ft^3)	Crew Size (No.)	Est. Vol. Per Man (Ft^3)
USAF-SAM	30	380	2	115
NASA-U. of Md.	150	140	1	90

A simulator at General Dynamics/Astronautics was designed for simulation runs of one month or more. However, it has, to date, been utilized for short runs only.

e. U. S. Prison Design Standards

These standards were reviewed but are considered of questionable applicability. While confining in nature, prisons probably have too few elements in common with space vehicles to provide useful data.

Based on this review, Congdon[2] suggests a combined living and working volume of 260 cubic feet per man for mission durations up to a month and 600 cubic feet per man for missions of several months duration. These are shown in Figure 2.1.

In addition to the preceding survey, Celentano[1] conducted a similar survey covering basically the same areas. He presented his results in the form of figures. These are shown in Figures 2.1 and 2.2.

2.2 AREA REQUIREMENTS

In addition to a literature survey, a study was conducted by the Systems Engineering Branch (SEB) of the Advanced Spacecraft Technology Division to determine the volume requirements for a long duration mission. Data for the Mercury, Gemini, and Apollo capsules, nuclear submarines, and the Antarctic expeditions are shown in Figure 2.3 for comparative purposes.

The study conducted by SEB was based on the assumption that habitability requirements only encompass private quarters for each crew member, a wardroom, an exercise area, hygienic compartments, and a sick bay.

2.2.1 PRIVATE CREW QUARTERS

The crew quarters should include individual compartments to enable the crew to exercise an option for privacy. The compartments should be designed to provide each man with sleeping facilities, personal storage compartments, and enough free volume to provide for relaxation. The results of the SEB study are shown in Figure 2.4. For long duration missions an area of approximately 36 square feet is considered desirable. This area will allow for a floor bunk for an artificial g configuration or a wall bunk for a zero gravity configuration. It was assumed the ceiling height would be approximately 7 feet. Therefore, a volume of 250 cubic feet would be provided. An allocation of 50 of the 250 cubic feet is assumed to provide the crew member with sufficient storage for personal effects.

2.2.2 WARDROOM AND FOOD PREPARATION AREA

The data used to formulate the recommended areas for the wardroom and food preparation area were taken from design data for

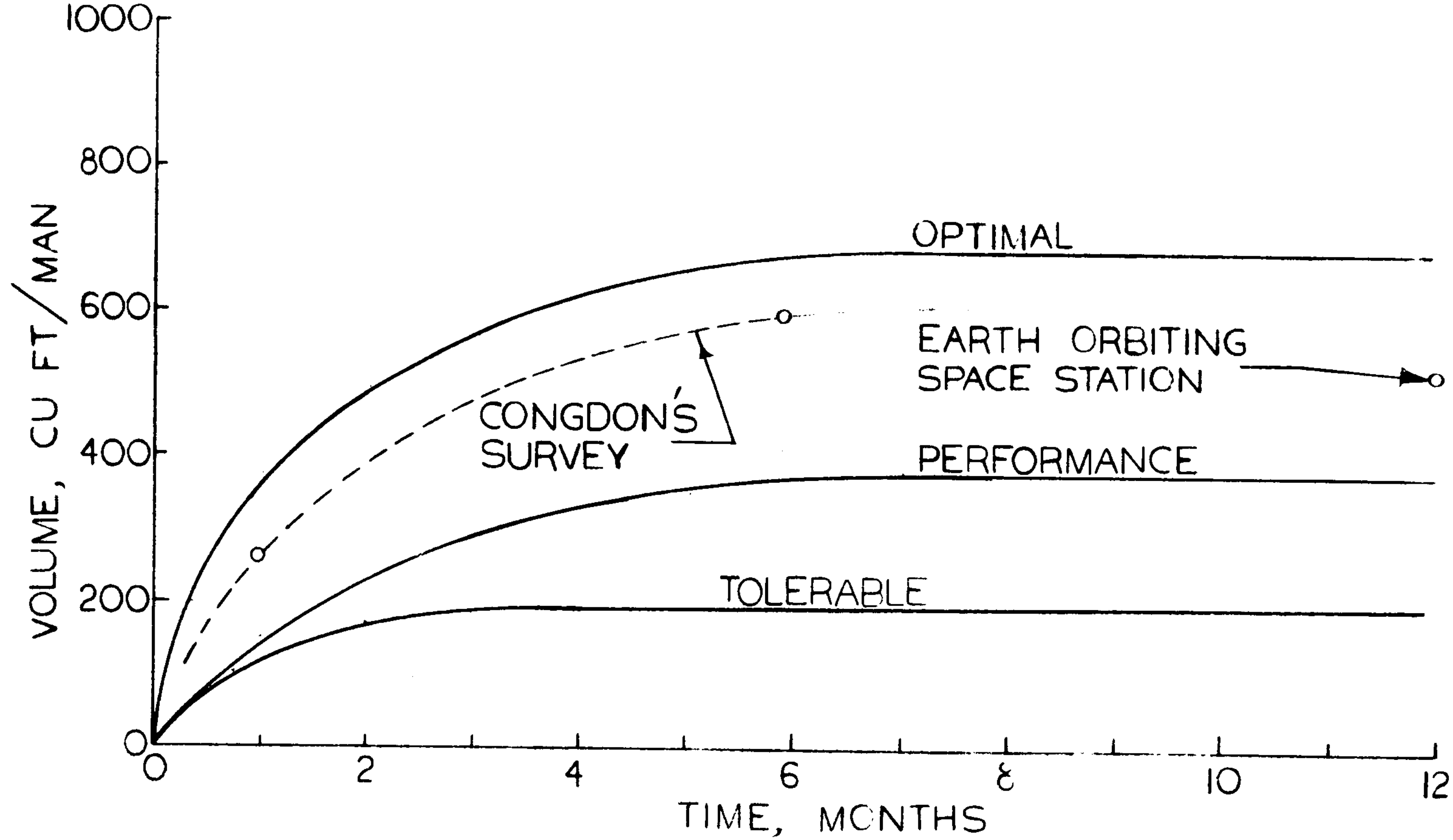


FIGURE 2.1 LIVING SPACE PER MAN (VOLUME)

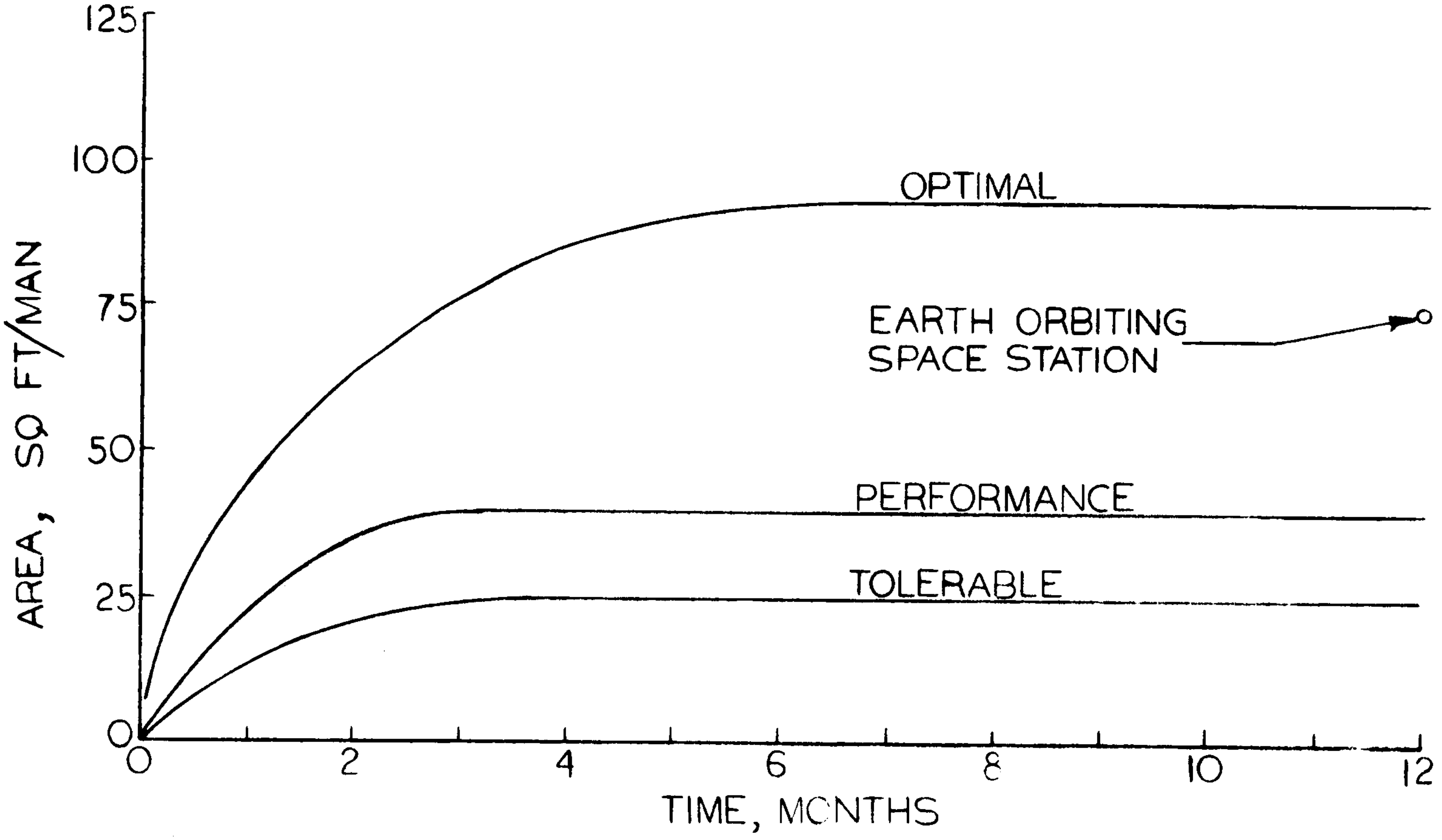


FIGURE 2.2 LIVING SPACE PER MAN (AREA)

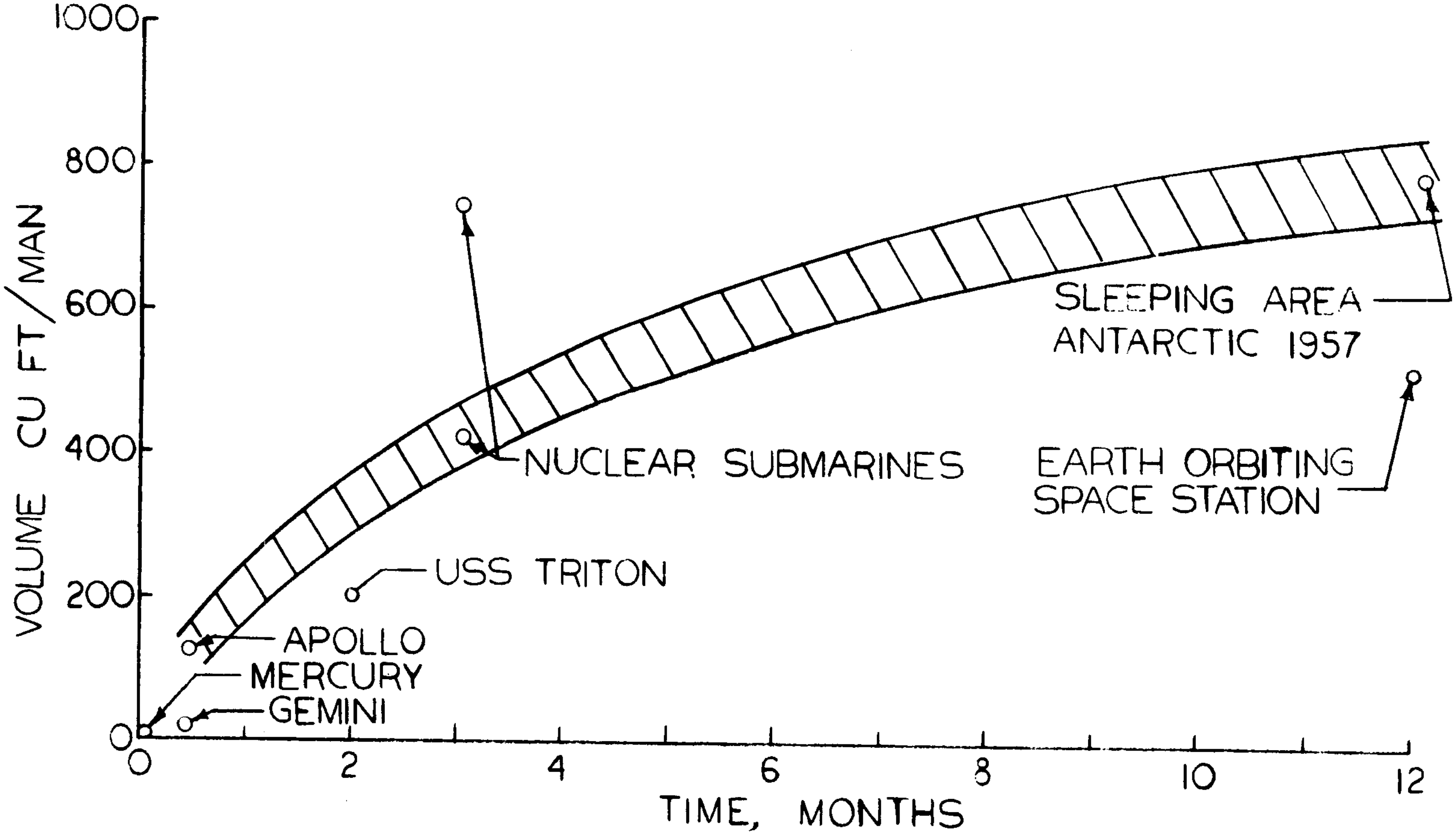
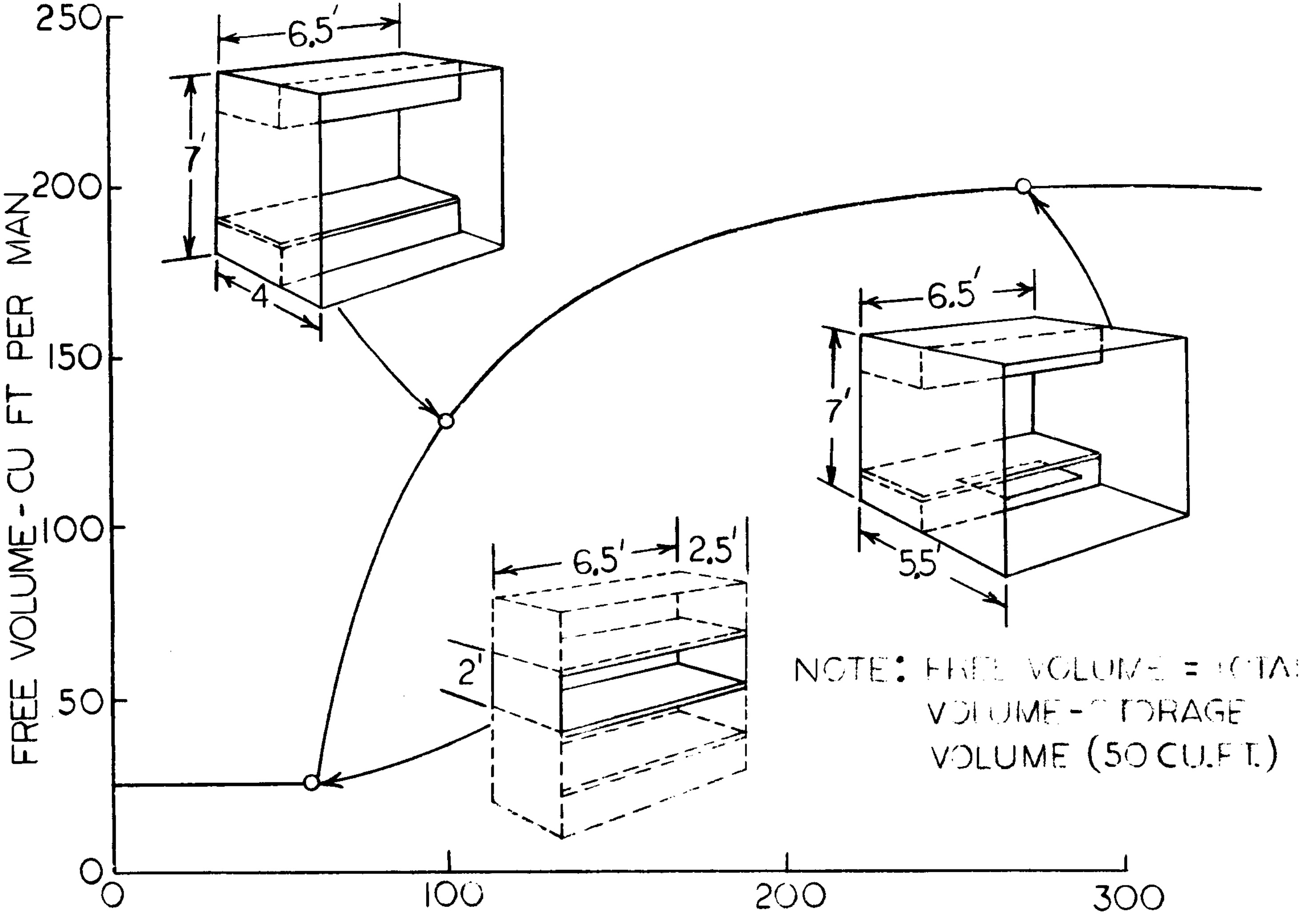


FIGURE 2.3 TOTAL HABITABLE LIVING VOLUME

CREW QUARTERS



NOTE: FREE VOLUME = TOTAL VOLUME - STORAGE VOLUME (50 CU.FT.)

FIGURE 2.4

nuclear submarines. The wardroom area is considered to be adequate for eating and recreation activities such as movies, card games, etc. The assumption that no more than two-thirds of the crew will be in the wardroom at any given time was made. Using the preceding assumption and anthropometry data for flying personnel,[5] a wardroom configuration study was conducted. The results of the configuration study indicated an allocation of approximately 21 square feet per man is desirable. The food preparation area was scaled from data for a nuclear submarine galley. For convenience, the food preparation area should be adjacent to the wardroom. This area is based on the assumption that, for the crew sizes of 9 to 24 crew men, only one man is required to prepare the food. The area allocated is 16 square feet.

2.2.3 EXERCISE AREA

For long term missions a physical exercise area for the crew is essential. A planned training and conditioning program will be necessary to maintain physical fitness and help reduce cardiovascular and musculoskeletol deterioration. The crew will have to be maintained in a physical condition which will enable them to withstand the reentry environment. Anthropometric considerations and the assumption that no more than one-third of the crew would be in the exercise area at any given time dictate that 15 to 20 square feet of area is desirable. Consideration of crew sizes larger than 12 men will necessitate the scheduling of activities in this area.

2.2.4 HYGIENIC FACILITIES

Personal hygiene and sanitation must be rigidly controlled. In cases of isolation, especially where boredom or stress is commonplace, there is a tendency for hygienic standards to deteriorate. Although highly motivated personnel might endure less than adequate hygienic facilities for an indefinite time, it has been demonstrated that adequate facilities contribute immeasurably to optimum performance. In addition, another vital reason for demanding personal cleanliness for a group restricted to a small area is the prevention of infection, disease, and contagion.

The hygienic area should provide facilities for body waste management and means for body cleansing. The location of these areas must be easily accessible to the crew. These should be one toilet for each four men and one shower for each twelve men. Each station should have a minimum of two toilets and one shower. Based on anthropometric considerations,[6] each shower should contain approximately 6 square feet of floor area and each toilet 11 square feet. In addition, provisions for shaving and personal grooming must be supplied.

2.2.5 SICK BAY

Considerations of long duration missions will require the provision of sick bay facilities. This space will provide the means for treating any illness or injury to the crew members that might occur. In addition, this area could be utilized for performance of biomedical experiments. The allotted area will vary with crew size but approximately 108 square feet will be required for a 9 to 12 man crew. In cases of illness where isolation is required, the private crew quarters could be utilized.

2.2.6 COMMAND STATION

The command station size was based upon a nominal requirement of two men to control the station at any given time. Assuming that the two men are seated side by side at a control panel, approximately 32 square feet of floor area will be required. For a crew size of 24 men, this area should be increased to approximately 48 square feet which would provide space for up to three men.

2.3 SUMMARY

The preceding area allocations are considered to be nominal values. In general, it appears that approximately 75 square feet of floor area per man with a ceiling height of seven feet is sufficient to fulfill the habitability requirements. The integrated results of the SEB study are included in Figures 2.1 and 2.2.

REFERENCES

1. Amorelli, D.; Celentano, J. T.; and Freeman, G. G.; Establishing a Habitability Index for Space Stations and Planetary Bases. AIAA/ASMA Manned Space Laboratory Conference, Los Angeles, California, Paper Number 63-139. May 1963.

2. Congdon, S. P.; Davenport, E. W.; and Pierce, B. F.; The Minimum Volumetric Requirements of Man in Space. AIAA Summer Meeting, Los Angeles, California, Paper Number 63-250. June 1963.

3. Department of Navey, OPNAVINST 9330.5, "Minimum Habitability Standards for Ships of the U. S. Navy," March 1960.

4. Office of Civil Defense Mobilization, "Fallout Shelter Surveys; Guide for Architects and Engineers," NP-110-2, May 1960.

5. Churchill, E.; Daniels, G. S.; and Hertzberg, H. T. E.; Anthropometry of Flying Personnel -- 1950. WADC TR 52-321, Wright Patterson Air Force Base, Ohio. 1954.

6. Cook, J. S. IV, and et.al.; <u>Human Engineering Guide to Equipment Design</u>. McGraw-Hill Book Co., Inc., New York 1963.

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 3.0

ARTIFICIAL GRAVITY

ADVANCED SPACECRAFT TECHNOLOGY DIVISION
ENGINEERING AND DEVELOPMENT DIRECTORATE
MANNED SPACECRAFT CENTER

3.0 ARTIFICIAL GRAVITY - INTRODUCTION

It is the intent of this paper to present the reader a quick reference to the artificial gravity considerations for a revolving space station. A review of the most significant experimental work that has been performed to date by earth based experimenters is presented. However, the reader is referred to the originial publications for the complete picture. The author has tried to acknowledge all of the data taken from the various references. However, there may be a few instances where data is used and not adequately referenced.

The artificial gravity environment associated with a revolving space station is presented. The author would like to point out that this work was performed after Loret[9] and that some of the pictorial techniques used by Loret are used in this paper.

In addition, a discussion of a design envelope based on human factors considerations is presented.

3.1 BACKGROUND

Human factors considerations, in the design of a space station for future space explorations, preclude the elimination of artificial gravity environment considerations. To date the aeromedical specialists and the design engineers have been unable to formulate a firm set of guidelines for an artificial gravity environment. Many specialists feel that data from earth based experimentation are only partially applicable to a space station design. These data from earth based experimentation contain the effects of the earth gravity vector. Experiments performed on either an orbiting spacecraft or an airplane flying along Keplerian trajectories either neglect rotational effects or have been of such short duration that the applicability of the data still remains questionable.

Various groups and individuals have either performed experiments in a rotating environment, using earth based equipment, or have written extensive articles postulating the effects of an artificial gravity environment in an orbiting space station. The major contributions of earth based experimental data are the U. S. Naval Aviation Medical Center at Pensacola, Florida; the Life Sciences Laboratories at General Dynamics/Convair, San Diego, California, and a group at Langley Research Center, Hampton, Virginia.

Figure 3.1 exemplifies the interior of the Slow Rotation Room (SRR) at Pensacola.[1] The SRR is a multisided, windowless room approximately 15 feet in diameter and 7 feet high with a nearly square center post. The motive power is supplied by a gasoline engine geared to a rubber-tired wheel in contact with the driving band of a flywheel to which the superstructure (SRR) could be clutched or unclutched. Electrical power is provided by utilization of slip rings.

REFERENCE I

1	FOOD SUPPLY
2	COUNTER
3	REFRIGERATOR
4	SINK
5	TELETHERMOMETER
6	CONSTANT TEMP. CIRCULATOR
7	CALORIC TEST SUBJECT
8	PREAMPLIFIERS
9	EXHAUST FAN
10	PULLIES AND WEIGHTS
11	ROTATING CHAIR
12	CONTROL BOX
13	TV FOR ENTERTAINMENT
14	TEST TV CAMERA
15	HEAD
16	EXPERIMENTER
17	LOGICAL INFERENCE TESTER
18	CENTER POST
19	PATCH PANEL
20	DIAL TEST SEAT
21	RESPONSE ANALYSIS TESTER
22	SCREEN

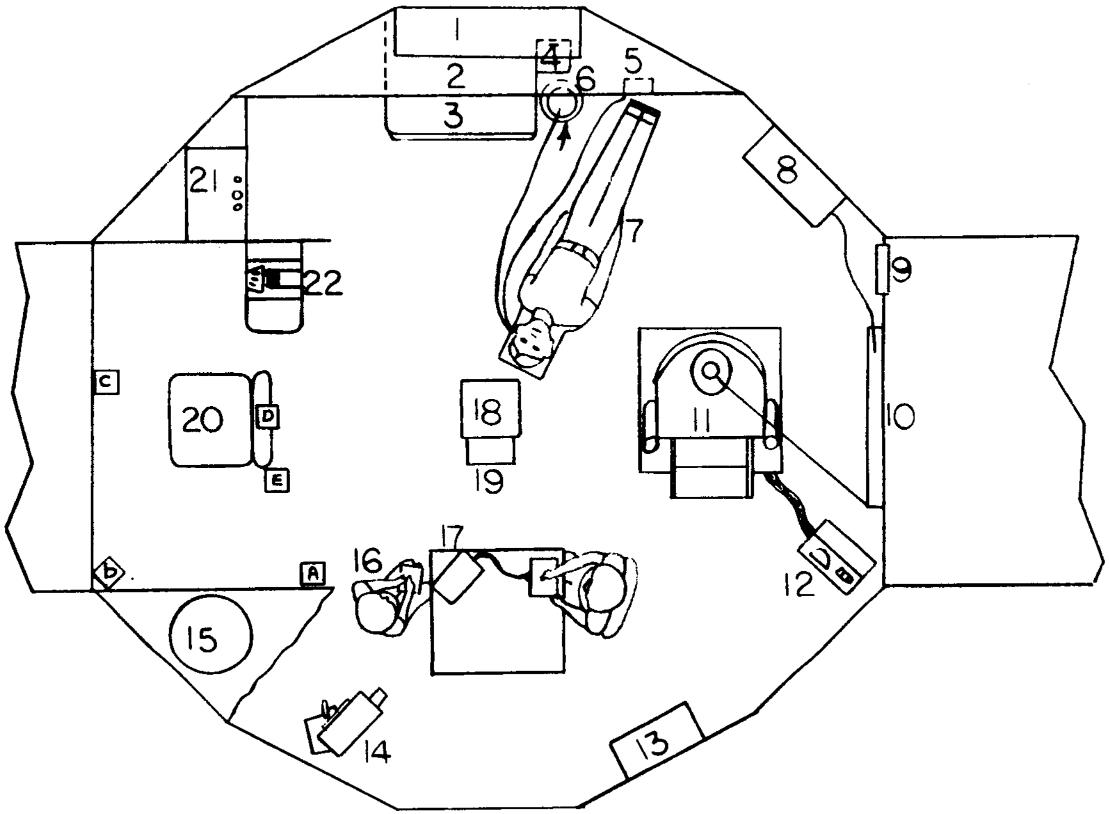


FIGURE 3.1 INTERIOR OF SLOW ROTATION ROOM AT PENSACOLA

The experimentation by Graybiel, Guedry, and others at Pensacola has been documented in various Government publications, medical journals, and NASA reports. During one group of experiments performed in the SRR the rotation rate was varied from 0 to 10 rpm. The SRR was rotated at speeds of 1.71, 2.22, 3.82, 5.44, and 10 rpm. Each run at each speed lasted two days. Four persons lived continuously in the room during each run. A control subject who had lost almost all of the functions of the inner ear was used. The results of the runs at the various speeds are summarized below.[2]

Observations at 1.71 rpm:

Two normal subjects not susceptible to motion sickness and an observer initially experienced mild symptoms by rotating at 1.71 rpm, but these symptoms did not interfere with the tasks they were asked to do and adaptation occurred during the first day. The control subject had no complaints but did exhibit some unsteadiness in carrying out the walking test. After-effects included some difficulty in walking after the centrifuge stopped, feelings of fatigue, and need of more sleep than usual.

Observations at 2.22 rpm:

The stress in this run was apparently not much greater than in the first, but one subject with a history of seasickness was slightly incapacitated the first day. All four participants adapted well. On cessation of rotation all experienced slight difficulty in walking and fatigue.

Observations at 3.82 rpm:

As before, the control subject had no complaints while two normal subjects, not susceptible to motion sickness, experienced only mild symptoms to which they readily adapted. Adaptation took longer in the case of a person less resistant to motion sickness. There were no after-effects for the control subject, but the two normal subjects showed difficulty in walking and increased fatigue.

Observations at 5.44 rpm:

This angular velocity will generate a field of centrifugal force of 1.0 G at a radius of 100 feet in a rotating space vehicle.

The data for the eight persons who participated in the experiment at 5.44 rpm suggest that with the exception of the control subject, this was a highly stressful situation. The control subject showed some difficulty in adapting to the centrifugal force but was otherwise essentially free of symptoms, both during and after the run. On the other hand, all of the remaining subjects were incapacitated to varying degrees during and even after the run. With one exception, they restricted their movements substantially and slept as much as possible. They all experienced dizziness and/or nausea, or both particularly during the dial test. The after-effects were also more pronounced than in previous experiments at slower angular velocities.

Observations at 10.0 rpm:

For this final experiment the participants, with the exception of the control subject, were selected on the basis that they were least likely to become incapacitated.

Excepting for the control subject, this experiment constituted a highly stressful situation for the two subjects and the inside observer. They all reported marked symptoms, severely restricted their head movements, and particularly in the early part of the run slept as much as possible. They also exhibited marked after-effects following the run. That the severe symptoms were directly or indirectly related to the labyrinth was shown by the fact that the control subject felt well and the only difficulty was in walking, due to the centrifugal force. None of the other participants was able to carry out all of the tasks assigned to him. Despite a certain amount of adaptation which went on, the unpleasant effects were sufficient to result in the general deterioration in fitness. Although the possibility existed that these participants might have been able to carry out ordinary tasks while rotating at 10 rpm, if a slower or more stepwise indoctrination program had been followed, it was clearly evident that at 10.0 rpm even resistant subjects not only became ill but also were unable to carry out tasks involving much head movement.

These test runs were followed by a test run at 10 rpm for a period of 12 days.[3] This rate of rotation is considered by Graybiel and others to be near the upper limits of angular velocity to which man might adapt without impractical side effects. Efforts were made to ensure the test subjects were motivated. The results of this test are summarized below.

An on-board experimenter, who had amassed more than 500 hours at different rotation speeds in the SRR, kept a record of effects on each subject and their overt behavior in terms of daily activities and interpersonal relations. Moreover, he recorded his own experiences, which were of particular interest in that he was active during the brief periods when the room had to be stopped for experimenters to go onboard and off; in other words, he was intermittently adapting to stationary and rotating conditions.

With the sudden onset of rotation all of the subjects immediately experienced difficulty in walking and in carrying out tasks involving bodily movements. The full impact was not felt at once, typical symptoms of canal sickness appearing only after a delay.

Even after symptoms of nausea and anorexia disappeared and no further head restrictions were enforced all of the subjects continued to experience drowsiness and fatigue and to restrict their physical activity which in turn minimized their head movements.

None of the subjects had fully adapted to the experimental conditions by the end of day 12.

Cessation of rotation created an impact but far less than at the start of rotation. The immediate effect was on neuromuscular coordination and was evidenced by ataxia which diminished rapidly during the first hour or two.

During the rotation period 15 different psychophysiological tests were given to the subjects. All of the subjects carried out all of the tests except on one occasion when one subject fell asleep during his watch. After making allowance for practice effects and time-to-time variance, it is obvious that significent changes in performance were either absent or small except in the case of the hand dynamometer test. It is interesting that these changes in performance, aside from those in close relation to the onset or cessation of rotation, were manifested more frequently in the late than in the early prerotation period. Hand dynamometry deserves particular notice inasmuch as the score seemed to reflect the general fitness of the subject throughout the entire experimental period. Moreover, the sharp rise in values after cessation of rotation suggests that disturbances in neuromuscular coordination were not a factor in carrying out the test.

Graybiel concluded that countermeasures in addition to adaptation are needed if rotational velocities of 10 rpm are required.

Transfer and retention of effects from the twelve days of rotation at 10 rpm have been discussed by Guedry.[4] Tests before and after the twelve day ride in the SRR were conducted with a Stille-Werner rotating chair. The test plan was to compare results of clockwise (CW) and counterclockwise (CCW) rotation tests in the Stille-Werner chair before and at several intervals after a twelve day period of CCW rotation in the SRR. The tests showed that responses to head movements during rotation in either direction were suppressed during chair tests at 48 hours and 3 weeks after cessation of the SRR test.

These results of the work done at Pensacola which are presented above are taken from the original papers and the reader is referred to the original papers for a more complete picture.

The Manned Revolving Space Station Simulator (MRSSS) complex at General Dynamics/Convair is depicted in Figure 3.2.[5] The MRSSS consists of an 8' x 14' x 7' cabin trunnioned to supporting I-beams 18' from the spin axis of a 220,000 g-pound centrifuge. The cabin is divided into two separate rooms, one containing the sleeping and toilet facilities, and the other food preparation and refrigeration facilities, and space for recreation, testing and study. Rotary couplings and slip rings provide running water, sewage disposal, and data transmission during rotation. Communication is provided by voice, TV, and FM telemetry. A loading port in the outboard bulkhead of the MRSSS permits tranfer of parcels during rotation.[6]

The experimental work performed by Brady, Newsom, and others at the Life Science Department, General Dynamics/Convair on the MRSSS. During one of the test runs[5] at General Dynamics, four test subjects were exposed to a rotational environment for 120 continuous hours. (i.e., 4 hours at 2 rpm, 4 hours at 4 rpm, 104 hours at 6 rpm, 4 hours at 4 rpm, and 4 hours at 2 rpm.) The length of time-step increments was not entirely arbitrary as a test array required 3 hours to complete. The subjects were given an array of psychophysiologic tests (e.g., vision tests, audition, caloric, oculogyral illusion, ballistic aiming, walking and standing, and mentation tests). The subjects were required to fill out routine psychosocial ratings on themselves and other subjects, keep diaries, and fill out 50-item medical histories. The diet consisted primarily of freeze-dry space food. Only those tests which appear to have been significantly affected by the test environment were discussed. The other tests were considered to be unaffected.

Feeling of Habituation:

The results indicate that by the end of 3 1/2 to 4 days of rotation, three of the four subjects felt as good as they would under conventional circumstances. However, the fourth subject showed effects until all rotation ceased.

Auditory Acuity Test:

All subjects showed increases in auditory acuity during rotation. However, the author felt one must hesitate to explain such a change until additional studies verify that it is not a learning artifact.

Oculogyral Illusion Tests:

The results suggested that little correlation can be drawn between the OGI response and a subject's ability to tolerate a rotating environment.

REFERENCE 2

	ITEM
1	HEAD
2	DOUBLE BUNK BED
3	KITCHEN
4	RECORDER
5	PURSUIT
6	CENTRIFUGE ARM
7	COUNTER BALANCE WEIGHT

	DIMENSIONS
A	24' RADIUS
B	8'
C	18'
D	14'
E	30' I-BEAMS

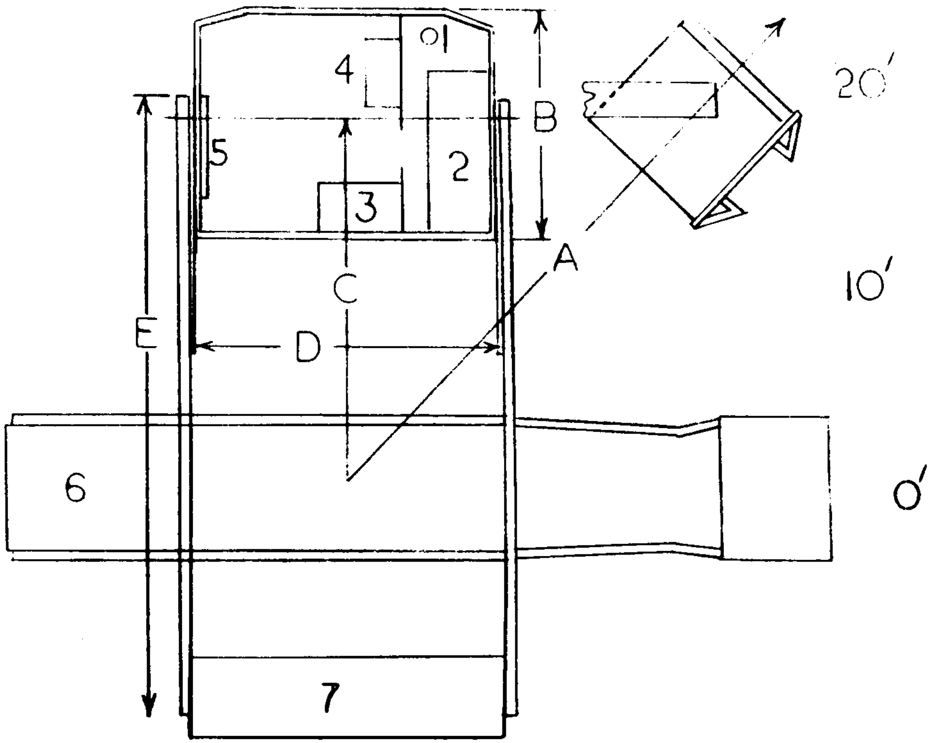


FIGURE 3.2 MANNED REVOLVING SPACE STATION SIMULATOR (MRSSS) COMPLEX

Digital Proprioception:

The subjects all showed effects during the spin up stages. During rotation the subjects started to become adapted to this test. However, at spin down initiation, the effects increased and continued into the post rotation period.

Tandem Walking with Eyes Open:

With vision the subjects showed a rapid adaptation in precision locomotion tests. The adaptations in this test also shows some correlation with overall habituation.

Tandem Walking with Eyes Closed:

Without vision all subjects showed a marked reduction in ability to adapt to precise locomotions in a rotating environment.

Tandem Standing with Eyes Closed:

The subjects were unable to perform this test with any facility at 6 rpm, and no improvement occurred with time. Only this test and the digital proprioception test showed post-rotation decrement. Both tests are performed with the subjects standing in one spot with their eyes closed. The deletion of vision and kinematic stimulus to the deep proprioceptors may account for the sensitivity of these tests to the inertial change.

Other than the digital proprioception and the tandem standing with eyes closed tests the subjects performed effectively. Coupled to their performance capability were the surprising phenomena of "complete" habituation and no apparent need for static readaptation with the step-wise spindown.

Only one vomiting episode occurred. During the first 24 hours at 6 rpm, one of the subjects had just taken a large drink of cold water when the operations engineer actuated the MRSSS positioning system to correct for an error in room inclination. The action resulted in a few seconds of severe oscillations. There was no later trouble.

Other tests performed on the MRSSS included equilibrium and walking change observations, and large excursion rotary tracking of target and target lights while the MRSSS revolved at 7.5, 10.0, and 12.0 rpm. During these tests a spinup rate of 0.2 radians/sec^2 was used. The subjects were given pre-spinup tests, prerotation tests, and post-rotation tests. The results of these tests were as follows.

Equilibrium and Walking Change Observations:[7]

Considerable degradation in performance occurred at all three levels of rotation (i.e., 7.5, 10.0, and 12.0 rpm). However, performance was better at 10 rpm than at 12 but not much different from 7.5 rpm. During balancing tests the time of balance differed from the right to the left leg. This may be due to a majority of right handedness or to the effects of the gravity gradient acting to the right when facing inward. Above 5 rpm the task of walking on a 3/4 inch rail and standing with eyes closed on a 2 1/4 inch rail were found to be too difficult for the average subject. During walking tests one mode of adaptation appears to be increased ability to maintain balance. The second part of adaptation is compensating for deviations from the path. During post-rotation walking tests the subjects had to readapt to the static environment. But during post-rotation balancing tests recovery was immediate when the room stopped spinning. The authors state that "Space Station design criteria should be based on physiological and psychological performance limits rather than nausea alone."

Large Excursion Rotary Tracking of Target and Target Light Tests:[6]

Of the 24 subjects, 11 missed one or more in-rotation test trials due to illness. The distribution of illness was:

RPM	N(Initial)	N(Ill)	N(Final)
7.5	12	7	5
10.0	8	4	4
12.0	4	0	4

The test data reveals an expected decrement in performance following spinup and spindown. Rapid adaptation appears to occur and in one to three trials maximum tracking efficiency is regained. For all parameters, decrement at 10 rpm appears to be not only the least but the most rapidly compensated for.

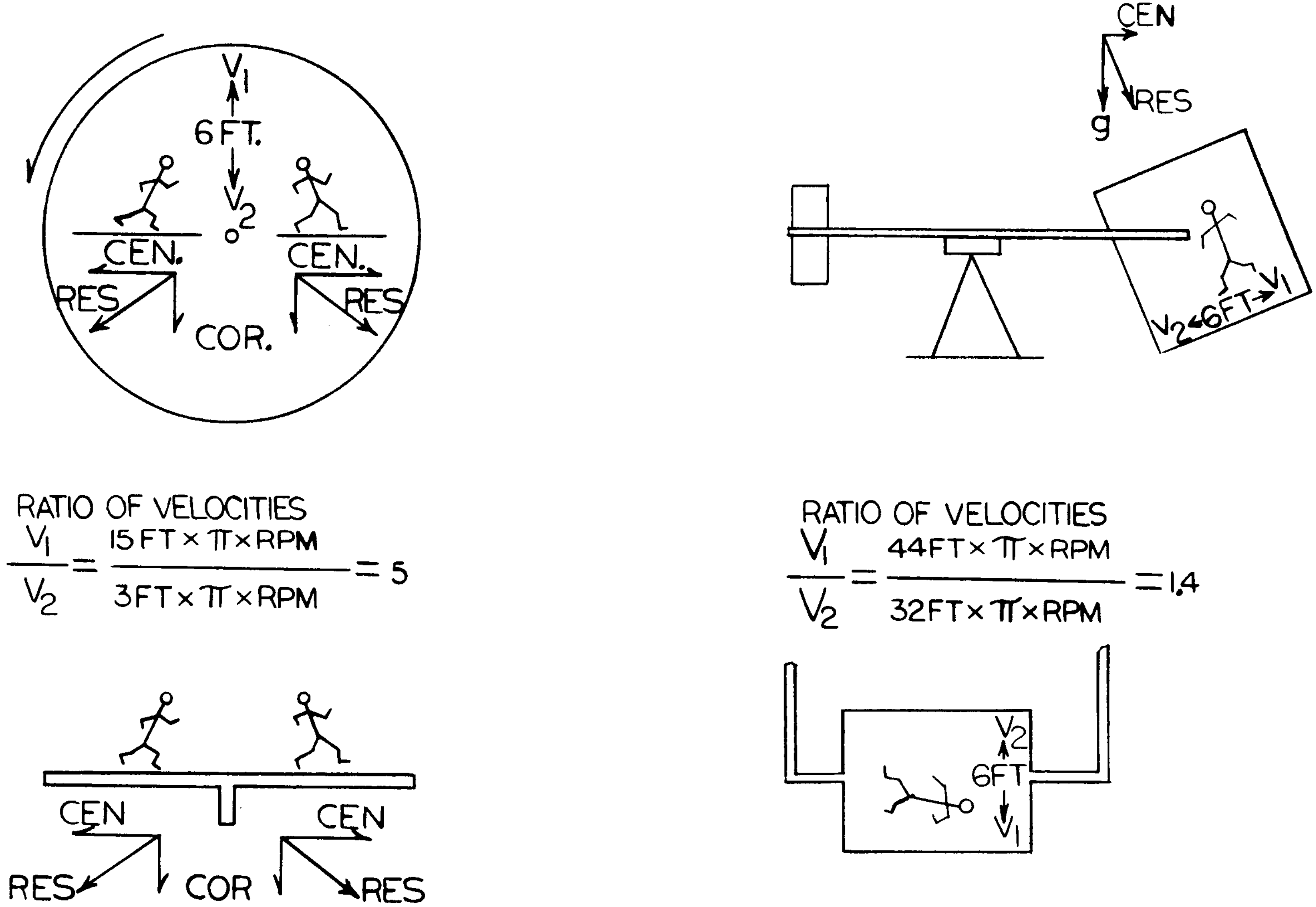
In addition to the preceding tests, GD is in the final phases of a contract sponsored by NASA (Contract No. NAS9-5232). The purpose of this study is to investigate the effects of the orientation of planes of head rotation relative to the spin plane on a specific sensory-motor performance, for the purpose of comparing and determining which types of head rotation are least disturbing to performance and for providing data useful for optimal design of displays and controls.

The Spacecraft Research Branch at Langley Research Center under the direction of Letko and Stone have performed several test runs on a rotating vehicle simulator.[8] The subjects lay on their backs in a stationary position with their feet 15 feet from and perpendicular to the axis of rotation. The subjects performed simple tasks which required head movements. The results of the tests indicate a level of tolerance for the test subjects for nodding of the head, turning of the head, and a combined nodding and turning motion.

A comparison of the methods of testing used at Pensacola, and GD was presented by Brady and Newsom. In the comparison they point out that the studies performed at Pensacola were not meant to simulate a space station. The SRR radius of rotation is small and although this does not affect the coriolis forces it does amplify the required velocity change when walking on any chord within the room. Figure 3.3 depicts the situation of a 15-foot diameter room revolving about its center. The subject must lean toward the axis; the angle of inclination must be continually adjusted. In addition walking past the center of rotation will reverse the direction of force adding further confusion and difficulty in adaptation. A man standing on the periphery of such a room has a linear velocity that is five times what his velocity would be if he were six feet closer to the axis. This means he must decelerate as he approaches such a point or the floor would have a slower linear velocity than his body. A situation would then result where he would fall to the right (in counter-clockwise rotation), as though a rug were pulled out from beneath him. To return to the periphery of the room he would have to accelerate to catch up with the higher velocity or an opposite reaction would occur. Continual acceleration and deceleration add to the bizarre stimuli to which the man is confronted, one in which there is little in the way of a constant force reference. It is possible to create a revolving simulator where the resultant inertial forces are normal to the floor by trunnioning a room at the end of a centrifuge as seen in Figure 3.3. This aligns the force vector with the man's spine when he is vertical and provides a constant sourse of reference for equilibrium. In addition it is possible to greatly reduce the artifact of velocity change by making the room narrow in proportion to its length and providing a twenty-foot working radius.

An 8- by 14-foot room was mounted in a cradle suspended by two I-beams across the boom of the 220,000 g lb. centrifuge at Astronautics. In this room a subject increased his linear velocity by a factor of only 0.4 when he moves six feet radially outward (Figure 3.3). The eighteen-foot radius to room center increases to twenty feet or more when the room swings out. This facility is an important step closer to simulating conditions in a revolving space station than others in present operation.

Tolerable rotation conditions could be defined as those that do not prevent nausea. It would seem more important however to describe the required envelope of RPM, radius and stability in terms of an environment where adequate adaptation can take place to achieve proper performance of duties.7



RATIO OF VELOCITIES

$$\frac{V_1}{V_2} = \frac{15\,FT \times \pi \times RPM}{3\,FT \times \pi \times RPM} = 5$$

RATIO OF VELOCITIES

$$\frac{V_1}{V_2} = \frac{44\,FT \times \pi \times RPM}{32\,FT \times \pi \times RPM} = 1.4$$

(A)

ROOM REVOLVING ABOUT
ITS CENTER

(B)

REVOLVING SPACE
STATION SIMULATOR

FIGURE 3.3 SRR AND MRSSS COMPARISON

3.2 ARTIFICIAL GRAVITY ENVIRONMENT

Since the design engineers have been unable to obtain a commitment from the aeromedical specialists, as to the human factors limitations for a rotating space station, the engineers must still assume that the requirement for an artificial gravity environment exists.

One of the ways of producing an artificial gravity environment is by rotation of the vehicle. This discussion is centered around the accelerations to which the vehicle and its occupants will be subjected in orbit.

If we consider the case of a rotating space station, the accelerations which may normally be neglected on earth may become significant. The station may be considered to be an isolated system with no external forces other than gravity acting on it. The geometry of the space station chosen for this discussion is a circular one. The selection was strictly for convenience and the principles discussed apply to any rotating geometry.

Considering the geometry shown in Figure 3.4 we can derive the relations for the acceleration and its components of a general point P, moving relative to body A, with respect to a set of rotating axes. The following assumptions are applied to the derivation.

1. Body A has plane motion, and the X, Y, plane is its plane of motion.

2. The XY axes are fixed in Body A, and they rotate with respect to the fixed axis X_1 Y_1. The origin of both sets of axes is at point O.

3. Counterclockwise, to the right, and upward are the positive directions.

The position of P at any instant is given by the following:

$$X_1 = X \cos \Theta - Y \sin \Theta$$

$$Y_1 = X \sin \Theta + Y \cos \Theta$$

The velocity of P at any instant is obtained by differentiating the position coordinates with respect to time.

$$\dot{X}_1 = X(\sin \Theta)\,\dot{\Theta} + \dot{X} \cos \Theta - Y\,(\cos \Theta)\,\dot{\Theta} - \dot{Y} \sin \Theta$$

$$\dot{Y}_1 = X(\cos \Theta)\,\dot{\Theta} + \dot{X} \sin \Theta - Y\,(\sin \Theta)\,\dot{\Theta} + \dot{Y} \cos \Theta$$

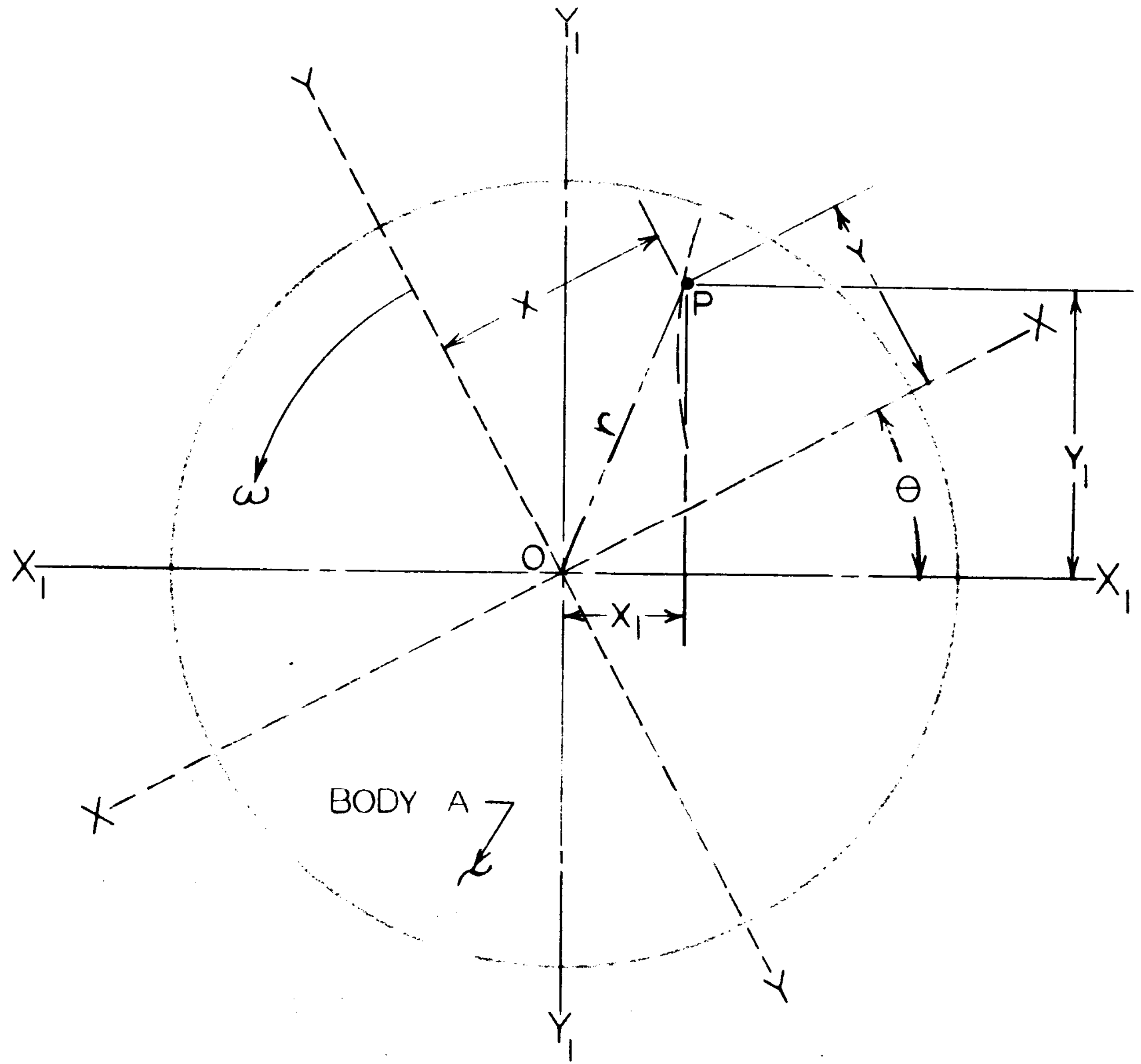


FIGURE 3.4 GEOMETRY OF A ROTATING BODY

where:

$$\dot{X} = \frac{dX}{dt}$$

$$\dot{\theta} = \frac{d\theta}{dt} = \omega_A$$

$$\dot{Y} = \frac{dY}{dt}$$

If we now assume point P is fixed on Body A (i.e., Point C) X and Y are constants and $\dot{X}$ and $\dot{Y}$ are equal to zero. Hence,

$$(Vc)_{X_1} = X(\sin\theta)\,\omega_A + Y(\cos\theta)\,\omega_A$$

$$(Vc)_{Y_1} = X(\cos\theta)\,\omega_A - Y(\sin\theta)\,\omega_A$$

If P is not fixed on Body A the X_1, Y_1 components of the velocity of P with respect to A is:

$$(V_{P/A})_{X_1} = \dot{X}\cos\theta - \dot{Y}\sin\theta$$

$$(V_{P/A})_{Y_1} = \dot{X}\sin\theta + \dot{Y}\cos\theta$$

since

$$\dot{X}_1 = (V_P)_{X_1}$$

$$\dot{Y}_1 = (V_P)_{Y_1}$$

we can substitute and get the following:

$$(V_P)_{X_1} = (V_C)_{X_1} + (V_{P/A})_{Y_1}$$

$$(V_P)_{Y_1} = (V_C)_{Y_1} + (V_{P/A})_{Y_1}$$

or

$$V_P = V_C \;{+\!\!\!\!\rightarrow}\; V_{P/A}$$

The acceleration of point P can be obtained by differentiating the expression for V_P with respect to time. Differentiating, and arranging the expression we get the following where:

$$\alpha_A = \dot{\omega}_A = \frac{d^2\theta}{dt^2}$$

$$(A_P)_{X_1} = \ddot{X}_1 = -(X\sin\theta + Y\cos\theta)\alpha_A - (X\cos\theta - Y\sin\theta)\omega_A^2$$
$$+ \ddot{X}\cos\theta - \ddot{Y}\sin\theta - 2(\dot{X}\sin\theta + \dot{Y}\cos\theta)\omega_A$$

$$(A_P)_{Y_1} = \ddot{Y}_1 = (X\cos\theta - Y\sin\theta)\alpha_A - (X\sin\theta + Y\cos\theta)\omega_A^2$$
$$+ \ddot{X}\sin\theta + \ddot{Y}\cos\theta + 2(\dot{X}\cos\theta - \dot{Y}\sin\theta)\omega_A$$

$$A_P = (A_P)_{X_1} +\!\!\!\rightarrow (A_P)_{Y_1}$$
$$= \Big[(X\sin\theta \overset{\leftarrow}{+} Y\cos\theta) +\!\!\!\rightarrow (X\cos\theta \overset{\uparrow}{-} Y\sin\theta)\Big]\alpha_A +\!\!\!\rightarrow \Big[(X\overset{\leftarrow}{\cos\theta}$$
$$- Y\sin\theta) +\!\!\!\rightarrow (X\sin\theta \overset{\downarrow}{+} Y\cos\theta)\Big]\omega_A^2 + \ddot{X}(\overrightarrow{\cos\theta} +\!\!\!\rightarrow \sin\theta)$$
$$+\!\!\!\rightarrow \ddot{Y}(\overleftarrow{\sin\theta} +\!\!\!\rightarrow \cos\theta) +\!\!\!\rightarrow 2\Big[(\dot{X}\overleftarrow{\sin\theta} + \dot{Y}\cos\theta) +\!\!\!\rightarrow (\dot{X}\cos\theta -$$
$$\dot{Y}\sin\theta)\Big]\omega_A$$

Now if we take the square root of the sum of the squares of the components in the brackets we will get a resultant vector.

The absolute acceleration of P can be obtained by vector summation of these components.

$$A_P = r\overset{\searrow}{\alpha}_A +\!\!\!\rightarrow \overset{\swarrow}{r\omega_A^2} +\!\!\!\rightarrow \overset{\nearrow}{A_{P/A}} +\!\!\!\rightarrow \overset{\nwarrow}{2V_{P/A}\omega_A}$$

Radial Movements:

If we assume that the point P is moving in a radial direction at a constant velocity then the term $A_{P/A} = 0$. The assumption of a constant angular velocity of the Body A dictates that $\alpha_A = 0$.

Therefore we have the following relationship:

$$A_P = r\omega_A^2 +\!\!\!\rightarrow 2V_{P/A}\omega_A$$

The two terms correspond to the centripetal acceleration and the coriolis acceleration, respectively.

Tangential Movements:

If we assume that the point P is moving in a tangential direction we must return to the general relation for A_P.

$$A_P = r\alpha_A + r\omega_A^2 + A_{P/A} + 2\,V_{P/A}\,\omega_A$$

where

$$A_{P/A} = \ddot{X}(\cos\theta \vec{+} \sin\theta) \vec{+} \ddot{Y}(\sin\theta \vec{+} \cos\theta)$$

The assumption of a constant angular velocity of Body A dictates that $\alpha_A = 0$. Therefore we have:

$$A_P = r\omega_A^2 \vec{+} 2\,V_{P/A}\,\omega_A \vec{+} A_{P/A}$$

If we assume that the velocity of P is constant relative to Body A and moving in a tangential direction at all times then the expression for $A_{P/A}$ is:

$$A_{P/A} = r\omega_{P/A}^2 \qquad V_{P/A} = r\omega_{P/A} \qquad V = r\omega \qquad \omega^2 = \frac{V^2}{r^2}$$

$$\therefore\ A_P = r\omega_A^2 \vec{+} 2\,r\omega_{P/A} \vec{+} r\omega_{P/A}^2$$

$$A_P = r(\omega_A^2 \vec{+} 2\omega_{P/A}\,\omega_A \vec{+} \omega_{P/A}^2)$$

If we analyze the expression the magnitude of the acceleration of Point P is:

$$A_P = r(\omega_A + \omega_{P/A})^2$$

However,

$$\omega_A = \frac{V_A}{r}$$

$$\omega_{P/A} = \frac{V_{P/A}}{r}$$

$$A_P = r\left(\frac{V_{P/A}}{r} + \frac{V_A}{r}\right)^2$$

$$A_P = \frac{1}{r}(V_A + V_{P/A})^2$$

Using the relations derived in the preceding paragraphs we can show the manner in which the forces react and the direction of this reaction for radial movement, tangential movement, movement in a direction parallel to the axis of rotation of the space station, and gravity gradients from head-to-foot for a man in the rotating vehicle.

Radial Movement:

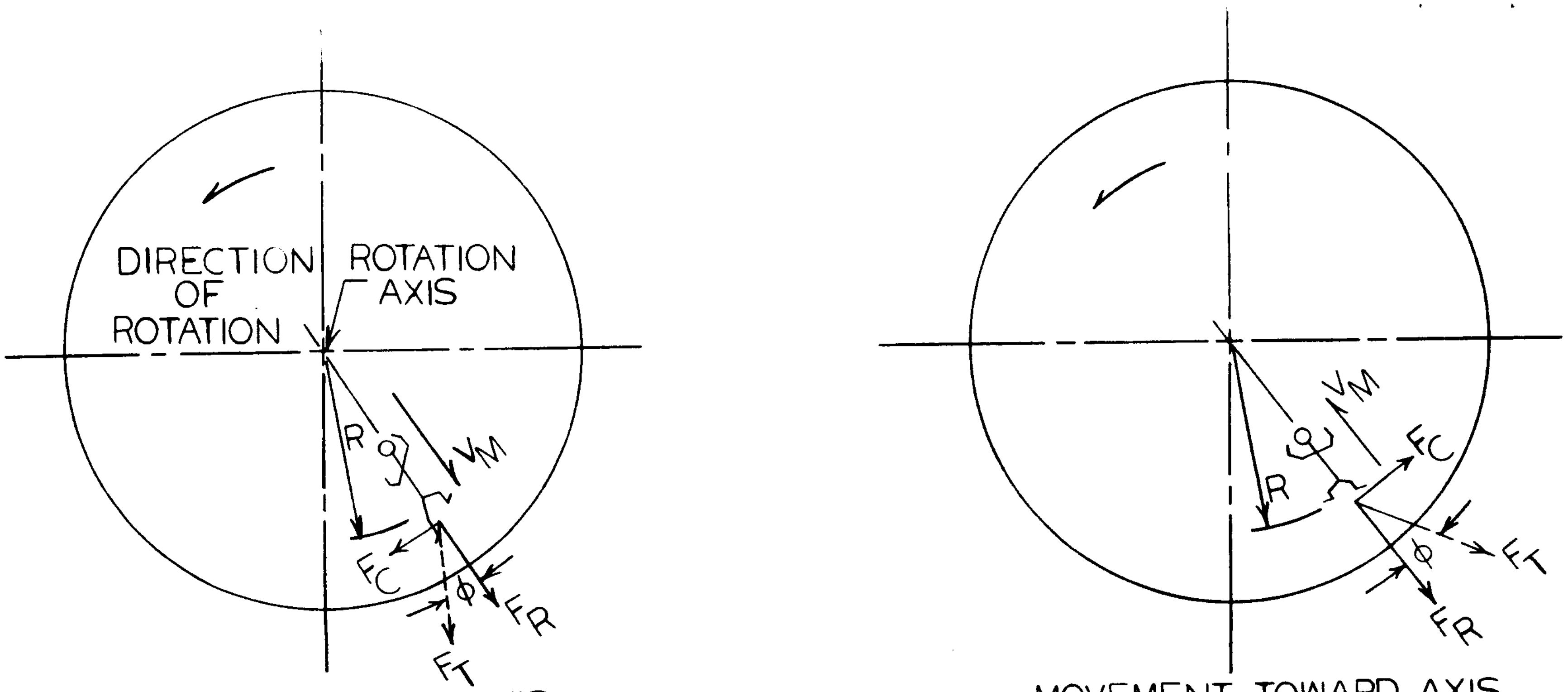
The forces and the directions in which they react are exemplified in Figure 3.5. The centrifugal force, F_R, always acts in an outward direction and is applied at the feet of the man. The direction of the coriolis force, F_c, is perpendicular to the direction of movement of the man and is dependent upon the direction of rotation of the vehicle. The resultant force, F_T, acts at an angle to the man's radial path. The variation of this angle is shown in Figure 3.6. The magnitude of the two components of the resultant force, F_T, is shown in Figures 3.7 and 3.8. For radial movement, the magnitude of the velocity of each point along the radius vector varies in proportion to the product of the angular speed of rotation, ω, times the radius of rotation of the point in question. Therefore, a man moving radially inward must decelerate to match his tangential velocity to the tangential velocity of the point to which he moves. The converse is applicable for outward radial movement.

Tangential Movement:

The inertial forces and the direction in which they react are shown in Figure 3.9. The coriolis force, F_c, acts in a direction parallel to the centrifugal force, F_R, adding to it if the man moves in the direction of rotation. Thus, a man moving in a tangential direction will feel "heavier" while moving in the direction of rotation and will feel "lighter" when moving in a direction which opposes the direction of rotation. The variation of the resultant force acting on the man is shown in Figure 3.10.

Movement Parallel to the Axis of Rotation:

Movement in a direction parallel to the axis of rotation will result in a coriolis force, F_c, equal to zero (Figure 3.11). Thus, the resultant force will be equal to the centrifugal force. However, there may be minor coriolis forces acting on various parts of the body due to their radial motion during the parallel movement of the man. The results of the coriolis forces with respect to head movement discussed by Loret[9] is represented by the formula, $|\omega_{head} \times \omega| < K$, which says that the absolute value of the angular velocity of the head times the angular velocity of the vehicle must be less than a constant, K. Clark and Hardy,[10] have suggested a value of $K = 0.06\ rad^2/sec^2$.



MOVEMENT FROM AXIS

MOVEMENT TOWARD AXIS

F_C = CORIOLIS FORCE
F_R = CENTRIFUGAL FORCE
F_T = TOTAL FORCE
V_M = MAN'S VELOCITY
ϕ = REACTION ANGLE

FIGURE 3.5 FORCES DUE TO RADIAL MOVEMENT

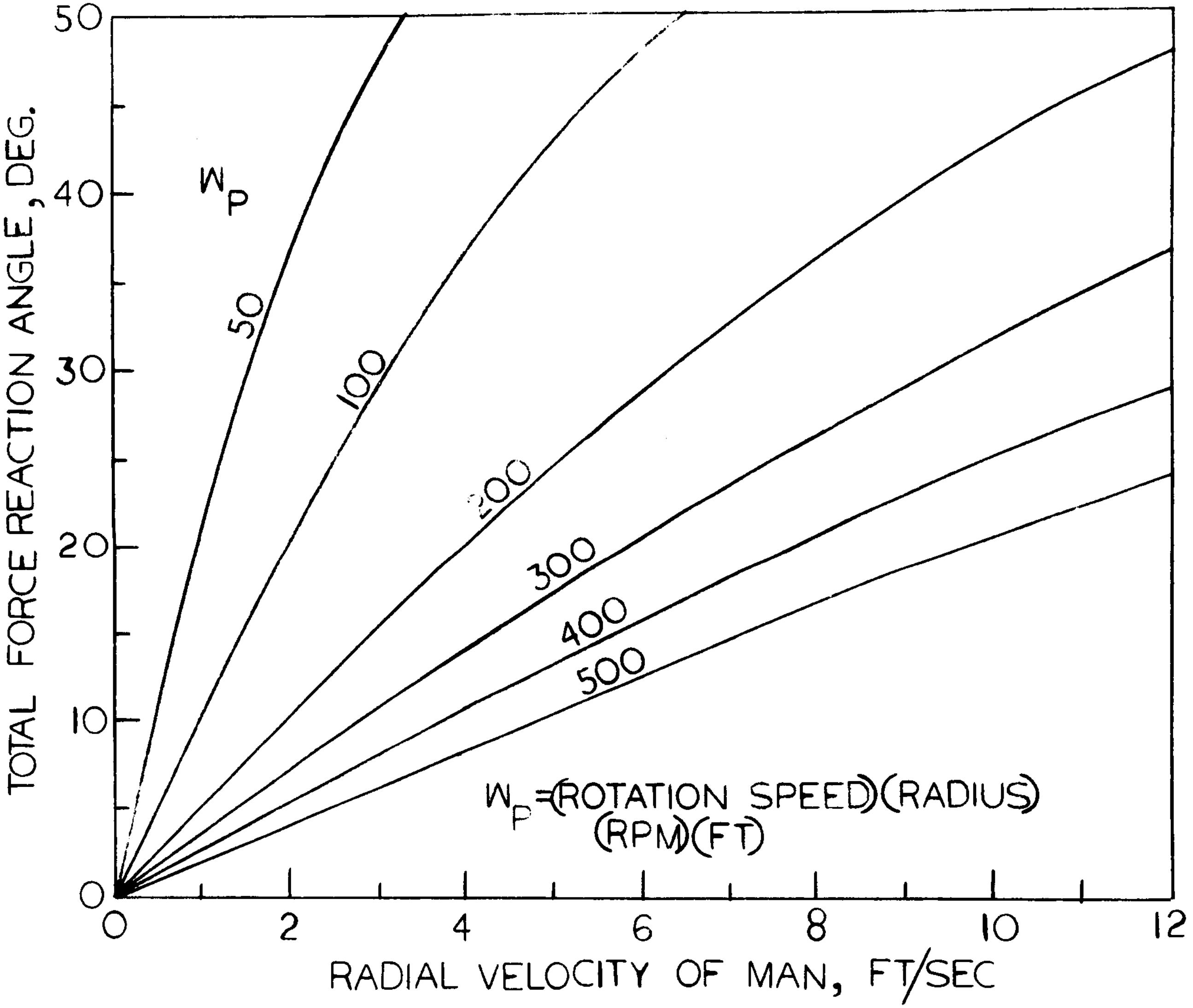


FIGURE 3.6 TOTAL FORCE REACTION ANGLE

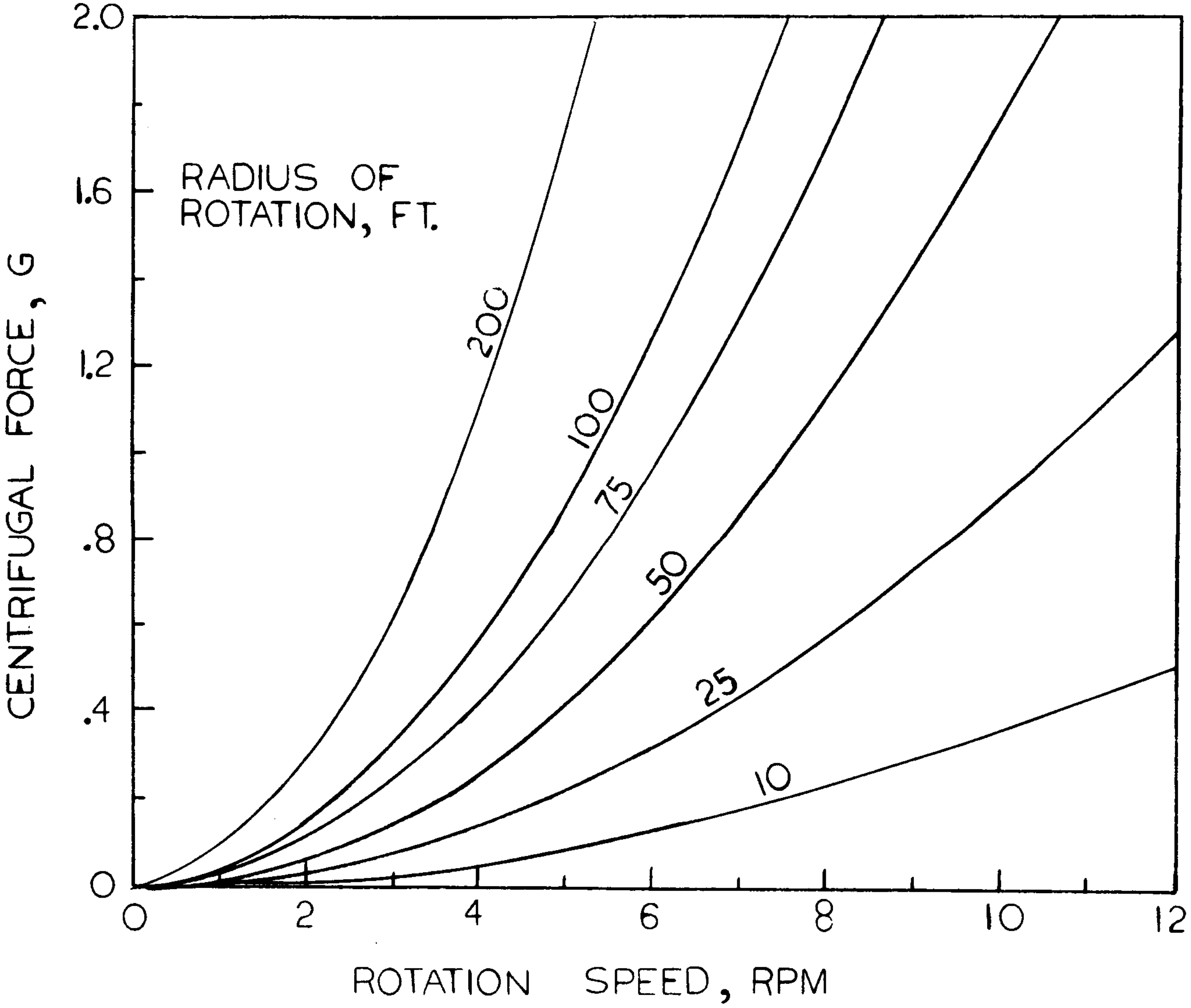


FIGURE 3.7 CENTRIFUGAL FORCE VARIATION

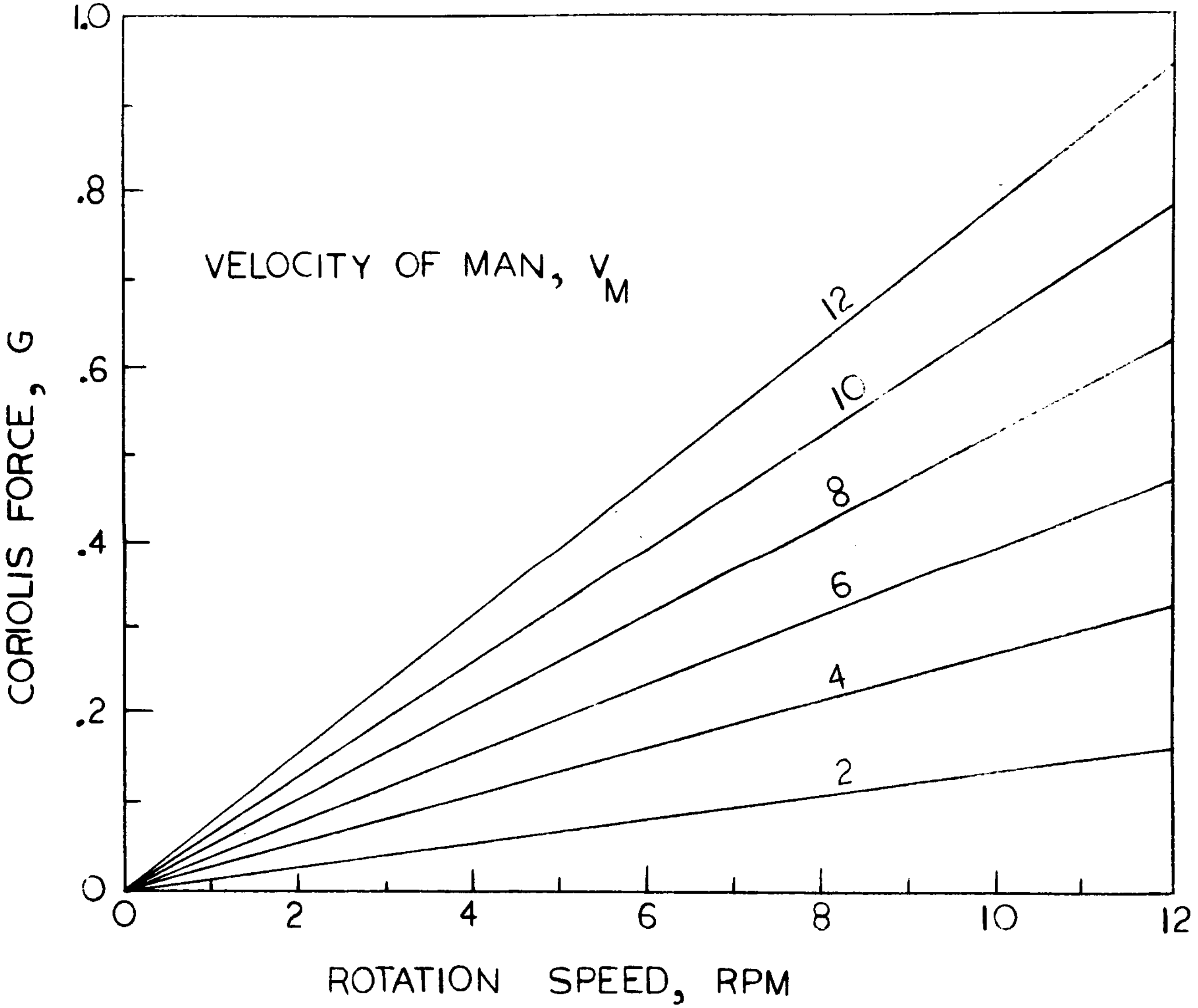
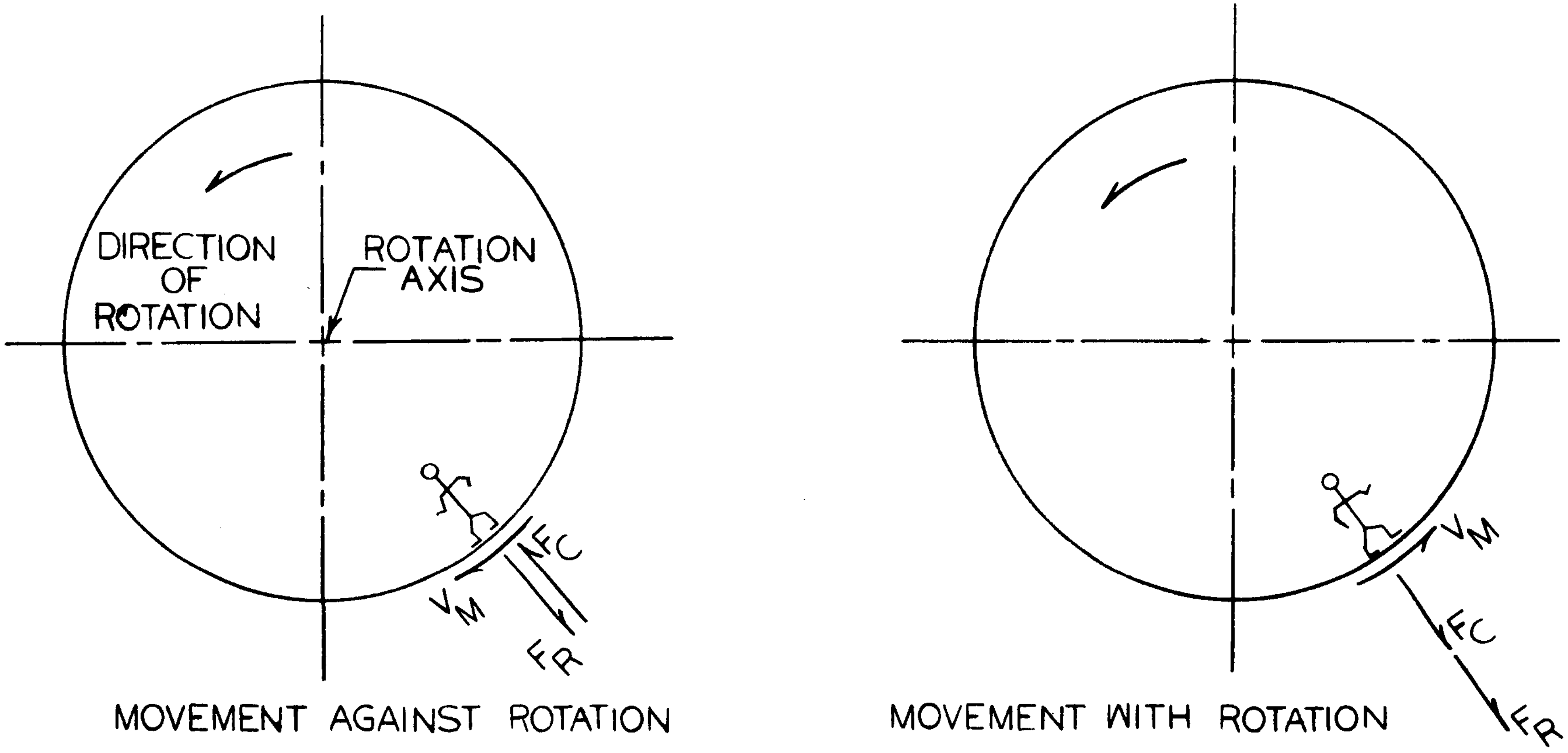


FIGURE 3.8 CORIOLIS FORCE VARIATION



MOVEMENT AGAINST ROTATION

MOVEMENT WITH ROTATION

FIGURE 3.9 FORCES DUE TO TANGENTIAL MOVEMENT

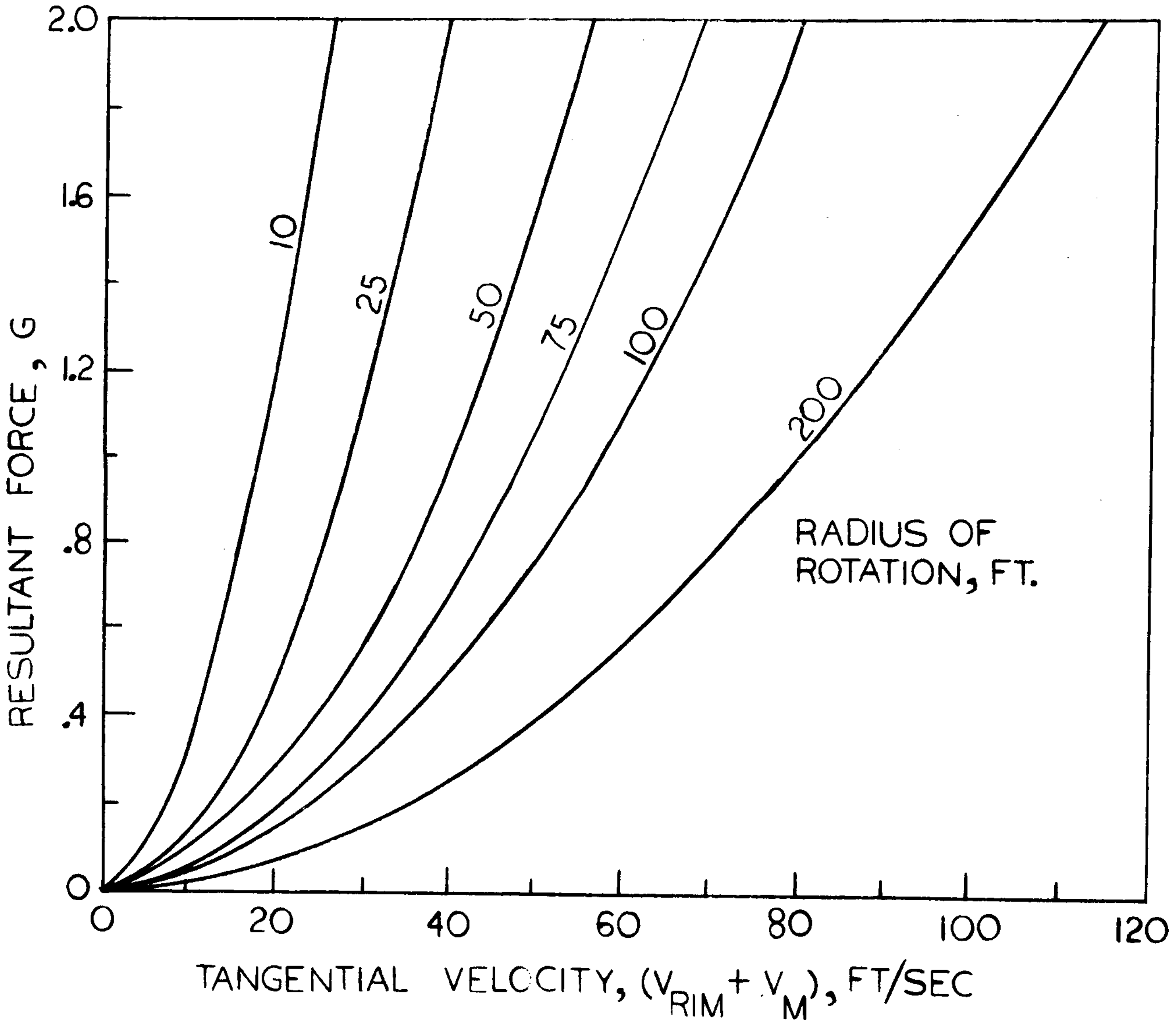


FIGURE 3.10 RESULTANT FORCE VARIATION

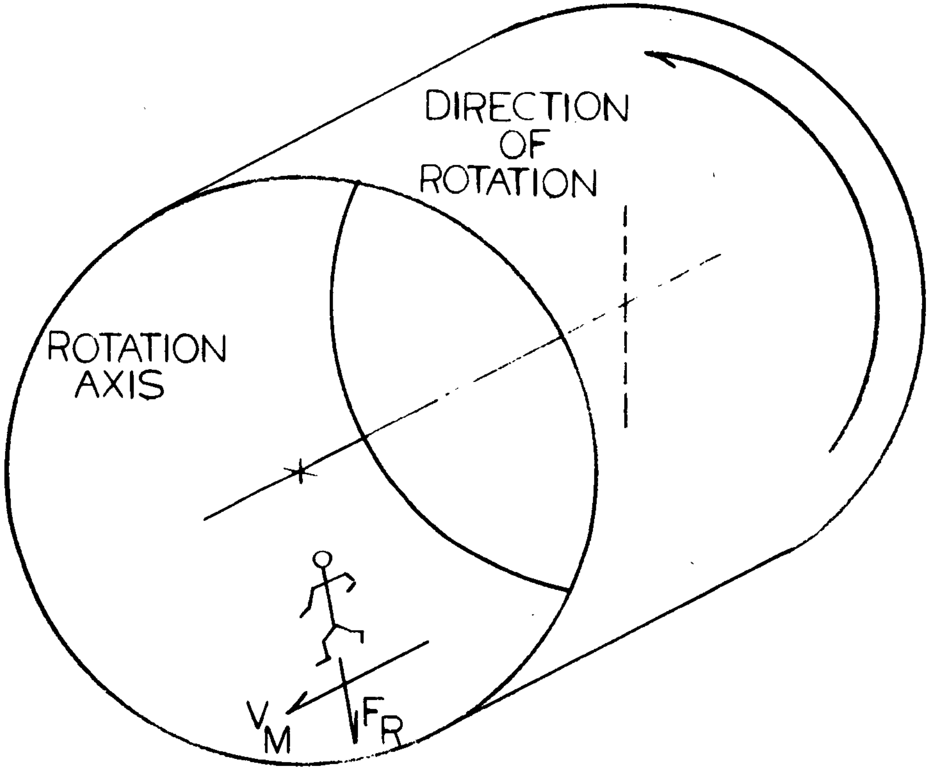


FIGURE 3.11 FORCES DUE TO PARALLEL MOVEMENT

Gravity Gradients:

Normally one would think of an artificial gravity environment as being a uniform value for each object in the rotating vehicle. However, this environment results in a gradient along the local radius vector for various objects. If a man is standing in the vehicle his head will experience a smaller acceleration force than his feet. The gradient from head-to-foot can be expressed as a percentage of the centrifugal force acting at the man's feet. Figures 3.12 and 3.13 depict the nomenclature and show the variation of the gradient versus the radius of rotation. A majority of designers have arbitrarily selected a value of 15 percent for the maximum allowable value for the head-to-foot gradient.

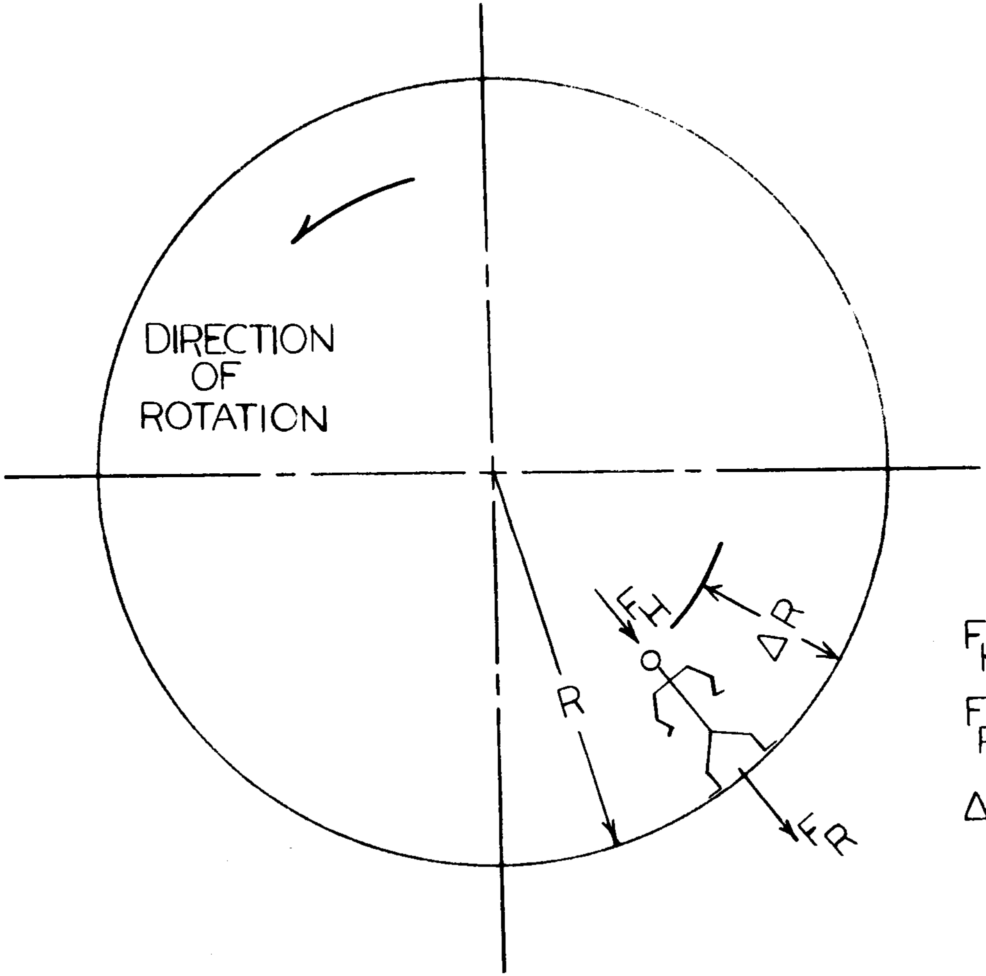
3.3 HUMAN FACTORS DESIGN CONSIDERATIONS

The design considerations, based on human factors, for a rotating space station are discussed below. The major portion of this discussion was taken verbatim from the outstanding work by Loret.[9]

In his terrestrial environment, man is subject to a 1-g force which always acts perpendicular to the earth's surface. While he is subject to minute variations in gravity from place to place, and to Coriolis forces due to the earth's rotation, these variations are so minute that they are below the threshold of man's senses. Such is not the case inside the rotating vehicle where variation in artificial gravity and Coriolis forces may be sufficient magnitude not only to disturb man but also to incapacitate him.

At what values these variations become significant or intolerable is largely conjecture. Since it is difficult, if not impossible, to create on earth the conditions which exist in a rotating space vehicle, only a bare minimum of experimental evidence is available upon which tolerance limits can be based. The best that can be done presently is to evaluate man's tolerance on the basis of this meager evidence. In some cases, where evidence of man's tolerance to a particular combination of stresses is not available, an attempt at extrapolation of data from related experiments may be made, but only with full knowledge that the results may not be precise. In other cases, where no evidence at all is available, assumptions must be postulated.

That the derived design criteria may not be exact should not bar an attempt to prescribe at least a rudimentary human factors design envelope and some general principles upon which vehicle design can be used.



F_H = FORCE AT HEAD

F_R = FORCE AT FEET

$\Delta F = (F_R - F_H)/F_R$

FIGURE 3.12 GRAVITY GRADIENT EFFECTS

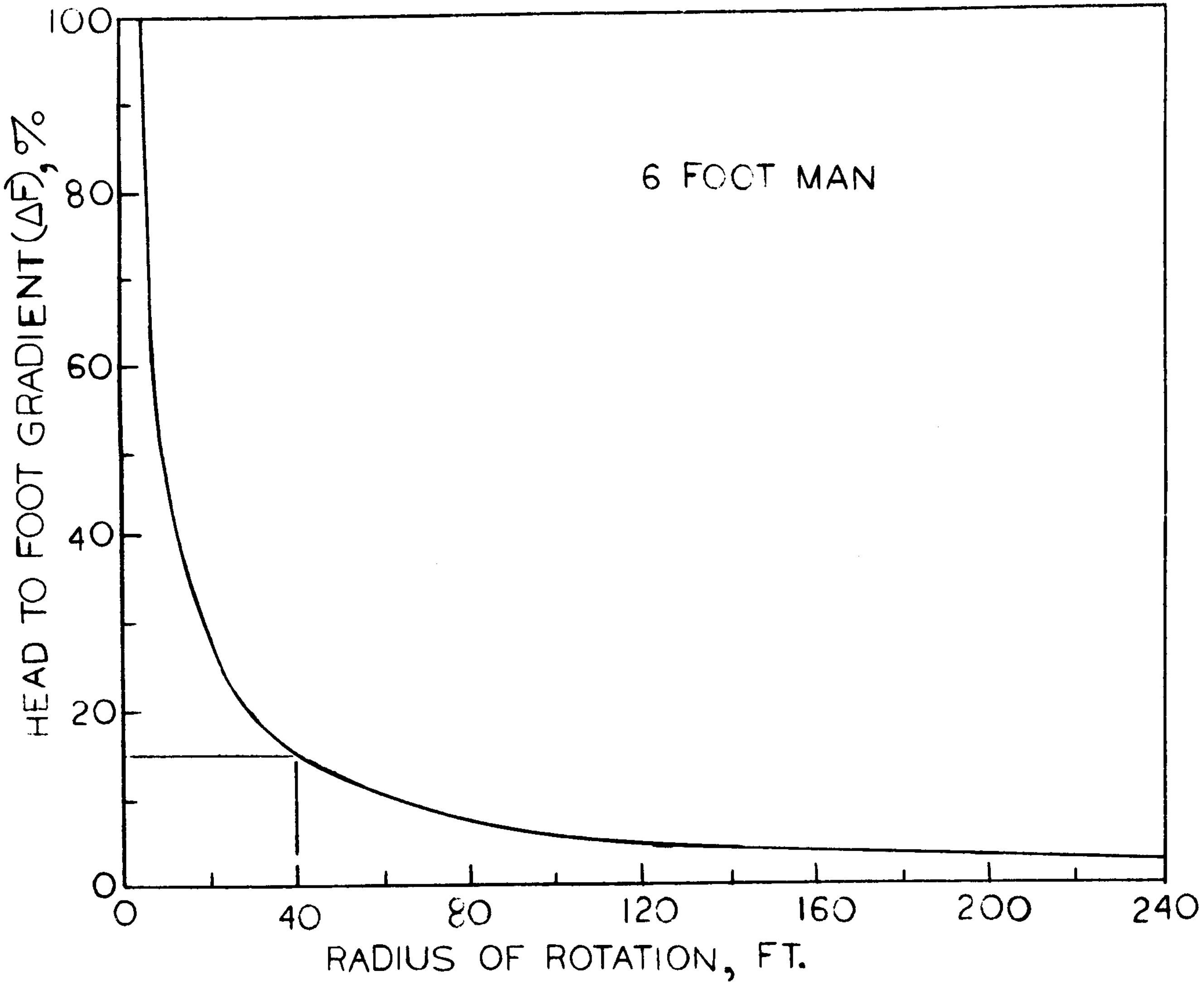


FIGURE 3.13 GRAVITY GRADIENT VARIATION

General Considerations:

As far as man is concerned, the ideal vehicle environment is one which would duplicate that on earth. Such an environment could be closely approximated using a vehicle with an extremely small value for angular velocity and the correspondingly large radius necessary to produce 1-g. As an example, for an $\bar{\omega}$ of 0.01 rad/sec, the radius required to provide 1-g is 61 miles. The construction of such a vehicle is clearly impractical.

Practicality dictates the use of a smaller radius of rotation, which necessitates the use of higher values of $\bar{\omega}$. Coriolis forces would be of sufficient magnitude to produce noticeable effects. Hence, the environment would be something less than ideal.

The designer is thus confronted with a dilemma. On the one hand, practicality dictates the use of as small a radius as possible. On the other, the corresponding increase in $\bar{\omega}$ acts to distort the desired ideal environment. The degree to which the environment may be distorted and still be acceptable to a human is the crux of the design problem.

Because it is the decrease in radius and the increase in angular velocity which distort the gravitational environment, the inner limit of $\bar{r}$ and the upper limit of $\bar{\omega}$ at which man can operate efficiently become parameters of interest. Since the artificial gravity level is intimately connected to these variables, the maximum and minimum permissible values of artificial gravity are additional parameters of interest. Thus, the human factors design envelope will be an open figure prescribed by: minimum permissible $\bar{r}$, maximum permissible $\bar{\omega}$, and the upper and lower limits on g. The figure will an open one because there is no maximum permissible value of $\bar{r}$, the only limit being one of practicality.

In the process of establishing the human factors design envelope, general principles may also be derived which, if observed in engineering design, will result in a vehicle gravitational environment which more nearly simulates the terrestrial one.

The Human Mechanism for Spatial Orientation:

Man maintains his spatial orientation through integration of information concerning the environment which is transmitted to his brain through his senses. Some discussion of the mechanism by which man senses his environment will assist in establishing his tolerance limits to the unusual effects of the rotating-vehicle environment.

The sensory mechanism, referred to as the "orientation triad," consists of the eyes, the vestibular organs (Figure 3.14) located in the inner ear (the semicircular canals and the otoliths), and finally the mechanoreceptors located in the muscles, tendons, and joints. Of these, the eyes are the primary sensors and, in the absence of any other stimuli, as in weightlessness, they provide sufficient information to permit orientation.

Of particular significance is the fact that both the otoliths and the semicircular canals operate on inertial principles. The otoliths sense linear and gravitational accelerations while the semicircular canals sense angular accelerations. Therefore, any accelerations (forces) which are applied to the organs act as stimuli. The impulses which result from the stimuli are sent to the brain, where they are integrated with impulses sent from the eyes and the mechanoreceptors to provide man with spatial orientation and balance.

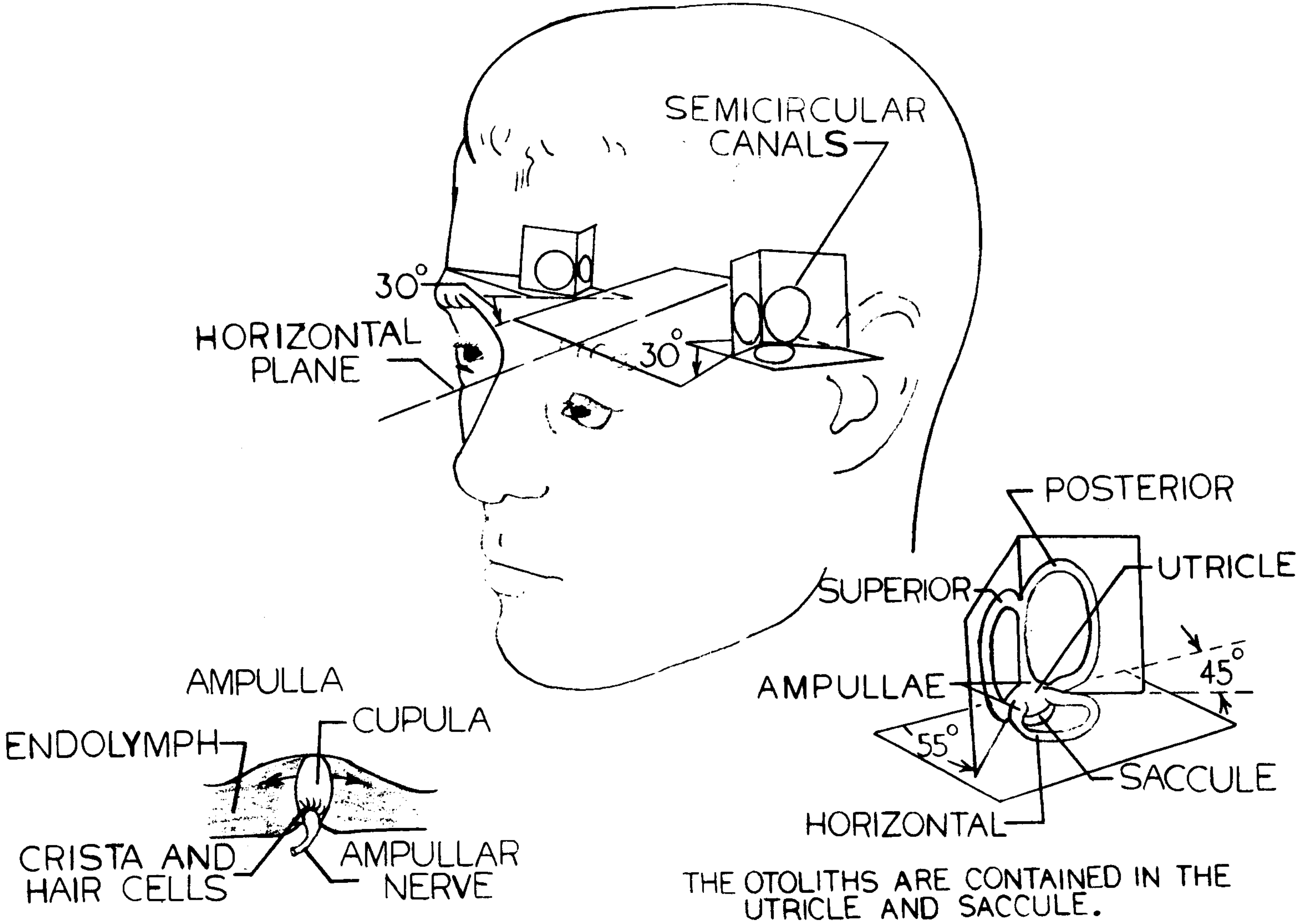
Under normal conditions on earth, maintenance of orientation and balance is a simple matter. The 1-g force acting on the otoliths causes impulses to be sent to the brain which are congruent with what man sees and feels. But under complex rotations, accelerations, and motions, which occur aboard ship in rough seas, for example, conflicting messages are sent to the brain. The results, some of which most people have experiences at one time or another, are dizziness, loss of orientation and balance, the appearance of visual illusions, nausea, and in severe cases even collapse.

The manner in which the conflicting impulses interact with one another, and the influence of other psychosomatic disturbances such as anxiety, fear, and fatigure on these interactions to produce detrimental effects is not completely understood, as is evidenced by the writings of authorities on the subject.

Design Limitations Due to Canal Sickness:

Man's response to the stimulus on the triad, and particularly on the inner ear, caused by the complex dynamic force environment peculiar to the rotating vehicle, is probably the most critical of all human factors in vehicle design.

The changing forces to which man's body is subjected while moving in the vehicle are also applied to the otoliths and semicircular canals. The changing gravity forces and Coriolis forces, which result from locomotion inside the vehicle or due to movement, rotation or cocking of the head, act on the vestibular mechanism. Such overstimulation is obviously conducive to canal sickness. Because of the deterioration in human performance and comfort which result, special attention must be given to vehicle design to prevent or minimize the possibility that Coriolis forces will produce canal sickness.



THE OTOLITHS ARE CONTAINED IN THE UTRICLE AND SACCULE.

FIGURE 3.14 ANATOMY OF THE VESTIBULAR SYSTEM[11]

Experimental data obtained by Dr. Graybiel at the U. S. Naval School of Aviation Medicine at Pensacola, Florida, have indicated the threshold of the occurrence of "canal sickness" to be approximately 3.82 rpm. However, the Life Sciences Department at General Dynamics Convair, San Diego, California, under the direction of Dr. Newsom has obtained data on a rotating vehicle that indicates man can adapt and function effectively at 6 rpm. Tests by both Dr. Graybiel and Dr. Newsom at higher rpm values have indicated problem areas. Therefore, a maximum rotation speed of 6 rpm is selected for use in the Human Factors Design Envelope in Figure 3.15.

The degree to which the crew member will in fact be affected by canal sickness can be minimized through proper design. As noted in paragraph 3.2, the cross product of head $\bar{\omega}$ and vehicle $\bar{\omega}$ is involved. Clark and Hardy[10] noted and Graybiel corroborated that, if the head rotation takes place about an axis parallel to the spin axis, the vector cross product is zero. Hence, there is minimum tendency for canal sickness to occur. From a design viewpoint, then, the crew station positions in the vehicle should be oriented so that the axis about which head rotation would occur most frequently is parallel to the vehicle spin axis.

Because he lives in a "flat" environment man most frequently rotates his head about his longitudinal axis, i.e., left-right. Unfortunately, any standing or sitting position in the rotating vehicle places man's longitudinal axis perpendicular to the spin axis. This situation cannot be avoided. Thus, the head rotation normally used most by man on earth is the rotation which must be minimized in the vehicle. Man will have to learn to restrict the velocities at which he turns his head in the left-right direction and substitute as much left-right eye movement as possible. In fact, the substitution of eye movement for head rotation was precisely what the subjects in the rotating room experiments unconsciously learned.

Although man cannot be oriented inside the rotating vehicle so that he can sit or stand normally and make normal left-right head movements, an advantage may be gained by orienting the crew station position so that, when man is in his normal position, his lateral axis--i.e., an axis through both his ears--will be parallel to the spin axis. This will permit maximum up-down rotation of the head with minimum Coriolis effects on the canals. It follows that the instrument display console at which the man works should have an up-down rather than a left-right orientation. The console and controls should be designed so that a minimum of left-right head movement is required in performance of duty-station tasks. Similarly, assuming that most head rotation while in bed would occur about man's longitudinal axis, the crew should be oriented axially.

No crew duty stations should be oriented so that the lateral axis lies along a tangential axis; for under this orientation both up-down and left-right head rotations would result in stimulating of the vestibular apparatus by Coriolis forces.

Establishment of the Upper Limit for Artificial Gravity:

A requirement for an upper limit in excess of 1.g seems necessary only for preconditioning a space crew prior to landing on a planet or other celestial body whose surface gravity level is greater than that on earth. Since this requirement lies in the remote future, it appears reasonable to select an upper limit of 1-g. The upper limit is therefore prescribed by the requirement that at no time at any position in the vehicle should the crew member experience more than 1-g (see Figure 3.15).

This basic limitation has further design implications because additional forces act when motion takes place tangentially in the direction of spin. Since the g-force increases due to this motion, it would be possible for a man in a vehicle rotated to provided 1-g to experience more than 1-g if he were to walk tangentially in the direction of spin. To permit him to walk tangentially in the direction of spin without exceeding the basic 1-g limit, the ambient g-level of the vehicle must be lower. This lower value sets the upper limit on artificial gravity.

For an assumed walking velocity of 4 ft/sec and for any given radius of rotation, the upper limit on g may be calculated. Assuming an 80-foot radius vehicle and a maximum permissible g-level of 1 for the walking man, the magnitude of $\bar{\omega}_{effective}$ can be computed as:

$$\omega = \frac{g_c}{r} = \frac{32.2}{80} = 0.635 \text{ rad/sec}$$

The corresponding linear velocity at floor level is:

$$\omega r = 0.635\ (80) = 50.80 \text{ ft/sec}$$

The maximum permissible linear velocity at floor level for the vehicle will equal the effective linear velocity for 1-g less the walking velocity of the man, i.e.:

$$(\omega r)_{\text{permissible for vehicle}} = (\omega r)_{\text{effective man}} =$$

$$50.80 - 4.0 = 46.80 \text{ ft/sec}$$

The corresponding value of vehicle $\bar{\omega}$ is:

$$\omega = \frac{\omega r}{r} = \frac{46.80}{80} = 0.585 \text{ rad/sec}$$

and the maximum permissible g-level for the vehicle is:

$$F_g = \frac{\omega^2 r}{g_c} = \frac{(0.585)^2 \, 80}{32.2} = 0.85 \text{ g}$$

Thus, a crew member in this vehicle could move tangentially in the direction of spin at normal walking speed without exceeding the 1-g limit. He would experience 0.85 g when stationary.

The upper g-limit curve showing limiting values of g for all values of r is shown on the graph of Figure 3.15. The curve diverges from the 1-g curve at small values of radius, where the high values of ω cause significant Coriolis effects, and approaches the 1-g curve at large values of radius, where the Coriolis effects are comparatively negligible.

The basis for the establishment of the 1-g limit is sound. The lowering of the limit due to Coriolis effects is to some extent arbitrary. It might well be argued that, once the man becomes accustomed to the ambient g-level, the increase in g-level experienced when walking tangentially in the direction of spin will be an added burden regardless of whether or not the total exceed 1-g. But since from a human factors viewpoint the difference between the two limits, except at very small r, is probably negligible, and since engineering practicality favors its selection, the lower value is a useful limit.

Establishment of the Lower Limit for Artificial Gravity:

Many designers have specified quite low values of artificial gravity. The low levels selected reflect one or more of the following considerations:

a. Belief that small values of artificial gravity are sufficient from a human factors viewpoint.

b. A requirement for practicality and simplicity, particularly for the minimal-capability vehicles of the immediate future.

c. Desire for a low level of g for convenience--i.e., to keep objects in place, to permit use of conventional plumbing, to make use of natural convection, etc.

Work conducted by Beebe[12] and Roberts[13] indicate that from a human factors viewpoint a lower limit of 0.2 g should be established. The experiments involved an evaluation of the ability of a man to walk unaided under various levels of fractional gravity (less than 1-g and more than 0-g). The fractional gravity levels were obtained by flying a C-131 aircraft through Keplerian trajectories. The work performed by Roberts indicate a discontinuity of almost all of the test variables at a level of 0.2 g. Beebe used Robert's test equipment and reached the following conclusion: "The lower limit of gravity at which a man could walk unaided was found to be 0.12g. However, this was for an unsuited condition and is assumed to be the lowest possible limit. The lower limit observed for subjects walking in pressure suits at 3.7 psi was about .17g."[12] Due to an inconsistent behavior observed in suited subjects, a value of 0.2g as a minimum level where man can walk unaided was selected for use in this paper.

From a human factors viewpoint, the g-level at which man can walk unaided appears to be a logical choice for the lower g-limit. Any lower value would probably provide an environment of convenience more than one which reflects the psychophysiological requirements of man.

Following the same reasoning applied to the basic upper limit of 1-g, the Coriolis effect for the crew member walking tangentially against the spin establishes a lower limit which is something greater than the basic 0.2-g limit. For the 80-foot-radius vehicle, the lower limit is calculated to be 0.277 g. The curve in Figure 3.15 shows the lower limit for all values of radius. As in the case of the upper limit, the modification is more significant at smaller values of radius.

If the basic lower limit as assumed to be that minimum level of g at which man can walk unaided, the modification of the basic lower limit due to Coriolis effects is easily justified, for under no circumstances would it be desirable for the walking man to experience a g-level at which he could not walk unaided.

Limitation Due to Gravity Gradient:

There is no experimental evidence available on the effect of a gravity gradient on man, nor is there any nonorbital experiment which can be performed to determine man's tolerance to a gravity gradient at levels of less than 1-g. As a result, it has been necessary to assume some maximum permissible percentage of head-to-foot gravity gradient to floor-level gravity. Payne[14] and Dole[15] select an arbitrary maximum 15 percent; i.e., no value of radius will be used for which the gravity gradient between head and feet is more than 15 percent of floor-level gravity. If a 6 foot man is considered it can be seen from Figure 3.13 that a lower limit on r of 40 ft is necessitated.

Other Limitations Due to Coriolis Effects on Locomotion:

A consideration of Coriolis effects on locomotion from a human factors viewpoint can best be analyzed by considering the effects for each of the three components of motion: radial, tangential, and axial, as was done in paragraph 3.2.

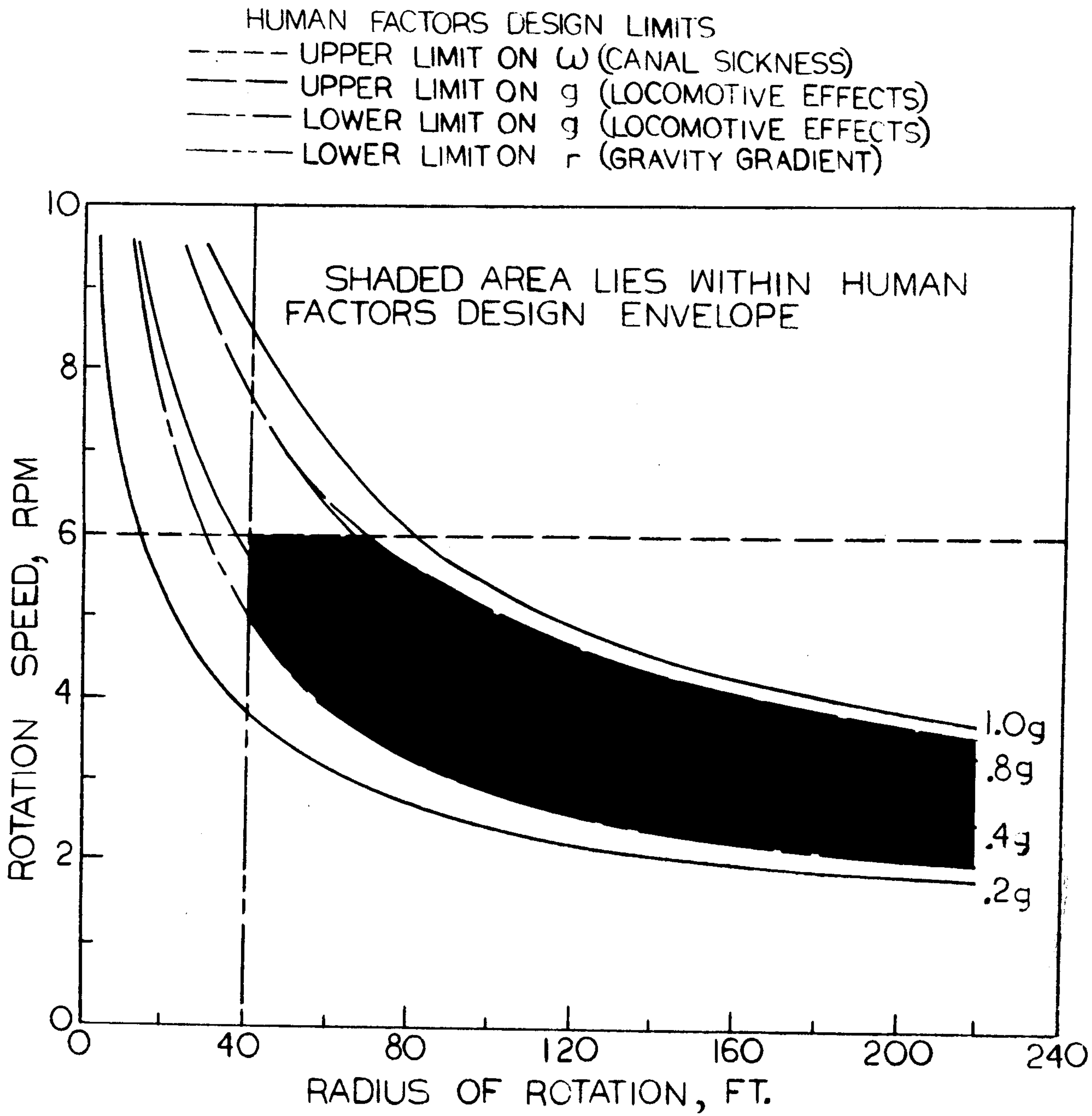


FIGURE 3.15 HUMAN FACTORS DESIGN ENVELOPE

For radial motion in the vicinity of the axis of rotation, the distortion of the gravitational environment due to the change in resultant force both in magnitude and direction, as discussed in paragraph 3.2, would probably cause the onset of illusions and mental confusion.

Radial transport across the axis of rotation would be particularly stressful since the direction of "down" would reverse. The 180-degree change in body position would have to be performed in the vicinity of the axis. Because of the changing stimuli to the vestibular apparatus which would accompany this maneuver, radial transport across the axis of rotation or even stationary activity at the rotating axis could probably not be tolerated unless the "hub" of the vehicle were nonrotating, with provision made for transfer from moving "spoke" to nonrotating hub at some minimum radius, as from 6 to 10 feet.

From a design viewpoint, the minimization of the adverse effects on man of radial motion can be effected by conducting all normal activity as far away from the axis of rotation as possible (since a large radius minimizes the effect), by keeping radial traffic to a minimum, by precluding transport across the axis or activity at the axis unless the hub of the vehicle is nonrotating, and finally, by minimizing radial movement of hands, arms, legs, and feet at the crew duty stations.

Tangential motion has previously been discussed in establishing upper and lower artificial gravity limits. The change in gravity experienced by the crew member walking tangentially poses a problem in that there is no experimental evidence to indicate the ability of man to discriminate between small gradations of gravity or on the maximum permissible deviation from local g-level which can be tolerated without adverse psychophysiological or locomotive effects. Dole[15] places a maximum permissible limit of 50 percent variation between tangential walking and stationary gravity levels.

For axial walking, the only peculiarity to be observed is that the radial components of limb velocity will result in applying side Coriolis forces to the limbs. But because the radial velocity component of the arms and legs will be small, and because the radial motion will be reciprocating in nature, the disturbance will probably be minor perturbations of the limbs accompanying rather than hindering locomotion. As a foot is raised, for example, it will be deflected sideways by a small Coriolis force. As it is planted, the force will act in the opposite direction with the result that the foot will more or less be planted in line with the intended direction of walk. There will be some effect on the vestibular apparatus due to Coriolis forces which result from radial bobbing of the head while walking (which will also occur when walking tangentially), but in general the effects will not be so critical as those which accompany radial and tangential motion. Because axial motion results in the least distortion of the artifical gravity environment, the vehicle should probably be designed to take advantage of this fact; i.e., the major dimensions of the living-working compartment should be placed parallel to the vehicle spin axis.

Results of Human Factors Analysis:

The Human Factors Design Envelope:

An examination of the tolerance limit curves superimposed on the basic $\bar{\omega}$ versus $\bar{r}$ graph of Figure 3.15 indicates that the human factors design envelope is prescribed on three sides by the upper g-limit, the lower g-limit, and the upper limit on $\bar{\omega}$ of 6 rpm. Since the other human factors stress-limit curves lie outside the envelope, the stress limits they represent will not normally be exceeded in the living-working compartment for any operating point of $\bar{\omega}$ and $\bar{r}$ which lies within the envelope.

Human Factors Design Principles:

In addition to the design envelope (Figure 3.15), the general principles that should be observed in a space station design are:

a. Radial traffic should be kept to a minimum.

b. Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is nonrotating.

c. The living-working compartment should be located as far as possible from the axis of rotation.

d. The compartment should be oriented so that the direction of traffic--i.e., the major dimension of the compartment--is parallel to the vehicle spin axis.

e. Crew duty-station positions should be oriented so that, during normal activity, the lateral axis through the crew member's ears is parallel to the spin axis. In conjunction with this requirement, the work console instruments and controls should be designed so that left-right head rotations and up-down arm motions are minimized.

f. Sleeping bunks should be oriented with their long axes parallel to the vehicle spin axis.

g. The presence of confusing visual stimuli should be minimized. For example, the apparent convergence of the vertical from any two points separated tangentially should be played down by proper interior decoration and, except for necessary observation ports, which should be covered when not in use, the living-working compartment should be windowless.

3.4 SUMMARY

The intent of this paper is to present a quick reference to the artificial gravity considerations for a revolving space station. The author has taken the liberty to select various passages from the references and insert them almost verbatim in this paper. The paper discussed the results of experimental work performed by Dr. Graybiel and Dr. Newsom. These experimental data provided the basis for the upper limit, for the rotation speed of a space station, in the human factors design envelope (Figure 3.15). In addition, the artificial gravity environment defined in paragraph 3.2 shows a quantitative picture of the theoretical aspects of the environment.

The human factors design envelope presented in Figure 3.15 accounts for more recent experimental data that was not available to Loret.[9]

The design envelope shown in Figure 3.15 prescribes the following parameters:

a. The Upper Limit on Vehicle Angular Velocity $(\bar{\omega})$ - established at 6 rpm, based on the work by Graybiel and Newsom.

b. The Upper Limit on Artificial Gravity - established as a 1-g maximum, modified to compensate for Coriolis effects for tangential walking in the direction of spin.

c. The Lower Limit on Artificial Gravity - established as 0.2 g minimum on the assumption that the lowest value of artificial gravity to be permitted is that minimum value (0.w g) at which man can walk unaided, the minimum limit modified to compensate for Coriolis effects for tangential walking against the spin.

d. The Lower Limit on Rotation Radius (r) - established at 40 feet. However, this radius is based on the arbitrary selection of 15 percent as the maximum value for the gravity gradient between head and feet, and corresponds to a man of 6 feet height.

In addition to the design envelope the following human factors design principles were proposed by Loret.[9]

a. Radial traffic should be kept to a minimum.

b. Transport across the spin axis and human activity at the spin axis should be prohibited unless the hub is nonrotating.

c. The living-working compartment should located as far as possible from the spin axis.

d. The compartment should be oriented so that its major dimension is parallel to the vehicle spin axis.

e. Crew duty-station positions should be oriented to provide the preferred orientation of the crew member's lateral axis.

f. Sleeping bunks should be oriented with their long axis parallel to the vehicle spin axis.

g. The presence of confusing visual stimuli should be minimized.

h. Selection and Training of Crew Members:

Because canal sickness is the most critical of human factors connected with the artificial gravity environment, screening of astronaut candidates should include an evaluation of susceptibility to canal sickness. Effort should be devoted to the design of the test device and test procedure.

Astronauts in training for duty in the artificial gravity environment should be exposed to the peculiarities of a rotating-vehicle environment to the extent that earthbound facilities will permit. Effort should be devoted to development of a training facility which will most nearly simulate the rotating-vehicle environment.

REFERENCES

1. Bergstedt, M; Stepwise Adaptation to a Velocity of 10 rpm in the Pensacola Slow Rotation Room. In: The Role of the Vestibular Organs in the Exploration of Space. NASA SP-77. U. S. Naval School of Medicine, Pensacola, Florida, 1965. pp 339-345.

2. Graybiel, A., and Zarriello, J.J.; Observations on Human Subjects Living in a Slow Rotation Room for Periods of Two Days: Canal Sickness. Research Project MR005.13-6001, Report No. 49, U. S. Naval School of Aviation Medicine, Pensacola, Florida, October 1959.

3. Graybeal, A., and Guedry, F. E., Jr., et. al.; Effects of Exposure to a Rotating Environment (10 rpm) on Four Aviators for a Period of Twelve Days. Project MR005.13-6001, Report No. 111, U. S. Naval School of Aviation Medicine, Pensacola, Florida, March 1965.

4. Guedry, F. E.,Jr.; Habituation to Complex Vestibular Stimulation in Man: Transfer and Retention of Effects from Twelve Days of Rotation at 10 rpm. Project MR005.13-6001, Report No. 109, U. S. Naval School of Aviation Medicine, Pensacola, Florida, March 1965.

5. Brady, J. F. and Newsom, B. D.; Observations on Subjects Exposed to Prolonged Rotation in a Space Station Simulator. In: The Role of the Vesitubular Organs in the Exploration of Space. NASA SP-77 U. S. Naval School of Medicine, Pensacola, Florida, 1965. pp 279-292.

6. Brady, J. F. and Newsom, B. D.; Large Excursion Rotary Tracking of Target and Target Light in a Space Station Simulator Revolving at 7.5, 10.0, and 12.0 rpm. Aerospace Medicine, Vol. 36, No. 4, April, 1965.

7. Brady, J. F., Goble, G. J., and Newsom, B. D.; Equilibrium and Walking Changes Observed at 5, 7.5, 10 and 12 rpm in the Revolving Space Station Simulator. Aerospace Medicine, Vol. 36, No. 4, April, 1965.

8. Letko, W. and Stene, R. W., Jr.; Some Observations on the Stimulation of the Vestibular Systems of Man in a Rotating Environment. In: The Role of the Vestibular Organs in the Exploration of Space. NASA SP-77. U. S. Naval School of Medicine, Pensacola, Florida, 1965. pp 263-278.

9. Loret, B. J.; Optimization of Manned Orbital Satellite Vehicle Design With Respect to Artificial Gravity. ASD TR C1-6888, Wright-Patterson Air Force Base, Ohio, December, 1961.

10. Clarke, C. C., and Hardy, J. D.; Gravity Problems in Manned Space Stations. In: Proceeding of the Manned Space Stations Symposium, 1960. Institute of the Aeronautical Sciences, New York, April, 1960.

11. Bioastronautics Data Book, NASA SP-3006. 1964. pp 363-381.

12. Beebe, D. E.; Force Analysis of Walking at Reduced Gravity. M.S. Thesis, Air University, Wright-Patterson Air Force Base, Ohio, August 1964.

13. Roberts, J. F.; Walking Responses Under Lunar and Low Gravity Conditions. M.S. Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, 1962. Also published as AMRL-TDR-63-112 Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio 1963.

14. Payne, F. A., "Work and Living Space Requirements for Manned Space Stations," in Proceeding of the Manned Space Stations Symposium, Institute of the Aeronautical Sciences, New York, New York, 1960.

15. Dole, S. H., Design Criteria for Rotating Space Vehicles, USAF Project Rand, RM-2668, Rand Corporation, Santa Monica, California, October 1960.

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 4.0

LOGISTICS REQUIREMENTS

ADVANCED SPACECRAFT TECHNOLOGY DIVISION
ENGINEERING AND DEVELOPMENT DIRECTORATE
MANNED SPACECRAFT CENTER

4.0 LOGISTICS - INTRODUCTION

The major differences that exist between logistic requirements for the artificial and zero gravity space station configurations lie in the type, number, and duration of the experiments which are to be performed within a given space station's mission. However, if the criterion is established that logistics requirements are not considered satisfied until the item(s) required are loaded on-board the space station, then considerable difference exists between the storage, handling and transfer techniques. This difference arises from the added complications encountered in servicing artificial gravity space stations as opposed to nonrotating zero gravity space stations.

4.1 CONFIGURATION IMPLICATIONS

Assuming that the logistics requirements are not satisfied until the equipment in question is transported from the logistics vehicle to the space station, installed, and in operation then, the logistics problem is greatly affected by the type and/or configuration of the space station. For the zero gravity configuration, the solution of the logistics problem is straightforward. Where an artificial gravity space station is involved, the logistics problem is more complex.

Transferring equipment from the logistics vehicle to a zero gravity space station involves a docking maneuver after which equipment may be transferred by use of special equipment mounted in the space station and/or logistics vehicle.

Transferring equipment from the logistics vehicle to an artificial gravity space station also involves a docking maneuver. The docking operation can only be performed with the hub or non-rotating portion of the space station. Transferring equipment to the rotating arms of the station can be accomplished in the same manner as a crew member transfers from the stationary to the rotating regions of the space station. As a result, it will not be possible to make effective use of the logistics vehicle in the installation and checkout of equipment as in the case of the zero gravity station. In addition, all equipment transferred in this manner will be limited in size, shape, weight (in the gravity induced regions) and installation requirements. A special lift may have to be provided in the connecting arms (acting as chutes) to transfer some or all of the required equipment. It is possible that it will be necessary to stop the rotation to complete the transfer process.

There are three major logistics areas associated with all space stations and their respective missions: experiments, orbit maintenance, and housekeeping. These areas are described in the following sections.

4.2 LOGISTICS REQUIREMENTS FOR SPACE STATION EXPERIMENTS

This area of logistics may or may not fall in the category of resupply. Logistics for experiments deal, primarily, with the transportation, to and from the space station, of experiment equipment, specially trained personnel and scientists, and special consumables and/or reactants related to particular experiments or equipment operation. Resupply in this area may be required depending on the duration of the experiments and the consumption rate of special experiment-related consumables. In respect to the latter, resupply will depend on the weight and volume available; the usable life span of the substance(s) in question; and the length of the logistics resupply interval. This is particularly true where radiation experiments are concerned, as well as for photographic missions involving large quantities of exposed and unexposed film of various types. Flexibility in the length of the logistics resupply interval may be desired in the case of the bioscience program where the exposure time of experiment specimens to various space conditions may be critical.

Details on special experiment-related test, maintenance, and installation equipment requirements require formal definition of space station equipment at the time of launch, as well as of the space station's mission and the equipment to be installed and/or operated during the course of the mission.

4.3 LOGISTICS REQUIREMENTS FOR SPACE STATION ORBIT MAINTENANCE AND STABILIZATION

Logistics requirements in this area are primarily related to propulsion and reaction control. Orbit maintenance is required because of space station orbital decay, but the extent and/or magnitude of the propulsion requirements depends on the mass and configuration of the space station and on the length of the interval between orbit maintenance maneuvers. Reaction control requirements exist for the purpose of space station stabilization, but the extent and/or magnitude of the logistics requirements depends on the size and activity of the crew and on the attitude hold and orientation requirements of particular experiments. Reaction control requirements are also dependent on the mass and moment of inertia of the space station.

If the propulsion requirements for orbit maintenance are to be met with an Apollo Service Module propulsion system, the entire unit will have to be replaced after 720 seconds of operation. This is the design life of the ablative chamber of the Apollo Primary Propulsion System. Since the Service Module is capable of carrying sufficient propellant for this burning time, no propellant resupply, as such, should be required. If this system is equipped with a propulsion system having the capability of a longer burning time, propellant resupply may be in order. However, it would be necessary to increase the burning time of the engine by multiples of 720 seconds to warrant propellant resupply for the Apollo system. In this case, propellant pressurant must also be resupplied. If orbit maintenance corrections are to be performed with the logistics vehicle's propulsion system, it will be necessary to load additional propellant and pressurant for this operation, but this requirement does not fall in the general category of resupply.

Reaction control logistics will consist primarily of resupplying the system with propellants and pressurant. Oxidizer and fuel must be supplied in accordance with the design mixture ratio (2:1) for the RCS engines, with a maximum requirement equal to the usable tank capacity plus the volumes of the transfer lines. Since these systems use positive expulsion bladders, the low pressure side of the pressurization subsystem will have to be vented at constant pressure during the propellant transfer operation to prevent unbalanced stresses in the bladders. Since the resupply system on the logistics vehicle must be of the same magnitude as that of the space station, the transfer requirements can be minimized by bleeding the low pressure side of the pressurization system to below operating pressure, thereby lowering the transfer pressure requirements. This will require closing the pressurization system regulators during this process. The high pressure system will have to be filled from another high pressure system, though a compression device could be utilized for this purpose. This choice, based on optimization of systems, will depend on the quantity of pressurant to be transferred. In any event, high pressure resupply logistics will require a cryogenic cooling bath to decrease the fill time due to compressive heating effects experienced by the pressurant during the filling process. The magnitude and/or extent of this requirement will depend on the amount of pressurant to be transferred, the final fill pressure, and the time allowed for the operation.

Periodic RCS propellant tank replacements may be required due to bladder recycle limitations. This would cause a considerable loss of propellants because of excess loads for contingencies provided at initial station launch (resupply interval plus 50 percent). If the contingency requirements can be minimized, it may be advantageous to replace all RCS propellant and pressurant storage subsystems at each logistics resupply interval. This is especially true of the high pressure storage system (provided the hardware problems of breaking and sealing high pressure lines can be resolved). It may be an integral part of the logistics requirement to perform an adequate check of all systems that have been opened in any way to insure that no leaks exist after the resupply operation has taken place. Special equipment will have to be supplied to perform the necessary systems checks to satisfy this requirement. Special hardware concepts will have to be devised to facilitate the work involved in these operations.

Reaction control rocket engines must be replaced periodically, depending on their mode of operation and total burning time. As these engines have ablative chambers, the char depth becomes critical with operation. Generally, greater total burning times can be obtained with long duration burns than with small periodic bursts. However, since not all engines are operated in the same sequence nor for equal time periods, not all engines will require replacement at the same time. As a result, it may be desirable to keep track of thruster operation to determine which engines must be replaced at each logistics resupply interval.

It is doubtful that the current Apollo RCS propellant tanks and helium pressurant can be used for the long duration logistics intervals presently planned for space station resupply. The reason for this is that helium permeates the teflon bladders used to expel propellants. As a result, helium becomes entrained in the propellant and passes into the combustion chamber where it can interfere with the combustion process. Because of this, a new pressurization system will have to be developed which decreases logistics requirements for hardware replacement.

4.4 LOGISTICS REQUIREMENTS FOR SPACE STATION HOUSEKEEPING

This area of logistics lies predominantly in the category of resupply. The logistics requirements are food, cryogenics, spare components, and space station personnel.

Food, spare components, etc. can be transferred bodily from the logistics vehicle. Since all systems are designed for initial loads having a 50 percent excess for contingencies, consumables should be capable of storage for the full resupply interval including the total amount for delays in resupply. Food can be packaged in small quantities which will facilitate consumption according to a dating system to prevent spoilage.

In the case of cryogenics, the aspect is quite different. These fluids are stored as cryogens and must be resupplied in the same state. However, because of the large thermal loads associated with long duration storage of low temperature fluids, it is essential to minimize the storage area in order to make the insulation requirements practical. This requirement is best satisfied by large spherical containers. For a given storage volume, the sphere offers the smallest surface area, and large storage volumes permit larger heat loads for the same operating conditions. As a result, logistics requirements in this area are governed not only by mission requirements but by hardware limitations and system operating philosophy. However, the requirement to resupply influences tank design and system operation also.

A certain amount of fluid waste is involved in any resupply operation involving cryogenic fluids. The amount of waste can be minimized or made as large as the excess contingency loads by proper choice of system operation. Under certain conditions, additional logistics requirements may be necessary in the form of electrical power in order to pressurize the storage system after loading.

Cryogenic storage is a necessary evil to which resort is made in order to obtain large storage densities. Practical considerations on earth dictate that space station storage systems be designed for fill or loading operations involving fluids in the liquid state in equilibrium with the vapor phase at one atmosphere of pressure. As a result a resupply operation must restore the system to its initial fill density condition. Once the system is filled, it may be operated in the subcritical range (where the liquid remains in equilibrium with its vapor) at any subcritical pressure desired. Also, the system may be permitted to pressurize at constant volume and constant bulk density until it becomes a pressurized liquid at any pressure above its saturation pressure. Where supercritical operation is desired, the pressurization operation is permitted to proceed until the pressure goes above the critical. Hence, since storage systems must operate at constant pressure, a subcritical system, being a low pressure system, contains a two-phase fluid involving a high density liquid and a low density vapor whereas a supercritical system involves a high density single phase fluid which goes from liquid to gas where the temperature or storage density goes beyond the phase transition point at its operating pressure. The fluid density of the supercritical system is not constant and decreases steadily throughout system operation. Further, the fluid density in a supercritical system is always greater than that of the vapor when the system is operated subcritical.

If a storage system is resupplied by replacing the partly empty storage tanks with full ones, then the weight of fluid wasted is the same for either a subcritical or supercritical system and is equal to the extra amount originally loaded for contingencies, i.e., approximately 50 percent of the weight of fluid actually required for resupply. If the system is resupplied through a transfer line whereby the tanks are refilled, then the logistic requirements are quite different for the two modes of system operation.

Transferring cryogenic liquids in space requires a positive expulsion device. This is practically limited to a bladder or bellows operated or compressed by a gas pressurant expanding from a high pressure source. If the required transfer pressure is sufficiently low, the expansion system will suffice to accomplish the operation. Where large fluid quantities are to be transferred and/or if the required transfer pressure is sufficiently high, the expansion system may be aided with a pump. However, pump operation imposes additional logistics requirements for electric power, and an optimization study must be performed to establish optimum transfer operation and logistics requirements.

All liquid transfer operations require storage system venting. This operation is required because the resupply liquid must take up the volume formerly occupied by the gas or vapor in the storage system. The weight of fluid lost in this operation must be made up in the resupply operation and constitutes an additional logistics requirement over and above the weight of fluid used in normal space station operation. Additional logistics fluid requirements must be supplied to cool and fill the transfer line during the fill or resupply operation. As venting must continue throughout the fill operation, the transfer operation must proceed at a sufficiently low rate to minimize agitation which will create entrained liquid particles in the expelled vapor. This condition may be controlled by proper storage tank design.

If the storage system to be filled is operating subcritical, the weight of fluid lost in the transfer operation is less than for any other type of operation. The reason for this is the low density of the expelled vapors, and the high latent heat of vaporization of the liquid which permits higher thermal loads throughout the flow network. Further, under subcritical conditions it is possible to fill the vessel completely while venting at operating pressure. In this manner the maximum amount may be resupplied, and the tank can be placed on stream immediately as no pressurization is required, and the liquid remains in equilibrium with its vapor at all times.

If the storage system is operated supercritical, the resupply operation is more costly and complex. If sufficient fluid has been extracted from the storage system to take the fluid to the gaseous state, (as will definitely be the case), then it will be necessary to vent the storage vessels to at least the saturation pressure of the liquid at its initial fill condition, i.e., one atmosphere. The remainder of the fill operation continues in the same manner as in subcritical fill until the required ullage volume is reached. At this time the vessel must be closed off and pressurized to above the critical pressure at a great cost in electrical power. Further, the vessel cannot be returned to the system for on stream operation until the pressurization operation is complete. Thus, supercritical storage leads not only to vent losses amounting to practically all of the fluid in the vessel (the 50 percent excess contingency loads as in the tank exchange method), but to additional logistics power requirements in the amount required to pressurize the entire system from beginning to end. The power requirements in this case are greater than for the tank interchange method, where the pressurizing requirements can be partially supplied on earth prior to logistic vehicle launch and through normal heat leak during the resupply operation.

All logistics requirements in this area are a function of crew size and logistics resupply interval. However, it may be safely concluded that the resupply requirement dictates subcritical operation for the cryogenic storage system of either space station configurations.

4.5 WEIGHT ESTIMATES FOR HOUSEKEEPING LOGISTICS AND STABILIZATION REQUIREMENTS

The logistic resupply graphs, Figures 4.1 and 4.2, show the estimated weights for spare components, tankage for expendable, expendables, and the total weight to resupply the housekeeping functions for resupply intervals from 1 to 12 months. These curves have been developed by assuming that:

a. The yearly requirement is divided into equal monthly increments.

b. The yearly requirement replaces items expended. (That is, no loss in replacement.)

c. Equipment for handling at the station will be available as needed either on the station or the logistic vehicle.

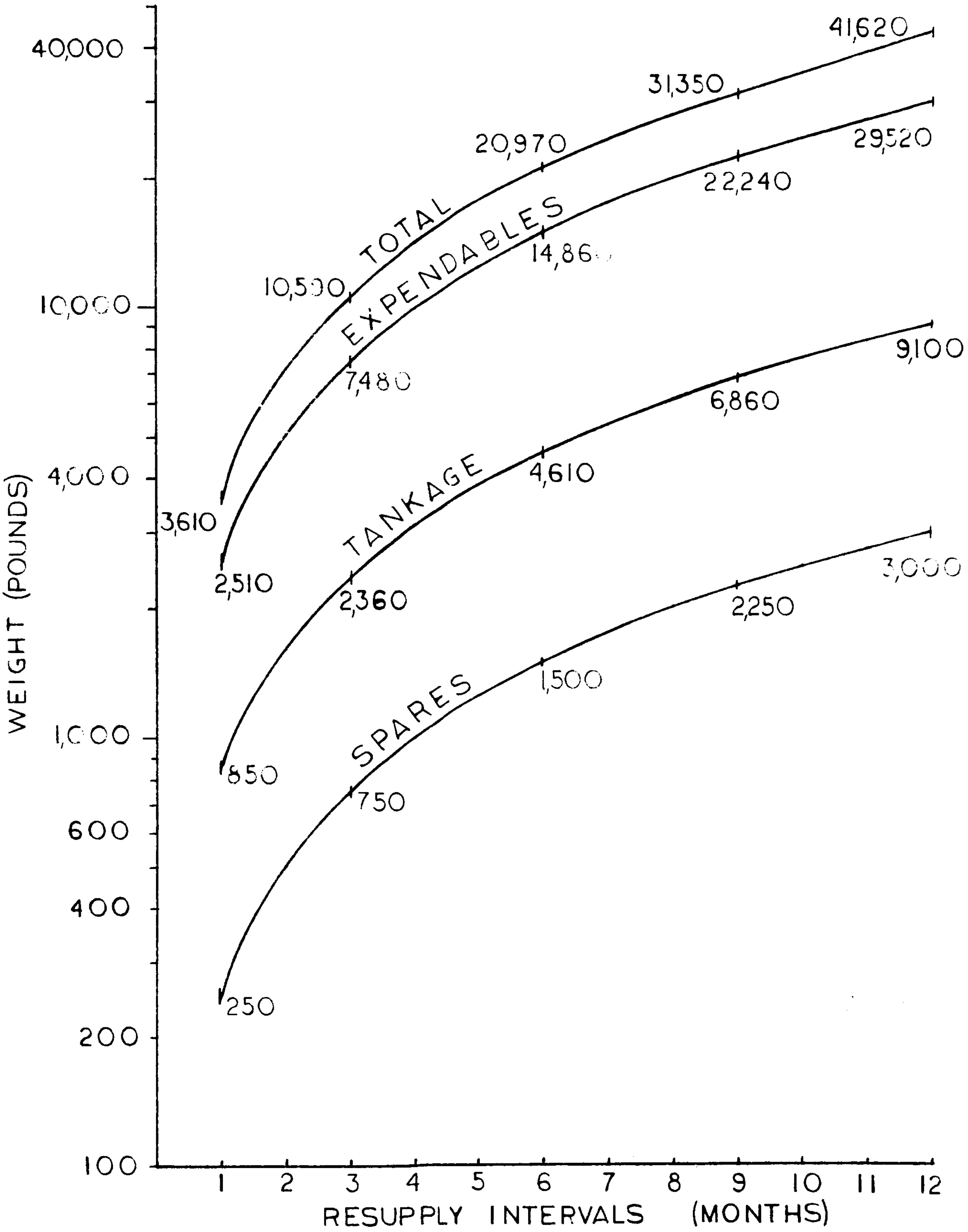
Table 4.1 shows the estimated spare components for 9 and 24 man crews on a yearly basis.

Table 4.2 indicates the estimated tankage weights for the expended liquids and gases for 9 and 24 man crews. Oxygen and nitrogen tankage weights are developed utilizing the curves shown in Volume III, Figure 4.36 for a L/D = 1, therefore the tanks are spherical. (Tank replacement as opposed to fluid transfer is assumed.) For quantities above 1200 pounds multiple tanks are used. The RCS propellant tankage is estimated to be equivalent to the Apollo service module tankages. The pounds of tank per pound of propellant is

$$.69 \left(\frac{\text{lb of tank}}{\text{lb of propellant}} = .69\right).$$

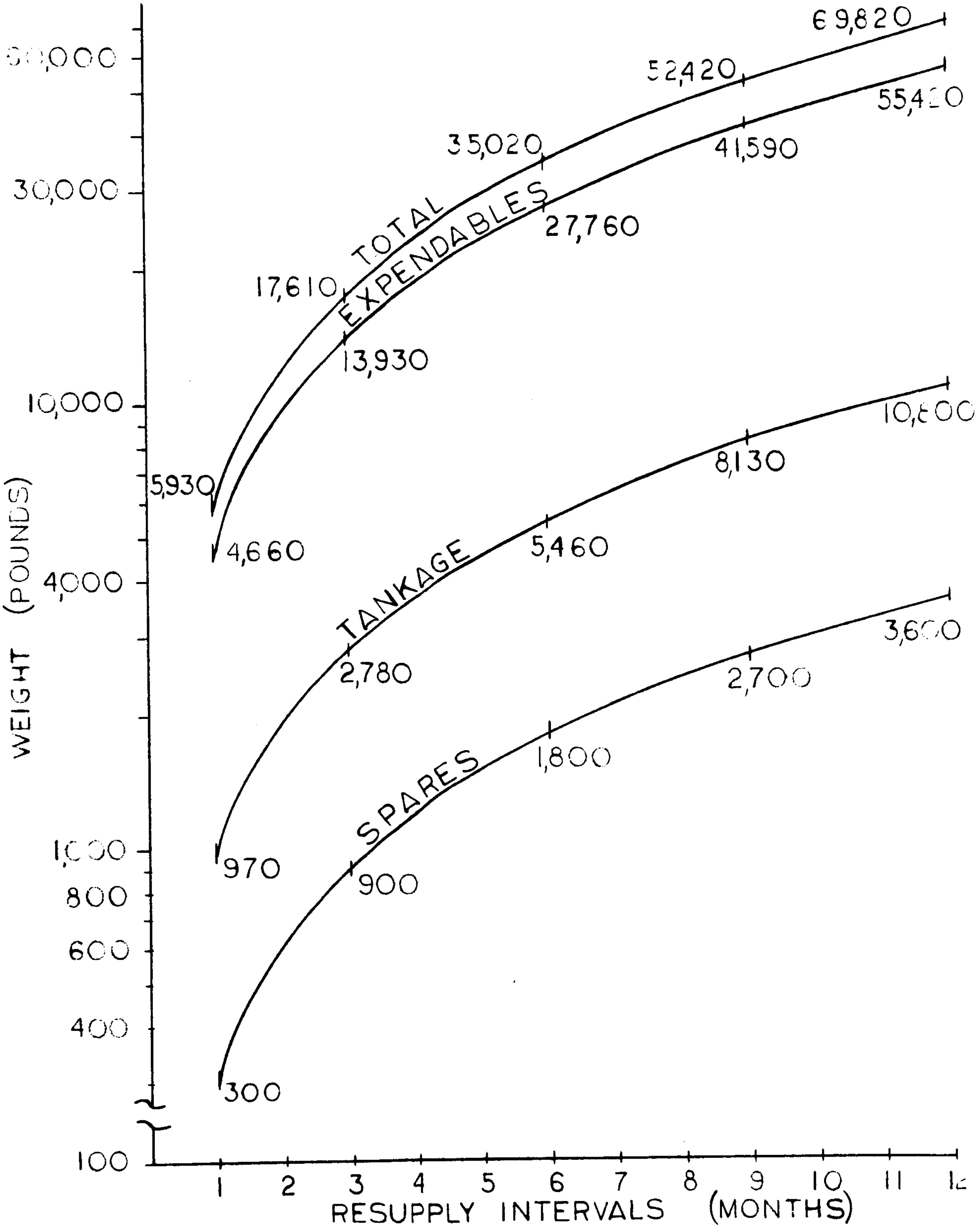
The water tank required for plss recharge water is assumed to be 10 percent of the liquid weight

$$\left(\frac{\text{lb of tank}}{\text{lb of water}} = .10\right).$$



9 MAN SPACE STATION
RESUPPLY REQUIREMENTS

FIGURE 4.1



<u>24 MAN SPACE STATION</u>
<u>RESUPPLY REQUIREMENTS</u>

FIGURE 4.2

Table 4.3 shows the estimated weight of the expendable items for 9 and 24 man crews by month for oxygen, nitrogen, plss water, plss LiOH, food, EC/LSS expendables such as desiccant gel, filter materials, etc., and RCS propellant.

WEIGHT - SPARE COMPONENTS 9 AND 24 MAN CREWS (ONE YEAR)

TABLE 4.1

SYSTEM/COMPONENT	9 MAN	24 MAN
Electrical Power	(2000)	(2600)
Batteries	1200	1800
AC Inverter	240	240
Battery Charger Components	350	350
Control & Display Actuators & Inductors	210	210
Data Storage	(600)	(600)
Digital Recorders	200	200
Video Bandwidth Recorders	120	120
Wide Bandwidth Analog Recorders	200	200
Portable Recording System	80	80
RCS		
Thrusters, Valves, Etc.	(130)	(130)
EC/LSS		
Valves, Regulators, Fans	(200)	(200)
Instrumentation	(70)	(70)
Displays & Controls	50	50
Timers	20	20
TOTAL	3000	3600
POUNDS/MONTH	250	300

WEIGHT - TANKAGE 9 AND 24 MAN CREWS

TABLE 4.2

COMPONENT	MEN	MONTHS											
		1	2	3	4	5	6	7	8	9	10	11	12
Oxygen	9	115	177	266	355	443	532	620	709	798	886	975	1050
	24	195	390	585	780	975	1170	1365	1560	1755	1950	2145	2340
Nitrogen	9	293	540	764	986	1207	1429	1649	1869	2089	2309	2529	2749
	24	293	540	764	986	1207	1429	1649	1869	2089	2309	2529	2749
Reaction Control Propellant	9	431	863	1294	1725	2156	2588	3019	3450	3881	4313	4744	5175
	24	450	900	1350	1800	2250	2700	3150	3600	4050	4500	4950	5400
Plss Water	9	10	20	30	40	50	60	70	80	90	100	110	120
	24	26	52	78	104	130	156	182	208	234	260	286	312
TOTAL	9	849	1600	2354	3106	3856	4609	5358	6108	6858	7608	8358	9094
	24	964	1882	2777	3670	4562	5455	6346	7237	8128	9019	9910	10801

WEIGHT - EXPENDABLES 9 AND 24 MAN CREWS

RESUPPLY IN POUNDS/MONTH

TABLE 4.3

	9 Man	24 Man
Oxygen	650	1500
Nitrogen	400	400
Plss Water	100	260
Plss LiOH	50	120
EC/LSS	35	90
RCS Propellant	625	650
Food	600	1590
TOTAL	2460	4610

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 5.0

CREW OPERATIONS AND TRAINING

FLIGHT CREW OPERATIONS DIRECTORATE

MANNED SPACECRAFT CENTER

5.0 CREW OPERATIONS AND TRAINING

Sufficient space station data is not currently available to allow definitive analysis of the operations and training requirements. The following sections, however, do provide some basic philosophy and rationale from which further studies can be conducted once data is available.

5.1 SPACE STATION CREW OPERATIONS

Space station operations are characterized by long duration, cruise type flight in which the vehicle operates quasi independently of the earth while being sustained through a logistics system. For such operations, the space station onboard crew activities can be classified into three areas irrespective of the mission objectives being flown. These are:

a. Command and control

b. Systems management

c. Technical projects

Operations requirements for the space station system will be defined by a task and resource allocation procedure such as that shown in Figure 5.1. The degree of operative specialization required will be dependent upon the magnitude of functions assigned to the station as well as the degree to which the station configuration permits physical centralization of the operations. In the latter, for example, zero gravity concepts such as the MORL allow close coupling and direct communications with the crewmen performing the tasks, whereas in the three radial module concept there are four distinct and separate internal work areas and, therefore, nearly four separate operating groups. The skills required of the crew will be determined to a large extent by the configuration and orbital state of the space station.

The command and control functions include station management, communications handling between the station and earth and/or the logistics spacecraft. These functions also may encompass medical activities associated with crew well being, diet and environmental atmosphere control.

System management is a support activity to both the command and control and the technical projects area. Functionally, it may be concerned with systems monitoring and control, and the work associated with inspections, maintenance, service, and repair. It may also involve activity associated with logistics and the transfer from and/or to the logistics spacecraft of cargo and supplies.

STUDY METHODOLOGY

FUNCTIONAL ANALYSIS

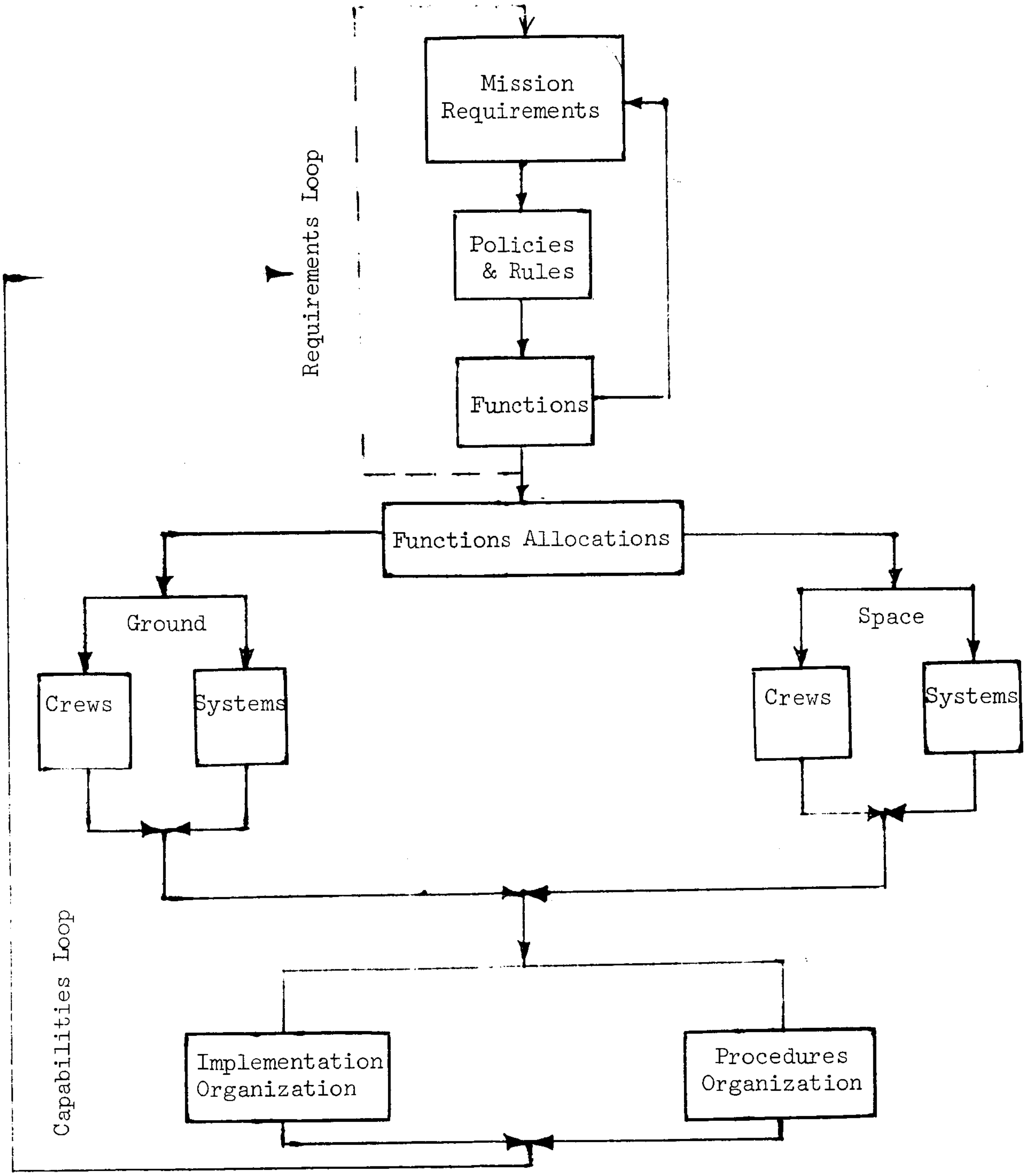


Figure 5.1

The technical projects area involves the setup, programming, and performance of inflight experiments and the acquisition, formatting and reporting of information and data. Crewmen in this area may participate in system management or command functions or may draw from those same areas to supplement their requirements.

Initial space station in-orbit activation and/or reconfiguration requirements would suggest emphasis on activities in the command and systems management functions. Once the station is established or restored to the operational state, the technical programs function becomes pre-eminent in operations.

One of the factors involved in the assignment of functions will be a tradeoff between the apportionment of tasks between onboard crewman and systems and the nature of the logistics payload. An important factor in the functional assignment is the price of the function to be performed in terms of where the best capability exists. Another consideration is the degree of control that can be exerted at the activity location. It is preferred that continuous control be maintained thereby permitting the activity to be performed in an orderly manner. For example, no activity should be undertaken at the space station which could lead to an accident requiring a sudden response from the mission oriented ground support system; i.e., launch of a rescue operation.

These considerations then suggest several configuration design elements:

a. Long term structural life; therefore, no requirement for in-orbit structural repair activity.

b. Minimum refurbishing of the station to update its technological state.

c. Transfer of propellants not be made by EVA handling of flexible hose lines; rather through rigid piping built into the structure of the vehicles and connected at the time the vehicles, space station, and logistics spacecraft become docked.

Finally, space station operations planning must be restricted to the inherent capability existent at the point entered. Any enlargement of the operational capabilities can only be accomplished through real-time experimentation performed at the expense of technical projects time and resources.

5.2 CREW TRAINING

Space station operations represent an extension of experience gained from Apollo flights, i.e., operating two classes of cooperative spacecraft, one of which is a reentry type vehicle, simultaneously and quasi independently of the manned space flight network. In such instant, the crew training experience and simulation equipment developed in Apollo will, in the main, form the basis for configuring the training needs for space station work.

The unique features of the space station are the long duration operations and the requirement to sustain this vehicle through crew rotation, consumable, expendable, and equipment transport using logistics spacecraft. The frequency of logistic spacecraft launches and the character of the payload will be dictated in part by mission requirements and the orbital status of the space station. The rate and the urgency of response to the operational needs of the space station will directly impact the training schedules and facility requirements.

Crew training for the space station system will encompass three specific areas: logistics spacecraft piloting operations, space station management, and technical projects. The former, involving transport type spacecraft flights, will more closely follow current Apollo earth orbital training philosophy and will use the Apollo Mission Simulator or some derivative thereof.

Space station management embraces the functions of command, control, navigation, communications, and system management. These functions are somewhat akin to Apollo crew station operations. However, because of the greater size and number of functions being performed on board, the degree of operative specialization will be dependent upon the mission configuration and the associated operational modes.

The technical projects area will require specific mission payload systems training involving part task trainers coupled perhaps to the mission simulators. To what extent participants will undergo pilot training needs to be identified but in any event, this group will undergo general space station systems and survival training including centrifuge and perhaps space environment simulation facility indoctrination.

The problem of accommodating to an artificial gravity environment is critical to operations of this class space station since no experience to date has been obtained in orbit to verify the simulations performed on earth.

Similarly, decisions bearing on whether the logistics spacecraft can dock while the artificial gravity station is rotating regardless of whether the docking interface is or not stationary will need to be made. Such decisions can be worked out in advance using simulation equipment developed from Gemini translation and docking trainer technology.

Space station systems maintenance needs to be restricted to first level operations, i.e., service, calibrating. Operations involving cutting, burning, etc. involve hazards for which no training will be scheduled. Space station extra vehicular activity at this time should be restricted to inspection and minor equipment deployment activities. The suitability of existent Apollo equipment to meet the training requirement will need to be investigated.

PRELIMINARY TECHNICAL DATA
FOR EARTH ORBITING SPACE STATION

VOLUME II

STANDARDS AND CRITERIA

SECTION 6.0

ENVIRONMENT

SPACE SCIENCE DIVISION

ENGINEERING AND DEVELOPMENT DIRECTORATE

MANNED SPACECRAFT CENTER

6.0 ENVIRONMENT CRITERIA

The following sections describe the models and assemptions made in specifying the meteoroid and radiation environments for the earth orbiting space station. The meteoroid flux model for a nominal Mars mission is also provided.

6.1 METEOROID PROTECTION

Meteoroid protective shielding requirements are determined for a synchronous orbit space station having an area-time exposure of the order of 10^4 ft^2-year. There are two factors modifying the omnidirectional meteoroid flux; the proximity to earth causes a reduction in flux by shielding; however, the earth also causes an increase of flux due to gravitational effects on meteoroid radiants. A near-earth satellite (at a 260 nautical mile altitude) is exposed to 68 percent of the omnidirectional flux and the synchronous space station to 78 percent of the flux. The shielding was determined for the synchronous station (that has the greater hazard) rather than for a near-earth space station.

The near-earth meteoroid flux, including meteoroid showers and corrected for gravitational concentration, is shown in Figure 6.1 and given as

$$N = 10^{-3.83}\ m^{-1.34} \qquad (\text{for } m \geq 10^{-2}) \qquad (1a)$$

and

$$N = 10^{-3.15}\ m^{-1} \qquad (\text{for } m < 10^{-2}) \qquad (1b)$$

where N is the flux per 10^4 ft^2-year of meteoroids of mass greater than or equal to m grams. An average velocity of 30 km/sec and mass density of 0.5 gm/cm^3 is used in determining the meteoroid shielding requirements.

The aluminum shielding S (lbs/ft^2) to prevent penetration of an impacting mass m (grams) is

$$S = 41.51\ K\ m^{0.352} + C_K \qquad (2)$$

For multiwall or bumper configurations the structural efficiency factor K is defined as the ratio of the total thickness of the number of sheets required to prevent penetration to the theoretical single sheet thickness. For a double wall of two inch spacing and without any filler, $K = 1/5$ and $C_K = 0$. For the same wall spacing with a filler material (low density open-celled foam) the factor is $K = 1/7$ and $C_K = .225$ to represent the added weight of the filler material.

Figure 6.2 is a graph of the required shielding as a function of area-time exposure for a K factor of 1/7.

METEOROID FLUX MODEL

(AVERAGE SPORADIC PLUS AVERAGE STREAM)

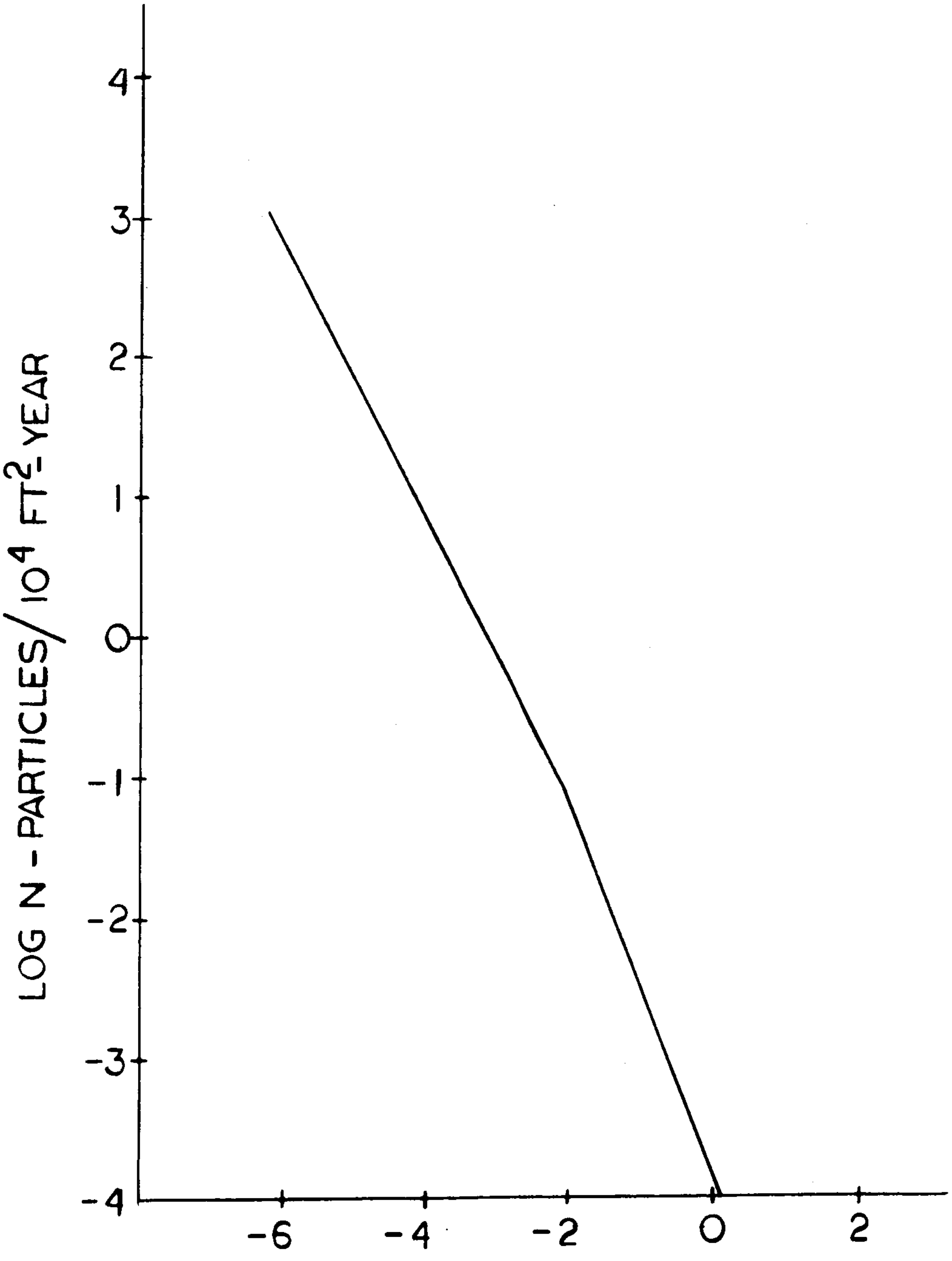


FIGURE 6.1

METEOROID SHIELDING WEIGHT

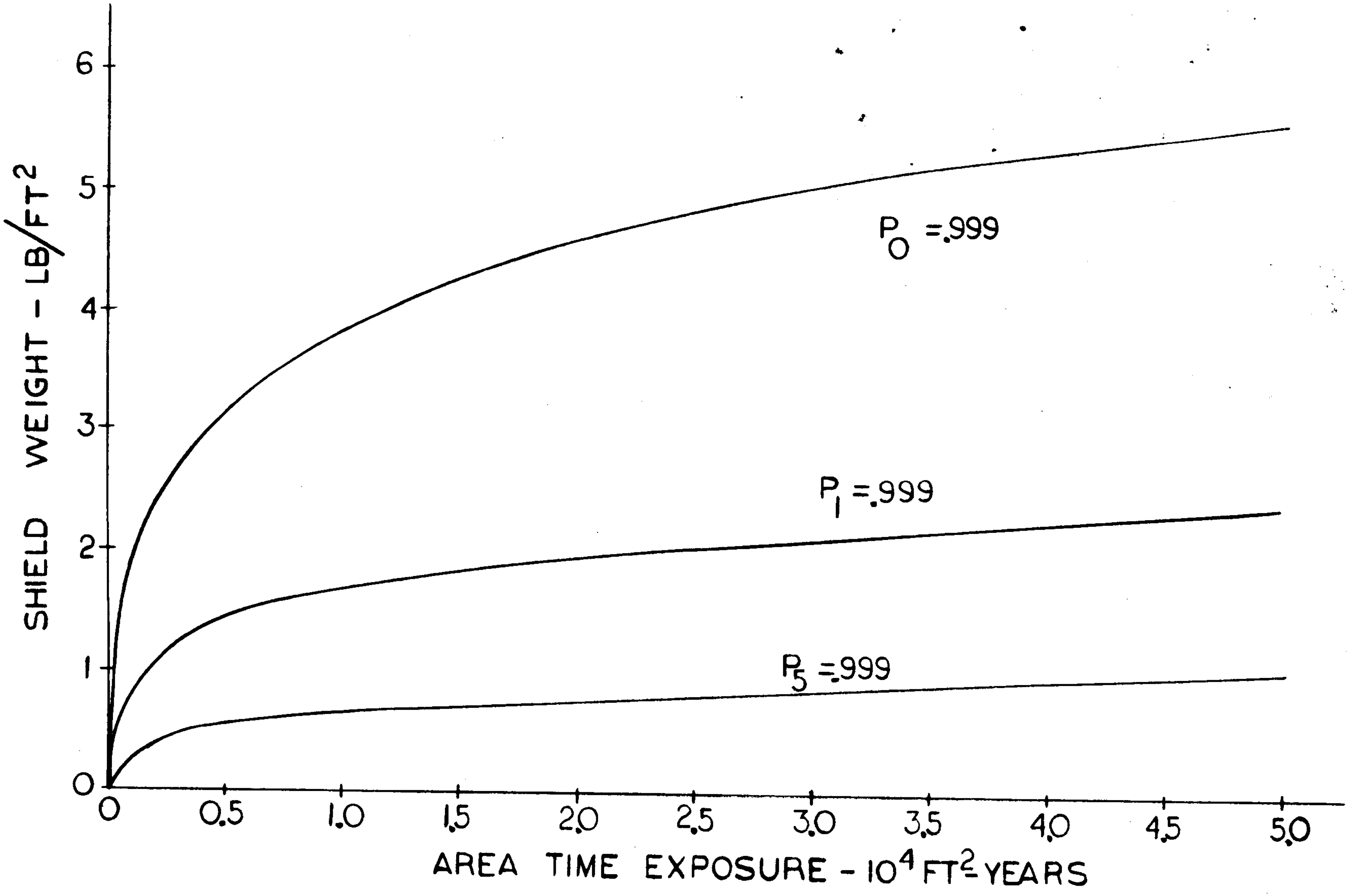


FIGURE 6.2

Meteoroid diameters corresponding to the particle design mass for 5×10^4 ft^2-year exposure are:

$P_n = .999$	diameter in centimeters
P_o	1.45
P_1	0.62
P_5	0.22

These values are determined using a mass density of 0.5 gm/cm^3.

6.1.1 DAMAGE CRITERION

The damage criterion implied by the use of equation 2 is no spallation off the inner surface of the second sheet of a double wall structure. This means that the damage sustained by the rear sheet will amount to a ring of partial penetrations with a central concentration of small craters on the outer surface with corresponding incipient spall bubbles on the inner surface. The diameter of the damage circle is a function of the spacing between the sheets but the magnitude of the damage is not if there is no foam or other filler. A probability of no penetration of 0.999 means that there is one chance in a thousand of encountering a meteoroid larger than the threshold size; a design based on a probability of no more than one penetration of 0.999 means a one in a thousand chance of encountering two meteoroids larger than the threshold. The penetrating meteoroid will be a little larger than the threshold size and the resulting hazard to men or equipment behind the second sheet amounts to fine-grain impacts and localized burns due to the detached spall. A more energetic penetration and resulting greater hazard is increasingly less possible as may be seen from the curve in Figure 6.3. The threshold masses corresponding to $P_o = .999$, $P \leq 1 = .999$, and $P \leq 5 = .999$ are indicated and it is apparent that the probability of encountering a mass double that of the threshold value is lower, e.g. for $P \leq 5 = .999$ the threshold mass is 10^{-3} grams and the corresponding encounter probability, 0.49 or a chance of one in two; the encounter probability for a mass of 2×10^{-3} grams is 0.32 or one chance in three. It is also apparent that a structure designed for no more than five penetrations runs the risk of a penetration by a mass much larger than the threshold with the corresponding greater hazard to the occupants, e.g. the chance of being penetrated by a mass approximately eight times larger than the threshold is only one in ten. This is not true of the design based on no more than one penetration which has a inherent low probability of encounter, approximately two in a hundred.

6.1.2 COMPARISON OF METEOROID ENVIRONMENTS FOR SPACE STATION AND MARS MISSION

The meteoroid environment for a Mars mission is appreciably different from the meteoroid environment of earth. The

PROBABILITY OF ENCOUNTER FOR THRESHOLD MASS

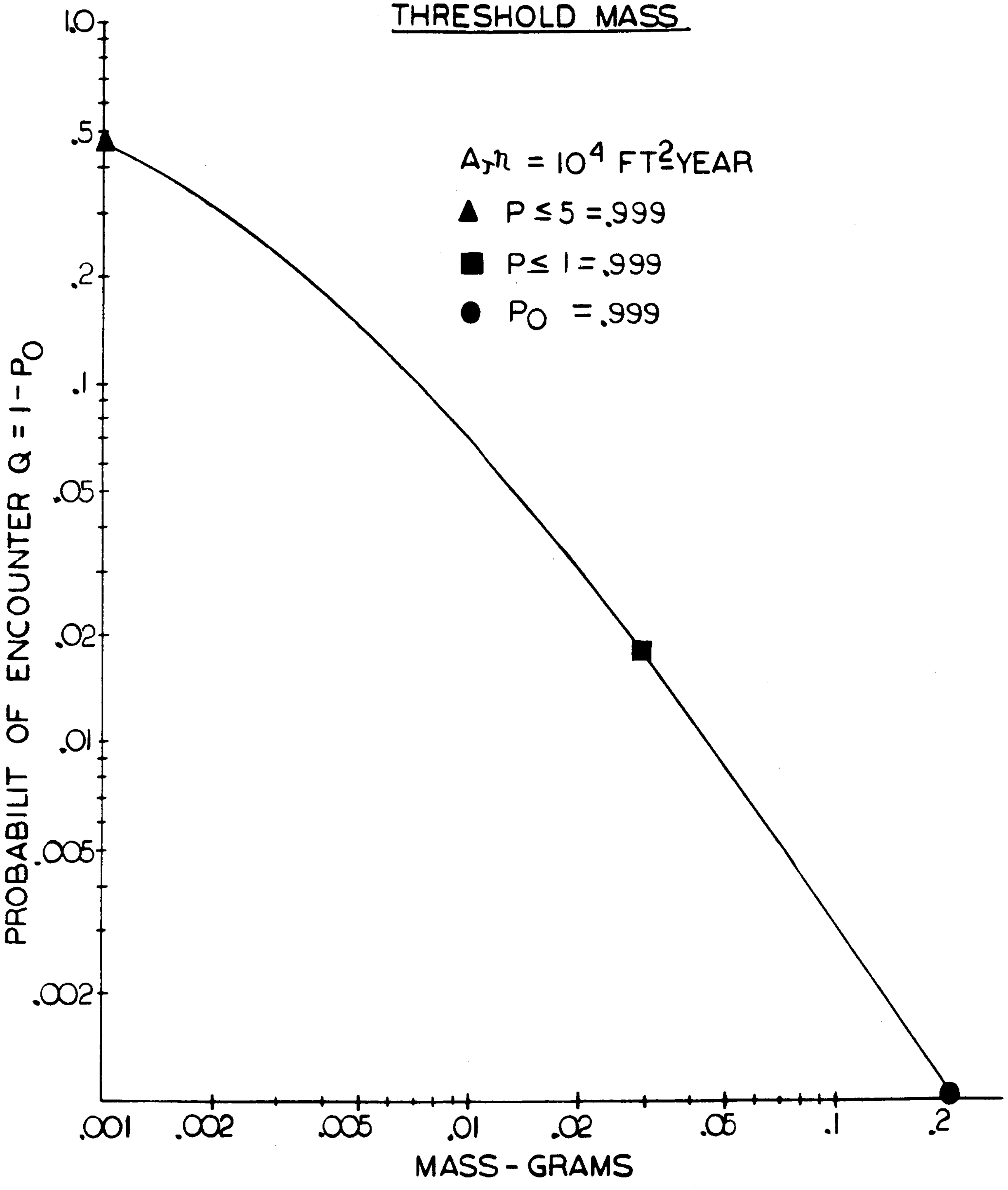


FIGURE 6.3

contribution of the asteroidal belt results in an increase of meteoroid mass density and particulate flux with A.U. (astronomical unit) as illustrated in Figure 6.4. The flux is defined by the following equation:

$$\log N = -13.62 + 3.0\ R - \log m$$

where N is the flux per ft^2-day for meteoroids of mass greater than or equal to m grams; R is the distance from the sun, either 1.5 or 2.2 A.U. The density of the meteoroids is 3.5 gm/cm^3 and the average meteoroid velocity is 15 km/sec at 1.5 A.U. and 10 km/sec at 2.2 A.U.

6.2 RADIATION ENVIRONMENT

The radiation environment to be encountered by an orbiting space station consists of galactic cosmic rays, particles trapped in the earth's magnetic field, and solar flare particle events. This radiation environment will contribute biologically damaging radiation dose to the space station crew following attenuation of these radiations by the vehicle's mass. This chapter will attempt to define the nature of the constituants of the radiation environment, the geographic space in which they apply, and the radiation doses that the environment is likely to produce.

6.2.1 ENVIRONMENT DEFINITION

6.2.1.1 GALACTIC COSMIC RAYS

Galactic cosmic rays are energetic positive ions, mostly protons, which constantly bombard the solar system. In deep space the fluxes of cosmic rays are relatively constant except during periods of enhanced solar activity when they have been observed to decrease. Near the earth the cosmic rays are influenced by the earth's magnetic field and show a spatial dependence. However, due to the relatively low dosages resulting from exposure, these dispersions need not be considered in detail. The near earth cosmic ray dose equals about 4.5 RAD/year and is about twice this in interplanetary space.*

6.2.1.2 TRAPPED PARTICLE RADIATION

The earth's magnetic field is populated with trapped protons and electrons from the top of the atmosphere to the boundary of the magnetosphere. The more energetic, and therefore more penetrating, of these particles are most intense in two radiation belts about the earth's equator extending in latitude to about ± 60°.

---

*Wright H. Langham, "Some Radiation Problems of Space Conquest," Astronautik 2 (1961).

INTERPLANETARY METEOROID MODEL

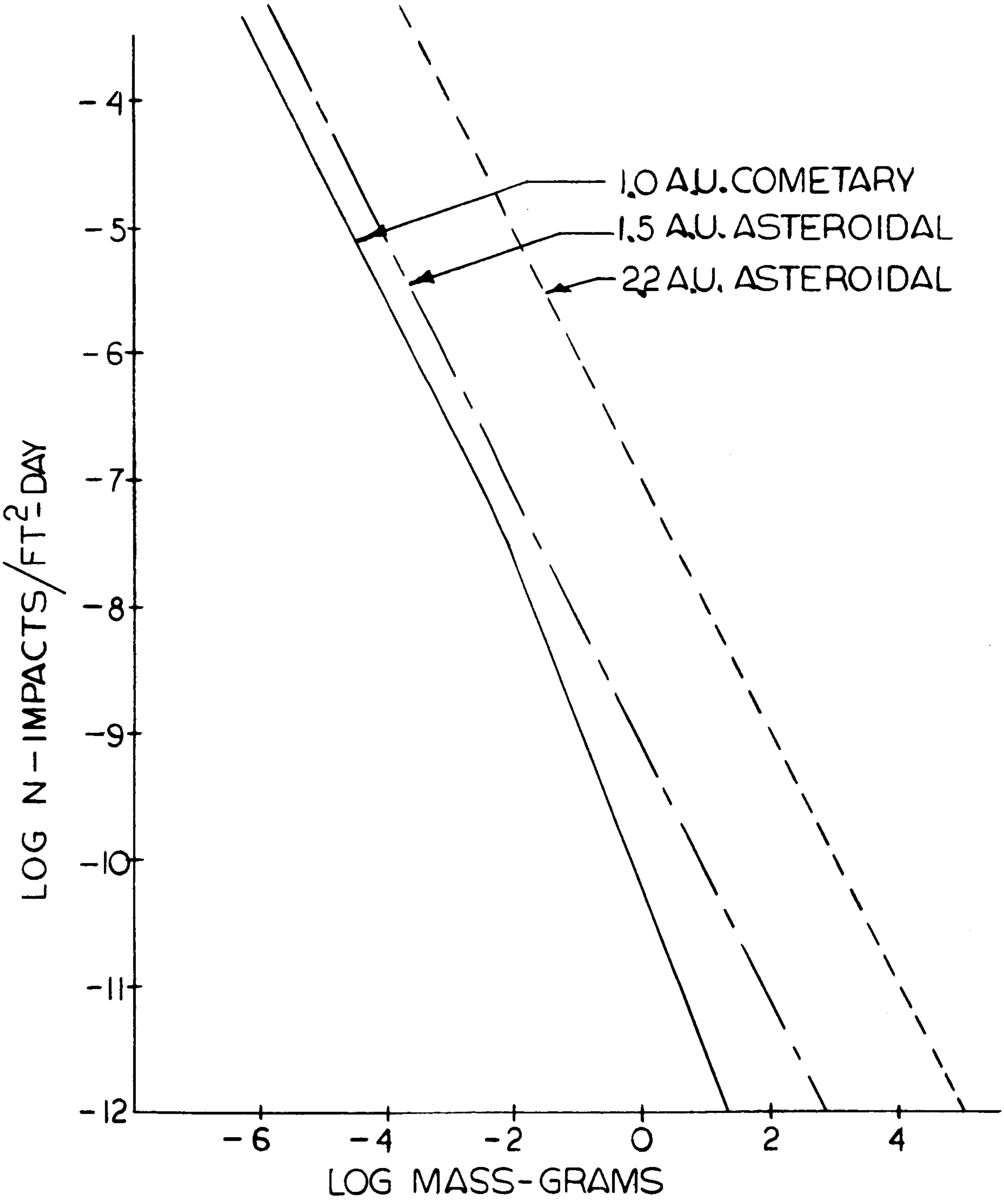


FIGURE 6.4

Figure 6.5 shows the distribution of trapped electrons of energies greater than 0.5 million electron volts (Mev) as a function of geomagnetic space. Many of the electrons were artificially injected into the magnetic field by high-altitude nuclear tests (particularly "Starfish", July 1962) and have since decayed out. What remains seems to be the natural electron component. This component is relatively stable with time in the inner belt. The outer belt ($r \geq 3$ Earth Radii) exhibits large variations with local time, geomagnetic storms, solar cycle, and perhaps other causes. In this region flux levels must be associated with a probability of encounter.

Figure 6.6 shows the spacial distribution of magnetically trapped protons of energies greater than 15 Mev. This flux region is approximately the same as the electron inner belt. As can be seen in this figure, the high energy protons do not extend into the outer belt.

The trapped particle environment used in the estimation of the radiation doses for the space station missions was prepared by Dr. James Vette, et al, of the Aerospace Corporation and has been published by NASA in SP-3024, volumes 1 and 2.

6.2.1.3 SOLAR FLARE PARTICLE EVENTS

Solar flare particle events consist of energetic protons and alpha particles from the sun, propagating through a large region of interplanetary space. Solar flare particle events originate from disturbed regions on the surface of the sun. These disturbed regions display sunspots, prominences, plages and solar flares and contain intense local magnetic fields. The magnetic fields are thought to provide the great energy needed to accelerate the particles.

In the last solar cycle (19th) there were about 57 solar flare particle events of significance measured on earth. These events were distributed such that all but three occurred in the upper six years of the solar cycle (1956-1961).

Solar particle events will contribute significant radiation dose to all of space in the earth-moon system except that portion shown in Figure 6.7. This region is such that particle events detected in the last solar cycle would not have contributed significant radiation dose to the crew of a moderately shielded space station. Exterior to this zone and interior to the boundary of the earth's magnetosphere (Figure 6.8) the dose from solar flare particle events will be reduced from the level received in interplanetary space by influence of the earth's magnetic field. However, this dose reduction cannot be generalized and must be considered as a specific case for individual missions.

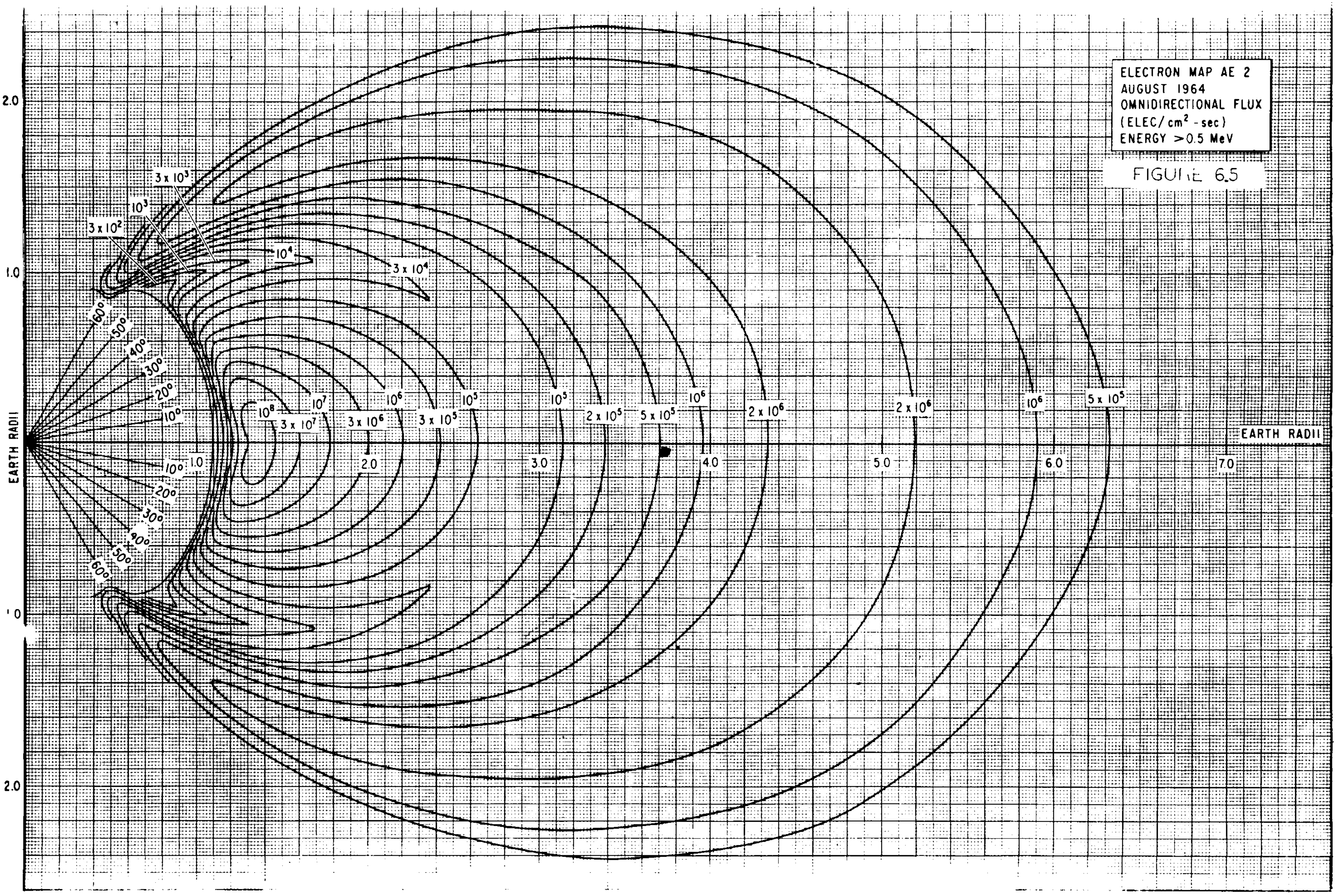


FIGURE 6.5

ELECTRON MAP AE 2
AUGUST 1964
OMNIDIRECTIONAL FLUX
(ELEC/cm² - sec)
ENERGY >0.5 MeV
EARTH RADII
EARTH RADII
2.0
1.0
1.0
2.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
10°
20°
30°
40°
50°
60°
10°
20°
30°
40°
50°
60°
3 x 10³
10³
3 x 10²
10⁴
3 x 10⁴
10⁸
3 x 10⁷
10⁷
3 x 10⁶
10⁶
3 x 10⁵
10⁵
10⁵
2 x 10⁵
5 x 10⁵
10⁶
2 x 10⁶
2 x 10⁶
10⁶
5 x 10⁵

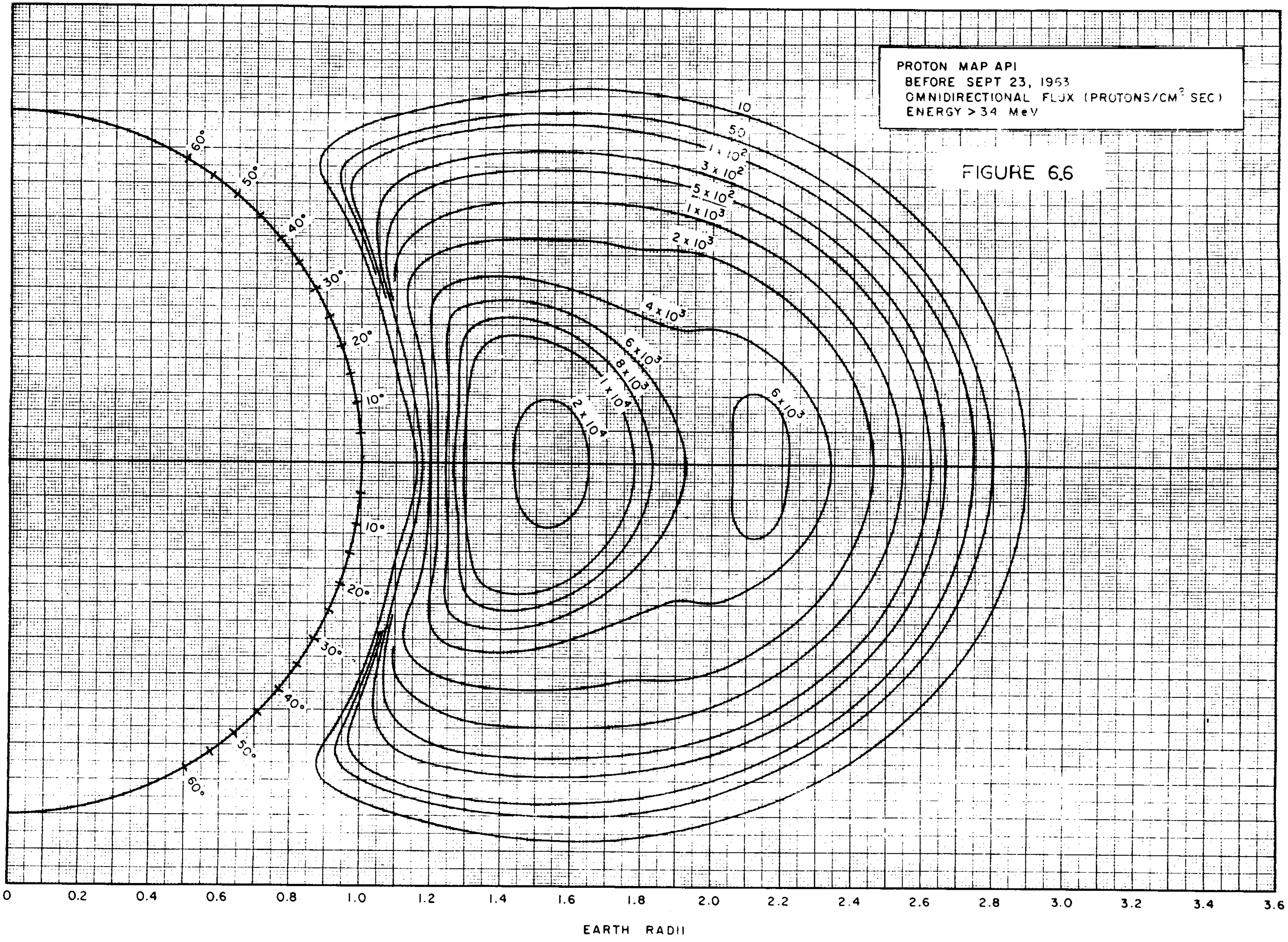
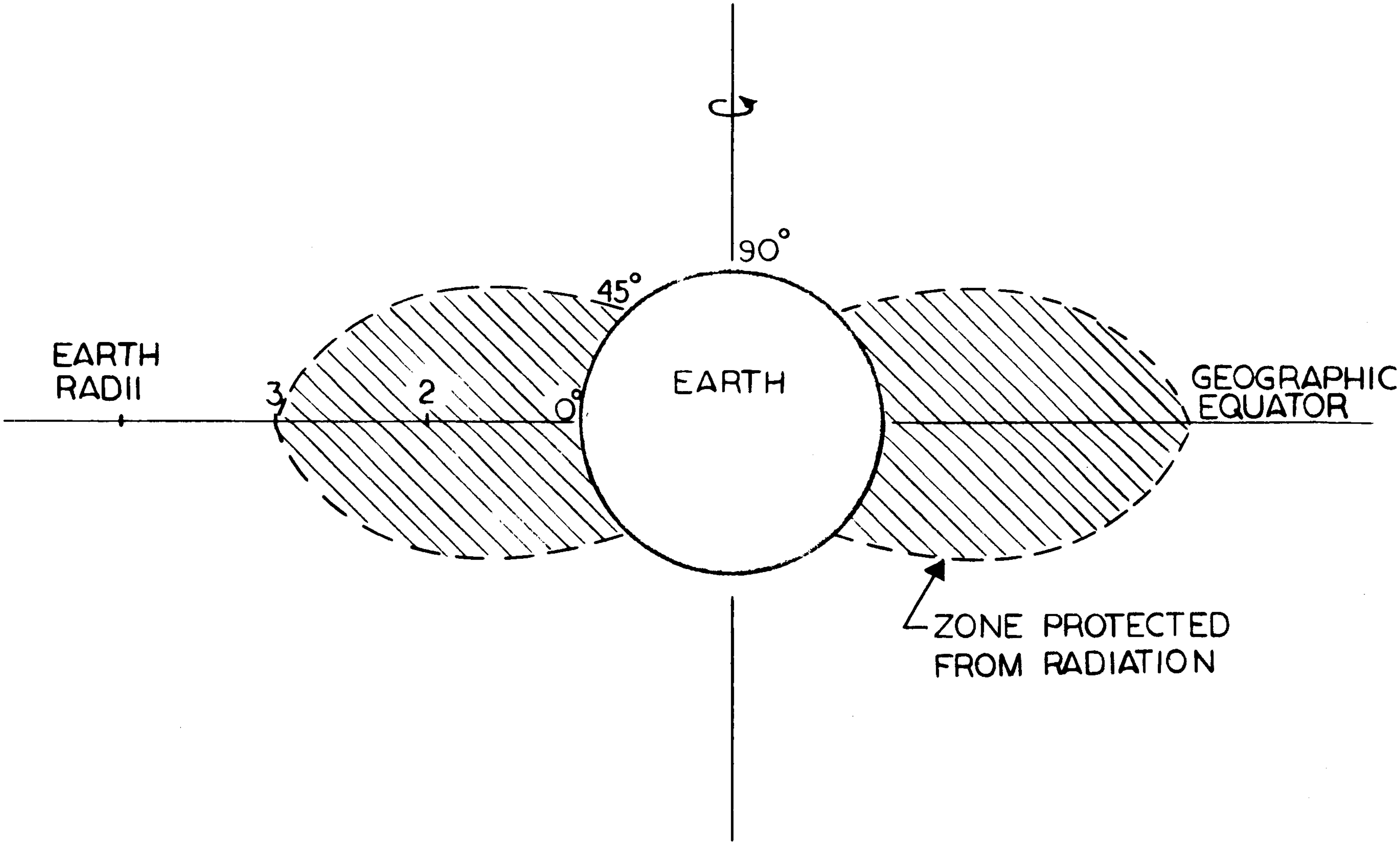


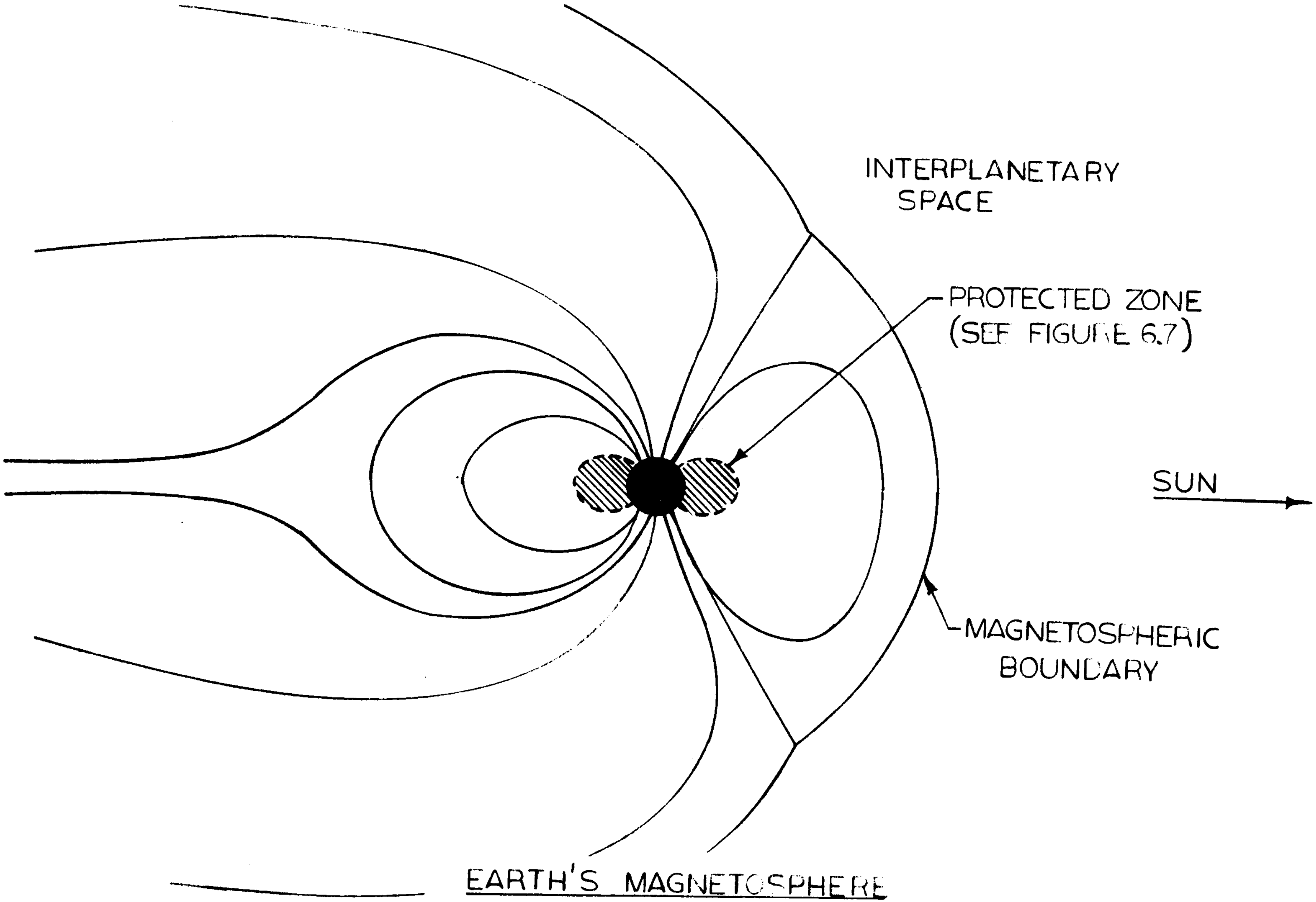
FIGURE 6.6

PROTON MAP API
BEFORE SEPT 23, 1963
OMNIDIRECTIONAL FLUX (PROTONS/CM² SEC)
ENERGY > 34 MeV
10
50
1 x 10²
3 x 10²
5 x 10²
1 x 10³
2 x 10³
4 x 10³
6 x 10³
8 x 10³
1 x 10⁴
2 x 10⁴
6 x 10³
60°
50°
40°
30°
20°
10°
10°
20°
30°
40°
50°
60°
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
EARTH RADII



ZONE PROTECTED FROM RADIATION
DUE TO SOLAR FLARE PARTICLE EVENTS

FIGURE 6.7



EARTH'S MAGNETOSPHERE

FIGURE 6.8

The spatial description of the effectiveness of solar particle events presented was derived from the theory of the interaction of charged particles with a diapole magnetic field.

6.2.2 DOSE ESTIMATES FOR PROPOSED SPACE STATION MISSIONS

6.2.2.1 GALACTIC COSMIC RAYS

Near-Earth Orbit	4.5 RAD/year
Interplanetary Space	9.0 RAD/year

6.2.2.2 TRAPPED RADIATION BELTS - NEAR EARTH ORBIT

Orbital integrations have been performed by Vette for circular orbits for 24 hour periods for the projected 1968 trapped particle environment. For example, in a 300 nautical mile circular orbit the fluxes encountered per day are shown as

	(Orbital Inclination) 0°	30°	60°	90°
$\frac{\text{Electrons}}{\text{cm}^2/\text{day}} > 0.5$ Mev	$2.67 \cdot 10^5$	$1.69 \cdot 10^9$	$4.71 \cdot 10^9$	$4.67 \cdot 10^9$
$\frac{\text{Protons}}{\text{cm}^2/\text{day}} > 30$ Mev	$7.01 \cdot 10^4$	$4.12 \cdot 10^6$	$2.81 \cdot 10^6$	$2.23 \cdot 10^6$

In the estimation of dose a uniformly shielded spherical space station was assumed having various wall thicknesses. Doses were calculated to the chest (skin dose) of a crew member at the center of the spherical shield. Consideration was given to the self-shielding of the man in attenuating the radiation. Orbital integrations were used giving flux and spectra for the near earth orbits. The flux and spectra were converted to dose as a function of shield thickness for various mission lengths. The results are shown in Figure 6.9.

6.2.2.3 TRAPPED RADIATION BELTS - SYNCHRONOUS ORBIT

The synchronous orbit trapped radiation dose contribution was determined through an analysis of the fluctuations of the outer radiation belts. The data taken at near-synchronous altitudes by Expl. 6, 12, 14, 15 ORS-III, IMP-A, OGO-A were analyzed by Vette and a flux as a function of probability of encounter relationship established. Figure 6.10 shows this relationship for synchronous orbit.

From the fluxes and spectrum established in Figure 6.10, the radiation dose resulting may be calculated as a function of shield thickness. These skin doses are shown in Figure 6.11 for the average environment.

SHIELD WEIGHT VS RADIATION DOSE

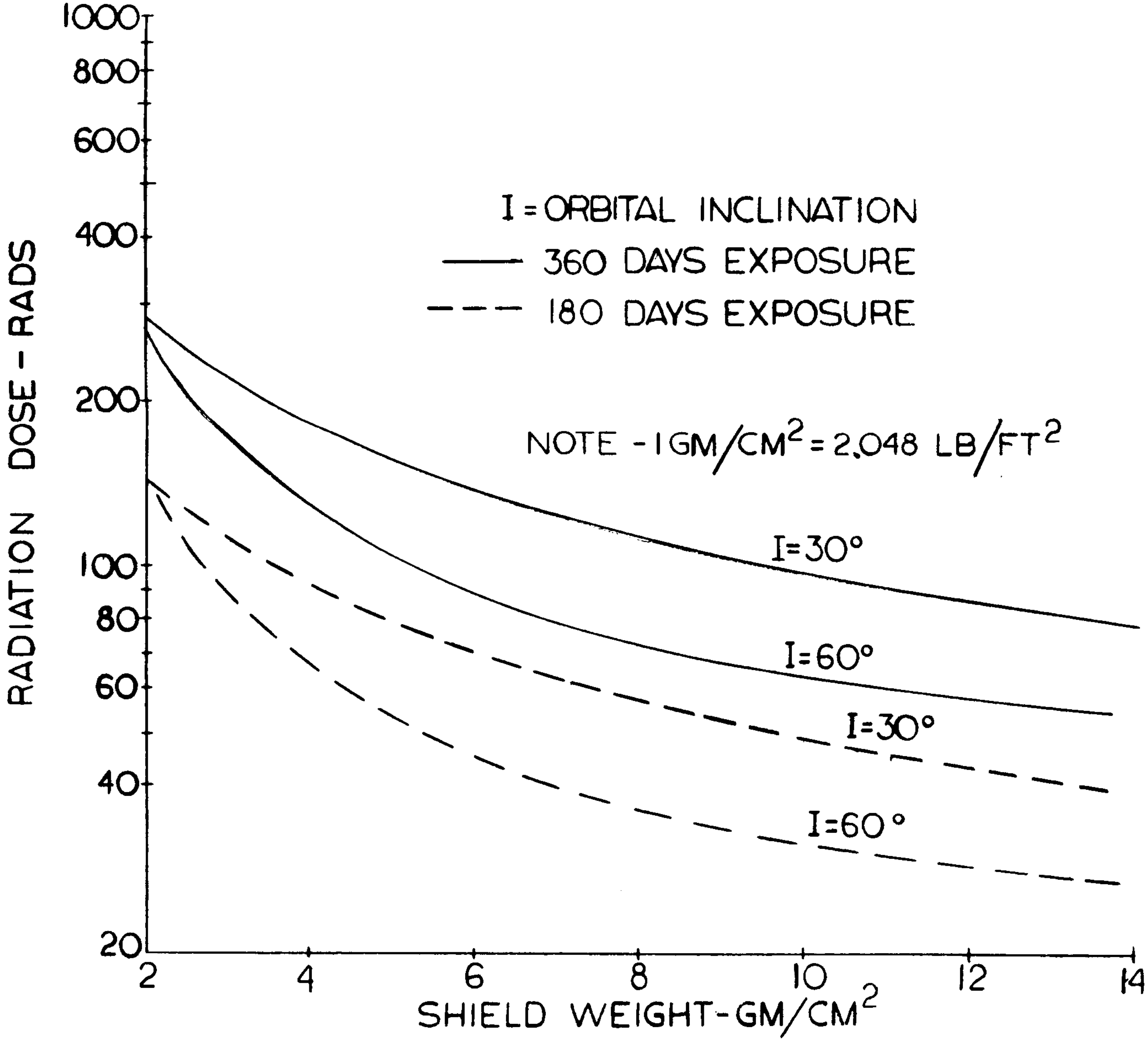
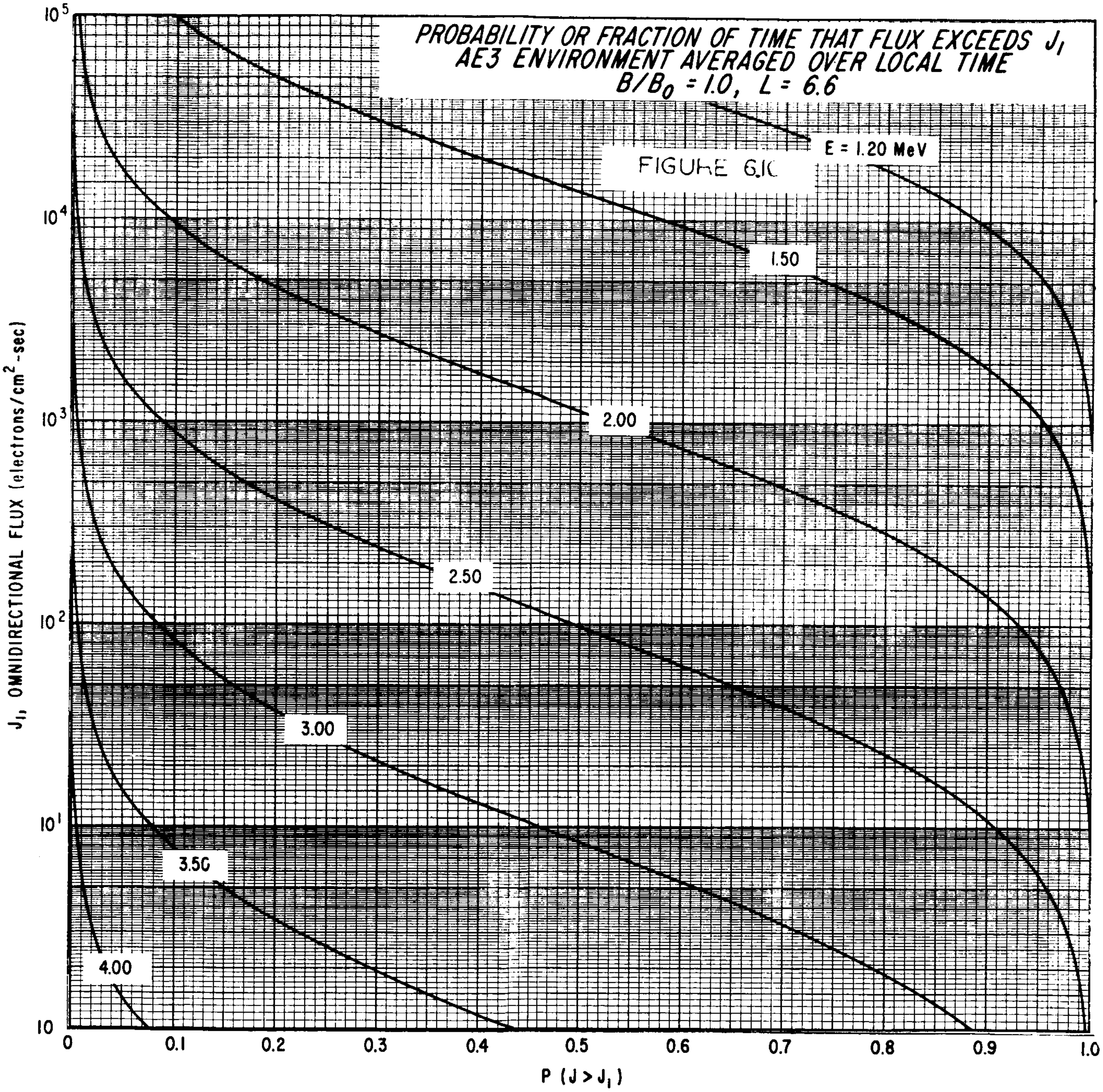
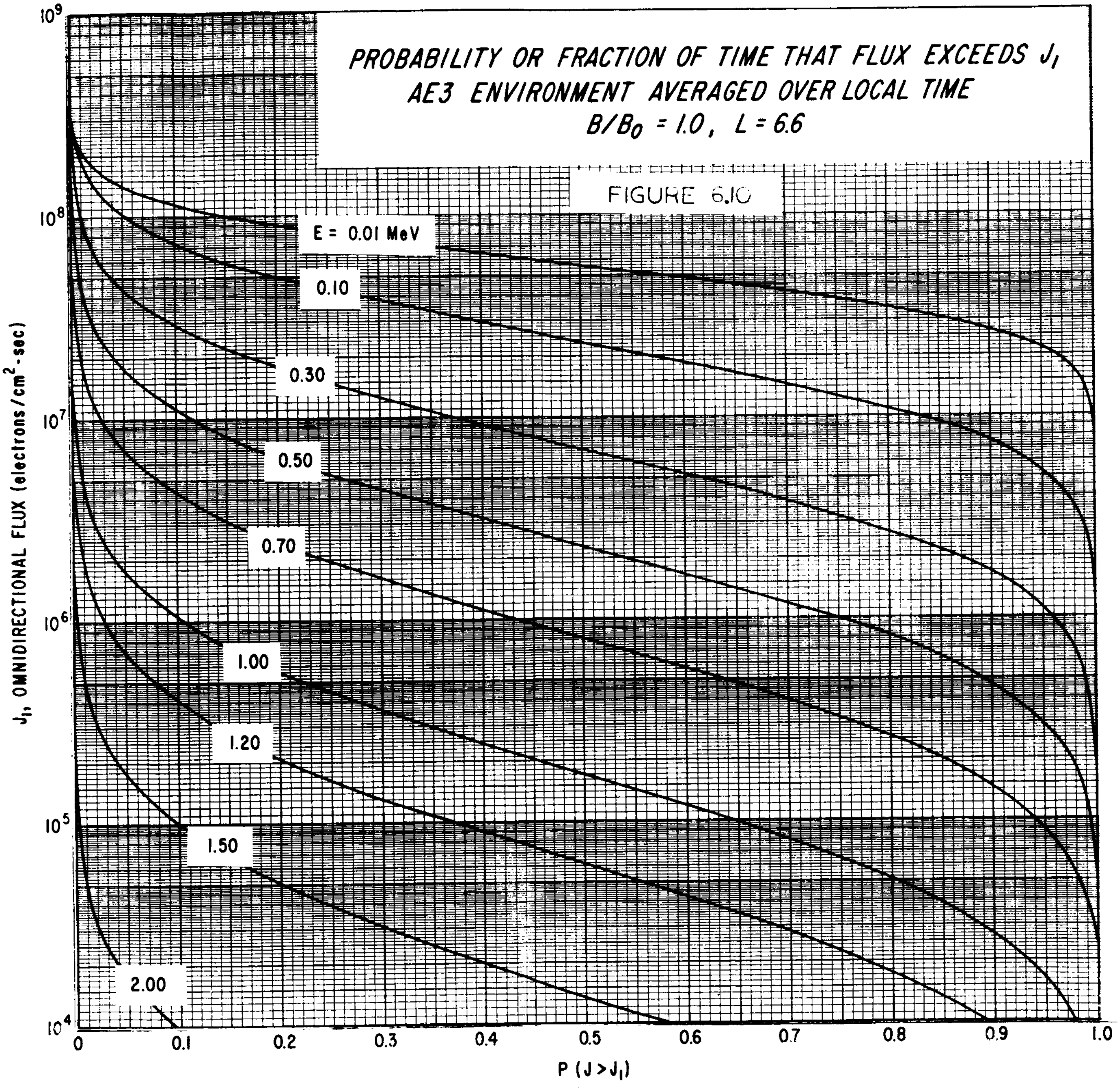


FIGURE 6.9



PROBABILITY OR FRACTION OF TIME THAT FLUX EXCEEDS J_1
AE3 ENVIRONMENT AVERAGED OVER LOCAL TIME
$B/B_0 = 1.0$, $L = 6.6$

FIGURE 6.10



PROBABILITY OR FRACTION OF TIME THAT FLUX EXCEEDS J_1
AE3 ENVIRONMENT AVERAGED OVER LOCAL TIME
$B/B_0 = 1.0$, $L = 6.6$

FIGURE 6.10

SYNCHRONOUS ORBIT DOSE FROM TRAPPED ELECTRONS

ONE YEAR MISSION, AVERAGE DOSE

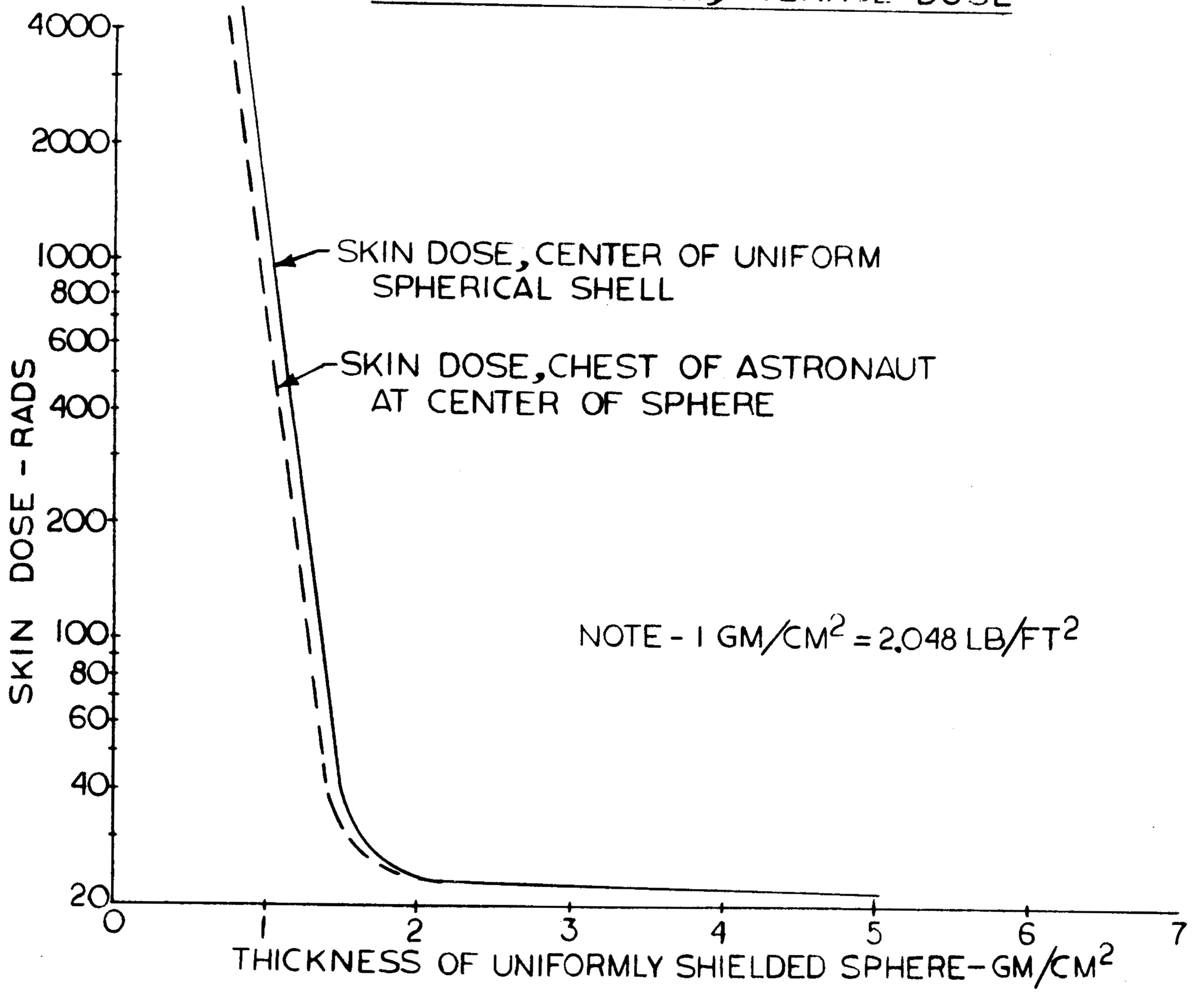


FIGURE 6.11

As shown in Figure 6.11 the skin dose produced by the primary electrons falls off rapidly with increasing shield thickness. The secondary radiation produced (bremsstrahlung) remains at a relatively low but slowly decreasing level.

The doses corresponding to the 1 percent or .1 percent design cases have not yet been determined. In order to establish these doses, a further analysis of the synchronous orbit data is required. Such studies have been begun at MSC and elsewhere and the results should become available next spring.

6.2.2.4 INTERPLANETARY SOLAR PARTICLE EVENT ENVIRONMENT

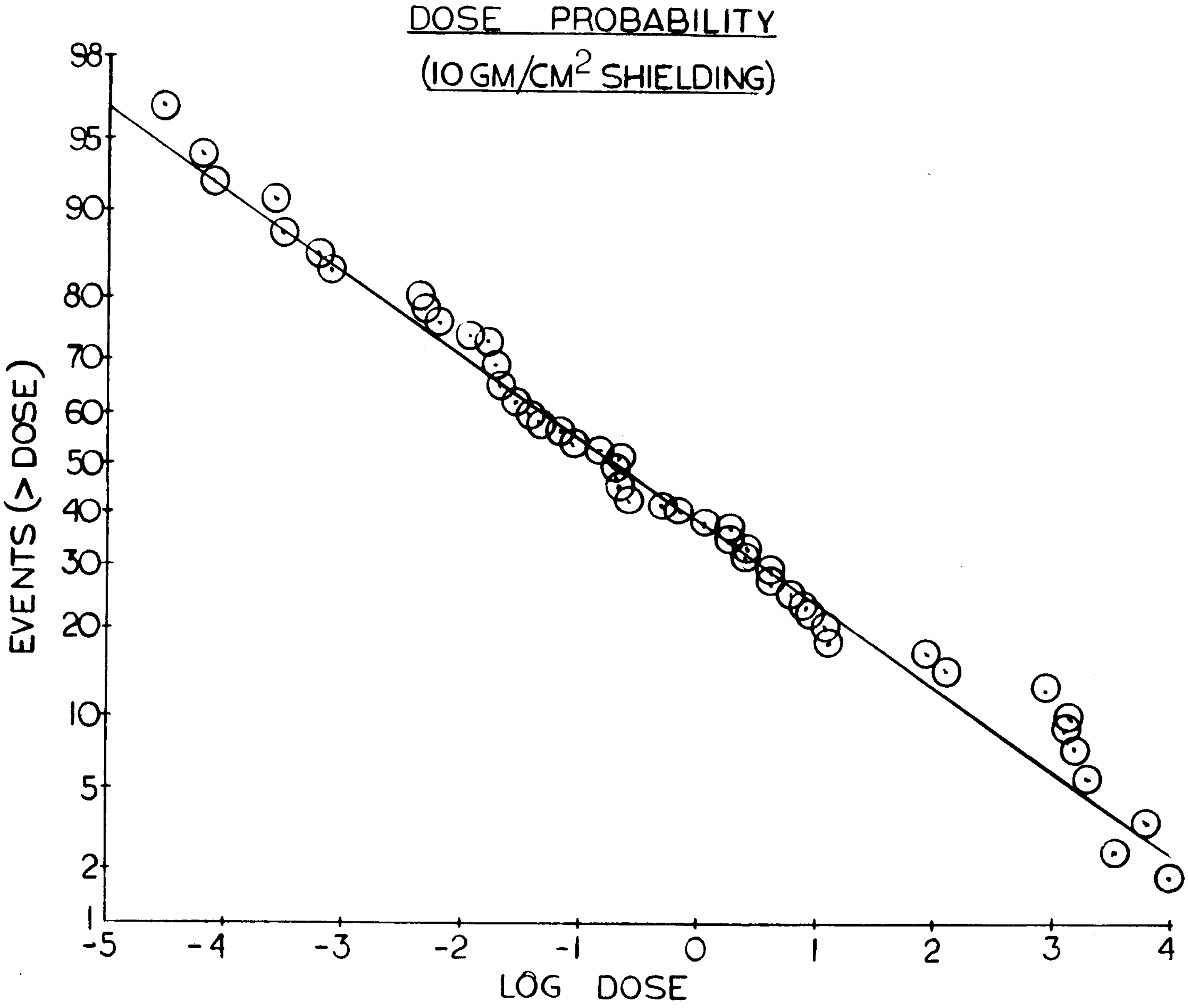
A statistical evaluation of solar particle events over the last eleven year solar activity cycle has been made by Snyder at MSC to determine the probability of receiving significant radiation doses behind various shield thicknesses.

During the six year period of maximum activity (1956-1961) 54 solar particle events were measured on earth. Only three events occurred during the remaining 5 year period of minimum solar activity. These frequencies (9/year for solar maximum, 0.6/year for solar minimum) were assumed to be an average for future solar cycles. In order to determine variations from the average a binomial probability distribution was assumed such that the mean of the distribution coincided with the average frequency.

Radiation doses for each event measured during the last cycle were calculated behind various shield thicknesses. These doses were ranked from smallest to largest and were discovered to follow a log-normal probability distribution. Figure 6.12 shows an example of this log-normal distribution.

A random sampling procedure was employed to select arbitrarily the number of events and a corresponding dose to be encountered on a given mission. Thousands of hypothetical missions were considered in the calculations so that all combinations of frequency and magnitude of dose would be calculated. This procedure was then repeated for a series of typical spacecraft shield thickness. The results of mission doses were ranked and distributed. These figures were also found to be distributed normally, allowing the determination of mission dose for any desired probability of encounter. Figure 6.13 shows these results at solar maximum, Figure 6.14 at solar minimum.

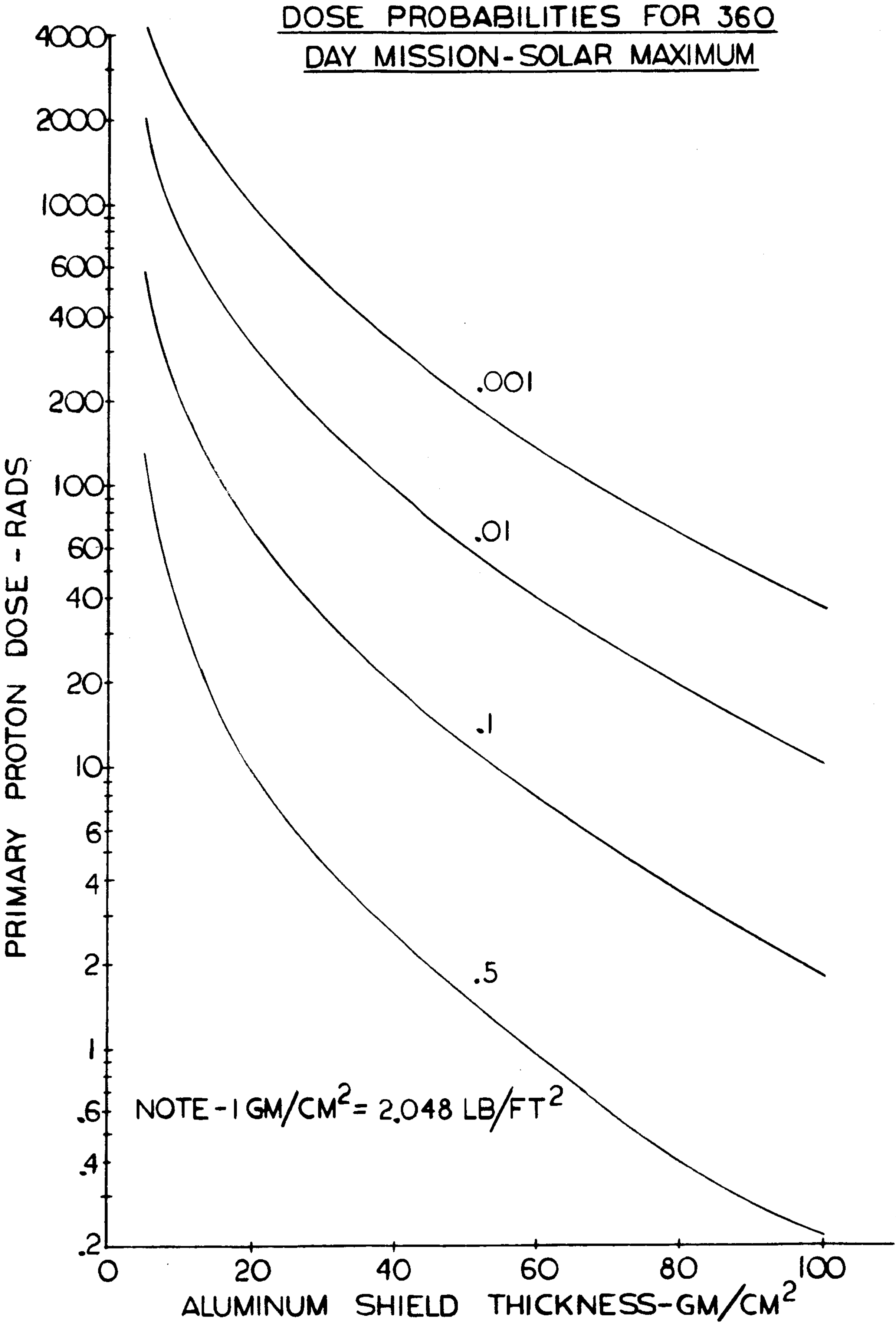
This evaluation takes into account all available information on solar flare particle events. Such events were undiscovered before the last solar activity cycle. The analysis also allows for the possibility that the last solar cycle did not produce the largest solar event possible. The later seems reasonable since the events of the last solar cycle constitute only a minute fraction of the total events produced by the sun since its creation.



DOSE PROBABILITY

(10 GM/CM^2 SHIELDING)

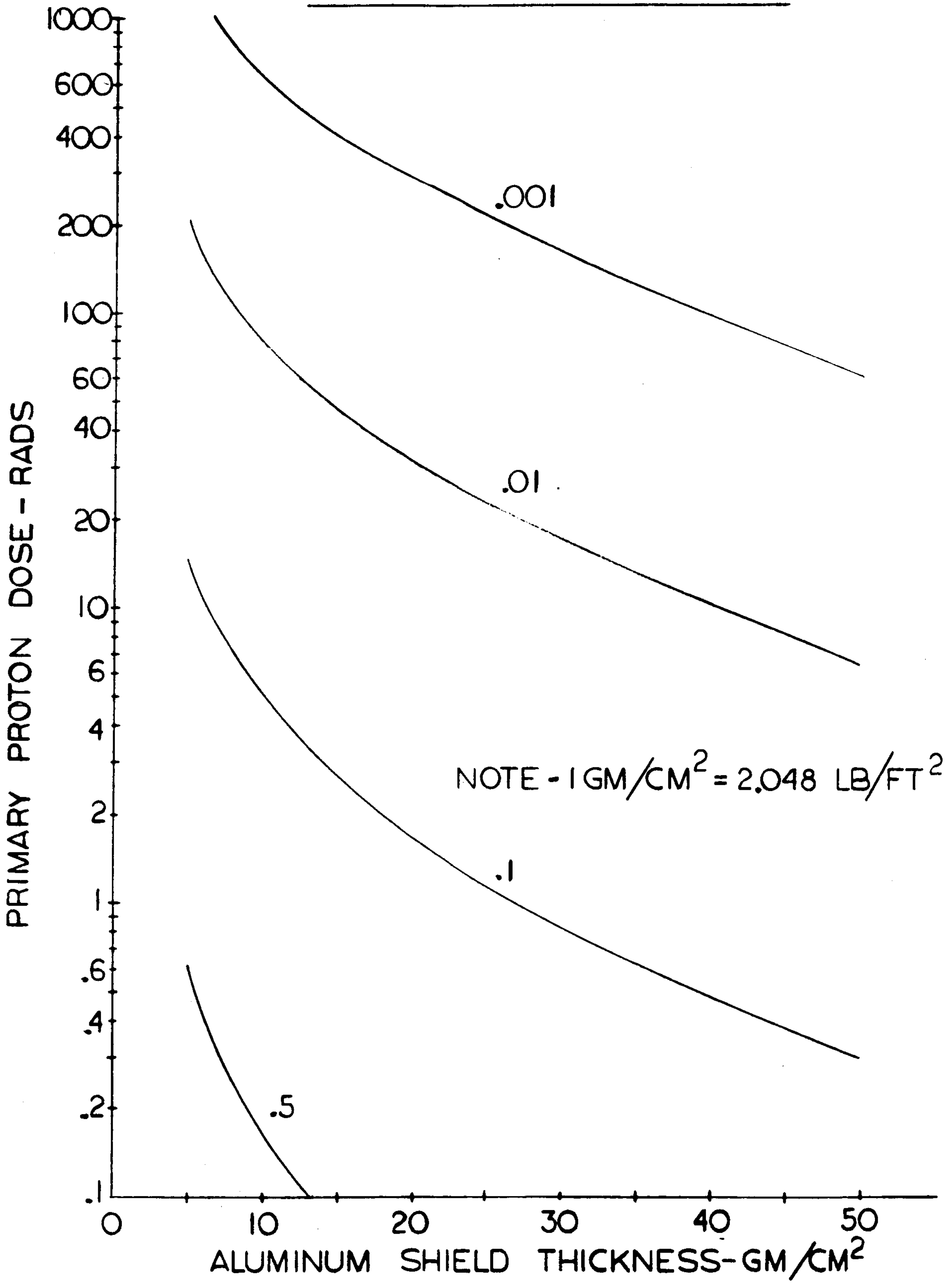
FIGURE 6.12



DOSE PROBABILITIES FOR 360 DAY MISSION-SOLAR MAXIMUM

NOTE-1 GM/CM^2 = 2.048 LB/FT^2

FIGURE 6.13



DOSE PROBABILITIES FOR 360 DAY MISSION-SOLAR MINIMUM

NOTE - 1 GM/CM^2 = 2.048 LB/FT^2

FIGURE 6.14

6.2.3 SPACE STATION APPLICATION

6.2.3.1 NEAR EARTH ORBITS

Solar particle events will not contribute significant radiation dose for space station orbits $\leq$500 n.m. with inclinations less than 60°. For higher inclinations, portions of the orbit will be exposed. A circular polar orbit will be exposed to solar particle events over 1/3 of the trajectory. As a first approximation of the dose encountered,the interplanetary dose curves should be used reduced by a factor of 6 (a factor of 3 reduction due to exposure reduction and a factor of 2 resuction due to earth shadow and self-shielding). The dose curves as a function of spherical shield thickness with the appropriate corrections for polar orbit are shown in Figure 6.15 for the 1 percent probability of encounter.

6.2.3.2 SYNCHRONOUS ORBIT

The radiation dose due to encounters with solar particle events was treated as a special case. Within the boundary of the earth's magnetosphere solar particle event protons and alphas are deflected by the magnetic field. This deflection is a result of the Lorentz force tending to bend the path of the particle in a direction perpendicular to both of the particle's instantaneous motion and the local direction of the magnetic field. The particles may be deflected in such a manner that they cannot penetrate into synchronous altitudes; or for those that do penetrate, they may only do so for a preferred direction. Since the same argument applies to all points of space exterior to the protected zone of Figure 6.8; each must be considered separately.

A detailed calculation was made of radiation dose encountered at synchronous orbit from a large solar flare particle event. The particle energy as a function of degree of directionality was considered. Figure 6.16 shows a comparison of the normalized dose versus thickness received at synchronous altitude with the dose versus thickness received in deep space. For space vehicles such as the Apollo Command Module the difference amounts to about a 20 percent reduction in dose. As seen from the figure, for much lighter vehicles such as the LEM the difference becomes significant.

6.2.4 CONCLUDING REMARKS

The physical radiation environment to be encountered by a space station in near-earth orbit is reasonably well known. At altitudes below 500 n.m. and inclinations less than 60° a moderately shielded space station mission should have little or no difficulty from natural space radiations. Experience from project

SHIELD WEIGHT VS RADIATION DOSE FOR POLAR ORBIT AND PROBABILITY = 0.01

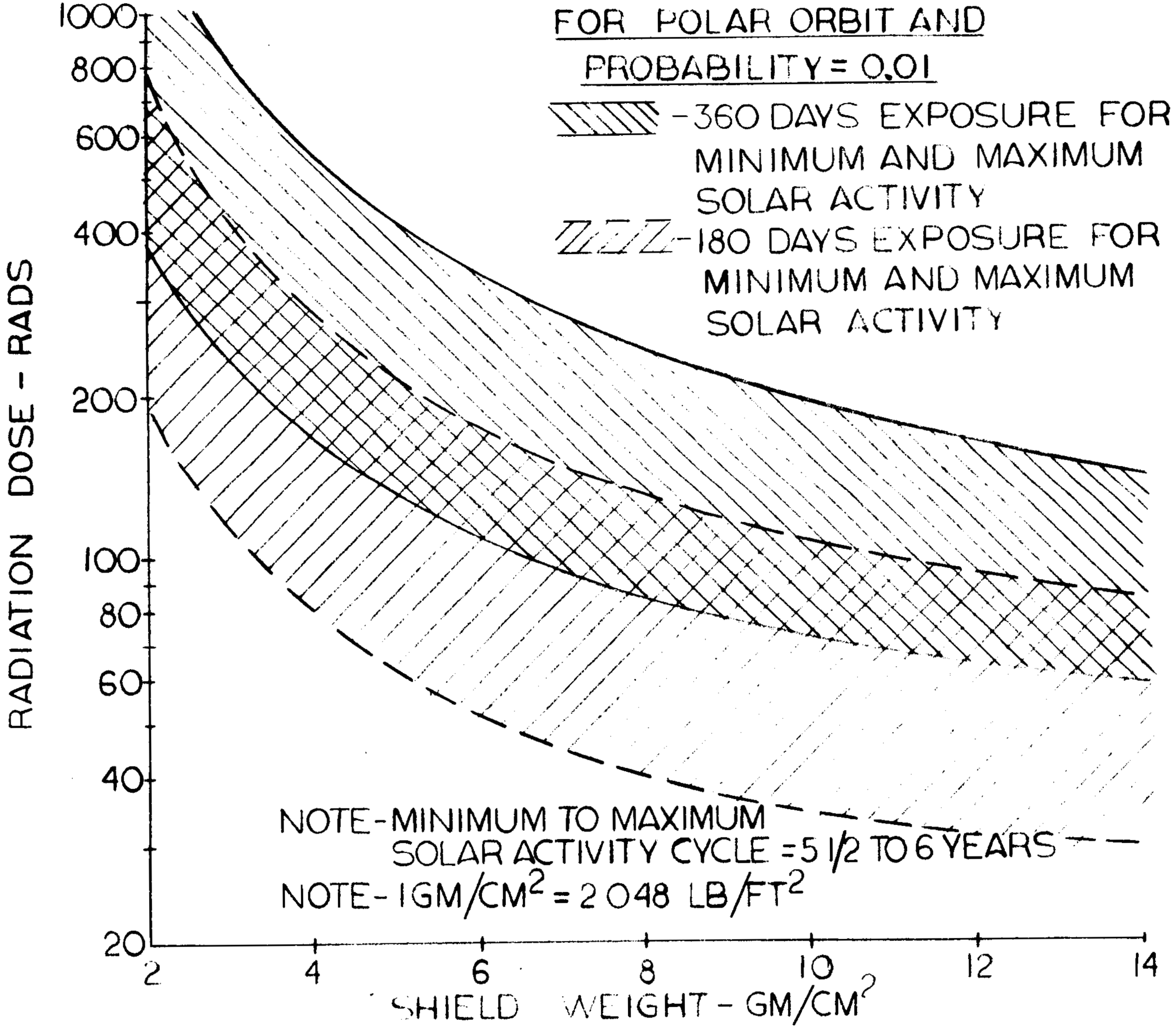
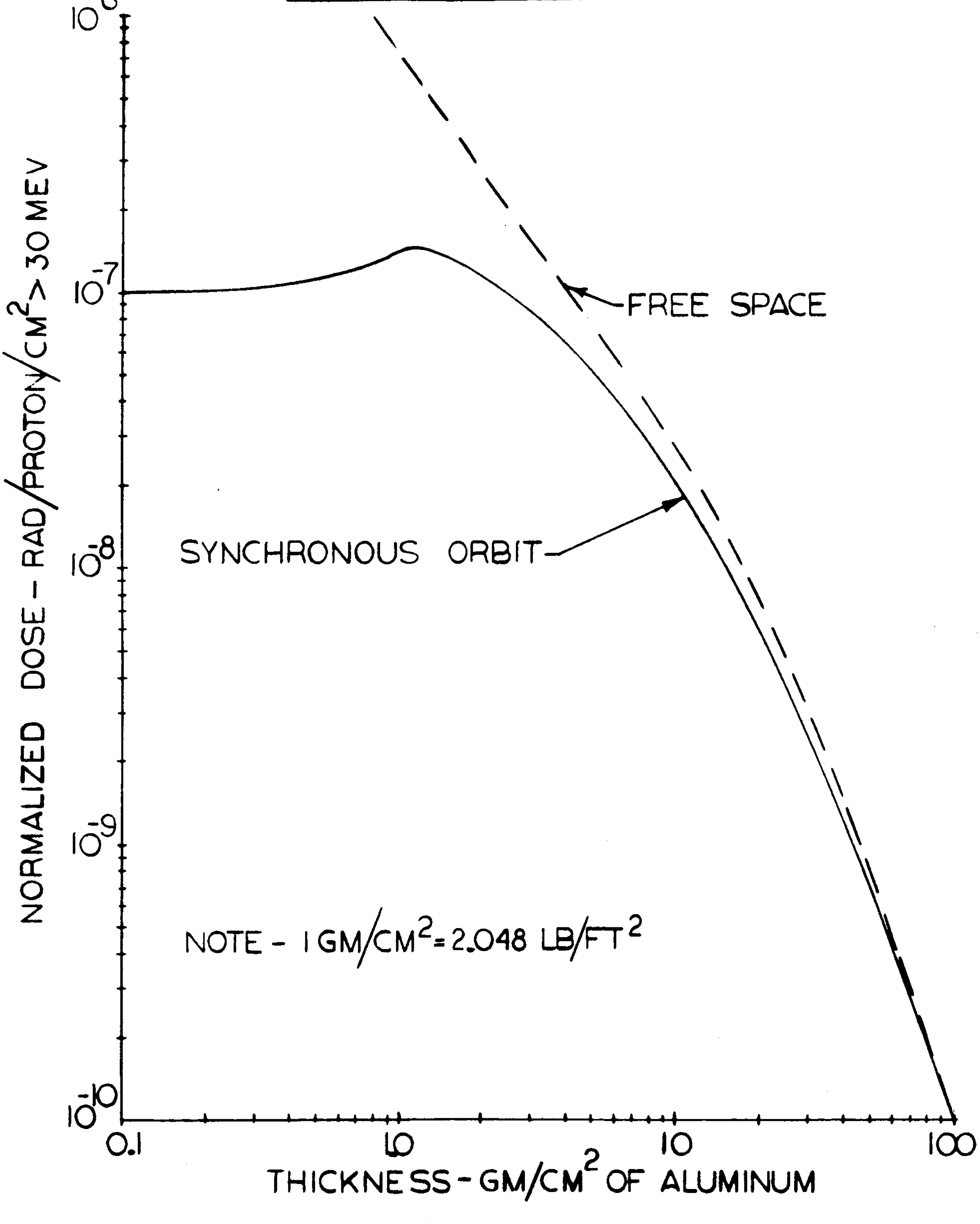


FIGURE 6.15

DOSE VS THICKNESS AT SYNCHRONOUS ORBIT FOR A LARGE SOLAR FLARE PARTICLE EVENT



NOTE - 1 GM/CM^2 = 2.048 LB/FT^2

FIGURE 6.16

Gemini has demonstrated this fact in operations at altitudes up to 750 n.m. At higher inclinations the effect of solar particle events must be considered. Such exposure can be quite severe, although the probability of encounter is small. Protection from these solar storms under these conditions is afforded by the earth's magnetic fields and its shadow shielding. In addition, a spacecraft operation of this type allows an abort if necessary bringing the crew rapidly back to the safety of the earth's atmosphere.

Farther out into magnetospheric space the radiations to be encountered become more difficult to define and to predict for a given space station mission. Trapped radiations are known to be less stable at several earth radii; and the effect of the earth's magnetic fields on solar particles is difficult to determine. Although these problems may turn out to be surmountable, much research and engineering development is yet to be done in this area.

At synchronous orbit the radiation environment seems to be dominated by that encountered in interplanetary space. The outer belt electrons can contribute very high doses, especially to a lightly shielded vehicle, such as LEM, but should not pose a severe problem to the proposed space station. Protection from solar particle events at this altitude is, however, almost nonexistant.