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International Space University Variable Gravity Research Facility Design

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A manned mission to Mars will require long travel times between Earth and Mars. However, exposure to long-duration zero gravity is known to be harmful to the human body. Some of the harmful effects are loss of heart and lung capacity, inability to stand upright, muscular weakness, and loss of bone calcium. A variable gravity research facility (VGRF) that will be placed in low Earth orbit (LEO) was designed by students of the International Space University 1989 Summer Session held in Strasbourg, France, to provide a testbed for conducting experiments in the life and physical sciences in preparation for a mission to Mars. This design exercise was unique because it addressed all aspects concerning a large space project. This report describes the VGRF design that was developed by international participants specializing in the following areas: the politics of international cooperation; engineering, architecture; in-space physiological, materials, and life science experimentation; data communications; and business and management.

Nomenclature

a = centripetal acceleration, g
g = Earth's gravity
I = moment of inertia, kg · m^2
r = radius of rotation, m
ω = rotation rate, rpm

Subscripts
x = x axis
z = z axis

Introduction

EXPOSURE to long-duration weightlessness (0-g) is known to be harmful to the human body. Some of the major problems are loss of heart and lung capacity, inability to stand upright, muscular atrophy, and loss of bone calcium.[1,2] This could result in the inability of space travelers to function effectively after a long-duration mission and still return safely to Earth.[3] On-orbit conditioning requirements to maintain physical fitness might dominate the majority of an astronaut's waking hours. Earth-bound medical treatment partially alleviates some of the problems but the countermeasures are not totally effective and free of side effects. In view of the renewed enthusiasm for a manned lunar base and human spaceflight to Mars, it is imperative that the debilitating effects of long-duration reduced-gravity exposure be minimized or counteracted. Creation of artificial gravity in a rotating centrifuge or spacecraft is one possible way to counteract the harmful effects of 0-g on the human body.[4] The gravity level, spin rate and duration compatible with human performance, and efficient engineering design must be determined before a long-duration mission to the moon or Mars can be undertaken.

The focus of this paper is to summarize the results of a study performed to design a variable gravity research facility (VGRF). A full treatment of technical details pertaining to all aspects of the VGRF can be found in Ref. 5.

The 1989 International Space University (ISU) convened July 1, 1989, in Strasbourg, France, at the Université Louis Pasteur. The student body was comprised of 125 students from 25 countries. For 10 weeks, they took courses in eight space disciplines (architecture, business and management, engineering, life science, policy and law, resources and manufacturing, satellite applications, and physical science) presented by an international faculty. Two design projects were conducted to promote interdisciplinary integration and interaction between students. The scope of each design project included mission objectives, engineering designs, management organization structure, project finances, program implementation, and system operations. The selected design projects for the 1989 ISU were a lunar polar orbiter (not described in this report) and a VGRF. The VGRF project was christened Newton. Members of the international faculty served as expert advisors, and additional support was provided by departmental assistants who were 1988 ISU alumni. A list of the students, departmental assistants, and ISU faculty involved with the Newton design project is provided in Table 1.[5]

The international nature of this project, encompassing all eight space-related disciplines just listed, led to a system design unrestricted by any one national space program. Recent VGRF design studies from the United States assume that all of the components will be launched on the U.S. Space Shuttle.[6-8] This restricts component size and system design, and potentially increases the number of launches needed for assembly since expendable launch vehicles (ELV) were not considered. Although the overall design and feasibility of the VGRF will no doubt receive its share of support and criticism, the entire project was a success on the basis of the intangible value of the achieved cooperation, collaboration, and understanding among the diverse student and faculty participants.

Mission Objectives

Newton was designed to permit experiments on human beings and animals at different gravity levels and spin rates. The VGRF will be deployed in low Earth orbit (LEO) to provide an easy access testing ground for studies of human adaptation to artificial gravity during long-duration space flight, e.g., a mission to Mars. Newton provides the capability to vary both the radius and rotation rate of the facility with the constraint of providing a gravity level-rotation rate combination of 1-g at 3 rpm. Human fatigue defined the boundary

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Table 1 Names of all individuals and their countries of citizenship who worked on the variable gravity research facility project

ISU students			
Bailey, Sheila	USA	Maxakov, Maxim	CIS
Barnett, Brian	USA	McCuaig, Kathy	Canada
Beck, Thomas	Germany	Miller, Bill	USA
Blokland, Renze	Holland	Miwa, Takashi	Japan
Bobba, Fabiana	Italy	Monserrat-Filho, Jose	Brazil
Brice, Jim	USA	Moore, Nathan	USA
Casgrain, Catherine	Canada	Munro, Shane	Canada
Chanault, Michelle	USA	Nordlund, Frederic	France
Chiaramonte, Fran	USA	Pierce, Roger	USA
Chincholle, Didier	France	Poilier, Alain	Canada
Chowdhury, Dilip	England	Polunin, Andrey	CIS
Colbeck, Pat	USA	Robinson, Ron	USA
Cordes, Ed	USA	Rose, Susan	USA
Crepeau, John	USA	Savastuk, Sergey	CIS
Dalby, Royce	Canada	Schmitt, Didier	France
Davidian, Ken	USA	Shimaoka, Eva	USA
De Dalmau, Juan	Spain	Sitch, Jennifer	England
Dunand, David	Switzerland	Smith, Clive	England
Eichold, Alice	USA	Spiero, Francois	France
Elkin, Eugene	CIS	Takarada, Shinichi	Japan
Fry, Cindy	USA	Tsao, Ding-ren	Thailand
Fukazawa, Hirofumi	Japan	Tse, David	Canada
Gu, Xuemai	PRC	Uche, Nena	Nigeria
Guillaud, Vincent	France	Verweij, Lucianne	Holland
Huang, Weidong	PRC	Vienot, Philippe	France
Jancauskas, Erin	Austria	Vix, Olivier	France
Kashangaki, Tom	USA	Wallman, John	USA
Komlev, Vladimir	CIS	Williamsen, Joel	USA
Le Merrer, Olivier	France	Wood, Lisa	USA
ISU department assistants			
Belashov, Dmitry	CIS	Thangavela, Madhu	India
Diedrich, Peter	Canada	Valter, Kristina	Canada
Perina, Maria	Italy	Viirre, Erik	Canada
ISU faculty			
Atkov, Oleg	CIS	Lemke, Larry	USA
Boudreault, Richard	Canada	Mendell, Wendell	USA
Crawley, Ed	USA	Norton, David	USA
Forman, Brenda	USA	Tolyarenko, Nikolai	CIS
Legostaev, Victor	CIS		

on upper-limit gravity levels. The rotation rate limit was conservatively selected to reflect the uncertainty of the limited data which exist concerning the effect of high spin rates on the performance of a small segment of the population. Newton's design encompasses both lunar and Martian gravity levels. Newton will provide unique variable gravity conditions not available in other space-based facilities. It will accommodate six international crew members. Political and financial constraints dictated a simple, minimal structure.[9]

In addition to finding a practical solution to long-duration human exposure in 0-g, the VGRF will be used to support physical and materials science research at a number of gravity levels. Manufacturing and fundamental science experiments will be conducted on the VGRF to develop gravity-dependent technologies to support a human settlement on the moon or Mars. Examples of such technologies include atmospheric gas processing and soil utilization. Easy experimental hardware exchange has been designed into the facility to allow for a flexible progression of experimental goals.

The anticipated Mars mission development time line drove the endpoint decision for Newton's operational lifetime as illustrated in the project schedule shown in Fig. 1.[5] Thirteen years, starting in 1990, were allotted for the development of international agreements and the completion of all design phases (phase A beginning in 1992, phase B in 1994, and phases C/D in 1998). Assembly and checkout of the facility will take place between the years 2003 and 2004. Newton will be operational for nine years (until 2013), at which time seven years will be allotted to build the Mars vehicle. This schedule provides for the commencement of the Mars mission in the year 2020.

International Organization and Structure

Political Structure

The political structure of the VGRF was based on goals, objectives, and requirements expressed in statements of intent by countries with active space programs. Primary partners, those who will have a need for the facility, include the only two nations with stated goals of sending human beings to the planet Mars: the U.S. and the Commonwealth of Independent States (CIS). Secondary partners are other nations which are actively involved in developing their own space program, have

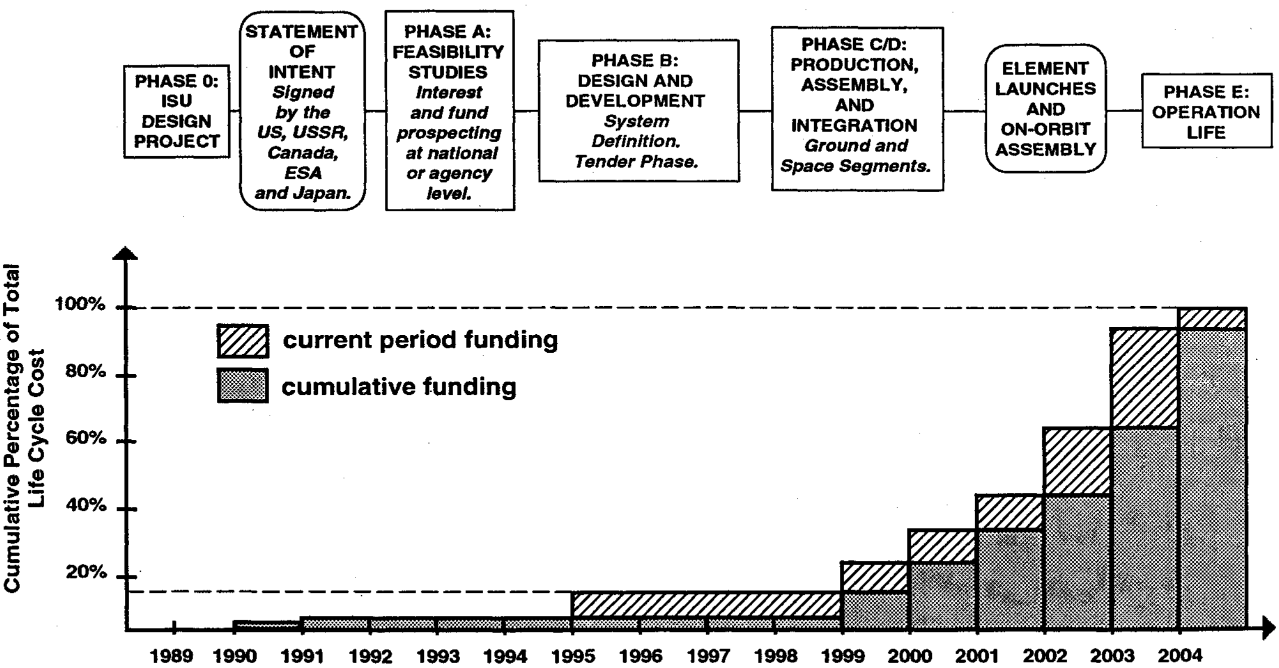

Fig. 1 Project schedule.

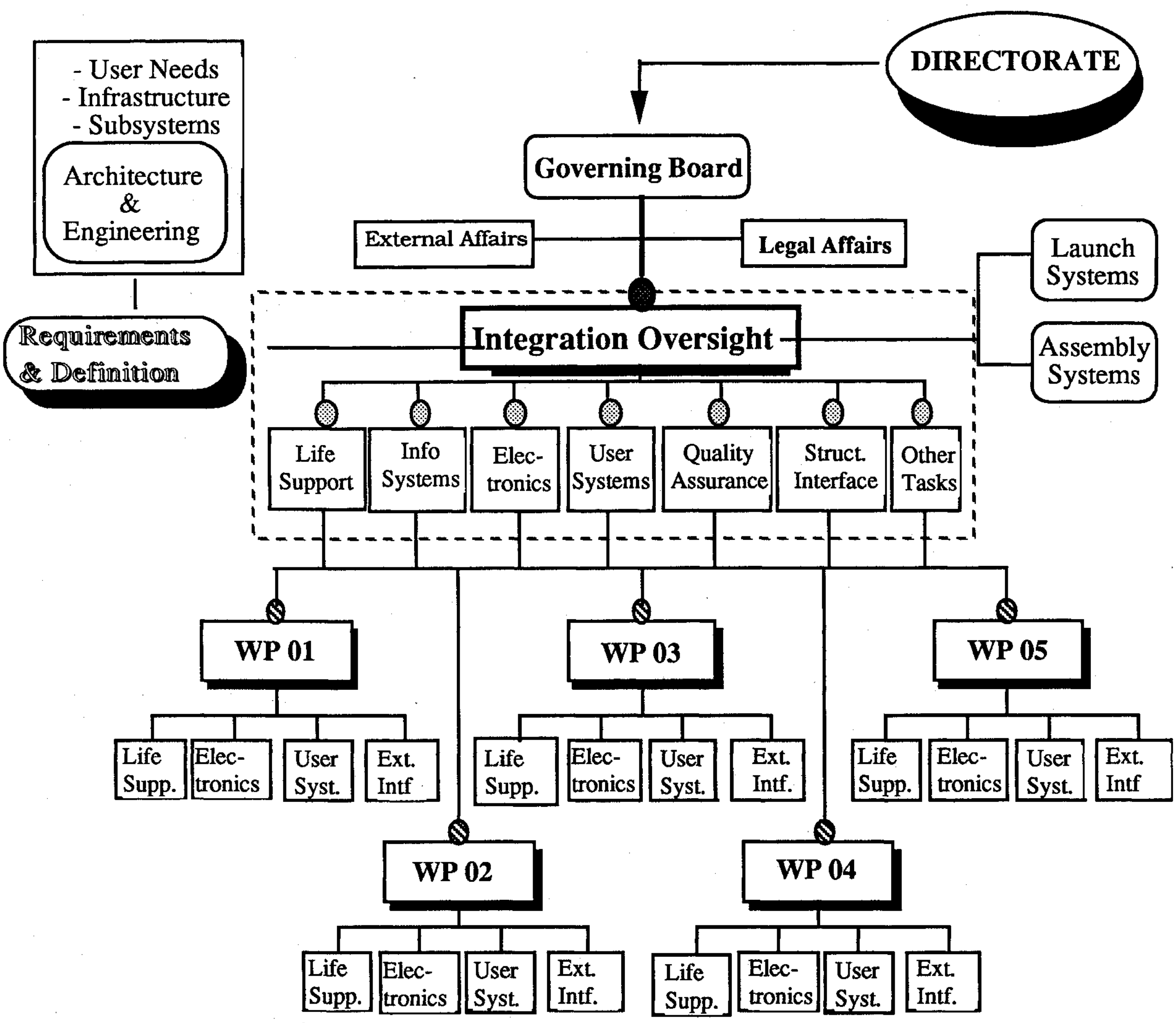

Fig. 2 Management structure.

their own astronaut program, and have expressed an interest in a manned mission to Mars: the European Space Agency (ESA), Japan, and Canada. Nations with space programs which have not been included in the top two echelons of the VGRF political structure include China and India. These nations do not have an astronaut program or a statement expressing an interest in a manned Mars mission. These countries, as well as corporations, universities, or other agencies, can participate in the VGRF project after negotiation with the primary and secondary partners of the project.

To produce a legally binding document without having to endure the problematic acceptance procedures of a treaty, a bilateral Statement of Intent (SI), as defined in the Vienna Convention of 1969,[10] was selected as the document that pairs the U.S. with the CIS as initiating partners and envelopes the goals, purposes, and principles of the VGRF mission. The agreement, signed in 1991, will recognize the need for international cooperation, the peaceful (nonmilitary) operation and use of the facility, and the value of the biomedical data that onboard experiments may yield. Both countries will agree in the SI that cooperation on the VGRF project will provide a testbed for future cooperative ventures. The U.S. and the CIS will then extend an invitation to Canada, Japan, and ESA to join the VGRF program as partners.

To detail the rights and obligations of the five partner nations, as well as to define the specifics relating to the cooperative agreement among the nations, a multilateral intergovernmental agreement will be drafted. This document will be signed in 1994 and reference the SI between the U.S. and the CIS, the acceptance by the governments of Canada, Japan, and ESA, the Outer Space Treaty,[11] the Astronaut Rescue Agreement,[12] the Liability Convention,[13] and the Registration Convention.[14]

Most of the total expenditure will be required for phase C/D; the production, assembly, and integration of Newton. Signing of the memoranda of understanding in 1996 by each country will allow initiation of this process.

Organizational and Management Structure

The management structure will be comprised of various levels of decision-making bodies whose purposes range from purely technical (for example, integration of subassemblies) to purely political, as shown in Fig. 2.[5] The Directorate consists of one member from the U.S. and one from the CIS and intervenes only when the governing board cannot reach a consensus. The governing board, consisting of one member from each of the primary and secondary partners, was created to make final decisions on program areas affecting two or more partners.

To manage Newton's development and operation, the specific duties of each participating country will be assigned via work packages. The content of each nation's work package, detailed in Table 2,[5] has been designed to utilize each country's demonstrated technical strengths. All facility and ground operation costs will be distributed proportionately among the partners of the Newton project.

To maintain participative equality, headquarters will be located in Vienna, Austria, during development and operation phases of the VGRF project. Although both ESA and the U.S. possess communications networks which could meet the

Table 2 Each nation's work package

Country	Contribution
U.S./NASA	Infrastructure truss elements
	Module support structure
	Two-reaction control systems
	Translating frame
	Launch services
	Habitation and propellant module
CIS	Two Energiya core vehicles
	Counterweight support structure
	Despun section truss
	All antennas
	Airlock
	Command module
	Launch services
ESA	Laboratory module
	Crew escape vehicles
	Ground and onboard communication and control facilities
Canada	Docking arm
	Two logistics modules
Japan	Power system (consisting of four solar arrays, radiators, and batteries)
	Data management system

VGRF's needs with no development or construction, the European network was selected for political reasons of just return. An existing facility in Toulouse, France, was chosen as the site for the control center. Individual training sites will be used for the initial crew training, but training of the entire group together will take place at a training facility in an undetermined location.

Four official languages for the ground-based operations of Newton's development and operation phases were chosen, based on prior international scientific cooperative missions: English, French, Japanese, and Russian.

Legal Issues

Each of the nations participating in the VGRF project, except the CIS, have technology transfer regulations. Even though the design and construction of Newton is meant to isolate each system from the others, there are inevitable amounts of interreliability. Data management, life support, and power systems are a few examples of systems which cannot exist independently of the others. To minimize technology transfer, the U.S. will launch its own hardware along with that of the Japanese and some Canadian hardware. The CIS will launch all CIS, ESA, and the remaining Canadian hardware. To provide an incentive for international cooperation, to reduce overall costs, and to improve Newton's safety and reliability, space onboard the VGRF or financial compensation could be traded for shared technology which is deemed not highly sensitive by the country who owns it.

Environmental protection and liability issues will be addressed through adherence to international space treaties. For example, all organic and inorganic refuse produced onboard will be returned to Earth as outlined in Article IX of the Outer Space Treaty.[11] The Liability Convention of 1972,[13] to which all of the participating nations in the VGRF project are signatories, states that "Each State Party to the [Outer Space] Treaty that launches or procures the launching of an object into outer space . . . is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons . . ." Therefore, it is applicable to the Newton facility. Each member state will register its own portion of the VGRF, thereby maintaining jurisdiction and control of their portion and personnel.

Science Requirements

The purpose of constructing and utilizing the VGRF, illustrated in Fig. 3,[5] is to achieve the following goals:

1) First, to determine a solution to the deconditioning effects of long term 0-g on the human body using artificial gravity, for the future purpose of a manned Mars mission.

2) Second, to support long duration manned missions by conducting research in life and physical science processes and space manufacturing at a number of gravity levels including lunar and Martian gravities.

To meet these goals, the following major operational requirements were imposed on the system design:

1) A range of constant artificial gravity environments including lunar, Martian, and Earth gravities.

2) A range of rotation rates at each gravity level with a maximum of 3 rpm to attain 1-g.

3) The duration of a gravity environment from a few months to several years.

4) Six crew members onboard.

5) Experiments to be accommodated include human, animal, plant, and physical science; and resources and manufacturing.

The data gathered will be used to plan a manned mission to Mars and assist in the design of the spacecraft(s).

Life Science

The life science experiments to be conducted on Newton are divided into two major categories: Mars mission enabling studies and a life science research program. The Mars mission enabling program focuses on human physiology, medical care, psychosocial studies, and advanced life support. The life science research program will emphasize basic science studies with animals, plants, and cellular systems. Experiments will be conducted over a range of low-gravity environments.

The Mars enabling studies must determine how to keep people healthy for a three-year manned mission to Mars. From previous space flights, it is known that physiological adaptations occur which result in muscle atrophy, bone demineralization, cardiovascular deconditioning and neurovestibular system changes.[1-3] Data to be recorded are the rate of deconditioning of all of the bodily systems with respect to time as a function of gravity level, rotation rate, and radius of the facility.

Analyzing the effects of reduced gravity on humans will include studies on the entire body and separate systems which are cardiovascular, endocrine, gastrointestinal, genito-urinary, hematological, immunological, muscular, neurovestibular, pulmonary, and skeletal. Initially, partial gravity will be used as the sole countermeasure to the anticipated decline in performance of a specific system.[4,15] However, if significant deconditioning occurs, then active countermeasures, such as

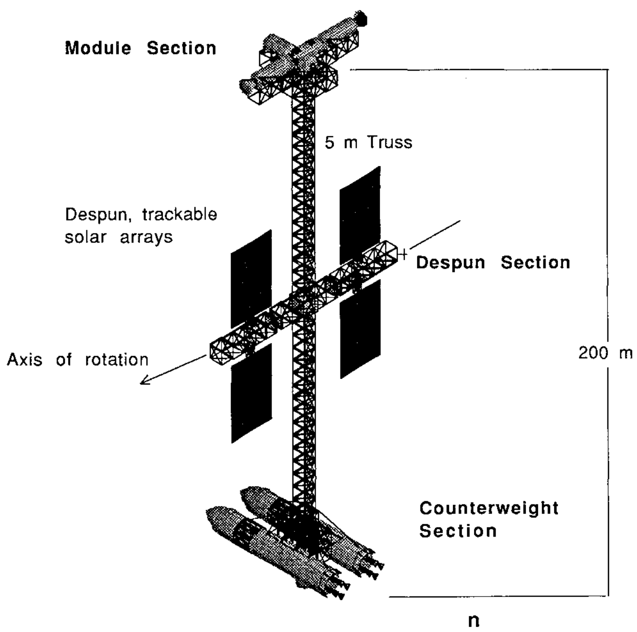

Fig. 3 Isometric view of Newton.

routine exercise, will be implemented. Each system will be studied by conducting tests. For example, measurements for cardiovascular studies include heart rate and cardiac output. Blood samples are needed for the endocrine, hematological, immunological, genito-urinary, and pulmonary systems. The voluntary muscle and skeletal systems will require noninvasive test methods such as x-ray diagnostics. In the event of illness or injury, a medical care facility is necessary to accommodate the six crew members who will be onboard for each six-month mission. Medical capability will provide inpatient, outpatient, critical care, and surgical capability for diagnosis and treatment. Onboard capabilities will include x-ray imaging, microbiology and hematology laboratories, operating room facilities, and pharmaceuticals. For immediate medical needs beyond the capability of the facility, the crew escape vehicle will transport the patient to Earth.

Because the Mars mission may require three years of space flight in a relatively small spacecraft, psychosocial factors will play a key role. The VGRF will model this scenario. Screening tests will be conducted for astronaut selection including life histories, social compatibility, behavior, and personality tests. Possible adverse physical effects that could occur include headaches, chest pain, aggression, and sleep disturbances. Preventive measures will include the placement of windows for viewing the outside, reminders of the Earth environment (e.g., music, books), and designated privacy areas for each astronaut. Monitoring the astronauts' psychological wellbeing will be performed by reports from other crew members, daily logs in each individual's diary, and by use of advanced expert systems for personality evaluation.

The life science research program will perform experiments with animals[16] to gain a better understanding of physiological effects of partial gravity on human beings. Using rats as test specimens, fluid balance and control tests will help explain changes in the cardiovascular and renal systems. Bone demineralization studies will assist in determining the relationship between weight bearing and stress unloading, and growth and remodeling. Data from these experiments will provide input to the Mars enabling studies program.

Science Processes and Manufacturing

Science processes and manufacturing experiments will be conducted in the variable gravity environment of Newton since human planetary settlements will require resource utilization. Processes which could be used for a human base on Mars include water extraction from the soil and oxygen processing from the predominantly carbon dioxide atmosphere.[17] For a moon base, resources such as oxygen, water, aluminium-based solid fuel, concrete, iron, and glass could be wholly or partially produced from the lunar soil (40% oxygen, 21% silicon, and metals such as iron, aluminum, and titanium) provided that manufacturing processes are available.

The goal of the process simulation experiments will provide experience in using the hardware and equipment as well as with the process itself. These experiments will therefore test automation, teleoperations, and remote maintenance procedures as well as demonstrate front-to-back production processes in a partial gravity environment.

Mars and lunar settlements will need plants for foodstuff production, however, the influence of radiation and partial gravity levels needs to be clearly understood. Furthermore, gravity-dependent basic science such as fluid physics (e.g., boiling), transport phenomena, biotechnology, materials processing (e.g., crystal growth), and combustion is necessary to support space-based processes. Basic science experiments will be conducted to advance the development of critical technologies by improving the fundamental understanding of the phenomena.

Facility Design

Newton is comparable with the U.S.-led International Space Station Freedom in scale and complexity. Newton's design incorporates political, economic, and schedule limitations as well as functional requirements.

An isometric view of Newton in Fig. 3 (Ref. 5) shows the major hardware components:

1) The module section includes the pressurized habitation, command, and laboratory modules where the crew lives and works, the logistics module which holds supplies, airlocks, or

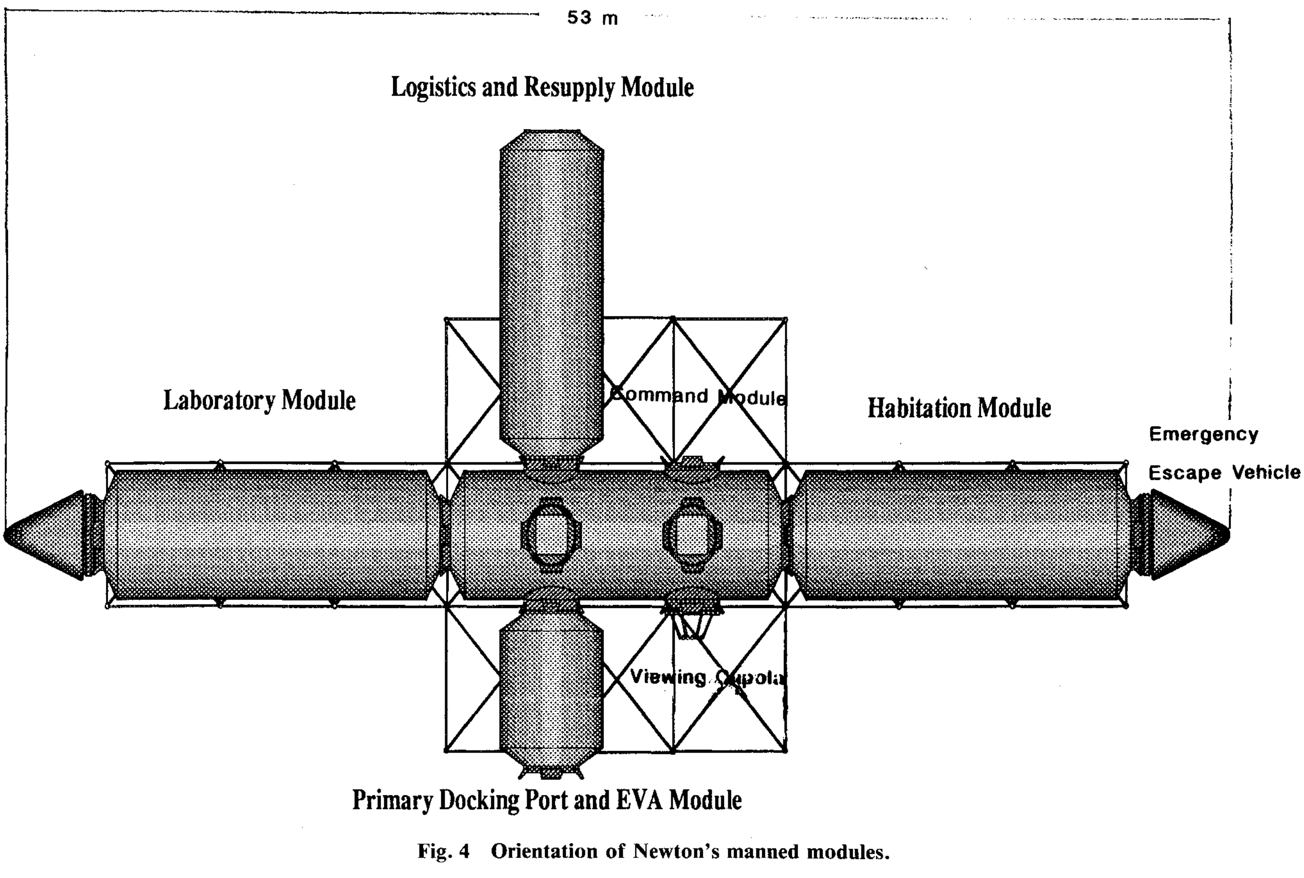

Fig. 4 Orientation of Newton's manned modules.

extravehicular activity (EVA) module for crew transfer during times of resupply when the facility is despun, a reaction control system (RCS) for spinning and despinning the facility, and two emergency escape vehicles shown in Fig. 4.[5]

2) The connecting truss provides a rigid but massive rotational arm for the entire facility. Instead of trusses, the use of tethers was explored but abandoned due to stability and control issues.[18]

3) The counterweight section, which roughly balances the mass of the module section, is comprised of two empty Energiya core vehicles fitted with mounting hardware to allow attachment to the connecting truss. This section can also be relocated along the truss to attain various gravity conditions within the module section.

4) The central despun section was necessary for the location of the photovoltaic panels and the communications transmitting and receiving equipment. Because the center of gravity (c.g.) will change locations during day-to-day operations as well as during 0-*g* reservicing operations, this equipment is attached to a moveable pallet which can be precisely controlled and positioned. A major source of c.g. movement, the burning of 5 metric tons of propellant during spin-up, will cause the c.g. to change location by more than 2 m.

System Budgets

Determination of masses of the different components of Newton was constrained by the rotational stability of the facility. Since the configuration is roughly that of a dumbbell, the rotational stability of the facility was assured by maintaining a moment of inertia about the z axis, I_z, greater than that about the x axis, I_x. Based on the mass budget given in Table 3 and mass distribution of Newton, the ratio of I_z to I_x was 1.002. Special attention was given to the alignment of the two Energiya counterweight tanks with respect to the rotational motion of the facility.

Power requirements for Newton were also assessed and specified. Based on a life support system requirement of 25 kW, 50 kW to run the scientific experiments, 78 kW to charge batteries, and 17 kW of various power losses (direct current to alternating current conversion, distance, and power distribution and control assembly), the end of life solar array output was determined to be 170 kW. Addition of a 10% solar array oversizing requirement to account for array degradation over the lifetime of the facility resulted in the total raw power requirement of 187 kW.[19]

Table 3 VGRF mass budget breakdown

Dry mass	Metric tons
Modules	
Habitation	25.0
Command	30.0
Laboratory	30.0
Logistics	15.0
Airlock (EVA)	5.0
Crew escape (2)	11.4
Structures	
Primary truss	2.0
Module support	1.0
Counterweight (2)	100.0
Counterweight support (2)	0.5
Despun support	1.5
Propulsion	
Tanks, engines, support	4.0
Power	
Solar arrays (4)	2.4
Batteries (2)	1.0
Radiators (2)	0.7
Mechanisms	
Despun section (2)	3.2
Translating frame	1.1
Robotic arm (2)	1.0
Total dry mass	234.8
Consumables	
Propellant	7.5
Propellant reserve	2.5
Life support	4.5
Total resupply mass	14.5

Orbital Dynamics

Concerns of orbital dynamics are made more complex when the spacecraft being analyzed is very large and is itself spinning. Issues of orbit and attitude selection, attitude control, and solar array and antenna pointing are more difficult to resolve when compounded with problems of centrifugal and Coriolis accelerations and facility spin and despin operations. Analysis of the Newton facility included each of these phenomena which affect orbital dynamics.

Maximum spin rate constraints of 3 rpm and gravity level requirements of up to 1-*g*, governed by the centripetal acceleration equation[6]

$$a = \omega^2 r \tag{1}$$

(a in units of meters per second squared and ω in units of radians per second) drove the size of Newton to be 200 m in diameter. Centrifugal acceleration of the rotating modules results in the creation of a force pointing radially outward from Newton's c.g. This force is the desirable artificial gravity for which the VGRF is being designed. However, a secondary force is also generated due to the existence of the Coriolis acceleration. This Coriolis force is evident when a person moves along the radius from the center of rotation, moves tangentially to the rotation, nods their head out of the plane of rotation, or tips their head from side to side.[15] With a linear velocity of 1 m/s and a facility spin rate of 2–4 rpm, a Coriolis force of up to 60 N could be felt when walking, sitting, standing, or while tipping or turning the head. This could result in a change of direction of movement (not walking in a straight line or not sitting where intended) or motion sickness.

Because of the lower radiation environment and ease of access from Earth, Newton will be put into orbit at a maximum altitude of approximately 550 km. The scenario of co-orbiting Newton with an existing space station such as the CIS's Space Station Mir was not feasible because the orbital decay of Newton (100 km in 6 months) was greater than that of Mir (30 km in 3 months).[5]

To allow both U.S. and CIS launch systems to reach the orbiting facility required that it is placed at an orbital inclination of 51 deg. This attitude will allow existing and future launch systems to deliver large payloads, including crew, to Newton. The CIS's Energiya can deliver approximately 100 metric tons to this orbit, the U.S. Space Shuttle can deliver approximately 15 metric tons, and the ESA's Ariane 5, when operational, will also be able to deliver approximately 18 metric tons to this orbit.

Two degrees of freedom (axes of rotation) are required to point both the solar arrays and the communications antennas. The first degree of freedom must be parallel to the angular momentum of the VGRF at a rotational rate equal to the algebraic sum of the facility spin rate and orbital rate. This despins the solar arrays with respect to the rotation of the truss and aligns their normal component with the projection of the sun direction into the orbit plane. The second degree of freedom, with a pointing capability of 90 deg, allows direct pointing of the arrays at the sun. To ensure a permanent communications link between Newton and the ground stations regardless of solar array orientation, two communications antennas located on top of the array mast were required.

Effects which disturb Newton's rotational motion, including atmospheric drag, gravity gradient, and solar pressure, were modeled as a system of differential equations and solved for using numerical integration. The most prominent of these is the gravity gradient between the two ends of the facility which manifests itself in effects on the rate of rotation and the rotation plane orientation. Another influence, caused by the oblateness of the Earth, was the rotation of the right ascension of the ascending node which causes a precession of the orbital plane of the VGRF. Since the rate of precession is substantial (5.2 deg/day for CIS's Space Station Mir, for example), the propellant requirement to perform in-orbit correction burns is prohibitive[5] and are not performed. Orbital maneuvers to counteract the effects of atmospheric drag, however, were necessary to maintain Newton in orbit. Of the various orbit-raising strategies available, viable options included a single, large orbit-raising burn to maximum altitude and allowing the facility's orbit to decay to a minimum altitude, or many, small orbit-raising burns to keep the facility at the same altitude all of the time. A strategy of raising the orbit and spinning up the facility with the same engine firings was discussed but abandoned due to the eccentricities that this method introduced to the facility's orbit.

Subsystem Design

Requirements of power, stability, and control for a rotating facility were met by using a truss as a primary support structure. Maximum bending and torsional strength, easy on-orbit assembly, and reasonable total system mass were the design criteria of the truss. The entire truss system is composed of many identical truss bays, 5 m to a side, with 7.07 m diagonals, and each member having a 3-cm radius and 0.2-cm thickness, made of aluminum clad graphite epoxy.[20]

Design constraints on Newton's power generation and distribution subsystem were radiation environment, thermal environment, component degradation with time, and system interaction. The low-orbital altitude of Newton exposes it to nonionizing radiation, unlike that found at higher altitudes. This determines the amount of radiation shielding required on the solar arrays. Another effect of orbiting at 51 deg at 500 km is that Newton will be in the Earth's shadow from 0 to 35 min for each 94-min orbit. This influences power storage performance requirements and mass. Thermal cycling of the arrays, up to 6000 cycles/yr with a temperature variation of ± 80°C, determined the aging effects on power degradation. Each of the four 400 m^2 solar arrays were composed of 62,500 4 × 4-cm GaAs/Ge solar cells with an efficiency of 22% and a derating factor of 0.75.[21] Overall performance indicators of the designed power system for Newton are the specific power, 10.1 W/kg, the area-specific power, 80.6 W/m^2, and the specific cost, approximately U.S. 4.0 M$/W.

The purpose of the main propulsion system was to initiate and control the spinup and spindown of Newton to induce the artificial gravity. To minimize propellant mass and for reasons of safety and structural integrity, the cluster of eight thrusters, four pointing in the direction of rotation and four pointing counter to it, were placed within a 5 × 5-m truss bay at the counterweight end of the VGRF. A total thrust level of approximately 10,000 N was required to attain the maximum gravity level at the maximum spin rate in a burn time of 10–12 min. The R-40A engine,[22] commercially produced in the U.S., was chosen for the main propulsion system. The estimated amount of propellant (monomethyl hydrazine and nitrogen tetroxide) to spin/despin the facility to 1-*g* at 3 rpm was approximately 9.5 metric tons.

Newton has a large inertial momentum and angular velocity which lead to a large angular momentum. Attitude stabilization is due to the spin-stabilization effect of the angular momentum. Laser gyros were used to provide angular velocity stabilization using small correction thrusters as feedback actuators. Nutation oscillations due to impact, disturbance torques, and thruster action were damped by using induced magnetic eddy currents created by the conductive covering of Newton (aluminum) cutting through the Earth's magnetic field at 90 deg. Reaction control thrusters were located on both the manned module and the counterweight ends of the facility.

Requirements for the communications system were broken down into the categories of onboard data handling, data transmission, and ground segment support. These requirements included provisions for uplink and downlink data encryption, and space/space communications for docking vehicles and neighboring stations (CIS's Mir). Nominal space/ground communications will use a high-speed Ka-band link, docking and contingency communications will make use of an S-band frequency, and EVA will use a K-band communication link.[23]

The environmental control and life support system (ECLSS) was required to provide a safe living environment for a crew of six with resupply every 180 days. The following ECLSS subsystems will require some level of resupply: temperature and humidity control, atmosphere control and supply, fecal waste management, fire detection and suppression, nutritional supply, biological/chemical contamination prevention and control, and propulsion integration. However, the air revitalization and water reclamation and management systems will be virtually closed using physiochemical processing methods.[24]

Internal cooling of Newton is managed by the internal thermal control system (ITCS) and was designed to maintain all equipment within specified temperature tolerances at all times. Active cooling uses water in transport loops to collect heat and carry it to thermal bus exchangers. An estimate of 25 kW of waste heat transported by the ITCS included system, payload, and metabolic heat rejection. External radiators with a total design heat load of 70 kW (20 kW at 2°C and 50 kW at 21°C) were oversized by one panel at each temperature level.[24]

Operations

Operations of the VGRF will begin with on-orbit assembly of modules and subsystems such as the truss and solar arrays. After the VGRF was completely assembled, shown in Fig. 3,[5] resupply will occur every 6 months providing consumables, propellant, and new experiments. Rendezvous operations will require facility despin and docking. The effect of despinning on life science experiments greater than 6 months in duration will be investigated using currently available statistical methods. Also included in operations are emergency procedures in the event of fire, loss of power, or use of the escape vehicles.

Assembly of the VGRF will require seven manned missions with some of the missions needing ELVs. Each assembly mission[5] will last a maximum of 14 days.

1) In the first mission, the U.S. will launch a Shuttle to deliver the first part of the module support structure, despun section, 70 m of main truss, truss bridge assembly structure, communication and power (solar arrays) systems, module RCS, and two robotic arms. The total mass will be 14,100 kg.

2) Energiya/Buran will be used by the CIS in the second mission to provide a man-tended facility. Payloads to be launched will be the command module and the first counterweight support structure totaling 30,250 kg. The Energiya tank will be added as the first counterweight.

3) The third mission will require two U.S. launches. The habitation module, at a mass of 25,000 kg, will be lifted into orbit via Shuttle-C or equivalent (assumed to be available). The Shuttle will be launched shortly thereafter carrying the remaining module support structure and will be used to conduct assembly operations.

4) On the fourth mission, the CIS will launch and assemble the laboratory module, air lock, and the second counterweight support structure. The total mass of these items is 35,250 kg and will require a Proton ELV to launch the air lock and the Energiya/Buran to launch the laboratory module and second counterweight. The counterweight is the Energiya external tank.

5) The U.S. will launch and assemble 130 m of main truss structure, counterweight propellant module, and two escape vehicles on the fifth mission. The U.S. will use the Shuttle to deliver the total payload mass of 14,700 kg into orbit.

6) On the sixth mission, the CIS will launch and assemble the logistics module with consumables. This module is 15,000

kg and will be launched on the Energiya/Buran. Spin and systems testing will be conducted on this mission.

7) The seventh mission will be the first operational mission and will be performed by the U.S. Propellant necessary for this task will be launched on an ELV and the crew will dock with VGRF from the shuttle orbiter. Logistics resupply will also be provided as a Shuttle payload during this mission.

The VGRF will be resupplied with propellants, ECLSS equipment,[24] replacement parts, and new experiments every 6 months. A propellant mass of 7500 kg will be necessary for attitude and altitude control. Necessary for each 6-month period will be about 4450 kg of ECLSS supplies. A mass of 50 kg of spare parts has been allocated during each resupply mission. Experiment rack changeout will occur at an average rate of one per resupply mission.

Rendezvous with the VGRF from a manned or unmanned vehicle will require Newton to be despun. Crew members could be transferred via two docking ports located on the airlock and command modules shown in Fig. 4.[5] Manned vehicles include the CIS Buran, U.S. Space Shuttle, the European Hermes, and the Japanese Hope, assuming Hermes and Hope are operational at the time. Propellant resupply will occur at the third docking port, located in the counterweight section, using unmanned vehicles. Propellant and consumables resupply will be provided by the unmanned CIS Progress or similar NASA and ESA ELVs.

Contingency operations will be necessary in the event of cabin fire, power failure, and for emergency escape to a safe haven or escape vehicle. Fire hazard could be minimized by using fire retardant materials and keeping the oxygen concentration below 30%. Emergency lighting and alarm systems will be required in the event of a power failure with alarm classifications such as those from NASA document STD 3000.[25]

Crew Issues

The Newton facility will be staffed with a maximum of 6 crew members at any one time: a Commander, a Deputy Commander, and four Mission Specialists. The Commander/Deputy Commander positions will revolve equally between the U.S. and the CIS. The four remaining crew positions, as well as their allotment of time and space onboard the facility, will be allocated among the participating nations according to their contribution to the construction of the facility. The contribution breakdown will be as follows: 29% for the CIS, 29% for the U.S., 14% for ESA, 14% for Japan, and 14% for Canada. Each partner state will have the right to negotiate with other partners for additional time onboard.

The crew members will have all of the rights and privileges of astronauts according to Article V of the Outer Space Treaty[11] and the Rescue Agreement of 1968.[12] Each element of Newton will be governed by the jurisdiction of the state of registry, and each partner state will be responsible for the actions of its nationals. A Code of Conduct will be drafted and signed by each of the partner states. This code will be used onboard to establish accepted rules of behavior for each of the Newton crew members. The Newton Commander will have the authority for personnel onboard Newton as well as for any personnel of a vehicle docked to Newton during servicing.

English will be the official language on board the VGRF. However, each crew member will be required to speak at least one other language. Crew selection will be decided by each of the partner states, with the stipulation that crew candidates meet fundamental standards developed by a committee made up of the participating nations. Crew training will consist of individual, ensemble, and onboard segments.

Cost And Financing

Two main factors introduce a high level of uncertainty to both the cost estimate and the financial structure of Newton. The first is the complex international organization which adds to the complexity of political agreements, management of the program, and the technical interfaces. The suggested approach will be to minimize currency transfers, and instead insure that contributing countries receive the same value of contracts that they contribute to Newton. In the case of disagreement about the rate of exchange, the number of engineering man-hours or equipment weight could be employed as proxies for money by agreement of the partners.

Table 4 Detailed breakdown of VGRF cost in billions of U.S. dollars

Component	Cost
Module section	12.50
Support	1.70
Despun section	1.90
Translating frame	1.00
Counterweight	3.30
Truss	0.05
Computer	4.00
Communication	1.10
Scientific equipment	1.00
Headquarters (10 years)	2.00
Crew training	0.12
Launch services	4.50
First year of operations	3.00
Total	36.17

The second factor is the very innovative character of the program, whose only valid references are the Space Station Freedom, and to some extent the CIS Space Station Mir. Although the cost of Mir is the subject of some discussion, Freedom's cost has grown steadily as plans on paper have developed into actual hardware. A rotating facility will require innovation in structural and control engineering when compared to Freedom and thus increases the difficulty of estimating development and on-orbit preoperational verification costs. Estimates which are presented here are comparable to those of Freedom. This seems reasonable since increased complexity may be offset by learning curve effects from using existing equipment.

The cost drivers considered include the level of technology and a relatively complicated international management with numerous interfaces. The cost estimates were based on the estimated prices for similar subsystems and operations of Space Station Freedom, known launch service prices, and cost estimating relationships. The total cost is approximately U.S. $36 billion, with a level of accuracy of 30%. A detailed breakdown of the total cost is given in Table 4.[5] The financing of Newton is expected to be entirely government funded. Although there may be limited commercial applications the major benefits will be nonfinancial.

Summary

The primary goal of the variable gravity research facility (VGRF) will be to find a practical solution to the harmful effects of long-term weightlessness (0-g) on the human body using artificial gravity, allowing a future manned mission to Mars. Long-term human physiological deterioration from previous space flights reveals muscle atrophy, bone demineralization, and cardiovascular deconditioning.[1-3] These effects must be minimized for humans to successfully make the two to three year Mars mission. Secondary goals of the VGRF will be to conduct experiments in science processing and manufacturing to prepare for human planetary settlements which will require resource utilization.

Designing a VGRF was the task of students of the International Space University during the summer of 1989. The VGRF was christened Newton and a comprehensive, multidisciplinary approach was adopted in its design.

The political structure for the VGRF will be comprised of three levels of involvement based on the stated wants and needs of each country's space policy. Primary partners are the U.S. and the CIS; the secondary partners include Canada, Japan, and ESA; countries such as China and India, as well as corporations, universities, or other agencies, could participate in the VGRF project after negotiations with the primary and secondary partners. A bilateral statement of intent between the primary partners and a multinational intergovernmental agreement between all five of the primary and secondary partners will define the roles and responsibilities of each within the context of the entire project.

Newton will be 200 m in length and is comprised of pressurized and unpressurized modules containing habitable environments and supply storage facilities. Attainable gravity levels fall between the range of 0.1–1-*g* at a spin rate not to exceed 3 rpm. The total dry mass and raw power requirements of the VGRF will be 235 metric tons and 187 kW, respectively. To make Newton reachable for all launch systems with little impact on their total payload to orbit capability, the orbital altitude and inclination were specified to be 550 km and 51 deg. Because of the greater orbital decay of Newton as compared to Mir, the two structures could not be co-orbiting even though they share the same orbit.[5,9]

On-orbit assembly and facility check out will require seven manned missions. Technology transfer issues were resolved by launching all U.S., Japanese, and some Canadian payloads by the U.S. The CIS will launch all CIS, ESA, and the remaining Canadian payloads. Once the facility is operational, resupply will occur every 6 months requiring the facility to be despun. Facility design and crew procedures have been considered to handle emergency situations such as fire or loss of power. The VGRF will have two escape vehicles for emergency crew egress. Further technical details pertaining to all aspects of the VGRF can be found in Ref. 5.

The Newton project was not only successful in producing a comprehensive report on a variable gravity research facility in low Earth orbit, but also in the intangible achievement of cooperation, collaboration, and gained understanding among the international student and faculty participants.

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