Systems Analysis of a Low-Acceleration Research Facility

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Worldwide, there is a growing interest in developing a capability to access the low-acceleration environment of space. Both science and industry have made long-term commitments to use this environment by investing in the development of specialized platforms and laboratories in space. A spacecraft concept capable of meeting the demands for very low-acceleration research and materials processing in the 21st century has been developed. The Low-Acceleration Research Facility (LARF) is an unmanned free-flier that is boosted from low-Earth orbit to a desired altitude using an orbit transfer vehicle. This paper describes the LARF concept and the design techniques that were used to minimize acceleration-causing disturbances and create an ultra-quiet workshop. Critical subsystems (specifically, electrical power and thermal control) that enable the LARF to accommodate submicrogravity levels for extended periods of time are described.

Introduction

SINCE man began his investigations into the physical world, one thing that Earth-bound laboratories and experiments have had in common is that they operate within the Earth's gravitational field. Much effort has been expended in developing a reduced-gravity capability on the Earth. With the advent of space flight, exploration into the effects of reduced gravity on processes has become more than just a theoretical exercise.

A wide variety of scientific disciplines are eager for the opportunity to carry out on-orbit experiments. Materials science alone is expected to produce a space-based, profitable industry in the near future from the production of crystals, alloys, and new products.[1,2] Life science investigations are expected to yield important information that can be used to design helpful drugs from the analysis of protein crystals grown in space.

Many types of low-acceleration experiments or processes can be performed on orbit. Some produce better results in space, while others cannot be conducted on Earth at all. Each experiment places unique requirements on a spacecraft as to the acceleration environment, power supply, thermal control, and other systems used to support the experiment. A unique spacecraft concept has been designed to meet the demands for low-acceleration research and manufacturing after the turn of the century and be robust enough to support many types of experiments. The study objective was to develop a feasible spacecraft design and to identify technology issues affecting the choice of subsystems.

LARF Design

In the early 1960's, the concept of a "drag-free satellite" was introduced.[3] The satellite consisted of two main components: a proof mass and a spacecraft bus. The proof mass was completely enclosed within a spherical cavity that was a part of the spacecraft bus. During operation, the proof mass stayed in free-fall without touching the wall of the chamber. To accomplish this, the spacecraft bus actively flew the orbit of the proof mass. At the time, it was pointed out that there would be benefits of such a concept to studies in geodesy, as a high-altitude drag probe, and for gyroscope experiments. Also suggested were studies on the possibility of time dependence of gravity and the prospect of a "zero-g" laboratory.

In 1972, the TRIAD satellite was launched into low-Earth orbit (LEO). The TRIAD successfully maintained a gap between the small proof mass and the chamber walls for 10 months.[4] The calculated magnitude of the residual accelerations on the small proof mass were less than 1/10 ng.

The Low-Acceleration Research Facility (LARF) (Fig. 1) is a logical extension of the drag-free satellite. LARF is composed of an external shell that completely encloses a low-acceleration module (LAM). The LAM contains the acceleration-sensitive experiments and support apparatus and replaces the proof mass of the drag-free spacecraft. The spacecraft is constructed so that the solar arrays face the sun while the spherical chamber, or shell, remains oriented with the LAM. The shell is a platform for mounting subsystems and support utilities, and shields the LAM from environmental disturbances.

When periods of low gravity are required, the shell maneuvers about the free-fall trajectory of the LAM, with no physical contact between the LAM and the external shell. The only interface between the supporting subsystems and the LAM is across the evacuated gap. Energy to power furnaces or other equipment and communications is transmitted across the gap, and heat is radiated directly from the LAM to specific portions of the shell's interior. The LAM is allowed to freely rotate while in free-fall. Because the heat radiated from the LAM could damage instrumentation mounted on the inside of the spacecraft shell, gimballed supports connecting the spacecraft bus with the external shell are used to maintain a safe orientation of the outer shell with the LAM. The rotating joints used to orient the exterior shell are depicted in Fig. 2. After mission completion, the orbiting free-flyer is retrieved by an orbit transfer vehicle (OTV), returned to LEO, and refitted at either the space station, Shuttle Orbiter, or other platform.

The design accommodates a variety of experiments or processes with only the requirement that each fit within the support apparatus of the LARF. This insures the precise align-

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Table 1 Sensed accelerations by an experiment onboard a spacecraft

Environment-induced	Spacecraft-induced	Experiment-induced
Gravity gradient	Crew movement	Thermal gradients
Atmospheric drag	Stationkeeping	Moving fluids
Solar radiation	Altitude maintenance	Mechanisms
Earth radiation	Machinery	g-jitter
Environmental electric effects	g-jitter	Magnetic effects
Environmental magnetic effects	Mass attraction	Electric effects
Meteorite impact	Magnetic effects	
	Electric effects	

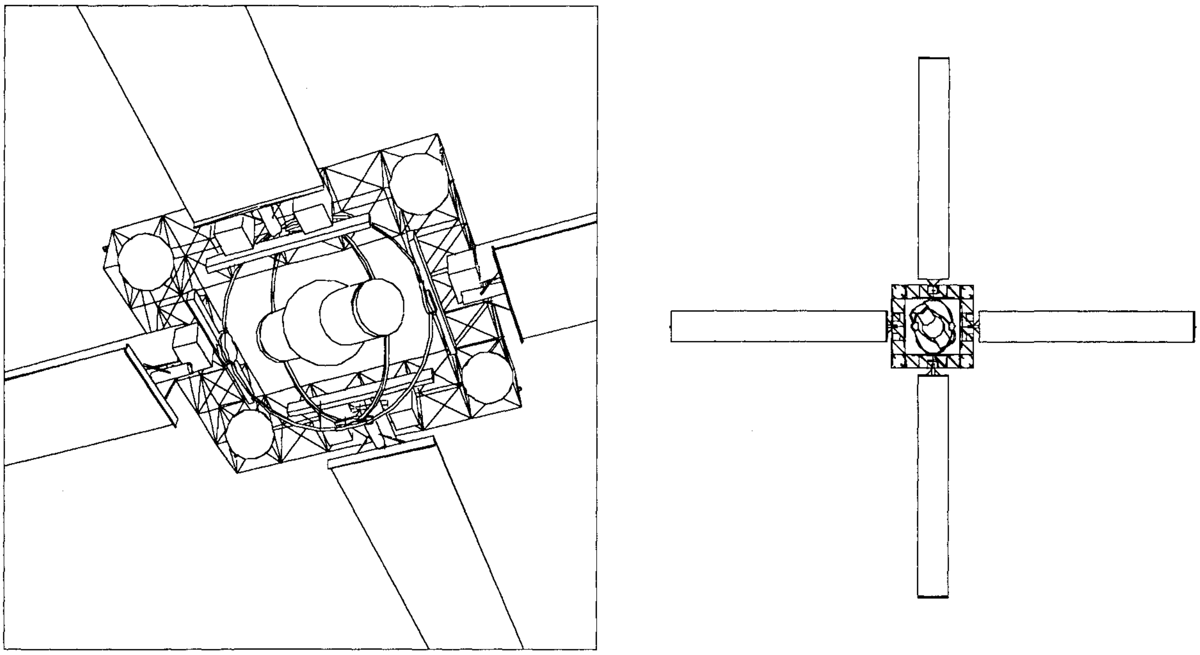

Fig. 1 Computer model of the LARF.

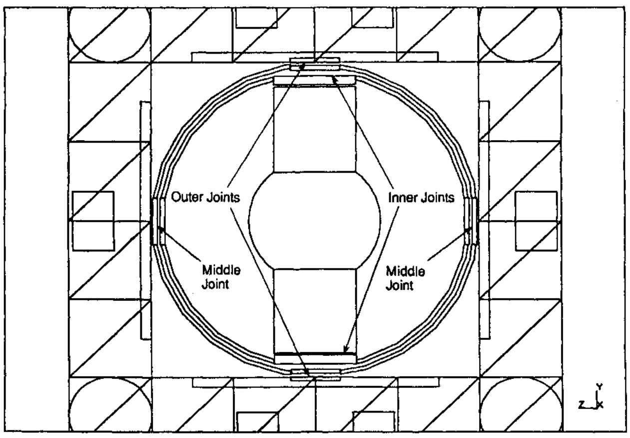

Fig. 2 Location of rotating joints on the LARF.

ment of receivers and transmitters for the information and energy links between the LAM and the shell. To maintain these links, the design uses an active control system that can sense the location and orientation of the LAM and maneuver the shell accordingly while sustaining a solar-pointing attitude for the solar arrays mounted to the spacecraft bus.

In the high-power mode, the LAM will supply the payload with 25.0 kW of power and up to 11.8 kW in the low-power mode. The high-power mode can operate during periods when the LARF is not eclipsed. This is achieved in either high-inclination sun-synchronous orbits or for periods of many months in high orbits such as geosynchronous. The low-power mode can be implemented in any orbit. The baseline design provides for a temperature range from -100 to 1650°C. However, low-temperature processes may need to limit power consumption because of fixed energy-dissipation rates determined by the configuration and the characteristics of the radiators.

The LAM was sized to accommodate any payload described in the report on the microgravity and materials processing facility (MMPF).[5] The LAM can service a payload mass up to 2000 kg. This mass does not include the mass of the LAM support structure and link interfaces that are common to all experiments. The LAM has the shape of a sphere with two flattened ends. The radius is 1.5 m and the flattened ends are cut 0.125 m into the sphere. This configuration provides a volume of 14.0 m^3.

Minimizing Residual Accelerations

Residual accelerations are kept to a minimum by decoupling the LAM from the spacecraft bus. Residual accelerations onboard the spacecraft (Table 1) can be separated into environment-, spacecraft-, and experiment-induced acceleration.

Environment-Induced Accelerations

A simplified overview of how the environmental-disturbance regime changes with altitude can be described as follows: In low-Earth orbit, atmospheric drag and gravity-gradient accelerations are the dominant disturbing forces affecting the acceleration environment of experiments onboard the spacecraft. As orbital altitude increases and the atmosphere thins, the effects of atmospheric drag decrease, and gravity-gradient forces become dominant. For the LARF operational altitude (above 1000 km), atmospheric drag is negligible.

Other environmental disturbances must be considered. For example, Earth's albedo imparts momentum on the spacecraft. The Earth's magnetic field affects the charged portions of the spacecraft. Also, disturbances caused by random meteorite and space-debris impacts can affect the integrity of the low-acceleration environment.

Near geosynchronous orbit, the effects of solar radiation become an important disturbing force on satellites with large surface areas. The external shell of the LARF protects the payload from these types of disturbances during operation by acting as a shield. The means by which the LARF design acts to minimize all types of disturbances are listed in Table 2. Many of these disturbances can be reduced by thruster firings or specialized construction.

Gravity-gradient accelerations become important for spacecraft with large masses located at discrete distances from the spacecraft center of gravity (c.g.). The magnitude of the spacecraft's velocity vector is constant around a circular orbit; however, the direction of the vector is constantly changing. The time rate of change of a velocity vector around a circle gives rise to a centripetal acceleration directed toward the center of rotation. In a spacecraft-centered-inertial (SCI) coordinate system, a differential mass directly above the spacecraft's c.g. has a greater velocity than the c.g. point and creates a larger centripetal acceleration. At the same time, the point mass is further from the Earth's c.g., and the acceleration due to gravity is reduced. This unbalance of forces gives rise to gravity-gradient accelerations.

The magnitude of the accelerations normal to the orbital plane are less than those accelerations along the SCI z axis. Gravity-gradient accelerations are plotted for the y and z axes as a function of distance from the spacecraft, e.g., at an altitude of 1000 km in Fig. 3. The variation in magnitude with position and the symmetry of the magnitude around each axis produces contours of constant-acceleration levels in the shape of ellipses normal to the velocity vector.

The variation of the gravity-gradient accelerations with altitude of an inertial-oriented spacecraft can be seen in Fig. 4. Here the magnitude of the acceleration per meter along the y and z axis is plotted as a function of altitude from LEO out to geosynchronous Earth orbit (GEO).

Earth-oriented spacecraft have an additional rotation around the SCI y axis of one revolution per orbit. This additional rotation produces greater centripetal accelerations along the z axis and reduces the accelerations along the flight path. This effect has been called the "gravity-gradient tube" because there is an extended area of the spacecraft along the SCI x axis with essentially zero-g over the course of an orbit.

To increase the envelope of the LAM for low gravity-gradient accelerations, different operational attitudes were explored using 6 degree-of-freedom Program-to-Optimize-Simulated-Trajectories (6D POST).[6] The goal was to use the gravity-gradient tube. However, it was not possible to find an optimum initial pitch rate that would keep a nonspherical apparatus Earth oriented when a gravity model of an oblate

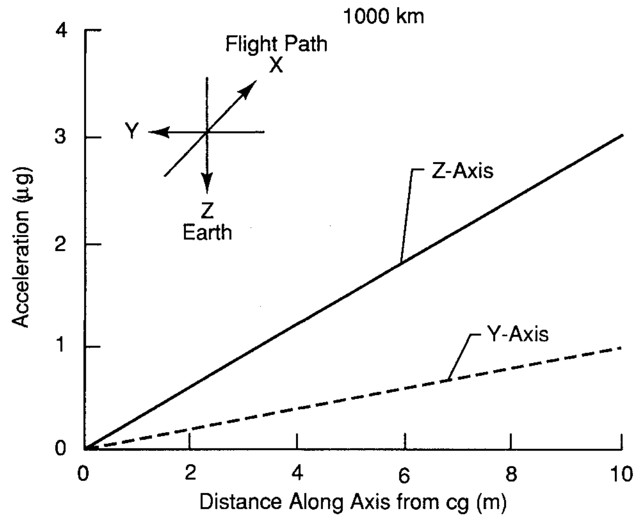

Fig. 3 Magnitude of gravity-gradient accelerations along SCI y and z axes at 100 km.

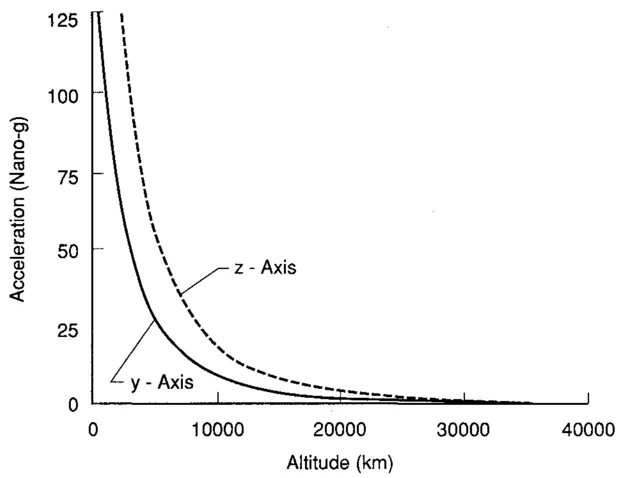

Fig. 4 Altitude dependence of gravity-gradient accelerations for point masses located 1 m from the c.g. on the y and z axes.

Table 2 LARF residual acceleration management

Residual acceleration	Effect on experiment	Method
Environmental		
Gravity gradient	Reduced	High-altitude orbit
Atmospheric drag	Absent	High-altitude orbit
Solar radiation	Absent	Isolated by shell
Earth radiation	Absent	Isolated by shell
Meteorite impact	Absent (unless penetration)	Isolated by shell
Magnetic (environmental)	Reduced	Shell and materials selection
Electric (environmental)	Reduced	Shell and materials selection
Spacecraft		
Crew	Absent	No crew
Stationkeeping	Absent	Isolated by evacuated gap
g-jitter	Absent	Isolated by evacuated gap
Machinery	Absent	Isolated by evacuated gap
Magnetic effects	Reduced	Shell and material selection
Electric effects	Reduced	Shell and material selection
Mass attraction	Reduced	Symmetry of spacecraft
Design-induced accelerations		
Power transmission	<1 ng	Microwave transmission
Heat radiation from experiment	<1 ng	Passive
Communications link with experiment	Absent	Optic link

Earth was used. An active Earth-orienting control system on the LAM is not considered practical because of the disturbance it could impart to the experiment. Nonspherical apparatus are more prone to rotation induced by gravity-gradient accelerations. For this reason, an overall spherical shape was chosen for the LAM. It was determined that the LARF will use high-altitude orbits to reduce gravity-gradient accelerations. After the mission acceleration requirements are set, the operational altitude of the LARF could be initially determined (Fig. 4).

Spacecraft-Induced Accelerations

Most spacecraft are very complex machines. To operate properly, they depend on pumps, rotating machinery, linear actuators, and in some cases, humans. Vibrations can be excited from any moving mass and can be transmitted to the experiment by means of the structure. Unlike the environmental disturbances, which are quasisteady in nature, the majority of accelerations in this category occur at higher frequencies.

To function, the crew must move from area to area, manipulate hatches and tools, and exercise to keep fit, even for short missions. Actions such as deep breathing, coughing, sneezing, and crouching produced accelerations up to 500 μg at the experiments on Spacelab.[7] On the space station, crew translations and exercise have been estimated to produce accelerations as high as 0.1 g.[8] From the beginning, LARF was designed to be unmanned to eliminate this source of disturbances.

Mass attraction refers to the acceleration caused by attraction of one mass to another due to gravity. It is important that the c.g. of the spacecraft bus remain at the c.g. of the LAM. This is accomplished by mass symmetry in the LARF design and the use of an active-control system during operation.

Most spacecraft stationkeeping maneuvers refer to the maintenance of a nominal orbit. This is usually done by thruster firings. Once the LARF has reached its desired altitude, all stationkeeping activities will cease for the duration of the experiment, and the system will be in a free-fall type of orbit. The spacecraft bus will use an active control system to maintain the correct attitude and to make the small corrections needed to keep the LAM from contacting the sides of the outer shell.

Attitude control of spacecraft refers to maintaining the orientation of the vehicle as it travels through its orbit. This can be accomplished in many ways such as small thruster firings, momentum-control devices, reaction wheels, and magnetic torquers. The LARF has solar arrays that must remain sun-pointing, while the shell remains properly oriented with the LAM so that the energy and information links maintain their integrity. The LARF will use a combination of thrusters and momentum-control devices to keep the spacecraft three-axis stabilized.

One of the largest gains to be made by the LARF design is the ability to decouple almost all of the spacecraft-induced disturbances that affect the LAM. This is accomplished by the evacuated gap that separates the LAM from the spacecraft bus. There are no structural links between the spacecraft bus and the LAM during operation in the low-acceleration mode. However, there are links for energy and information transfer as well as a weak link to dissipate excess energy. These links produce accelerations of less than 1 ng on the LAM in the form of radiation pressure.

Experiment-Induced Accelerations

It is not possible to list all of the experiment-induced disturbances that are likely to occur. This area would have to be explored in more detail before designing an experiment for the LAM. A process or experiment may be composed of many complex operations and mechanisms that enable the experiment to operate. For example, mechanisms to change samples or to perform other tasks can excite g-jitter of the experiment apparatus that may persist during the operation of the LAM.

Optimum Acceleration Level

Different material processes need different qualities of low-acceleration environments. Accelerations can be characterized by the frequency of their applications and their overall magnitudes. Disturbances, like gravity gradient, are considered low frequency or steady state, whereas other accelerations, like g-jitter, can generally be characterized as high frequency. This is because g-jitter consists of many disturbing impulses occurring in a short time span. The manner in which certain processes are affected by disturbances are both frequency- and magnitude-dependent.

The production of metal alloys in space is a possible future space industry. It has been demonstrated that tin/lead alloys with higher tin concentrations can be produced at low-acceleration levels.[9] This suggests that more exotic metallic alloys can be produced at lower accelerations.

Defects in crystals are caused by surface tension, adhesion forces, and residual accelerations. By lowering the total acceleration levels during growth, larger crystal sizes can be obtained with less defects. Low acceleration also increases the purity of some crystals.

There is interest in the ability to establish stable suspensions in fluids. As residual accelerations decrease, the size and quantity of particles that can be suspended increases.[9] For particles of only 100 μ in diameter, an acceleration level of less than 0.1 μg is needed. This represents a residual acceleration level lower than any of the other methods could accommodate.

Table 2 summarizes the LARF design responses to residual accelerations. There is a need to have a low-acceleration work space with residual levels less than 1 μg for the types of experiments listed. The LARF subsystems are selected to meet these requirements. The subsystems and their effects on the disturbances are discussed in the subsequent sections.

Energy-Management Subsystem Features

Subsystems dealing with energy management must interface using noncontacting links between the spacecraft bus and the LAM. These subsystems include power and thermal control. To receive and transmit energy, there are electromagnetic links maintained between the LAM and the shell.

Power Subsystem

Many materials science low-acceleration experiments involve the melting of materials. Heating can be the largest drain on the spacecraft power. Heat can be supplied by many methods such as chemical reactions, electron beams, electricity, lasers, and rf power. The most versatile method for the LARF is to transmit power electromagnetically directly to the LAM across the evacuated gap. At the LAM the energy is converted to dc electrical power. Each facility can then plug into the LAM for the power it requires.

The LARF power system was sized to provide 25-kW peak power to the payload. This level of power was chosen so that any of the experiment facilities described in the MMPF can be accommodated by the LARF design. This power level is actually greater than any facility in the MMPF requires to allow for growth. Major elements of the LARF power system include the production, transmission (to the LAM), and control of the power.

Power Production

Power production on the baseline LARF is composed of a combination of solar arrays and nickel-hydrogen batteries. The solar arrays are the NASA/Lockheed blanket type.[10] These arrays are well suited for the LARF configuration. They provide the power that is needed to meet the design goal. Also, the arrays are constructed so that they can be extended and retracted many times. The LARF requires arrays that can be retracted for ease of servicing the LAM and for stability during orbit transfer.

The baseline design incorporates four wings arranged symmetrically with respect to the LARF payload center of mass. Each array is fixed to the truss. The total power supplied to the spacecraft is 54.8 kW.

The nickel-hydrogen battery energy-storage system being considered for use on the space station is similar to that used on the LARF. Each battery operates in conjunction with a dedicated battery charge/discharge unit (BCDU).[11] The BCDU supplies the current-regulated power for charging the batteries during sunlight and provides voltage-regulated dc battery power at 160 V to the spacecraft during darkness.

The LARF requires six battery units (each with a BCDU). They are located symmetrically around the LAM center of mass. The energy-storage system supplies 27.6 kW at LEO. To maintain similar power levels at GEO, the depth of discharge must be increased from 35 to 63%. The total power needed by the BCDU to charge the batteries is 27 kW. This represents the total output of two solar arrays. After the batteries are fully charged, very little power is needed for maintenance.

Power Transmission to LAM

Most methods that have been devised for noncontacting power transfer are concerned with either large amounts of power transported over significant distances using microwave and laser systems, or power transmission over very small distances using transformers or capacitors. The LARF must transmit power over a moderate distance with a high-power maximum of 25.0 kW. Most of the aforementioned methods can be adapted to the LARF concept.

A microwave energy-transfer system was chosen to get power from the shell to the LAM. Using a frequency of 2.45 GHz, the system can be constructed with existing technology. This frequency lies within the industrial, scientific, and medical band (ISM) where off-the-shelf hardware (except rectenna diodes) exists. The energy link is composed of two main elements: a transmitter and a receiver. The type of transmitter used is a klystron, which converts dc power to microwaves, and the receiver is known as a rectenna (rectifying antenna), which converts microwaves into dc power. The entire power transfer is on the order of 66% efficient.

Klystron tubes are tuned for specific power levels and are less efficient at other power levels. In order to produce the variability in power levels needed for the LARF application, klystrons of lower power ratings are arranged in an array. In this manner different combinations of klystrons, switched on and off, can produce the desired power input to the LAM.

Two sets of klystrons are needed by the LARF. Each klystron array can transmit high-power loads of 12.5 kW. The LARF design places the two equal-power transmitter arrays diametrically opposite each other to produce the power levels needed, while reducing the overall disturbances to the LAM.

The resulting accelerations produced on the LAM by two klystron arrays operating in unison will be less than 1 ng, providing that output errors remain less than 10%. Assuming the worst case (at high power and only a single array operating), the acceleration resulting from power transfer is on the order of 5 ng.

Power Control

The power input into the system comes either from the solar arrays or the battery units. The LARF has two regulated electrical buses with a dc voltage maintained at 120 Vdc. The high voltage is used to decrease current losses and to increase commonality with the space station. The dual-bus system supplies power for the housekeeping subsystems, carries power to the payload, and provides redundancy to reduce the risk of single-point failure. The majority of the power produced is supplied to the payload and must be transferred from the truss to the shell. This entails the transfer of power through three rotating joints for each of the electrical buses. At each joint there are two 25-kW rotary transformers.

A joint meeting requirements similar to the LARF has been designed. This joint is a face-to-face rotary transformer. The power transfer across each rotating joint is estimated to be 95% efficient or 86% for the entire trip from truss to shell. The joints include drive mechanisms and heat pipes that carry heat to thermal rejection surfaces. Total mass of each joint is 51 kg, including the mass of the rotary-power-transfer device, power-conditioning electronics, motor, speed controller, and drive electronics.

Battery power is conditioned by the BCDU. The array-produced power is also conditioned to supply the proper voltage and current. Series- or shunt-dissipative regulators can be used to control the amount of power output from the arrays. The spacecraft bus can be reoriented so that a reduced sun angle is used to decrease the power generated by the arrays.

Power control from the ground can be conducted on the LARF through a telescience command channel. After a high-power period, an experiment may only need a minimum of power support. The LARF can bring in two arrays and operate at reduced levels, supplying about one-half the full power peak and nominal amounts.

In summary, the entire power budget for the LARF can be seen in Table 3. The worse-case disturbance to the payload is estimated to be on the order of 5 ng and is expected to be much less in actual operation.

Thermal-Control Subsystem

The thermal-control subsystem can be split into two separate discussions, one that covers the LAM and the other associated with the remaining spacecraft. There is no provision for active cooling or refrigeration on the LAM in the baseline design. On the LARF spacecraft bus, heat is conducted away from the components and radiated to space. Heat is actively removed from the more energy-intensive areas by heat pipes.

The major source of heat on the LAM is expected to come from the experiments, many of which contain furnaces. Another source of heat arises from the conversion of microwave energy into electrical energy. During this process, 10% of the received radiation is converted to heat.

To lessen disturbances to experiments due to thermal control, only passive methods of radiation and conduction are employed on the LAM. The LAM is equipped with 24.1 m^2 of radiating surface located on the spherical portion of the LAM. The shell's radiator lies directly above the LAM radiator and is separated by a 0.1-m evacuated gap. There are 25.7 m^2 of radiating surface on the shell.

To determine how this configuration would operate in two different temperature regimes, mathematical models were constructed. The first model examined the efficiency of the system and its ability to reject excess energy. The second examined the requirements of the LARF when high-temperature furnaces are operating within the LAM.

Thermal Model 1

The first model assumes that both the shell and LAM radiators are at constant temperatures and all energy entering

Table 3 LARF power budget

Item	Peak, kW	Nominal, kW
Power conditioning (96% efficient)	2.2	2.2
Battery charging	—	27.0
Housekeeping, communications, GN&C	2.0	2.0
Power transfer through rotary transformers (86% efficient)	7.1	3.3
Shell electronics	0.5	0.5
Power transfer over gap (66% efficient)	14.6	6.7
LAM electronics	0.5	0.5
Payload	25.0	11.8
Margin	2.9	0.8

the LAM must be removed. Heat produced by the experiments and LAM electronics is assumed to be conducted to the LAM radiators. Figure 5 presents a diagram of the model. The view factor from the LAM radiator to the shell radiator is assumed to be unity, even though the two concentric spheres do not radiate out of the flattened areas. Energy is prevented from entering the equipment areas through the use of reflectors and baffles.

The model was derived from an equation developed for diffuse grey concentric spheres.[12] The effective temperature for space (−116°C) was determined from a relation used to define spacecraft equilibrium temperature.[13] Space is modeled as a sphere of infinite radius surrounding the shell. In a true orbit, solar radiation would impinge on only one-half the LAM at any time. By treating the outside environment in this manner, view-factor effects from the spacecraft bus and the flux due to the Earth's albedo can be estimated.

The results of this simulation can be seen in Fig. 6. There are two curves on this graph; one represents the theoretical limit of energy dissipation for this configuration, and the other represents the computed data generated by the mathematical model. The computed curve exhibits the ability of the radiators to dissipate energy. Any experiment with parameters that place it above the LARF curve will require refrigeration, whereas those falling below the curve will need insulation.

The model 1 curve was calculated by using the most efficient combinations of surface coatings that could be found from a list of typical spacecraft thermal-control coatings. By making the coating combination less efficient, the insulation requirement can be lessened.

Refrigeration and active cooling will cause disturbances to the payload, and so experiments should avoid this option. At peak power, the LAM radiator must be at 190°C to maintain an energy equilibrium, and it should be noted that sensitive electronics would need refrigeration. To avoid this solution for the LAM thermal control, coupled with the need to incorporate high-power and high-temperature furnaces, another thermal model was created.

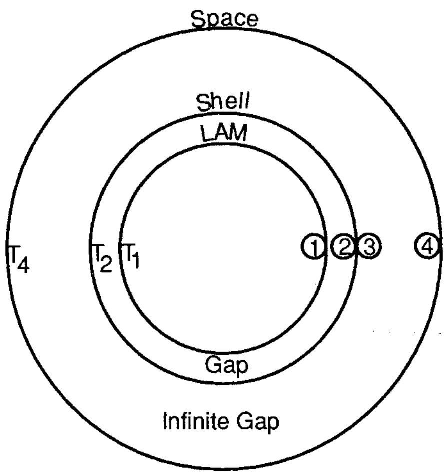

Fig. 5 Thermal model 1.

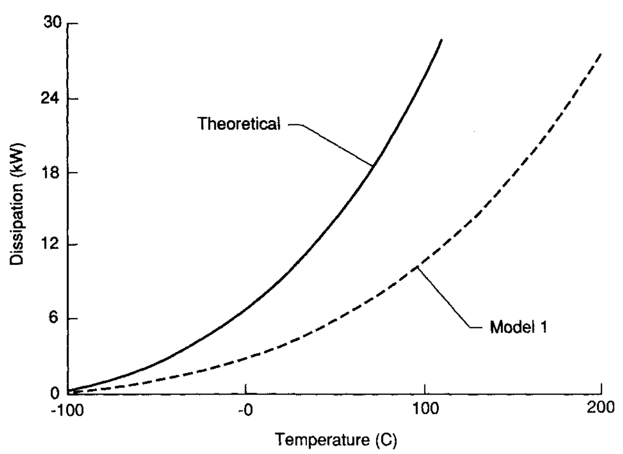

Fig. 6 Energy dissipation vs radiator temperatures (model 1).

Thermal Model 2

Model 2 is an extension of model 1 and includes a cylindrical furnace placed at the center of mass of the LAM. The furnace is enclosed within a layer of insulation whose thickness can be varied to change the amount of heat conducted to the outer surface of the insulation. This configuration provides for an additional evacuated gap that is located between the insulation and LAM shell. To maintain the energy balance, the furnace must maintain high temperatures while the LAM radiators remain relatively cool.

The single-piece isothermal radiators located on the LAM and shell are replaced by three radiators. The center section is the high-temperature radiator directly above the furnace; the two outer sections are low-temperature radiators for the dissipation of excess energy from the LAM electronics.

Model 2 concentrates on the interaction of the furnace, its insulation layer, and the high-temperature radiators on the LAM and shell. Figure 7 illustrates the model 2 configuration. The solution to the model is found by fixing the energy needed to be dissipated from the system. Once this is done, the temperature of the shell and LAM radiators can be found by assuming that all absorptivities, emissivities, and areas remain fixed. For model 2, all surfaces have been given the characteristics of white paint except for the outer surface that remains a solar reflector. A graph of the radiator temperatures as a function of dissipated energy is given in Fig. 8.

In the same manner as the radiators, the temperature on the outside of the insulation layer can be found.[14] Once this temperature is known, the thermal conductivity needed by the insulation can be determined. The thickness of the insulation can then be varied until the thermal conductivities of existing materials are obtained.

A high-temperature case was studied using a furnace of 0.5-m diam with a length of 1.3 m, at a temperature of 1650°C. A specific insulator was chosen to solve this case. It is a material similar to that used on the Shuttle thermal protection system (TPS), known as LI-1500. This insulation was used to calculate the temperatures in Fig. 8.

The amount of insulation needed varies with the power input. At a high power of 25 kW, only 0.013 m of LI-1500 is

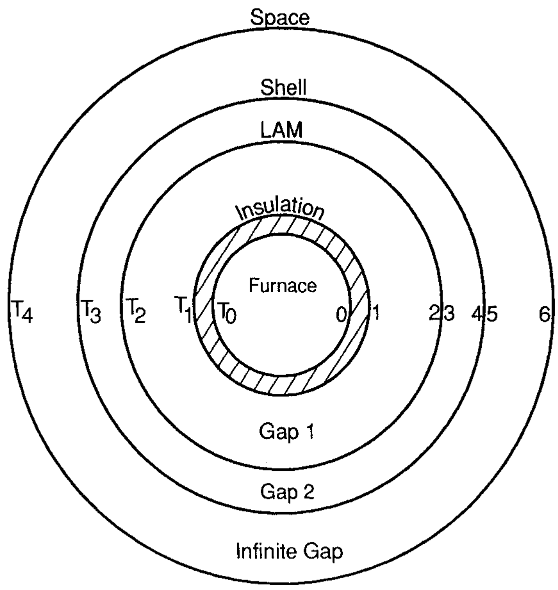

Fig. 7 Thermal model 2.

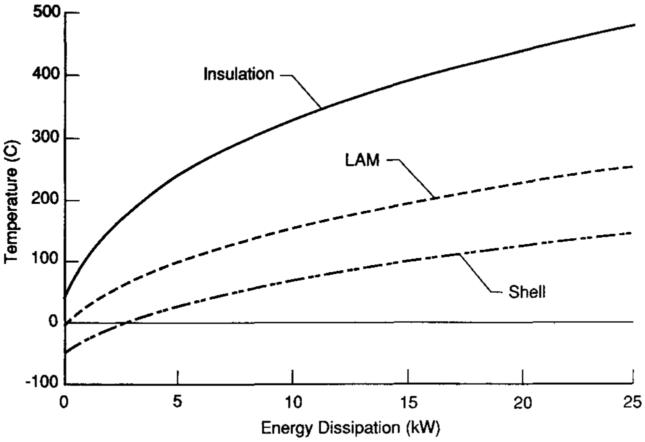

Fig. 8 Energy dissipation vs radiator temperatures (model 2).

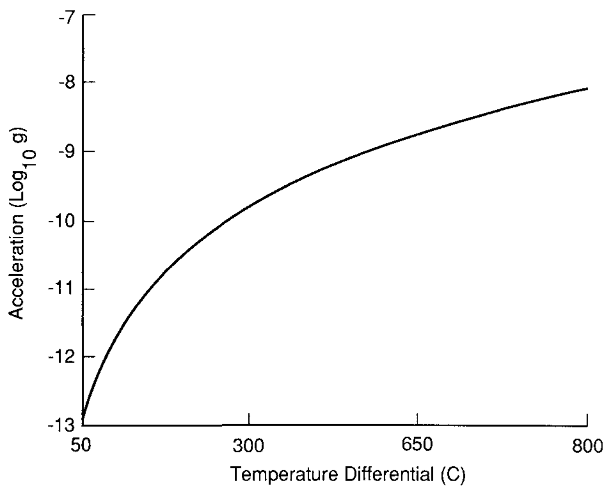

Fig. 9 Accelerations vs temperature differences.

needed, whereas an input of 5 kW requires 0.094 m of insulation around the furnace. At the same time, temperatures on the radiating surfaces fall as input power is decreased. This model illustrates that the configuration can handle the high-temperature furnaces that are needed in low-acceleration materials science.

The low-temperature radiators are insulated from the high-temperature radiators on both the shell and the LAM. Most of the energy to be dissipated in the equipment section of the LAM comes from the rectenna. During the conversion process, inefficiencies in the diodes on the order of 10% of the received radiation convert microwave energy to heat. This translates into 1.25 kW of excess energy on each side of the LAM at high-power levels. Gallium arsenide diodes can operate in temperatures up to 200°C without degrading their expected lifetimes, but other electronics used to control the experiment and communicate with the LARF cannot be required to endure these temperatures. The operating temperatures for satellite electronics should be kept below 55°C.

Each side of the LAM's low-temperature radiators (operating at 50°C) can reject 1.37 kW of energy at high power. This leaves 0.12 kW for the LAM instrumentation after the rectenna requirements are meet. This presents a total of 0.24 kW available. At 55°C, a total of 0.44 kW for instrumentation can be accommodated. Operating at less than peak power reduces the requirements needed by the rectenna. In return, higher power electronics could be placed on the LAM.

Thermal control on the remainder of the spacecraft is approached in a component-by-component method. Most excess energy is radiated by a housing or attached structure. Only the batteries and the two outermost rotating joints must have additional radiating area added to the spacecraft. The non-LAM equipment is thermally controlled in a modular fashion. Proper radiative areas have been assured in the baseline design to meet all high-power requirements.

The two models show that the LAM is capable of handling the variety of energy dissipation loads and temperature ranges required by mission guidelines.

Accelerations Due to Thermal Gradients

If all surfaces are kept at constant temperature, there are no accelerations caused by thermal radiation to the LAM. However, temperature differences existing on either the inner-shell radiator surface or on the LAM radiator can produce accelerations. The acceleration due to temperature differentials are presented in Fig. 9. The temperature differences must be kept under 475°C in order to keep disturbances under 1 n*g*. The concept provides the power necessary to meet the energy requirements for the LAM using current and near-term technology. Table 4 details the mass breakdown for the energy-management subsystem. The total disturbances to the experiments can be kept less than 1 n*g*, and the total energy-management-subsystem mass is 3912 kg.

Table 4 Energy-management-system mass breakdown

Item	Unit mass	Quantity	Total, kg
Array blanket w/hardware	261	4	1044
Batteries with BCDU	181	6	1086
Battery radiators	155	6	930
Electrical buses/harnesses	50	—	50
Joints	51	6	306
Shell power transfer	60	2	120
LAM receiver/converter	10	2	20
Subtotal			3556
Margin, 10%	—	—	356
Total	—	—	3912

Supporting Subsystems

Data Management

For the accomplishment of telescience, the data management subsystem must accommodate data produced by the experiments. Certain remote experiments may require the utilization of television cameras mounted inside the LAM. Data transfer from the LAM and commands to the LAM experiments and processes are accomplished by an optic link, and so there are no electrical connections between the LAM and the external shell, thus the disturbances are absent. Information can be processed either by the spacecraft onboard computers or at the experimenter's site.

Communications

To maintain compatibility with the space station, the LARF will use the Tracking and Data Relay Satellite System for communications with both the space station and the Earth. The technology required to enable this subsystem to become operational exists today.

Guidance, Navigation, and Control

The ability of the spacecraft to avoid colliding with the LAM during operation is vital to the success of the design. Meanwhile, the bus must maintain a three-axis-stabilized solar orientation. The LARF control system operation can be broken down into four major regimes. These are 1) the acquisition mode, used when interfacing with the OTV, 2) the normal mode, which maintains the three-axis-stabilized solar-oriented attitude of the spacecraft body during low-acceleration operation, 3) the rotational-control mode, used to maintain the energy and communication links between the LAM and the spacecraft, and finally 4) the translational avoidance-control mode, to keep the spacecraft from running into the LAM. Only the translation avoidance-control mode will be introduced.

The LAM in free-fall is subject to the forces discussed earlier. The difference in the effects of perturbations between the spacecraft and the LAM is the cause of translational errors other effects (such as mass attraction).

The earliest drag-free control system was designed in 1963[3] and flew on the TRIAD satellite in 1973[4]. Triad used the Disturbance Compensation System (DISCOS). The position of the proof mass was sensed by three capacitance bridges. Each bridge was located on an axis of an orthogonal coordinate system. Signals from each bridge were used independently to turn corresponding pairs of cold gas jets off and on. As the satellite moved toward the proof mass, thrusters fired to restore the symmetry of the gap. The thrusters operated only in an on/off mode to minimize valve leakage and for simplicity. The deadband used by TRIAD was ± 0.9 mm.

There is a new type of drag-free satellite under design at Stanford University. It incorporates a very precise attitude control system that is more sensitive than the DISCOS system. The satellite is called the Stanford Relativity Satellite. This system uses differential-thrust helium thrusters and a proof mass similar to TRIAD for position sensing. The proof mass position is sensed with optical sensors.

The LARF translational-control system is based mainly on the earlier TRIAD DISCOS system, but with the optical pickoff for position similar to the Stanford satellite. The optical sensors consist of a laser distance-sensing system. There are laboratory instruments existing using helium-neon lasers with accuracies up to 0.6 nm. These lasers are mounted on the shell collars, two on each side of the LAM. They are arranged so that position and velocity of the LAM can be determined at all times.

Structure

The structure of the LARF requires no new technology. Space-station-similar truss members, 5-cm-diam graphite-epoxy composite tubes, are used for the trusses supporting the subsystems. The outer shell of the LARF is made of two materials: composites for strength and metal (possibly aluminum) for the radiation of heat out to space and to prevent atomic oxygen degradation at the lower orbital altitudes. The LAM outer covering would be constructed similarly to the outer shell for thermal energy to cross the evacuated gap to the outer shell.

Conclusions

The Low-Acceleration Research Facility (LARF) represents another step toward submicrogravity research and materials processing. Because of the LARF's design, most of the disturbances are minimized by the outer spacecraft. Accelerations caused by atmospheric drag, albedo flux, and subsystem functioning will not affect the LAM because the LAM is only weakly coupled to the outer shell by microwaves and heat radiation. Gravity-gradient accelerations are altitude-dependent and can be minimized by using higher orbits. Mass-attraction effects can be reduced by symmetry of mass on the outer shell and the LAM. Magnetic and electrical accelerations can be reduced by design and choice of materials. Accelerations induced by the experiment or process can be controlled by limiting or isolating temperature gradients and fluid and mechanical movements, and by the design of proper isolation, insulation, and damping devices.

Two primary problems indigenous to this design—the means of transferring power and thermal energy across an evacuated gap—are addressed. Electrical-power transfer to the LAM was performed using microwaves with existing hardware. Thermal-energy transfer from the LAM to the outer spacecraft radiators was obtained by passive thermal-control methods (including the use of radiators and insulation).

Remaining spacecraft subsystems can be drawn from available off-the-shelf technologies. These have minimal impact on the LAM and its low-acceleration environment. Advanced technologies could enhance the overall performance of the LARF system, but further analyses would be required to quantify the increase in the quality of the low-acceleration region on the spacecraft.

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