JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 30, No. 4, July–August 1993

Mechanical Design and Simulation of a Microgravity Isolation Mount for Columbus

R. G. Owen,* D. I. Jones,† and A. R. Owens†
University of Wales, Bangor, Wales, United Kingdom
and
A. A. Robinson‡
European Space Research and Technology Centre, Noordwijk, The Netherlands

A microgravity isolation mount (MGIM) designed to provide active vibration isolation for microgravity payloads is described. The required microgravity level is achieved by adopting a noncontact strategy, whereby the payload floats inside its enclosure and its position is controlled by magnetic actuators. The design concentrates on the requirements of materials science payloads and provides a detailed description of the locking mechanisms used to release and capture the payload during microgravity periods. A nonlinear model used to simulate payload release shows that a successful release depends on the severity of the input vibration level.

Introduction

COLUMBUS is the European contribution to the International Space Station Freedom. Microgravity experiments will be performed aboard two elements of the Columbus program, namely the Columbus Attached Laboratory and the Columbus Free-Flying Laboratory. The microgravity isolation mount (MGIM) facility is intended to provide high-quality vibration isolation for sensitive payloads and is designed to be accommodated in a standard Columbus rack aboard the two pressurized laboratories.

The basic structural outline of the MGIM facility is illustrated in Fig. 1. The five main elements of the facility are as follows:

1) A platform unit, which supports the payload, and which constitutes the isolated element.

2) A liner unit, which is designed as an orbital replacement unit (ORU) and which interfaces with standard resource interfaces at the rear of the rack.

3) A cage unit, which encloses the platform and accommodates a locking mechanism that secures the platform to the cage during nonmicrogravity periods. The cage is attached to a slide system inside the liner to enable easy withdrawal of the platform in orbit.

4) A platform supervisor, which holds the platform control electronics. This unit also contains an electrical interface which supplies all electrical services to the platform.

5) A payload supervisor, located above the platform supervisor, which is responsible for monitoring and controlling the payload.

The MGIM design is based on a completely noncontact concept, whereby the platform and payload float inside the liner and its position is controlled by magnetic actuators.[1] Position information is obtained from capacitive-type displacement transducers, and control is based on these signals, with damping provided by a lead-lag compensator. Electrical power is supplied to the platform by means of a power transformer with a loosely coupled secondary coil that is attached to the platform frame. Up to 1 kW of power can be transmitted to the platform in this way without any mechanical contact. An infrared optical link is used to transmit control and data signals. Heat energy is dissipated from the platform to the liner by thermal radiation using a set of cooling panels arranged on the outer and inner surfaces of the platform and liner, respectively.

Microgravity Payloads

Potential microgravity payloads were surveyed to determine their sensitivity to various onboard vibrational distrubances, their physical requirements in terms of rack accommodation, and the necessary rack services vis-à-vis power, cooling, data, and vacuum/venting.[2] The Columbus Applications Study reviewed a number of payoad studies ranging from materials and fluid science experiments to biochemical and biological experiments.

It was found that the materials experiments, which accounted for the majority of the microgravity payloads, were the most sensitive to vibrational disturbances and would therefore benefit the most from the use of a MGIM. The experiments were conveniently subdivided into two categories according to their vacuum and venting requirements.

Experiments in category A are those that require the continuous use of the Columbus vacuum facility throughout the experiment and, in addition, may require the use of a payload-provided high-performance vacuum pump. These experiments also require use of venting facilities to initially evacuate the experiment processing chambers and also to remove waste gases produced during the experiment. Some experiments in this category only require the use of the venting facility, although this may be used throughout the duration of the experiment. Typical category A experiments are the materials science experiments that invariably contain some form of furnace.

Category B experiments are those that either do not need the use of any vacuum or venting facilities or only require use of the venting facility at the start of the experiment to evacuate their processing chambers. Experiments in category B are mainly fluid science, biochemical, and biological experiments.

A number of existing experiments, shown in Table 1, have been identified that could be accommodated (with some modification) on the proposed MGIM, and that are compatible with the MGIM's power and cooling capacities. However, the requirement of rigid vacuum and venting pipes permanently

Presented as Paper 90-3628 at the AIAA Space Programs and Technologies Conference, Huntsville, AL, Sept. 25–28, 1990; received Dec. 20, 1990; revision received June 21, 1991; accepted for publication July 6, 1991.

*Research Fellow, School of Electronic Engineering Science. Member AIAA.

†Senior Lecturer, School of Electronic Engineering Science.

‡Senior Engineer, Structures and Mechanisms Division, European Space Agency, Technical Directorate.

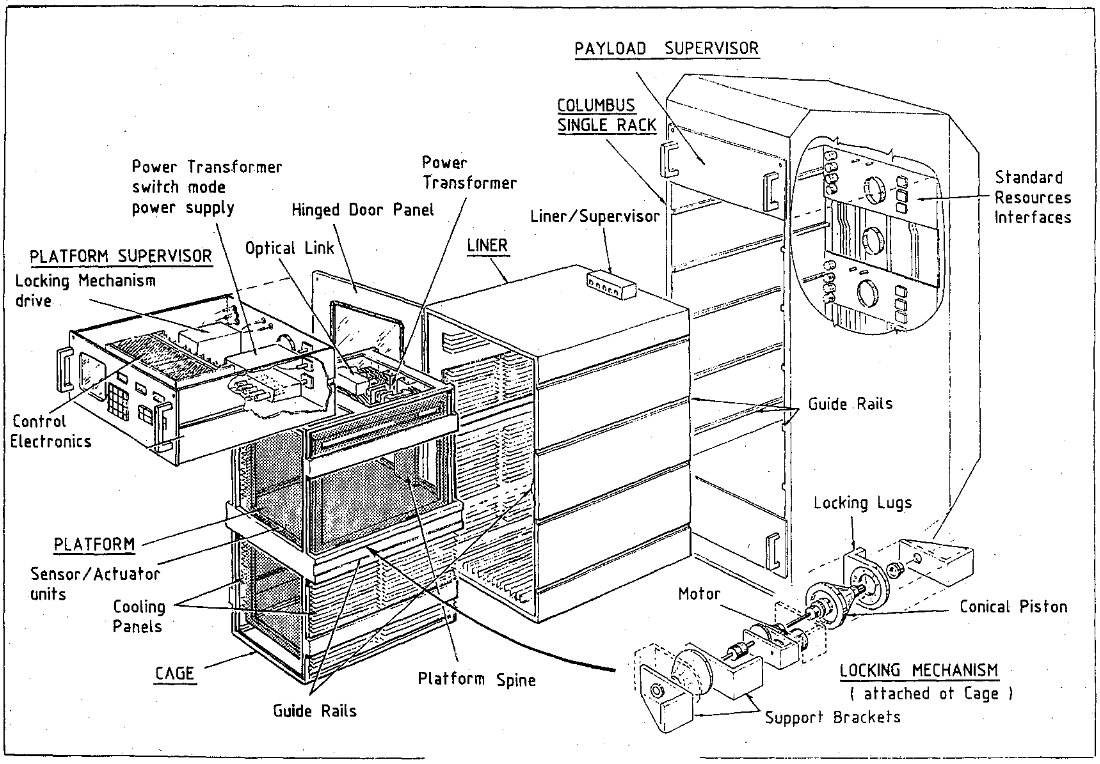

Fig. 1 Outline of MGIM facility.

Table 1 Selection of suitable experiments

Payload	Category
Advanced gradient heating facility	A
Containerless float zone	A
Vapor or solution growth	A
Crystal growth	A
Protein crystal growth	B
Critical point facility	B
Advanced fluid physics module	B
Bubble, drop, and particle unit	B

connected between the payload and rack for the majority of category A experiments presents a severe problem, as an MGIM clearly cannot operate when connected to such pipes.

Some preliminary studies have been carried out to investigate this problem.[3] One possibility involves connecting the Columbus vacuum and venting lines to the payload during the initial stages of the experiment to remove the bulk of the gases and to provide an initial vacuum. These lines would then be automatically withdrawn at a predetermined time before the main microgravity phase of the experiment. Any subsequent vacuum or venting requirement could be satisfied by onboard pumps and storage containers. However, the feasibility of such a scheme is highly application dependent.

Mechanical Design Objectives

Category A experiments are usually high mass payloads that often occupy a large percentage of the available rack volume. One of the primary design objectives is therefore to enable the MGIM to accommodate the maximum payload mass and volume. The platform must also be capable of dissipating 1 kW of power, in the form of low grade heat, from the payload to the rack. However, due to the noncontact concept, this heat must be dissipated by means of radiation between the sides of the platform and liner walls. This means that the platform must have sufficient surface area to accommodate the correct number of cooling panels.

This section discusses how achieving the aforementioned objectives influences the location of the locking mechanisms and the sensor/actuator units (SAUs).

Location of Locking Mechanisms

The location of the locking mechanisms and the thermal heat dissipation capacity of the platform are highly interdependent. The three most realistic options for locating the locking mechanisms inside the liner, as shown in Fig. 2, are 1) option A—across the upper and lower surfaces of the platform, 2) option B—along the sides of the platform, and 3) option C—at the platform's corners.

With all three options, the platform is enclosed within a cage and is secured to it by means of the locking mechanisms.

With the first option, the platform is secured to its cage by two locking mechanisms located transversely across its top and bottom surfaces. With the second option, two locking mechanisms are accommodated along the sides of the platform, whereas the third option accommodates the locking mechanisms within the four corners of the liner (volume that otherwise might be unused).

Options A and B involve sacrificing some cooling panel area, whereas option C allows the maximum possible cooling area. However, a direct consequence of attaching the platform at its corners is that four locking mechanisms are required.

Option B allows the platform to be secured at or very near to its center of mass and therefore offers an important advantage over the other two options (assuming the payload's center of mass is near to the platform's geometric center). With options B and C the long depth dimension of the rack can be used to lock the platform at points as far apart as possible, whereas with option A only the narrow width dimension is available.

The advantages and disadvantages of the three options are summarized in Table 2. Option B, which is a compromise between cooling capacity and mechanical complexity, is the preferred choice for the MGIM design. A mock-up of the platform, secured to its cage by two locking mechanisms, is shown in Fig. 3.

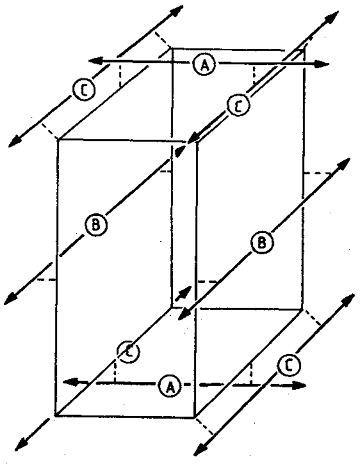

Fig. 2 Possible locations of locking mechanisms.

Table 2 Summary of locking mechanism locations

Option	Thermal cooling capacity	Number of locking mechanisms	Point of attachment of platform to cage	Distance between locking lugs
A	No cooling panels on upper and lower surfaces of platform	2	At periphery of platform	Minimum (limited by narrow rack width)
B	No cooling panels around midsection of platform	2	At or near center of mass of platform	Maximum (long depth dimension of rack used)
C	All surfaces available for accommodating cooling panels	4	At periphery of platform	Maximum (long depth dimension of rack used)

SAU Location

The main objective is to choose SAU locations that result in the minimum loss of cooling capacity and, in addition, allow the platform to be satisfactorily secured to its cage. Three possible arrangements are shown in Fig. 4. In the first option, Fig. 4a, the y SAUs, which control translational motion along the y axis and rotational motion about the z axis, are located along the sides of the platform. This, however, coincides with the location of the locking mechanism's attachment points. Although it is physically possible to accommodate both SAUs and the locking mechanism next to each other, to do so would mean reducing the distance between the attachment points (along the x axis). Arranging the y SAUs as shown in Fig. 4b is therefore preferred, although this results in a reduction in cooling capacity as the y units (and supporting structure) occupy a volume that could otherwise be used to accommodate cooling panels.

Once the locations of the y SAUs have been determined, then the lines of action of the x and z SAUs (but not their precise location) become automatically fixed. The x SAU units do not result in any reduction in cooling capacity, since no cooling panels can be attached around the center of the platform due to the presence of the cage's central belt. In contrast, locating the z SAUs as shown in Fig. 4b would result in considerable loss of cooling capacity. The platform/cage is required to slide inside the liner, and consequently no cooling panels can be attached along the central strip between the z SAUs. A better arrangement would be to locate the z SAUs on the central belt of the cage as shown in Fig. 4c. This arrangement results in the minimum reduction of cooling capacity. The SAU arrangement according to Fig. 4c is therefore regarded as the most suitable for the MGIM design.

Payload Cooling

Heat is removed from the payload using cooling panels attached to the sides, rear, top, and bottom surfaces of the platform and liner, respectively (Fig. 5). Each panel consists of several fins, each with a thickness of 2 mm. The fins allow the platform a free movement of 10 mm in any direction. Cooling water circulates through a number of cold plates attached to the reverse sides of the liner fins.

Detailed thermal analysis indicates that a continuous heat dissipation capacity of 1 kW is possible if the MGIM is accommodated in a facility rack[4] but not without a considerable mass penalty. It should be noted, however, that the MGIM design shown in Fig. 1 is based on a subunit rack, and its heat dissipation capacity will be less than 1 kW.

The mass breakdown of the main elements and subsystems of the mock-up MGIM are tabulated in Table 3. Note that the cooling panels account for approximately 49 kg of the total mass if a heat dissipation capacity of 1 kW is required.

The maximum payload mass, subdivided as shown in Table 4, is estimated to be approximately 91 kg for the mock-up MGIM. This includes the mass of the central plate that will be required in some form by almost all payloads. In the absence of any cooling panel requirement (e.g., for fluid science experiments), the total payload mass may be increased to approximately 140 kg. Refinements of the MGIM's mechanical design will undoubtedly increase this mass yet further for a flight version of the MGIM.

A representative pair of cooling fins have been fabricated, and a thermal test rig, shown in Fig. 6, has been set up to measure their radiative cooling characteristics. The cooling fins are fixed at a distance of 10 mm apart and are enclosed in a large bell jar. The thermal tests are carried out in a vacuum

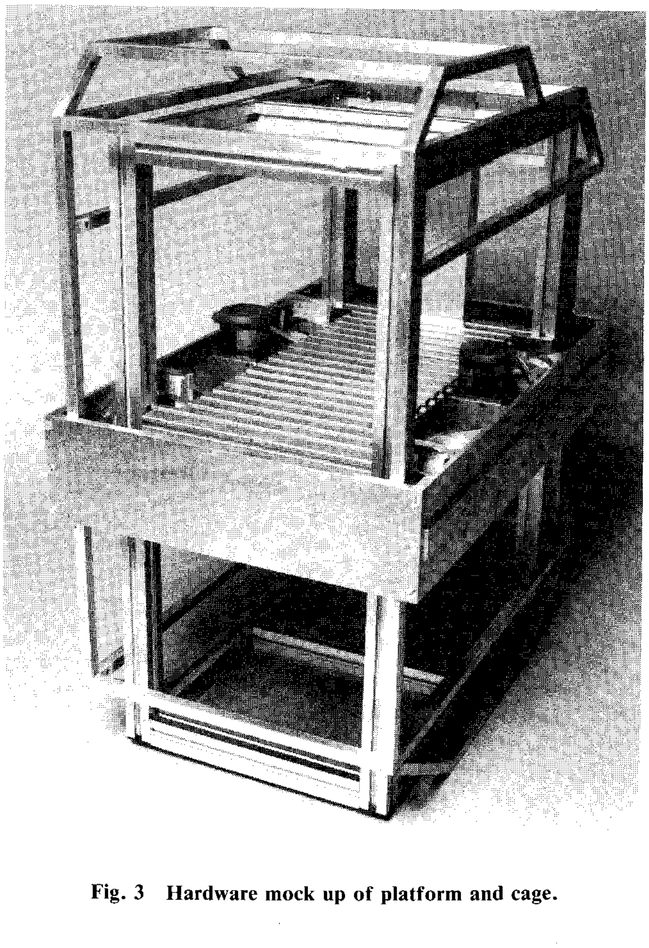

Fig. 3 Hardware mock up of platform and cage.

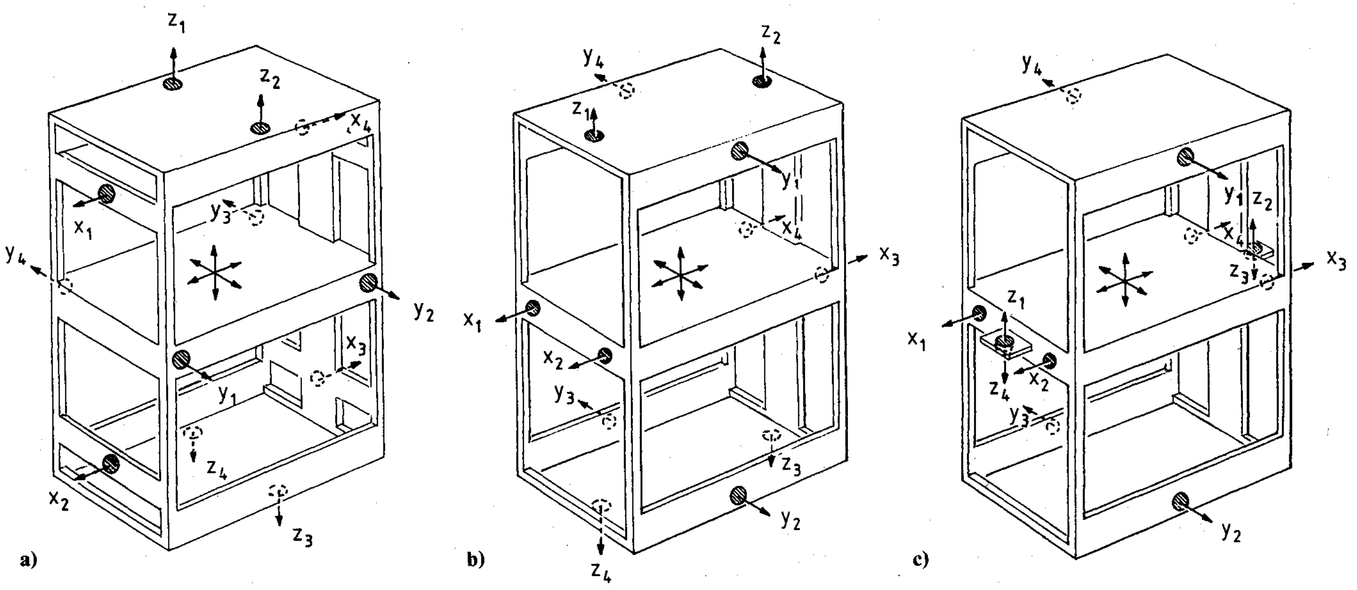

Fig. 4 SAU locations.

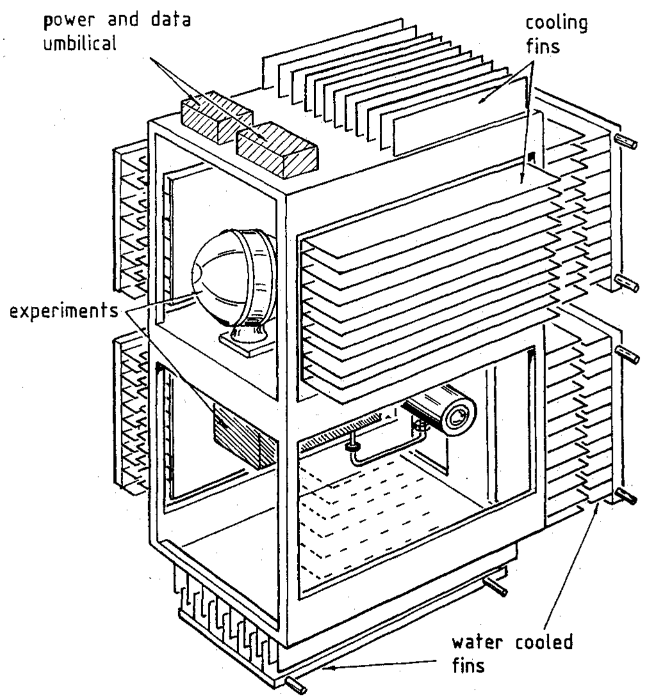

Fig. 5 Cooling panel configuration.

to simulate the gravity-free environment of space by minimizing heat transfer due to convection.

Locking Mechanism

The locking mechanism is required to secure and release the platform inside the liner and withstand maximum launch stresses. The locking mechanism design is shown in Fig. 7.

Description of Locking Mechanism

Each locking mechanism consists of two conically shaped pistons driven in opposite directions on separate leadscrew half-shafts. The pistons engage with a pair of similarily shaped lugs fixed to the side of the platform, thus locking the platform to the cage. Each half-shaft is supported, via steel bush inserts, by two aluminium brackets screwed on the inside of the cage side plates. Thrust collars are machined on the half-shafts in order that the locking mechanism may withstand axial loads. The aluminium brackets, as well as the locking lugs on the platform, are milled from solid blocks of aluminium.

A 20 mm trapezoidal thread is machined on the end of each half-shaft between the aluminium brackets. The opposite end of the shaft is connected via a coupling to a reduction gearbox driven by a stepper motor (Fig. 8). Rotation of the leadscrew shaft by the motor results in a linear movement of the piston along the shaft due to the restraining effect of a pin connected between the locking piston and one of the brackets.

The efficiency of a leadscrew depends on the friction characteristics of the piston material as well as the lead or thread pitch of the screw. The piston is made from polyacetal plastic (Delrin) that has an extremely low friction coefficient enabling it to operate without lubrication.

Launch Stresses

All ORU assemblies with a mass > 50 kg must be subjected to the sinusoidal vibration test specificiation shown in Fig. 9.[5] This specification applies to payloads flown in all launch vehicles. As seen from the diagram, a peak acceleration level of 12 g occurs between 17 and 60 Hz. This corresponds to a peak input vibration displacement of 10.34 mm at 17 Hz.

For a 100 kg MGIM, the maximum load on the locking lugs will be given by

$$F_{\max} = 100 \times 12g = 11{,}760 \text{ N} \tag{1}$$

For a four-lug locking mechanism design, the load/lug will therefore be 11,760/4 = 2940 N.

If the MGIM is subjected to a purely axial force, then the total axial load must be shared by two locking pistons. This means that each piston must be capable of withstanding an axial loading of 5880 N. The locking mechanisms have been designed to withstand the aforementioned launch stresses. A stress analysis of each element of the locking mechanism is given in Ref. 6.

Simulation

A nonlinear model has been developed to study the platform's dynamical behavior during its release from the locked in ACSL, is confined to a single-degree-of-freedom model of the MGIM. The model is subjected to a stochastic input with a standard deviation of 1.3 mm and band-limited by a second-order roll-off at 3 Hz.

During the release phase, the platform may have considerable momentum that must first be "dumped" before it can assume its nominal position in the middle of the rack. Initial simulations revealed that the platform could not be successfully released without substantially increasing the control system bandwidth beyond the nominal 0.03 Hz operational bandwidth. The required increase in bandwidth proved to be impractical and beyond the capabilities of the actuators. An additional passive means of restraining the platform during release is therefore necessary.

In the model, the passive restraints take the form of a layer of sponge material 2 mm thick located on the contacting surfaces of the locking mechanisms. The model assumes stiffness and damping values of 15,000 N/m and 50 Ns/m, respectively for these passive restraints.

Figure 10 shows an unsuccessful release, whereby the platform repeatedly strikes the cage and never achieves its operational position. During the first second of the simulation, the platform is held only by the passive restraints, and as a result it gains considerable momentum. During the next 5 s, the locking mechanism retracts into its fully open position. The platform now acquires a greater freedom of movement resulting in a series of hard crashes against the cage.

The simulation of Fig. 10 is repeated in Fig. 11 but with a reduced input amplitude. This time a successful release of the platform is observed.

The two simulations show that the successful release of the platform depends on the level of the input vibration. The input vibration level of Fig. 10 is in fact a worst-case scenario. Although the MGIM is designed to isolate the payload from

Table 3 Mass distribution of MGM rack

Unit	Mass, kg
Payload supervisor	15
MGIM superviosr	15
MGIM	
Platform	16
Frame and plates	4
Payload	60
Cooling panels	22
Sensors, actuators, power transformer, optical link	6
Subtotal	108
Liner	
Frame	20
Cooling panels (including cold plates)	27
Cage and locking mechanism	15
Subtotal	62
Total	200

Table 4 Total payload mass

Unit	Mass, kg
Payload on platform	60
Platform	16
Payload supervisor	15
Total	91

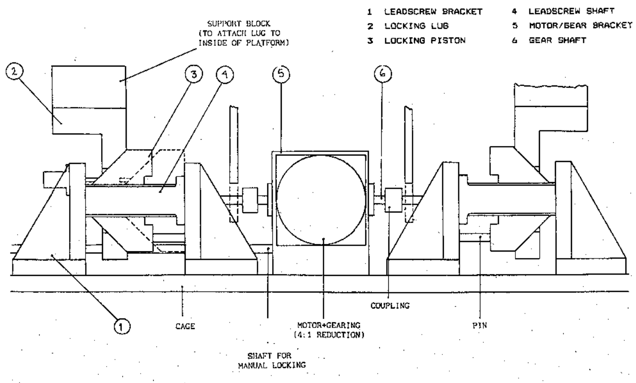

Fig. 7 Locking mechanism design.

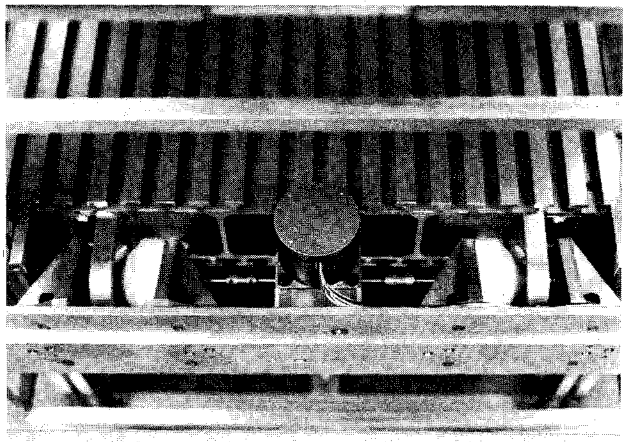

Fig. 8 Locking mechanism mock ups.

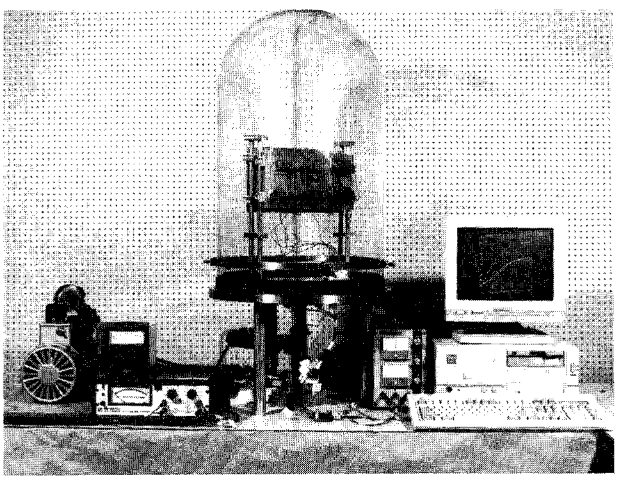

Fig. 6 Thermal test rig.

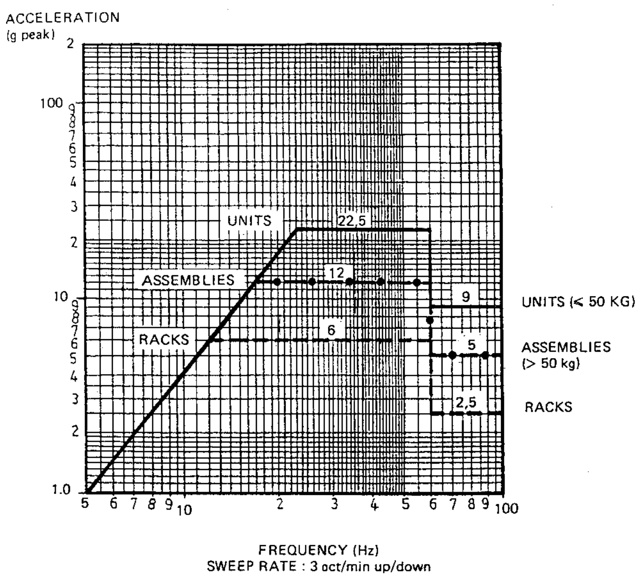

Fig. 9 Sinusoidal qualification test levels.

this extreme vibration environment, the actural release and capture of the platform could be timed to occur in a much "quieter" period.

Test Rig

The main elements and subsystems of the MGIM facility have already been constructed. The sybsystems are currently being integrated with the main elements inside the single rack. The rack will form part of a three-degree-of-freedom test rig, shown in Fig. 12, enabling the MGIM to be subjected to a vibrational disturbance along one axis. The rack is attached to a pair of linear slides that enable it to be moved back and forth by the vibrator. The cage and liner will be fixed to the rack and will therefore move with it. The platform, on the other hand, will be supported on an air table and will be free to move within a horizontal plane, with three degrees of freedom (x, y, ϑ), within the (moving) confines of the cage. The test rig will be used to assess the vibrational characteristics of the facility. Previous experimental results from an earlier test rig[7] indicate that the output acceleration levels and transmissibility characteristics of Fig. 13 (curves B and C, respectively) can be achieved. The rig will also be used to test the functioning of the locking mechanism by means of a series of release and capture tests.

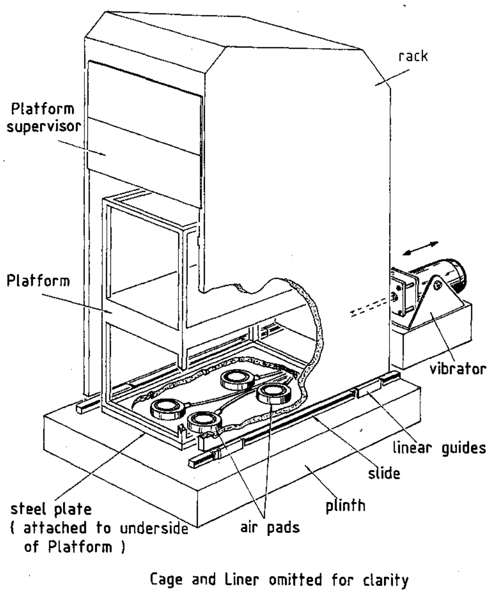

Fig. 12 Test rig.

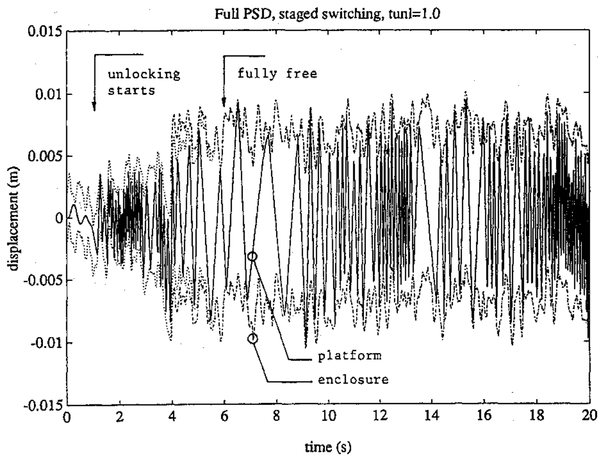

Fig. 10 Platform response with specified input vibration (full power spectral density).

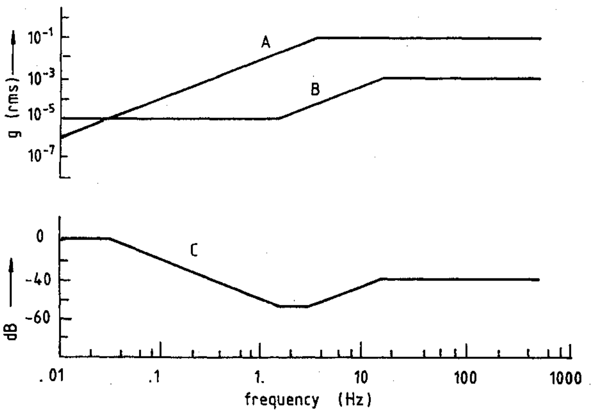

Fig. 13 Sinusoidal vibration specifications; curve A—estimated spacecraft vibration at payload interface, curve B—allowable payload microgavity level, and curve C—transmissibility function for MGIM.

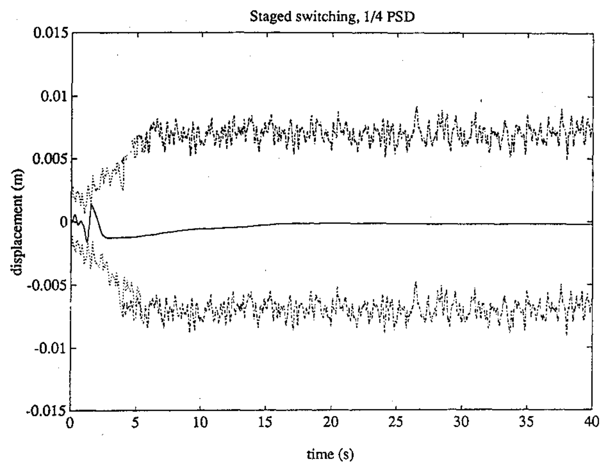

Fig. 11 Platform response with specified input vibration (¼ power spectral density).

Conclusion

This paper has highlighted the difficulties involved in accommodating materials science payloads on an MGIM. In addition to being the most demanding experiments in terms of their microgravity requirements, category A experiments are also demanding in terms of their mass, power, cooling, and vacuum/venting requirements and, as a result, are the most difficult to accommodate on an MGIM. These requirements have an important influence on the mechanical design and location of the cooling panels, locking mechanisms, and SAUs.

Although the MGIM has been designed to provide a continuous heat dissipation capacity of 1 kW, some materials experiments may only require this capacity for a few minutes. In such cases, the thermal mass of the platform might be sufficient to limit the maximum temperature rise. Thermal simulation of individual experiments must be performed to determine the correct number of cooling panels. Similarily, each experiment must be considered on an individual basis to circumvent the vacuum/venting problem. It is anticipated that fluid science, biochemical, or biological experiments would be more likely candidates for early utilization of the MGIM.

Acknowledgment

This work was performed under European Space Agency Contract 7637/88.

References

[1]Owen, R. G., Jones, D. I., and Owens, A. R., "Integration of a Microgravity Isolation Mount within a Columbus Single Rack," *Acta Astronautica,* Vol. 22, No. 1, 1990, pp. 119–128.

[2]Owen, R. G., and Jones, D. I., "Columbus Applications Study," Univ. of Wales, BTN001, Bangor, Wales, UK, Sept. 1988.

[3]Jones, D. I., Owens, A. R., Owen, R. G., and Roberts, G., "Microgravity Isolation Mount: Phase 1 Design Report," ESTEC, Contract 7637/88, Noordwijk, The Netherlands, Sept. 1989.

[4]Owens, A. R., "Calculation of MGIM Cooling by Thermal Radiation," Univ. of Wales, BTN004, Bangor, Wales, UK, March 1989.

[5]Pahling, W., "Columbus Environment and Test Specifications," MBB/ERNO Document No. SPE 1211363, Bremen, Germany, Jan. 1989.

[6]Owen, R. G., and Roberts, G., "Detailed Definition of MGIM Concept," Univ. of Wales, BTN005/B, Bangor, Wales, UK, Jan. 1990.

[7]Jones, D. I, Owens, A. R., Owen, R. G., and Roberts, G., "Microgravity Isolation Mount: Phase 2 Design Report," ESTEC, Contract 6380/85, Noordwijk, The Netherlands, Feb. 1987.