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RESEARCH OPPORTUNITIES IN MICROGRAVITY SCIENCE AND APPLICATIONS DURING SHUTTLE HIATUS

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SUMMARY

The opportunity to conduct microgravity and related research still exists, even with the temporary delay in the U.S. Space Shuttle program. Several ground-based facilities are available and use of these facilities is highly recommended for the preparation of near and far term Shuttle or Space Station experiments. Drop tubes, drop towers, aircraft, sounding rockets and a wide variety of other ground-based equipment can be used to simulate microgravity. This paper concentrates on the materials processing capabilities available at NASA Lewis Research Center (NASA Lewis), Marshall Space Flight Center (MSFC), and the California Institute of Technology Jet Propulsion Laboratory (JPL). Also included is information on gaining access to these facilities.

INTRODUCTION

Gravity pervades all aspects of materials processing from the liquid or gaseous state. Gravity driven fluid flows redistribute dopant or alloy additions limiting crystalline perfection and device efficiency. The earthbound necessity of holding liquids in a container introduces both bulk contaminants and catalysts for premature nucleation. Subtle phenomena such as thermocapillary flow or critical point behavior may be largely masked by bouyancy driven flows. Other processes are especially difficult in our usual 1-g environment such as the growth of large diameter crystals by the float zone process or the production of stable metallic foams from the melt. For these reasons and many more, materials scientists, fluid physicists, combustion scientists, and biotechnologists view an orbital Shuttle or Space Station as an appropriate laboratory.

Given the high cost and limited accessibility of space it is axiomatic that ground-based research must proceed and accompany space processing. The early use of ground-based research facilities can sharpen the focus of microgravity research, enhancing the likelihood of profitable work in space. In some cases it is possible that ground-based research may even eliminate the need for on-orbit trials. In this paper ground-based facilities for microgravity materials science research are described. The use of these facilities is always recommended and recent difficutly with access to the Shuttle suggests greater attention be given to their potential.

The facilities described fall into one of three categories: those which provide an actual microgravity environment for a limited time such as rockets, planes, or drop towers and drop tubes; those which emulate one or more aspects of the microgravity environment such as electromagnetic or acoustic levitators; and those which may be used to further understand system behavior in or out of the microgravity environment such as model furnaces or computational facilities.

DROP TUBES AND TOWERS

Drop tubes are an expeditious way to study the effects of short term microgravity and/or containerless processing on melting and solidification of materials. Small material samples can be melted and then allowed to solidify during free fall. Most materials science drop tube experiments conducted thus far have studied the relationship between undercooling and material microstructure/properties. To accurately determine the direct amount of undercooling achieved, the temperature of the sample must be measured while it is in free fall. Optical pyrometry has been used because of its nonintrusive nature. A drawback is that the sensitivity of most detectors to thermal radiation below 1000 K is poor and limits experiments to higher melting point materials (ref. 1).

Drop Tubes

Currently there are five drop tubes available (see table I for user contacts). These range in length from 5 to 100 m. The drop tubes are discussed below in order of descending magnitude of free fall time.

The 100 m drop tube (ref. 4) located at the MSFC provides up to 4.6 sec of low gravity. A stainless steel bell jar mounted atop the tube contains the melting apparatus used to process the material samples. The tube/jar atmosphere can consist of argon, helium, helium with 6 percent hydrogen, nitrogen or the tube can be evacuated to a pressure of 1×10^{-7} kPa. These various gases are used to increase convection cooling required for lower melting point materials when radiation is not the predominant form of heat loss.

Acceleration of 10^{-6} g is obtainable during vacuum free fall. Larger accelerations (10^{-3} g) are observed in gaseous environments. Various methods are available to receive the falling samples via a detachable catching device. Deceleration media include diffusion pump oil, a copper block and various foils.

Infrared detectors mounted along the length of the tube are used to determine the onset of nucleation by sensing the increase in sample temperature as the heat of fusion is released (ref. 4).

Three types of melting apparatus are presently operational for use in conjunction with the drop tube. An electron beam bombardment furnace operates in the range of 1600 to 2500 °C and is for use under vacuum type conditions. An electromagnetic levitation furnace operates over the range of 500 to 3000 °C and can operate in either a vacuum or gaseous environment. Samples must be electrically conductive to electromagnetically levitate. A resistance heating capillary tube employing a quartz capillary crucible to contain the sample during melting may be used for nonconductive materials.

A 30 m drop tube is also located at MSFC. Capable of up to 2.6 sec of free fall time this tube possesses characteristics similar to the 100 m drop tube previously discussed. An air tight bell jar located on top of the tube contains the sample processing apparatus which may either be an electron bombardment furnace, a resistance heating capillary tube or any furnace which can be adopted to the bell jar (refs. 1 and 3).

Jet Propulsion Laboratory maintains a forced free drop tube that eliminates aerodynamic drag. By drawing air down the tube via a suction fan at the base, an acceleration is imposed on the air column due to the convergent nature of the tubes crossection. While in free fall the air and sample move at the same velocity. This helps eliminate aerodynamic drag and sample distortion although convective cooling is reduced. The facility provides up to 1.7 sec of free fall time. Principle research activities include the study of fluid surface phenomena and the formation and spheroidization of metallic and glass microballoons (ref. 2).

The cryogenic drop tube located at JPL allows up to 1.7 sec of free fall time under vacuum. Three separate temperature zones are consecutively located along the tube length for control of ambient gas temperature and density as a means of improving solidification. A balance between convection and radiation cooling is obtained by using cryogenic temperatures in one section of the tube. Internal gas pressure can be controlled between 10^{-5} and 200 kPa.

Located at NASA Lewis is a 5 m drop tube facility capable of 1 sec of vacuum free fall time. Temperatures from 700 to 4000 °C are measured optically by four high speed, two color optical pyrometers. An additional pyrometer mounted at the bottom of the tube will be used to observe samples while they fall during the entire drop. This is achieved by employing tracking optics and higher sensitivity pyrometers.

A 25 kW electromagnetic levitator (EML) is housed in a water cooled vacuum chamber attached to top of the drop tube. The drop tube/EML may be operated in a vacuum or an inert gas atmosphere. The chamber portion of this facility is approximately 75 cm in diameter and 45 cm deep. Different types of furnace devices, designed to fit in the vacuum chamber, are currently being developed for working with nonconductive samples. Up to 10 samples may be arranged on a computerized turntable assembly for serial processing during a single pump down cycle.

Currently under construction at JPL is a 14 m drop tube. This stainless steel drop tube will be capable of operation at pressures in excess of 10 atm or a vacuum of 10^{-7} kPa. External coolant tubes attached to the five lower drop tube sections provide control from room temperature to -180 °C. Each of these five 2.4 m sections can be individually temperature-controlled.

Drop Towers

Drop towers, as opposed to drop tubes, can accommodate large experimental drop packages consisting of sample processing and data acquisition equipment. Construction of these facilities began in the late 1950's and early 1960's when research programs were geared towards the study of propellant sloshing, settling, and draining (ref. 5). At present there are three drop towers of varying capability available for low-gravity experimentation (see table I for user contacts).

The two drop facilities at NASA Lewis have been widely used for combustion and fluid physics studies. The 30 m drop tower offers 2.2 sec of free fall behind a drag shield in air; the 145 m drop tower offers 5.2 sec of free fall in vacuum, with residual gas drag approximately 10^{-5} g. Both facilities can accommodate large packages, up to 70 and 450 kg respectively. Typical packages include high speed cameras, actuating systems, onboard power (28 V), and up to 18 channels of data transmission. Thus materials can be examined or affected (by radiation for example), during the drop. Technology has been developed for applying a very gentle controlled acceleration during drop to simulate the behavior of spacecraft. Evacuating the 145 m long, 9 m diameter tower limits the drops to one or two per day (the 30 m tower can provide as many as ten drops per day).

A 100 m drop tower, located at Marshall Space Flight Center, is currently used extensively for ground based research in microgravity science. The facility permits experimentation for a period of microgravity up to 4.27 sec and is capable of accommodating experimental packages as large as 0.76 m^3 and weighing up to 204 kg. The configuration includes a drag shield equipped with battery, electrical distribution, and telemetry system to meet experimental requirements. An auxiliary thrust is provided to overcome aerodynamic drag during the free fall period (ref. 6).

Current materials science interests in the drop facilities include the study of phase separation during polymerization, undercooling of metals, positioning of liquids for float zone solidification, containment of liquids for thermocapillary flow experiments, and weld pool behavior. Experiments at MSFC have shown that the containerless feature of drop tube processing is more important than the freedom from acceleration in attaining undercooling (ref. 4).

AIRCRAFT AND SOUNDING ROCKETS

Aircraft

NASA uses three aircraft for microgravity research (see table I for user contacts): the KC135 and F-104 both stationed at MSFC, and a Model 25 Learjet stationed at NASA Lewis. The KC-135 cargo jet has the largest carrying capacity with a 3 by 16.4 by 1.8 m bay size. The KC-135 is capable of up to 40 floats per flight with free float time ranging from 5 to 15 sec. The Learjet can provide up to six, 20 sec, low gravity parabolic flight paths per day for small and medium size attached packages only. The investigator may accompany and operate experiments on the KC-135 and the Learjet. Only fully automated very small, e.g. 15 kg, packages can be carried in the F-104, but low acceleration time can last up to 60 sec; one parabolic flight path per flight is available.

A typical low-gravity flight profile follows a parabolic trajectory consisting of a slight dive requiring a 2 to 3 g pullup followed by the ascent. When the aircraft reaches about a 50° ascent angle, a pushover maneuver is performed at which time the low gravity conditions begin (typically 10^{-1} to 10^{-3} g are the best low-gravity conditions obtainable).

Sounding Rockets

Originally used to develop and test experimental equipment, before the time of manned space flight, today the use of sounding rockets for microgravity materials science processing fills the gap between research performed on aircraft (maximum 60 sec of low-gravity) and research performed on the Space Shuttle (days of low-gravity). A family of suborbital sounding rockets capable of up to 275 kg payload provide typically 4 to 7 min of accelerations remaining below 10^{-4} g (ref. 7). These conditions exist during the unpowered coast phase after launch and before re-entry into the atmosphere (see table I for user contact).

ADDITIONAL FACILITIES

The facilities described above provide an actual microgravity environment for a limited amount of time. But, as will be explained, it is not necessary to be in a microgravity environment in order to study the effects microgravity has on material processing. For example, convection free solidification may be studied in orbit or in 1 g environment. Emulating microgravity convection in conductive melts can be accomplished by the imposition of a steady magnetic field to dampen fluid flow. Bouyancy driven convection in binary liquid systems can be reduced by choosing liquids of nearly equal density.

The Microgravity Materials Science Laboratory established at NASA Lewis is available to scientists and engineers from industry, university, and government agencies nationwide. The laboratory is equipped with pieces of experimental hardware which (1) are functional duplicates of those flown on the Space Shuttle or being developed for use on future Shuttle/Space Station missions; (2) provide a temporary low-gravity environment; (3) emulate conditions of the low-gravity environment; (4) or provide 1 g testing and research capabilities for developing and/or expanding microgravity experimental ideas. The laboratory also provides a place where the process in question can be studied in detail and mathematical modeling employed to remove or enhance the effect of gravity.

Currently under construction at the MMSL is a high temperature Directional Solidification Furnace designed to perform experiments on metal samples. The sample is sealed in an ampoule (typically quartz) and the furnace coil/cooling assembly is moved along the length of the sample ampoule. The unique feature of this particular system is that the sample is exposed to a large magnetic field which is used to reduce convection as discussed above. Other MMSL equipment include electromagnetic and acoustic levitation systems, various resistance and induction melting systems and materials characterization support hardware.

The Jet Propulsion Laboratory hosts a variety of unique materials processing/handling equipment. The vertical and horizontal quadrupole levitators permit fine particles or liquid droplets to be positioned and transported in the vertical and horizontal directions respectively. The levitators operate in a high ac voltage mode which produces the electrostatic forces necessary to center the sub-millimeter samples within the 4 pole fields. The electrostatic-acoustic hybrid levitator also located at JPL is a general purpose, room-temperature system by which drop oscillation, rotation, and fission can be induced acoustically while a drop is being levitated in 1 g. Charged water or aqueous drops approximately 3 to 4 mm in diameter can be levitated with less than 3 percent loss in sphericity. Using this system experiments such as charged liquid drop dynamics or crystal growth from aqueous salt solutions can be performed. With minor modifications the present system can be adapted to a microgravity environment such as the KC-135 research aircraft. Presently under experimental study and development are a dual temperature acoustic levitator, a high temperature siren levitation facility and a high temperature, single-mode levitation facility.

Ground-based laboratory facilities located at MSFC support a multitude of material processing capabilities. Containerless processing facilities include an airjet levitator which uses a compressed air stream to levitate material samples. During levitation the samples can be melted with a 700 W CO_2 laser (up to 2700 °C) and then allowed to resolidify without the physical contact of a containment vessel. An electromagnetic levitator with electron bombardment heating has been used successfully to levitate and melt tungsten and is capable of similar experiments in containerless processing of refractory metals. A single axis acoustic levitation system is capable of levitating samples as large as 3 mm having a density of 3.8 g/cm^3. Temperatures above 1000 °C have been achieved.

In addition to these ground based levitation facilities, MSFC maintains various microgravity apparatus used aboard the Space Shuttle for material processing experimentation. Ranging from crystal growth equipment to devices for separation of biological materials, many of these systems may also be operated in an earth-based mode to develop and prepare experiments for space flight.

CONCLUSIONS

The facilities available for ground-based microgravity research have been described. Table I contains a guide intended to help those interested individuals obtain additional information regarding the facilities and equipment discussed in this paper.

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TABLE I. - MICROGRAVITY MATERIALS SCIENCE FACILITIES

Facility	Location	Contact
Additional facilities		
Microgravity Materials Science Laboratory	NASA Lewis	Thomas Glasgow (216) 433-5013
Marshall Space Flight Center	MSFC	Richard E. Black (205) 544-1983
Jet Propulsion Laboratory	JPL	Daniel D. Elleman (818) 354-5182
Drop tubes		
100 m	MSFC	Michael B. Robinson (205) 544-7774
30 m	MSFC	Kenneth R. Taylor (205) 544-0640
13.1 m Force free	JPL	Charles L. Youngberg (818) 354-3559
13.1 m Cryogenic	JPL	Charles L. Youngberg (818) 354-3559
5 m	NASA Lewis	Thomas Glasgow (216) 433-5013
Drop towers		
145 m	NASA Lewis	William Masica (216) 433-2864
100 m	MSFC	William F. Kaukler (205) 544-7782
30 m	NASA Lewis	William Masica (216) 433-2864
Research Aircraft		
KC-135	MSFC	Peter Curreri (205) 544-7763 Robert E. Shurney (205) 544-2189
Learjet	NASA Lewis	William Masica (216) 433-2864
F-104	MSFC	Kenneth R. Taylor (205) 544-0640
Sounding rockets		
Contact Office of Space Commercialization	NASA Lewis	Anthony F. Ratajczak (216) 433-2921

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16. Abstract

The opportunity to conduct microgravity and related research still exists, even with the temporary delay in the U.S. Space Shuttle program. Several ground-based facilities are available and use of these facilities is highly recommended for the preparation of near and far term Shuttle or Space Station experiments. Drop tubes, drop towers, aircraft, sounding rockets and a wide variety of other ground-based equipment can be used to simulate microgravity. This paper concentrates on the materials processing capabilities available at NASA Lewis Research Center (NASA Lewis), Marshall Space Flight Center (MSFC), and the California Institute of Technology Jet Propulsion Laboratory (JPL). Also included is information on gaining access to these facilities.

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