ADVANCES IN CERAMICS • VOLUME 5

MATERIALS PROCESSING IN SPACE

Edited by Bonnie J. Dunbar

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The American Ceramic Society, Inc.
Columbus, Ohio

Proceedings of a special conference held at the Convention-Exposition Center, Cincinnati, Ohio, May 4-5, 1982, during the 84th Annual Meeting of the American Ceramic Society.

Library of Congress Cataloging in Publication Data

Main entry under title:

Materials processing in space.

(Advances in ceramics, ISSN 0730-9546 ; v. 5)

"Proceedings of a special conference held at the Convention-Exposition Center, Cincinnati, Ohio, May 4-5, 1982, during the 84th Annual Meeting of the American Ceramic Society"—T.p. verso.

Includes bibliographies and indexes.

1. Space stations—Industrial applications—Congresses. I. Dunbar, Bonnie J. II. American Ceramic Society. Annual Meeting (84th : 1982 : Cincinnati, Ohio) III. Series.

TL797.M327 1983 666'.1 83-21416

ISBN 0-916094-51-0

Printed in the United States of America.

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Volume 1 Grain Boundary Phenomena in Electronic Ceramics

Volume 2 Physics of Fiber Optics

Volume 3 Science and Technology of Zirconia

Volume 4 Nucleation and Crystallization in Glasses

Contents

PREFACE

On May 4, 1982, the National Institute of Ceramic Engineers and the National Aeronautics and Space Administration sponsored a special coloqium on Materials Processing in Space (**MPS**) at the Annual ACerS meeting in Cincinnati, Ohio. It was the first time that representatives from the United States, Japan, and Europe had met in the United States to present overviews and technical papers on their respective programs. The purpose of the coloqium was to acquaint members with current advances in the processing of materials in a microgravity environment and to stimulate discussions within the ceramic industry on its potential application to the state-of-the-art processing and future research activities. At the time of that meeting, NASA had just finished launching its third space shuttle. As this volume is prepared for press, NASA readies for its eighth flight using space shuttle *Challenger* and its ninth using space shuttle *Columbia. Columbia* will carry the European Space Agency's (ESA) *Spacelab,* the first European payload specialist, and over 30 experiments in materials processing. *Spacelab* will fly in 1984 with US experiments in MPS, and in 1988 Japan plans to utilize the Spacelab for materials experiments, (also flying their own payload specialist.) In the interim, private industry and other researchers are also utilizing get-away specials, materials processing pallets, their own unique hardware, or a free-flying carrier to conduct experiments or produce products. The study of MPS has progressed from one of limited scope and resources to one of far-reaching benefits to both commercial and research users. The commercial production of materials in the microgravity environment of Space will very likely be a significant activity of a United States Space station in the 1990s.

This volume of Advances in Ceramics should be considered an introduction to the study of materials processing in Space as well as a collection of technical papers which were presented at the colloqium. An overview of the space shuttle system, avenues for experimentation, and a theoretical consideration of the liquid forces in microgravity are also presented. As is reviewed in the technical papers, the microgravity environment of Space offers several advantages in studying physical and chemical phenomena and in preparing materials which are prohibited in the gravity field of Earth. Some of these advantages include (1) absence of thermal and solutal convection and sedimentation, (2) containerless processing in order to eliminate contamination and heterogeneous nucleation, and (3) lack of hydrostatic pressure effects and deformation at high temperatures. In addition, research in the microgravity environment of Space will increase our fundamental understanding of the behavior of materials, so that processes restricted to Earth may be enhanced. Those areas of science already benefiting from Space studies include continuous flow electrophoresis, semiconductor technology, and crystal kinetics.

As with all new fields of study, the successful utilization of the microgravity environment of Space will depend on an understanding of both its benefits and limitations. There is yet much work to be done in understanding all the driving forces in chemical kinetics which are normally masked by the force of gravity. However, there are many scientists and engineers, both in the United States and in other countries, who believe we are embarking upon the next era in Space industrialization.

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Space shuttle: a new era

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In less than one generation, we have progressed from the first powered flight on December 17, 1903, to a landing on the moon 66 years later, to the first flight of a reusable vehicle on April 12, 1981. The U.S. space shuttle represents the beginning of a new era in transportation and is the critical element in the industrialization of the near-Earth space. Most of its flights are dedicated to reducing costs of launching commercial satellites, a "business" for over 20 years. However, it is the potential for processing unique and improved materials in a microgravity environment which is currently generating interest in both civilian and military sectors and internationally. The space shuttle is also the necessary step in establishing a permanent Space station which could potentially host orbiting materials analysis laboratories and commercial processing facilities. This paper reviews the different elements of the space shuttle transportation system, chronicles the successful commercialization of the satellite communications industry, and discusses current and future activities in Materials Processing in Space (MPS).

The space shuttle may be a venture unique in technology but not in philosophy. "Space," if we define it as an extension of airspace into two broad bands: (1) near-earth Space up to 500 nautical miles (nm) and (2) geosynchronous orbit at 23,000 nm, has been a business arena for over 20 years. NASA has and continues to launch a variety of satellites for the commercial communications industry, the Department of Defense, and other users. The satellites have been invaluable for communications, remote sensing, navigation, and weather forcasting. The types of payloads typically launched are shown in Table I. Most of them are reimbursable to NASA for launch costs and each requires the use of an expendable booster costing several million dollars.

However, expendable boosters have several limitations which can be eliminated through the use of a reusable launch vehicle, including: (1) weight and size constraints. Quite often the amount of power that can be put into a satellite in the form of batteries or solar power is limited by size and weight. (2) No predeployment check-out. Once launched, there is no means to check or repair a satellite. Therefore, much of the cost of developing a satellite must be invested in expensive redundant systems and, if the satellite fails in orbit, there is no way to retrieve or repair it.

The space shuttle will change all of this; about the size of a DC-9 jetliner, it is designed to carry multiple payloads in a cargo bay 18 m long and 4.5 m in diameter. It can launch with 29,484 kg and return with 14,515 kg.

Once established in orbit, the satellite can be checked via ground transmission or on board by the crew. In any case, it will not be released to orbit until operationally certified.

No example is more illustrative of the commercialization of Space than that of the commerical satellite.

On August 12, 1960, the U.S. launched the passive communications satellite, ECHO-1, and later, on October 4, 1960, the first active communications test satellite, COURIER-1. The venture with communications satellites proved to be so successful that on July 10, 1962, NASA launched the first commercial communication test satellite, TELESTAR-1. TELESTAR-1 was built, launched, and financed through a joint agreement with American Telephone and Telegraph (AT&T). On August 31, 1962, President John F. Kennedy signed into law the Communications Satellite Act. The result was a new government-chartered corporation, Communications Satellite Corporation (COMSAT), to be a government-regulated but privately owned corporation. In a unique arrangement, communications companies such as AT&T, General Telephone, ITT, and others were permitted to purchase and own up to 50% of the common stock of COMSAT. The remaining 50% was offered to the general public.

COMSAT spent this equity capital on a series of constantly improved larger communications satellites and on an expanding system of ground stations. After six years, COMSAT became a dividend-paying operation and now is the general managing agent of INTELSAT, an international consortium of 102 nations.

COMSAT also operates a maritime communications satellite system called "Marisat" and a domestic system called "Comstar." Another venture, Satellite Business Systems, which was formed as a partnership between COMSAT General, Aetna Life and Casualty, and IBM, provides a communications system for large companies and the government.

Currently, NASA launches communications satellites on expendable boosters for COMSAT, INTELSAT, various U.S. companies, and several other countries, including Japan, India, Indonesia, Canada, and Great Britain.

Furthermore, this business is expanding. Within the last two years, 13 companies have joined COMSAT in seeking authority from the FCC to launch direct broadcast satellites. Eleven of the applicants who added 31 requests for launch premits included CBS, Inc., Home Broadcast Television Partners, National Christian Network, Inc., Unitel Corp., and Western Union Telegraph.

The communications satellite has provided concrete economic gains for its users and has facilitated the development and education of Third World countries. Union Carbide has reduced its long-distance telephone bill by $1,884 per month by shifting its land-line system to RCA communication satellites. The company uses satellite transmission for teletype communication as well as voice. In many parts of the world, a communication satellite is the only practical way to link populations. Indonesia, with its 13,500 islands, has financed its own communications satellites called PALAPA-A and -B. Forty ground stations have tripled the nation's telephone service and are providing telephone, telegraph, television, and radio service to all 26 provinces, extending elementary education to 85% of the nation's youth, and speeding development of its natural resources. A consortium, headed by the Bank of America, financed the satellites and Indonesia is paying its bill through the Export-Import Bank.

(Palapa-A was launched on the seventh shuttle flight in June 1983, and Palapa-B will be launched early in 1984.)

The space shuttle will accommodate more than satellites; it is capable of carrying an orbiting laboratory and conducting Earth observation, solar physics, and materials-processing experiments, and will be instrumental in the construction of large Space-based structures, such as the Space Operations Center (SOC), currently being reviewed by the Office of Management and Budget (OMB). Space shuttle is the inevitable step in near-Space utilization. It represents the start of a new era, no less important than the first flight of the Wright brothers.

The space transportation system

The new era in Space opened at 1:21 pm, EST, April 14, 1981. At that time, the crew of the space shuttle orbiter *Columbia*—John W. Young, commander, and Robert L. Crippen, pilot—landed on the hard-packed bed of Rogers Dry Lake in California's Mojave Desert, after a 54.6-hour flawless voyage into Space (Fig. 1). It marked the first time a spacecraft had made an airplane-like landing from orbit. Moreover, *Columbia* appeared hardly the worse for wear after surviving atmospheric reentry temperatures >1600°C. The space shuttle thermal protection system (TPS), largely low-density ceramic tiles, was only one of several technology innovations demonstrated by *Columbia*.

The space shuttle is the principal element of the Space Transportation System (STS), which is being built by over 180 United States subcontractors with some key elements provided by the European Space Agency and Canada. The collective components of STS are (1) the orbiter and launch boosters, (2) the ESA *Spacelab*, and (3) upper stages which are used to boost satellites into geosynchronous orbit, i.e. the altitude at which an orbiting body remains over a fixed point on Earth.

Space Shuttle. The space shuttle is composed of the orbiter, manufactured by Rockwell International, Downey, California, an external tank (ET) manufactured by Martin Marietta, Denver, Colorado, which contains the liquid hydrogen and oxygen propellants used by the orbiter's three main engines (SSME) manufactured by Rocketdyne Div., Rockwell International; and two solid rocket boosters (SRB) manufactured by the Thiokol Corp., Utah. The orbiter and SRBs are reusable. The solid rocket boosters which were launched with *Columbia* were recovered in the Atlantic off Daytona Beach and, following minimal refurbishment, will be returned to operational status. The external tank is expended on each launch, although its future utilization on orbit is being evaluated.

The orbiter's exterior is covered with a thermal protection system which protects against both solar radiation and the heat of atmospheric reentry. Over 60% of the orbiter's surface area is protected by coated SiO_2 fiber tiles with densities of 0.144 and 0.352 g/cm³ (9 and 22 lb/ft). On *Columbia* the high-temperature reusable surface insulating tiles (HRSI) were nominally 15.24 by 15.24 cm and varied in thickness from 1.90 to 9.52 cm. The thickness and density of the tiles were optimized to minimize orbiter weight and to prevent the aluminum substructure from experiencing more than 176°C during peak reentry heating. In addition to surviving extreme thermal excursions, the tiles must withstand launch acoustic environments up to 165 dB.

In general, the TPS has been designed for ease of maintenance and for flexibility of ground and flight operations, while satisfying its primary function of maintaining acceptable airframe outer-skin temperatures.

The orbiter can carry up to seven personnel in its two-level cabin. The flight deck (Fig. 2) contains the controls and displays used to pilot, monitor, and maneuver the orbiter as well as payload controls. Seating for the crew is provided on this level. The lower or mid-deck contains living quarters, including a galley for food preparation, an eating area, personal hygiene facilities, and sleeping accommodations. Current mission scenarios provide for a maximum duration of 30 days.

Below the mid-deck is the environmental control equipment which is readily accessible through removable floor panels.

Electrical power for the space shuttle and the payloads is generated by three fuel cells which use cryogenically stored hydrogen and oxygen. The quantities of fuel (H_2 and O_2) normally carried will be enough to generate ≈ 1530 kWh energy. The by-product of chemical conversion, water, is used for human consumption.

The orbiter data processing system (DPS) provides monitoring and control for the orbiter. It consists of five IBM general-purpose computers (GPC) for computation and control, two magnetic-tape mass memories for large colume storage, time-shared serial digital data buses to accommodate data traffic between the computers and orbiter systems, 19 multiplexer/demultiplexers, three engine interface units to command the SSMEs, and four multifunction CRT display systems for crew interface. In-flight software programs monitor the status of vehicle systems; provide consumable computations; control operations of the payload bay doors and the remote manipulator; perform fault detection and annunciation; provide for payload monitoring, commanding, control, and data acquisition; provide antenna pointing for communications systems; and provide primary and backup guidance, navigation, and control for ascent, on-orbit, landing, and abort mission phases.

The software programs are written so that they can be executed by a single GPC or by several concurrently. Redundant computers are used in critical phases such as launch, entry, and aborts. The CRTs are interactive via a keyboard and present both dynamic digital data and graphics.

The broad spectrum of shuttle missions requires that the orbiter accommodate many types of payloads. Numerous points along the cargo bay provide for physical attachment and interfaces with electrical and communication (telemetry and command) systems. In addition, payload-dedicated cargo such as the remote manipulator system (RMS) being built by SPAR, Toronto, Canada, is carried in the bay. The RMS is a mechanical arm which maneuvers a payload from the bay to its deployment position and releases it, or grapples a free-flying payload and berths it.

Spacelab. *Spacelab* (Fig. 3), a modular space laboratory built by a consortium of 11 European nations under the guidance of the European Space Agency (ESA), will enable both academic and industrial research establishments to conduct experiments in orbit for up to 30 days. Both European and U.S. payload specialists will conduct investigations in biological medicine, materials processing, earth observations, and many other areas.

The NASA-ESA agreement for *Spacelab* represented a major step in the sharing of space costs. The estimated cost of *Spacelab* to be borne by ESA member nations is calculated at approximately $400,000,000. The module, which is not deployable from the orbiter, has a design lifetime of 50 missions or 5 years. Nominal mission duration is seven days. In addition to the pressurized module which provides a laboratory with shirtsleeve environment, there are several open pallets which expose materials and equipment to Space. Approximately 15 flights, beginning in 1983, are scheduled through 1986.

Upper Stages. Two upper stages are currently being designed for shuttle use: the spin-stabilized upper stage (SSUS), and the inertial upper stage (IUS). Payloads with requirements for geosynchronous orbit, deep-Space missions, elliptical orbits, and higher circular orbits will require an additional propulsive stage. Shuttle will deliver the payload with its upper stage to near-Earth orbit (normally about 150 nm) and stand by until a successful on-orbit launch is completed.

Mission scenario

By 1985, the United States will have an operational shuttle system. Current payload demands (Table II) extend at least that far. To demonstrate all the capabilities required by government, civilian, and military entities, NASA embarked on a graduated flight test program. The first four flights were designed to sequentially expand the operational envelope, each successive flight more complicated than the last. The fifth flight has been designated as the first fully operational flight, although active payloads are being carried on the second, third, and fourth flights.

The first flight, as designed, demonstrated the capability to safely launch, operate in orbit, and land. Additionally, various subsystems hardware and software were flight-verified. STS-1 was considered a highly successful flight.

A typical missison scenario is shown in Figs. 4 and 5. A space shuttle mission will begin with installation of the payload into the orbiter cargo bay. The payload will be checked and serviced; only after reaching orbit will it be activated.

At lift-off the SRBs and main engines ignite to provide a combined thrust of 3.08×10^7 N. After ≈ 2 min at an altitude of 27 nm, the SRBs will burn out and be jettisoned. Relative velocity at this point is 4,625 km/h. The main engines continue to burn from the ET until ≈ 8.75 min from lift-off. Main engine cutoff occurs at an altitude of 60 nm and an inertial velocity of 26,715 km/h, 1,363 nm downrange over the Atlantic Ocean. However, the shuttle is in an 80 by 13 nm elliptical orbit. To attain a desired apogee and perigee of 150 nm (nominal), two insertion burns (Hohmann transfer) are made with the two orbital maneuvering engines (OMS). The final insertion burn is completed at 45.25 min into the mission. Each subsequent revolution of the earth takes ≈ 90 min.

Once established in orbit, the payload bay doors are opened, both for exposing the payload and for allowing deployment of the heat-rejecting radiators. Reaction control thrusters (RCS) provide attitude control and precision velocity changes for rendezvous and docking. They also operate in tandem with the aerodynamic control surfaces during the early portions of entry.

Payload operations in orbit may be multiple, depending on the mission objectives: retrieving or servicing satellites, deploying satellites, conducting experiments, or constructing Space platforms.

After orbital operations are completed (1 to 30 days), deorbiting maneuvers will be initiated with the OMS engines. After a retrograde tail-first firing, the RCS thrusters will turn the orbiter nose forward for entry.

Guidance, navigation, and flight control software for the entry phase are initiated by the flight crew ≈5 min before entry interface (EI), an altitude defined as that at which aerodynamic forces can be sensed. EI occurs at 65.8 nm over the western Pacific Ocean, 4,300 nm from Edwards Air Force Base, and just 32 min from touchdown.

Just prior to EI, the orbiter is maneuvered into a predetermined attitude: roll and yaw equal to zero degrees and a variable angle of attack. In the initial development flight tests, the angle of attack is 40°, but this angle will vary in subsequent missions as the entry thermal envelope is enlarged.

Descent rate and downranging are controlled by bank angles: the steeper the bank angle, the greater the descent rate and drag. Cross range is controlled by bank reversals. The entry thermal control phase is designed to keep backface temperatures within design limits. During STS-1, peak heating of the orbiter lower surface occurred from EI plus 5 min to EI plus 15 min and averaged 60 Btu/ft²/s. Because of the heat generated as the spacecraft enters into the atmosphere, a shield of ionized air is formed which prevents communication. This period of communications blackout lasts ≈15 min.

The fundamental guidance requirement during entry is to reach a target called the terminal area energy management interface (TAEM) at 25,298 m altitude, 762 m/s velocity, and on-range 52 nm from the landing runway. From an orbital velocity of >26,000 km/h the orbiter dissipates its energy to touchdown at a speed of 335 km/h, and at a sink rate of <0.5 m/min.

Although the test flights will continue to land in the Mojave Desert, the primary shuttle landing facilities are planned at Kennedy Space Center in Florida and Vandenberg Air Force Base in California, with several alternate landing sites available for contingencies.

Following landing and mission completion, the orbiter will be towed to ground facilities, where any returned payload will be removed. Orbiter turnaround operations, which follow, are currently being optimized to approximately two weeks.

The Johnson Space Center in Houston, Texas, will remain the primary operations center for the space shuttle. However, the real-time flight control support we see today in mission control is likely to decrease as the orbiter becomes more autonomous. During mature operations, most communications are likely to be with payload or user representatives.

Materials processing in space—a commercial venture

Utilization, industrialization, and habitation have followed exploration throughout the history of mankind. Similarly, with the advent of routine operations in Space comes the unique opportunity to utilize the Space environment for both Space and terrestrial applications. One promising arena of Space application is the new field of "materials processing in Space" (MPS).

The interest in the behavior of materials in low gravity grew out of a variety of disciplines. The earliest and most compelling need to understand fluid behavior in a spacecraft grew out of the propellant management program. This effort spawned a number of excellent studies of fluids dominated by surface tension and inertia in partially filled containers. Studies on the erection of large Space structures prompted research on the behavior of metals during welding and brazing processes in low gravity. It was recognized that the low-gravity environment offered unique advantages for processing metals in their molten state, and a number of manufacturing processes to be operated in Space were postulated for the production of improved or unique products.

Several demonstration experiments were carried out during the *Apollo* flights where it was shown that, in the absence of gravity, heat flow in fluids is predominantly by conduction. It was also found that flow in a simple static electrophoresis demonstration experiment resulted from electroosmosis.

Skylab offered the first opportunity to carry out extensive experiments in Space processing of materials. A total of 15 experiments and 9 demonstrations was conducted. The complement of experiments included crystal growth, metal composites, eutectics, welding and brazing, fluid effects, and combustion processes. The *Apollo-Soyuz* test project (ASTP) carried 12 Space processing experiments and 3 demonstration projects. Several were similar to the *Skylab* experiments where verification and refinements were required. In addition, two electrophoresis experiments were attempted on ASTP.

To provide some continuity between the ASTP flight and the advent of the shuttle, NASA-Marshall Space Flight Center established the SPAR sounding rocket program in 1975. The *Black Brandt* rocket, launched from the White Sands Missile Range in New Mexico, was to provide a number of short duration (5 to 7 min) flight opportunities to several investigators so that they could continue their low-gravity research. It was also an opportunity to develop concepts and techniques which could be applied to later shuttle flights.

The low-gravity environment on SPAR was found to be excellent; levels of 10^{-5} to 10^{-6} G were maintained during the coast period. However, the short duration and harsh launch environment, including spin-up and spin-down, provided a real challenge for experiment design and limited what was accomplished scientifically. Despite these limitations, SPAR has been successful in maintaining a cadre of experienced groups interested in conducting materials research under low-gravity conditions. Considerable experience has been gained in developing and testing new hardware, and an impressive inventory of off-the-shelf hardware has been built up that can also be used to conduct longer-duration experiments which will be flown on a space-available basis during shuttle operations.

SPAR flights are expected to continue until the advent of the materials experiment assembly (MEA) to be used on shuttle missions. A version of MEA flew on STS-7. (Fig. 6). MEA is a self-contained experimental package with its own power source, heat rejection capability, and processing ap-