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OPPORTUNITIES FOR COMMERCIAL PARTICIPATION IN MICROGRAVITY MATERIAL PROCESSING

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ABSTRACT

Signifying the evolution and confidence of our Nation's space effort has been the relatively recent involvement of both large, well established commercial firms as well as the newly created, almost unknown companies in space research of new materials and processes. The dynamic mechanisms of our capitalistic society are now at work in the continuing adventure of space.

The challenge to NASA is to provide the most appropriate business environment to these pioneering firms, at a cost which can be financially acceptable to both NASA and each company.

This paper describes the existing facilities and procedures which are being used by these companies as stepping stones to space and to full commercial production in space. It introduces some of the potential programs and procedures which, if adopted and implemented, could lead quickly to even greater participation of commercial firms in space.

INTRODUCTION

The dramatic advances in science and technology in our generation are derived in large measure from the development of new, advanced techniques of research. The capability of space flight opens up an entirely new field of advanced research techniques - microgravity research. Free from the influence of
gravity, entirely new techniques for manipulating materials, investigating phenomena, and exploiting basic processes are made possible. The microgravity environment of space has already been shown to have novel and potentially exploitable effects on key phenomena involved in technologically important processes.

NASA's microgravity science program had its beginning in the later Apollo flights and Skylab where simple demonstrations were performed. Later experiments were flown on the Space Processing Applications Rockets (SPAR), aircraft, and Space Shuttle flights. In the future, more work is planned when the Space Station becomes a reality.

With the Space Shuttle, a new era of space transportation has come into being. Its ability to transport sizable cargoes to and from orbit promises to increase the effectiveness of using space for scientific and commercial needs. The realization of this promise requires that the impressive capacity of the Shuttle be used effectively. Several locations in the Shuttle afford accommodations in varying degrees to perform materials research in the environment of microgravity.

One process has already produced a space product having application on Earth. This is the monodisperse latex microspheres processed on the Space Shuttle in the Monodisperse Latex Reactor (MLR). The MLR illustrates vividly that unique products which have application in today's society can be produced in space. It is expected that other applications using these space-produced microspheres will evolve.

In the past twenty (20) months or so the number of approved joint agreements has grown from three (3) to twenty (20). In addition, about fourteen (14) more agreements are pending.

In order for others having ideas for space applications to understand the facilities and services available to them at NASA, this paper gives an overview which describes both the existing facilities and discusses some of the developmental considerations one must evaluate in order to successfully utilize a low-gravity environment.
STIMULATING COMMERCIAL USE OF SPACE

The scientific and technological benefits which can be derived from the use of low-gravity are fundamental in nature and will surely result in significant improvements in material utilization and producibility; the potential economic benefits are expected to be substantial and viable. However, utilization of this new technology must be approached with deliberation and sound realism. It is necessary that we in NASA and industry construct well coordinated and thorough research programs.

In early work there was considerable emphasis on investigating material processes in suborbital and orbital experiments that could rapidly lead to the production of commercially viable products in space. While a number of interesting results were obtained, it became clear that much more sophistication was required in process control and diagnostics, particularly with regard to the control and measurement of thermal gradients and quenching rates used in many of the processes. For example, sample preparation was found to be especially critical in the control of oxide formation or to completely homogenize a specimen. In containerless processing, much has been learned about the precise positioning and rotational control needed to prevent the sample from contacting the levitating device, as well as disruptive accelerations and unwanted stirrings within the sample. Better methods for obtaining flow and temperature fields were found to be necessary in order to observe what is happening during a process. Present scientific and technological work sponsored by NASA concentrates on the identification of basic process mechanisms and gravitational influences on these mechanisms. Examples of areas in which NASA-sponsored work are presently being carried out are shown in Figure 1.

For several years NASA has been posturing itself to interface with and stimulate commercial interest in utilizing the low-gravity environment of space (ref. NASA Task Force report on commercialization). These commercial interests in space vary from obtaining new technical knowledge to producing unique products in space for sale on Earth. The foundation of NASA's program is its applied research program where scientific work is sponsored at universities and companies and in-house NASA research. Included in NASA's research program are the areas of bioseparation, electronic materials, glasses, metals and chemicals. NASA actively publishes results of these efforts in
scientific journals, in brochures, and participates frequently in technical meetings and symposia. The Agency has made available a film which illustrates the results obtained thus far within these technologically important fields of research. NASA has maintained a vigorous flight experiment program for several years, although there was a lack of ample flight opportunity in space between the Saturn and Space Shuttle programs. The Skylab and Apollo-Soyuz Test Project missions carried several microgravity materials experiments.

NASA continues to welcome direct interaction with interested commercial firms. NASA is also looking at ways to streamline the flight requirements it places on users, such as interface control (mechanical fit, electrical compatibility, thermal dissipation, etc.) which must be compatible with the particular flight vehicle of interest.

Whenever substantial work such as preliminary design, concept development, flight accommodation analysis and manifesting on a Shuttle flight are required, some form of a written agreement is required. Examples of current agreements are: (1) Memorandum of Understanding (MOU), (2) Technical Exchange Agreement (TEA), and (3) Joint Endeavor Agreement (JEA). MOU's are most appropriate when concept development work is involved; JEA's are the most formal and are utilized for process development flights on the Shuttle.

NASA is willing to negotiate flight opportunities on the Space Shuttle to firms having a desire to perform research in space in exchange for a commitment of resources by that firm. NASA encourages firms to build their own apparatus and may request partial use of it in exchange for flight opportunities. Also, NASA is developing an inventory of apparatus so that the entrepreneur can concentrate his efforts on his sample for research investigations where there is sufficient industrial interest and participation. Ideas of this kind are under discussion at the present time. In any event, it should be recognized that NASA is actively posturing itself to foster private sector involvement in space.

One might ask why are MOU's, TEA's, and JEA's required? The microgravity materials processing in space activities have proven to be very different from other disciplines such as Earth resources or astronomy. This is because of the different infrastructure in these technical disciplines and because so
many differing processes are involved that the apparatus can have broad differences in size, power consumed, etc. Typically, an entrepreneur hears about the microgravity possibilities and brings his idea to the table without a 25-year history of space flight; therefore, the development status of his apparatus may compare with optical or communications payloads flown in the late fifties and early sixties. His knowledge of the services available and constraints during flight may be limited. Assuming that his idea is a good one, he normally is not ready to give firm requirements for, say, a Shuttle accommodation analysis. Perhaps his best initial activity would be to use ground-based facilities such as the drop tower. In any event, a certain amount of concept development work is needed and should be accomplished with flight experiences and economic considerations in mind.

Often, a trivial secondary aspect of a ground process in one-gravity becomes a near "show stopper" in zero-gravity. For instance, fluid management can be a challenge where crystal growth processes are employed that do not allow contact with a seed crystal except during growth.

Some microgravity processes are power intensive. This can be of paramount importance in planning a space experiment, because power and heat rejection capability are limited on current space vehicles. For example, bulk crystal growth of electronic materials normally requires large amounts of power. The labor and overhead associated with the development of apparatus is usually not trivial so costs are often underestimated, leading to a costly front-end investment.

DISCUSSION OF GOVERNMENT'S ROLE AND CORPORATE RISK

Industrial organizations considering commercial space ventures will normally examine the technical and financial risk assuming there are no legal barriers present. Front-end expenditures both in terms of rate of expenditure and time over which the expenditures are made are crucial considerations for a prospective venture. Technical and financial risk tend to be large, if the venture requires long periods of time through proof-of-concept. This implies a long time before payback. Therefore, two kinds of activity within NASA drastically affect the attractiveness of a potential venture: the status of
research and development on the microgravity processes being considered, and the hardware integration time associated with flying on a manned vehicle. It is crucial to the microgravity program that a strong research base be maintained by NASA and that "fast-track" integration times be used. Quick turnaround between flights is also necessary.

With the above thoughts in mind, industrial firms should periodically review the MPS program in order to take full advantage of the hardware and science advancements. By utilizing what is available, considerable reductions in initial investment and risk may be realized. Another key point is that microgravity science endeavors should be viewed in the systems's context as outlined in Figure 2.

Figure 2 is proposed as a working model of R&D activities leading to potential commercial space endeavors for two reasons. One is that it employs the systems approach which we are all familiar with, since it is basic to any technical endeavor. The second is that this approach led to NASA's first successful joint endeavor. On the right side of Figure 2 are listed the various results using this approach on the biological purification process. These results were sufficient to engage the interest and participation of an industrial firm in a further developing process.

This is, in fact, the general process of how an advanced R&D program works. Now, let us consider how potential industrial users might take advantage of it.

The Return on Investment (ROI) curve is a key tool for the evaluation of a proposed endeavor. Figure 3 shows two typical space R&D projects - one starts with no precursor work; the other has been partially worked through the system outlined in Figure 2.

Figure 3 compares cash flows and cumulative cash flows for a typical R&D product, both with and without prior front-end R&D typically done by NASA's microgravity science program as outlined in Figure 2. Without this precursor work (top of Figure 3), industry would make all up-front investments and would realize a payback point of T. In most cases, however, T will be too long for industry because many sequential steps are required for a space product to evolve from the research phase
to the commercialization phase. If, however, the user exploits the front-end R&D done by the NASA Microgravity Science Program, the resultant industry payback period can be reduced significantly as indicated at the bottom of Figure 3. There is a question of how much seed work should be done by NASA or where "to draw the line." Also, shortening the payback period with fast-track hardware integration is a must.

By investing a relatively modest amount of money in the early phases of a venture, the government can significantly reduce the downside risk of private industry and shorten the payback period. These factors would make potential space ventures appear more like normal Earth-based high technology ventures.

Since microgravity materials processing for commercial purposes is such a revolutionary new concept, government leadership is initially required to establish a firm research base and to supply the initial operating base of space transportation and utility systems.

Such government investments have traditionally been made to shorten the time between the discovery of new knowledge and the exploitation of that knowledge. Atomic energy is a case in point. Investments of this type have contributed to continued U.S. leadership in technology, which is directly related to our standard of living and quality of life in general and also provided a base for commercialization. By investing in the promising high technology of microgravity materials, the government will lower the risk perceived by industry in an area which is now unfamiliar to industry. Furthermore, the required transportation system to and from space already exists and should be applied to the benefit of the U.S. With the addition of the Space Station, all required systems will be in place to initiate routine, systematic space R&D. Also, investments in such basic capabilities must be made now in order to engage industrial participation later in this decade. Such investments are a key factor in stimulating new growth and maintaining technical leadership, which in turn are keys to maintaining prosperity.

In addition to the foregoing time value of money benefits, precursor R&D can lower technical risk associated with commercial use of space. Figure 5 presents the concept of a Risk Adjusted ROI curve.
In the beginning of any project, financial returns can only be assessed in terms of risk; and risk adjustment for new product ventures is usually based on experience. Stated very simply, if an industry's normal ROI on proven products is X%, they will probably require 2 or 3 X% ROI before they will risk an investment in new unproven products.

Figure 5 graphically illustrates the concept of using time-estimated risk probabilities to arrive at a risk adjusted ROI. Three elements of risk are considered: technical, legal and market.

Technical risks tend to decrease as technical milestones are reached. Likewise, legal risk will go down in step with technical progress, since precedents are established on issues such as proprietary rights; but market risks tend to escalate with time, since competing products/processes are continually under development by others. Again the process obtained in Figure 2 will tend to lower technical risk.

INDUSTRIAL ENGINEERING FOR COMMERCIAL MATERIALS PROCESSING IN SPACE

Industrial activity in space or here on Earth must have adequate power, time, and facilities. Furthermore, productivity and cost are paramount considerations.

Power and Time Requirements

Power and time vary with different experiment samples and processes. The physics of each process was analyzed to identify relationship between requirements such as power and time versus experiment sample variables such as size melting points and thermal gradients. Typical curves depicting the results of these analyses can be seen in Figure 6. It was found that power requirements vary with experiment sample melting points in an exponential way in all cases except isothermal. This exponential increase in power requirements is particularly
evident in the containerless processing area. Time requirements for MPS processes vary in a more direct, straight line way. However, the quality of some MPS experiment samples is directly related to the time in process. For example, the quality of crystals is to some degree determined by the thermal gradient (G) across the growth interface divided by the rate (R) of growth. So while many MPS experiments have finite process time requirements, other experiments have process time needs that are proportional to the desired quality of the resulting sample. So power and time are key factors that determine the processes that can be addressed, the productivity of MPS and the quality of MPS processes.

**Organization of MPS Research Requirements**

Based upon the organization of MPS research shown in Figure 7, MPS physical and engineering requirements for MPS candidate payloads were identified. These experiments were grouped according to process concepts and processing parameters.

Further analysis was then done to identify the time and power levels for these candidate payloads, the results are shown in Figure 8. It should be emphasized that these results are very preliminary and are based upon assumptions that have not been validated. However, it does represent a systematic approach to identifying needs for power and time.

**In-Orbit Facilities**

The Space Shuttle is particularly well suited to serve the multi-flight requirements of initial MPS research. The Shuttle mode of operation is consistent with the practice associated with a research program. The Shuttle offers frequent, short-duration missions, which are well suited to verifying theoretical analysis, refining experiment protocols, and evaluating equipment performance.
Role of the Space Station

The role of the Space Station in the evolving MPS program is critical. While the Shuttle can accommodate low power, short-duration MPS R&D, factors such as specimen size, sample size, and higher melting points, pose the need for the Space Station as well as carrier systems that are compatible with both the Shuttle and Space Station flight modes.

As previously mentioned, MPS requires R&D in both modes. Currently, the MPS program is developing automated payloads to fly in the Shuttle cargo bay and manned payloads to fly both in the Shuttle middeck and in the Spacelab module. Manned payloads are required because research is a very high man-involvement activity. Automation is needed for reasons of precision, productivity and safety.

As investigations move from the research phase toward production, the degree of automation increases just as with Earth based processes. So, there is a need for both automated and manned payloads.

However, automation of materials processing in space to the degree that communication satellites are automated is not foreseen at this time. The data from MPS experiments are wrapped-up in the sample which must be thoroughly analyzed, whereas, data from communication satellites can be returned in the form of electronic signals.

Approach to Increase CMPS Efficiency

Figure 9 depicts three typical potential MPS production processes. Both processes, one and two, require frequent resupply of raw materials from Earth. Process three involves culturing of raw materials in orbit and recycling of production materials like water.
Process three, if feasible, could reduce resupply flights and increase economic returns, since a major cost of doing anything in space is transportation.

The point is that the prospect of reducing transportation cost warrants at least the study of ways to increase on orbit processing efficiency. However, permanent in orbit facilities are needed to make such operations possible. Also, permanent in orbit facilities can be used to reduce cost by providing a transportation mode. A Space Station in a "high traffic" orbit will make logistics more economical, since the Shuttle can deliver roughly twice as much to orbit as it can return to Earth. Therefore, it makes sense to leave assets in space rather than haul everything up and down on each mission.

Also, assuming the Space Station has propulsion capability, its orbit can be slightly adjusted to rendezvous with planned Shuttle missions. A slight change in velocity could change the ascending mode of the Station orbit by a small amount. If such an adjustment were done at the proper time the Station could be on the right ascending node to rendezvous with routine Shuttle missions for satellite deployment, etc. Thus, the station resupply mission cost could be shared. Such an approach, if feasible, could save up to half the cost of the Shuttle mission for both users. Such an approach warrants further consideration.

FACILITIES AVAILABLE AT NASA

Drop Tube/Drop Tower

NASA’s Marshall Space Flight Center has two fully operational drop tubes: a 30-meter and a 100-meter. In addition, there is also a 100-meter drop tower. These facilities are being used for research on a variety of materials, including high-temperature refractory metals and alloys, high-temperature nickel super-alloys, and promising superconducting materials.

The 30-meter drop tube melting apparatus is enclosed in a stainless steel bell jar located directly over a 10 cm I.D.,
30-meter long, stainless steel tube. The bell jar and tube assembly are evacuated to a pressure of $2 \times 10^{-5} \text{ N/m}^2$ ($1 \times 10^{-5} \text{ torr}$). The instrumentation ports and view ports are located on each floor level. The tube can be backfilled with helium gas to increase the cooling rate of the sample. This is especially useful for low-temperature metals or alloys. The samples are decelerated and caught by a detachable catcher which has a foil inner surface. During insertion or retrieval of a sample, dry nitrogen or argon gas can be used to prevent water vapor from entering the system.

The 100-meter drop tube is similar in configuration and operation to the 30-meter tube. The increased length of the 100-meter tube offers the opportunity to use a larger sample.

Basic operating parameters for these tubes are:

- Sample melting temperature: 600°C to 3500°C
- Sample size: 1 to 5 mm
- Acceleration during cooling:
  - 10⁻³ g in vacuum
  - 10⁻² g with helium in tube
- Free fall time - 30-meter tube: 2.6 sec
- Free fall time - 100-meter tube: 4.5 sec

Heating the samples during the melting operation may be accomplished in either of two ways, depending on the furnace being used and the specific materials involved. The thermal history of samples melted in the electron bombardment and electromagnetic levitation furnaces can be digitally recorded by an automated fast response (0.1 sec) pyrometer. In the resistance-heated capillary tube furnace, thermal history (heat up) is measured with thermocouples installed in the furnace. Spectral emissivity measurements can be made, if these data are not available.

Two infrared detectors, located at each end of the tube looking along its length, are used to determine the time of nucleation, as the sample falls down the tube and nucleation takes place. At that time there is a rapid rise in temperature due to release of the latent heat of fusion. This recaslescence produces increased luminosity which is recorded by the infrared detectors. Figure 10 gives some additional views of the facilities. It should be emphasized that the data and capabilities shown are to some extent generic and can be adapted to suit a range of specific requirements. Figure 11 presents a brief overview of the MSFC 100-meter Drop Tube as well as a
Aircraft

Low-gravity materials research is also being conducted using aircraft in parabolic flight.

F-104

Using a modified F-104 supersonic jet flying a parabolic trajectory from 25,000 to 65,000 feet and back, a free fall period of about 60 seconds can be obtained.

The most severe impact on experiment equipment is the 3-G acceleration going into and leaving the parabolic trajectory. The experiment package size is constrained to a volume of 25 in. high x 14 in. x 1 in. deep. The power regulator takes up to 12 x 3 x 6.5 in. of the total volume. All equipment must be restrained during the flight. There is no access 30 minutes before takeoff, hence all experiments must be completely automated. Figure 12 depicts some operational aspects of the F-104 low-gravity experimentation capability.

KC-135

NASA's KC-135 is an early Air Force cargo aircraft (Figure 13). Similar to the F-104, it achieves a low-g state by flying a prescribed parabolic trajectory. The low-g effect lasts for about 25 seconds and can be repeated up to 50 times per flight. (Notice that low-g handstands are rather easy.)

During its climb, about 2 to 2.5 Gs are experienced with the next 15 to 25 seconds experiencing .01 g. The pullout again experiences about 2 to 2.5 g-force. During about 5 to 15
seconds of the free-float time, a g-force on the order of .001 is experienced.

Experiment equipment that is flown on the KC-135 must be able to withstand the 2 to 2.5 g-pull sustained while going into and out of the parabolic flight pattern. For safety purposes, all equipment is fastened down during landing and must be capable of remaining intact and in place during the high-g acceleration periods.

The KC-135's 6 ft x 14 ft bay, with a maximum floor loading of 200 pounds per square foot, allows the use of large equipment. Hands-on personnel may accompany and operate equipment during the low-g parabolic trajectories.

Support power provided by the aircraft is 28 Vdc to 80 amps, 110 V/400 Hz to 50 amps, and 110 Vac 60 Hz to 25 amps. There is also a storage capability for O\textsubscript{2}, CO\textsubscript{2}, N\textsubscript{2}, and cryogenics.

Both the F-104 and KC-135 aircraft are operational and low-gravity flights are made periodically. The lead time for scheduling experiments typically varies from one to six months depending on the nature of the experiment.

**MATERIALS EXPERIMENT ASSEMBLY (MEA)**

The MEA is a self-contained Space Shuttle payload package which accommodates three payloads which are enclosed in Experiment Apparatus Containers (EAC's). The other bay contains subsystems for thermal control, data management, data recording, and power distribution. MEA power is obtained from two batteries located between the experiment bays. MEA also contains a low-gravity accelerometer, a data recorder and storage bottles for gases and liquids. The top of the MEA package is a rectangular thermal radiator. For ground operation and checkout, the MEA radiator is hinged to allow access to the experiments and subsystems.

The primary advantage of the self-contained automated facility is its ability to accommodate a large variety of space processing experiments while maintaining a single integration
interface with the Shuttle. In its first flight (OSTA-1, Office of Space and Terrestrial Applications), the MEA carried three experiments in the disciplines of crystal growth/transport phenomena, metallurgy, and glass technology, namely:

- Vapor growth of alloy-type semiconductor crystals
- Liquid Phase Miscible gap materials
- Containerless processing of advanced optical glasses

The MEA is turned on manually from the orbiter cabin. This activates the MEA computer, which in turn activates and controls the experiments in the pre-programmed way.

Figure 14 gives an incisive overview of MEA capabilities and depicts the configuration of MEA on the OSTA-2 mission. On this flight, MEA accommodated the:

- Single Axis Acoustic Levitator (SAAL)
- Gradient-General Purpose Rocket Furnace (G-GPRF)
- Isothermal-General Purpose Rocket Furnace (I-GPRF)

SPACELAB

The Spacelab module offers a unique opportunity to perform many types of experiments in a "shirt-sleeve" low-gravity environment. Spacelab, a cooperative venture of the European Space Agency (ESA) and NASA, is a versatile modular facility installed in the Shuttle and exposed to space when the cargo bay doors are opened (Figure 15). It consists of an enclosed, pressurized laboratory containing utilities, computers, work benches, and instrument racks for conducting experiments, as well as outside platforms (pallets) where such equipment as telescopes, antennas, and sensors are mounted for direct exposure to space. These units may be used in various combinations, returned to Earth, and reused on other flights. Spacelab can be outfitted with several tons of laboratory instruments for studies in astronomy, physics, chemistry, biology, medicine, and applied engineering. Uniquely, Spacelab is built for the use of scientists and engineers who are not necessarily astronauts or payload specialists; men and women from industry, universities, research institutions and government agencies (of many nations) who will conduct research and investigations in the Spacelab.
Microgravity materials processing payloads currently available in Spacelab consist of the Fluid Experiments System (FES) and the Vapor Crystal Growth System (VCGS). Figure 16 shows both in Spacelab racks. Figures 16 and 18 give more detailed views of the VCGS and FES.

**SHUTTLE MIDDECK**

The Shuttle Middeck (crew quarters) offers a routine way to conduct small MPS experiments. Some of the Middeck storage locker spaces (42 in number) can be used to accommodate small payloads of opportunity on a fairly frequent basis. Each locker provides about 2 ft³ of volume and about 60 pounds of weight capacity. A single adapter plate may be used instead of the standard module locker. The plate has a universal role pattern for attaching experiments or payloads directly to the plate.

In certain cases where an experiment cannot be mounted on a single adapter plate or the experiment exceeds 2 ft³ and/or 60 pounds, a double adapter plate can be used. The double adapter plate will have a maximum load carrying capability equal to twice that of the single adapter plate.

The Orbiter provides both 28 Vdc (up to 10 amps) and 115 Vac (400 Hz, 3-phase, up to 3 amps per phase) power in the middeck. This power can be made available for payload use depending on mission phase and other demands (Figure 19). (For those interested in more details regarding use of this area for conducting experiments, see NASA’s Orbiter Middeck Handbook, JSC-16536.)

**GET-AWAY SPECIAL (GAS) (SMALL SELF-CONTAINED PAYLOADS)**

The Agency has now flown 22 Get-Away Specials. With the exception of one GAS test payload flown on STS-3, all payloads were for NASA, educational, commercial and DoD investigation.
The objective for providing this opportunity was to encourage the use of space research by all researchers - private individuals, educational institutions and small companies and organizations that could not possibly afford the investment required to fly a major class payload. It was felt that these payloads could possibly generate new activities unique to space, thus providing a stepping-stone to development of larger scientific or commercial payloads on future Shuttle flights. To accomplish this objective, NASA established the criteria that payloads of this class must be for scientific research and development purposes. While NASA will not attempt to judge the scientific merit of a proposed experiment, all users will be required to furnish NASA evidence of scientific research and development intent and sufficient information for verification by NASA that the payload is for peaceful purposes and complies with applicable law and policy.

In order to facilitate flight scheduling, it was further decided to limit this class of payload to a maximum weight of 100 pounds and maximum volume of 5 cubic feet. NASA provides a standard container and standard mounting Orbiter interface for these payloads. Figure 20 shows the GAS cannister in more detail.

SUMMARY

This paper has presented an overview aimed at prospective entrepreneurs considering new ventures in space commercialization. NASA's efforts to stimulate interest in space commercialization in the area of microgravity materials processing through mechanisms such as Joint Endeavor Agreements were identified. The risk associated with space commercialization was touched upon. Finally, facilities available for low-gravity research were described.
Bibliography


SYSTEMS APPROACH TO MICROGRAVITY MATERIALS PROCESSES

**General Research & Proof of Concept Model**

- **Science Base**
  - Ground Research

- **Limitations on Ground Processes**
  - Quality
  - Purity
  - Quantity

- **Equipment Inventory**
  - Technology Assessments
    - Gravity Dependent
    - Power
    - Configuration
  - Technology Development
    - Analytical Models
    - Lab Models
    - Bread Boards

- **Flight Systems**
  - Systems Requirements
    - Concepts
    - Resources
  - Accommodation Analyses
    - Design Studies
    - Ground & Flt Ops
  - Flights
    - Reports
    - Data Analyses

**Electrophoresis Accomplishments**

- Fluid Models
- Thermal Models
- Economic & Technical Feasibility Studies
  - Enzymes
  - Hormones
  - Cells
  - Etc

- Lab Models
- Sample/Insertion/Collection
- Non-Gassing Electrodes
- Zeta Potential Coating
- Pumps
- Etc

- Flights
  - Apollo
  - Astp

**Figure 2**
COMPARISON OF CASH FLOWS

FIGURE 3
FIGURE 4

RISK ADJUSTED ROI

PROBABILITY OF SUCCESS

PORTION OF DOLLARS AT RISK DUE TO TECHNICAL RISK

TIME
RISK ADJUSTMENT ROI FACTORS

TECHNICAL

IDEA | GROUND R&D | CONCEPT DEFINITION | PROOF OF CONCEPT FLT. | ON ORBIT PILOT DEMO. | NASA SYS. ON LINE

LEGAL

RIGHTS GRANTS | REGULATIONS BASELINED

MARKET

MARKET & PRICE | COMPETING PROCESS PRODUCTS

FIGURE 5
MPS PROCESS THERMAL MODELS

**Isothermal Process**
- Insulation
- Sample
- Process Chamber
- Power (T₁, T₂, T₃)
- Size
- Moderate power
- Moderate to long durations
- Moderate to high energy
- Moderate samples

**Gradient Processes**
- Sample
- Heat
- High gradients
- Low gradients
- Power (T₁, T₂, T₃)
- Size
- High power
- Long duration
- High energy
- Moderate samples

**Containerless Processes**
- Sample
- Heat
- Power
- Diameter
- Temperature
- High power
- Short duration
- Low energy
- Big sample

** Float Zone Processes**
- Heater
- Melted zone
- Sample
- Heat leaks for gradient
- Power (T₁, T₂, T₃)
- Diameter
- High power
- Long duration
- High energy
- Small samples

**Diffusion Processes**
- Saturated solution
- Crystal cool
- Power (T₁, T₂)
- Size
- Low power
- Long durations
- Low energy
- Moderate sample

**Biological Separation Processes**
- Cells
- Proteins
- Heat
- Power
- Moderate power
- (Must refrigerate)
- Short duration
- Moderate energy
- Moderate sample

**Figure 6**
MPS RESEARCH AREAS

FIGURE 7
BIOLOGICAL PROCESSING TYPICAL PROCESSES

**PROCESS (1)**
- Mixture of Proteins
- Purify
  - Proteins from Earth
  - Purified Proteins
  - Electrophoresis
  - IEF
- Proteins to Earth

**PROCESS (2)**
- Mixture of Cells
- Purify
  - Cells from Earth
  - Purified Cells
  - Electrophoresis
  - Cells to Earth

**PROCESS (3)**
- Mixture of Cells
- Purify
  - Purified Cells
  - Incubate (Culture)
  - Cells
  - Recycle Waste Products
- Cells from Earth
- Purify
  - Lysis
  - Return Cells to Earth
  - Return Proteins to Earth

<table>
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<tr>
<th>PROCESS</th>
<th>RESEARCH PHASE</th>
<th>PROCESS OPTIMIZATION PHASE</th>
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<td>MANNED</td>
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**FIGURE 9**
Low Gravity Free Fall Facilities

Figure 10
DROP TUBE FACILITY

ONLY SAMPLE IS DROPPED
ZERO G TIME 4.5 SEC
HEIGHT 100 METERS
TUBE DIAMETER 30 cm
SAMPLE MASS 170-300 mgr
VACUUM LEVEL 10^-6 TORR
GAS ARGON
HYDROGEN
HELIUM
MIXTURES

DROP TUBE PROCESSED Al_Ni SPHERES

HIGH COOLING RATE
(0.85 mm DIAMETER)

LOW COOLING RATE
(1.7 mm DIAMETER)

Figure 11
LOW GRAVITY EXPERIMENTATION
IN THE F104

LOW G TIME 40 - 60 SEC
EXP SIZE 10 X 15 X 21 IN
EXP WEIGHT 35 LB
ACCELERATIONRecorded
LIMITED DATA TRANSMISSION
ONE PARABOLA PER FLIGHT
POWER 28V / 35 AMPS
LOW GRAVITY EXPERIMENTATION IN THE KC135

LOW G TIME 15 - 30 SEC
POWER 28 V DC 80 AMP
110 V AC 400 Hz 50 AMP
110 V AC 60 Hz 25 AMP
LIQUID AND GASEOUS NITROGEN
VENT SYSTEM
MANY PARABOLAS PER FLIGHT

CAST IRON SAMPLE

Figure 13
MATERIALS EXPERIMENT ASSEMBLY (MEA)

MEA (SELF CONTAINED)

| WEIGHT   | 2000 LBS |
| VOLUME   | 76 CU FT |
| ENERGY   | 32 KWH@32 VOLTS |
| HEAT REJECTION | 500 W NOMINAL 1000 W MAX |

EXPERIMENTS

| NUMBER | 3 |
| DIAMETER | 17 INCHES |
| LENGTH   | 36 INCHES |
| WEIGHT   | 200 LBS |

Figure 14
SPACELAB LONG MODULE

21 FLIGHTS PLANNED DURING NEXT DECADE
FIRST FLIGHT — DECEMBER 1983
PAYLOAD WEIGHT — 5500 – 9100 Kg
EXPERIMENT VOLUME — 22 m³
ELECTRICAL POWER — 2.5–4.5 Kw
DOWNLINK DATA RATE — 50 MBPS
DOWNLINK VIDEO — 4.5 MHZ
UPLINK DATA RATE — 2 KBPS
DATA RECORDING — 30 MBPS

SINGLE/DOUBLE RACK EXPERIMENT MOUNTING

Figure 15
FLUID EXPERIMENT SYSTEM (FES) AND VAPOR CRYSTAL GROWTH SYSTEM (VCGS)

**FES**
- Double rack in Spacelab
- Optical bench for holography
- Transmission of video
- Microcomputer control system
- Test cell preheat enclosure

**VCGS**
- Single rack in Spacelab
- Microscopic viewing of sample
- Video of ampoule transmitted
- Interchangeable furnace/ampoule
- Protective sample storage
- Control by FES computer
VAPOUR CRYSTAL GROWTH SYSTEM

CRYSTAL IN EXPERIMENT ENCLOSURE IS VIEWED THROUGH MICROSCOPE (VIDEO AVAILABLE ON BOARD/GROUND)

STORAGE ENCLOSURE PLACES CRYSTAL IN COMPRESSIVE LOAD DURING LAUNCH/LANDING

CONTROL PANEL AND MICROSCOPE

Figure 17
FLUID EXPERIMENT ASSEMBLY (FES)

OPTICAL ASSEMBLY
- DIRECT/TRANSVERSE HOLOGRAMS
- HE/NE LASER (15 CM DIA)
- VIDEO DISPLAY OF SCHLIEREN

POST FLIGHT ANALYSIS OF
HOLOGRAMS YIELD
- SHADOWGRAPH
- SCHLIEREN
- INTERFEROMETRY
- MICROSCOPY

ACCELEROMETER

FES HOLOGRAPHIC COMPONENTS

HOLOGRAPHIC OPTICAL ASSEMBLY ON BENCH
Figure 18
THE ORBITER MIDDECK

MIDDECK LOCKER
- SIZE: 10 X 17 X 20 INCHES
- WEIGHT CAPABILITY: ~50 POUNDS

MIDDECK CANISTER
- SIZE: 17” DIA X 20” LENGTH
- WEIGHT CAPABILITY: ~100 POUNDS

MIDDECK ELECTRONICS MODULE AVAILABLE

MIDDECK RESOURCES
- POWER: 200 W DC/600 W AC

COOLING: CABIN AIR

CREW INVOLVEMENT

MIDDECK GALLEY
- WEIGHT CAPABILITY: 300 POUNDS
- COOLING: WATER LOOP

Figure 19
GET AWAY SPECIAL

FOR SMALL SELF-CONTAINED PAYLOADS

VOLUME 5.0 CU FT

USER ENVELOPE 19.75” DIA X 26.25” LENGTH

PAYLOAD WEIGHT 100 LBS

CONTAINER IS A PRESSURE VESSEL
— VACUUM
— OPEN TO SPACE
— 1 ATMOSPHERE PRESSURE

MINIMAL ORBITER INTERFACE
— 3 SINGLE POLE DOUBLE THROW RELAYS
— NO ACTIVE THERMAL CONTROL

Figure 20