NASA’s Microgravity Materials Science Program – A Review of Experimental Investigations

materialsLAB Workshop
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Historical Reference

NASA was not the first to understand and utilize the benefits of processing materials in a microgravity environment. That honor likely goes to William Watts of Bristol, England who in 1753 built a “drop tower” to process molten lead into uniformly spherical shot for firearms.

Molten lead is poured through a sieve. Uniform drops freefall (microgravity), buoyancy effects are minimized. Surface tension dominates forming uniform spheres. Solidified shot lands in a cushion of cooling water.

Boughton Shot Tower
Chester, England
1799, 168’ tall

Phoenix Shot Tower
Baltimore, MD, 234’ tall
1828, tallest structure in US
2.5 million pounds shot/year
Microgravity and Physical Phenomena

Gravity drives thermal and solutal convection
- Detrimentally impacts solidification microstructures
- Compromises diffusion studies

Gravity responsible for sedimentation/buoyancy
- Promotes non-uniform particle distributions

Gravity necessitates, usually, a container to process/study liquids
- Compromises accurate study of material properties such as viscosity
- Compromises nucleation/undercooling studies

Gravity overwhelms subtle physical features
- Thermocapillary effects, surface tension are masked
Microgravity and Physical Phenomena

Microgravity minimizes thermal and solutal convection
- Promotes diffusion controlled growth and uniform solidification microstructures

Microgravity minimizes sedimentation / buoyancy
- Promotes uniform particle distributions
  → Advances our understanding of coarsening and sintering

Microgravity minimizes pressure heads
- Reduces defects in semiconductor materials
- Allows study of granular materials

Microgravity eliminates a container to process / study liquids
- Improves accuracy of material properties measurements such as viscosity and surface tension
- Facilitates nucleation studies
Microgravity allows observation of subtle physical phenomena

- Thermocapillary effects, surface tension are now dominant

<table>
<thead>
<tr>
<th></th>
<th>Large Bubble (0.53mm)</th>
<th>Small Bubble (0.36mm)</th>
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<tbody>
<tr>
<td>Measured Velocity</td>
<td>5.6 mm/s</td>
<td>4.1 mm/s</td>
</tr>
<tr>
<td>Calculated Velocity</td>
<td>5.6 mm/s</td>
<td>4.4 mm/s</td>
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</tbody>
</table>
Microgravity “Platforms”

Drop Towers
- Glenn Research Center
  - 432’ (~5.2s μg)

Levitators
- ~30s μg

Sounding Rockets
- 15-25 min μg

Space Vehicles / Stations
- Long duration μg

Parabolic Aircraft
Long Duration Microgravity Physical Sciences Research

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<th>Foundational Era</th>
<th>Shuttle Era</th>
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<td>1950’s to 1980</td>
<td>1980 to 2000</td>
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<tr>
<td>Mercury / Gemini / Apollo / Soyuz</td>
<td>STS and MIR</td>
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<tr>
<td>Spacecraft / Skylab</td>
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**Soyuz 6 1969 1st Welding Experiment**
**Apollo 14 1971 Composite Casting**
**Skylab 1973-1979**

**Skylab Materials Processing Facility Multipurpose Furnace System**

**Skylab**: “such tests proved that the processing of metals without using containers is feasible in space”.

**Technology**

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<th>D008</th>
<th>RADIATION IN SPACECRAFT</th>
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<td>THERMAL CONTROL COATINGS</td>
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<td>M479</td>
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<td>M517</td>
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<td>M534</td>
<td>GALLIUM ARSENIDE CRYSTAL GROWTH</td>
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<td>M536</td>
<td>CREW ACTIVITIES / MAINTENANCE STUDY</td>
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<tr>
<td>M531</td>
<td>MULTIPURPOSE FURNACE SYSTEM</td>
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<td>M558</td>
<td>RADIOACTIVE TRACER DIFFUSION</td>
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<td>M559</td>
<td>MICROSEGREGATION IN GERMANIUM</td>
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<td>M560</td>
<td>GROWTH OF SPHERICAL CRYSTALS</td>
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<td>M561</td>
<td>WHISKER-REINFORCED COMPOSITES</td>
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<td>M562</td>
<td>INDUMI ANTIMONIDE CRYSTALS</td>
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<tr>
<td>M563</td>
<td>MIXED M V CRYSTALS GROWTH</td>
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<tr>
<td>M564</td>
<td>METAL AND HALIDE CRYSTALS</td>
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<tr>
<td>M565</td>
<td>SILVER GRIDS MELTED IN SPACE</td>
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<td>M566</td>
<td>COPPER-ALUMINUM CRYSTALS</td>
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<tr>
<td>T003</td>
<td>IN-FLIGHT AEROSOL ANALYSIS</td>
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<td>T027</td>
<td>ATM CONTAMINATION MEASUREMENT</td>
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<td>T053</td>
<td>EARTH LASER BEACON</td>
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**STS3 1982 Latex Spheres**
**STS9 1983 Spacelab 1**
**STS17 1985 Spacelab 3**
**STS51B 1985 Spacelab 2**
**STS61A 1985 Spacelab D1**
**STS40 1991 Spacelab LS1**
**STS42 1992 IML1**
**STS50 1992 USML**
**STS46 1992 EUREKA**
**STS47 1992 Spacelab-J**
**STS55 1993 Spacelab D2**
**STS57 1993 LEMZ**
**STS60 1994 CLPS**
**STS62 1994 USMP2**
**STS65 1994 IML2**
**STS73 1995 USML2**
**STS76 1996 QUELD LPS**
**STS77 1996 CFZF SEF**
**STS78 1996 LM2**
**STS94 1997 MSL**
**STS87 1997 USMP4**

**STS3 Latex Spheres**
**STS9 InP**
**THM**
**IML1**
**Hg I**
**VCG**
**USMP2**
**IDGE**
Long Duration Microgravity Physical Sciences Research

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<th>ISS Era</th>
<th>Exploration Era</th>
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<td>2000 to 2024</td>
<td>2024 to -</td>
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<tr>
<td>STS and ISS</td>
<td>Moon / Mars / Others</td>
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ST107 2003 Columbia
ISS Assembly
Destiny Lab – MSRR
MICAST
ICDGSC
GTCS
DSI
SETA
METCOMP
CETSOL
SISSI
GEDS
FOGS
FAMIS
µg Science Glovebox
CSLM
PFMI
SUBSA
Maintenance Workbench
ISSI
Columbus Laboratory – ESL
THERMOLAB
QUASI
PARSEC
Russian Lab
Japanese Module JEM

In-Situ Resource Utilization
In Space Fabrication and Repair
Summary

Microgravity materials science arguably began in 1753

First long duration $\mu g$ experiments were Apollo, Soyuz, MIR, Skylab
  - Much Russian welding work
  - Wide range of Skylab materials experiments

Spirited period of $\mu g$ materials science was during the Shuttle age
  - Many dedicated flights
  - Generally good documentation of results
  - Advances made in our scientific understanding
    → Metals processing, semiconductors, crystal growth, dendritic growth, nucleation

Hiatus due to Columbia tragedy, ISS construction

Microgravity materials science initiated on the ISS
  - Generally good results, still a long line of experiments