Materials Development using Levitation Techniques on Ground and in Microgravity

National Aeronautics and Space Administration

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Breakthrough Materials for Space Applications

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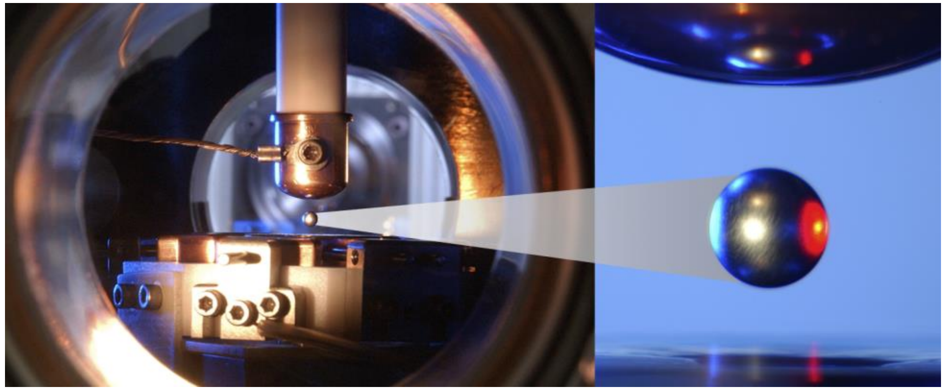
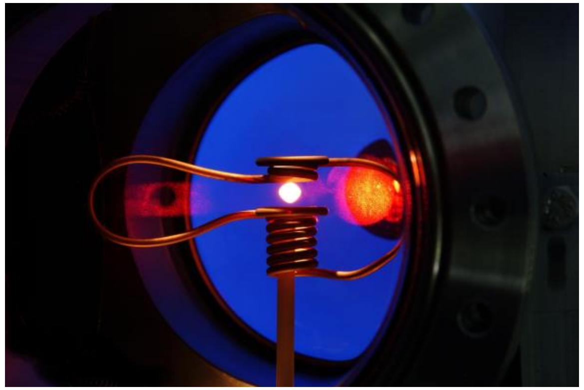
Levitation Techniques



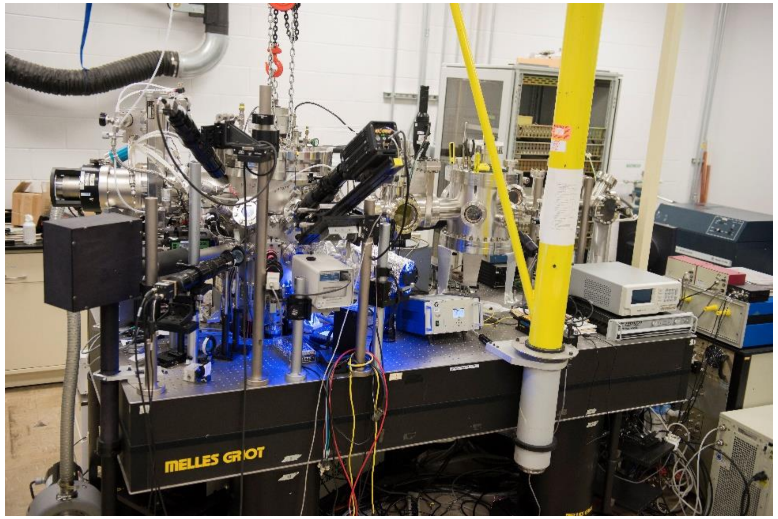
Electrostatic levitation



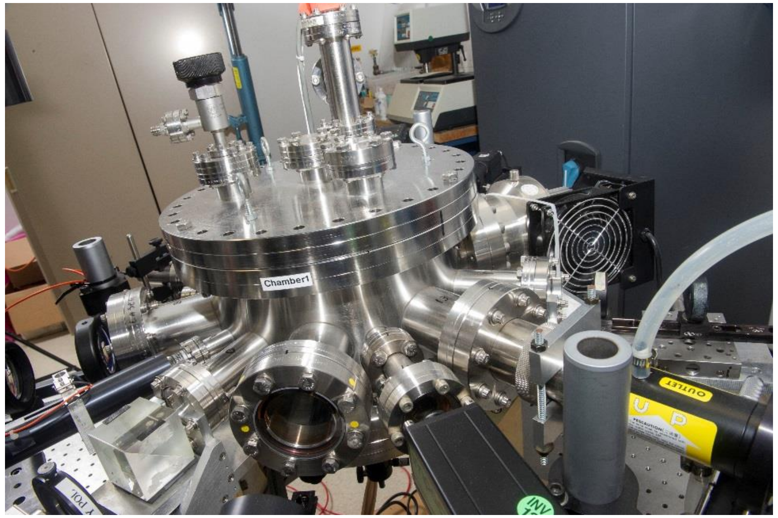
Electromagnetic levitation.
Photo credit: German Aerospace Center, DLR

- **There are several levitation techniques for materials science experiments and thermophysical properties measurements, including:**
  - Aerodynamic
  - Acoustic
  - Electrostatic
  - Electromagnetic
- **Electrostatic and electromagnetic levitation provide a containerless method for the study of undercooled melts and metastable states.**
  - Samples do not contact a container and, therefore, will not be contaminated by the container or react with it.
  - The atmosphere can be high-vacuum, inert gas, or even pressurized.

Ground-Based Levitation Capabilities at MSFC



MSFC ESL Lab's main levitation chamber



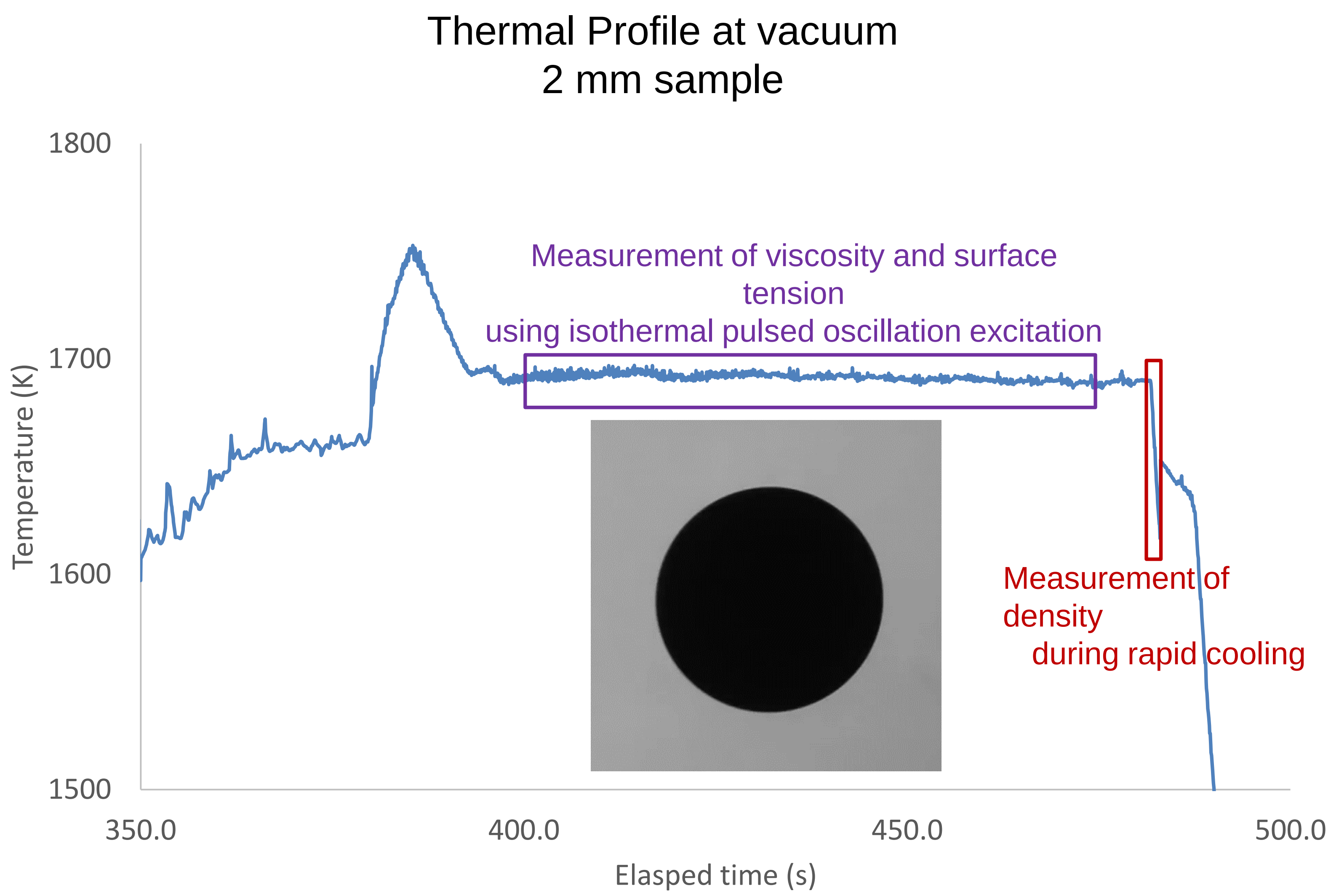
MSFC ESL Lab's portable levitation chamber

- **NASA MSFC Electrostatic Levitation (ESL) Laboratory**
- **2 electrostatic levitation chambers**
  - Main unit & portable
- **Typically runs in high vacuum (~10^{-7} torr)**
  - The main unit can run under pressure (2-5atm)
- **Fiber optic (~1064nm) and CO2 lasers (10.6um) are available for sample heating**
- **Pyrometer for temperature measurement**
- **High-speed camera for thermophysical properties measurements**
  - 30fps for density measurements
  - 1000fps for surface tension & viscosity measurements
- **Small sample size (~2-3mm DIA)**
- **Portable chamber**
  - Used in a high-energy beamline for determination of equilibrium and non-equilibrium phase diagrams[1] at Argonne National Laboratory
  - Used for structure and phase determination of quasicrystals[2]

References:
1. Gangopadhyay, A.K., et. al., Review of Scientific Instruments 76, 073901, 2005
2. Kelton, K.F., et. al., Physical Review Letters, 90, 195504, 2003

More details about the ESL lab can be seen at:
https://partnerships.msfc.nasa.gov/content/electrostatic-levitation-laboratory

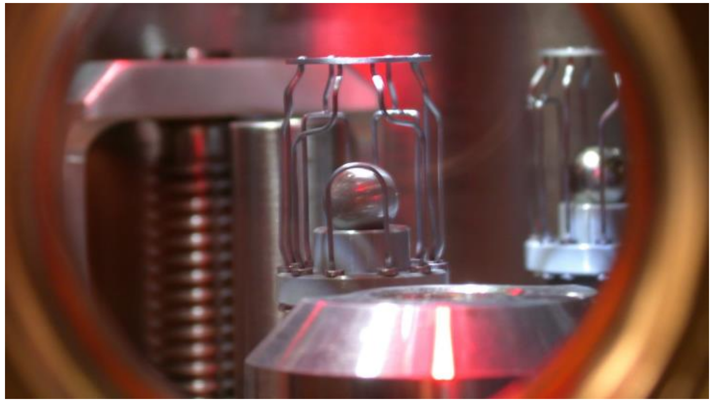
ESL Processing Conditions



- **Density**
  - By measuring the size of the liquid droplet, the density can be evaluated from the digital video images

- **Surface Tension & Viscosity**
  - The levitation field can also be used to “squeeze” the sample to induce surface oscillations which indicate
    - Sample surface tension (the motion frequency)
    - Viscosity (how fast motion dampens out).

ISS Levitation Capabilities



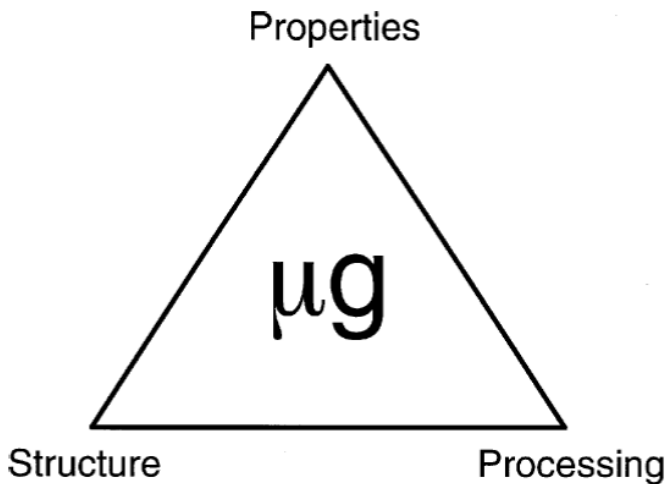
ESA's Electromagnetic Levitator. Photo Credit: ESA/DLR

The Electrostatic Levitation Furnace (ELF) sample cartridge. Photo Credit: NASA

- **There are 2 levitation facilities currently in use on the International Space Station (ISS)**
  - ESA's International Space Station Electromagnetic Levitator (ISS-EML)
    - Has been in operation since 2015.
    - US investigators are on several of the European research projects.
    - Used to study conductive materials, including
      - Steel analogues (e.g. FeCrNi)
      - Bulk metallic glasses (e.g. Vit106)
      - Nickel-based superalloys (e.g. CMSX-10)
  - JAXA's Electrostatic Levitation Furnace (ELF)
    - Launched to the ISS in 2015 and is also in operation.
    - There are several US Principal Investigators and Co-Investigators
    - Used mainly for the study of metal oxides, including
      - Calcium aluminate, barium titanate, aluminum oxide, etc.
      - Can also study metallic and glass materials

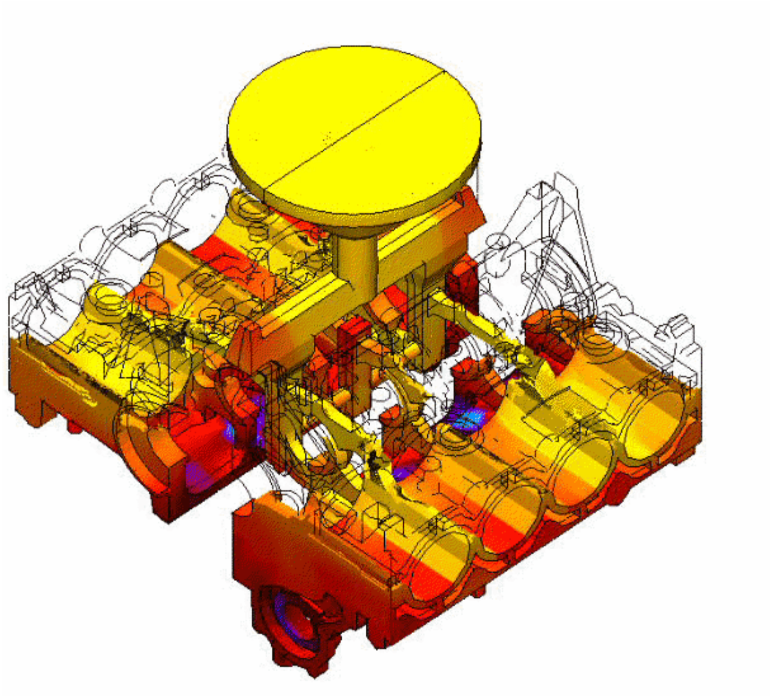
Why Levitation in Microgravity

- **The International Space Station (ISS) provides a long-duration spaceflight environment for conducting microgravity experiments.**
- **The microgravity environment greatly reduces buoyancy-driven convection, pressure head, and sedimentation in fluids.**
- **Many thermophysical properties can be measured in a levitator on Earth, but with convective contamination.**
  - This contamination plays a significant role in the formation of the intermediate phases.
  - In particular nucleation and viscosity measurements demand quiescent conditions.
- **In the case of metal oxide materials, it is often extremely difficult, or impossible, to effectively study these materials using ground-based levitation**
  - The JAXA ELF provides a method to study these materials
  - The materials of interest are precursors to high value-added glass materials that are used in photonics, lasers, optical communications, and imaging applications.



Establishing quantitative and predictive relationships between the way a material is produced (processing), its structure (how the atoms are arranged), and its properties is fundamental to the study of materials.

Applications of Thermophysical Properties



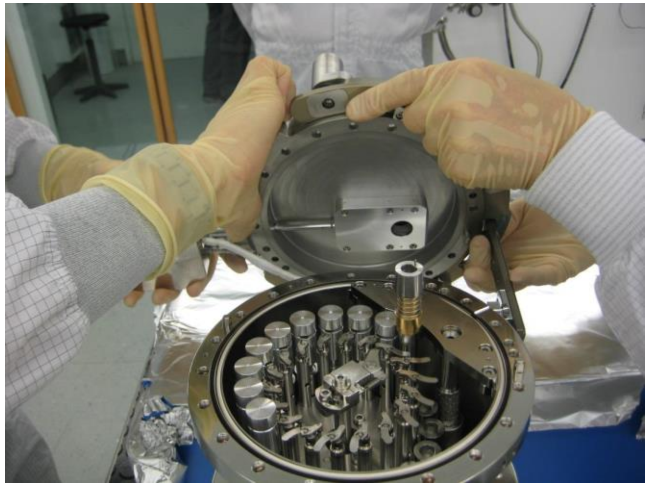
A model of a casting process[1]

- **Need high quality thermophysical properties of high-temperature materials.**
- **These properties are critical for developing accurate models with predictive capability**
  - Casting
  - Welding
  - Additive Manufacturing
- **Measurements will improve manufacturing of propulsion components, leading to higher performance and higher reliability.**
- **More efficient and more reliable production of metallic parts for exploration, commercial, and industrial applications using these alloys.**

References:
1. http://www.technalysis.com/casting_software.aspx

ISS-EML Investigators

- **Robert Hyers (University of Massachusetts)**
  - Member of research projects: THERMOLAB, ICOPROSOL, and PARSEC
  - Objectives:
    - Provide magnetohydrodynamic (MHD) modeling support of macroconvection in various materials for PARSEC, THERMOLAB-ISS, and ICOPROSOL
- **Kenneth Kelton (Washington University in St. Louis)**
  - Member of research projects: THERMOLAB, ICOPROSOL, and QUASI
  - Objectives:
    - Determine the influence of liquid and solid short-range order on the nucleation barrier.
    - Correlate the nucleation kinetics with the local structure of the liquids.
- **Douglas Matson (Tufts University)**
  - Member of research projects: PARSEC, THERMOLAB, and ELFSTONE
  - Objectives:
    - Investigate the effect of fluid flow on the solidification path of peritectic structural alloys.
    - Research the influence of convection on the formation of different microstructure in a wide range of commercial alloys.



ISS-EML sample chamber

- **ISS-EML Research Teams with US involvement**
  - ELFSTONE: Electromagnetic Levitation Flight Support for Transient Observation of Nucleation Events
  - PARSEC: Peritectic Alloy Rapid Solidification with Electromagnetic Convection
  - THERMOLAB-ISS: Thermophysical Properties of Liquid Metallic Alloys – Modeling of Industrial Solidification Processes and Development of Advanced Products
  - ICOPROSOL: Thermophysical properties and solidification behavior of undercooled Ti-Zr-Ni liquids showing an icosahedral short-range order
  - QUASI: Quasi-Crystalline Undercooled Alloys for Space Investigation

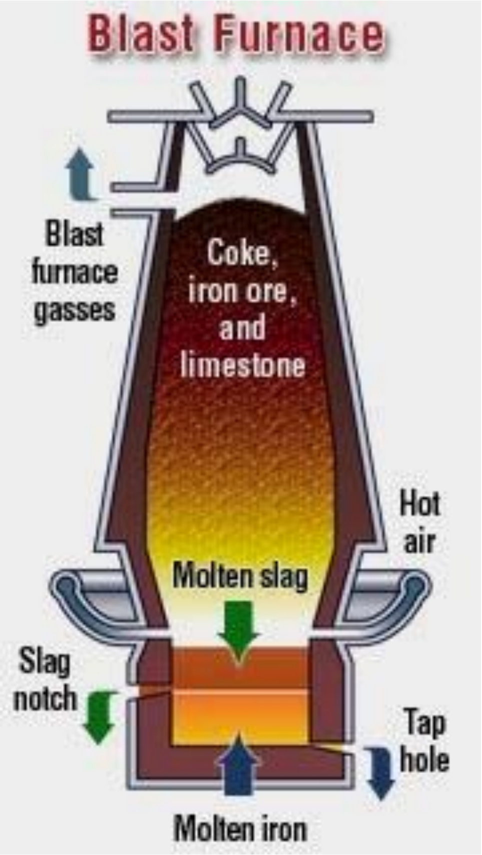
ELF Investigators

- **Robert Hyers (University of Massachusetts)**
  - Modeling and Simulation of Electrostatically Levitated Multiphase Liquid Drops
    - Dr. Hyers is a Co-Investigator on a Japanese research team.
    - Experiments for this project on ELF began in 2018.
  - Thermophysical Properties and Transport Phenomena Models and Experiments in Reduced Gravity
- **Douglas Matson (Tufts University)**
  - Round Robin - Thermophysical Property Measurement
- **Ranga Narayanan (University of Florida)**
  - A Novel Way to Measure Interfacial Tension Using the Electrostatic Levitation Furnace
- **Richard Weber (Materials Development, Inc.)**
  - Microgravity Investigation of Thermophysical Properties of Supercooled Molten Metal Oxides

Electrostatic Levitation Furnace (ELF) attached to the Multi-purpose Small Payload Rack 2 (MSPR-2). Photo Credit: JAXA/NASA
Ref: http://iss.jaxa.jp/en/kiboexp/news/1810_elf_en.html

Applications of Metal Oxide Experiments

- **Dr. Hyers (University of Massachusetts) is collaborating with Japan to investigate the effects of the interfacial phenomena between the molten steel and the oxide melts during processing from the viewpoint of the thermophysical properties.**
  - During steel making processes, such as continuous casting, the impurity in the cast steel is influenced by the interplay between the molten steel and molten slags.
  - Understanding the interfacial phenomena is necessary in order to produce higher purity steels.
  - The results of the project are expected to be utilized for more efficient production of higher quality steel
  - The samples of interest are Iron/Welding Flux (Cao-SiO2-TiO2-FeO) and Iron/Slag (CaO-SiO2-Al2O3)

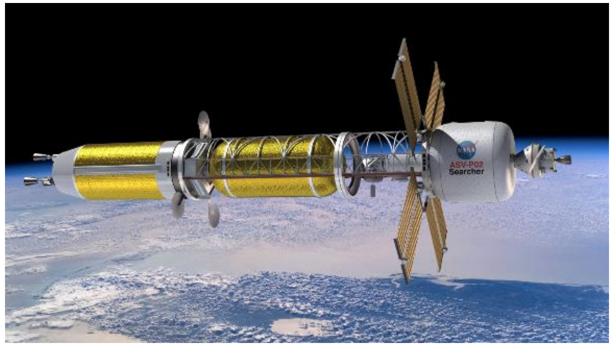


Schematic of a blast furnace, showing slag layer on top of molten iron.
Photo Credit: National Slag Association.

Application: High Temperature Materials for Nuclear Thermal Propulsion

- **The US ISS-EML Investigators and their teams are collaborating with ESA's THERMOLAB project**
  - One part of THERMOLAB is measuring thermophysical properties and solidification behavior of zirconium alloys used in nuclear reactors
  - Alloys provided by Areva
    - a French manufacturer of nuclear power plants.
  - Synergistic design goals with NASA NTP
  - Measurements will improve manufacturing of reactor components
    - leading to higher performance and higher reliability
  - The results of this study will be used to improve safety, reliability, and cost of nuclear power in space and on Earth

Fuel rods for nuclear propulsion.
Photo Credit: NASA



Concept of nuclear-thermal crew transport for a Mars mission.
(NASA Illustration)

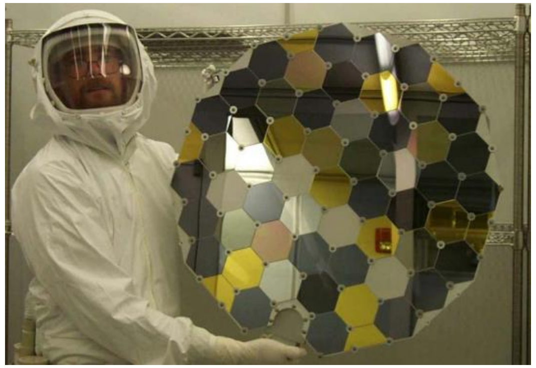
Bulk Metallic Glass Development at MSFC

- **Bulk metallic glass (BMG) alloys are metallic alloys that form a non-crystalline (or glass-like) structure when solidified.**
- **The MSFC ESL lab was utilized in 1999 to determine the glass-forming ability of Vitreloy 106a, the first non-beryllium-bearing BMG to fully vitrify under the radiative cooling conditions of ESL.**
- **Liquidmetal Technologies and Liquidmetal Golf was spun off from the research done at MSFC**

Golf club heads made from BMG by Liquidmetal Golf.
Ref: https://spinoff.nasa.gov/spinoff2001/ch3.html

Liquidmetal engineers and Rawlings Sporting Goods designers developed a baseball bat that offers superior durability while dramatically reducing the energy loss experienced with other materials upon impact with the ball.
Ref: https://www.nasa.gov/vision/earth/technologies/liquidmetal.html

Genesis Mission



One of the solar arrays loaded with 55 detectors

Drawing of the Genesis spacecraft

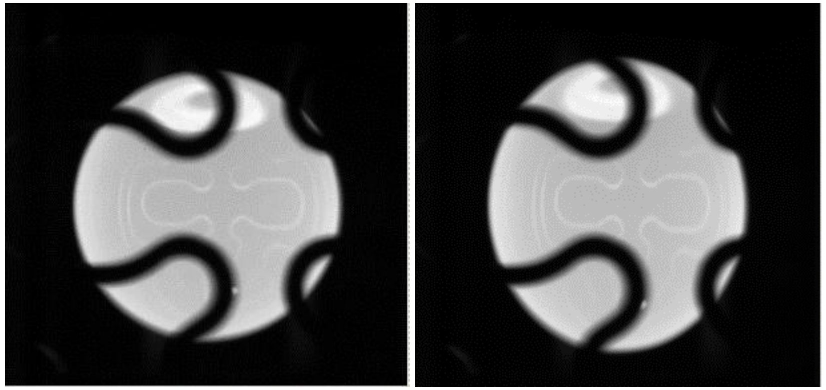
- **Genesis was a sample-return probe that collected a sample of solar wind particles and returned them to Earth for analysis**
- **The Genesis Mission Spacecraft consisted of different collectors for different solar winds.**
- **From TRL-1 to Flight in 3 Years**
  - The BMG (bulk metallic glass) Vitralloy 106a was processed in the ESL Laboratory levitation chamber as a TRL-1 project in 1998.
  - The material was used as one of the 15 different materials in the Genesis collector arrays which launched on Nov 30, 2001.
- **The collector arrays returned to earth on September 8, 2004.**

Further Applications of BMGs

- **NASA is currently studying BMGs for cryogenic gears for planetary exploration. Bulk metallic glass doesn't get brittle in extreme cold, and that makes the material perfect for robotics operated in space or on icy planets**

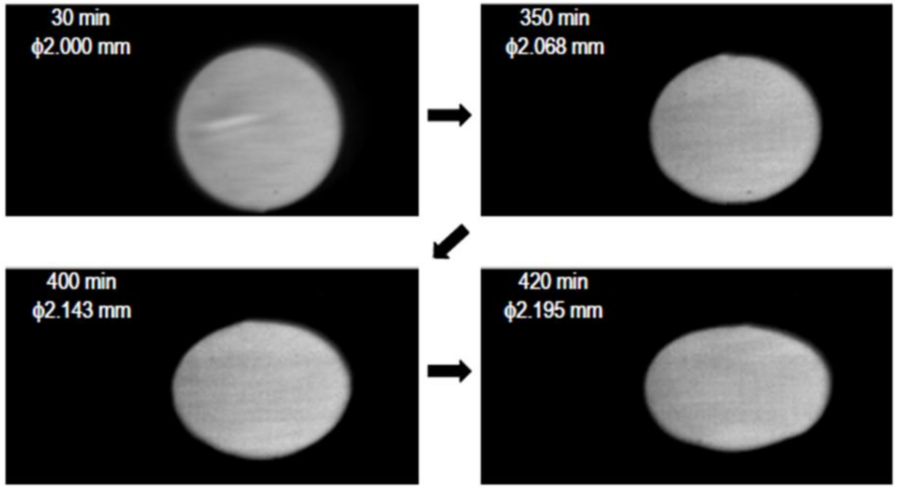
- **Gears made from BMGs can operate both cold and dry, which will allow the gears to have strong torque and smooth turning without lubricant**

A bulk metallic glass (BMG) gear during cryogenic testing by NASA.

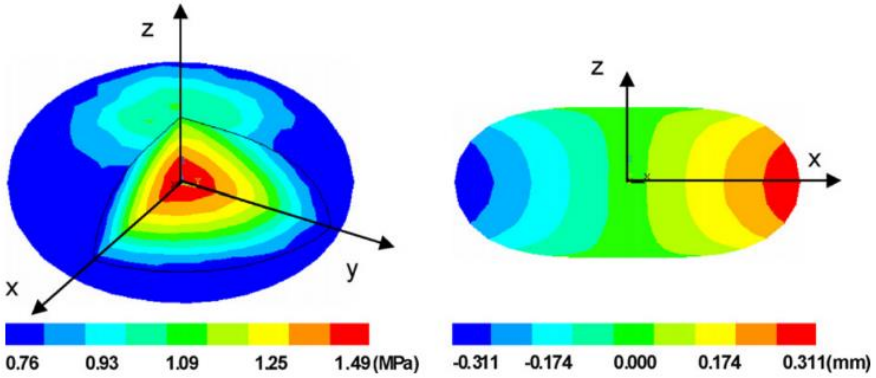


Left: An undisturbed, spherical Vitreloy106a liquid in the ISS-EML. Right: Image of the Vitreloy106a liquid elongated along it's vertical axis. The amount of time it takes this elongation to decay back to it's original spherical shape is related to the sample's viscosity.

Creep Strength



High-speed camera images of a sample taken at several times during a creep measurement



Numerical prediction of stresses (left) and deformation (right) of a crept Nb sample. The stress exponent of an ESL sample is determined using both experimental and numerical results.

- **Definition of creep: Time-dependent plastic deformation of a material at constant stress which is lower than the yield point.**
- **At temperatures greater than ~50% of the melting point creep becomes significant**
- **Once a near-spherical sample of 2-3 mm in diameter is levitated stably by ESL, a heating laser is applied to the sample.**
- **The stress within the sample is generated by fast rotation of the sample.**
  - Sample rotation can be induced either by the photon pressure exerted from the heating laser or by a rotating electromagnetic force field generated by an electromagnetic rotor
  - The sample can be rotated up to 30,000 Hz
- **In the course of an ESL test, the deforming sample will be captured using a high-speed camera.**
- **The creep constant is to be determined by analyzing the sample deformation combined with a series of numerical simulations.**
- **This technique was used to measure the creep resistance of Haynes 230 for J2X nozzle extension**

Ref: J. Lee et al., "Non-Contact Measurements of Creep Properties of Niobium at 1985 °C,“ Measurement Science and Technology, vol. 26, p. 015901, 2015.

Conclusions

- **Materials Science research utilizing levitation is a useful tool for the study and development of breakthrough materials for space exploration**
  - Levitation research takes advantage of the unique microgravity environment available on ISS

- **This research has applications to NASA exploration needs as well as for ground-based industry, including:**
  - Better turbine blades for aerospace engines
  - Higher quality steel
  - New materials for optical devices, lasers, and photonics
  - Improved semiconductor devices
  - Nuclear Thermal Propulsion (NTP)

- **SLPSRA is planning a joint Materials Science Workshop with CASIS at the ISS R&D conference in Atlanta, July 29 – August 1, 2019. Workshop details TBD.**
  - Anticipate developing a new NASA Research Announcement (NRA)

- **Acknowledgment: NASA Space Life and Physical Sciences Research and Applications (SLPSRA)**