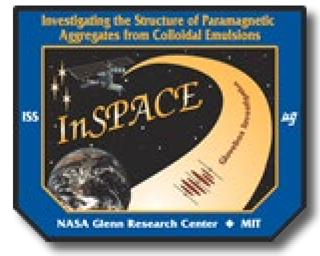
# Investigating the Structure of Paramagnetic Aggregates from Colloidial Emulsions (InSPACE)




is a microgravity fluid physics experiment that was performed on the International Space Station (ISS). The purpose of this investigation is to obtain fundamental data of the complex properties of an exciting class of smart materials termed magnetorheological (MR) fluids.

MR fluids are suspensions of micron-sized superparamagnetic particles in a nonmagnetic medium. These controllable fluids can quickly transition into a nearly solid like state when exposed to a magnetic field and return to their original liquid state when the magnetic field is removed. Their relative stiffness can be controlled by controlling the strength of the magnetic field.

Due to the rapid-response interface that they provide between mechanical components and electronic controls, MR fluids can be used to improve or develop new brake systems, seat suspensions, robotics, clutches, airplane landing gear, and vibration damping systems.

**Science Background and Objectives**

The objective of InSPACE is to determine the true three-dimensional equilibrium structure of an MR emulsion in a pulsed magnetic field. The microstructure of MR fluids plays a significant role in determining their bulk rheological properties.

InSPACE will conduct a microscopic video study of the MR fluid in a pulsed magnetic field to determine the effect of varying magnetic field, pulse frequency, and particle size on the equilibrium microstructures. On Earth, gravity causes sedimentation, which means heavier groups of particles sink while lighter ones remain suspended. The low gravity environment that is provided on the space station facility will eliminate the effects of sedimentation, which otherwise become significant for these relatively large aggregate structures.

A pulsed magnetic field will be used to mimic the forces applied to these fluids in real applications, such as vibration damping systems. A pulsed field also tends to produce intricate thick structures with different properties than structures produced by a constant magnetic field.

InSPACE's results may be utilized to enhance applications on Earth and provide an early understanding of the behavior of MR fluids in microgravity to aid in the development of highly technical experiments.

**Experiment operations**

Most of InSPACE's hardware was launched to the ISS on Flight UF–2/STS–111, June 5, 2002. The MR samples were launched on Flight 11A/STS–113, November 23, 2002. Experiment operations by the ISS astronaut crew occurred during ISS Expedition Six and Seven in the MSG located in the U.S. Destiny Laboratory Module. The MSG includes an enclosed work volume that provides power and interfaces for data and video that can be downlinked to the science team while the experiment is operating.

Before the flight, three primary Helmholtz coil assemblies —electromagnets that produce a uniform magnetic field— and three spares, each with a small precision rectangular borosilicate (low melting point) glass vial, 50 mm long by 1 mm internal square, were outfitted with the MR fluid. Each fluid sample is composed of small, magnetizable particles of uniform size suspended in an aqueous medium.

The particle sizes are different in each of the three primary coil assemblies. The crew will install a coil onto an optics assembly that includes two cameras for imaging the samples from a straight-on and right-angle view during test runs. The cameras will focus on a very small area of the vial, only 0.3 mm across. A backlighting system will be used to illuminate the samples.

The astronaut will set a specified electrical current and frequency on an avionics assembly that will produce a pulsed magnetic field inside the coil. This magnetic field will cause the particles in the fluid to group together, or aggregate, and form microstructures inside the fluid.

For a period of one to two hours, the cameras will record the microstructures. This video will be distributed to scientists at Massachusetts Institute of Technology and the Telescience Support Center at NASA's Glenn Research Center in Cleveland, Ohio, where scientists and engineers will observe the microstructures as they form and change.

Video recorded onboard the ISS will be returned to Earth for more in-depth analysis. Nine tests will be performed for each coil for a total of 27 experiment runs.

**Benefits**

This is the first time this experiment has been conducted in space. It will provide fundamental data on the way the particles and aggregate structures in the fluid respond to a pulsed external magnetic field in a microgravity environment. When these fluids are used in braking systems or other electromechanical devices, they are often exposed to such fields that affect their operations.

Data from the experiment can be used to test theoretical models of the structure of suspensions of small particles in applied fields. By understanding the complex properties of these fluids and learning how the particles interact, scientists can develop more sophisticated methods for controlling these fluids and using them in a variety of devices.

InSPACE completed a Post Flight Assessment Review at GRC on March 18, 2014.

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# Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion-2


Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsion – 2 investigation is a continuation of the InSPACE investigation begun on ISS Expedition 6, providing new and improved samples for operation in the Microgravity Science Glovebox (MSG).

Magnetorheological (MR) fluids are suspensions of paramagnetic particles that can quickly solidify when exposed to a magnetic field and return to their original liquid state when the magnetic field is removed. This solidification process produces viscoelastic properties that can be harnessed for a variety of mechanical devices from intricate robotic motions to strong braking and clutch mechanisms.

Understanding how to precisely control these properties and states will enable the use of MR fluids as a working fluid in exploration robots to produce a range of articulated motions ranging from delicate —e.g., picking up an egg —to firm response, and proper encapsulation pressure around bone fractures. Current robotic technology depends on conventional mechanical components like gears, dashpots, and clutches, while MR fluid interfaces provide significantly faster response, strength, tenability, and physical flexibility to enhance human and robotic movement and strength.

Gravitational effects in MR fluids are manifested as variations in particle concentration and phase separation due to particle sedimentation, directly impacting rheological (viscoelastic) properties and application performance. Long-duration microgravity is needed to study the internal structural evolution in the MR fluids in the absence of these additional effects.

InSPACE-2 will provide feasibility data on the gelation transition in MR fluids under steady magnetic fields and perform runs using new samples with an improved cell design for imaging the resulting large aggregate structures, based on previous InSPACE data.

InSPACE-2 hardware consists of two new Helmholtz coil assemblies containing sealed vials of MR fluid and eight new vial assemblies that hold the test fluid. The new hardware will interface with the InSPACE hardware currently on ISS. InSPACE-2 data will significantly impact design of human robotic interfaces for exploration missions.

**Science Background and Objectives**

**Science Objectives**

InSPACE-2 will obtain data on magnetorheological fluids which change properties in response to magnetic fields —that can be used to improve or develop new brake systems and robotics.

**Science Results**

Magnetorheological fluids are colloids —fine particles suspended in fluid —that can form solid-like gels when exposed to a steady, uniform magnetic field. This experiment observed two distinct particle growth processes: one where particle-rich and particle-poor regions form, and another where the structure suddenly collapses and particle columns form.

Magnetic field strength and frequency determine which of these two processes occur, and in microgravity, the particular structures can be maintained as long as the magnetic forces are applied. The results suggest how manipulating magnetic fields may be used to harness colloidal suspensions to create unique materials and electro-mechanical devices.

**Experiment Operations**

InSPACE-2 will be conducted inside the MSG work volume, and the hardware will be powered with 120 volts via MSG. Experiment runs will be recorded by MSG's video system. Using the optics from InSPACE-1 already on ISS, InSPACE-2 will visually study new samples. An improved cell design over that used in InSPACE-1 will be used for better imaging of the resulting aggregate structures. The new cells are dimensionally very thin in one direction which reduces the optical thickness in that direction and thus provides better viewing.

A new coil is also provided that allows the substitution of multiple samples in two orthogonal orientations for alternate views. InSPACE-2 will provide data on the performance of magnetorheological (MR) fluids in a microgravity environment, under steady and intermittent operation (pulsed fields). InSPACE-2 is not a fully automated payload. The crew will be responsible for in-orbit operations, such as sample changes and video tape changes.

The crew will set up InSPACE inside the MSG work volume and conduct 27 experiment runs using the glove ports. They will change out the coils after nine experiments and replace video tapes as necessary.

**Applications**

**Space Applications**

At the practical level, these fluids are used in electromechanical interfaces and devices in which the fluid is operationally exposed to similar fields which can affect their operation. Current commercial MR fluid products include tunable dampers and brakes, while future applications in robotics, clutches, and a host of vibration-control systems are envisioned.

**Earth Applications**

The study of MR fluids on Earth is difficult because the small magnetic particles remain suspended while the sediments (large particles) sink. The ISS' low-gravity environment will eliminate the effects of sinking sedimentation. After the magnetic field is applied to an MR fluid, the microstructures form a rigid lattice that causes the suspension to stiffen.

The rapid transformation of these fluids without the iron oxide grains clumping have many possible applications on Earth, especially for actuator-type devices. This technology has potential to improve design structures, such as bridges and buildings, to avoid earthquake damage.

**Previous Missions**

InSPACE —the precursor to InSPACE-2 —was performed on ISS Expeditions 6, 7, 12 and 13.

## Publications

### Journal Papers

- Biswal, S.L. and Gast, A. P. “Micromixing with linked chains of paramagnetic particles” Analytical Chemistry, 76 (21), 6448-6455, (2004).
- Biswal, S.L. and Gast, A. P. “Rotational dynamics of semiflexible paramagnetic particle chains” Physical Review E, 69 (4), Art No. 041406, Part 1 Apr 2004.
- Lyles, B.F., Terrot, M.S., Hammond, P.T. and Gast, A. P. “Directed patterned adsorption of magnetic beads on polyelectrolyte multilayers on glass” Langmuir, 20 (8), 3028-3031 (2004).
- Biswal, S.L. and Gast, A. P. “Mechanics of semiflexible chains formed bypoly(ethylene glycol)-linked paramagnetc particles” Physical Review E, 68 (2), Art No. 021402, Part 1 Aug 2003.
- Furst, E.M. and Gast, A. P. “Dynamics and lateral interactions of dipolar chains” Physical Review E, 62 (5), 6916-6925 (2000).
- Furst, E.M. and Gast, A. P. “Micromechanics of magnetorheological suspensions ” Physical Review E, 61 (6), 6732-6739 (2000).
- Furst, E. M., and Gast, A. P. “Micromechanics of dipolar chains using optical tweezers” Physical Review Letters, 82 (20), 4130-4133 (1999).
- Furst, E. M., and Gast, A. P. “Particle dynamics in magnetorheological suspensions using diffusing wave spectroscopy,” Physical Review E, 58, 3372 (1998).
- Furst, E. M., Suzuki, C., Fermigier, M., and Gast, A. P.”Permanently-linked monodisperse paramagnetic chains” Langmuir, 14 (26), 7334 -7336 (1998).
- Promislow, J.H.E.; and Gast, A.P., ”Magnetorheological Fluid Structure in a Pulsed Magnetic Field. Langmuir,”, vol. 12, no. 17, 1996, pp. 4095-4102.
- Promislow J.H.E and.Gast, A.P, “Low-Energy Suspension Structure of a Magnetorheological Fluid,” Phys.Rev. E 56 (1997) 642:651.
- Promislow, J.H.E, Gast, A.P. and Fermigier, M., “Aggregation Kinetics of Paramagnetic Colloidal Particles.” J.Chem. Phys. 102 (1995) 5492:5498.

### Conference Presentations

- P.A. Vasquez, J. Agui, and E. M. Furst “Structural Transitions of MR Fluids in Microgravity,” Poster presentation, 79th Society of Rheology meeting, October 7-11, 2007, Salt Lake City, UT.
- A. Gast, B. Lyles, K. Bentley, J. Agui, and D. Pettit. “Magnetic Emulsions in Space”. Symposium in Honor of Darsh Wasan I: Interfacial and Colloidal Phenomena. AIChE annual meeting, November 16-21, 2003, San Francisco, CA.

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## Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions-3


The use of external fields to control the microstructure of colloidal suspensions has long been recognized as a powerful means for tailoring the mechanical, optical and electronic properties of materials.

Magnetorheological (MR) suspensions, in particular, provide a striking example. These normally stable fluids undergo a dynamic transition to a solid within milliseconds after the application of an external magnetic field. They are also important models for developing methods of bottom-up fabrication of micro- and nano-structured materials and devices using field-directed self-assembly.

Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions-2 (InSPACE-2) experiments focused on the structure of magnetically polarizable particle suspensions over long times in steady direct current and pulsed magnetic fields. In pulsed fields especially, the long-time kinetics of the suspension micro-structural coarsening provided new and important results.

The InSPACE-2 experiments were the first to yield information on the full, three-dimensional aggregation process over timescales much longer than those accessible on the ground, which are limited by catastrophic sedimentation. Furthermore, the experiments identified a novel dynamic instability in which the suspension microstructures were observed to buckle at specific field frequencies and field strengths.

InSPACE-3 investigates the effect of particle shape on the micro-structural evolution of MR suspensions. Recent ground-based experiments demonstrate a startling effect that particle shape has on the interactions of dipolar chains and the resulting suspension microstructure. Specifically, the suspensions of paramagnetic ellipsoid-shaped particles are investigated. In combination with the results of InSPACE-2, it is hypothesized that particle shape will dramatically alter the aggregation kinetics, microstructures and microscopic mechanics.

This potentially leads to the ability to engineer enhanced properties of these suspensions, including suppression of the lateral aggregation in magnetorheological fluid-based electromechanical devices or the ability to create new colloidal materials through field-directed self-assembly.

**Science Objectives**

InSPACE-3 studies magnetic colloidal mixtures under the influence of various magnetic fields. A magnetic colloidal fluid contains materials which solidify when a magnetic field is applied to it, thus changing the physical properties of the liquid as a whole. Conducting these experiments aboard the International Space Station allows scientists to examine the network and arrangement of the 'frozen' solid structures unaffected by the force of gravity which can deform them on Earth.

**Experiment Operations**

InSPACE-3 is conducted inside the MSG work volume. The fluid sample in the vial assembly must be uniformly mixed prior to test operations. Thirty-six tests are performed, two or three per day. The vial assemblies may be reused indefinitely after restoring an even distribution to the particles within the fluid.

Video downlink is monitored on the ground during testing and provided to the Principal Investigator as desired. Sample return of the vial assemblies is not required. Video imagery is stored on 72 Mini-DVCAM tapes and 36 Hi-8 tapes for later return to the ground for more complete analysis.

The crew installs the hardware into the MSG, and uniformly distributes the particles in the fluid of the first vial assembly prior to installation in the hardware. Two DVCAMs and one Hi-8 tape are loaded into the video recorders in the video drawer. The crew member next focuses each optical train onto the particles in the center of the vial.

A test run starts by setting the current per the test matrix and then setting the pulse frequency of the current. Both are simple adjustments of dial pots by the crew while observing digital displays of the values of each. The current level controls the strength of the magnetic field applied to the MR fluid. A field of view (FOV) sweep and a focus sweep are performed right away with each optical train and then again about 20 minutes later.

The experiment runs autonomously with ground monitoring for the next two to three hours. Another FOV sweep and focus sweep for each optical train is performed prior to removing the magnetic field from the vial by setting the current to zero. Another run may be started with the same vial assembly after remixing the particles in the fluid, or a different vial assembly may be used. Upon completion of all testing, the hardware is removed from the MSG.

**Applications**

**Space Applications**

The quick phase-shifting property of magnetic colloidal fluids makes them potentially useful for devices such as optical interfaces and active noise and vibration dampers inside spacecraft. Future uses could include robotics, energy-transfer devices such as clutches, and other control systems.

**Earth Applications**

The work has application to directed self-assembly of crystalline structures from particles that may eventually allow creation of new nano-materials fabricated from nanoparticle building blocks, with potential applications in medicine, energy storage, chemical separations, and catalysis.

Magnetic colloidal fluid technology is currently used for shock absorbers in race cars and sport cars. This technology is expanding to include making large-scale building foundation stabilizers for areas prone to earthquakes.

**Previous Missions**

InSPACE, the precursor to InSPACE-2 was performed on ISS Expeditions 6, 7, 12 and 13.

**Publications**

**Journal Papers**


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## Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions-4