FLUID PHYSICS AND TRANSPORT PHENOMENA IN A SIMULATED REDUCED GRAVITY ENVIRONMENT

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We describe a ground-based apparatus that allows the cancellation of gravity on a fluid using magnetic forces. The present system was designed for use with liquid oxygen over the range 0.001 - 5 g's. This fluid is an essential component of any flight mission using substantial amounts of liquid propellant, especially manned missions. The apparatus has been used to reduce the hydrostatic compression near the oxygen critical point and to demonstrate inverted phase separation. It could also be used to study pool and film boiling, and two–phase heat transfer and flow in Martian, Lunar or near-zero gravity, as well as phenomena such as Marangoni flow, convective instabilities and the effects of interfacial forces. These studies would contribute directly to the reliability and optimization of the Moon and Mars flight support systems. Systems using higher magnetic fields can be built to study other fluids, including water.

INTRODUCTION

In recent years the magnetic levitation of many ordinary substances against the earth's gravity field has been demonstrated[1]. Materials from wood to water to small living creatures have been freely suspended in air against gravity for significant periods. This effect can be used to perform a wide range of interesting fluid studies, including convection with a variable driving force and thermal stratification effects, two phase flow and heat transport and film boiling to name a few. In some cases the magnetic field requirements are sufficiently modest that the materials can be levitated indefinitely using superconducting magnets or in the case of a few materials such as oxygen and bismuth, with permanent magnets. This capability opens up exciting research opportunities previously only accessible in space. An essential property of magnetic levitation of a single component material is that the force is applied to all molecules equally, canceling gravity in the bulk, as opposed to applying surface forces as is done in a rotating bioreactor, for example. On the other hand, the levitation of complex objects involves cancellation of gravity only on average, in a similar fashion to buoyancy. In this paper we describe some work conducted with a liquid oxygen levitator and point out some future directions that could be of value to the Moon and Mars program.

With current technology, magnetic levitation is in principle achievable for any material with a susceptibility greater than about $\pm\ 3.5\times10^{-10}\ m^3/kg$. This limit is set by the design constraints of high field magnets, and could be lowered in the future, as new magnet technologies are developed. The levitating force is proportional to the susceptibility times $B\nabla B$, where B is the magnetic field intensity and ∇B is its gradient, and must of course be directed upwards. For most materials susceptibilities are in the range ±1 to $5\times10^{-10}\ m^3/kg$, requiring quite high fields and gradients to achieve levitation, if it can be done. The high fields complicate experiment design and tend to restrict the choice of fluids to those of low atomic weight, but fortunately include water, oxygen and hydrogen, the fluids most likely to be used on deep space manned missions. Liquid oxygen is an exceptional case, having an extremely high susceptibility of $2.41\times10^{-7}\ m^3/kg$ at 90K. This implies typical levitation values of $B\nabla B$ that are 300 times smaller than for water. In the poster charts below, we show some photos of an oxygen levitation demonstration using a small samarium-cobalt permanent magnet.

The goal of the system described here was to perform an improved investigation of critical phenomena entering deep into the asymptotic region by making use of magnetic levitation to reduce the hydrostatic compression of a fluid. A magnetic technique to cancel the hydrostatic pressure variations in a small column of liquid helium to the 1% level was demonstrated at JPL[2]. A similar magnet was also used at Brown University[3] to levitate large drops of helium. These experiments needed very large $B\nabla B$ values to achieve levitation due to the small value of the susceptibility of helium. The resulting magnet design constraints severely limit the sample volume where accurate cancellation of gravity can be achieved. In contrast, a much more effective cancellation of the hydrostatic pressure over larger volumes can be accomplished with a sample of liquid oxygen in relatively modest magnetic fields using wide bore solenoids and carefully designed gradient coils. We note that the magnetic effects on oxygen were demonstrated[4] at the Bitter Magnet Laboratory at MIT many years ago. Since biological material is composed primarily of water, and the other components have similar susceptibilities, it can typically be levitated.

OXYGEN LEVITATION

We have built a magnetic levitation system that is capable of canceling the effect of gravity on an oxygen sample to about 0.1%, a capacitance cell with associated electronics for local fluid density measurements, and a thermal enclosure designed to achieve a thermal stability and homogeneity of about 1 microdegree when operating near 154 K. The levitation system consists of a solenoid and a gradient coil configured to provide a lift force uniformity of about 0.1% over a disk-shaped volume 1 mm high and 1 cm in diameter. The uniform field and the gradient can be adjusted independently. To minimize the perturbations to the field distribution all components within the bore of the magnet are fabricated from non-magnetic materials. A schematic view of the apparatus is shown in the charts below.

The cell contains a narrow gap capacitor formed from aluminum films deposited on sapphire. The structure was designed to be very stable mechanically and have low sensitivity to pressure. The capacitor gap was located below the center of the cell about 1 mm from the bottom, and it was 0.5 cm in diameter. By applying a pulsed dc bias to the plates the effect of electrostriction on the fluid can be observed, allowing the compressibility to be estimated. The internal height of the cell was 3 mm and the large spaces were filled with copper blocks.

A significant component of the apparatus is the thermal control system. We designed a system to achieve a stability and homogeneity of about 10^{-8} near the critical point, allowing good operation at the resolution goal of $t \sim 10^{-7}$. This is at about the level obtained in state-of-the-art thermal controllers such as those used on the Zeno and CVX flight experiments. The mechanical portion of the control system is a multi-shell enclosure operated in a high vacuum. A photograph of the partially disassembled system with the shells removed is shown below. The temperatures of the stages were measured using calibrated thermistors and conventional high resolution ac bridge techniques involving high stability ratio transformers.

Recently, we used the levitator system to reduce the hydrostatic compression of oxygen near its critical point, allowing a new investigation of thermodynamic phenomena in this region. The effect of the levitator is to cancel gravity on each volume element within a fluid, mimicking the conditions of space flight on the ground. A basic problem in the study of second order phase transitions is that fluids are the only materials free of distortion due to impurity and stress inhomogeneities, but near the transition, the compressibility diverges, causing distortion due to hydrostatic compression. Space experiments, which eliminate the hydrostatic effect, have become one of the few ways that much progress can be made in this field. Wilson's application[5] of the renormalization group calculation scheme to the problem of the critical point led to predictions for the exponents and many 'universal' amplitude ratios in the model. These predictions for fundamental thermodynamic quantities are currently the most accurate ones in the entire field of bulk critical phenomena in statistical physics. The project described here was designed to improve the testing of these predictions.

The sample density was measured by monitoring the change in capacitance between the aluminum electrodes plates due to the fluid filling the gap. A commercial capacitance bridge with a resolution $\Delta C/C \sim 10^{-7}$ is used for the measurements. In a figure below we show some typical electrostriction data obtained as the sample cools at constant average density close to critical. This curve shows three regions. Well above the critical temperature the fluid responds quickly to the square wave voltage applied to the plates. As the transition temperature is approached the amplitude of the response is seen to increase as expected since it is proportional to the compressibility. Very close to the transition a sharp increase in the thermal relaxation time is observed possibly due to the presence of two fluid phases within the capacitor gap. With further cooling the time constant is reduced and the density deviation from the original value increases rapidly. Typically, this region corresponds to a branch of the coexistence curve. Commonly, the density will change rapidly once more as the temperature is lowered further and the opposite branch of the coexistence curve will be traced out. A figure below shows some initial measurements of the compressibility in the critical region. From separate coexistence curve measurements it appears that for this set of data the mean density of the sample is within 1% of critical, and possibly much closer. The data shows some rounding for $t < 5\times10^{-6}$. Also shown are results obtained with the magnet turned off. Significantly more rounding is observed. This demonstrates that the magnetic levitation system is capable of reducing the effect of gravity at the critical point.

MOON AND MARS MISSION SUPPORT

In the mission support arena, three acceleration environments are of primary interest: the levels seen on the Moon and Mars, and the level encountered during transit. Clearly, in low gravity situations, the magnetic manipulation of fluids is relatively straightforward. For example, for water, a $B\nabla B$ of only 1.4 T^2/m is needed to hold the fluid against milli-g accelerations. In unmanned vehicles, it is easy to achieve micro-g accelerations when thruster firing is avoided. In that situation, liquid hydrogen can be controlled at $B\nabla B \sim 5\times10^{-4}$ T^2/m. At this level, surface tension forces over radii of 0.1 m compete with the magnetic force. An obvious application for long space voyages, say to Mars, is the controlled venting of cryogenic propellants without the need for fine mesh screens within the tanks. In some cases, permanent magnets could be used near the venting orifice. Magnetic separation of the phases would avoid the 'blow-through' problem with meshes since the separation would be intrinsically stable. Any loss of control due to transient forces would be recovered from automatically.

The effective gravity environments on the Moon and Mars are 0.17g and 0.39g respectively. The table below[6] shows some representative values for the $B\nabla B$ values required to create various artificial gravity environments for some commonly used liquids. A lift force of 1g – 0.39g = 0.61g is needed to create the equivalent artificial gravity environment for Mars in an Earth based laboratory. Since the created effective gravity is linear in $B\nabla B$, the table can be used to determine arbitrary gravity compensations for the fluids listed.

Another potential application is low dissipation pumping, using time varying magnetic attraction. The inertia of the fluid could be used to draw fluid into a multi-stage magnetic attraction system and expel it in a region of repulsive force. The technique described here can also be used to suppress or enhance convection in certain fluids. This would allow the study of stratification effects encountered, for example, in cooled propellant tanks. Magnetic forces could also be used to apply artificial gravity in small regions for critical applications. For example phase separation in a small boiler could be enhanced, possibly simplifying the design in other areas.

In addition, the magnetic levitation technique could be of significant value to other studies of convection and thermally induced flows. This would allow the study of many flow phenomena in the environments of interest without tying up the extremely scarce microgravity resources currently available. In the case of intermediate g values, magnetic cancellation of gravity gives us the only way to look at flow phenomena for more than a few seconds without actually going to the Moon or Mars. For studying the behavior of oxygen as a typical fluid in Martian gravity, for example, an accessible volume of more than 50cc would be possible, more than enough for many experiments. Applications in other fields are also quite possible, for example, protein crystal growth[7] and biological studies[3].

ACKNOWLEDGMENTS

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		Earth	Moon	Mars	Low gravity
Substance	Susceptibility (m^3/kg)	B∇B (1g) (T^2/m)	B∇B (0.17g) (T^2/m)	B∇B (0.39g) (T^2/m)	B∇B (.001g) (T^2/m)
Hydrogen	-1.99E-09	-492	-81	-194	-0.49
Helium	-4.73E-10	-2074	-342	-817	-2.07
Water	-7.21E-10	-1360	-224	-536	-1.36
Nitrogen	-4.29E-10	-2287	-377	-901	-2.29
Oxygen	2.41E-07	4.07	0.67	1.60	4.07E-03
Neon	-3.34E-10	-2934	-484	-1156	-2.93
Argon	-4.91E-10	-1998	-330	-787	-2.00

Susceptibilities and magnetic levitation forces as a function of g for some fluids. Transport phenomena and fluid mechanics could be studied for all these materials in simulated Moon and Mars gravities and for all except Neon in simulated zero gravity. To get the actual magnetic lift force needed to simulate the Moon's gravity on Earth for example, for a particular fluid, subtract the entry under Moon from that under Earth.

For materials other than oxygen the sample size is somewhat restricted depending on the accuracy required in the gravity simulation. Typical simulations to 1% accuracies are possible in 1 cc spherical regions.

MAGNETIC LEVITATION

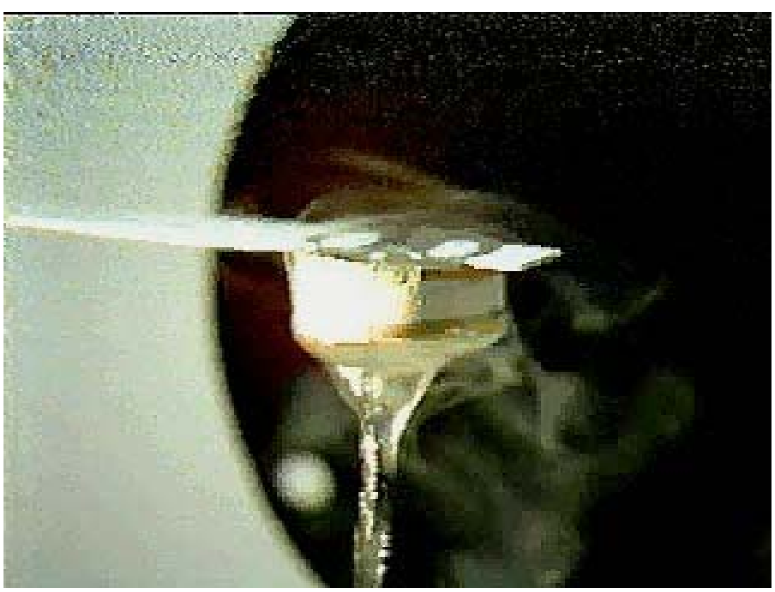
Gravitational effects in fluids come about because the gravitational force acts on every atom in the sample. If this force can be compensated by another force acting on the atoms, then we have simulated microgravity and the gravitational effects should be reduced. We use the magnetic force, B x grad(B), acting on the oxygen molecule magnetic dipole to compensate gravity. Since oxygen has an unusually high magnetic dipole moment, only moderate (1 – 3 Tesla) magnetic fields and modest field gradients are needed. This allows a relatively large working space with small residual forces without the need for state-of-the-art solenoids. In fact, levitation can be achieved with permanent magnets (see demonstration photos).

- *Magnetic levitation has space exploration applications which include intermediate gravity simulation, fluid management, pool boiling studies of fluid propellants in low gravity, thermal stratification effects, long term bone loss studies, low gravity simulation for small living things, three-dimensional cell cultures.*
- *It has scientific applications in suppressing gravity effects in fluids: the removal of hydrostatic compression at critical points and the lambda point, the suppression of convection in Marangoni flow studies (thermocapillary effect), reduced convection in protein crystal growth.*

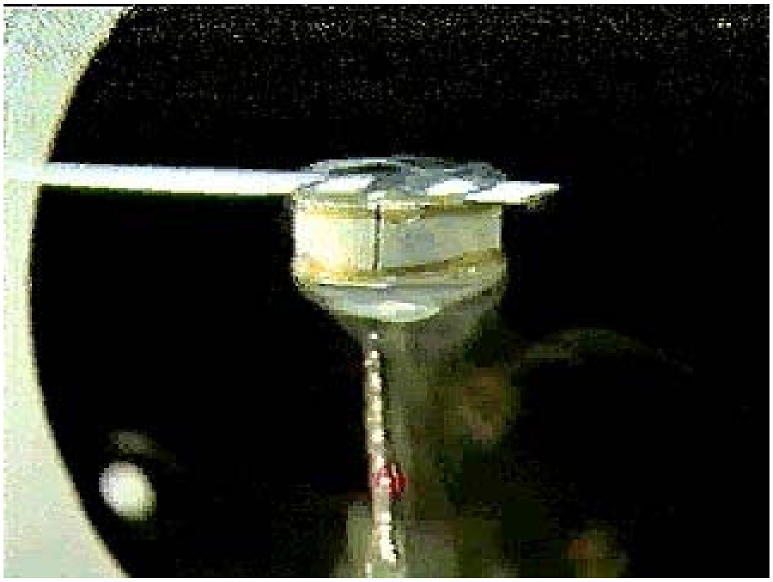
- *It has industrial applications in magnetic bearing systems, Maglev vehicles, and projectile launchers, and possibly protein structure analysis.*

LIQUID OXYGEN LEVITATION DEMONSTRATION

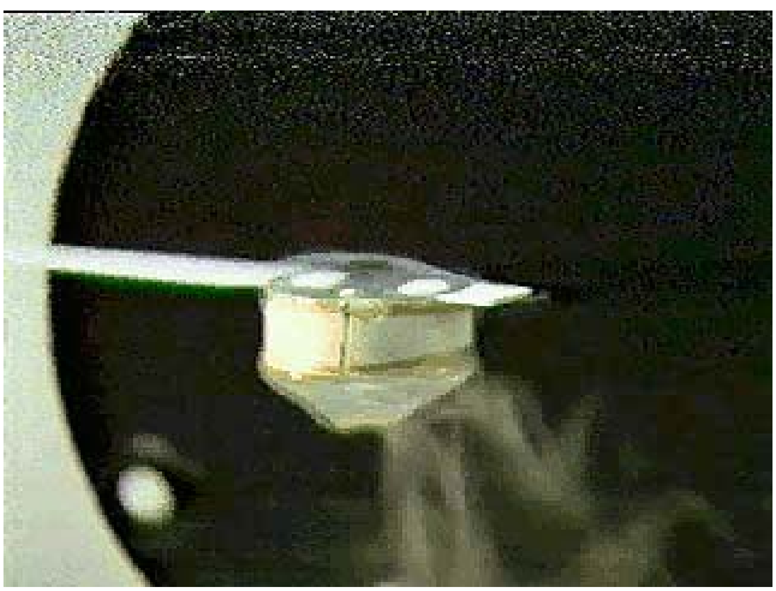
This photo shows the setup used to demonstrate liquid oxygen magnetic levitation: cylindrical magnet attached to steel ruler; tray of cryogenic fluids; circular black screen; lamp.



This photo shows the removal of a large droplet of liquid oxygen from the bath and the subsequent draining of excess fluid that is not supported against gravity.



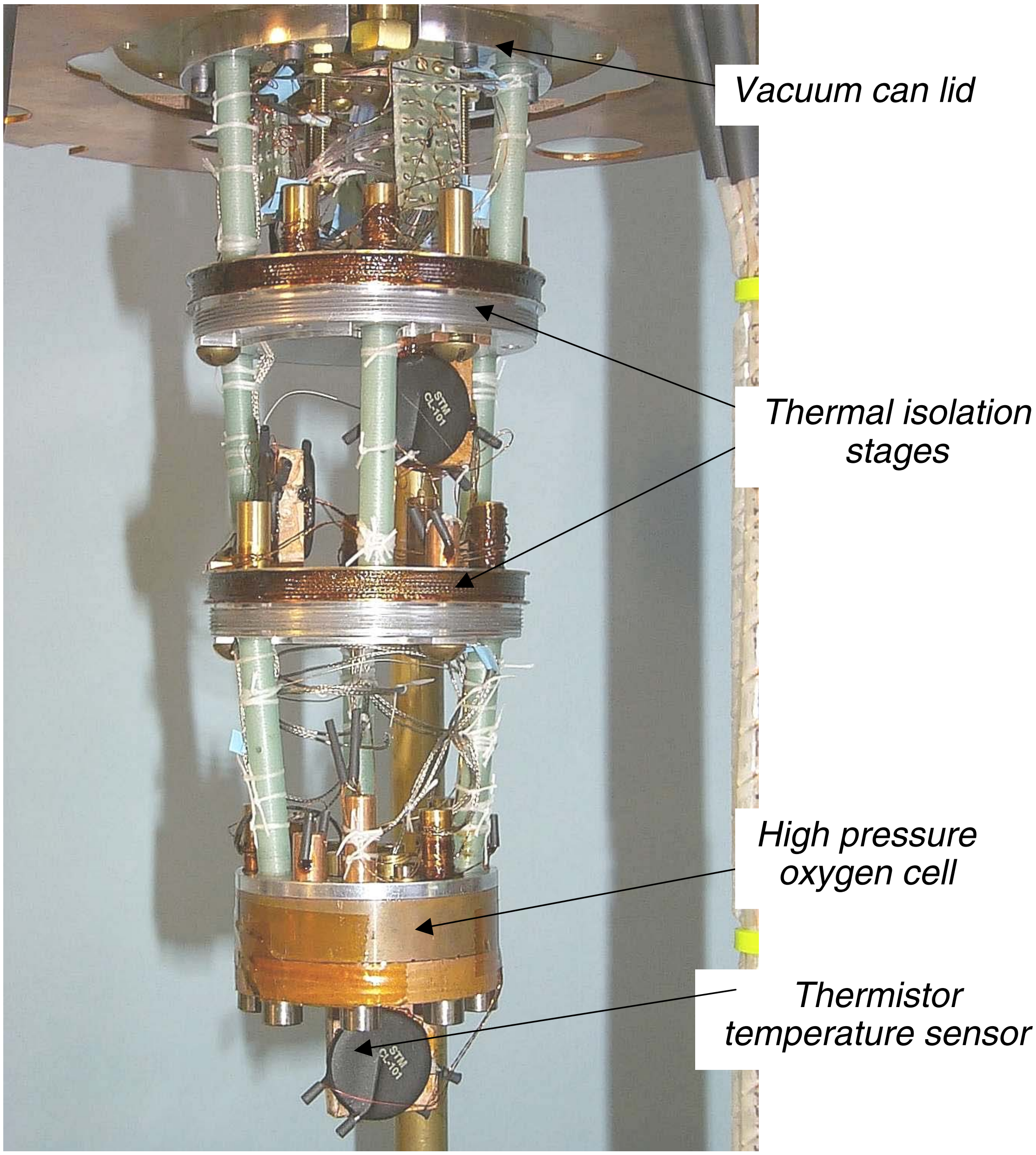
This shows the cessation of the draining event and the formation of a stable droplet attached to the magnet.



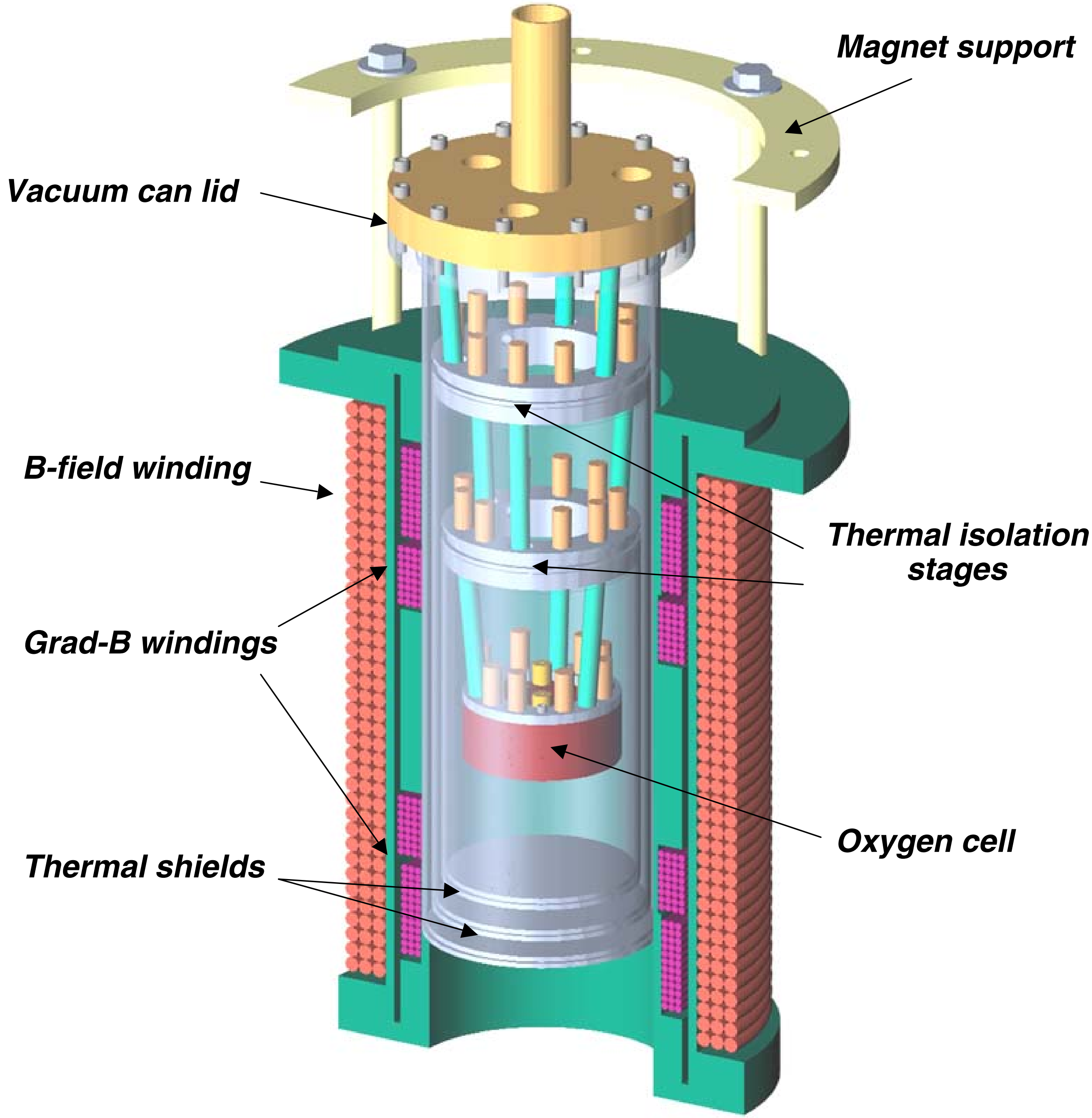
Stable levitation of liquid oxygen with a permanent magnet! Liquid nitrogen will NOT do this.

MAGNETIC LEVITATION OF A LIVING CREATURE
- A. Geim, U. Nijmegen

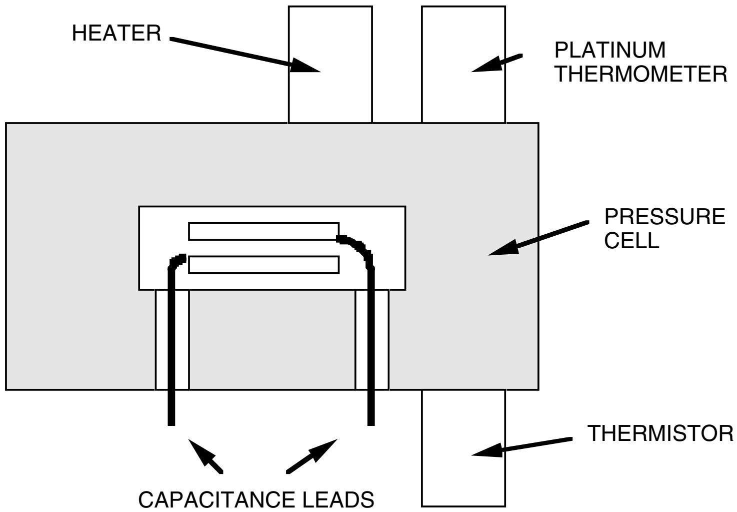
This picture shows the top view of stable magnetic levitation of a live frog in a high field hybrid magnet. Many common materials can now be levitated.



Internal view of thermal control system and oxygen cell used in critical point studies at Stanford. Two thermal shields and the vacuum can have been removed.

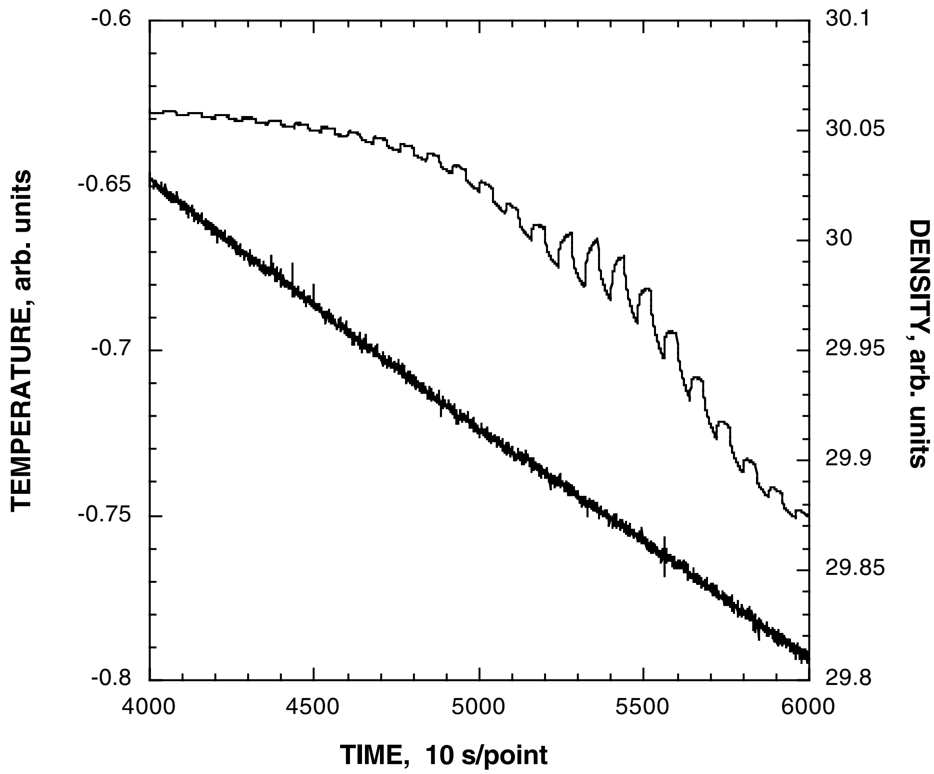


Schematic cross-section of oxygen levitator

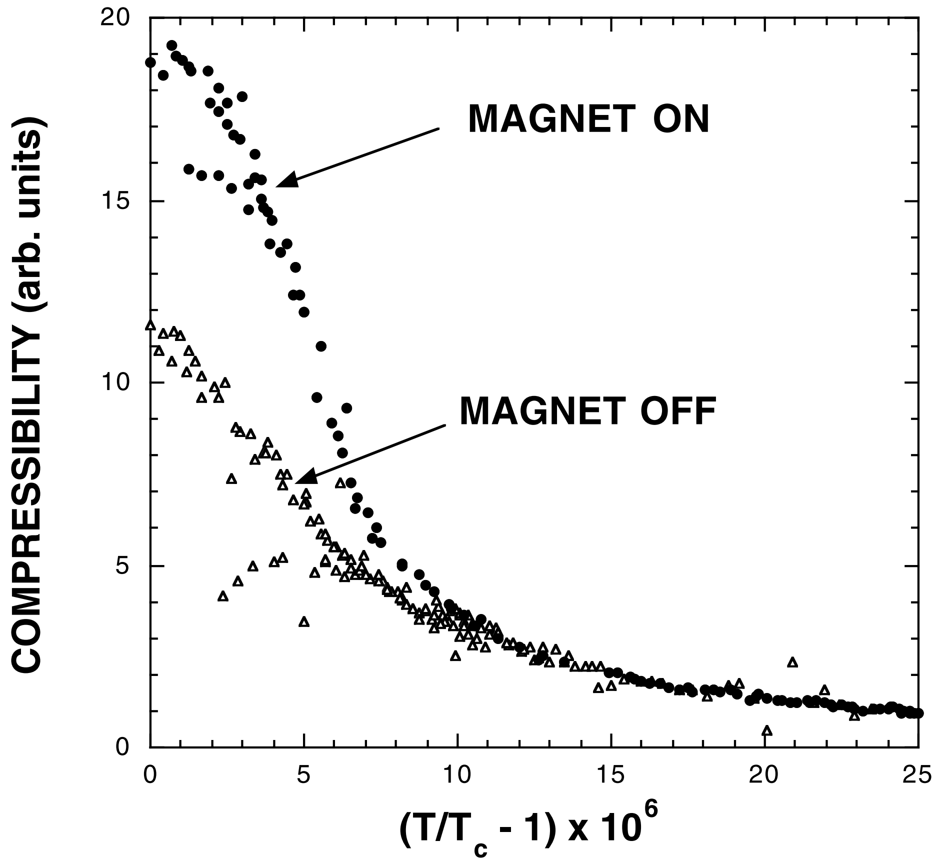


Simplified sketch of oxygen sample cell designed for operation near the critical point (~150K, 50 bars). Gap between sapphire capacitance plates is 0.004 cm.

Near the critical point of a fluid the compressibility diverges, leading to a flattening of the pressure – density isotherms. This causes a significant averaging of the states of the fluid in a finite height sample on earth, making accurate measurements near the critical point very difficult. Magnetic levitation can help reduce this effect.



Upper curve: typical electrostriction data obtained as the sample cools at constant average density close to critical. This curve shows three regions. Well above the critical temperature the fluid responds quickly to the square wave voltage applied to the plates. As the transition temperature is approached the amplitude of the response is seen to increase as expected since it is proportional to the compressibility. Very close to the transition a sharp increase in the thermal relaxation time is observed possibly due to the presence of two fluid phases within the capacitor gap. With further cooling the time constant is reduced and the density deviation from the original value increases rapidly. Typically, this region corresponds to a branch of the coexistence curve.
Lower curve: sample temperature vs time



Compressibility of oxygen vs temperature just above the critical point showing the reduction of gravitational effects with magnetic suspension of the fluid. In zero gravity the compressibility should show divergent behavior at the critical temperature.