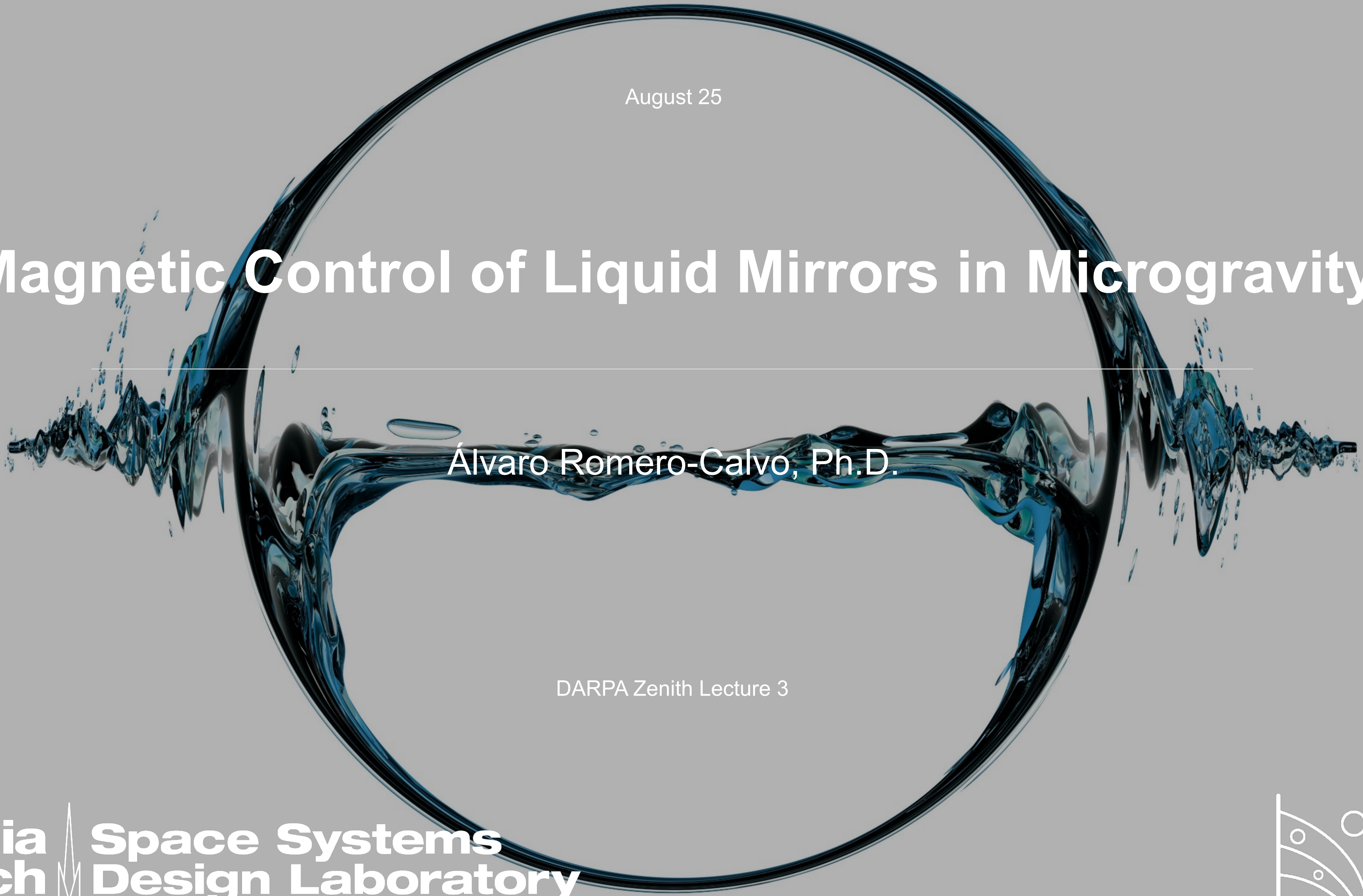
August 25

Magnetic Control of Liquid Mirrors in Microgravity



Álvaro Romero-Calvo, Ph.D.

DARPA Zenith Lecture 3

Georgia Tech Space Systems Design Laboratory

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Ferrofluids

An overview

The origins

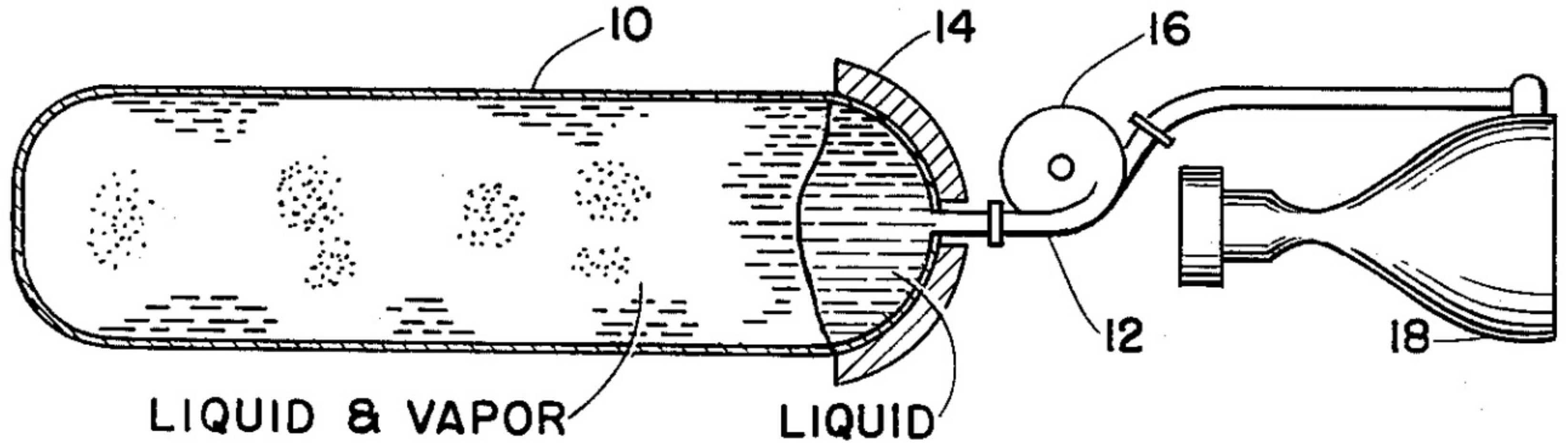


FIG. 2

INVENTOR
SOLOMON S. PAPELL

United States Patent Office

3,215,572
Patented Nov. 2, 1965

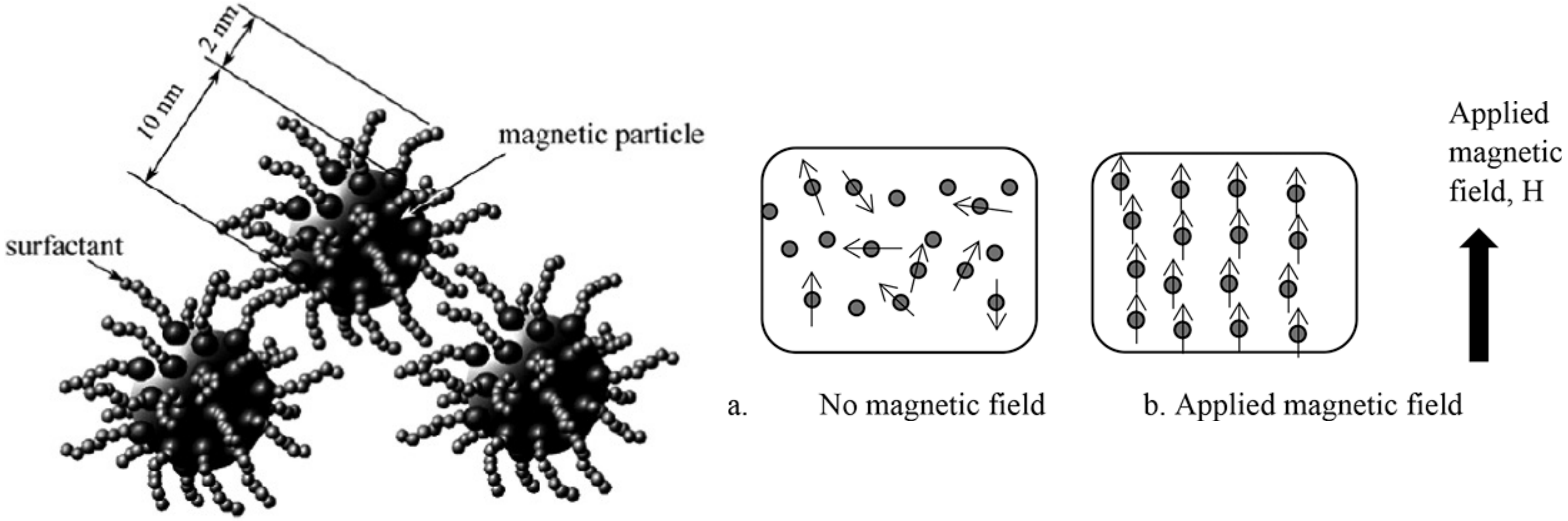
1

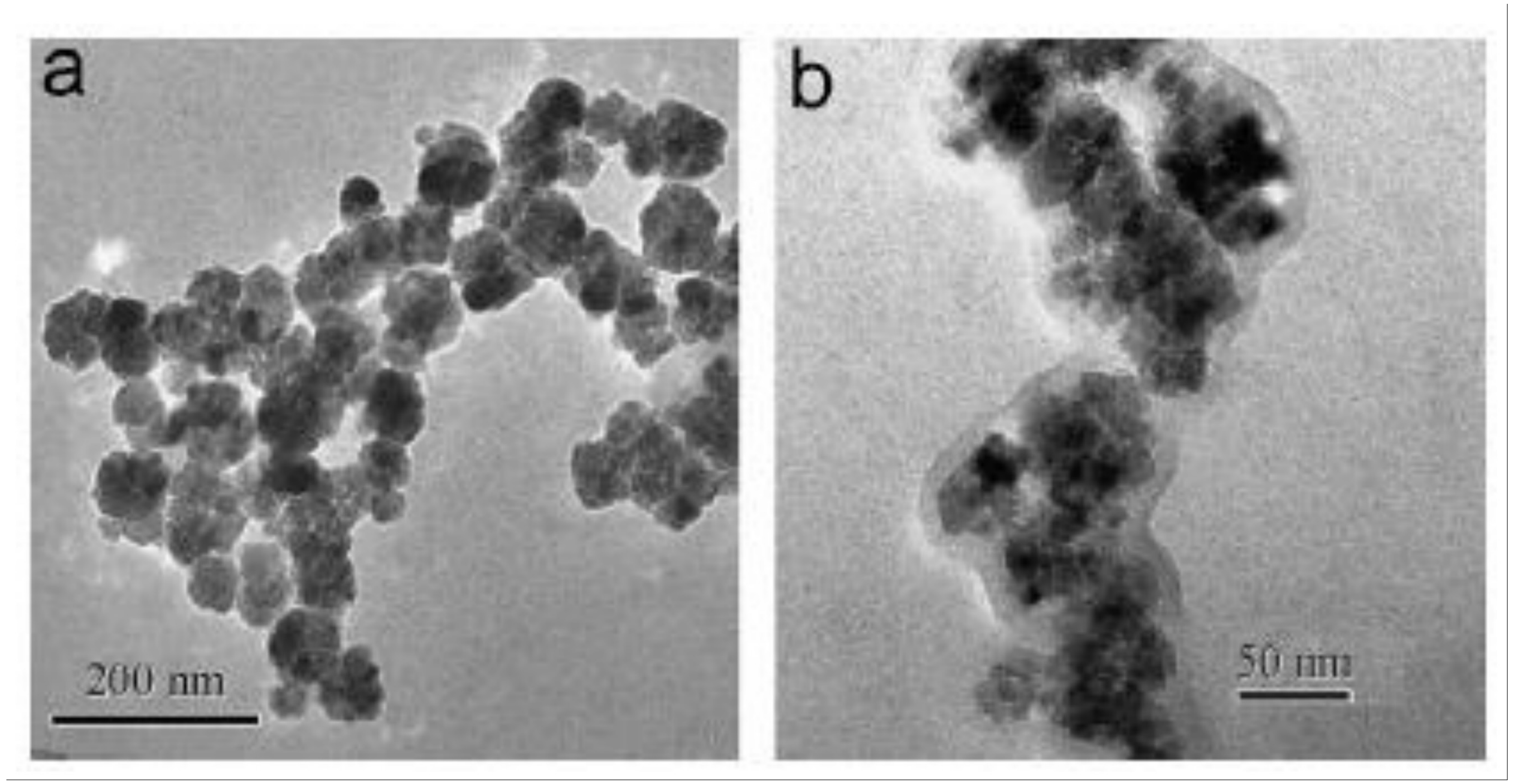
3,215,572
LOW VISCOSITY MAGNETIC FLUID OBTAINED BY THE COLLOIDAL SUSPENSION OF MAGNETIC PARTICLES
Solomon Stephen Papell, Berea, Ohio, assignor to the United States of America as represented by the Administrator of the National Aeronautics and Space Administration
Filed Oct. 9, 1963, Ser. No. 315,096
11 Claims. (Cl. 149—2)
(Granted under Title 35, U.S. Code (1952), sec. 266)

2

magnetized liquid propellant. The magnetic particles are dispersed throughout the propellant and colloidally suspended therein, by utilizing particles of submicron size, so that the surface area of each particle is extremely large in relation to its mass. Because of the small particle size and large surface area, the particles attract and hold the molecules of propellant (the dispersion medium) by surface tension and/or adsorption, thereby assuring that the magnetized particles cannot settle out of the fluid propellant. Additionally, because of the relatively small amount of magnetic material present, the propellant forms

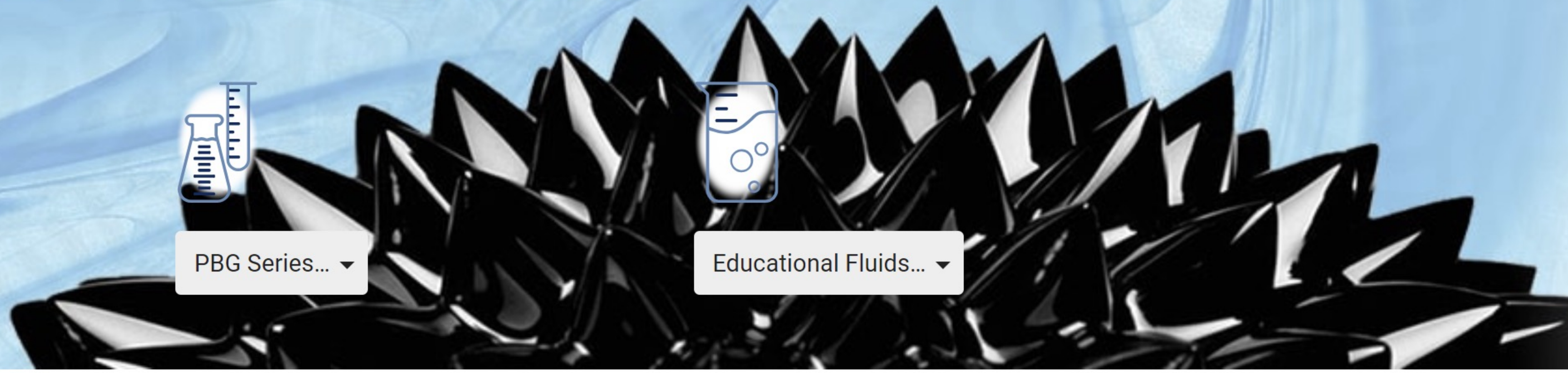
Colloidal suspensions of magnetic nanoparticles





Innovating Ferrofluid for More Than 50 years

Full Range of Fluids for Precision Applications



Audio Fluids...

EMG Series...

PBG Series...

Educational Fluids...

Born at NASA. Perfected at Ferrotec.

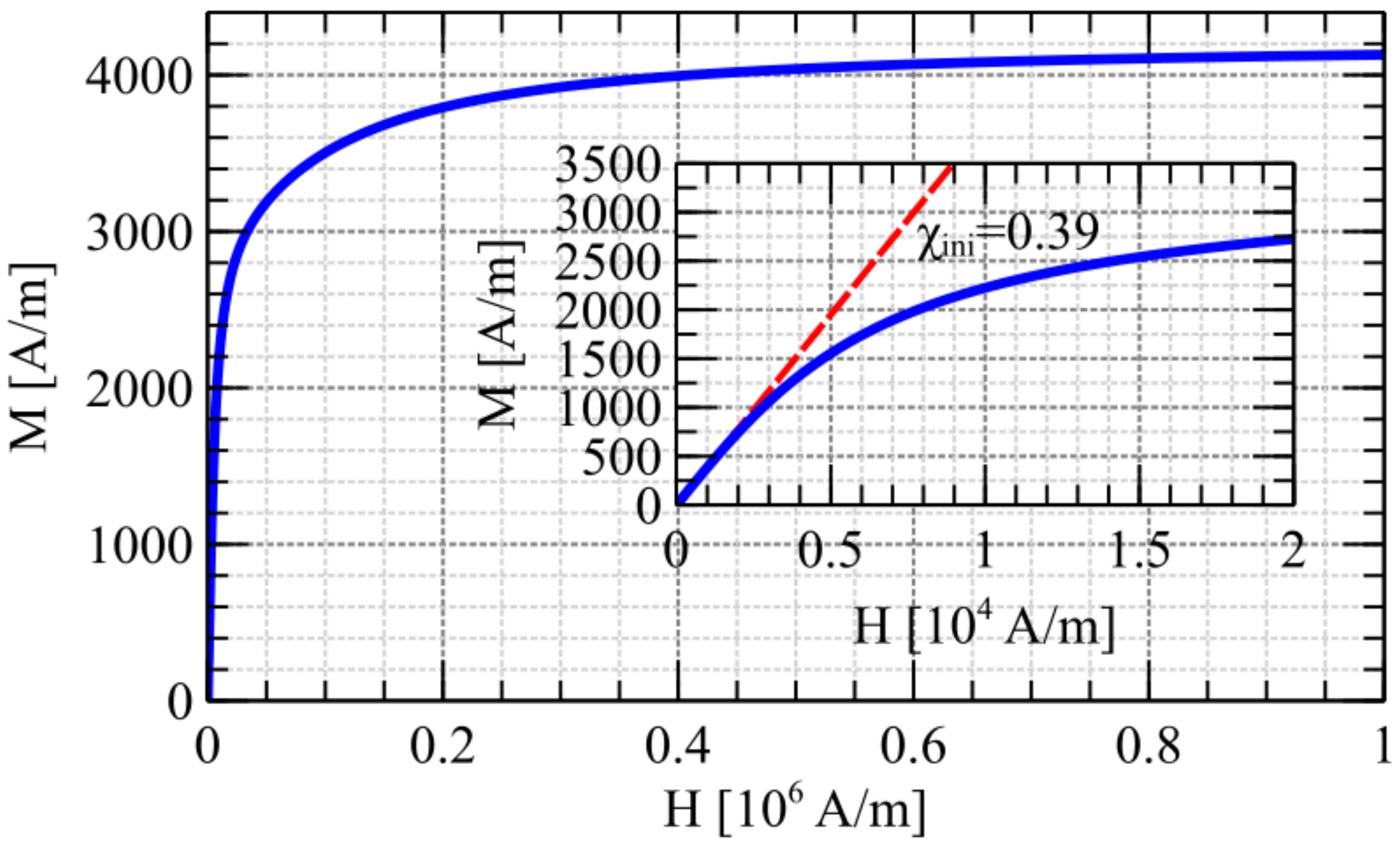
Ferrotec has led the development of ferrofluid technology since 1968 and has worked closely with many companies as their new product teams incorporate ferrofluids in next-generation products. With a comprehensive fluid development and applications laboratories in both the US and Japan, and an experienced staff of scientists and engineers available to assist you, Ferrotec is well placed to help you solve your engineering challenges using ferrofluid.

Learn more

Ferrohydrodynamics

Theory of ferrofluids

Ferrofluid characterization



The **magnetization curve** determines the magnetic response of the ferrofluid

$$\boldsymbol{M} = \chi(H)\boldsymbol{H}$$

A first-order approximation to this curve is the Langevin function (see Rosensweig Sec. 2.7)

$$\frac{M}{M_{\mathrm{sat}}} = L(\alpha) = \coth(\alpha) - \frac{1}{\alpha}\text{, with } \alpha \propto H$$

If the ferrofluid is assumed paramagnetic, then we simply adopt

$$\boldsymbol{M} = \chi\boldsymbol{H}$$

This is reasonable if the magnetization curve is linearized.

Magnetization curves are measured with a Vibrating Sample Magnetometer (VSM) among other methods.

Fluid-magnetic coupling

Incompressible, electrically neutral, viscous fluids

$$\nabla \cdot \boldsymbol{v} = 0$$

$$\rho \frac{D\boldsymbol{v}}{Dt} = \rho \boldsymbol{g} + \nabla \cdot \mathrm{T}$$

Static magnetic fields inside the fluid

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{H} = 0$$

Normal fluid-magnetic surface balance

$$\mathrm{p}^* - 2\eta \frac{\delta v_n}{\delta x_n} + p_m - p_0 = 2\sigma\kappa$$

Incompressible, viscous Maxwell stress tensor

$$\mathrm{T} = \mathrm{T_p} + \mathrm{T}_\nu + \mathrm{T_m}$$

$$\mathrm{T_p} = -p^* \boldsymbol{I}$$

$$\mathrm{T}_\nu = \eta[\nabla \boldsymbol{v} + (\nabla \boldsymbol{v})^{\boldsymbol{T}}]$$

$$\mathrm{T_m} = -\frac{\mu_0}{2} H^2 \boldsymbol{I} + \boldsymbol{BH}$$

Coupled problems!*

* For para/diamagnetic liquids $\boldsymbol{H} \approx \boldsymbol{H}_0$ and the fluid/magnetic system **uncouples**

The magnetic force…

$$\boldsymbol{f_m} = \nabla \cdot \mathrm{T_m} = \mu_0 \mathrm{M} \nabla H = \mu_0 (\boldsymbol{M} \cdot \nabla) \boldsymbol{H}$$

$$\boldsymbol{p}_m = \boldsymbol{n} \cdot \mathrm{T_m^+} - \boldsymbol{n} \cdot \mathrm{T_m^-} = \mu_0 \mathrm{M_n^2}/2\boldsymbol{n}$$

Romero-Calvo Á., "Novel Electromagnetic Space Applications: Touchless Potential Sensing and Low-Gravity Ferrohydrodynamics", PhD Thesis, University of Colorado Boulder

Romero-Calvo Á et al., "Total magnetic force on a ferrofluid droplet in microgravity", Experimental Thermal and Fluid Science, Vol. 117, 1 2020, 110124

Magnetic force potential

$$\Pi = gz - \frac{\omega^2 r^2}{2} + \Pi_m$$

Isothermal

$$\Pi_m = -\frac{\mu_0}{\rho}\int_0^H M(H')dH'$$

THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 12 DECEMBER 1964

Ferrohydrodynamics

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Avco Research and Advanced Development Division, Wilmington, Massachusetts
(Received 6 July 1964)

A phenomenological treatment is given for the fluid dynamics and thermodynamics of strongly polarizable magnetic fluid continua in the presence of nonuniform magnetic fields. Examples of the fluids treated here have only recently been synthesized in the laboratory. It is found that vorticity may be generated by thermomagnetic interaction even in the absence of viscosity and this leads to the development of augmented Bernoulli relationships. An illustration of a free-surface problem of static equilibrium is confirmed by experiment and information is obtained regarding a fluid's magnetic susceptibility. Another illustration elucidates the mechanism of an energy conversion technique. Finally, an analytical solution is found for the problem of source flow with heat addition in order to display the thermomagnetic and magnetomechanical effects attendant to simultaneous heat addition and fluid motion in the presence of a magnetic field.

I. INTRODUCTION

FERROHYDRODYNAMICS is defined here as the fluid dynamic and heat transfer processes associated with the motion of incompressible, magnetically polarizable fluids in the presence of magnetic field and temperature gradients. In general, strong thermomechanical coupling exists when the induced polarization is both temperature and field

Earlier work by Rabinow[4] led to the inventions of magnetic-fluid clutches, dashpots, brakes, and casting procedures. However, the fluids developed there differ from those described now since the magnetic clutch fluid solidified in the presence of the field.

We begin this treatment by considering the nature of the magnetic body force as described in the next section.

https://pubs.aip.org/aip/pfl/article/7/12/1927/825415/Ferrohydrodynamics

Governing equations for axisymmetric flows

Navier-Stokes equations (fluid domains)

Mass balance

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rw)}{\partial r} = 0,$$

Momentum balance (r)

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p^*}{\partial r} + \eta\left(\frac{\partial^2 u}{\partial r^2} + \frac{\partial(u/r)}{\partial r} + \frac{\partial^2 u}{\partial z^2}\right) + \boxed{\mu_0\left(M_r\frac{\partial H_r}{\partial r} + M_z\frac{\partial H_r}{\partial z}\right)},$$

Momentum balance (z)

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p^*}{\partial z} + \eta\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right) + \boxed{\mu_0\left(M_r\frac{\partial H_z}{\partial r} + M_z\frac{\partial H_z}{\partial z}\right)},$$

Magnetostatic Maxwell equations (all domains)

$$\left.\begin{aligned} \nabla\cdot\boldsymbol{H} &= -\nabla\cdot\boldsymbol{M}, \\ \nabla\times\boldsymbol{H} &= \boldsymbol{J}_e. \\ H_r &= -\frac{1}{r}\frac{\partial\Psi}{\partial z} - \frac{\partial\Phi}{\partial r} \\ H_z &= \frac{1}{r}\frac{\partial\Psi}{\partial r} - \frac{\partial\Phi}{\partial z} \end{aligned}\right]$$

$$\nabla\cdot\boldsymbol{H} = -\left[\frac{\partial^2\Phi}{\partial z^2} + \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r}\right]$$

$$\boxed{\nabla\times\boldsymbol{H} = -\frac{1}{r}\left[\frac{\partial^2\Psi}{\partial r^2} + \frac{\partial^2\Psi}{\partial z^2} - \frac{1}{r}\frac{\partial\Psi}{\partial r}\right]\boldsymbol{u}_\phi}$$

For fluid domain

$$\frac{\partial^2\Phi}{\partial z^2} + \frac{\partial^2\Phi}{\partial r^2} + \frac{1}{r}\frac{\partial\Phi}{\partial r} = \boxed{\frac{1}{1+\chi^{\mathrm{vol}}(H)}\left(H_r\frac{\partial\chi^{\mathrm{vol}}}{\partial r} + H_z\frac{\partial\chi^{\mathrm{vol}}}{\partial z}\right)},$$

Constitutive Relation

$$\chi^{\mathrm{vol}} = a_M\frac{\arctan(c_M H)}{H} + b_M\frac{\arctan(d_M H)}{H} + e_M$$

ψ is uncoupled!!

Romero-Calvo Á et al., "Coupled Monolithic Magnetohydrodynamic Model for Axisymmetric Multiphase Flows", Applied Mathematical Modeling, Vol. 111, pp. 836-861, 2022

Tasks

Task 1

Create a 2D magnetic simulator that takes the position (**x, y**), orientation ($\boldsymbol{\theta}$), geometry (**w, h**), and magnetization ($\boldsymbol{M_m}$) of N magnets and provides the resulting magnetic field of the system. Implement speeding up procedures as needed.

- One function must generate the magnetic field produced by an individual magnet
- The **main** file takes the parameters and generates the system
- (Optional) A different function provides the parameters for main (6 parameter vectors) for a linear Halbach array of thickness h and pattern frequency λ centered at X,Y.

Use Github's 2D magnet folder

Task 2

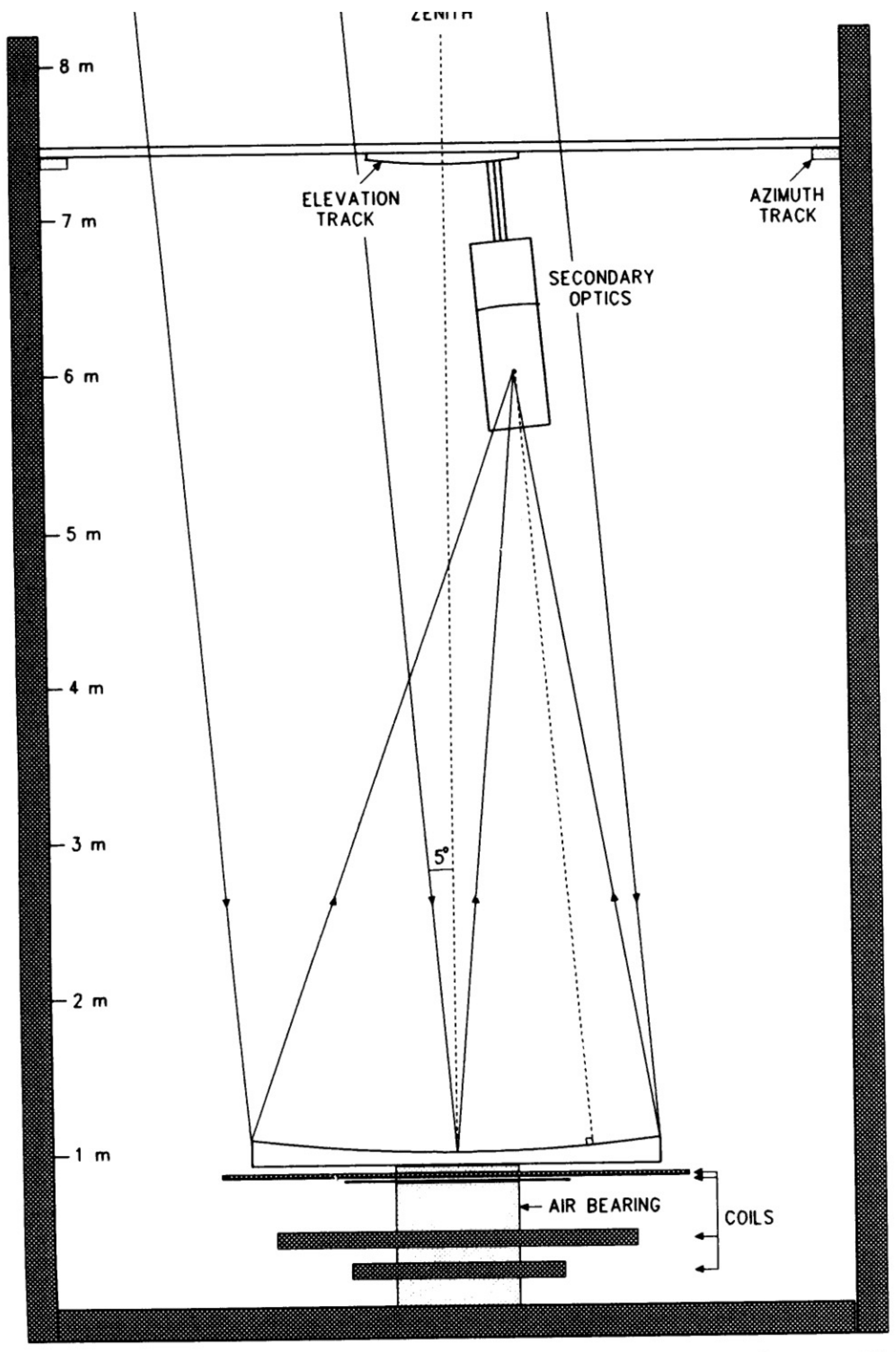

FIG. 2.—Example layout for a telescope having a 2.65 m diameter f/1.9 spherical ferrofluid mercury mirror.

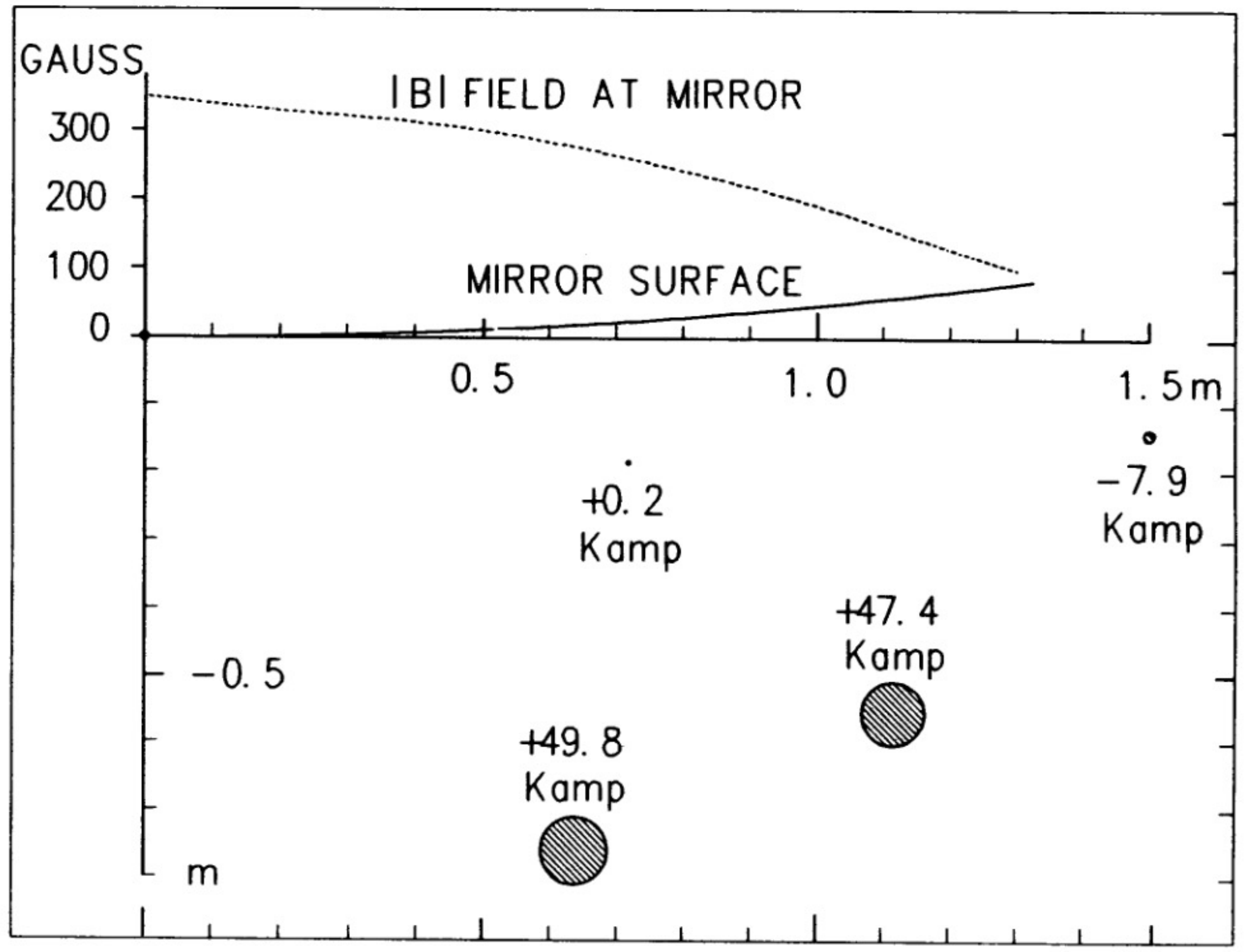

FIG. 1.—A cross section showing the location and currents of the four coils, and the magnitude of the magnetic field that they produce just above the ferrofluid mercury mirror surface.

THE ASTROPHYSICAL JOURNAL, 424:L139–L141, 1994 April 1

A WIDE SKY COVERAGE FERROFLUID MERCURY TELESCOPE

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Received 1993 December 7; accepted 1994 January 17

ABSTRACT

Liquid mirror optical telescopes use rotating mercury to form precise paraboloidal primary reflectors. These telescopes, which represent an inexpensive alternative to traditional telescopes, to date have been limited in their sky coverage to a small viewing area (typically $\frac{1}{4}$ deg^2) centered on the zenith. We propose to increase the sky coverage area of a mercury optical telescope by at least two orders of magnitude, using the same concept as that employed in the 305 m diameter radio telescope at Arecibo, Puerto Rico, which has a spherical primary reflector. We have shown that it should be possible to deflect a 2.65 m diameter f/1.9 rotating mercury paraboloid into a precise spherical shape, by using ferrofluid mercury in a carefully tailored magnetic field. The 10° × 10° sky coverage of such a telescope could make it the instrument of choice in a number of astronomical observing programs.

Subject headings: telescopes — instrumentation: miscellaneous

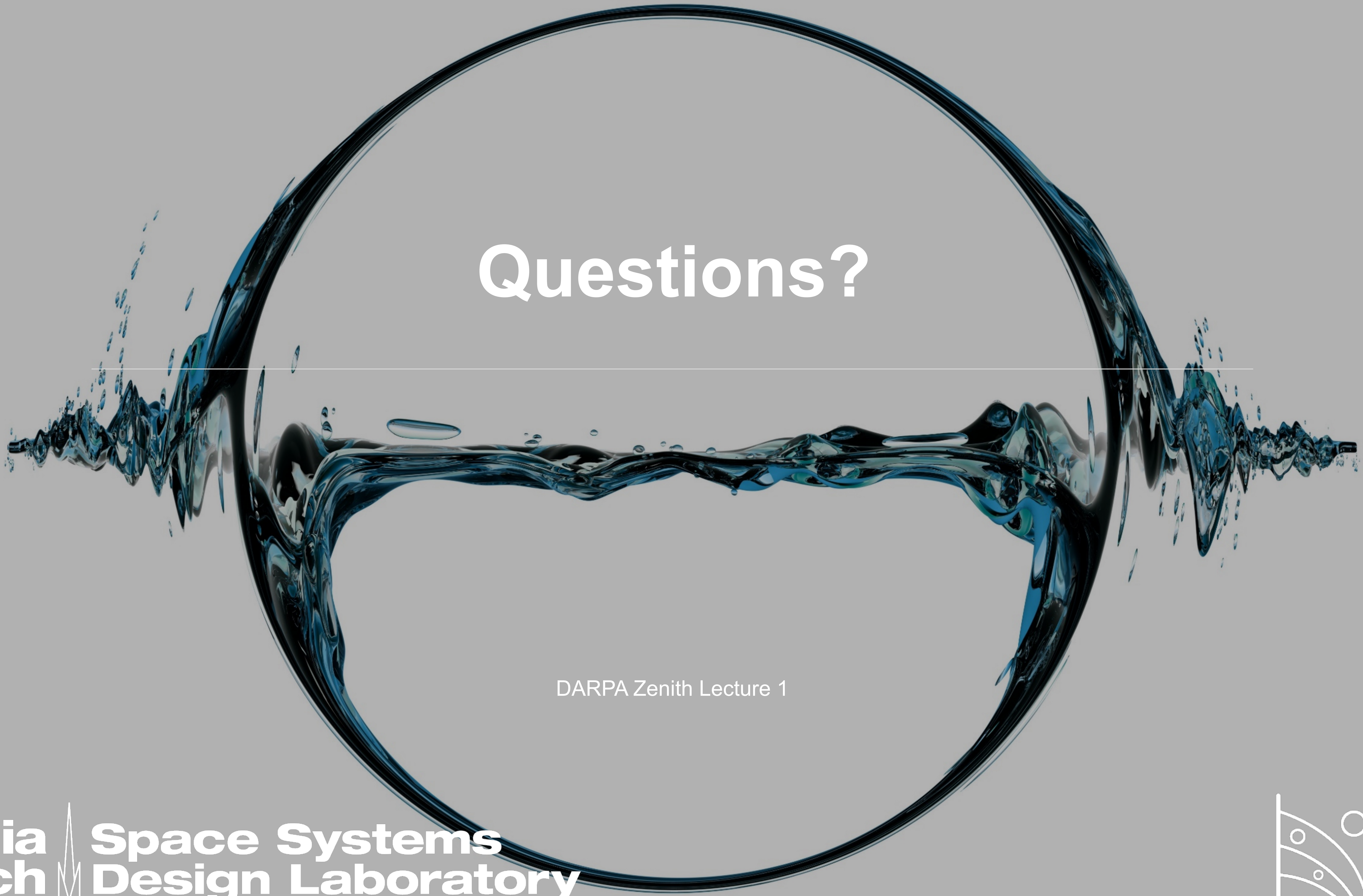
1. Compute magnetic field produced by N circular magnets located at (r_i, z_i) with current I_i → FUNCTION
2. Compute the total mass force potential Π after computing the magnetic mass force potential Π_m
3. Interpolate mass force potential along the objective interface
4. Compute cost function so that the mass force potential along the objective interface is constant

$$C.F. = \int_0^L \left(\Pi\Big|_\Sigma(t) - \overline{\Pi}\Big|_\Sigma \right)^2 dt$$

5. Optimize so that you minimize the objective function given reasonable constraints:
   - Coils do not invade liquid mirror
   - The maximum size of the coil domain is X m radius and X m height
   - The maximum current is X (based on REBCO superconductors – check Acta Astronautica paper with Russians)

Suggestion: explore genetic algorithm optimization (GA in Matlab) and other constrained optimization algorithms. Limit yourselves to the 1994 paper for now.

Questions?



DARPA Zenith Lecture 1

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