mK to km: How Millikelvin Physics is Reused to Explore the Earth Kilometers Below the Surface

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Transitioning from Academic Physics to the “Real World”

This is a fully worked out example of how one physicist made the transition from esoteric laboratory science to very practical real-world inventions.

By the end of this talk, you will have learned how to measure which way the wind was blowing 10 million years ago, and how to measure the sizes of pores in sedimentary rock – and why those are important.

You will also get a lesson in corporate jujitsu.

Your experiences will be different. I adapted to my time and place. You will adapt to yours.
Graduate School: University of California, San Diego
Superfluid $^3$He    $T < 0.003$ K

A dilution refrigerator with its pumping lines emerging above (left foreground) hangs over an open pit in Wheatley's copper-screened lab. Another one (behind it and to the left) is enclosed in its Dewar.

Wheatley's assistants shown in this photo are (left to right) Douglas Paulson, Ronald Sager, Evelin Pichelman, Robert Kleinberg and Matti Krusius. Photograph by Douglas Paulson.
Why the Oil Industry?

1970s Gas Lines

Grad School Housemates

Grad School Experience

Pressing National Need

Geoscience

Measurements

EXXON

Schlumberger

RV Knorr

Tek 5103
Part I

Which Way Was the Wind Blowing Ten Million Years Ago?
You have drilled a water well. Where is the oil and natural gas?
You don’t put the sample into the machine, you put the machine into the sample.
More Rules of the Game

Apparatus must operate after being:

> transported in arctic, tropical, desert, or marine environments
> subjected to 100 g shock
> dragged through kilometers of rough rock borehole

Apparatus must operate while:

> exposed to $-25^\circ C$ to $+175^\circ C$ in salt-saturated water at 140 MPa
> temperature conditions are changing
> moving at 15 cm/s

Apparatus must operate:

> at the end of 10 kilometers of multiconductor cable
> autonomously, and simultaneously with other nuclear, electromagnetic, and acoustic instruments

I’m a low temperature physicist. What the heck am I doing here?

Once the initial panic subsided . . .
Exciting Millikelvin Physics . . . With No Practical Application

Magnetic Susceptibility Thermometry

Curie-Weiss

\[ \chi = \frac{C}{T - T_c} \]

Fig. 1. Scale drawing of the adiabatic demagnetization cell.

Heat Flow in Superfluid $^3$He*

R. T. Johnson, R. L. Kleinberg, R. A. Webb, and J. C. Wheatley
Department of Physics, University of California at San Diego, La Jolla, California
(Received September 3, 1974)

JLTP 18,5/6,501-517 (1975)
Balanced-Secondary Mutual Inductance Coil Set
Turned Inside Out & Applied to the Borehole Wall

CMRR = -70dB @ 2 µm tolerance

Laboratory Prototype
Would not survive dunking in a bathtub, but proved the principle
Put sensors on the four arms of a borehole-robust apparatus
Measure the Slope of the Subsurface

Sensor #1
Sensor #3

15 cm/s

Sensor #1
Sensor #2
Sensor #3

Borehole

σ₁
σ₂

σ₁
σ₂
Which way was the wind blowing? We know in today's deserts by looking at sand dunes.
Which way was the wind blowing? We know in today's deserts by looking at sand dunes.
Corporate Jujitsu

- This was not the approach initially endorsed by management
- It started as a “skunk works” project, after hours and on weekends
- After some initial favorable results, I got a technician
- After more favorable results, a theorist asked to join the team
- Our development group in Paris had their own ideas how to do it
  - I built a copy of their device, optimized it, and showed that my approach was superior
- The instrument was successful, and saved our business in the most important oil field of the day
- When we were done, the technician, the theorist, and I “had time on our hands” . . . during which we invented something even more important . . .
Part II

How Large Are Pores in Rock

Two Miles Below the Earth’s Surface?
Fluid permeability ~ (pore size)^2
Nuclear Magnetic Resonance

- Strong constant magnetic field $B_0$
- Oscillating magnetic field $B_1$ perpendicular to $B_0$
- Oscillating field frequency $\omega = \gamma B_0$ (For protons: 42.58 MHz/T)
Mechanism of NMR Relaxation of Fluids in Rocks
Analyze NMR Multiexponential Decay to Find Pore Size Distribution

3 sizes of pores

$T_2 = 20$ ms

$T_2 = 5$ ms

$T_2 = 80$ ms

Echo amplitudes are sums of exponential decays

Area under curve proportional to fluid volume

Multiexponential Decay

Echo Amplitude vs. Echo time (ms)

$T_2 = 5$ ms

$T_2 = 20$ ms

$T_2 = 80$ ms

T2 Distribution

Area under curve proportional to fluid volume

T2 (ms) vs. time (ms)
Pore Size Distribution from NMR

Pore Diameter (µm)

Berea 3

T₂ (sec)
Nuclear Magnetic Resonance Experience

SQUID-Detected NMR of Liquid $^3$He

Conventional NMR of Layered Intercalation Materials

Borehole NMR

How hard can this be? . . .
Rules of the Game

- Borehole: 20 cm
- Earth
- 10 km cable

Diagram: North and South magnetic poles, borehole marker.
Borehole Nuclear Magnetic Resonance
Focus on Physics Principles

- Strong constant magnetic field $B_0$
- Oscillating magnetic field $B_1$ perpendicular to $B_0$
- Oscillating field frequency $\omega = \gamma B_0$  (For protons: 42.58 MHz/T)
With time on our hands, we came up with this

![Diagram of the Novel NMR Apparatus for Investigating an External Sample]

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Novel NMR Apparatus for Investigating an External Sample
Field Strength Saddle Point Inside Earth

volume of relatively uniform field strength

Magnetic Field Contour Lines (Gauss)

Novel NMR Apparatus for Investigating an External Sample
Underground Nuclear Magnetic Resonance

Novel NMR Apparatus for Investigating an External Sample
Mating Borehole NMR with Unmanned Submarine

4000 m water depth: \(~0°C, \sim 6000 psi\)
I might even have said it was “too easy”.

The Role of the Theorist / Modeler

- Design based on physics principles
- Theory of the measurement
- Optimization of design
- Performance prediction
To Sum Up

There are challenging and interesting problems to be solved in unexpected places.

Your physics education has provided you with a tool box of techniques and skills that may prove to be useful in unexpected ways in the future.

Your experiences will be different. I adapted to my time and place. You will adapt to yours.
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John C. Wheatley, Helium Three
Physics Today 29, 2, 32 (1976); doi: 10.1063/1.3023313
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