Applications of Cryogenics to Classical and Quantum Fluid Dynamics

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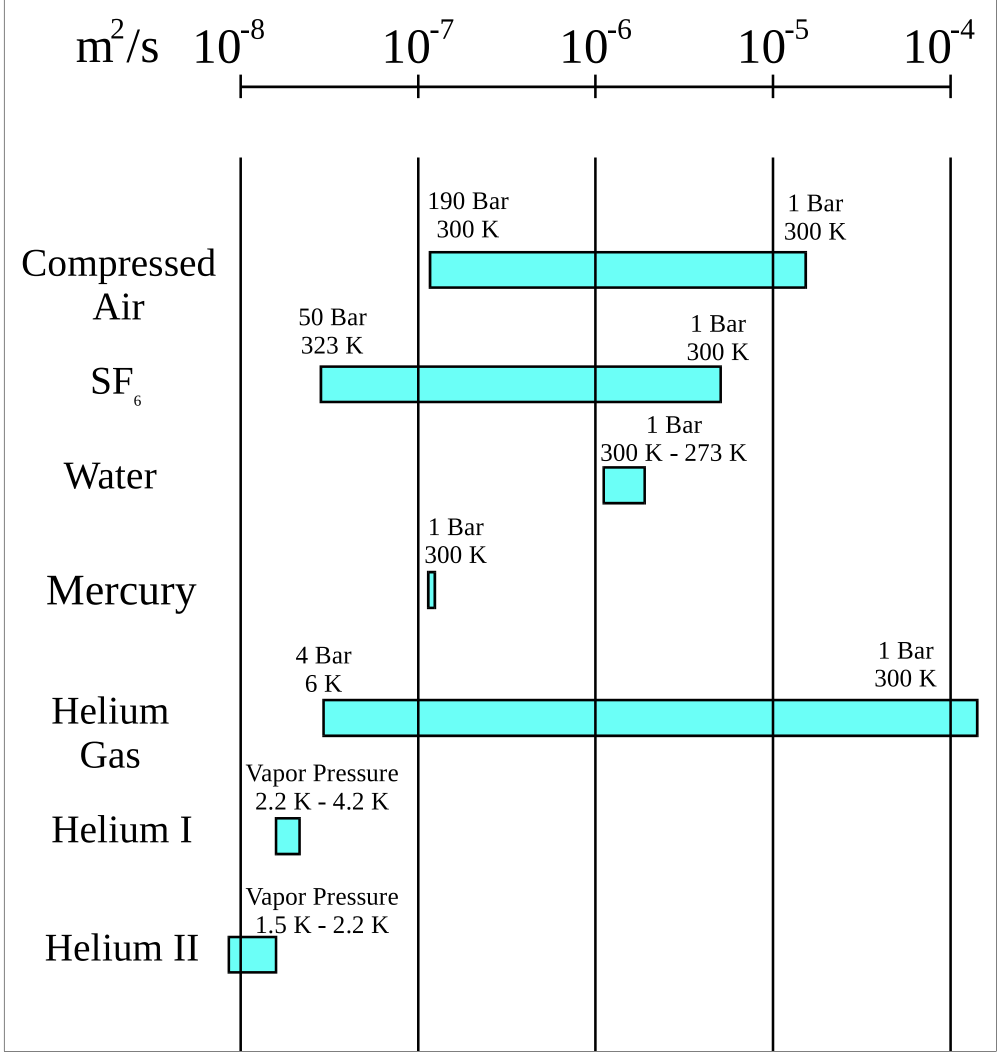
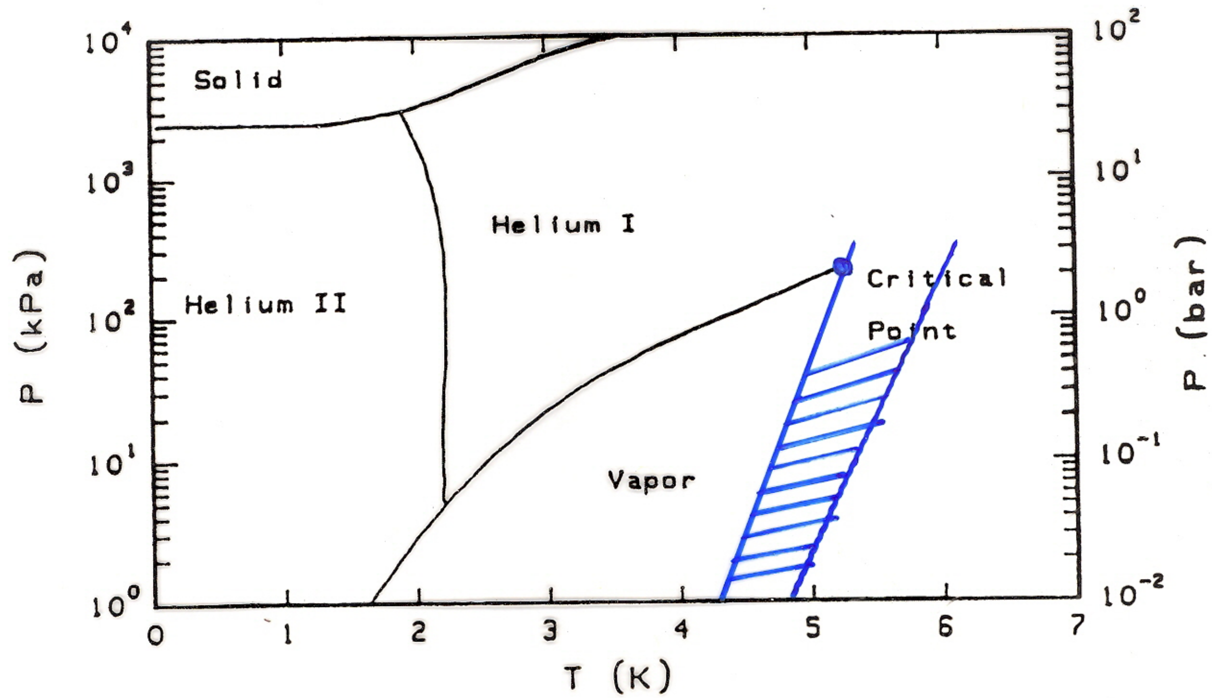
The enormous variety of applications of cryogenics to fluid mechanics is not widely appreciated.

In this talk we will explore the properties of cryogenic fluids and their applications to branches of fluid dynamics, including fundamental research in classical and quantum fluids and in various branches of engineering.

Kinematic Viscosity of Fluids for Turbulence Research





Boussinesq condition violated if $\Delta\rho / \rho > 0.2$,
Or alternatively $\alpha\Delta T > 0.2$

History of High Reynolds Number Concepts in Helium

- When the first measurements of the viscosity of helium were made at Toronto ~1937 it was realized that the viscosity was very low and that false values of viscosity might be generated if the flow became turbulent.

- Kapitza ~1941 realized the same thing and spoke about Reynolds numbers for helium II. This idea met with skepticism because theorists were coming to believe helium II was a quantum liquid. They didn't believe scaling laws used in classical hydrodynamics could possibly have any relevance.

- Onsager ~1950 began to talk about a "superfluid wind tunnel" with the idea of reaching extremely high Reynolds numbers with a fluid of no viscosity.

- Feynman and Pellam ~1956 actually built a superfluid wind tunnel at Caltech. High velocities were not reached because quantized vortices were formed.

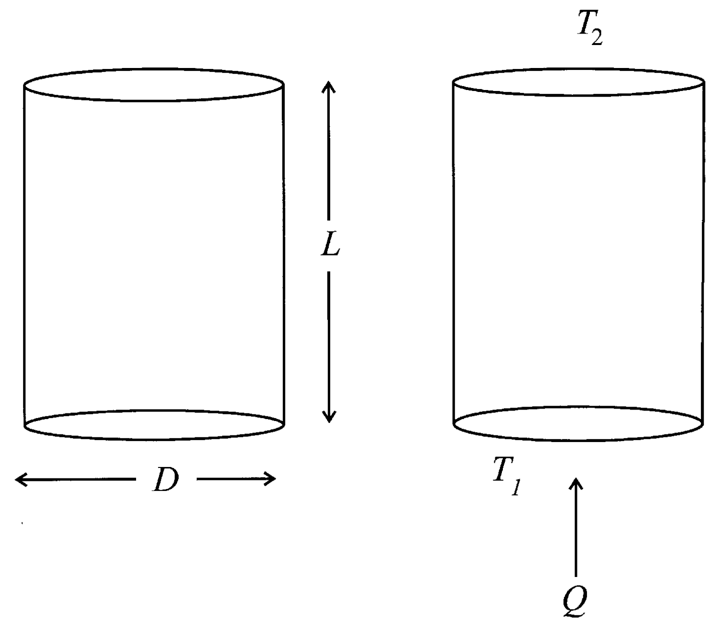
- Liepmann ~1979 had a workshop at Caltech to consider a superfluid "blowdown tunnel". The idea was thoroughly shot down by those who attended.

- Threlfall, a Pippard student at Cambridge was the fist to realize that critical helium gas is a very useful working fluid for thermal convection.

- Libchaber and Wu ~1987 used Threlfall's idea to cover 11 orders of magnitude in Rayleigh number.

- Our group were the first to realize that helium I and helium II have enormously attractive possibilities for flow facilities and tow tanks.

Notation for Rayleigh-Bénard Convection



$$Ra = \frac{g\alpha\Delta T L^3}{\nu\kappa}$$

$$Nu = Q / Q_c$$

$$\Pr = \nu / \kappa$$

$$\Gamma = D / L$$

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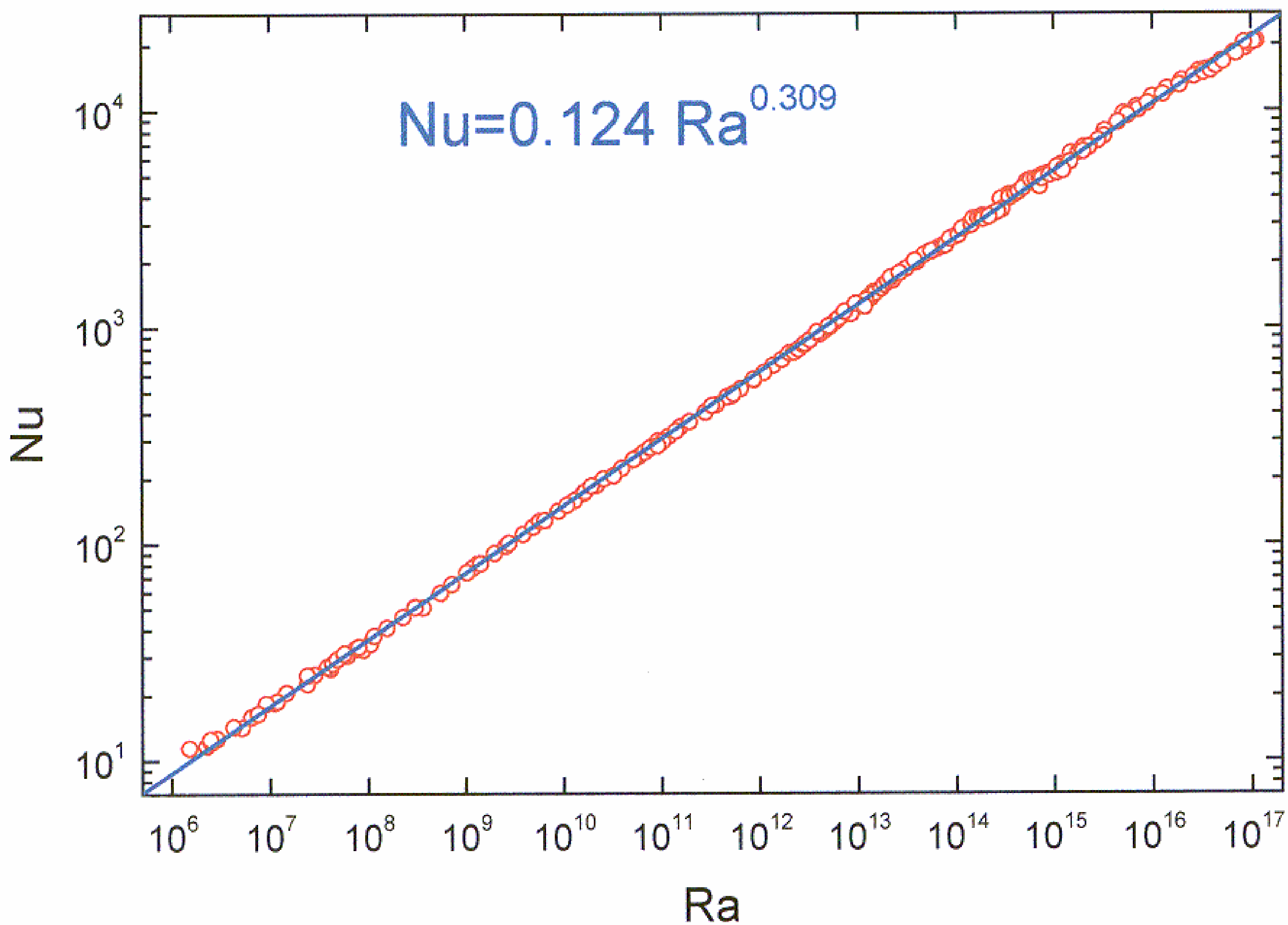
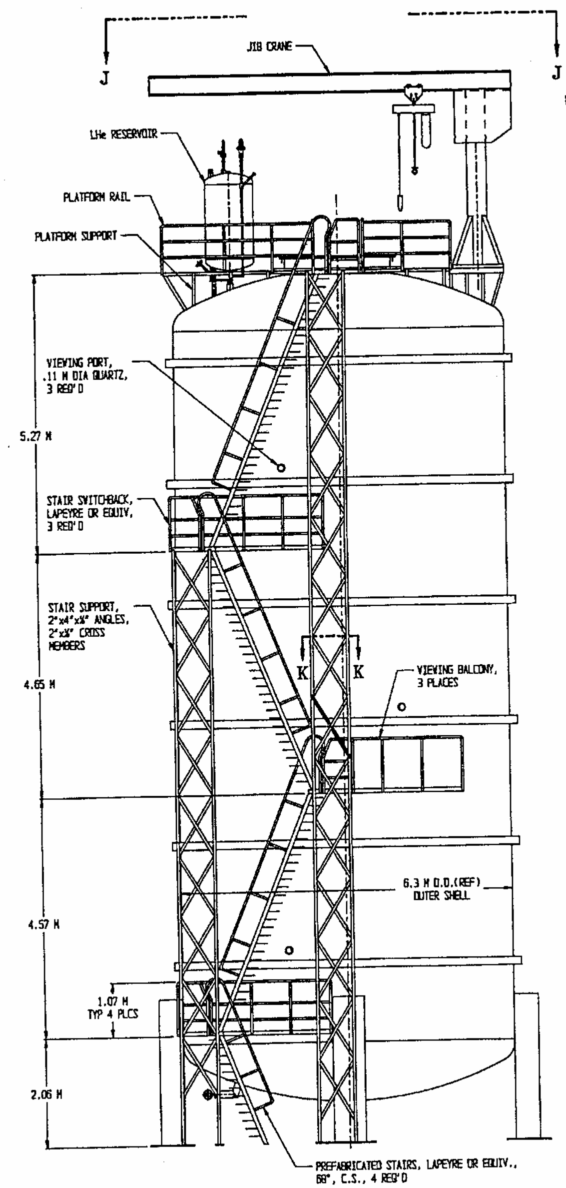
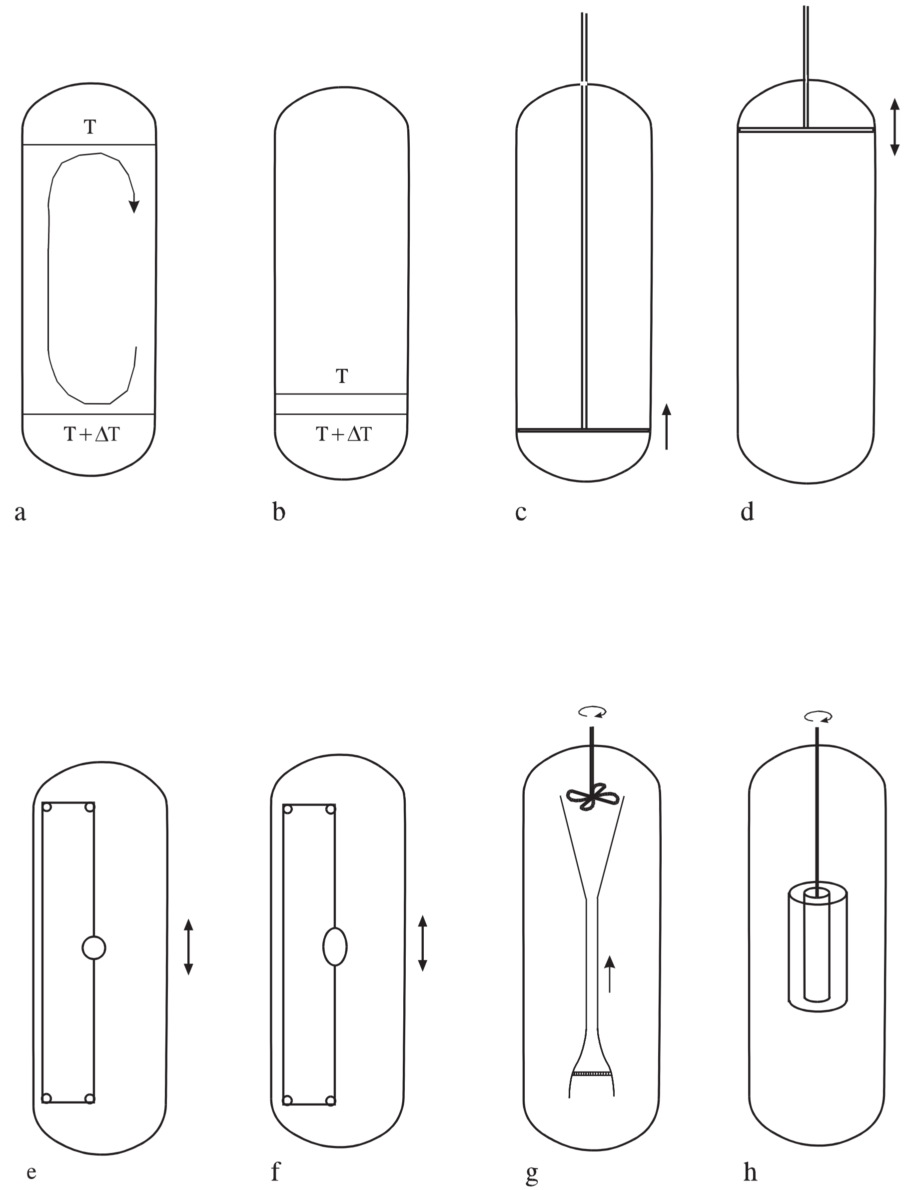


Nu=0.124 Ra^0.309
Nu
Ra
10^1
10^2
10^3
10^4
10^6
10^7
10^8
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17



The proposed BNL tank was 10m high and 5m in diameter operating near 5 K @~1500 torr. It would conservatively reach Ra~10^20 with a power dissipation of about 700 Watts. It would take ~60,000 liters liquid equivalent to fill.



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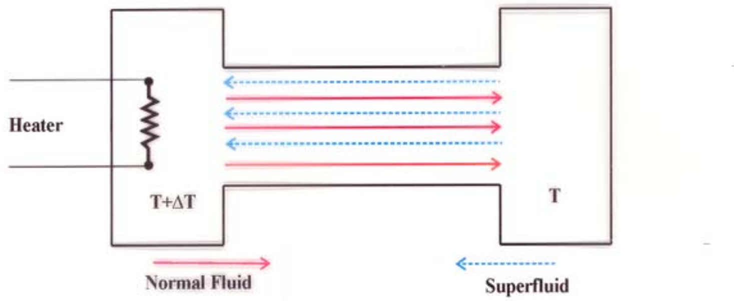
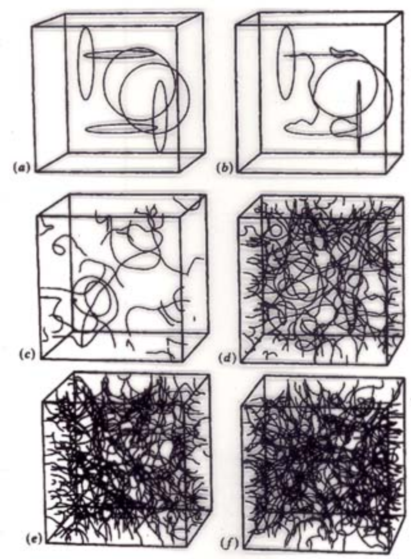
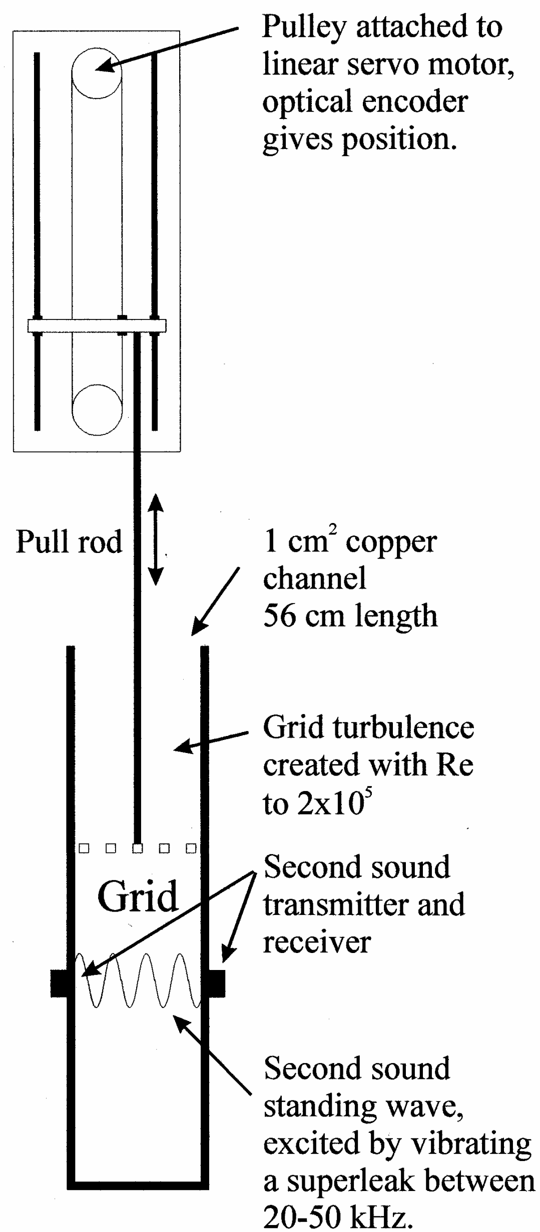
Counterflow turbulence



Schwarz simulation of growth of counterflow superfluid turbulence.




Pulley attached to
linear servo motor,
optical encoder
gives position.
Pull rod
1 cm² copper
channel
56 cm length
Grid turbulence
created with Re
to 2x10⁵
Grid
Second sound
transmitter and
receiver
Second sound
standing wave,
excited by vibrating
a superleak between
20-50 kHz.

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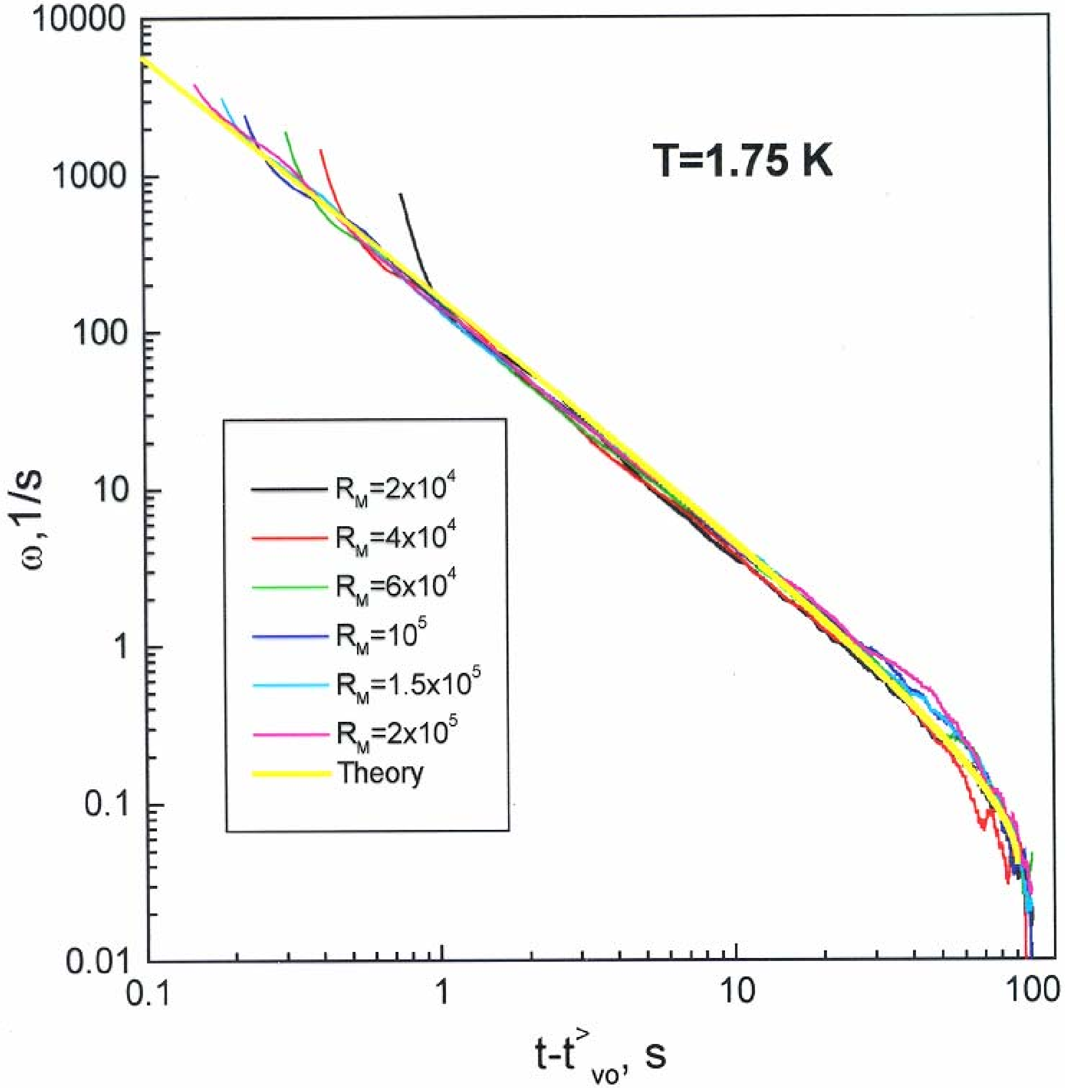


Enormous dynamic range:

6 orders of magnitude of Vorticity

3 orders of magnitude in time

Range of decay is phenomenal:

A classical wind tunnel would have to be 1000 km long to obtain the same data as we observe in a 1x1 cm channel, 40 cm long

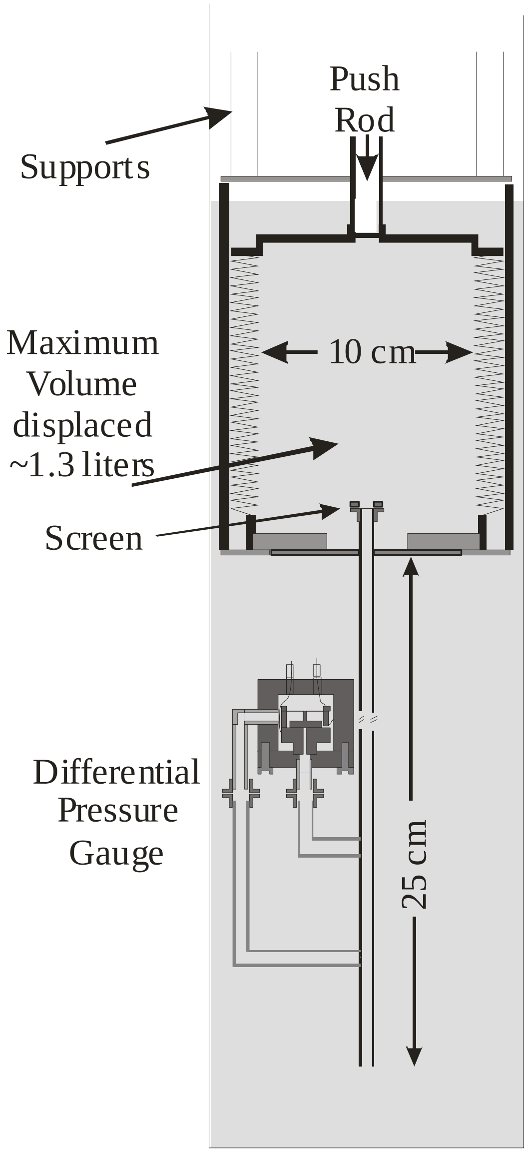
Summary

- The object of the experiment was to observe the decay of vorticity in homogeneous turbulence.
- The apparatus used was a towed grid in superfluid helium II.
- The technique was to observe the attenuation of second sound by quantized vortices.
- The assumption is that the quantized vortices track the vorticity in the normal component of the helium II.
- The entire decay range, almost seven decades in vorticity and four decades in time, appears to be classical in nature (i.e. does not scale with the normal fluid density)
- There are four regions of decay clearly present. The last, an exponential decay, is not understood (too many possible explanations !)
- A classical wind tunnel for the same experiment would need to be about 1000 km long.

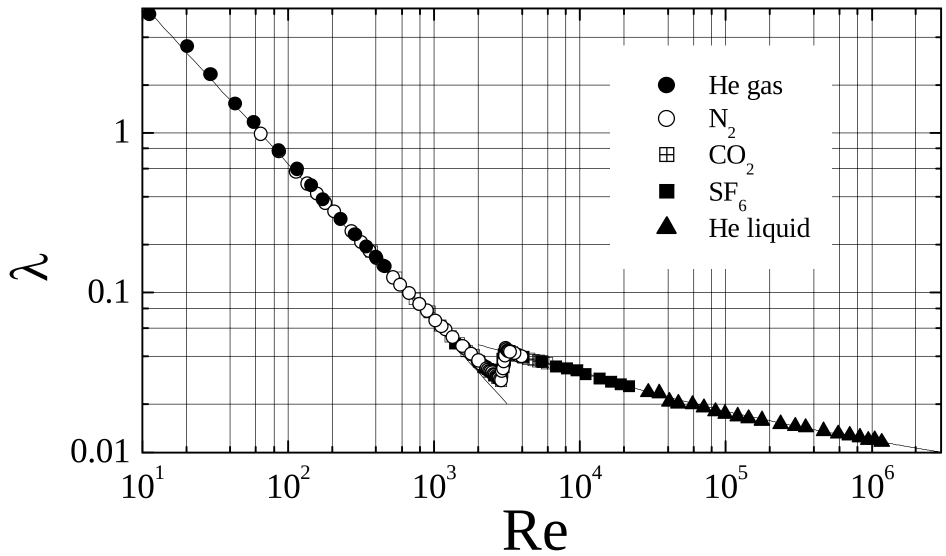
• Physical Review Letters 85, 2973 (2000)

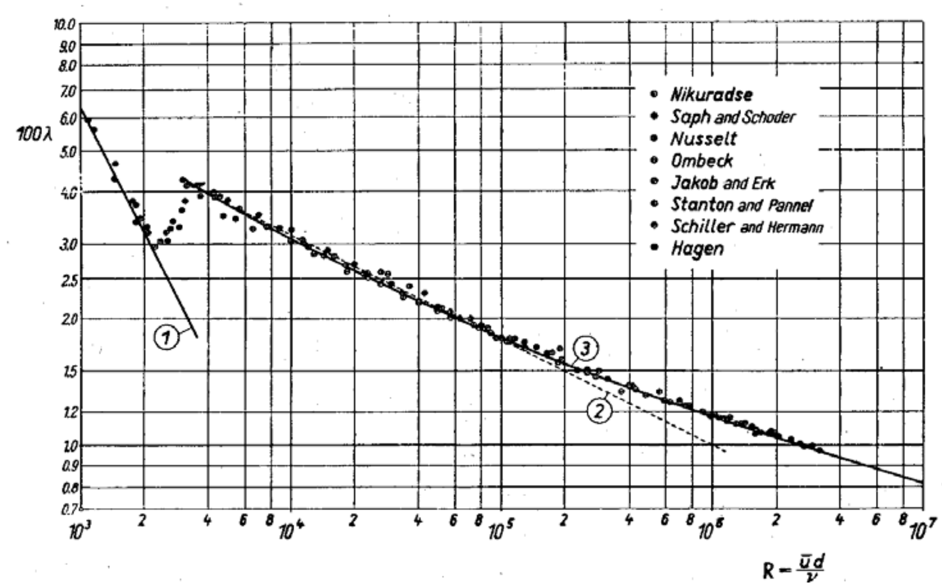
There are a number of devices and experiments one can do with cryogenic helium. Examples are:

- Thermal convection in a tank using supercritical helium gas
- Flow tunnels for generation of high Reynolds numbers for basic research and for testing models
- High Reynolds number pipe flow
- Tow tanks for generation of wave experiments and for testing surface vessels
- Towed grid experiments
- Taylor-Couette experiments



Bellows flow system for studies of pipe flow with room temperature gases and helium I and helium II.





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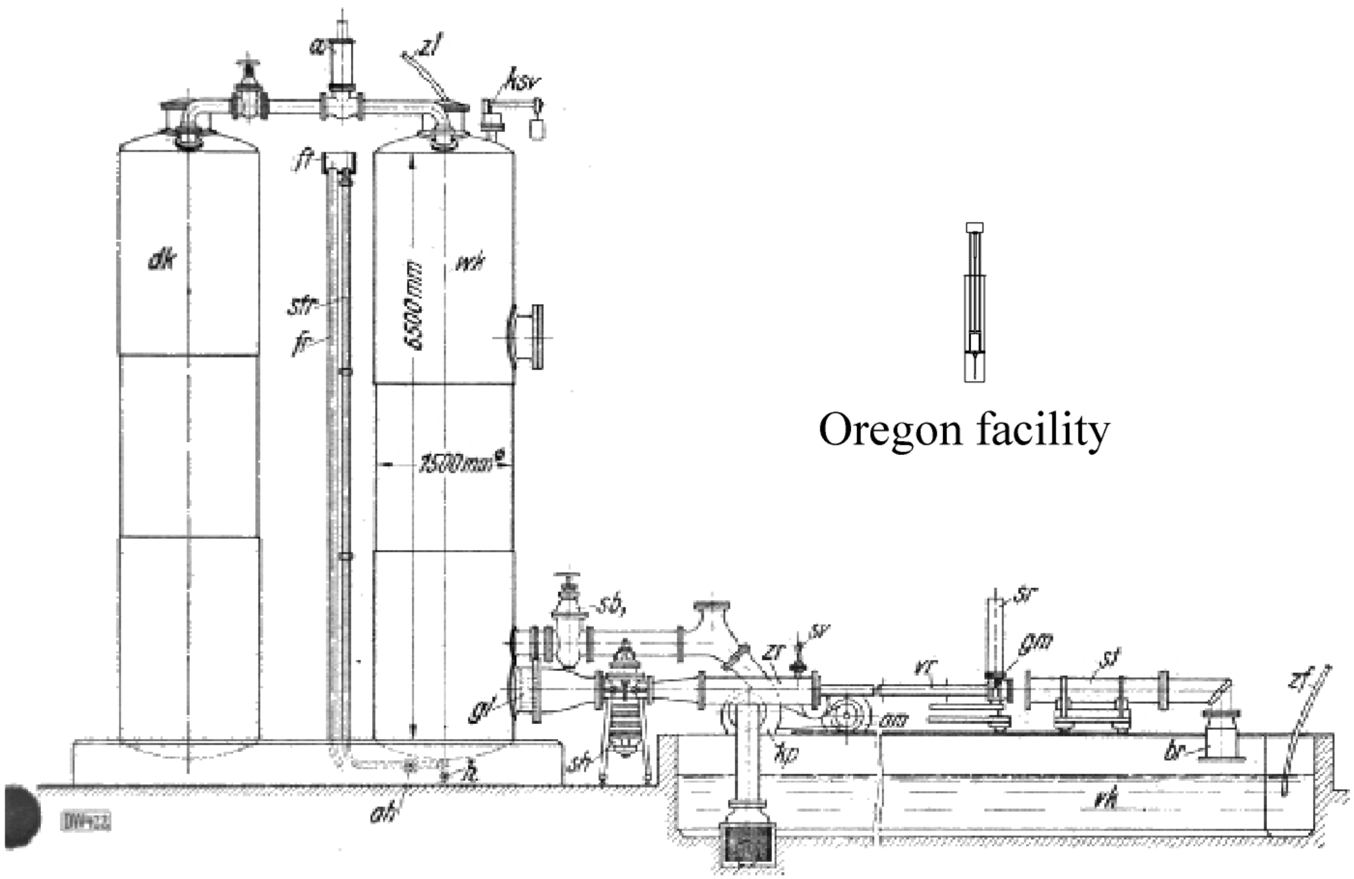
Nikuradze's apparatus for pipeflow measurements at Göttingen, ca1930



Oregon facility

Water facility

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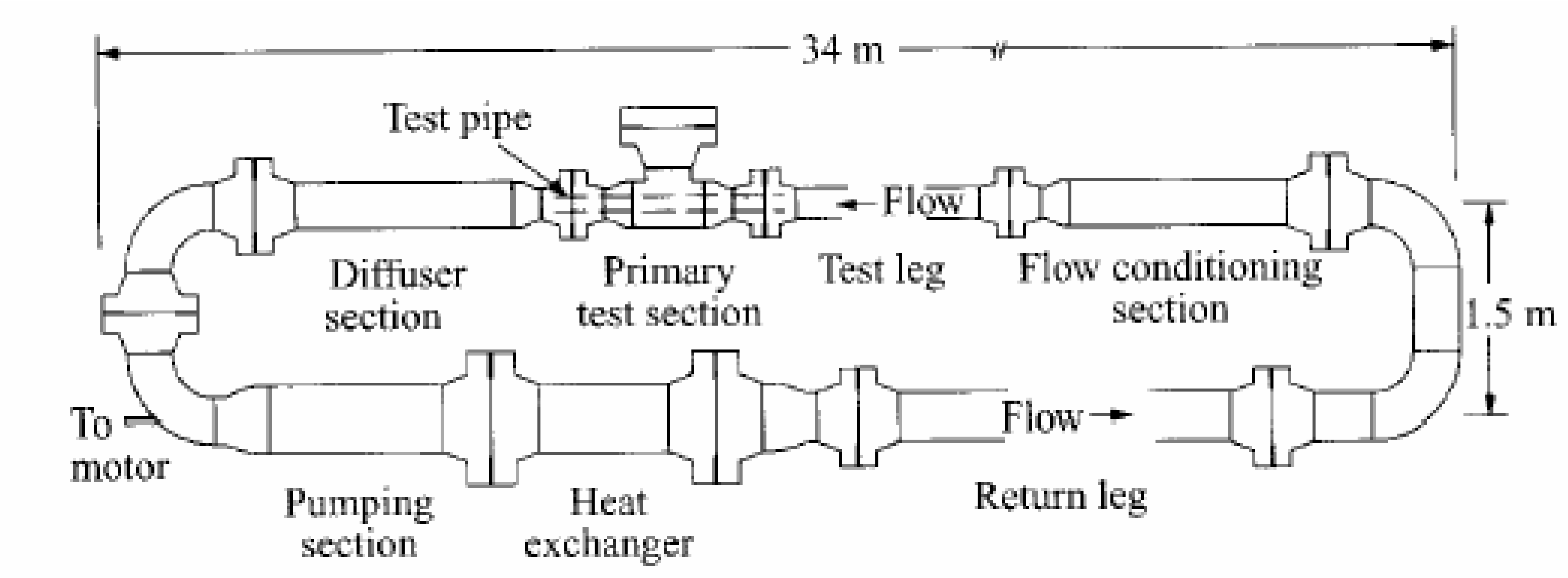
Princeton Super-Pipe: weight about 35 tons



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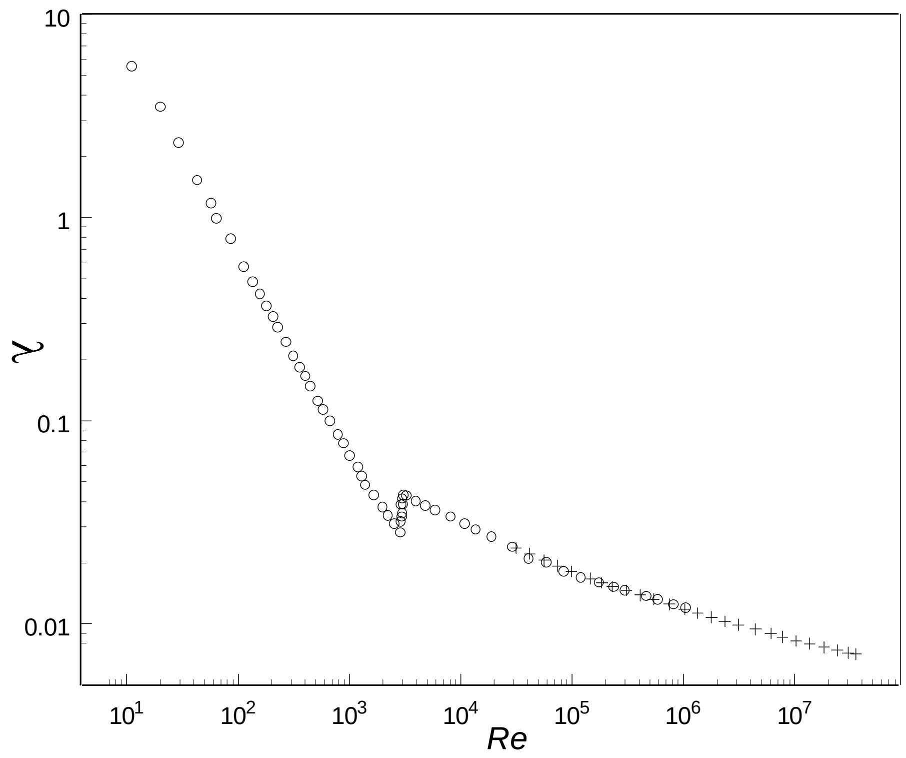

Combined data sets. The circles are from Oregon and the crosses from Princeton.

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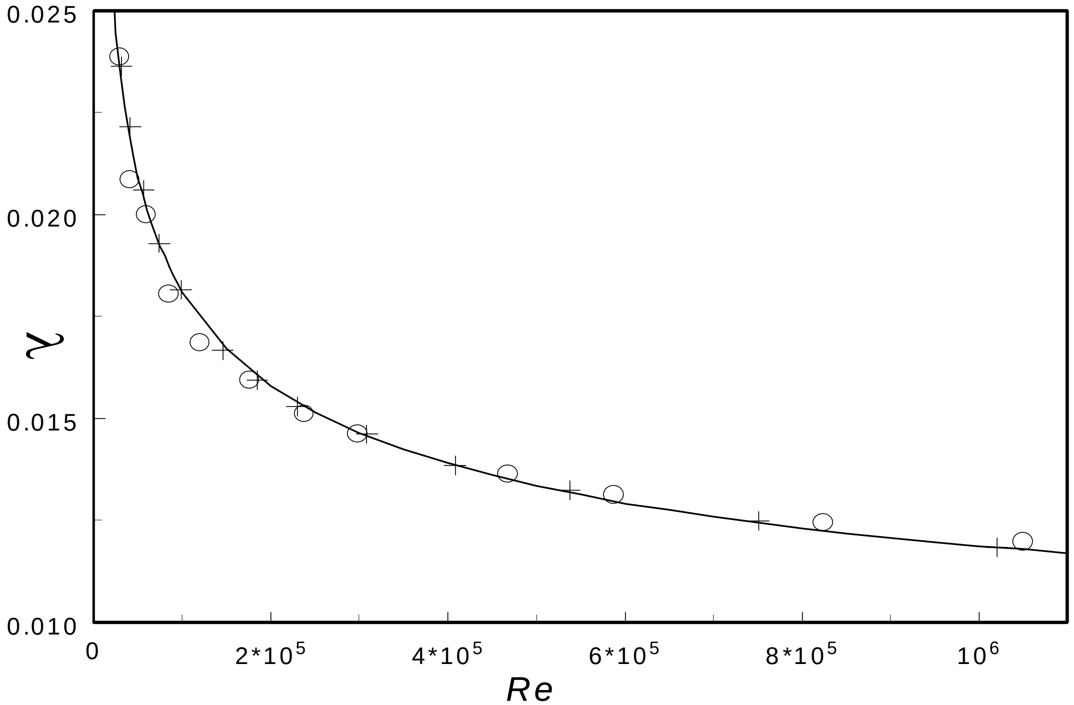

Linear plot of the overlapping regions of the two data sets. The crosses are from Princeton and the circles from Oregon. The average deviation is less than 2%. The line is a fit proposed by Beverly McKeon.

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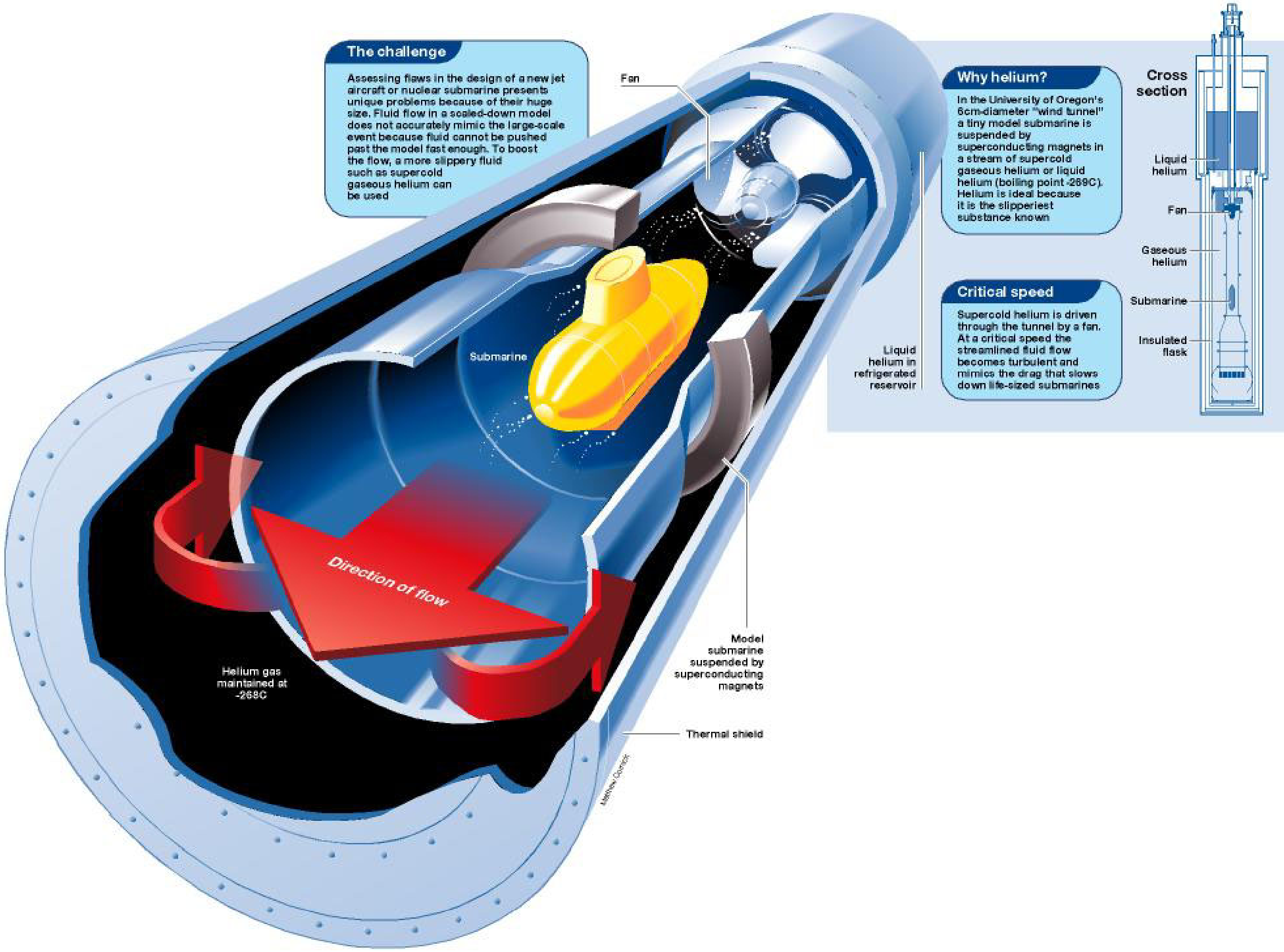

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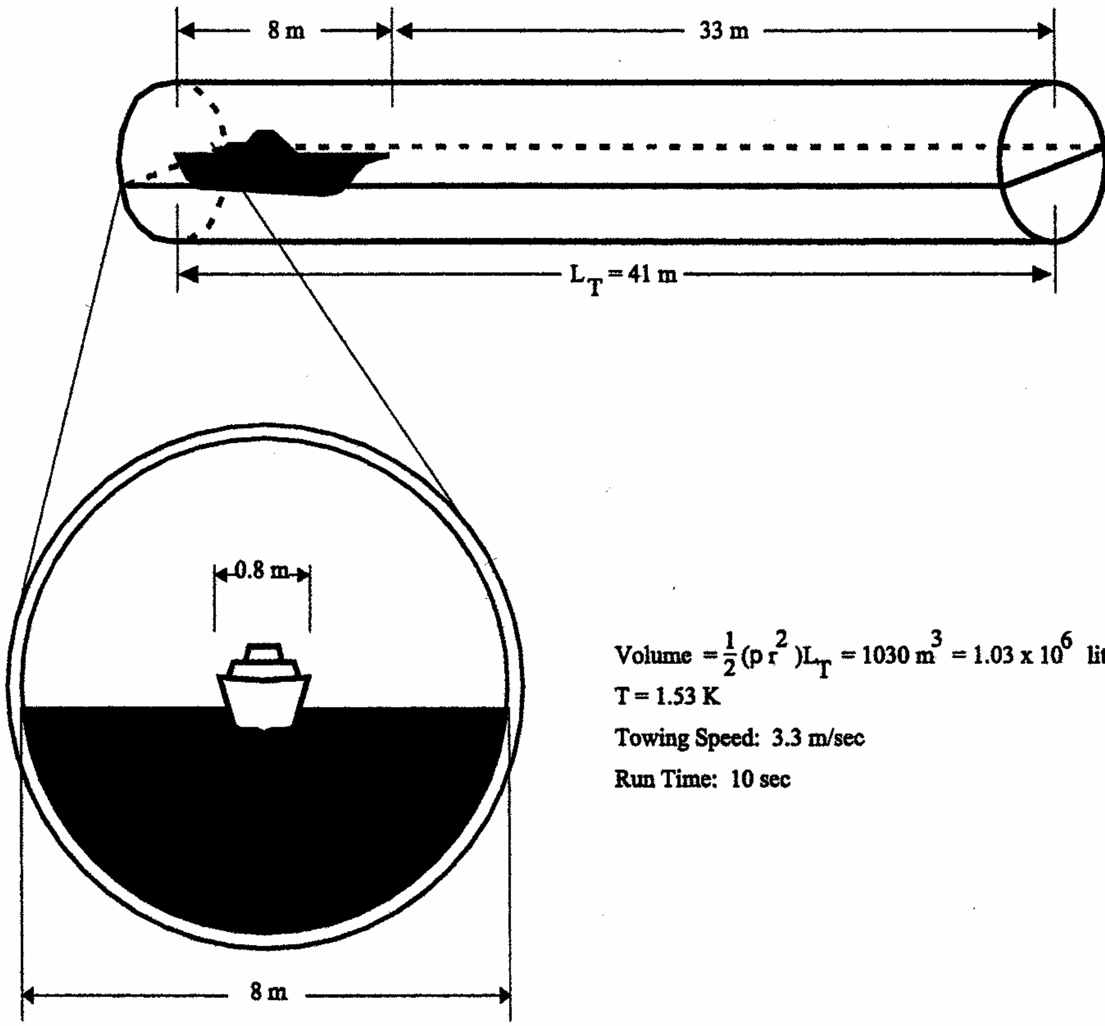
Operation of a 125 cm tunnel in helium II atT=1.6 K,	
Size of test section (cm)	125
Unit Reynolds number (cm^{-1})	$3.9x10^6$
Mach number	0.015
Flow velocity (cm/sec)	357
Dynamic head (lb./ft.)	19.3
Flow volume (liters per second)	4377
Shaft power (hp)	1.31
Cooling power required (W)	1000
Total power for tunnel (hp)	1630
Total liquid helium (liters)	$1.2x10^6$
Submarine length (cm)	446
Submarine diameter (cm)	44.6
Drag coefficient	0.10
Submarine Reynolds number	$1.75x10^9$



Volume $= \frac{1}{2}(p\, r^2)L_T = 1030\ m^3 = 1.03 \times 10^6$ liters LHe

T = 1.53 K

Towing Speed: 3.3 m/sec

Run Time: 10 sec

What are the advantages of using liquid helium for a tow tank?

Consider a water tank modeling a ship 200 m long moving at 32 knots, 16.5 m/sec. If we make a 1/25 scale model and match the Froude number (0.373: measures wave resistance) we need to tow at 3.3 m/sec. However under these conditions Re=2.34x10^7 compared with 2.89x10^9 for the real ship.

If we use liquid helium for a tow tank we find that at 1.53 K we can match the Froude number and Reynolds number at once.

Low Temperature Physics Measurement Techniques

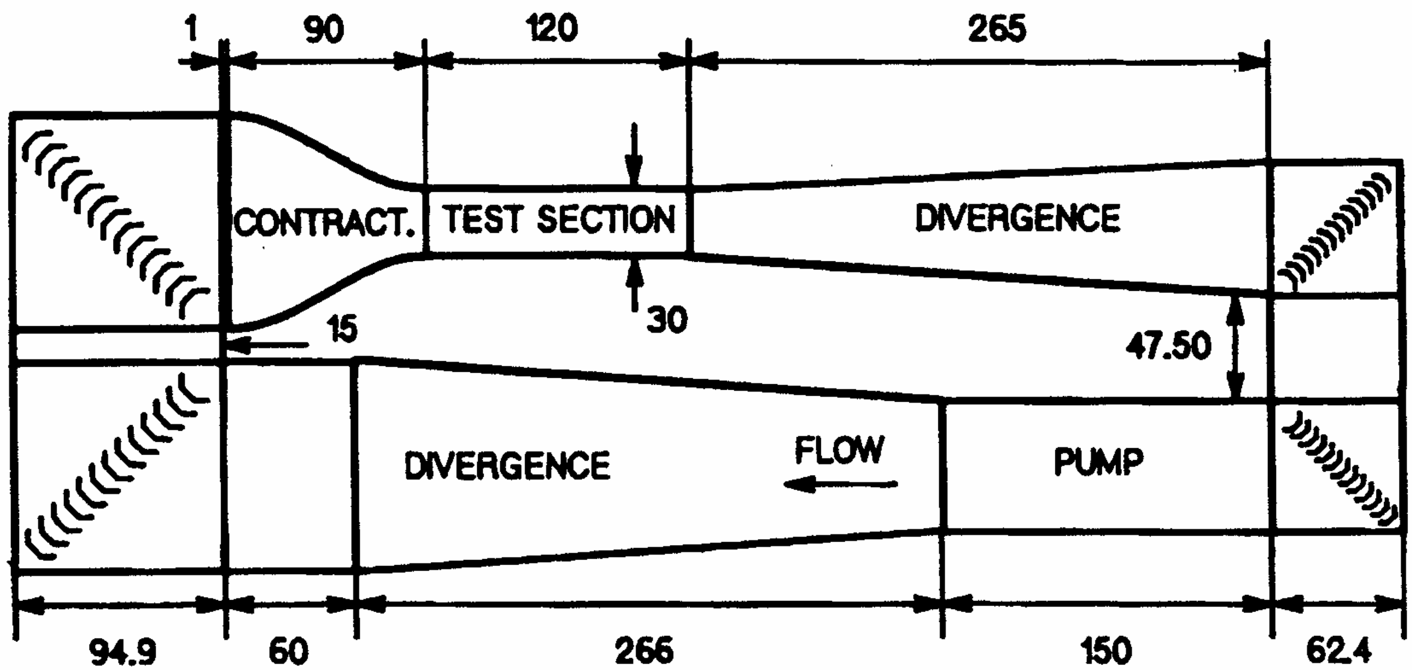
- Measurement techniques are enormously enhanced by availability of low temperature physics techniques:

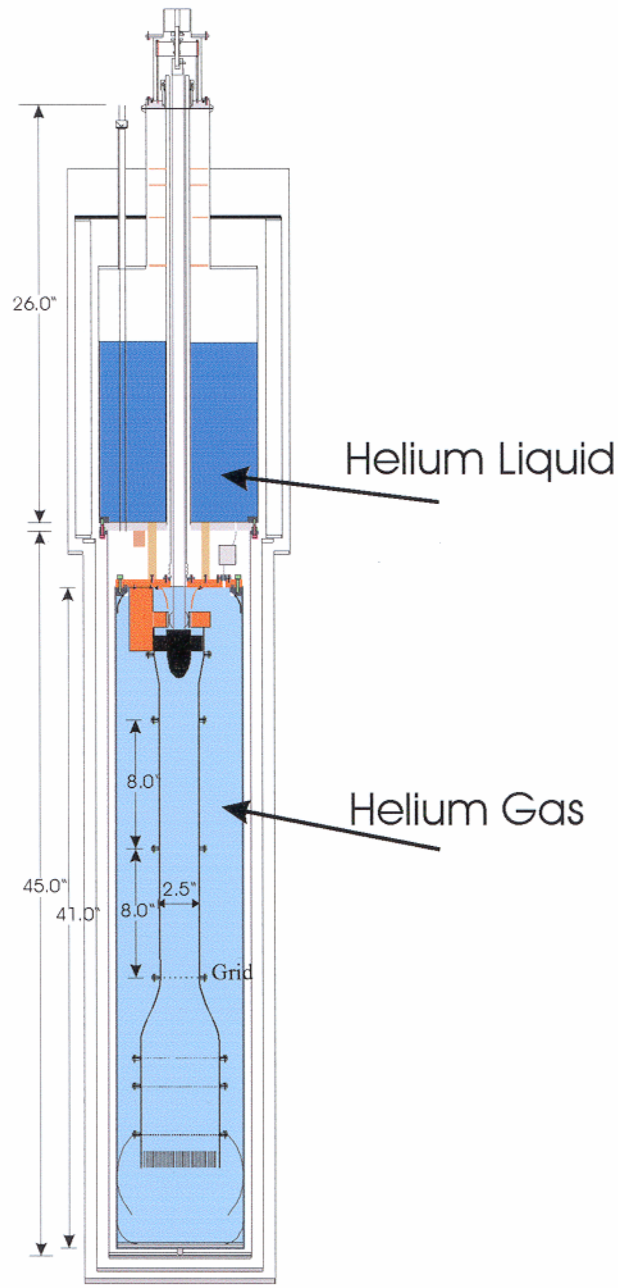
a. Superconductivity

i. SQUIDS
ii. Superconducting bolometers
iii. Superconducting magnetic suspensions

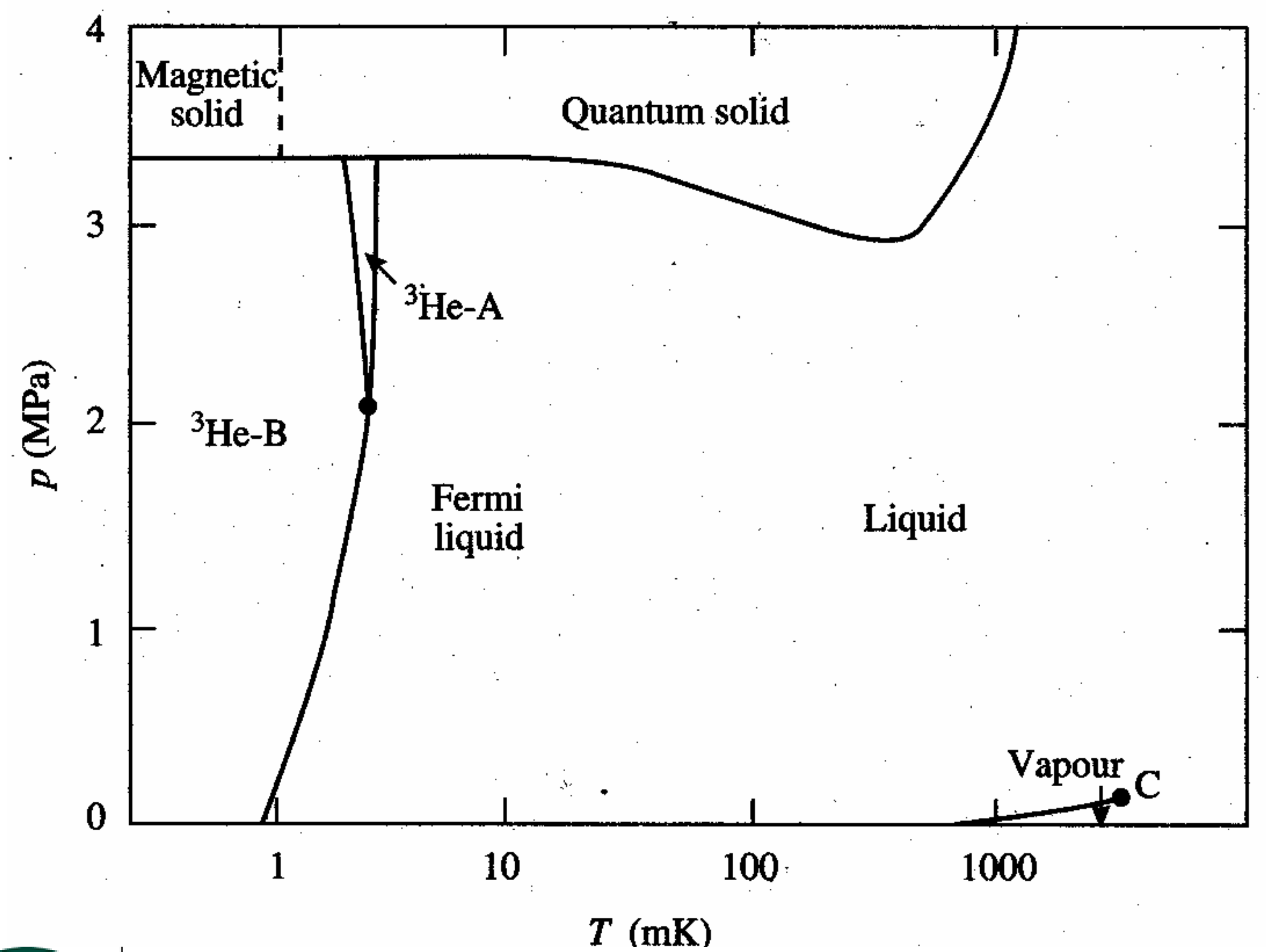
b. Helium II

i. Direct measurement of vorticity by second sound
ii. Direct measurement of vorticity and differences in vorticity by chemical potential probes


1
90
120
265
CONTRACT.
TEST SECTION
DIVERGENCE
15
30
47.50
DIVERGENCE
FLOW
PUMP
94.9
60
266
150
62.4


26.0"
Helium Liquid
Helium Gas
8.0"
2.5"
8.0"
45.0"
41.0"
Grid

Phase diagram, He^3



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Quantum Turbulence

Quantum Turbulence is the turbulence of superfluids, where vorticity is confined to quantized vortex lines and rings. This is a very vigorous field of physics and except for experiments in He II such as we have described earlier, does not need the large scale facilities being discussed in this conference.

T_λ

He II is the superfluid phase of ^{4}He below $T_\lambda = 2.1768\,K.$

^{3}He becomes superfluid (^{3}He-B) at zero pressure at $T_c = 0.93\,mK$

The quantum fluids useful in turbulence are:

(1) He II above 1K
(2) He II below 1 K
(3) ^{3}He-B at “high” temperatures 0.4 Tc<T<Tc
(4) ^{3}He-B at low temperatures .

It is very interesting to contrast and compare turbulence in all these different systems.

Conclusions

There are many applications in both basic turbulence research and applied engineering which can usefully use a major low temperature facility.

One would guess that as experience is gained in this technology, many more opportunities will present themselves.

Here is a case where the techniques developed by ingenious cryogenic engineers for high energy physics can revolutionize another field of physics.

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