John Wheatley and his first dilution refrigerators

Oscar E. Vilches

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Fifty Years of Dilution Refrigerators, Manchester, UK 2015

OEV research program on adsorption on carbon nanotubes and graphene is supported by NSF, grant DMR 1206208

This talk is partially based on a “Memoir” written for the USA National Academy of Sciences and a talk given at the ULT 2014 conference in San Carlos de Bariloche, Argentina

John C. Wheatley

1927-1986

JOHN CHARLES WHEATLEY

A Biographical Memoir

ROBERT E. ECKE (Los Alamos National Laboratory), GREGORY W. SWIFT (Los Alamos National Laboratory), OSCAR E. VILCHES (U. of Washington)

USA NAS web site, published in 2013.

Following John Wheatley: Bariloche, Illinois, San Diego. His firsts dilution refrigerators

Oscar E. Vilches

ULT 2014, S. C. de Bariloche, Argentina

John Wheatley's short biography

February 17, 1927, Tucson (Arizona) – March 10, 1986, Los Angeles (California)

Bachelor in Electrical Engineering, U. of Colorado at Boulder, 1947.

PhD in Physics, U. of Pittsburg (Pennsylvania), 1952, David Halliday thesis advisor (Nuclear orientation of Co, thermometry at very low temperatures)

i. U. of Illinois (non-tenure track faculty position), 1952-54

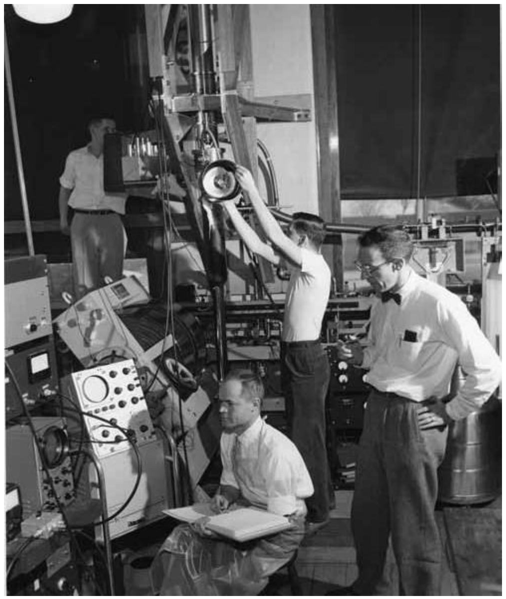
ii. Kammerlingh Onnes Laboratory, Leiden (1954-55) and Oxford U. (1955), with both Fulbright and Guggenheim fellowships.

iii. U. of Illinois 1955-1967 (Assistant, Associate and Full Professor)

iv. San Carlos de Bariloche, 1961-1963, with Fulbright fellowship

v. U. California, San Diego, 1967-1981
vi. Los Alamos National Laboratory, 1981-1985
vii. Los Alamos-U. California, Los Angeles, 1985-1986

John's visit to Leiden (1954-55): had a tremendous impact on his work. He was very impressed by the quality of the work being done there, and especially by the very well trained technical staff assisting with the experimental program. It was at Leiden that he decided to stop working on nuclear orientation and start working on liquid ^{3}He, and thoughts of having his own technicians and instrument shop developed.



The lab at U. of Illinois (1952 -67),

was shared with Mapother and Ginsburg's groups. Work on the properties of normal ^{3}He and the dilute solutions of ^{3}He and ^{4}He (thermal conductivity, heat capacity, first and zero sound, CMN thermometry, spin diffusion above 3 mK), plus measurements of electrical, magnetic and thermal properties of solids and interfaces was done there. First dilution refrigerator was built where Mapother is standing.

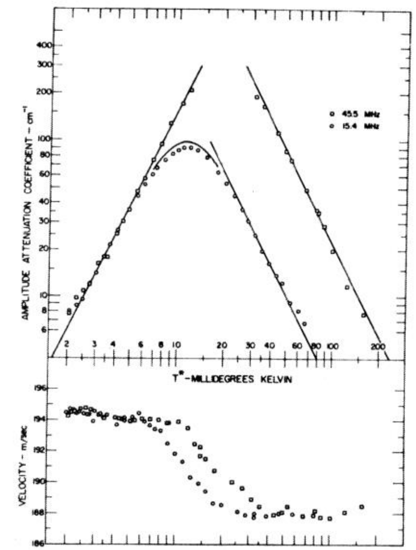


Fig. 6.16. Attenuation and propagation velocity of sound in liquid He^3 showing the characteristics associated with the transition from first sound to zero sound for two frequencies, ν = 15.4 and 45.5 Mc/sec [from Abel *et al.* ([86])].

First Illinois Lab, April 1957. Wheatley, seated, with Dillon E. Mapother (standing, right), Thomas Estle (standing, center), and Howard Hart (rear).

From Illinois Alumni News Vol 36, #3. Photo by Gliessman Studios, University of Illinois Alumni Association Archives, courtesy AIP Emilio Segre Visual Archives.

Zero sound measurement, W. R. Abel, A. C. Anderson and J. C. Wheatley, *Phys. Rev. Letters* **17**, 74 (1966)

John Wheatley spent 18 months in Argentina (1961-62) helping finish the construction of a low temperature research laboratory in San Carlos de Bariloche

View from ULT2014 hotel/conference site

Ansel C. Anderson (Andy), 5th (?) Wheatley student and post-doc, he was instrumental in running lab while Wheatley was in Bariloche, sending supplies from the USA. Assistant, Associate and Full Professor, eventually Head of Illinois Department of Physics until retirement (d. 2015)

The Bariloche group, 1964

Francisco (Paco) de la Cruz, Maria Elena Porta de de la Cruz, Ricardo Platzeck, John Wheatley, Claudio von Lucken (H_2 liquefier operator), Oscar Vilches, Ana Celia Mota, Heriberto Tutzauer (instrument maker) and Jose Miguel (Coco) Cotignola (March 1964 photo, during Wheatley's short return visit)

I was hired as an assistant in Wheatley's lab in December, 1964

Long Term Visitors: David Edwards (Ohio State, he had just shown that there was a finite solubility of ^{3}He in liquid ^{4}He at very low T), Bill Zimmerman (Minnesota).

Frequent lab visitors: John Bardeen, David Pines, Leo Kadanoff, Gordon Baym

Constant contact with Bariloche lab via amateur radio! Ana Celia Mota project on a high precision measurement of the heat capacity of liquid ^{3}He starts in 1964-65.

John Wheatley in front of small cryostat used for adiabatic demagnetization (and my thesis), Champaign-Urbana Courier, Oct. 19, 1965 (Courtesy Celia Elliott, U. of Illinois)

John Wheatley October 17, 1965

J. Wheatley

CHAMPAIGN-URBANA COURIER

Lowest Temperature in World Is Achieved by U.I. Physicist

By Robert Setlik

What happens in a laboratory in the Physics Building at the University of Illinois makes frigid Antarctica seem like a seaside resort.

Prof. John C. Wheatley has achieved the lowest sustained temperature in the world: .002 above absolute zero or about -460 degrees Fahrenheit.

He reaches the low temperatures by cooling liquids inside flasks which resemble oversized thermos bottles.

An outer flask contains liquid nitrogen at room temperature. Inside, a flask containing Helium-4 undergoes a pumping process which reduces the temperature to one degree above absolute zero. The most inner flask contains Helium-3 which, when pumped, drops to a temperature of one quarter of a degree above absolute zero.

From that point, use of a magnetic cooling substance brings the temperature to the current low of .002 above absolute zero.

Remains a Gas

The flasks serve as shields which reduce outside heat. The pumping drives out heat. Helium never solidifies, unlike other gases, and thus is used in low temperature research.

Wheatley, 38, began working with the helium - 3 isptope in 1958. He reached the low temperature mark two months ago.

He expects to reduce it still further. The slightest reductions in temperatures near absolute zero have significant effects on the helium isotope.

But absolute zero is an insurmountable barrier. Like the speed of light, it represents a

LOW-TEMPERATURE LAB

Prof. ~~Raymond~~ Wheatley inspects a cooling system which has enabled him to achieve a record low sustained temperature in the University of Illinois Physics Building. Wheatley has reduced the temperature of liquid helium to .002 above absolute zero, or about -460 degrees Fahrenheit.

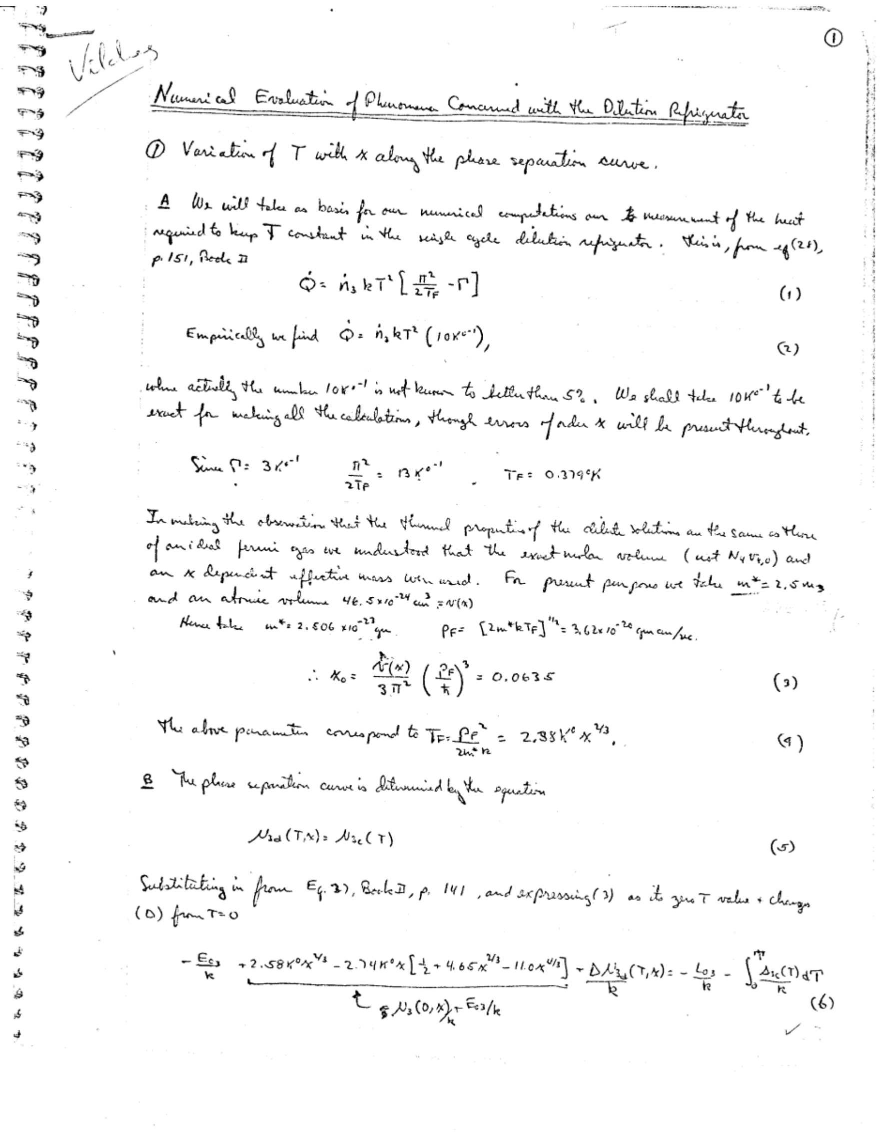
Small adiabatic demagnetization cryostat built adjacent to large screen room cryostat. It had an electromagnet similar to the one in Bariloche: heat capacity of paramagnetic salts (my thesis), heat transfer between ^{4}He and paramagnetic crystals (follow up on thesis work), superconductivity and critical field of tungsten below 10 mK (with Suso Gygax from Matthias' group at UC San Diego), critical phenomena at phase transitions (Rayl's thesis), all work done in 1965-67, plus….

John's "first" circulating dilution refrigerator

John went to the LT (QFS?) conference in England in 1966 (?) where Henry Hall spoke about his successful dilution refrigerator!

H. E. Hall, P. J. Ford and K. Thompson, Cryogenics 6, 80 (1966) (continuous heat exchangers)
B. S. Neganov, N. Borisov and M. Liburg, Sov. Phys. JETP 23, 959 (1966) (discrete heat exchangers)

On flight back (may be from Helsinki?) John designed and calculated his own version of the refrigerator using sintered copper discrete heat exchangers. He carried to all conferences a wire wound notebook which had all the then known properties of ^{3}He and the solutions, plus many of his own Kapitza resistance measurements, electrical and magnetic properties of materials used at low temperatures, and his own calculations.


Vilches

Numerical Evaluation of Phenomena Concerned with the Dilution Refrigerator

① Variation of T with x along the phase separation curve.

A We will take as basis for our numerical computations our measurement of the heat required to keep T constant in the single cycle dilution refrigerator. This is, from eq(28), p. 151, Book II

$$\dot{Q} = \dot{n}_3 k T^2 \left[\frac{\pi^2}{2T_F} - \Gamma \right] \quad (1)$$

Empirically we find $\dot{Q} = \dot{n}_3 k T^2 (10K^{\circ -1})$, (2)

where actually the number $10K^{\circ -1}$ is not known to better than 5%. We shall take $10K^{\circ -1}$ to be exact for making all the calculations, though errors of order x will be present throughout.

Since $\Gamma = 3K^{\circ -1}$ $\quad \frac{\pi^2}{2T_F} = 13K^{\circ -1}$, $\quad T_F = 0.379°K$

In making the observation that the thermal properties of the dilute solutions are the same as those of an ideal fermi gas we understood that the exact molar volume (not $N_4 V_{4,0}$) and an x dependent effective mass were used. For present purposes we take $m^* = 2.5 m_3$ and an atomic volume $46.5 \times 10^{-24} cm^3 = v(x)$

Hence take $m^* = 2.506 \times 10^{-23} gm$ $\quad p_F = [2m^* k T_F]^{1/2} = 3.62 \times 10^{-20} gm\, cm/sec.$

$$\therefore x_0 = \frac{v(x)}{3\pi^2} \left(\frac{p_F}{\hbar} \right)^3 = 0.0635 \quad (3)$$

The above parameters correspond to $T_F = \frac{p_F^2}{2m^* k} = 2.38K^{\circ} x^{2/3}$, (4)

B The phase separation curve is determined by the equation

$$\mu_{3d}(T,x) = \mu_{3c}(T) \quad (5)$$

Substituting in from Eq. 37, Book II, p. 141, and expressing (3) as its zero T value + changes (Δ) from T=0

$$-\frac{E_{c3}}{k} + \underbrace{2.58K^{\circ}x^{2/3} - 2.74K^{\circ}x\left[\tfrac{1}{2} + 4.65x^{2/3} - 11.0x^{4/3}\right]}_{\mu_3(0,x)/k + E_{c3}/k} + \frac{\Delta\mu_{3d}}{k}(T,x) = -\frac{L_{03}}{k} - \int_0^T \frac{S_{3c}(T)}{k} dT \quad (6)$$

Page 1 of Book 3 of John Wheatley's notes on ^{3}He, dilute solutions, and dilution refrigerators, 1967

<u>Next day back at lab</u>: he told me "drop everything you are doing and we will build a dilution refrigerator!" <u>I had no idea of what it was, but obliged!!!</u> He got some space from Mapother's group, ordered the 2M4 Edwards mercury pump (as in Manchester), arranged for Gösta Ehnholm from Lounasmaa's lab in Finland to come over, and the three of us built his first fridge in three months or so, including the cryostat to house it with pumping lines, electronics….. Gösta built the heat exchangers.

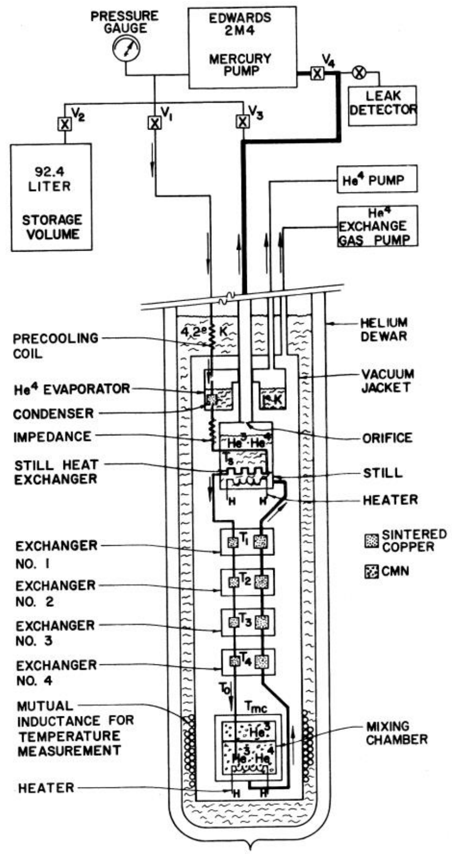
First version reached 40 mK on the first try! It had four small heat exchangers in a Quechua-flute arrangement

Further attempts at improving its performance seemed to increase its final temperature!

In typical Wheatley fashion, he decided that we did not understand exactly why it worked, so… the refrigerator was completely dismantled and each component was tested individually. First, we studied the still alone, when understood, added one side of a heat exchanger and measured heat transfer, then one complete heat exchanger, and so on… finally, a month or so later, the complete second version with four heat exchangers was running! Lowest T in continuous mode was 20 mK, single mode 13.7 mK.

“Experiments with a He^3-He^4 Dilution Refrigerator”

Preprint was submitted to PRL and widely distributed by mass mailing. Several dilution refrigerators were built following the information in the pre-print, including the first one in Canada by Jim Daniels at Toronto, the founder of the Bariloche laboratory! Article was not accepted ☹



Second version, unpublished

COO-1198-410

Experiments with a He^3 - He^4 Dilution Refrigerator*

O. E. Vilches and J. C. Wheatley

Department of Physics and Materials Research Laboratory

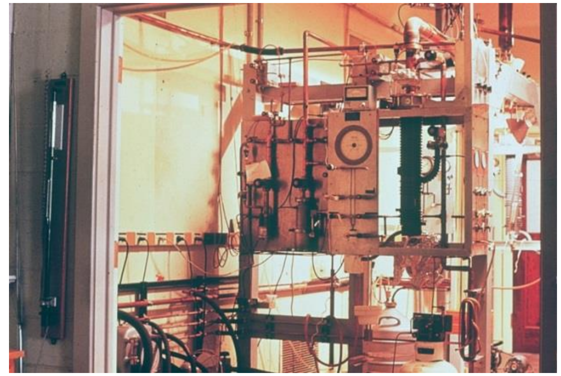
University of Illinois, Urbana, Illinois

Characteristics are given of three versions of a device which produces refrigeration by dilution of He^3 with He^4. Satisfactory agreement is found between experiment and theory for the dilution process. One device, operating continuously, produces a temperature of 0.020°K. In transient operation a temperature of 0.0137°K was obtained.

*This work was supported in part by the U. S. Atomic Energy Commission unde Contract AT(11-1)-1198, Report No. COO-1198-410.

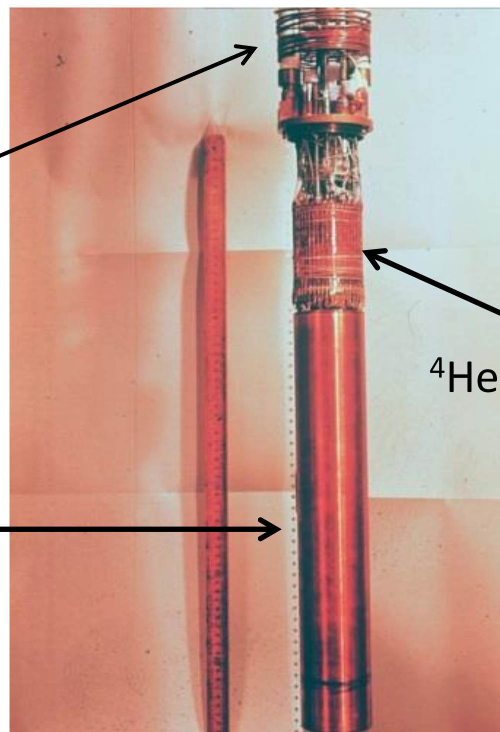
Replica of Wheatley's second refrigerator (my own at UW, built in 1968-1969, photos circa 1972)

Mercury pump was replaced for a mechanical pump and oil booster pump. Added a fifth heat exchanger.

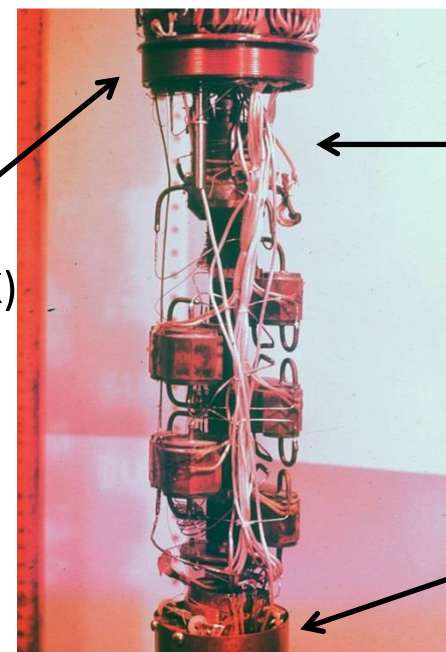


He bath ^{3}He cooling coil (4.2K)

1.1K shield



^{4}He pot (1.1K)



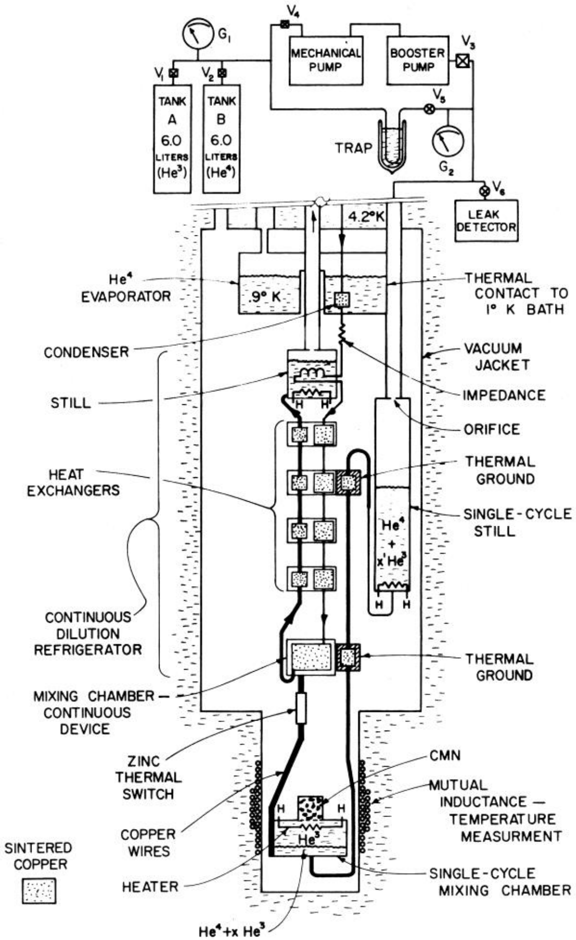
Still

Heat exchangers

Mixing chamber

The single-cycle refrigerator

A month after the continuous refrigerator was running, a second, one cycle dilution refrigerator with its vacuum system had been built and was attached to the four exchangers version of the continuous one, it went down to 4.5 mK!



COO-1198-424

Production of Very Low Temperatures by Dilution of He^3 with He^4 *

O. E. Vilches and J. C. Wheatley
Department of Physics and Materials Research Laboratory
University of Illinois, Urbana, Illinois 61801

A temperature of 4.5 m°K has been obtained, and maintained for a substantial period of time, by a simple device in which refrigeration is produced by dissolving He^3 in He^4. Magnetic cooling is not employed anywhere in the apparatus. Necessary precooling is provided by a continuously operating He^3–He^4 dilution refrigerator. Theory and operation of the device are in quantitative agreement.

Submitted to PRL and rejected twice for “having nothing of scientific interest” ☹

A shorter paper without the schematic of the double fridge but with the same results, was accepted by *Physics Letters*

"Experiments on dilution of ^{3}He with ^{4}He at very low temperatures"

O. E. Vilches and J. C. Wheatley, Physics Letters, **24A**, 440 and **25A,** 344 (1967)

Volume 24A, number 9 PHYSICS LETTERS 24 April 1967

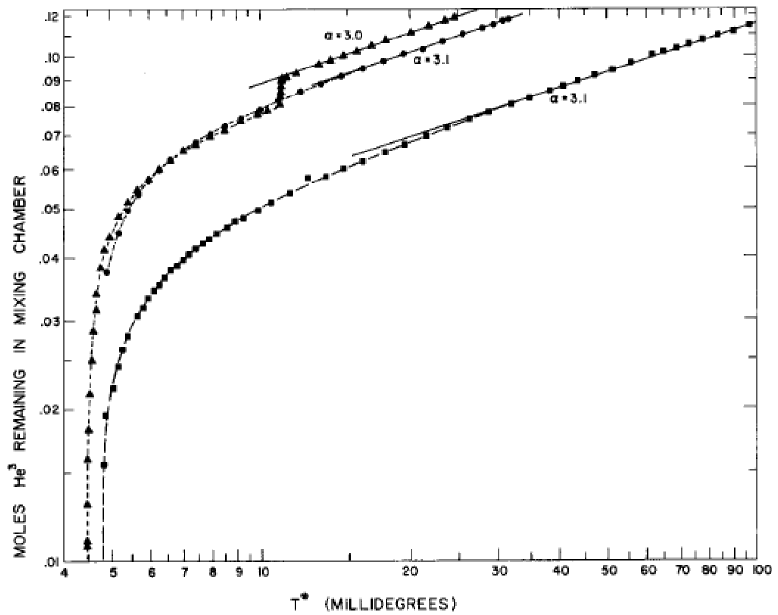
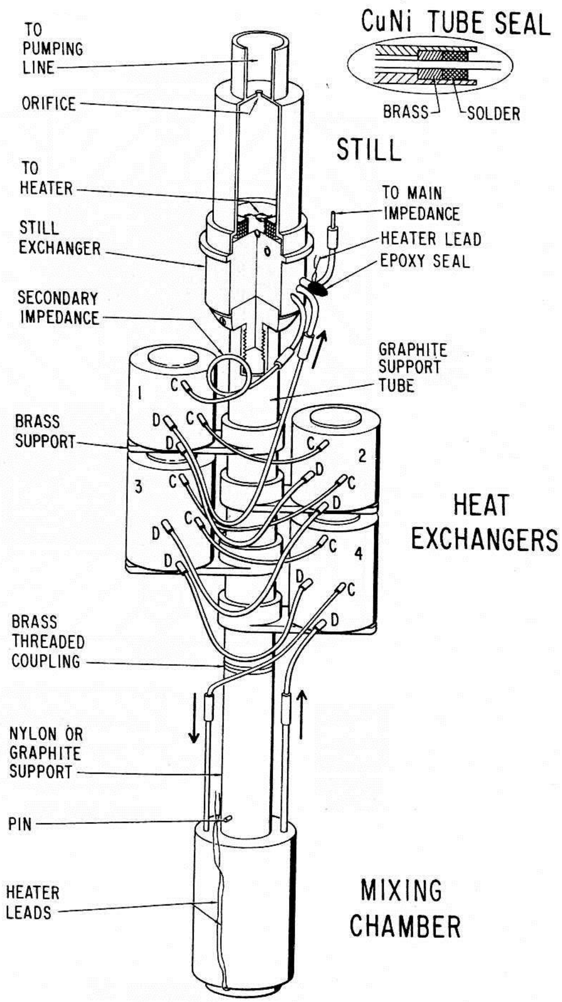
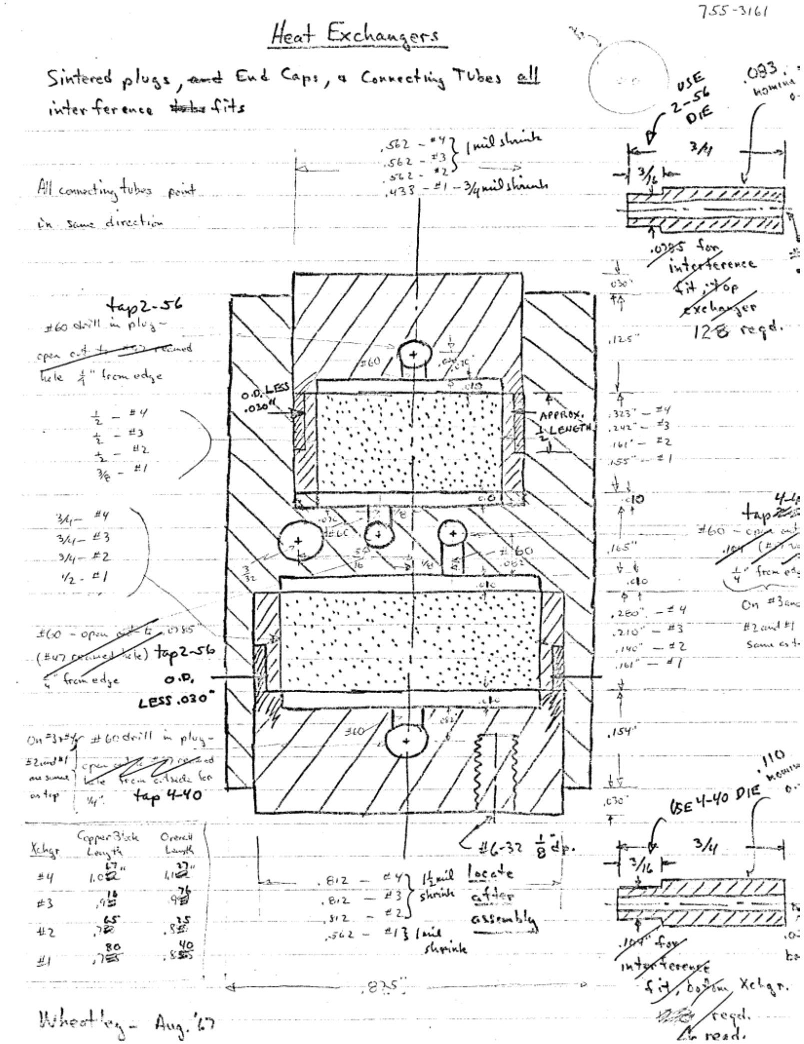


Fig. 1. Dependence of temperature on the number of moles of ^{3}He remaining in the mixing chamber for various starting temperatures. The quantity α is that given in eq. (1).

Third Version, *"Principles and Methods of Dilution Refrigeration"*, J. C. Wheatley, O. E. Vilches and W. R. Abel, *Physics* **4**, 1 (1968)





Wheatley's drawing for machine shop for the four heat exchanger (version 3) of his dilution refrigerators from August 1967 (U of Illinois)

1967: Off to UCSD

Wheatley planned an all out assault on pushing down the ^3He and solutions measurements to lower temperatures in search of superfluidity, using a larger dilution refrigerator for the base temperature and nuclear cooling for the final stage. More space than available at Illinois was needed. He wanted a dedicated low temperature technician and machine shop (following the Leiden and Bariloche experiences). He also wanted to move closer to his parents.

In the Autumn of 1966, John, Martha and I made a three day trip to San Diego. John had an offer from UCSD with a large space for lab, shop of his own, space for students and offices for post-docs. After one day of measuring lab space, negotiations, measuring rf and 60Hz noise in the space, and making a rough sketch of what could go in, the decision was made to move.

In February 1967, Richard Johnson and I moved part of the lab and Martha (his wife) moved the family and home. John remained in Urbana to work on Bill Abel and Bill Black's thesis projects. Abel and Wheatley continued working on next version of refrigerator.

The 1967-68 year I spent building the UCSD lab, both Abel and Black finished their thesis and moved to UCSD (Abel with Wheatley, Black with Matthias), and Ana Celia Mota finished her doctoral thesis in Bariloche, the first complete thesis done in the Low Temperature lab, and moved to UCSD with a post-doctoral position in Matthias group.

"Experimental Heal Capacity of Pure Liquid He^3", A. C. Mota, R. P. Platzeck, R. Rapp and J. C. Wheatley, Phys. Rev.**177**, 266 (1969)

1967-68 at UCSD:
Work on Pomeranchuck cooling begins!

1. A small machine shop exclusively dedicated to Wheatley's work was put in place and a full time technician was hired (Gene Porter).

2. Work on fabricating a cell that could withstand 40 atm below 1K and be flexible enough to change its volume by 10% or more was began. During the time I was on the project plastic cells were used. We built and destroyed more than one cell per day! The eventually successful stainless steel double "tube" cell with a stainless steel spring and ^{4}He providing the "extra" pressure was designed and built after July, 1968

3. I looked for a possible permanent track job!

I left Wheatley's group to pursue my own destiny in July, 1968. We remained very good friends until John passed away. My participation on the dilution refrigerator project helped me land the job at Washington, working with J. Gregory Dash on two-dimensional phenomena.

The Pomeranchuk cooling work: R. T. Johnson, R. Rosenbaum, O. G. Symko and J. C. Wheatley, Phys. Rev. Letters **22**, 449 (1969)

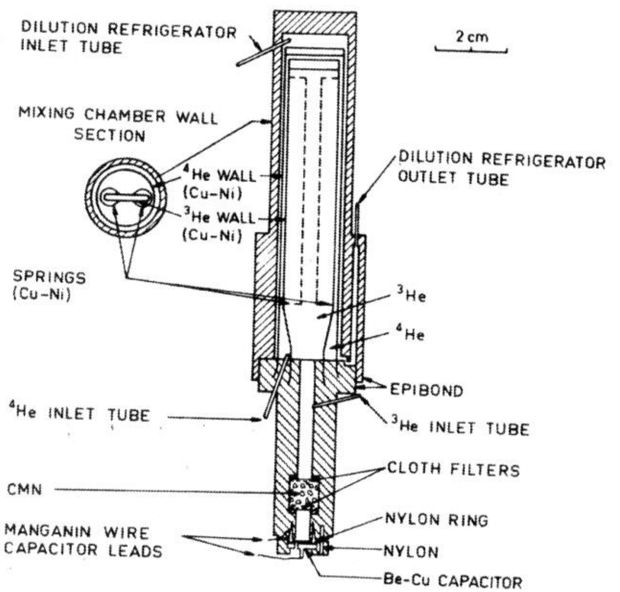


Fig. 4.7. The Pomeranchuk cell of Johnson, Rosenbaum, Symko and Wheatley (1969) with some later additions.

Figure 4.7 from O. V. Lounasmaa's book, "Experimental Principles and Methods below 1K" Academic Press, 1974

ADIABATIC COMPRESSIONAL COOLING OF He^3†

R. T. Johnson, R. Rosenbaum, O. G. Symko, and J. C. Wheatley
Department of Physics, University of California at San Diego, La Jolla, California 92037

(Received 23 December 1968)

By adiabatic compression of a two-phase mixture of liquid and solid He^3, temperatures below 2.5 mK have been obtained. These are in the range expected for nuclear ordering in solid He^3.

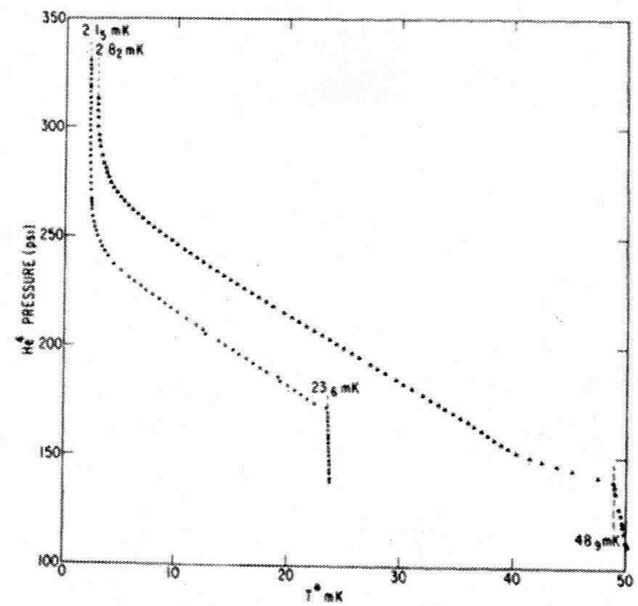


FIG. 1. Dependence of He^3 temperature, as indicated magnetically with cerium magnesium nitrate, on the pressure of liquid He^4 used to compress the He^3.

PHYS. REV. LETT 22, 449 (1969)

Work at UCSD, in parallel with work on Pomeranchuck cooling

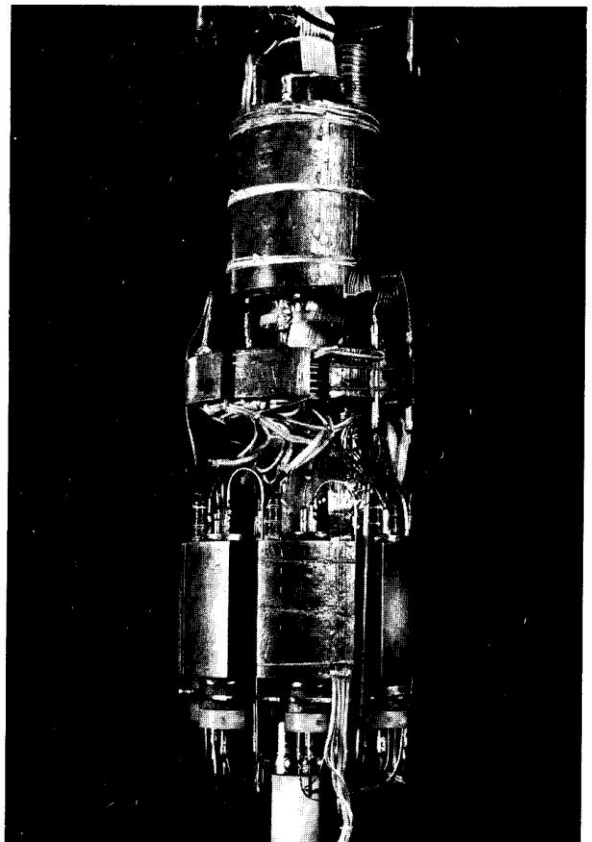


Fig. 8. Photograph of dilution refrigerator showing the still above the continuous exchanger in its mount above the set of six horizontally arranged step exchangers.

Journal of Low Temperature Physics, Vol. 4, No. 1, 1971

Principles and Methods of Dilution Refrigeration. II*

John C. Wheatley, R. E. Rapp, and R. T. Johnson

Department of Physics, University of California at San Diego
La Jolla, California

(Received August 26, 1970)

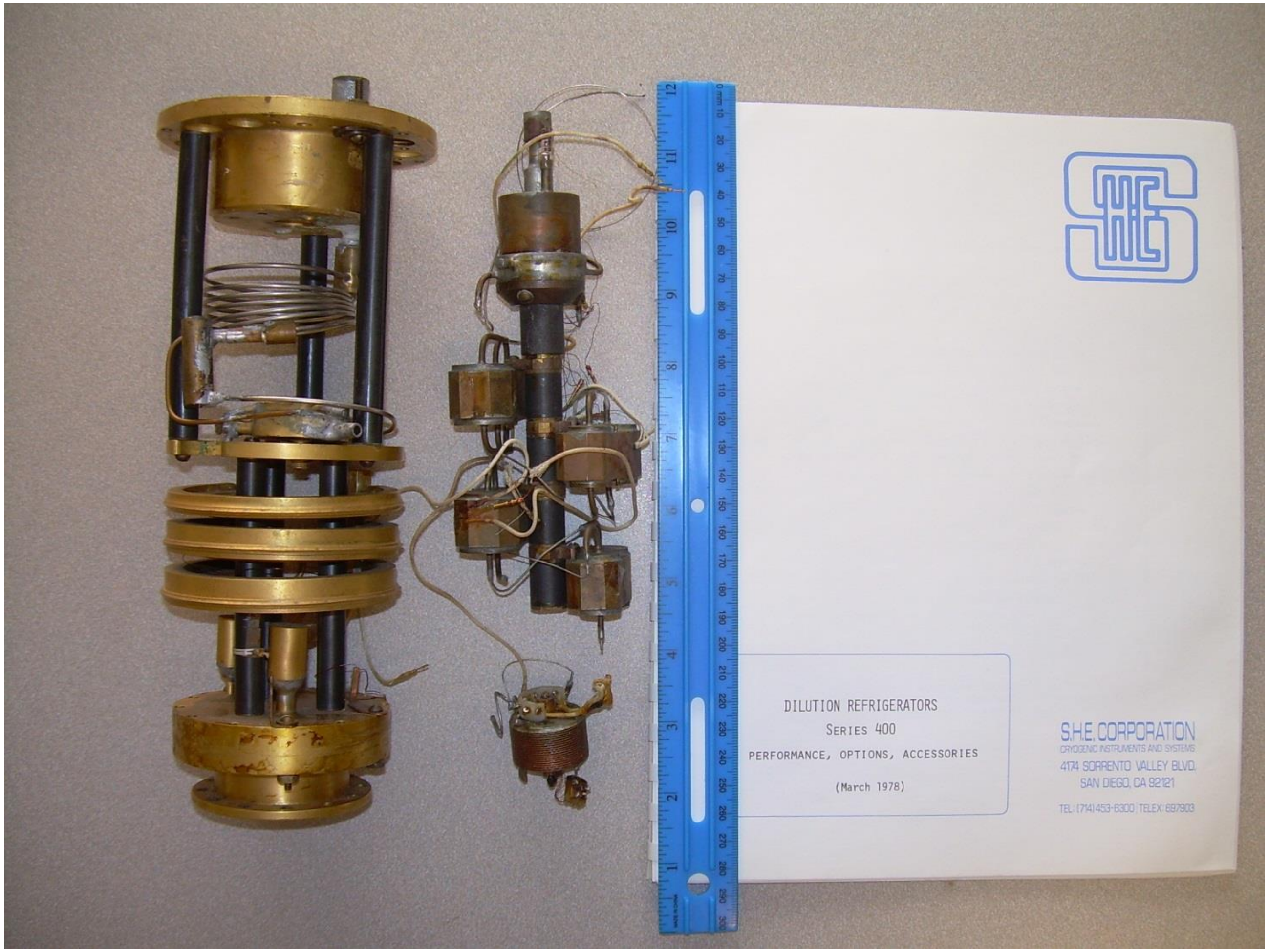
This paper is an extension of, and complementary to, an earlier paper by Wheatley, Vilches, and Abel. Some important fundamental questions which lead to degradation in the performance of a dilution refrigerator are considered: namely, convection on the dilute side and superfluid on the concentrated side. Experimental results are presented for a film suppressing still used in conjunction with a continuous-heat exchanger (several designs are considered) and a variable number (0–6) of step-heat exchangers of a copper-foil type with a high surface-area-to-viscous-impedance ratio. The first quantitative measurements of viscous heating on the dilute side are presented as well as measurements of thermal resistance on the dilute and concentrated side. Finally, the properties of the refrigerator under external heat load are considered.

1. Study of still with film suppressor heater
2. Study of effect of continuous heat exchanger in suppressing convective instabilities
3. Study of continuous refrigerator with continuous exchanger and six discrete exchangers (T_L = 7.89 mK)

The Superconductivity Helium Electronics Corporation

In the early 1970s, Wheatley, other physicists, and investors founded the SHE corporation with the purpose of building and marketing dilution refrigerators, rf SQUIDs, and electronics for cryogenic applications

In spite of early success, the company eventually dropped the dilution refrigerator line, became Biomagnetic Technologies, and doesn't exist any more!

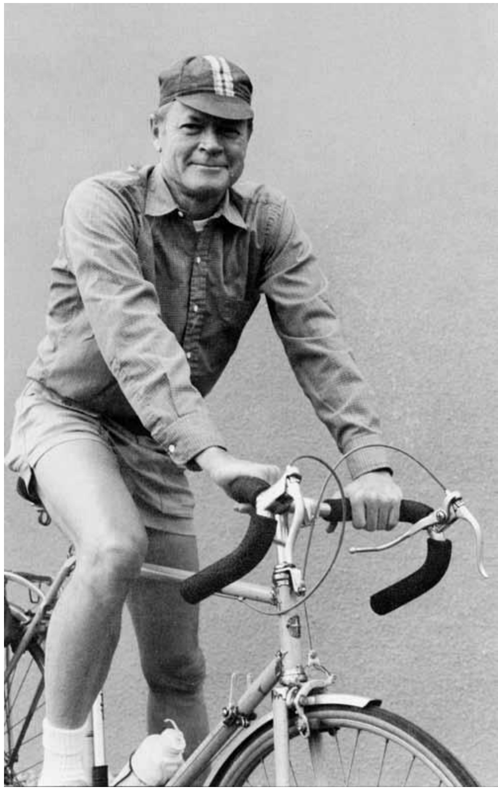


Skeletal remains of SHE Model 430 refrigerator

Skeletal remains of my refrigerator

Early SHE brochure

Some of the older physicists remember John as in the picture at right: He loved to ride his bike. At Illinois in Summer he went from home (in St. Joseph) to work (in Urbana) and back almost every day, ten miles each way.



He travelled from UCSD to New Hampshire for a Gordon Conference in his motorcycle.

He loved to ice skate, had some “clip-on” Dutch skates he had bought while in Leiden. He took many of us on skating “tours” of the ice connecting the ponds formed by abandoned coal strip mines near the border between Illinois and Indiana.

He once made a six week trip with family from Urbana to Alaska, camping all the way. His small Land Rover truck was meticulously prepared for the trip, with space for groceries, camping stove, tents, children and wife!

He had a passion for low temperature physics and doing experimental physics “right”, and a great ability to disconnect from work on weekends and be extremely warm to family and friends. Summer weekends at his home in Illinois, about a hectare with a creek running through it, sitting on his screen porch, with fireflies all over are warmly remembered….

Bill, Jane, Martha and John Wheatley on Bariloche beach, around January, 1963 (Silvia Vilches in baby carriage and Oscar Vilches next to carriage)

A volleyball game at Wheatley's home in Rancho Santa Fe, CA, 1968. A swimming pool was eventually built in this space?

Bill, Ben, John, Martha and John's mother (Alicia Vilches in front of John), Rancho Santa Fe, CA 1968

John in their cabin on Lopez Island, WA, photograph by Greg Swift

Thank You Very Much!

The low temperature lab in San Carlos de Bariloche: from James M. Daniels to John W. T. Dabbs to John C. Wheatley

J.M. Daniels
Chairman, 1969-74

Photograph from "*Physics at the University of Toronto*", Elizabeth J. Allin, U. of Toronto, 1981

Photograph from family obituary

The low temperature lab in Bariloche was designed by James (Jim) Maurice Daniels, a professor at the University of British Columbia (Canada), former student of Nikolas Kurti at Oxford. Daniels and Robinson developed the CMN thermometer. Three students from Bariloche spent 1959-1960 at UBC working with him (Porta, Cotignola, Vilches), and Daniels returned to Argentina from Sept. 1960 to Aug. 1961 to work on the project.

John Dabbs, Oak Ridge National Laboratory, followed Daniels from August to October, 1961.

John Wheatley, then at U. Illinois, followed Dabbs in 1961, rebuilt part of the lab, designed new experiments, and stayed in Bariloche for 18 months until lab was operational.