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A TECHNIQUE FOR OBSERVING MAGNET NORMALCIES

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The availability of a continuous fast responding linear liquid level indicator[1] has made possible the measurement of fluctuations of the surface of a liquid helium bath. Liquid level fluctuations can be caused by such things as mechanical vibrations, thermoacoustic oscillations, boiling effects due to constant and nonconstant heat leaks, dewar pressure changes, and normal state transitions in superconducting magnets. Observation of changes in the liquid surface is particularly important in large superconducting magnet dewars where one needs as many clues as possible to indicate the status of the magnet and cryogenic system. This paper gives some information about the detector and level fluctuations in helium which may be useful to others.

The Detector

The detector is a 0.0016 in. diameter NbTi wire which when carrying an appropriate current (60 mA) will remain superconducting below the liquid helium surface and normal above the liquid surface. The normal state is initiated by a small heater and is maintained in the gas phase by the heat generated in the NbTi wire. The difference in the heat transfer properties between the gas and the liquid prevents the normal zone from propagating below the liquid surface; therefore, the liquid level can be determined by measurement of the wire resistance. The superconducting wire is very fragile; therefore, it is usually contained in a phenolic tube for protection with helium access to the wire being assured by perforating the tube in some manner.

Cusp Coil Experiments and Liquid Helium Fluctuations

In March 1970, we were performing experiments with small Nb_3Sn coils (referred to as "cusp coils") as a preliminary step to building a large superconducting mirror quadrupole coil system[2] for the Thermonuclear Division of Oak Ridge National Laboratory (designated the IMP experimental facility). The cusp coil consists of two identical coaxial coils which are wound close together (1.32 cm apart) on a very strong coil form (ID = 8.9 cm). The unit consisting of the two coils energized in series opposition has an inductance of ≈ 0.015 H and produces a cusp field. The experiment consists of placing the entire cusp coil in an external magnetic field produced by a water cooled copper solenoid, then increasing the current in the superconducting cusp coil simultaneously with the external magnetic field to simulate conditions in a section of the IMP system. The top of Fig. 1

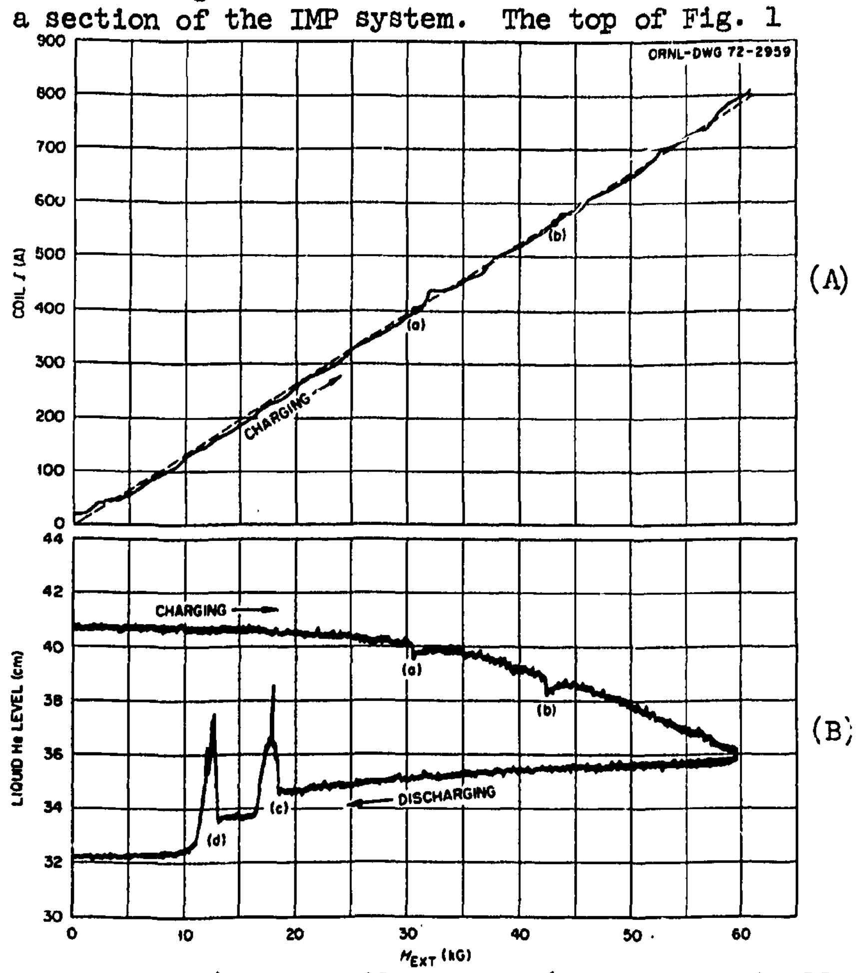

Figure 1. A) Cusp coil current (manually controlled) vs externally applied magnetic field H_{ext} (motor controlled). B) Liquid helium level during charge and discharge of the cusp coil along load line in A.

shows the current in the cusp coil versus the externally applied magnetic field for the case of increasing current. After charging to the maximum value, the coils were discharged along the same curve (discharge not shown). The lower half of Fig. 1 shows a trace of the liquid helium level made simultaneously with the coil test. Three points of interest can be observed from this curve. First, when the charging rate was reduced to zero for a short time (Points a and b), the liquid helium level dropped. This level change was due to the disappearance of bubbles which were continuously being generated below the surface by the heat produced as the magnetic field penetrated the superconducting ribbon. Secondly, although the magnet was discharged at the same rate as it was charged, the liquid losses above about 30 kG were smaller when discharging than when charging. (Note: At any point the slope of the discharge curve would be the negative of the slope of the charging curve if the losses were equal going up and going down. The charge rate is actually a function of

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H_{ext} due to the hysteresis of the iron in the current generators for the external field. The rate varies from a maximum of about 8.8 kG/min at H_{ext} = 20 kG to about 3.5 kG/min at H_{ext} = 60 kG.) This effect is easily understood since complete field penetration has occurred in this range and heat is generated throughout the superconductor when charging at approximately a constant rate per unit volume. Conversely, when the magnetic field is decreasing from its maximum value, full field reversal does not occur throughout the superconductor until the external field has dropped to an appropriately lower value.[3,4] Only when complete field reversal has occurred is heat produced throughout the volume of the superconductor. The third and most obvious thing to notice is that large changes in liquid helium level occurred when the coil went normal during discharge (Points c and d). The secondary transition at d occurred when an attempt was made to increase the current back to the discharge curve after the transition at c while the external magnetic field was still decreasing. A similar normal state transition was recorded in more detail with the aid of a visicorder as shown in Fig. 2. The liquid level seems

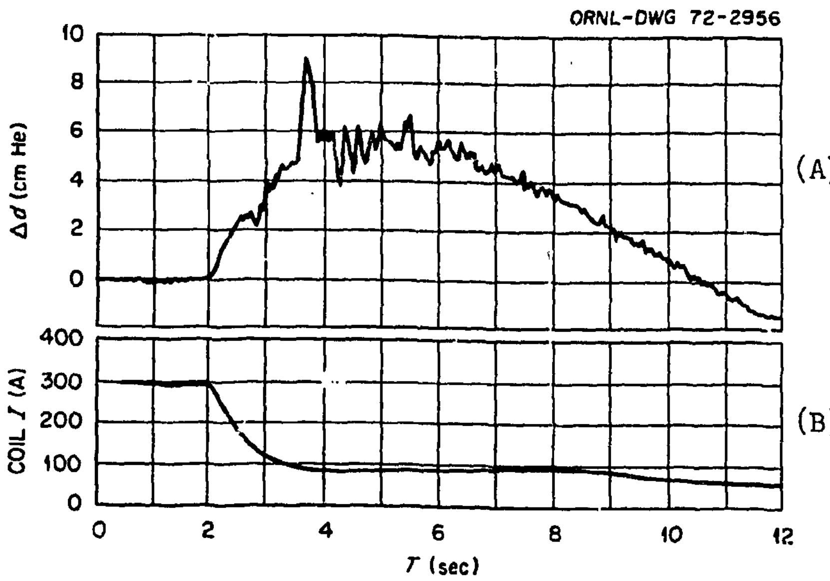

Figure 2. A) Change in liquid helium level, Δd, resulting from normal state transition in cusp coil. B) Shows drop in cusp coil current during the transition.

to signal the transition about as fast as the coil current and thus could have been used as a detector of the normal state transition.

Boiling Effects

The experiment just described served to point out that the level detector could be used for something more than just measuring absolute liquid level or helium losses. In particular, using a level detector as an auxiliary system for detecting normal state transitions in superconducting coils seems to be a definite possibility. Since normal state transitions and other effects make themselves known through heating effects, a few experiments are necessary to determine if there is any relationship between heating effects and liquid surface fluctuations.

It is well known that heating of a surface immersed in liquid helium can produce gas bubbles in the nucleate and film boiling regimes. This gas occupies a volume of about seven[5] times greater than the source liquid so that the liquid level depends on the quantity of gas bubbles contained within its volume. In steady state boiling, the gas fraction remains relatively constant. The gas fraction and thus the liquid level will undergo transient changes with changes in dewar pressure or upon suddenly changing the heat input. A sudden increase in activity at the liquid surface could signal such things as loss of pressure above the liquid in closed systems, a superconducting to normal state transition in a magnet system, a thermal short in the dewar, absorption or a radiation pulse from controlled fusion experiments, etc.

In order to obtain some idea of the relationship between the magnitude of the fluctuations of the liquid helium surface and the size of the heat input, a heater was placed in the bottom of a 10.2 cm ID dewar at a depth d below the varying liquid surface. The heater was an uninsulated Nichrome wire (No. 26 AWG) 11 cm long which had a resistance of 1 Ω. The experiment was performed by turning on a constant current in the heater at time t_0 and observing the signal from the level detector. A typical result of this type experiment is shown in Fig. 3. The lower trace represents

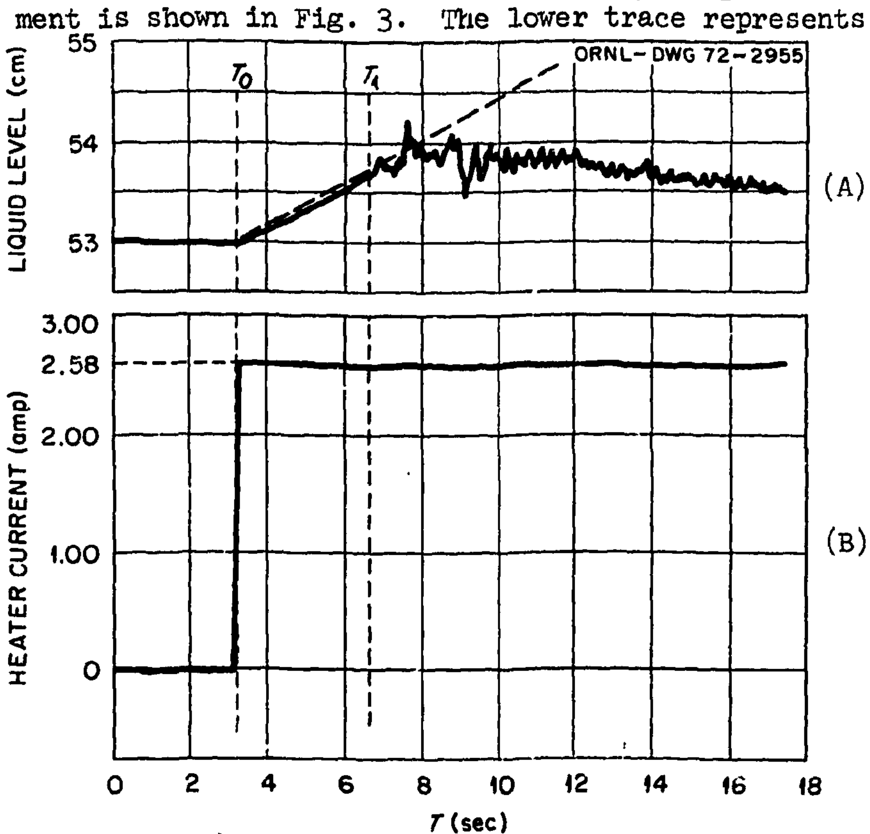

Figure 3. A) Change in liquid helium level resulting from a heat pulse 53 cm below the surface. B) Shows the heater current in the 1 Ω heater.

the current in the heater which was turned on to $I = I_0 = 2.58$ A at time $t = t_0$. The top trace is the position of the liquid surface as read by the level detector. The liquid level rises smoothly and nearly linearly for a short time ($t_1 - t_0$) and then rises still further with superposed random fluctuations. The result is related to the formation of bubbles below the surface. A constant heater power generates a constant volume of bubbles per unit time below the liquid helium surface.

This should result in a linear increase in liquid level until the first bubbles exit at the surface (assuming the entire liquid surface moves upward without change in shapes). This increase should be given by

$$d = \frac{I_o^2 Rf}{AL\rho} (t_1 - t_o) + d_o \qquad (1)$$

where $R = 1.0\ \Omega$ is the heater resistance, $f \approx 7$ is the volume of the gas produced by evaporation of unit volume of liquid, $A = 81\ cm^2$ is the area of the helium surface, $L = 20.5$ J/g is the latent heat of liquid helium at 4.18 K, and $\rho = 0.125$ g/cm^3 is the liquid density. This equation is shown as a dotted line in Fig. 3 and matches well with this experiment and others over a range of values of input power.

The linear region lasts until time t_1, when the bubbles reach the surface and fluctuations begin (confirmed visually). Assuming a constant bubble rise velocity v, the duration of the linear region should be

$$(t_1 - t_o) = \frac{d}{v} . \qquad (2)$$

For heat inputs of from 1 to 16 W at heater depths of 50 to 54 cm, Eq. (2) gives an average bubble rise velocity of $v \approx 14$ cm/sec.

The size of the fluctuations after time t_1 does not seem to be a predictable quantity. It has been visually observed that the size of the rising bubbles is small compared to the size of the fluctuations so that the fluctuations are not produced by the simple exit of bubbles at the surface. Instead, clouds of rising bubbles are accompanied by mass motion of the liquid which terminates at the surface creating turbulence. The turbulence increases as the liquid level gets closer to the heater, primarily because the rising column of liquid and bubbles has a smaller cross section closer to the heater and thus a greater velocity. To observe the effect of heater depth on the size of the fluctuations, a constant power of 9 W was maintained, and fluctuations were recorded on a visicorder as the liquid helium level fell. The results of the experiment are shown in Fig. 4. The trend towards larger fluctuations as the level drops is quite evident. Similarly, it was found that varying the heater power from 1 to 16 W had very little effect when the liquid surface was far from the heater but produced larger changes when the liquid surface was near the heater. For example, when the heater power was varied from 1 to 16 W, the fluctuations were ≈ 2 mm with very little dependence on power with a level of 48 to 54 cm above the detector but varied from 2 mm at 1 W to ≈ 8 mm at 16 W when the level had dropped to 34 - 36 cm above the heater.

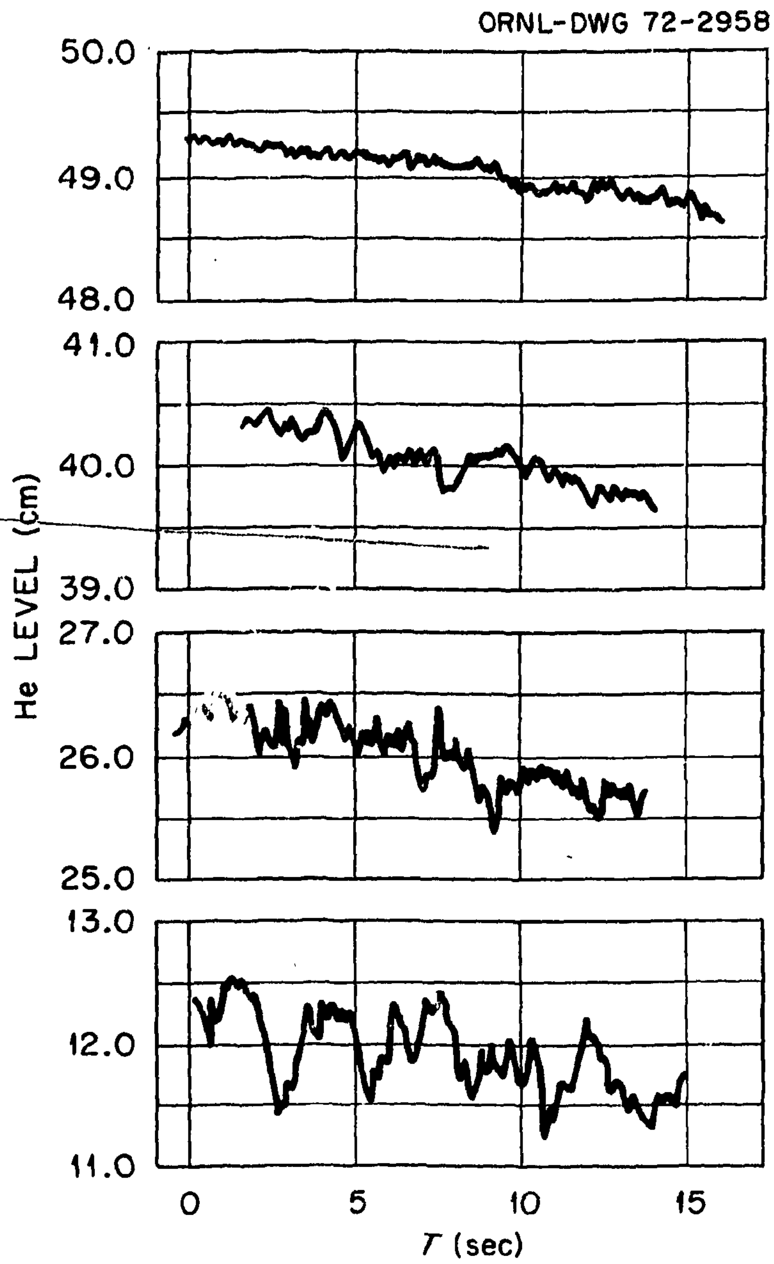

Figure 4. Liquid helium level fluctuations vs time for various heater depths. A heater power of 9 W was used in all cases.

Liquid Helium Fluctuations in IMP

The IMP superconducting coil system at ORNL has a 4 ft ID dewar and utilizes a 70 cm long superconducting level detector enclosed in a 3/8 in. OD phenolic tube. Helium access to the superconducting wire is through a 1/8 in. longitudinal slot in the tube. An identical spare detector is also installed. The total liquid helium level and amplified liquid level fluctuations are simultaneously monitored on a two channel time base recorder. The liquid level versus time plot is used to determine fill rates and loss rates and to adjust refrigerator output. The refrigerator runs continuously and is adjusted to produce excess liquid when working against the heat leak of the system. When the liquid helium rises to a fixed point on the level detector, a heater just below the helium surface is energized at a power level greater than the excess refrigerator capacity. The liquid level then falls to a lower point where the heater is turned off. The heater is surrounded by a tube which prevents liquid helium surface disturbances from propagating across the rest of the helium surface. The fluctuation versus time channel monitors transient conditions. The electronics for this section incorporates a high-pass filter with an RC time constant of 1.5 sec. This choice of time constant effectively eliminates the slow changes of helium level due to normal gain and loss of liquid during the refrigeration cycle but allows the faster surface fluctuations to be observed with little loss in amplitude. The circuit has a variable trigger adjustment which sounds an alarm if the liquid level changes rapidly by a preset amount (usually set to trip on ± 3 mm fluctuations). The same signal can also be used to automatically engage an energy dump if desired. Elimination of the dc component of the level detector signal is particularly useful because it allows great amplification of the signal due to surface fluctuations without any worries about dc compensation. In addition to being able to observe the large effects such as normal state transition of the superconducting coils or loss of pressurization in the liquid helium system, one is able to observe very small effects such as a mechanic working on the dewar or the heating effect of the magnetic field penetrating the superconducting coils during charging. Figure 5A shows a relatively large effect observed with the ac channel when overpressure from a maladjusted refrigerator was causing an automatic pressure relief valve to cycle during initial start-up procedures. The valve was opening at about 7 psig and closing at about 4 - 5 psig. Figure 5B shows the relatively minor fluctuations which occur when the Nb_3Sn quadrupole set is charged. The charge begins at Point 1 where the fluctuations increase from the normal background level of ≈ 0.4 mm to ≈ 1 mm. The fluctuations decreased again at Point 2 where the charge was momentarily halted. The size of the fluctuations decreased as the magnet was charged because we intentionally charged slower as the magnetic current increased to reduce heating in the superconductors at higher currents (the coil current is shown at the top of Fig. 5B). Although it is not shown, any normal state transition immediately drives the recorder off scale and sounds the alarm.

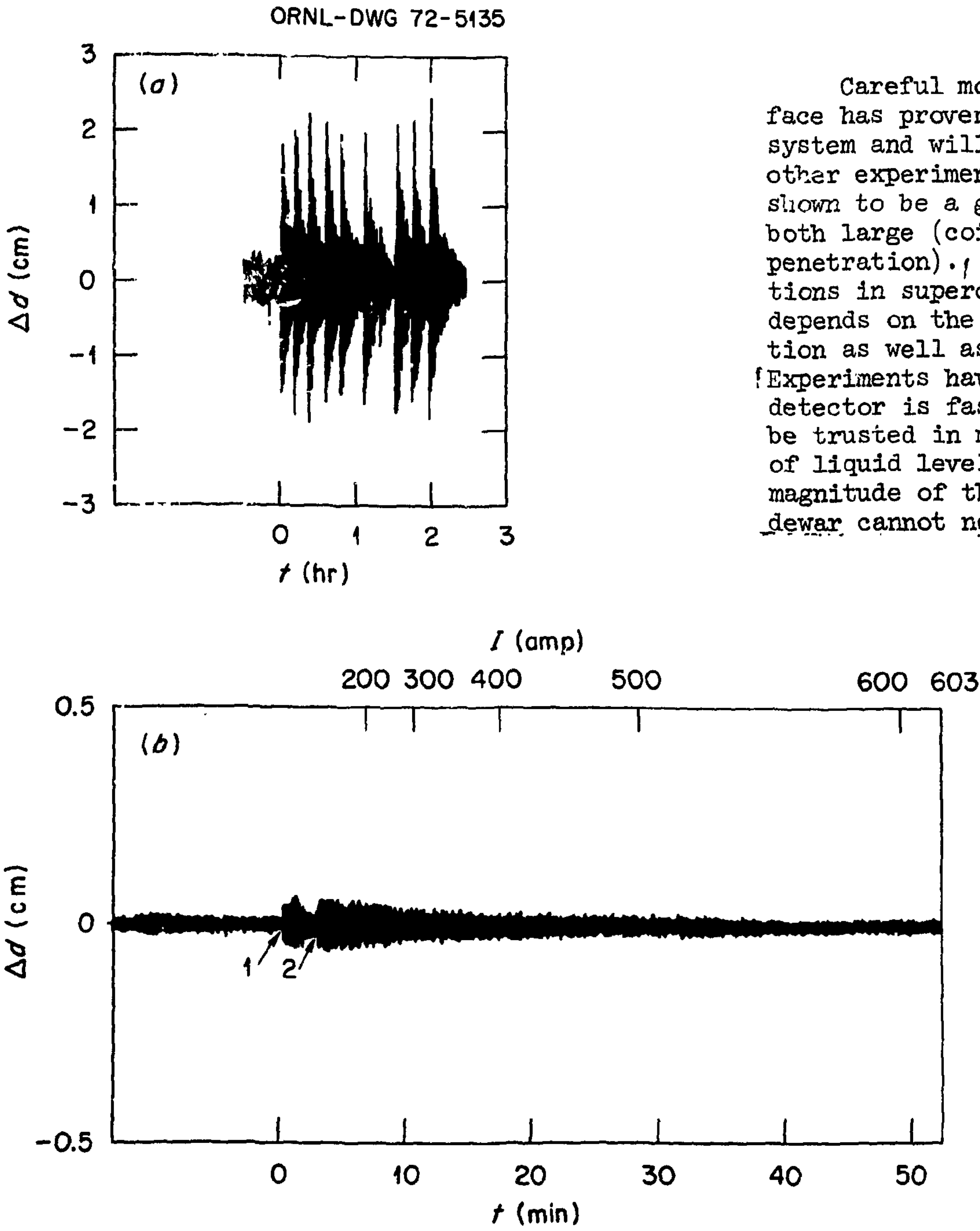

Figure 5. A) ac component of liquid helium surfaces in IMP when a pressure relief valve was periodically opening. B) ac component observed when charging the IMP quadrupoles. The charge was started at Point 1, halted for a short time at Point 2, and then continued.

Conclusions

Careful monitoring of the liquid helium surface has proven to be useful in the IMP magnet system and will probably be found worthwhile by other experimenters. The liquid surface has been shown to be a good indicator of heating effects, both large (coil transition) and small (flux penetration). Detection of normal state transitions in superconducting coils by this technique depends on the power dissipated during the transition as well as the geometry of the helium system. Experiments have shown that the liquid level detector is fast enough and sensitive enough to be trusted in measuring the various fluctuations of liquid level which occur (see Appendix). The magnitude of the effects occurring in a 4 in. ID dewar cannot necessarily be extrapolated to large dewars but can furnish some guidance. For example, localized heat s[illegible]es on one side c[illegible] .arge dewar might [illegible] se effects similar to those described if the detector is directly over the heat sources, but a detector on the other side of the dewar will see a delayed attenuated effect. Thus, usefulness of liquid helium surface monitoring will depend on the experimental arrangements and proper interpretation of the output signals.

Acknowledgments

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APPENDIX: DETECTOR CHARACTERISTICS

Experiments were performed to determine how faithfully a superconducting liquid helium level detector would produce various motions of the liquid surface. Since it is difficult to produce controlled motion of the liquid helium surface, we decided to move the level detector relative to the helium. This was done by attaching the top of a NbTi wire to a loudspeaker drive system and the lower end to a spring. The loudspeaker could be driven by a current source to produce the desired motion of the wire. A Bourns "linipot" was also attached to the loudspeaker drive to measure the position of the NbTi wire. One experiment performed with this system was to pulse the speaker device with a square wave. Figure A-1 shows the result of this type experiment. The level detector was raised 4 mm out of the liquid and then dropped to its original position by the square wave input as indicated by the "linipot" signal. Note that the level detector signal shows an average response of ≈ 2 cm/sec over the 4 cm displacement when it is rising although locally it responds faster, e.g. the initial rise. It seems quite likely that the limiting velocity is due to liquid helium being dragged along with the detector. After 1.4 sec, the detector is dropped back to its original position (some temporary overshot occurs). In this case, the level detector signal changes about as rapidly as the position signal. It was not possible to move the detector down fast enough to define a limiting velocity of response as was the case for the rising detector. All that can be said is that the limit for the falling detector (or rising liquid) is at least 25 cm/sec.

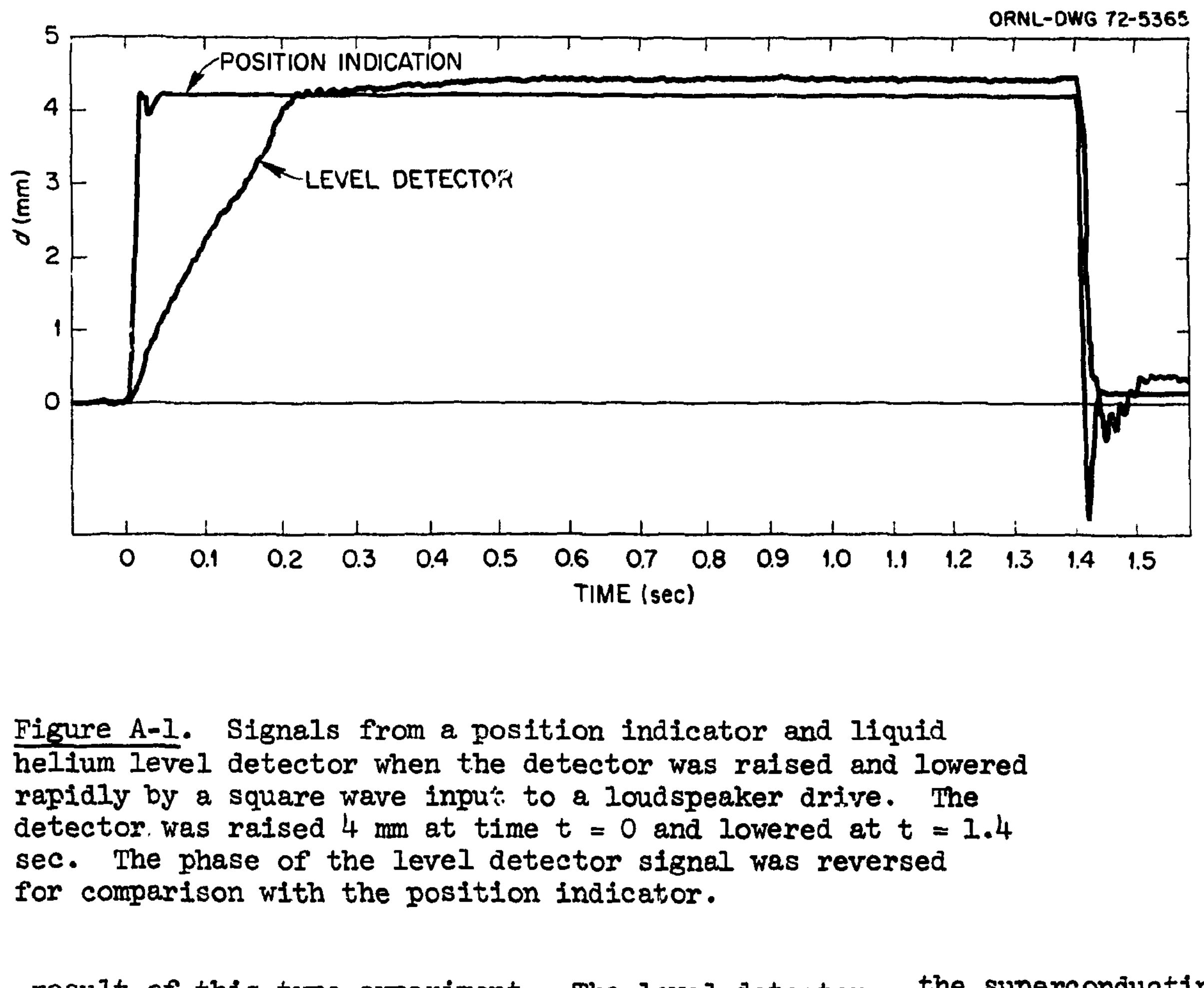

Figure A-1. Signals from a position indicator and liquid helium level detector when the detector was raised and lowered rapidly by a square wave input to a loudspeaker drive. The detector was raised 4 mm at time t = 0 and lowered at t = 1.4 sec. The phase of the level detector signal was reversed for comparison with the position indicator.

The propagation velocity of the normal zone of the detector was measured in the gas just above the liquid surface in order to find the maximum response possible for the case of falling liquid. This was accomplished by pulsing the current in the detector from I = 0 to I = 60 mA and observing its voltage. It was found that the normal zone approached the surface with a slowly decreasing velocity until it was within 2 to 3 mm of the surface where it suddenly decreased from ≈ 12 cm/sec to ≈ 4.5 cm/sec. The variation of velocity is mostly due to the temperature gradient in the dewar until the zone is very close to the surface where some other effect such as an enhancement of the heat transfer coefficient to the gas may occur. This point was not pursued. The 4.5 cm/sec propagation velocity of the normal zone near the surface indicates that the response velocity of ≈ 2 cm was probably due to liquid rising with the level detector in the previous experiment.

The result of the difference in response of the detector for rising and falling liquid levels is readily seen by shaking the dewar to excite large fluctuations. Figure A-2 shows this result. In contrast to the rising detector experiments, the falling level responds at the propagation velocity of ≈ 4.5 cm/sec (the straight-line character at the back side of each of the waves indicates that a limiting velocity has been reached). The rising level is indicated much more rapidly, for example, the slope of the front side of the fourth peak is too great to make an accurate measurement.

It is not understood why the result obtained by raising the superconducting wire is not equivalent to that obtained when the liquid falls. Since physical motion of the liquid is the most important case,

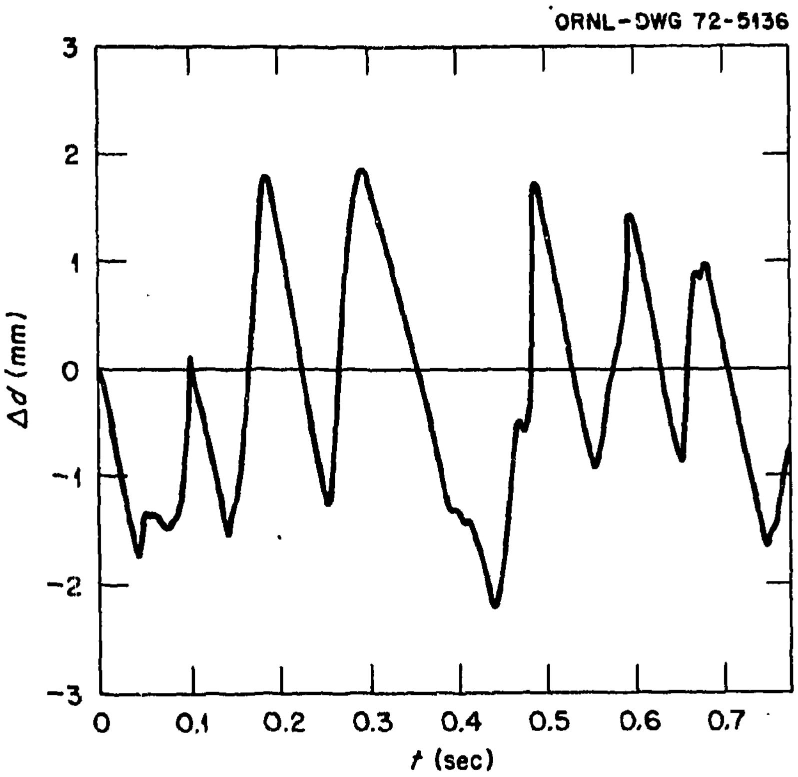

Figure A-2. Liquid helium fluctuations were obtained by shaking the dewar. Sawtooth character of signal results from the liquid falling at velocities greater than the velocity of response of the detector.

one should assume that the detector responds to falling liquid levels at the propagation velocity of ≈ 4.5 cm/sec (I = 60 mm). The response time of the detector to rising or falling liquid levels seems to be more than adequate for observations of the events occurring in magnet systems.

The lower level of resolution of the detector is unknown but very small. Since the normal zone moves in a continuous and linear fashion over the range of amplifications used in these experiments, a small resolution is possible by applying sufficient amplification. A 2.54 cm long detector was built to check the lower limit of resolution of the detector. Signals obtained from this detector are shown in Fig. A-3. Figures A-3A and A-3B represent, respectively, the signal output with the detector above the liquid level (completely normal) and submerged (completely superconducting). These two traces show the low noise level of the measuring system. Figure A-3B shows the signal immediately after the detector was half submerged, while Fig. A-3C is the trace after the dewar was undisturbed for five minutes. For the most part, the fluctuations in Fig. A-3C are less than 0.1 mm peak to peak and have varying periods of the order 0.02 sec. These fluctuations appear to be real and are probably caused by a combination of boiling and building vibrations. However, the remote possibility does exist that the normal zone is unstable to this extent. In real magnet systems, fluctuations will almost surely exceed 0.1 mm in normal operation rendering these small fluctuations unimportant.

It should be pointed out that the experiments described in this appendix were performed in liquid helium at atmospheric pressure. The properties of the detector at higher or lower pressures have not been investigated enough to include results in this report. However, the detectors in the IMP facility seem to work quite well (pressure ≈ 1.4 atmospheres).

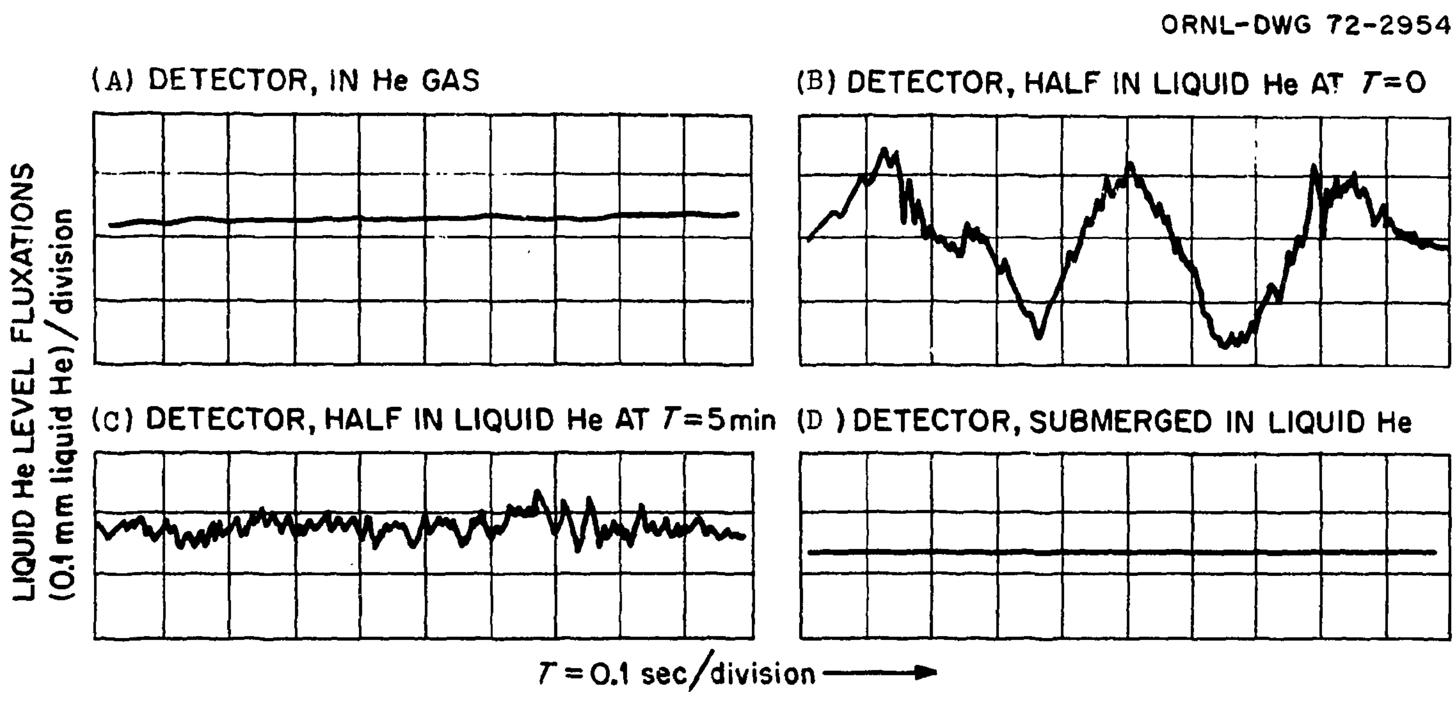

Figure A-3. Liquid helium level fluctuation signals as obtained from a 2.54 cm long detector. The signals in Fig. A-3A (detector above liquid) and Fig. A-3D (detector submerged) show the low noise level of the measuring circuit. Figure A-3B shows fluctuations excited by positioning the detector half in liquid. Figure A-3C shows the very small signals obtained after the dewar was undisturbed for five minutes.