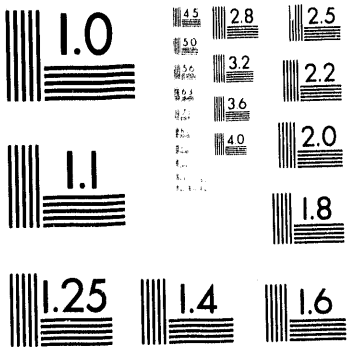
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NORMAL ZONE PROPAGATION AND THERMAL HYDRAULIC QUENCHBACK IN A CABLE-IN-CONDUIT SUPERCONDUCTOR

J. W. Lue and L. Dresner

Oak Ridge National Laboratory*
Oak Ridge, TN 37831-8040

ABSTRACT

When a local normal zone appears in a cable-in-conduit superconductor, a slug of hot helium is produced. The pressure rises and the hot helium expands. Thus the normal zone propagation in such a conductor can be governed by the hot helium expansion, rather than the heat conduction along the conductor. The expansion of the hot helium compresses the cold helium outside of the normal zone. This raises the temperature of the cold helium. When the temperature rise reaches the current sharing limit, the superconductor in contact goes normal. Thus a rapid increase in normal zone propagation occur. This phenomenon is termed Thermal Hydraulic Quenchback (THQ). An experiment was performed to investigate this process. The existence of THQ was verified. Thresholds of THQ were also observed by varying the conductor current, the magnetic field, the temperature, and the initial normal zone length. When THQ occurred, normal zone propagation approaching the velocity of sound was observed. A better picture of THQ is obtained by a careful comparison of the data with analytical studies.

INTRODUCTION

In a cable-in-conduit, force-cooled superconducting magnet the coolant is limited to the interstitial helium inside the conduit. It can not be replenished fast enough to provide steady state heat transfer when the conductor goes normal. Hence the quench behavior of the conductor depends strongly on the thermal hydraulics of the coolant. In a numerical analysis Luongo et al.[1] discovered a hitherto unsuspected normal zone propagating phenomenon - a sudden acceleration of the normal front. They called

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it Thermal Hydraulic Quenchback (THQ) and gave the following explanation: Cold fluid elements outside the normal zone are displaced and compressed by the expansion of the hot helium in the normal zone. Because of the compression and the friction with the cable strands, the temperatures of these fluid elements rise. When their temperatures reach the current sharing threshold, the strands they wet become normal and a sharp increase in normal zone propagation follows. Figure 1 presents a schematic illustrating the development of THQ.

The numerical analysis pointed out the possible existence of THQ but did not show how the phenomenon depended on the many parameters that controlled it. An analytical study based on similarity solutions by one of us[2] remedied this shortage at the cost of some idealizing assumptions. This theory treated the motion of the hot helium as though it were induced by a piston moving down a long, slender pipe. The displacement of this piston was taken to be proportional to a power of the elapsed time. A formula for the onset time of THQ was derived which gave its dependence on the various parameters of the coolant and the conductor.

An experiment was also undertaken to verify the existence of THQ and its dependence on the conductor current, the magnetic field, the initial normal zone length, and the coolant temperature. During the first series of experiments no THQ was observed[3]. Normal zone propagation was found to increase gradually with time. By applying magnetic field and changing the coolant temperature, sharp increases in propagation velocity were observed in the second series of experiments[4]. The existence of THQ was verified experimentally.

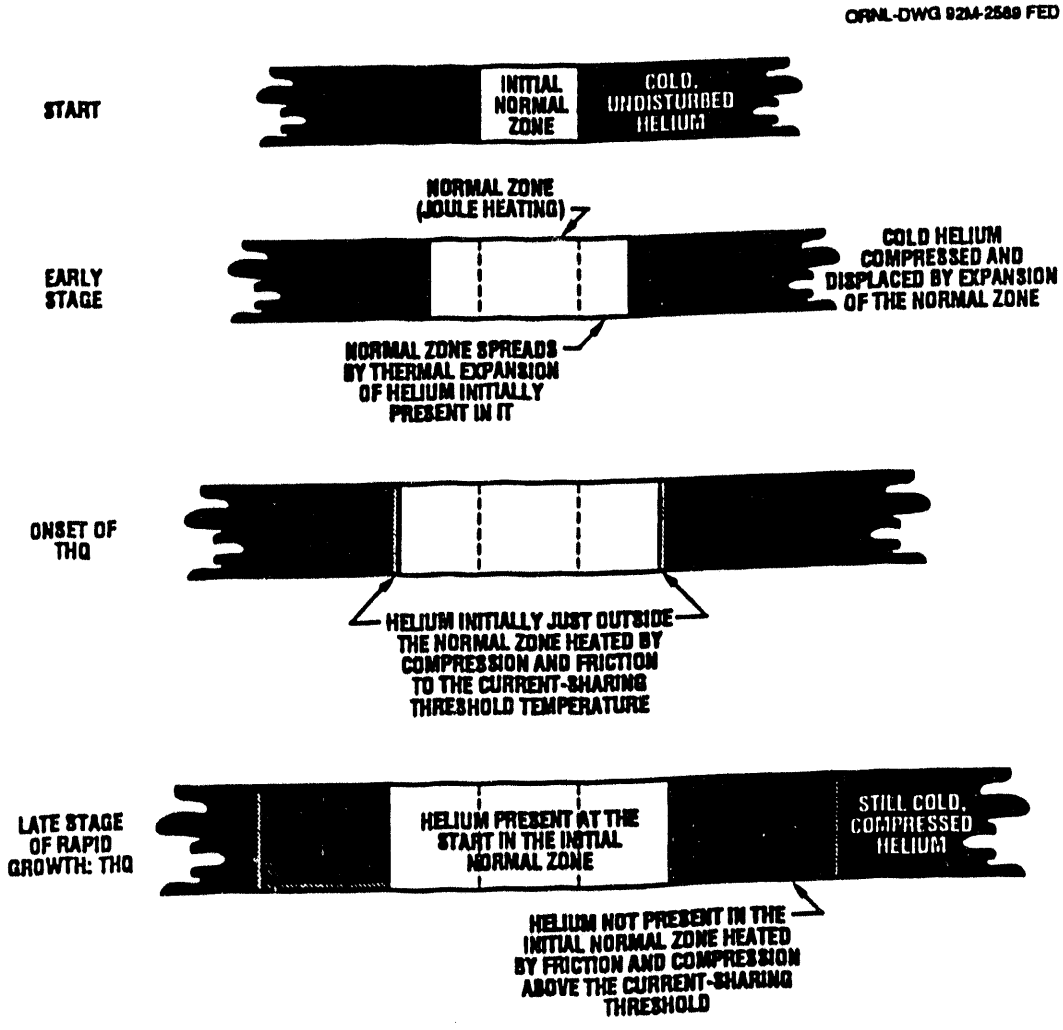

Figure 1. Schematic Illustration of the Development of THQ.

In comparison with the theory of Ref. 2, we had however, noticed a discrepancy. The experiment showed that there is a threshold for THQ, namely small changes in conductor current or magnetic field can cause the THQ to appear or disappear. The theory indicated that such small changes should slightly advance or delay the onset of THQ, rather than turn it on or off completely. It is the purpose of this paper to present more analysis of the experiment and to show that the existence of thresholds for THQ can indeed be accounted for by the existing theory.

EXPERIMENT

Normal zone propagation experiments were performed on a 50-m long, single triplex cable-in-conduit NbTi superconductor. Figure 2 shows a schematic of the sample and its instrumentation layout. The experiment was focussed on determining the conditions under which THQ exists. Heaters 3 (0.38 m long) and 4 (0.72 m long) in the middle of the conductor were used to create the initial normal zone. Voltage taps (V) and thermocouples (T) along the conductor monitored the propagation of the normal zone and the conductor temperatures. A dp-cell at the outlet end of the conductor measured the pressure differential over a 3.7-m length of the conductor to give the imposed flow rate of the coolant and the helium expulsion velocity. Other details of the experimental setup were given in references 3 and 4.

Table 1 lists the test conditions of selected shots and whether THQ was observed in a shot. Helium pressures, p_o of about 3.5 atm and imposed helium flow, v_{He} of about 3 m/s were used in most shots. Temperature, T_b was raised beyond 6 K before THQ was observed. A shot was judged to have THQ when a sharp increase of normal zone propagation was detected. This occurred mostly within one second after the heat pulse. Shots with quite significant increases in propagation more than halfway downstream (after 2 seconds) were judged to have a late THQ.

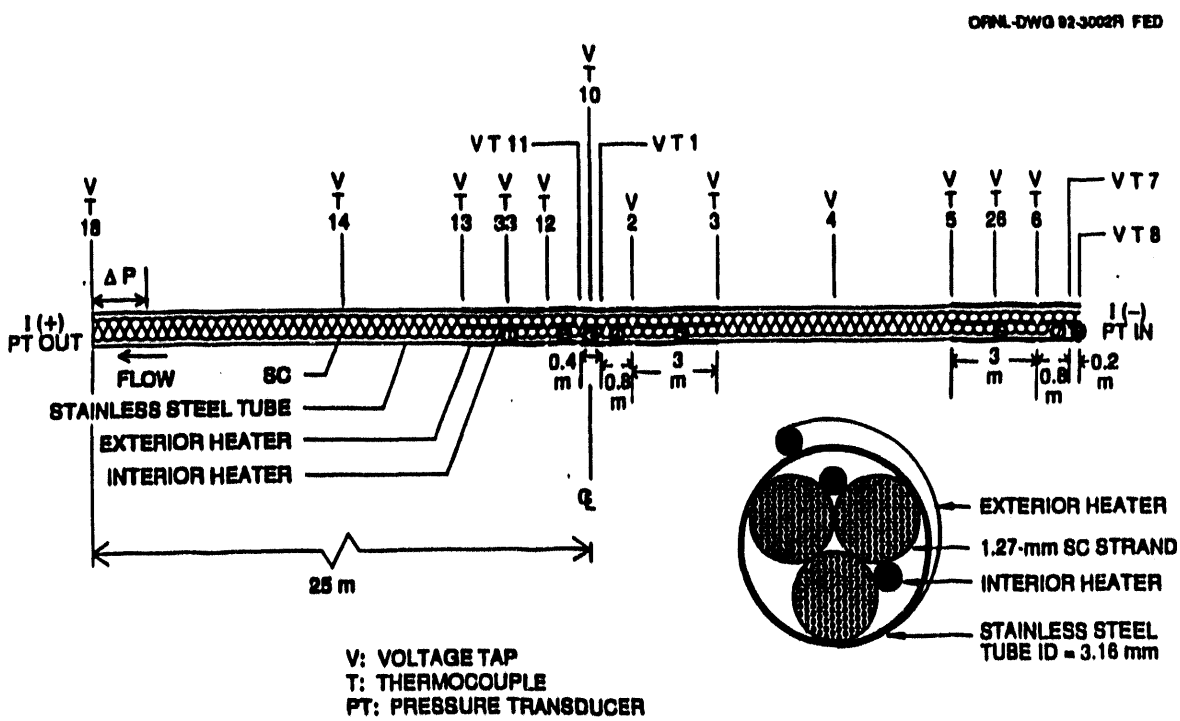

Figure 2. Cable-in-Conduit Sample and its Instrumentation Layout.

Table 1. Shot Conditions and the Existence of THQ

Shot	heater	I_s (A)	B (T)	T_b (K)	p_o (atm)	v_{He} (m/s)	THQ	(T_m-T_b)	ΔT_{Max}
2057	4	980	0	6.3	1.8	2.0	No	1.72	0.83
2066	4	870	0	7.5	3.1	3.5	Yes	0.64	0.80
2069	4	660	0	6.0	3.9	1.2	No	2.37	1.57
2070	4	660	2.4	6.5	3.6	1.5	Yes	0.73	1.09
2073	4	560	2.4	6.4	2.9	1.9	No	0.95	0.91
2074	4	595	2.4	6.6	2.8	2.9	Yes	0.71	0.92
2075	4	600	1.2	6.6	3.1	2.9	No	1.27	1.07
2076	3	600	2.4	6.6	3.0	3.2	Late	0.70	0.83
2077	3	700	2.4	6.7	3.3	3.1	Yes	0.48	0.81
2081	3	695	1.2	7.1	4.8	3.0	Late	0.66	0.80
2078	3 & 4	500	2.4	6.8	3.5	3.2	Late	0.63	1.46
2079	3 & 4	550	2.4	6.8	4.0	3.2	Yes	0.56	1.42
2080	3 & 4	590	2.4	7.0	4.5	3.2	Yes	0.32	1.93

Comparison of shots 2073 and 2074 shows a threshold for THQ between 560 A and 595 A when a field of 2.4 T was applied and the 0.72-m-long heater was used. This current dependence shifted to between 600 A to 700 A when the 0.38-m-long heater was used, and to between 500 A and 550 A when the 1.1-m-long heater (combination of #3 and #4) was used. Comparison of shots 2074 and 2075, and shots 2077 and 2081 also shows a clear threshold between 1.2 T and 2.4 T.

The normal zone propagation was measured with an imposed flow. In order to facilitate comparison with the theory in the next section, this flow velocity should be subtracted from the measured velocity for downstream propagation between successive temperature taps to find the normal front arrival time in a no imposed flow condition. The resulting normal front arrival times for the shots using heater #4 were plotted in Fig. 3. Only a single line was drawn through the shots without THQ to show the general trend of those shots.

When THQ existed, transient velocities of more than 100 m/s were observed. This is further illustrated by plotting the average velocities between successive temperature taps in Fig. 4. These velocities approached the sonic velocity of 130-150 m/s under the present helium test conditions. It is not clear why the velocity dropped later on. Before THQ occurred and for the shots without THQ, there was a trend of slowing down in the hot helium expansion velocity before a gradual increase took place later on. This phenomenon was actually predicted in some numerical examples in another analytical study.[5]

Similar results were found for shots using 0.38-m and 1.1-m long heaters. Shots were also taken with helium pumped out of the conduit. They showed that normal zone propagation by conduction through the conductor were on the order of 1-2 m/s. Measured upstream propagations were all slower than the downstream ones, but THQ also occurred upstream for every shot in which it occurred downstream. Before the hot helium expansion picked up enough speed, the upstream normal zone propagation was dominated by the conduction through the conductor. It was not possible to find a meaningful propagation velocity upstream in a no-imposed-flow condition.

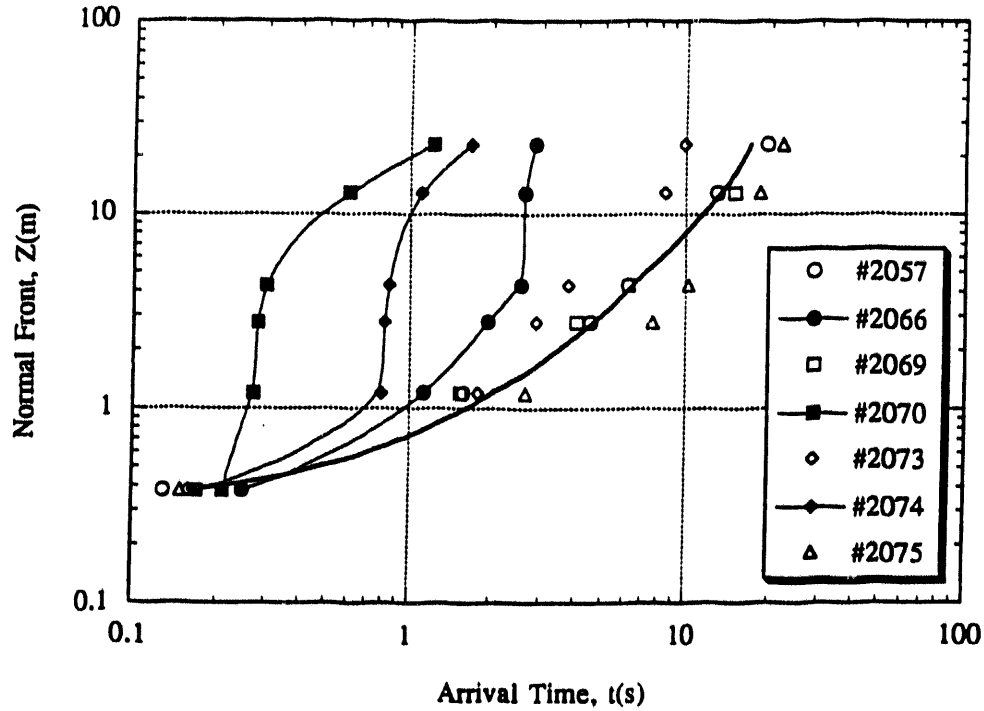

Figure 3. Normal Front Arrival Time in No Imposed Flow Condition.

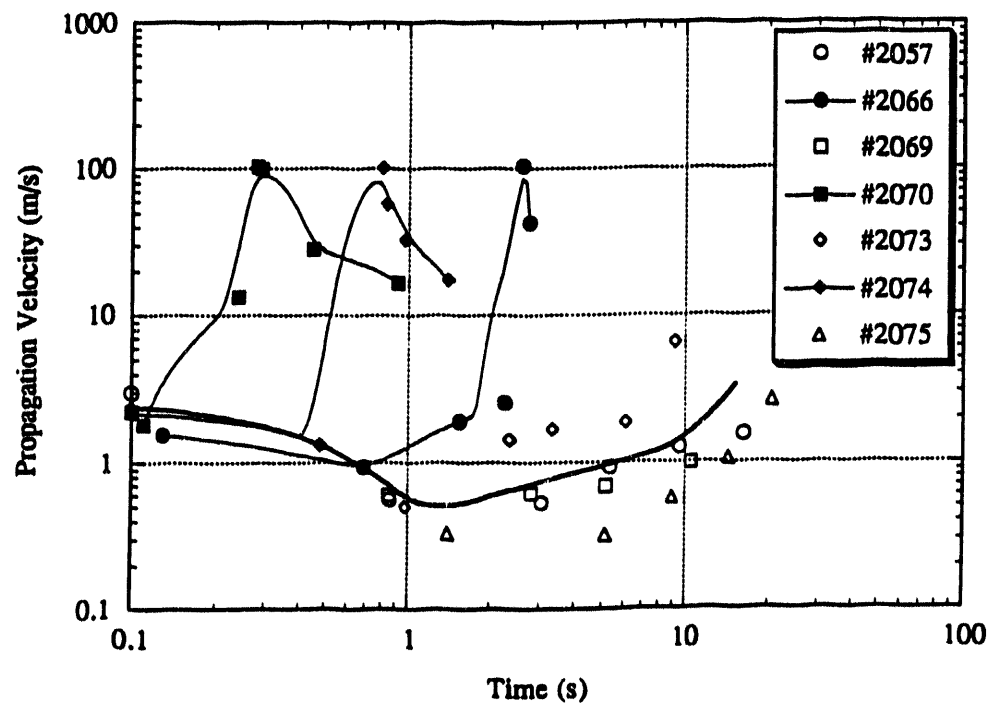

Figure 4. Normal Zone Propagation Velocity in No Imposed Flow Condition.

DISCUSSION

The temperature rise, ΔT of the cold helium adjacent to the hot helium by the compression of the expanding hot helium and the friction with the cable strands can be written as

$$\Delta T = \Delta p \left(\frac{\partial T}{\partial p}\right)_V + \frac{2f}{DC_p} \int_0^t \dot{Z}^3 dt \,, \tag{1}$$

where Δp is the pressure rise of the hot helium (at the piston), f is the friction factor, D is the hydraulic diameter, C_p is the specific heat, and $\dot{Z}$ is the hot helium (piston) expansion velocity. Early, when the disturbance has not yet reached the open end of the flow path the pressure rise at the piston was found to be

$$\Delta p = A\rho c^2 \left(\frac{4fZ}{D}\right)^{3/2} \left(\frac{D}{4fct}\right) , \tag{2}$$

where A is a constant depending on the power of time that the piston expands, ρ is the cold helium density, c is the sonic velocity, and Z is the piston displacement. The time at which ΔT reaches $(T_\infty - T_b)$ marks the onset of THQ. In Ref. 2, it was further shown that the frictional term is much less than the compressional term for the onset of THQ. Thus a formula for the onset of THQ was derived:

$$\left(\frac{4fZ}{D}\right)^{3/2} \frac{D}{4fct} = \left[\left(\frac{\partial p}{\partial T}\right)_V \Delta T \right] / A\rho c^2 \,. \tag{3}$$

In order to calculate the onset time, the rate of growth of the normal zone before THQ, i.e. the piston displacement Z(t), must be known. In Ref. 2, it was assumed that the piston displacement was proportional to a power of the elapsed time

$$Z = X\, t^n \,. \tag{4}$$

Now, the left-hand side of Eq. 3 varies as the (3n/2 - 1) power of the time. So if $n > 1$, as we first imagined, then $(3n/2 - 1) > 0.5$. A small change of the right-hand side (for example in ΔT) would require a comparatively small change in t to satisfy the left-hand side. On the other hand, if $n < 1$, say 0.7 for example, then $(3n/2 - 1) = 0.05$. A small change in the right-hand side, say by a factor of 1.2, would require a change in t by a factor of 38. Such a vast delay in onset would appear experimentally as a threshold.

It is to be noted that if $n < 2/3$, the left-hand side of Eq. 3 would vary as a negative power of t. However, it was shown in Ref. 2 that Eq. 3 is valid only if $2/3 < n < 2$, and loses its accuracy as n approaches 2/3. The singularity of the solution given in Ref. 2 when $n = 2/3$ is a result of the idealizing assumptions made to permit analytical solution of the THQ problem. Since we expect that the exact solution to the THQ problem would not have a singularity at $n = 2/3$, we infer from the analytical solution that threshold behavior will occur when the value of n is less than 1 and becomes more pronounced the smaller the n is.

Hot Helium Expansion Power, n

To find the value of n we need to study the rate of expansion of the normal zone either before the onset of THQ or in cases in which THQ does not occur. From Fig. 3, we found that for shots without THQ, n varied from about 0.5 to 1.5 in the time between 0.2 s to about 6 s. And n was less than 1 for several seconds. Thus a threshold behavior could be expected, and was observed. This threshold behavior of THQ seemed to have been seen by Wachi et al.[6], too.

Ref. 5, which treated the hot helium slug as a perfect gas, can also be used to infer n. This theory required a knowledge of the temperature of the heated helium as a function of the elapsed time. The nemerical examples presented in Ref. 5 were based on a temperature that rises as the 0.4-power of time for the first few seconds; the corresponding values of n were found to be around 0.5 for short initial normal zones. Further numerical exercises showed that temperatures that rise with powers of time less than 1 are coupled with low values of n.

Compressional Heating

The temperature excursion at the initial normal zone was measured in the present experiment. Fig. 5 shows a couple of the examples. When THQ occurred at about 1 s for shot 2066, the temperature rise stopped for about 1 s before it rose again. Similar behavior was observed for all other THQ shots. Using the measured temperature and the technique given in Ref. 5 one can calculate the temperature rise of the adjacent cold helium due to the compression by the expanding hot helium. The results for shots 2066 and 2069 are shown in Fig. 6. It is seen that in shot 2069, the temperature rise never reached the current sharing margin of $(T_{cs} - T_b)$, and no THQ was observed. In shot 2066, ΔT quickly exceeded $(T_{cs} - T_b)$, and THQ was observed within 1 s. The calculated maximum temperature rise, ΔT_{Max} for the selected shots were listed in the last column of Table 1 in comparison with $(T_{cs} - T_b)$. It is seen that $\Delta T_{Max} > (T_{cs} - T_b)$ for all the shots that THQ was observed and $\Delta T_{Max} < (T_{cs} - T_b)$ for all the shots that THQ was not observed. The existence of a threshold behavior in THQ is clear from this analysis.

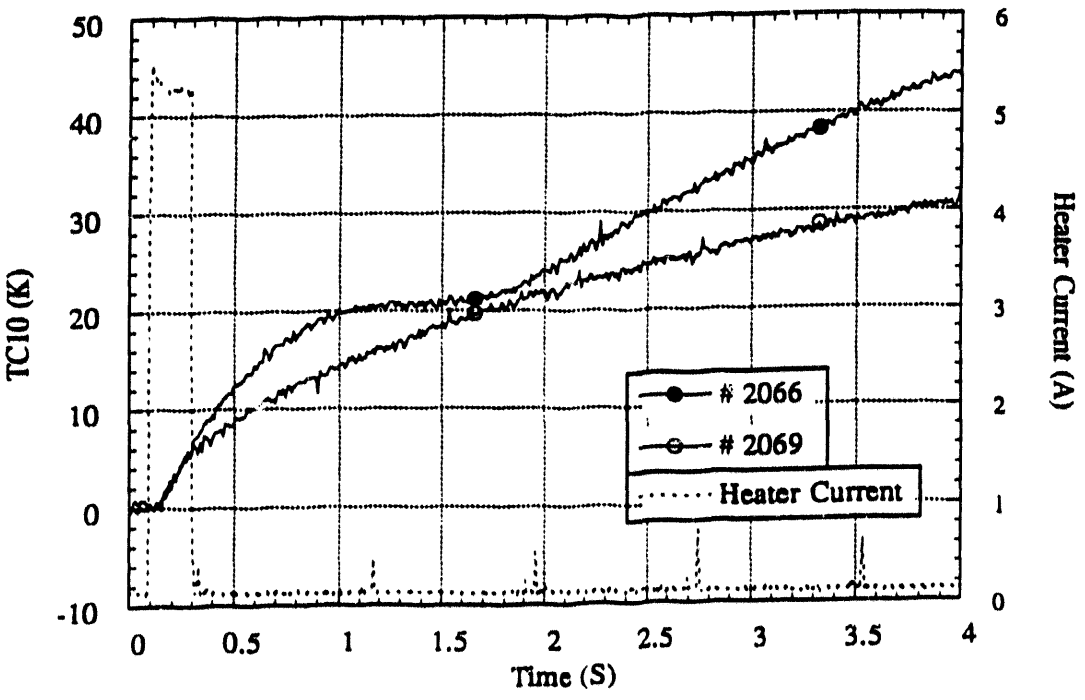

Figure 5. Examples of Temperature Excursion at the Heated Zone.

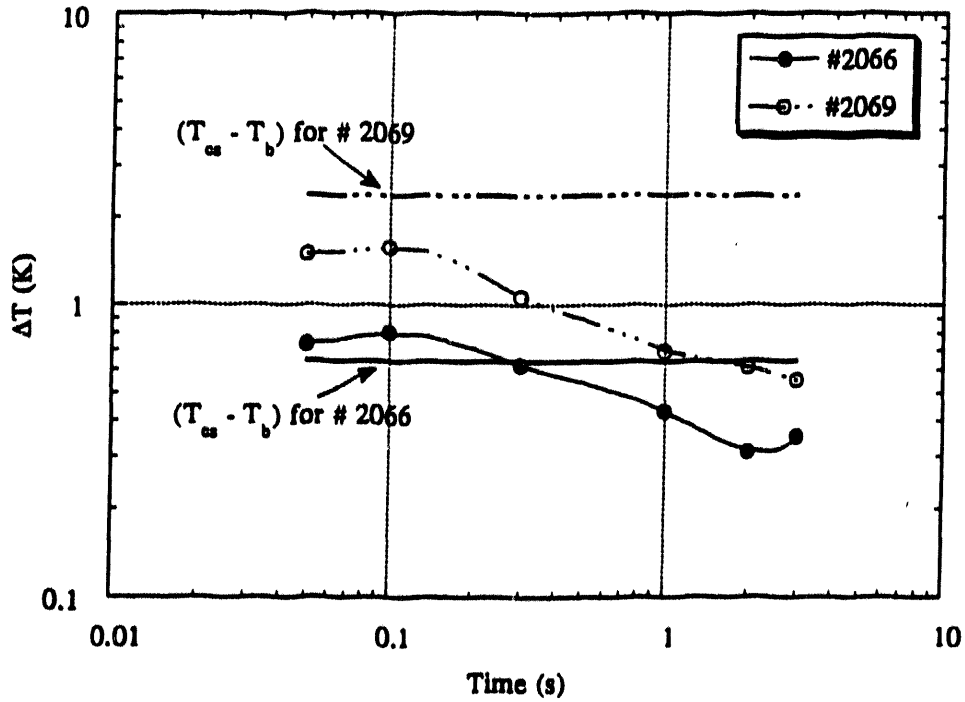

Figure 6. Calculated Temperature Rise in Cold Helium by the Compression of the Expanding Hot Helium.

CONCLUSION

The existence of thermal hydraulic quenchback was verified experimentally. When THQ occurred, normal zone propagation approaching the velocity of sound was observed. By varying the conductor current, the temperature, the heated length, and the external magnetic field, thresholds for THQ were observed. More detailed analysis of the experimental data and re-examination of the theory showed that this threshold behavior of THQ can indeed be accounted for by the theory presented earlier.

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