Abstract. We have created solid $^4$He from the superfluid at fixed temperature by adding helium to a cell of fixed volume through Vycor fill lines. Affixed to the cell are two capacitive pressure gauges. We monitor the P, T coordinates of the solid by use of a thermometer on the cell and the two $in situ$ pressure gauges. We observe apparently random, sharp pressure drops as the cell nearly fills with solid, and after the solid has finished growing and is off the melting curve. These pressure drops are accompanied by transient changes in the temperature of the cell. We will describe the details of the experiment and report on some of our measurements.

1. Introduction
Due to its quantum nature and simplicity, helium at low temperatures has historically received much attention. One of the most interesting aspects of helium is the growth of solid helium from the superfluid, where a quantum solid grows from a quantum liquid. Much of the work done in this area has focused on the nucleation of crystals in the liquid [1, 2], and on the growth kinetics of helium crystals [3, 4]. We report here on experiments done between 0.4 and 0.8 K that show the behavior of solid helium during and immediately following the completion of its growth. We observe events in the form of pressure drops and temperature transients during the growth and subsequent pressurization of hcp solid $^4$He grown from the superfluid. We will describe the apparatus and the solid helium growth technique, show the results and discuss aspects of the data.

2. Experiment and results
The cell used for these measurements is shown schematically in figure 1, and was the same as that used in a previous experiment to investigate a possible flow of mass through solid helium [5]. It consisted of a cylindrical copper chamber $S$, with volume $V_c = 1.84$ cm$^3$, used to grow the solid helium, with two capacitive pressure gauges, $C1$ and $C2$ for $in situ$ pressure measurements. The cell was cooled from below by connection to the mixing chamber of a dilution refrigerator. Three capillary fill lines led to $S$, two (1, 2) were heat sunk only at 4 K and led to the tops of Vycor rods $V1$ and $V2$. A third fill line (3) was heat sunk at 1 K, and led directly to $S$, bypassing the Vycor. Carbon thermometers were placed on top of the cell and at the top of the Vycor rods. The Vycor rods (1.52 mm in diameter, 76.2 mm long) were epoxied into thin stainless steel tubes and heaters, $H1$ and $H2$, were placed at the top of these stainless steel tubes. Inside the pores of Vycor the melting curve of liquid helium is elevated, which allows helium to remain a liquid at up to 10 bar higher than the bulk melting pressure [6, 7, 8]. In this way, using $H1$ and
H2 to keep capillaries 1 and 2 in the liquid portion of the phase diagram, we could continuously feed atoms into the cell not only while the solid was growing, but after it left the melting curve. The top of figure 2 shows a typical record of the growth of solid helium from the superfluid. In this example we start with the cell pressure at $\approx 22.5$ bar, and a temperature $T_{cell} \approx 415$ mK. We then simultaneously admit helium to capillaries 1 and 2 raising their pressure to 28 bar. As the liquid helium goes through the Vycor, the cell pressure increases until the melting curve is reached, at which point the solid starts to form, and is in equilibrium with the liquid. As the solid grows, the pressure stays constant on the melting curve, and we continue to feed atoms into S through both V1 and V2. Several times, beginning at about 1.6 hours, the pressure recorded by C2 leaves the melting curve and returns to it until the pressure recorded by C1 leaves the melting curve at about 2.5 hours. At this point the regions of the cell adjacent to C1 and C2 are presumed to be completely filled with solid helium. But, additional atoms are still being added to the cell through both Vycor rods. Since the solid is contained in a constant volume, its pressure increases. This general type of growth process occurs for each sample made at $T_{cell} \leq 500$ mK.

The bottom of figure 2 is an expanded view that shows changes in C1 and C2 and associated transient changes in the cell temperature as atoms continue to be added to the solid through both Vycor rods. At random times, C1 and C2 drop by a $\sim 10 - 100$ mbar. These drops are accompanied by transient increases in the temperature of the cell, usually between 1 and 5 mK. Most of the time, as at $t = 167$ minutes, these drops are visible on both capacitors. However, occasionally, such as at $t = 153$ minutes, we observe a pressure drop that is visible on C1, but less obvious on C2. Finally, in a few instances, such as at $t = 157$ minutes, the pressure drop is only very weakly resolved on one side of the cell.

Figure 1. Cell used for solid helium measurements: Vycor rods, V1 and V2; solid helium chamber, S; capacitance pressure gauges, C1 and C2, and heaters, H1 and H2, are shown.
Figure 2. Top: A record of the growth of solid hcp He\textsuperscript{4} from the superfluid showing the pressure of the solid in S during growth as measured on capacitors C1 and C2. Bottom: An enlarged view of the cell pressure as atoms are fed into S via both V1 and V2. A slowly changing background drift of T\textsubscript{cell} was observed and a polynomial vs. time was fit to the data and was point-wise subtracted from T\textsubscript{cell} to enhance visibility of the transients.

3. Discussion
Presuming for the moment that the transient temperature response represents the behavior of solid freezing on the melting curve, given the slope of the melting curve[9], a temperature rise of 5 mK at 400 mK would result in a pressure change of 0.09 mbar. We observe pressure drops in the range of 10 to 100 mbar and thus doubt that equilibrium liquid on the melting curve is responsible for these anomalies. These pressure drops, however, could be due to regions of metastable liquid embedded in the solid as it grows, which solidify. Such regions were thought to have been observed by Mikhin et al [10] and by Grigor’ev et al [11] on warming their samples near to the melting curve above 1.5 K. If we assume this to be the case even at our lower temperatures, then the accompanying temperature transients could be due to the latent heat of fusion released on solidification. If we take the event at t = 167 minutes in figure 2, and use the heat capacity of the copper cell, base and supports; the helium inside the cell; the
copper mixing chamber and the $^{3}$He - $^{4}$He mixture, and further assume that the temperature change measured on the cell is the same as in the mixing chamber, then we can compute that the energy released from the solid is at most $E \approx 3.4 \times 10^{-3} \text{ J}$ However, because the latent heat in converting liquid helium to solid helium below 1 K is so small[12], we would need a volume of liquid, $V_{l}$ that is several times $V_{c}$. If the mixing chamber is left out of the computation, we find $V_{l} \sim 0.4 V_{c}$, which is still too large considering that we observe several of these events.

If we assume on the other hand, that most of the energy is not coming from the latent heat, but rather from the work done by the sample on increasing the volume of solid helium, then we can estimate that a volume of $1.2 \times 10^{-3} \text{ cm}^{3}$ changed from liquid to solid for the event at $t = 167 \text{ min}$. This we can compare to an estimate of the amount of solid formed based on the observed pressure drop. Using the data at $t = 167 \text{ minutes}$ in figure 2 we conclude that a volume of $1.5 \times 10^{-3} \text{ cm}^{3}$ of liquid would have converted to solid. The difference between these two numbers can be attributed to our assumptions about how much total mass absorbed the released thermal energy. The fact that the two capacitors record different pressure drops is itself an interesting fact, which indicates stress formed and was retained in the solid.

In conclusion, we have observed random pressure drops accompanied by temperature transients during the growth, and subsequent pressurization of solid helium grown from the superfluid at $T_{\text{cell}} \approx 415 \text{ mK}$. We believe it likely that these pressure drops are associated with the solidification of supercooled liquid regions within the solid. We have shown that the observed temperature transients are consistent with the work done in the process. Furthermore, a possible connection can be made between these observations and recent experiments investigating the possibility of inducing a DC mass flow through solid helium [5, 13]. In these experiments no flow was observed at temperatures $\geq 600 \text{ mK}$, and several samples grown at 600 and 800 mK did not show any transient events during growth.

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