DYNAMX: A LOW TEMPERATURE MICROGRAVITY INVESTIGATION OF PHASE TRANSITIONS

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Abstract

The Critical Dynamics in Microgravity Experiment, DYNAMX, is under development for space flight at Sandia National Laboratories and the University of New Mexico with Dr. Rob Duncan as the Principal investigator. This experiment will investigate the effects on the superfluid transition in ^{4}He of currents generated by heat flow, measuring the thermal conductivity in the fluid as a function of applied heat. DYNAMX will also take advantage of the weightless environment to measure the conductivity properties in the region of the interface between the two phases, 'J'bus, DYNAMX represents an experiment that will explore a system drive.n far from equilibrium. The experiment development is sponsored by the Microgravity Science and Applications Division of NASA, with the Jet l'repulsion laboratory as the managing center. This paper will describe the science objectives, the current design of the experiment apparatus, the steps being taken to prepare this experiment for flight, and the results of gmund-based feasibility demonstrations now underwa y.

Introduction

The superfluid transition in pure liquid ^{4}He provides an excellent opportunity to test modern theories of second order phase transitions. The 4,Ie sample is ultra-pure, with only the ^{3}He i sot opc presenting an impurity, Typically this ^{3}He impurity level can be reduced to a pat-t in 10^9[1], and impurity levels as low as a few parts in 10^{12} have been reported [2]. Unlike solid samples which support vacancies and grain boundaries even in the high-purity limit, the ^{4}He near its superfluid transition is spatially homogeneous.

The order parameter in superfluid ^{4}He has two components, and it is often referred to as the 'wavefunction of the condensate', consistent with the psi-theory of superfluidity [3]. In most critical phenomena studies, the field conjugate to the order parameter creates a rounding of the transition. The ^{4}He superfluid transition is unusual in that the field which is conjugate to the order parameter is not physical[3]. Hence, the superfluid transition in ^{4}He remains sharp even in the presence of stray fields. Since the superfluid transition temperature varies with pressure (-113 Bar/K near SVP [4]), the superfluid transition varies with the hydrostatic pressure along the height of the ^{4}He column under Earth's gravity. To avoid these gravitationally-induced sample pressure gradients, extremely precise specific heat measurements in bulk ^{4}He have been conducted on Earth orbit in late 1992 [5]. Another specific heat experiment, one in a confined geometry where finite-size effects are measurable, is now under development for space deployment in 1997 [6].

Although the static critical phenomena near the superfluid transition are very well studied, very little is known about transport properties through criticality in this system. This is unfortunate, since in nature virtually all phase transitions occur while being driven far away from equilibrium conditions. Hence a first-principles understanding of critical phenomena under highly nonequilibrium conditions is of fundamental importance to virtually all real-world processes. In transport measurements the system is held out of equilibrium and maintained in an exceptionally well controlled steady-state condition. The thermal gradients very near the normal fluid - superfluid interface (HeI-HeII) are then measured with subnanokelvin resolved thermometry [7]. Under gravity the position of the HeI-HeII interface may be set (or maintained) by adjusting (or regulating) the temperature of the superfluid component. This superfluid component is isothermal in the low heat flux (Q) limit, which is realized in our experiment. On Earth orbit this interface should be stabilized by the heat flux as predicted by theory [5].

Scientific Motivation

Recently, dynamic renormalization group theory has been applied to predict the thermal profile through the HeI-HeII interface subjected to a heat flux Q [9]. This theory predicts that the effective thermal conductivity of the HeI will not diverge, but rather will approach a constant value which itself is strongly dependent on Q, as $T \to T_\lambda$. If this prediction is realized experimentally, it will constitute the first carefully controlled study of how a system's linear response to an external heat flux breaks down near criticality, resulting in a non-ohmic thermal conductivity. This theory [9), and another theory based primarily on a dynamic scaling approach [8], predict that the width of the HeI-HeII interface shall decrease with increasing heat flux as $1/\sqrt{Q}$. Since this interfacial width is essentially the correlation length at the superfluid transition temperature $T_\lambda(\xi(T=T_\lambda))$, these measurements would provide us with the first well controlled measurement of how the correlation length in a system at criticality varies with the non-equilibrium parameter (in our case the heat flux Q).

Both the renormalization group theory [9,10] and the dynamic scaling theory [8] have predicted a depression of the superfluid transition temperature T_λ with the heat flux Q. This effect, which is analogous to the depression of a superconductor's transition temperature T_c with an electric current I, has been observed experimentally [11], and only small discrepancies exist between the theory and the experimental result. The dynamic renormalization group theory for the thermal profile through the HeI-HeII interface under a heat flux [9] references only T_λ in the $Q=0$ limit, and it makes predictions for the thermal profile only down to $T_\lambda(Q=0)$. For small Q, the helium is isothermal below $T_\lambda(Q)$[11]. The nature of the thermal profile within the helium at temperatures $T_\lambda(Q) < T < T_\lambda(Q=0)$ is as yet unknown. Its determination remains an exciting challenge to both theory and experiment.

Measurement of the bulk helium properties described above are plagued by the presence of the experimental cell's endplates, especially very close to the superfluid transition temperature where these boundary effects diverge. The thermal resistance between superfluid helium and a solid (usually metal) endplate, which is referred to as the Kapitza resistance, has been observed to be weakly singular at T_λ and to exhibit a sudden onset to a strongly non-ohmic (Q-dependent) region which then saturates at a Q-independent value very close to T_λ[12,13, 14]. Only the origin of this weak Q-independent singularity has been explained theoretically[15]. Although it is much more difficult to measure the thermal boundary resistance between normal fluid helium and the endplate, initial experiments [15, 16, 17] suggest that singular (and possibly Q-dependent) boundary resistance exists on this side of the transition as well. The depression of the superfluid transition temperature with a heat flux (mentioned above) was measured with the HeI-HeII interface forming at the bottom endplate of the cell [11]. This proximity to the cell end plate could be the reason for the discrepancy between the theoretical predictions [9,10] (which assume bulk helium) and the experimental results. Clearly future experiments must be conducted to determine whether this is so. Theoretically, these singular boundary effects are predicted to fall off exponentially into the helium from the endplate with a characteristic length of the bulk correlation length ξ. Since these boundary effects become pronounced at much larger reduced temperatures than do the nonlinear bulk effects, they are often more than an order of magnitude larger than the predicted bulk nonlinear helium properties [9] we wish to study experimentally. Since we hope to make at least a 1 % measurement of these bulk nonlinear properties, we must make our measurements at a distance at least 10ξ from either cell endplate. A reduced temperature $t = (T- T_\lambda)/T_\lambda = 109$ may be realistically maintained in this experiment. At this reduced temperature, $\xi \approx 0.22$ mm, and the 10ξ rule would mandate that the measurements be made at least 2.2 mm from the endplates. In the experimental cell described below we have placed a thermometry stage at 7 mm from the cell endplate. This immediately sets an upper bound on Q, since this 7 mm layer of normal helium must not be allowed to convect. Based on the results of helium convection experiments [18] this limits us to Q s 3 $\mu W/cm^2$ in this experiment while on Earth.

Need for Microgravity

Experiments-performed under gravity have qualitatively (but not quantitatively) confirmed the existence of the nonlinear thermal conductivity region predicted by theory [19]. These measurements *were* made in small cells to avoid the convective onset. Hence, it appears to be very difficult, if not impossible, to conclusively separate out the singular boundary effects from the nonlinear bulk thermal conductivity effects in these measurements. in these measurements only the helium very near the cold endplate of the cell was in the nonlinear region, while the remaining helium was in the linear region due to the thermal gradient across the helium layer. More data must be taken in order to systematically separate out the singular and nonlinear boundary effects from the nonlinear bulk effects under study. Only then can a conclusive test of the theoretical predictions [9] be performed. in order to observe other predictions from theory, such as the Q-dependence of the interface width (and hence of $\xi(t=0)$), it is necessary to measure the actual thermal profile near and through the HeI-HeII interface with the highest possible thermal and spatial resolution. Only microgravity conditions sustained over many days will permit these effects to be conclusively studied experimentally.

One concern motivates the microgravity requirements for the static (specific heat) experiments[5,6], namely the need to avoid the pressure-induced sample nonuniformity. For heat flux $Q \leq 0.1 \mu W/cm^2$, this same concern applies to the dynamic measurements. At these small values of Q the pressure-induced variation in T_λ pushes the system away from criticality more than dots the resulting thermal gradient in the normal fluid. At the opposite extreme, values of $Q > 3\,\mu W/cm^2$ create such a large thermal gradient in a 0.7 cm cell that they trigger the onset of convection in the normal fluid on Earth, thereby destroying our ability to measure the normal state's diverging diffusive thermal conductivity. Microgravity would permit much higher values of Q to bc used.

The width of the HeI-HeII interface has been predicted to vary inversely with the square root of Q [8,9]. Under gravity this width cannot bc directly measured since the gravitational field reduces the initial width of the Q= O interface to only a few tens of micrometers. On orbit, this initial Q= O width has been predicted [8] to increase to about a millimeter. Such a width would make measurements of the Q-dependent interfacial thickness practical.

Experiment al

All the measurements described above will bc conducted within an all-aluminum experimental cell shown in Figure 1. The sidewall platforms 3 and 2, located .25 mm and 7 mm from the warmer endplate, will bc used to measure the temperature profile as the interface is positioned at multiple locations very close to each ring. Measurements taken with platform 3 will bc affected by the nearby cell endplate near criticality, while measurements taken with platform 2 will not. Platform 1, located about 14 mm from the warmer boundary, will be used to reference and control the temperature of the superfluid phase, and to check for any thermal gradients in the superfluid at the higher values of Q. At each position the interface will remain stationary until steady-state conditions are obtained.

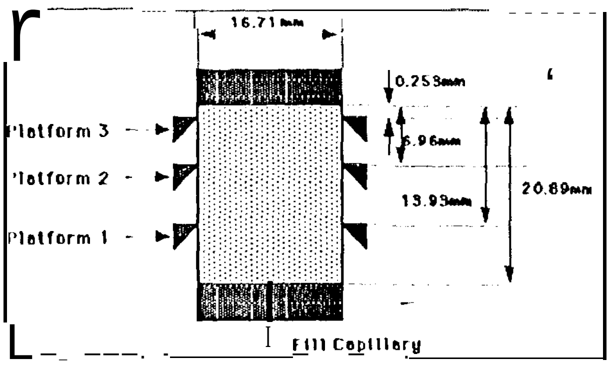

Figure 1 : The experimental cell constructed for these measurements. On Earth the cell is mounted with its fill capillary up. The heat flows from the bottom to the top to avoid convection (the isobaric thermal expansion coefficient is negative near T_λ). Both on Earth and on orbit the endplate with the capillary will bc the cooler end of the cell.

The insulating sidewalls of the cell arc constructed of aluminum alloy 5456. Although wc know of thermal conductivity measurements in this alloy only down to 20K, the thermal conductivity of aluminum alloy 5083-0, of a similar composition, has been measured down to 4K [20]. Extrapolating these values down to 2.2K results in an expected conductance of about 12 mW/cmK. The isothermal cell endplates and the thermometry stages located along the cell's length arc made ofultra-pure (99.999-I %) aluminum which is expected to have a thermal conductivity y of about 80 W/cmK [20]. This all-aluminum cell construction provides two major advantages over conventional cell designs. First, since the cell is entirely aluminum, it may be e-beam welded. Unlike solder or epoxy joints, these all-aluminum welds arc unaffected by differential thermal contraction on thermal cycling so they arc extremely rugged and reliable. Secondly, this all-aluminum construction has only about one-third of the total cosmic ray absorption cross-section of that of a copper and steel cell construction. This cell construction will result in low parasitic heating from the cosmic flux once the apparatus is on orbit.

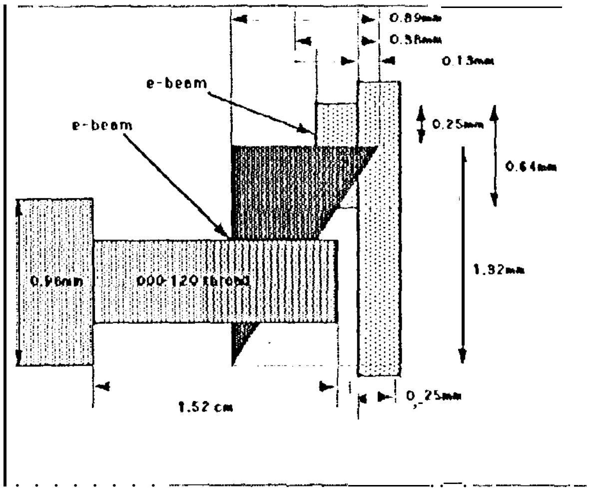

Figure 2: The cell sidewall thermometry platform design and construction, shown in cross-section. The ultra-pure aluminum thermometry platforms arc rings with a pointed inner diameter. They are pressed into a mating groove with a collet while they arc electron-beam welded in place. An ultra-pure aluminum wire (shown to the left) which is threaded into the platform is used to thermally connect the platform to a thermometer a few centimeters below the cell.

The cell thermometry stage design is illustrated in Figure 2. Each stage is constructed by machining two circular rings with a taper to produce a sharp edge on the inner diameter. One ring is then tapped to a 000-120 thread at one position on the ring's circumference. A 99.999-I % pure, 1 mm diameter aluminum wire is threaded into this 000-120 threaded hole and welded in place. This wire makes the thermal contact between the platform and the thermometer. The rings arc then split using a wire electric discharge machine. The cut is offset from the ring's diameter by the thickness of the wire's cut (about 70 pm) so that, when mated to the sidewall of the cell, the ring will be continuous around the sidewall's circumference. The insulating wall is thicker in the region of the sidewall stage to allow a groove to be machined into the wall with a precision-ground tool which has the same taper as the sidewall probe ring itself. This allows the groove to position precisely this sidewall probe ring; the c-beam welding process dots not set this position. Typically, the height variation of the sidewall probe ring is only about ±8 μm from its intended height.

The pressure of the helium sample must be maintained to within about 10-3 Pascal to assure that pressure fluctuations do not create any more than a 0.1 nK fluctuation in T_λ. A new method of superconductive pressure regulation, using the magnetic (Meissner) pressure exerted against a thin membrane to actuate pressure changes isothermally, is currently under development as a collaboration between Sandia/UNM and the Low Temperature Group at JPL. Other methods, such as the use of a vapor bubble to maintain saturated vapor pressure conditions, are also being considered. However, these bubble techniques are very difficult to use in transport experiments in microgravity conditions.

Very high thermal resolution near T_λ and exceptional spatial resolution at thermometry stages located along the sidewall of the cell are required to definitively observe the nonlinear thermal conductivity regime discussed above. Thermometers, similar in design to those developed at Stanford University within Prof. John Lipa's group [7] have been manufactured for this experiment by lb-. “l’also Chui, Dr. Peter Day, and Dr. Al Nash of JPL. These thermometers differ from the Stanford design only in that they arc fabricated using aluminum (rather than copper) for better cosmic ray immunity once on orbit. Similar (copper) thermometers have achieved a noise level of 0.2 nK in a one Hertz bandwidth, and a drift rate of less than 0.1 pK/s, near $T_\lambda = 2.1768$ K. These thermometers, with noise levels approaching the statistical limit of thermometry [21], provide adequate thermal resolution to make the measurements described above. The spatial resolution of the thermometry is greatly affected by the construction of the sidewall probe rings discussed above. The performance of these probe rings has been extensively modeled in order to optimize the design, and to take into account the small variation (A) between the physical height of the probes and their effective thermal height. This thermal height will be very sensitive to the probe design and construction, and for a fixed probe design it will vary with temperature and the heat flux, as described below.

Thermal Simulations

In all the thermal simulations discussed here, the normal fluid helium bulk thermal conductivity λ is approximated [22] as $\lambda(t,Q) =- [\lambda^{-4}(t,0) + L'(O,Q)]^{-1}$" where the zero-Q thermal conductivity is approximated [16] as $\lambda(t,0) = (122.2 + 7.05\, t^{-0.48})\,\mu W/cmK$ and the $t = O$ limit of the thermal conductivity is taken as its theoretical value [9] as $\lambda(0,Q) = 27{,}400 \times Q^{-0.31}\,\mu W/cmK$ where Q is in units of $\mu W/cm^2$. In the equations above, the reduced temperature is defined relative to $T_\lambda(Q = O)$.

For $T < T_\lambda(Q = O)$, the superfluid phase, the helium is forced isothermal by selecting $\lambda(\text{superfluid}) = 10{,}000$ W/cmK. Clearly, thermal gradients exist in the helium for $T_\lambda(Q) < T < T_\lambda(Q = 0)$. However, these gradients have yet to be measured carefully and no theoretical guidance is available across this temperature range. This isothermal restriction below $T_\lambda(Q = O)$ must be relaxed once a more detailed knowledge of this profile becomes available. in these simulations the thermal conductivity of the aluminum alloy 5456 is taken to be 0.01 W/cmK and the conductivity of the 99.999-I % pure aluminum is taken to be 100 W/cmK. The actual thermal conductivity of the materials used to fabricate the cell will be measured soon; however, these initial simulation numbers arc expected to be within ±30% of the true values. The thermal boundary resistance R_k between all metal surfaces and the liquid helium is taken to be constant at 0.4 cm^2K/W. The next level of simulation will include the known variation of R_k with t and Q [12,13,14]. however, the maximum value of R_k is not expected to exceed about 1 cm^2K/W, and the simulations arc not very sensitive to this parameter. In the simulations which follow, the HeI-HeII interface is forced to remain at some height δ above the sidewall thermometry platform. The helium sample is isobaric: No gravitationally-induced pressure variation along the column of helium is taken into the model, consistent with on-or-bit conditions.

A simulation of the thermal profile near the sidewall platform ring is displayed in Figure 3. Here the HeI-HeII interface is located at $\delta = 50\ \mu m$ above the platform ring and normal fluid exists at the position of the platform. A constant heat flux Q: 0.1 $\mu W/cm^2$ flows through the cell from the bottom to the top (see Figure 3). Notice that the radial thermal gradient in the cell is large within about 1 mm from the sidewall. The temperature read by the sidewall platform ring differs from the helium temperature near the center (r- O) of the cell. The helium temperature near the center of the cell, where no radial temperature variation is noticed, is taken to be the true bulk helium thermal gradient since it shows no sensitivity to the measurement apparatus at the sidewall (which is at r = 8.35 mm). We determine A graphically as displayed in Figure 3. Once these corrections have been applied, it should be possible to maintain the thermometer's thermal position to about ± 10 pm, which is predominantly limited by the machining accuracy of the sidewall platform's physical position (± S pm), and not by uncertainties created by the thermal offsets.

Although virtually no heat is generated or absorbed in the thermometry platform, the abrupt change in the sidewall's effective thermal conductivity in the vicinity of the platform creates a radial component of the heat flux which perturbs the otherwise purely axial heat flux through the cell. This radial heat flux, when integrated over the entire cell, must equal zero since neither sources nor sinks are present on the platforms. Through many simulations, we observe that this radial heat flux perturbation may be minimized by placing the tip of the thermometry platform well away from the helium space, recessed in the low-conductivity sidewall. 'he effect of the thermomet ry platform's shape, of the depth of penetration, and of the proximity to an endplate has been simulated and reported previously [23]. For our design displayed in Figure 2, simulations show that this radial heat flux may become as large as 43% of the total Q = 0.1 $\mu W/cm^2$. However, this large radial heat flux exists over only about a 100-}lnl distant.c on either side of the interface. The result is the sizable radial gradients displayed in Figure 3 which are accounted for in the values of A obtained from the simulations described above.

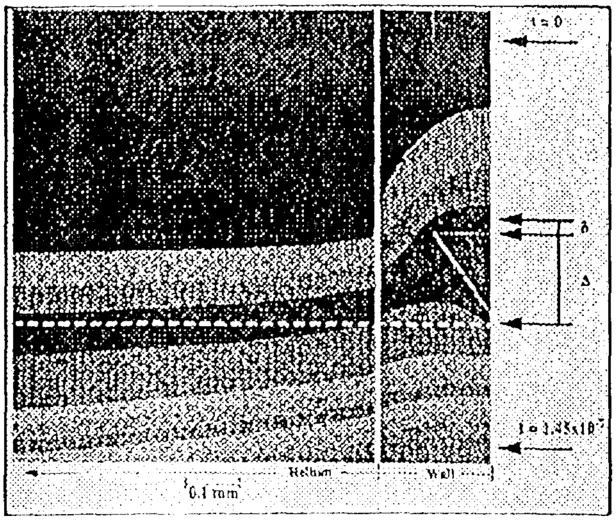

Figure 3 : Results of the thermal simulation for the temperature profile near a cell sidewall thermometry platform which samples the bulk helium. Here Q = *0.1* $\mu W/cm^2$ (flowing from bottom to top) and the HeI-HeII interface is located a distance δ = 0,05 mm above the top of the platform. Each change in gray scale indicate.s a 10"8 change in the local reduced temperature t. The solid black region at the top of this figure corresponds to t: O. The value of Δ is determined graphically by determining the height of the helium at the center of the cell which is isothermal with the platform (the dashed white line), and subtracting this height from the physical height of the platform. This A is non-zero only in regions where a radial component of the heat flux exists,

Development

DYNAMX development is following the science and technology feasibility demonstration model established by NASA's Microgravity Science and Applications Division's workshop in November 1992. This model emphasizes science-led development of ground apparatus, test equipment, and procedures to demonstrate the proposed science as limited by 1 g. Proceeding in this manner allows surprises (mistakes) to be found early in the process where they arc easily and quickly correctable. Continuous science peer review throughout this definition phase ensures mature science concepts, strong correlation of hardware with objectives, and justification for the need to go to space. Collection of data from instrumented ground apparatus provides for verification of thermal and performance models and determination of error sources and performance requirements which arc key to experiment success.

This approach contrasts with the traditional method of forming an engineering and science design team which developed functional requirements, preliminary designs, and implementation plans. This paper approach often leads to a false sense of design maturity and significant cost and schedule overruns can occur when wel- documented but erroneous untested assumptions are discovered late in the flight hardware development process.

For DYNAMX, the definition phase challenges were to build the experiment cell and the thermal and pressure control systems, plus the servicing devices required for its operation; to collect data; and to compare results with theoretical models and results from other ground studies.

Specifically, the DYNAMX team was required to build a nanokelvin thermal and nanotorr pressure control platform with cryogenic and electronic feedthroughs to a newly conceived 99.999%-pure aluminum cell. Cell temperature will be controlled by fractional nanowatt heaters at each end and temperatures will be measured by three high resolution thermometers attached along the cell walls with 10"]0 K resolution. To test this design the science team also needs to develop a low temperature laboratory, including a screened room, dewar, liquid and gas servicing lines, and laboratory support hardware and software.

This challenge was met by combining the strengths of Sandia National Laboratory (SNL), University of New Mexico (UNM), Jet Propulsion laboratory (JPL), and the low temperature science community. Precise machining, development of cell thermal performance models, and cryogenic valve design were performed by SNL. High resolution thermometers were developed at JPL and delivered to SNL for integration with the cryoprobe. A pressure regulator was designed by the UNM and delivered to JPL for testing. All team members contributed to the development of the ground laboratory at the UNM. Collaboration with ground experimenters such as Profs. Gunther Ahlers and John Lipa and theorists such as Profs. Volker Dohm and Rudolph Haussmann further strengthened DYNAMX experiment definition and demonstration. A review by the Low Temperature Science Steering Group found the science of exceptional merit and verified the need to go to space.

In November 1994 the cryoprobe and cell were cooled twice to liquid helium temperatures. The first cooldown isolated typical leaks associated with cryogenic work and the second verified thermal performance and provided the first thermal conductivity data. The pressure regulator developed in parallel completed its first test, was redesigned and is in retest.

Work is proceeding on schedule to an October 1995 confirmation of science feasibility and technology demonstration known as a Science Concept Review (SC]<). A successful SCR will be followed one year later with a final Requirements Definition Review (RDR) when a final decision will be made whether to proceed to flight.

Flight development is scheduled to begin in October 1996 and will involve the same team members with the addition of Industry participating as a full partner. SNL will develop the flight instrument, using industry and JPL developed flight-qualified sensors. The operational instrument will be delivered to JPL for integration with the existing low temperature platform currently supporting the flight of the" Confined Helium Experiment (CHeX). The integrated system will be functionally, performance, and environmentally tested, and then will be shipped to Kennedy Space Center for integration with the carrier and the Shuttle Orbiter. Launch on the fifth United States Microgravity Payload is scheduled for late 1999. Experiment operation begins a few hours after launch and continues for about 10 days. Experiment operation will be interactively controlled from SNL using telescience interaction to enhance the science data return.

in general the MSAD development model is working well. Problems have been dct cct ed early and were quickly resolved in the research laboratory environment. The combination of science and engineering personnel emphasizing science with just enough programmatic for organization have created a single focused team from three diverse organizations, Achieving a real understanding of the experiment and its requirements and building a strong integrated team arc exactly the products MSAD had in mind with the new development model. This model will be further proven during development of the flight system.

Conclusions

Strong scientific motivation exists to study the nature of continuous phase transitions in a system driven well away from equilibrium in a carefully controlled fashion. Technology is now under development which should permit such measurements on Earth orbit before the year 2000. Clearly, microgravity conditions arc required to fully explore the validity and ramifications of recent predictions near the superfluid transition in pure ^{4}He.

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