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A Refrigerated Dewar for the Josephson Array Voltage Calibration System

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***Abstract*—A refrigerated dewar has been used successfully with the Josephson array voltage calibration system. It has been used to reliquify helium with no degradation of the calibration system's performance. The independence of the array voltage from temperature has been confirmed to three parts in 10^8 per kelvin over the range 1.6 K $\leq T \leq$ 4.6 K. No significant change in the array operation on a quantized state near 1.018 V was detected when its surrounding bath was pumped superfluid, nor when it was cooled by helium vapor at 4.6 K.**

INTRODUCTION

SERIES arrays of Josephson junctions have been developed which are capable of producing quantized voltage levels over a wide voltage range [1]. These arrays have been used in a voltage calibration system since February 10, 1987, to maintain the U.S. Legal Volt [2] at the National Institute of Standards and Technology (NIST, formerly NBS). A similar system within the Primary Standards Laboratory (which is operated for the Department of Energy, Albuquerque Operations Office by Sandia National Laboratories (SNL) has been in operation since July 1989. Complete automation of these and other such systems will require the development of an automated cryogenic subsystem. Here we present details on the design and performance of a new refrigerated dewar to maintain the Josephson junction array near 4K with no liquid helium loss and no routine operator intervention. No degradation in the stability of the array-based voltage calibration system was noticed while it was used with the refrigerated dewar, even when re-liquifaction of helium was underway. Careful measurements of the quantized array voltage near 1.018 V were made over a wide temperature range to confirm the expected independence of the array voltage from temperature, and in so doing to insure that the refrigerator temperature would not systematically affect the array voltage standard.

SYSTEM DESIGN

The refrigerated dewar design is displayed in Fig. 1. It was manufactured for SNL by the Research and Manufacturing Co., Inc. (RMC) of Tucson, AZ. The dewar's helium space consists of a 3.81-cm diameter neck, a 25.4-cm diameter belly section with a 15-l capacity, and a 4.45-cm diameter tail section, all made of stainless steel. The liquid helium region is surrounded by two coaxial copper heat shields which attach to the neck at their appropriate positions. Each shield is wrapped with a few turns of thin metalized plastic. The outer heat shield is cooled to about 60K by the first stage of a Gifford–McMahon cycle (GM) refrigerator. The second stage of the GM cools the inner shield to about 17 K. A Joule-Thomson cycle (JT) loop then provides in excess of 1.5 W of useable refrigeration power to the liquid helium bath through an annular heat exchanger located at the top of the belly region. The temperature of the liquid helium in the belly can be varied from 3.8 to 5.2 K by varying the regulated return pressure on the JT line. Thermometers are located on the two heat shields, the JT expansion nozzle, and on the tail section of the dewar. Their temperatures are read out by a controller which may be automated over an IEEE-488 bus. The flow rate of helium gas in the JT loop is monitored by a flow meter with a digitizable analog output. Finally, the compressor's supply tank pressure may be monitored through the analog output of a pressure transducer. Hence all parameters critical to the performance of the refrigerated dewar may be computer monitored. If necessary the JT return line pressure regulator can be computer actuated, resulting in fully automated temperature control of the dewar. The thermometer in the tail section of the dewar is located 8.9 cm above the bottom of the helium space, which places the thermometer at the same height as the array during voltage calibrations. Consequently this thermometer will accurately read the array temperature even if a vertical temperature gradient exists in the column of liquid helium.

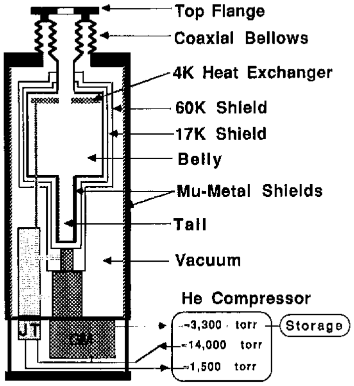

Fig. 1. Refrigerated dewar design. The compressor is located 15 m from the dewar during operation.

A set of coaxial bellows separates the top flange from the neck of the dewar. This permits the apparatus mounted on the top flange to be mechanically isolated from the rest of the dewar which is rigidly mounted to the refrigerator. Two coaxial mu-metal shields were located in the dewar to protect the array from stray magnetic fields. One was located next to the outer

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wall of the vacuum space while the other was located within the helium space in the tail section of the dewar.

The array used in this work contains 2076 Josephson junctions connected in series [1]. It was manufactured at NIST in Boulder, CO, on February 4, 1987 and was numbered 211-03. The SNL array voltage calibration system is quite similar to the NIST system [2]. Only the differences between these systems are mentioned here. The SNL system utilizes a probe which features cryogenic filtering, and a lower heat loss than conventional probes which also use metal waveguides [3]. The SNL system operates with the dewar pressure approximately 50 torr above ambient, while the NIST system operates near ambient pressure. Here the array temperature in the SNL system was about 70 mK warmer than the NIST system when they were both operated side-by-side in Gaithersburg, MD. The SNL system uses an automated switch while the NIST system uses a manual switch to inter-compare the array and unknown voltages. The measurement procedures described in [2] are identical to those used in this paper, except that these data were taken manually during development.

RESULTS AND DISCUSSION

The entire SNL array system was transported between Albuquerque, NM, Gaithersburg, MD, and Tucson, AZ, during 1989. The SNL system was operated with the refrigerated dewar only in Tucson. The results of using the SNL system to calibrate a single DC voltage reference over the last year are displayed in Fig. 2. Both the SNL system and the dc reference appear to transport nicely, as evidenced by the good repeatability between the different locations. While in Gaithersburg, the SNL system was compared with the NIST system. Both systems and the dc voltage reference of Fig. 2 were located in the NIST screen room. The dc reference voltage was measured throughout a 100-h interval, with the two array systems taking turns making the measurements. Only one calibration system was attached to the voltage reference at a time. Both systems experienced the same 0.01-μV scatter (1 sigma) during 12 calibrations of this 1.018-V reference, as displayed in Fig. 3. Each calibration followed the procedure described in [2] and consisted of 200 s of data averaging. The SNL system was found to read 0.026 μV below the NIST system, and hence a 0.026-ppm difference has been taken into account for the SNL system calibrations. The source of this difference has not been determined.

The refrigerated dewar was used with the SNL system in Tucson to check for any dependence of the quantized array output voltage on its temperature. The dc reference of Fig. 2 was calibrated five times within a 13-h interval and with the array at different temperatures on day 318. The dc reference of Fig. 2 displayed a drift in its norminal 1.018 V output of -0.005 μV per day from day 318 to day 391, during which time it was used with the refrigerated dewar. The array temperature was set by varying the JT return pressure. The array was biased with 83 440 600 000(5) Hz radiation, and the $n = 5900$ step of the array was used to create a quantized array voltage of 1.018002194 V, using the $2e/h$ value of 0.483593420 GHz/μV (which was the NIST accepted value prior to 1990). The results of these five measurements are shown in Fig. 4. No systematic variation of the array voltage with temperature was detected. These measurements were taken as the array temperature was raised, lowered, and raised again. This indicates that any temperature coefficient of the array voltage must be less than 0.03 μV/K over the range $3.94 \text{ K} < T < 4.59$ K. The 4.35(1) K measurements in Fig. 4 were made at 1.0 bar and 1.7 bar, and no systematic variation of the array voltage with pressure was detected. Two similar measurements were made at the University of New Mexico (UNM) in Albuquerque two months later. They were taken at 1.56 and 4.48 K and displayed no systematic temperature variation, consistent with the previous measurements. Differences in the helium bath temperatures between NIST and SNL array calibration sytems cannot account for the 0.026-ppm discrepancy displayed in Fig. 3.

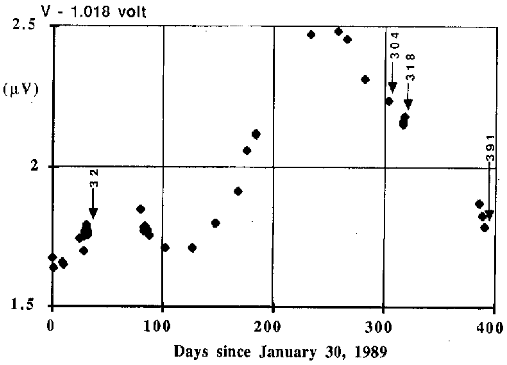

Fig. 2. SNL array system calibrations of the voltage reference versus time. The data were taken at NIST through day 32, at SNL through day 304, at RMC through day 318, and at UNM through day 391.

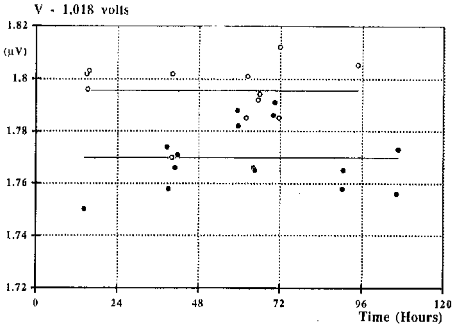

Fig. 3. Comparison of the SNL system (solid dots) to the NIST system (open dots) which is used to maintain the US legal volt. These data were taken in collaboration with Richard Steiner of NIST.

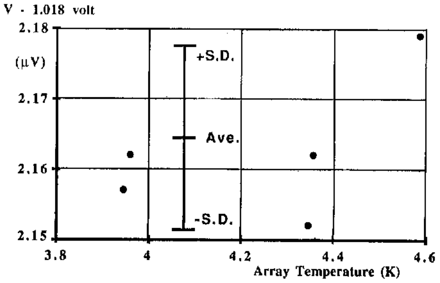

Fig. 4. Temperature-independence of the array voltage. The calibration system noise level is indicated.

The measurement at 1.56 K was taken with the surrounding helium bath in is superfluid phase. This dramatic improvement in the bath's thermal conductivity did not effect the stability of the array or the value of its quantized voltage output. The bath superfluid transition did, however, slighly reduce the noise level in the array's dc electrical characteristics [4].

At 4.6 K the array was operated with no liquid helium in the dewar. The array was surrounded by helium vapor at 4.6 K which was cooled by the 4.2 K heat exchanger at the top of the belly region. This convecting helium vapor provided sufficient cooling to keep the array stable at a quantized voltage output near 1.018 V.

This refrigerated dewar is capable of producing over four liters of liquid helium from room-temperature gas per day. Calibrations using the array voltage standard were not disrupted by helium liquifaction. Hence, ^{4}He gas may be recovered from other cryogenic apparatus (i.e., a cryogenic current comparator or a quantum Hall effect resistance standard) and re-liquified by this refrigerated dewar. With all refrigeration to this dewar off, the steady state liquid helium loss rate was less than 2 l per day.

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