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On-Orbit Measurement of the Superconductive Transition Temperatures of $YBa_2CU_3O_{7-x}$ Thick Films

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On-Orbit Measurement of the Superconductive Transition Temperatures of $YBa_2Cu_3O_{7-x}$ Thick Films

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Abstract—Thick film superconductors were integrated into hybrid circuits and tested in the Materials In Devices As Superconductors (MIDAS) spaceflight experiment which operated autonomously aboard the Mir space station for 90 days. MIDAS was designed to cool the circuits from 300 to 75K, maintain the temperature at 75K for 28 days, and warm the circuits back to 300K. This cycle was performed a total of three times, during which the superconductive transition temperature was measured during each cool-down and warm-up portion of the experiment. All of the thick films used in this experiment exhibited superconductive transition temperatures of approximately 87K, and no significant differences in the resistance versus temperature properties of the materials were observed among the data collected during pre-flight, flight, and post-flight operations.

Keywords: high temperature superconductivity, thick films, hybrid circuits, space-flight, MIDAS

Introduction

Since the discovery [1] of superconductivity above 77K in $YBa_2Cu_3O_{7-x}$ ceramics, several applications of these materials have been proposed for use in spacecraft systems. These applications include electronic devices (e.g., antennas and microwave resonators) [2], infrared detectors [3], and electrically conductive, thermally insulating sensor leads [4]. In each instance, the use of a superconductive device would either increase the performance capability or reduce the size of the payload. Furthermore, the increased use of cryogenics in space systems [5] provides an operational environment well-suited for the insertion of superconductive devices because the low temperatures necessary for superconductive operation are an integral part of these instrument designs.

To date, researchers have successfully produced both thick and thin film superconductive devices using conventional manufacturing techniques. Thick film superconductors have been deposited onto polycrystalline ceramic substrates such as Al_2O_3 and ZrO_2 using traditional screen printing processes [6-7]. These materials typically possess critical current density, J_c, values on the order of 100 A/cm^2 [8-9]. More recently, thick film superconductors have been integrated into multilayer hybrid circuits containing thick film conductors (e.g., gold) and insulators as well as surface mounted electronic components [10].

Thin film superconductors have been successfully produced using several vacuum deposition processes including sputtering [11], laser ablation [12], and vapor deposition [13]. These materials are typically deposited onto single crystal substrates such as (100) $SrTiO_3$ and (100) $LaAlO_3$ which have lattice constants similar to that of $YBa_2Cu_3O_{7-x}$. The similarity of the lattice constants allows the growth of superconductive films with the c-axis perpendicular to the substrate. Because of the preferred orientation within thin films, these materials have been reported to exhibit J_c values in excess of 1×10^6 A/cm^2 [14].

Although several opportunities exist for the inclusion of superconductive devices in space-based systems, no data describing the performance of these materials over time while in space is currently available. To assess the performance of thick and thin film superconductors in a space-based system, the Materials In Devices As Superconductors (MIDAS) experiment was developed and launched aboard STS-79. MIDAS was then transferred to the Mir space station and installed aboard the Priroda module, where measurements of the superconductive transition temperature and critical current density were made continuously over a 90-day period. This report compares the resistance versus temperature properties of $YBa_2Cu_3O_{7-x}$ thick films measured during pre-flight, flight, and post-flight operations of the MIDAS experiment. The performance of the thin film specimens will be described elsewhere.

Experimental Procedure

MIDAS Payload

The MIDAS experiment is a science payload which evaluates the electrical properties of high temperature superconductors in space. MIDAS was designed to operate autonomously, measuring the resistance versus temperature and critical current properties of these materials over a 90-day period and storing the data electronically. The electrical characterization of the superconductive materials was performed over three 30-day intervals. Each of these measurement cycles included a cool-down from 300 to 75K, a period of 28 days at a constant temperature of 75K, and a warm-up from 75 to 300K. Resistance versus temperature data was collected during each cool-down and warm-up phase of the experiment, and the critical current density of each superconductor was measured once every 30 minutes while at 75K. After a two-day inactive period, this cycle was repeated until it had been performed a total of three times.

The major subsystems required to cool the superconductive materials and to characterize their electrical properties are: (1) a set of four hybrid circuits containing both superconductive and conventional electronic devices; (2) a vacuum chamber, ion pump, and cryocooler; and (3) a data acquisition system capable of performing d.c. four probe resistance measurements (i.e., sourcing current and measuring voltage) and storing the data gathered. A schematic of the MIDAS experiment illustrating the system level components is shown in Figure 1. A more complete description of the flight hardware is given elsewhere [15].

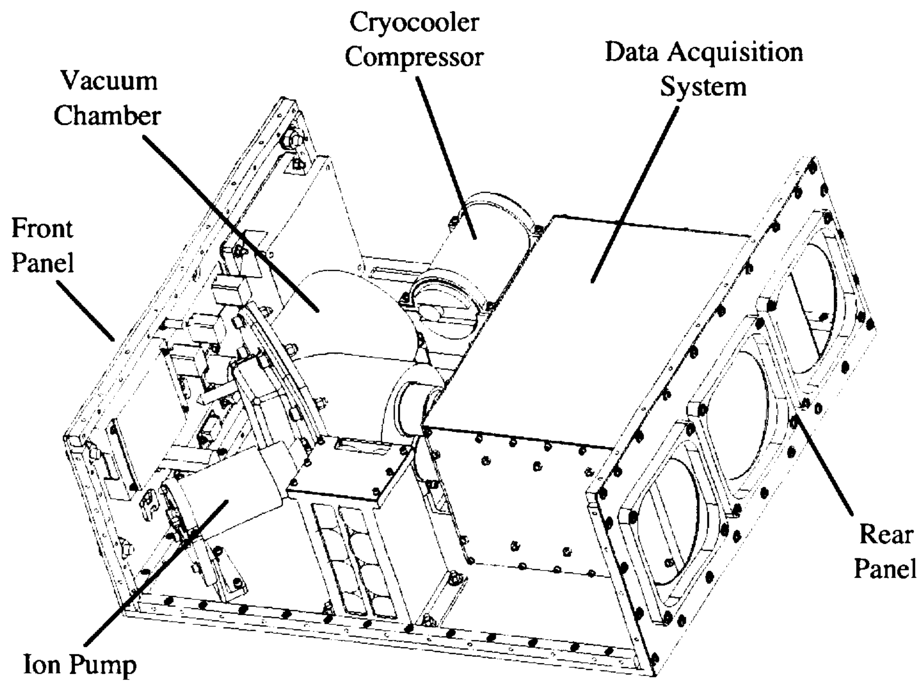

Figure 1. Schematic of the MIDAS experiment (top cover not shown).

Hybrid Circuits

The superconductive materials used in the MIDAS experiment were integrated into thick-film hybrid circuits as shown in Figure 2. In this design, four electrical contacts were made to each superconductive specimen to perform four-probe resistance measurements. The surface-mounted components shown in Figure 2 include two multiplexers, one amplifier, and four Platinum Resistive Thermometers (PRT's). One of the multiplexers directs electric currents across the outer two contacts to each superconductor, and the other returns the voltage signal generated across the inner two electrodes to the data acquisition system for measurement and storage. The three PRT's located among the superconductors measure the temperature of the materials under evaluation. The fourth PRT measures the heat generated by the active electronic components.

Four hybrid circuit boards containing superconductive specimens were flown aboard the MIDAS experiment. Two of the four circuits (Circuits 1 and 3) contain thick film $YBa_2Cu_3O_{7-x}$ superconductors produced at NASA-Langley Research Center. Circuits 2 and 4 contain thin film superconductive specimens supplied by outside sources. The four circuits were mounted on a copper cube which was in turn attached to a titanium stand located in the vacuum shroud as shown in Figure 3.

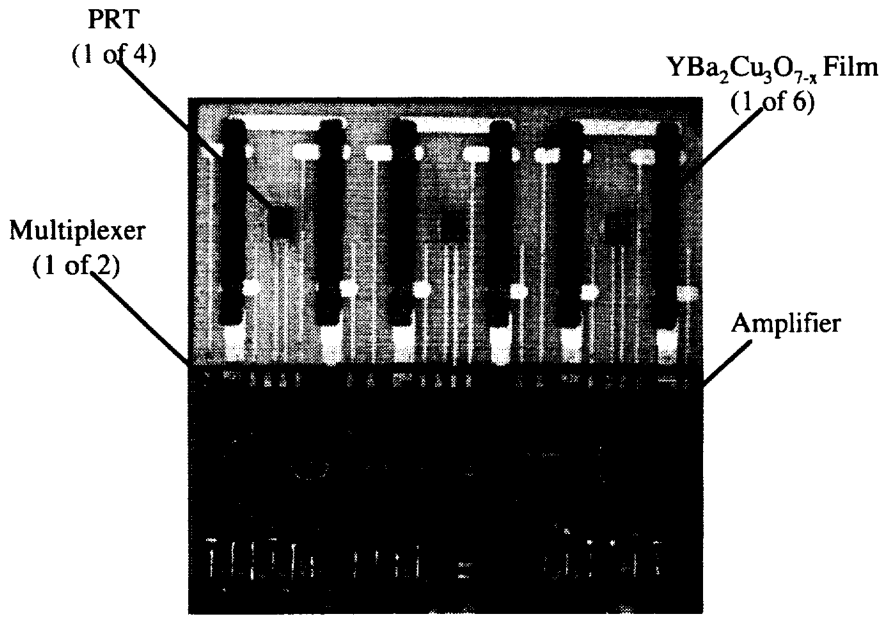

Figure 2. Photograph of a hybrid circuit containing six $YBa_2Cu_3O_{7-x}$ superconductors and conventional electronic components.

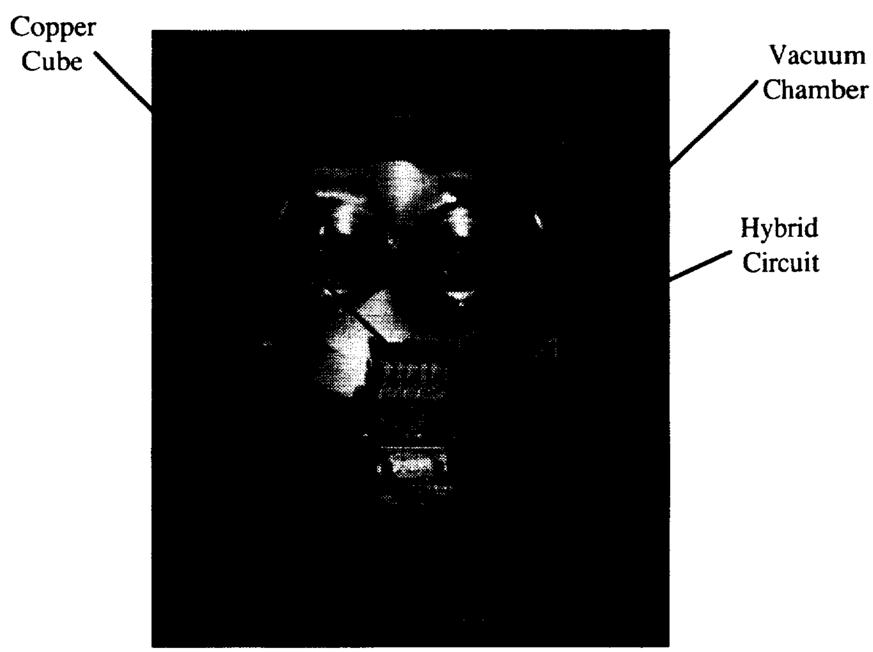

Figure 3. Hybrid circuits installed in the vacuum chamber prior to sealing the chamber.

Resistance vs. Temperature Measurements

The electrical resistance measurements were performed by directing positive and negative currents of equal magnitude (i.e., +0.1 and -0.1 mA) to each superconductive film. The absolute values of the voltages generated across the inner two contacts were then averaged as shown in Equation 1:

$$\overline{V} = \frac{|V^{+}| + |V^{-}|}{2} \tag{1}$$

where $\overline{V}$, V^{+}, and V^{-} represent the average voltage, the voltage resulting from the application of positive current, and the voltage resulting from the application of negative current respectively. Once the average voltage was determined, the resistance was calculated using Ohm's Law (R=V/I). During the T_c measurement phases of the experiment, resistance data was collected between 250 and 75K.

Experimental Results

While aboard Mir, the MIDAS experiment initially cooled the superconductive circuits to 74.5K over a six-hour period. Due to a hardware anomaly, the instrument maintained this temperature for only 14 hours. After this time, the specimens warmed to 95K over a 4-day period, and continued to warm to approximately 115K over the remainder of the first 28-day cycle. During both the second and third iterations of the experiment, the specimens were cooled to approximately 115K where the temperature remained relatively constant throughout each 28-day cycle. Although the resistance versus temperature and current-voltage data was collected according to schedule, no information was obtained which describes the electrical properties of the materials below their superconductive transition temperatures during the second and third cycles. Figures 4a and 4b show the temperature of the cryocooler cold finger during the first and second iterations of the experiment respectively. The temperature of the cryocooler cold finger during the third iteration is very similar to that of the second iteration shown in Figure 4b.

Although the planned temperatures were not maintained during the 90-day experiment, the superconductive transition temperature of each specimen was successfully measured during the first iteration of the experiment. During this measurement cycle, each of the twelve thick film specimens entered a superconductive state at approximately 87K. Figures 5a and 5b show the resistance versus temperature data for each of the six superconductors on Circuits 1 and 3 respectively. The abbreviations used in the legends of these graphs indicate the circuit and specimen number associated with each superconductor. For example, the abbreviation C1 S1 refers to Circuit 1 - Specimen 1. The specimens were numbered from 1 to 6 as viewed from left to right in Figure 2.

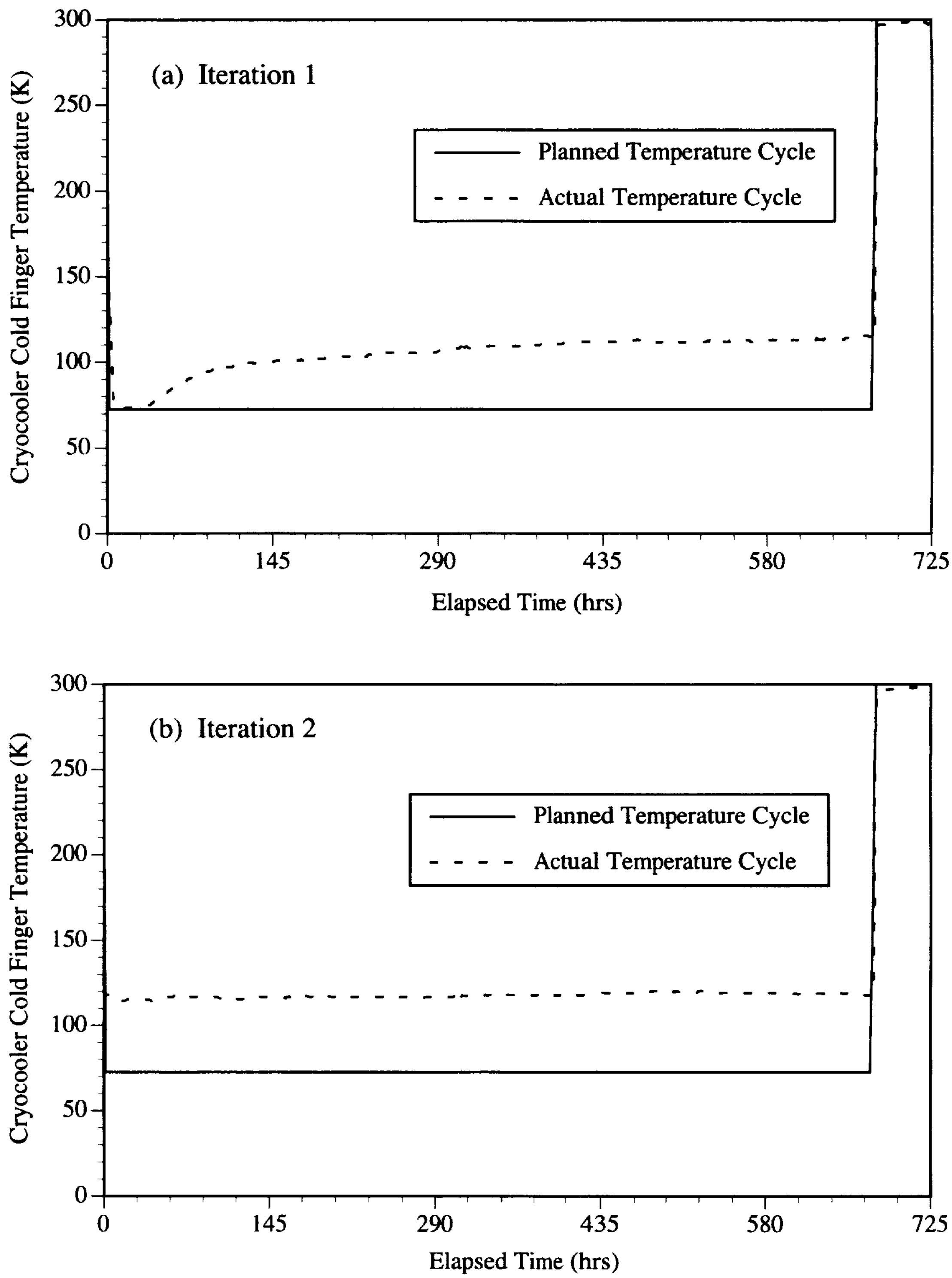

Figure 4. Cryocooler cold finger temperature during the (a) first and (b) second iterations of the MIDAS experiment.

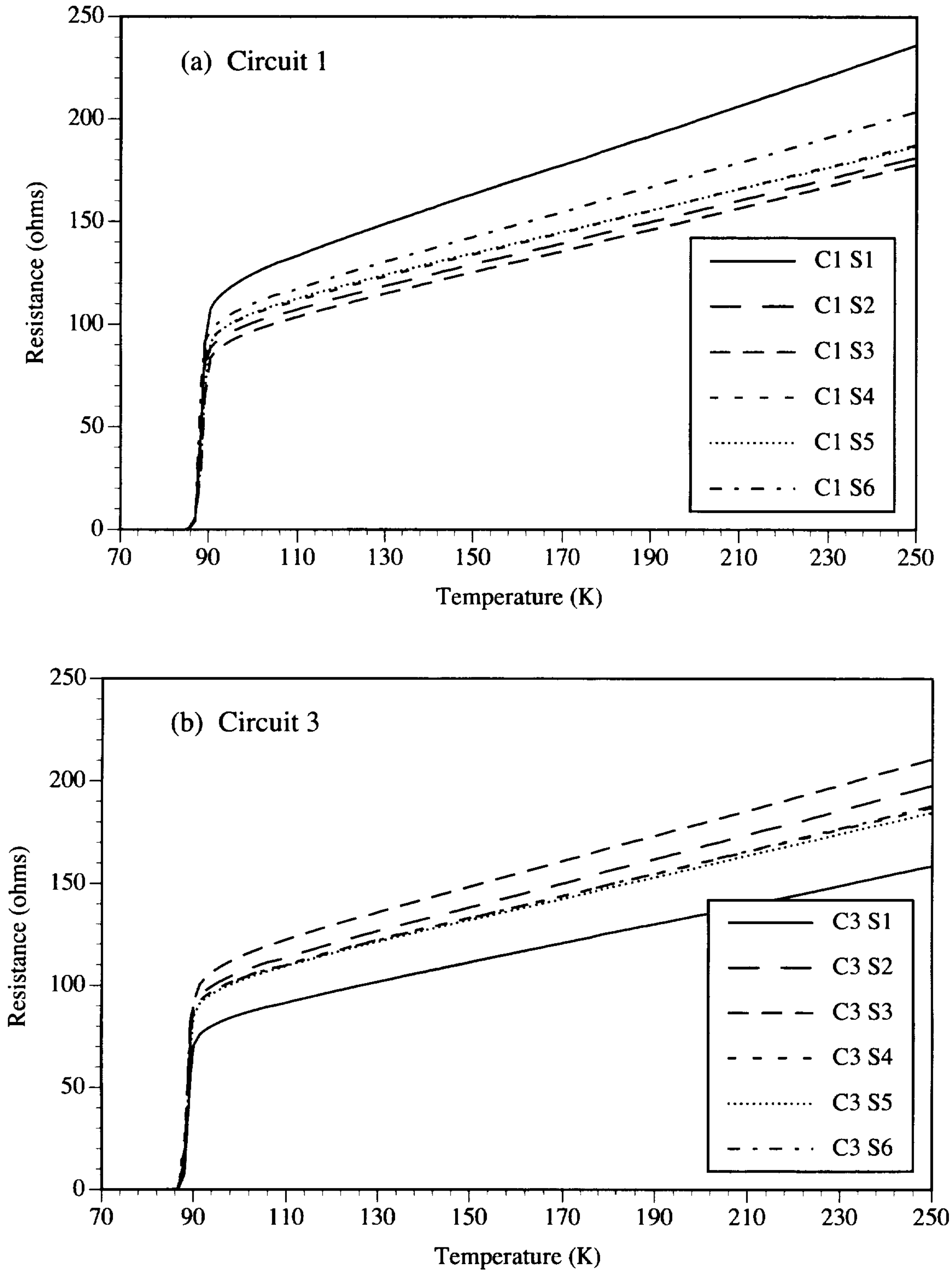

Figure 5. On-orbit resistance versus temperature data for the thick film superconductors on Circuits 1 (a) and 3 (b).

During the second and third iterations of the flight experiment, resistance versus temperature data was collected between 115 and 250K. Over this temperature range, the resistance values were found to be equal to those obtained during the first iteration of the experiment. Most notably, the resistance data taken during the final warm-up cycle was identical to that collected during the initial cool-down over the temperature range for which data is available. Figure 6 shows a typical example of the similarities between the resistance versus temperature data collected during the initial and final measurement cycles. The data collected during each intermediate measurement cycle is in good agreement with the data shown below.

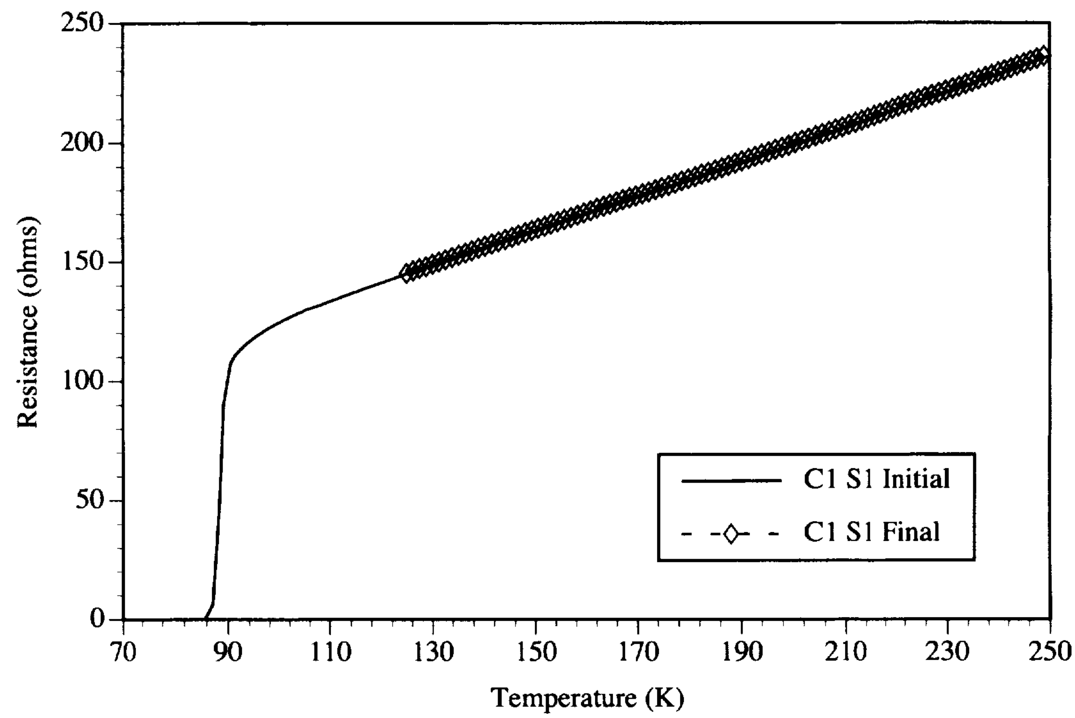

Figure 6. Typical example of the on-orbit resistance versus temperature data collected during the first cool-down and the final warm-up of the superconductive materials.

As shown in Table I, during flight and post-flight testing, each specimen exhibited a superconductive transition temperature that was within ±0.1K of its pre-flight value. Any differences among the $T_{c,zero}$ values shown in Table I are within the temperature measurement accuracy limits of the experiment [16]. This finding indicates that these materials possess similar resistive properties in space as are exhibited on the ground. Furthermore, the data shows that the resistive properties of these materials do not degrade over time while in in space.

Table I. Superconductive transition temperatures of $YBa_2Cu_3O_{7-x}$ thick films measured during pre-flight, flight, and post-flight operation of the MIDAS experiment.

Specimen	Pre-flight T_c (K)	On-Orbit T_c (K)	Post-flight T_c (K)
Circuit 1			
1	87.2	87.2	87.2
2	86.9	86.9	86.9
3	87.1	87.1	87.1
4	86.8	86.9	86.8
5	86.7	86.7	86.8
6	86.9	86.9	87.0
Circuit 3			
1	87.3	87.3	87.3
2	87.1	87.0	87.1
3	86.9	86.9	86.9
4	87.0	86.8	86.9
5	86.8	86.9	86.7
6	87.1	87.1	87.1

Although the $T_{c,zero}$ values were found to be unchanged throughout the MIDAS experiment, the post-flight resistance values between 90 and 250K were found to be 1 to 2% higher than those observed during all previous tests. A typical example of this behavior is shown in Figure 7. The reason for this slight increase in resistance is unclear considering the last resistance values recorded while on-orbit were in good agreement with all previously acquired data at that temperature. Additionally, it is important to note that the $T_{c,zero}$ and $T_{c,onset}$ values obtained during post-flight testing were the same as those observed during all pre-flight and flight operations.

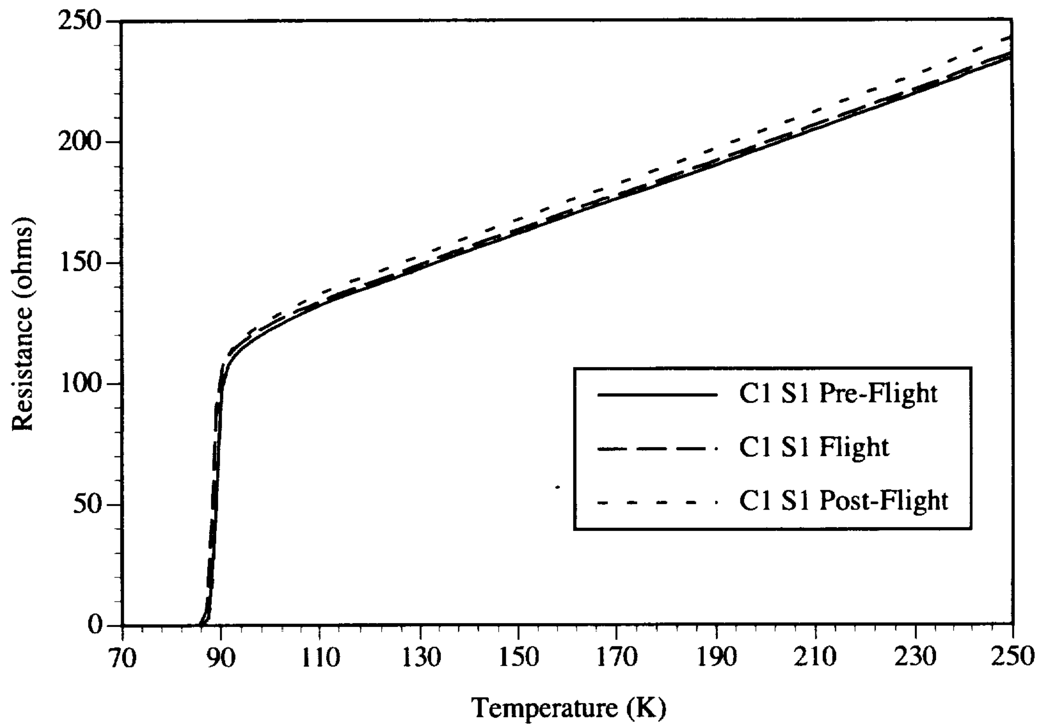

Figure 7. Typical example of the resistance versus temperature data collected during pre-flight, flight, and post-flight operations.

Discussion

The results of the MIDAS experiment show that superconductive materials can be successfully integrated into hybrid circuits and used in conjunction with conventional surface mounted electronic components. These circuits were integrated into a mechanical system which was vibration tested [10], launched into orbit aboard STS-79, and installed aboard the Priroda module on the Mir space station. Once installed, the experiment was initiated and the circuits were cooled to cryogenic temperatures, maintained at cryogenic temperatures for 28 days, and warmed back to room temperature a total of three times. While the experiment was active, the resistance versus temperature and current-voltage properties of each superconductive specimen were measured at predetermined time intervals.

Throughout this duty cycle, the hybrid circuits maintained their mechanical integrity and functioned as designed for 90 days. During flight operations, each of the twelve $YBa_2Cu_3O_{7-x}$ test specimens exhibited $T_{c,zero}$ values of approximately 87K. In each instance, the T_c value measured on-orbit was the same as that obtained during pre-flight testing. Once the 90-day experimental cycle was complete, the payload automatically shut down, and was returned to earth via STS-81 six weeks later. Upon its return, the superconductive specimens were subjected to a battery of tests similar to those performed aboard Mir. During these tests, the superconductive properties of each specimen were found to be in good agreement with the data gathered during both pre-flight and flight operations.

The only difference between the post-flight data and all previously obtained data was a 1 to 2% increase in the resistance values between 90 and 250K. This increase in resistance may be associated with the re-evacuation of the vacuum chamber prior to post-flight testing. During this procedure, the vacuum chamber was opened in an argon atmosphere to permit the installation of a vacuum valve so the chamber could be evacuated using an external vacuum system. The installation of this valve was necessary because the system automatically shut down once the 90-day experiment was complete. The ion pump used in the MIDAS experiment was designed only to sustain the vacuum level in the chamber while the system was active and was therefore not capable of evacuating the chamber from the higher pressure that would have developed during the six-week idle period aboard Mir. Despite the 1-2% increase in resistance between 90 and 250K, the $T_{c,onset}$ and $T_{c,zero}$ values were not significantly different than the pre-flight observations. Furthermore, the fact that the last resistance values measured on-orbit were identical to the pre-flight values indicates that no degradation to the materials occurred during the 90-day space experiment.

Conclusions

A science payload designed to test the properties of high temperature superconductors in space was built and operated for 90 days aboard the Mir space station. The superconductors evaluated in this work were integrated into multilayer hybrid circuits containing superconductive films as well as conventional electronic components. The on-orbit measurement cycle was designed to cool the circuits to 75K, maintain the devices at 75K for 28 days and then return the test specimens to room temperature. This cycle was to be repeated a total of three times while on-orbit.

Due to a hardware anomaly, however, the experiment was unable to sustain the 75K temperature for the duration of the experiment. However, a complete set of resistance versus temperature data was collected during the first iteration of the measurement cycle. During this iteration, each of the twelve superconductive thick films exhibited a $T_{c,zero}$ value of approximately 87K. The $T_{c,zero}$ values observed during flight and post-flight operations were all found to be within ±0.1K of the data acquired during pre-flight testing.

The results of this experiment show that superconductive thick films can be successfully produced and integrated into durable electronic packages and used in spaceflight systems. While in space, the superconductors exhibited properties that approximate those observed on the ground. This finding validates the survivability and performance of superconductive devices over time while in space. Additionally, this data mitigates some of the risks associated with the incorporation of these new materials into space systems where their performance over time was previously untested.

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