A Space-Qualified Experiment Integrating HTS Digital Circuits and Small Cryocoolers

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(Invited Paper)

Abstract— **High temperature superconductors (HTS) promise to achieve electrical performance superior to that of conventional electronics. For application in space systems, HTS systems must simultaneously achieve lower power, weight, and volume than conventional electronics, and meet stringent space qualification and reliability requirements. Most effort to date has focused on passive RF/microwave applications. However, incorporation of active microwave components such as amplifiers, mixers, and phase shifters, and on-board high data rate digital signal processing is limited by the power and weight of their spacecraft electronic and support modules. Absence of data on active HTS components will prevent their utilization in space. To validate the feasibility in space of HTS circuits and components based on Josephson junctions, we need to demonstrate HTS circuits and critical supporting technologies, such as space-qualified packaging and interconnects, closed-cycle cryocooling, and interface electronics. This paper describes the packaging, performance, and space test plan of an integrated, space-qualified experimental package consisting of HTS Josephson junction circuits and all the supporting components for NRL's high temperature superconductor space experiment (HTSSE-II) [1]. Most of the technical challenges and approaches are equally applicable to passive and active RF/microwave and digital electronic components, and this experiment will provide valuable validation data.**

I. Introduction

An important attribute of superconductivity is high performance in RF/microwave and digital electronics. Space is a unique environment for communication and imaging systems to which high temperature superconductors (HTS) electronics are applicable. Most of the international HTS electronics R&D effort to date has focused on passive RF/microwave and analog components and is now moving into their applications [2]. But modern information and telecommunication systems are moving rapidly and inexorably to digital electronics. In order for this new cryoelectronic technology to gain acceptance and eventually revolutionize autonomous space systems, we need to demonstrate circuit functionality and survivability of all aspects of the complete cryogenic system in space. Enabled by newer cryocooler systems, superconductive signal processing promises to provide a new generation of on-board processing for advanced communications and imaging spacecraft. We describe the development of an experiment which will demonstrate these features for HTS Josephson junction (JJ) digital devices.

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This experiment in space must address and resolve all the following issues:

- HTS JJ and circuit fabrication and operation;
- HTS circuit in-flight control electronics;
- HTS circuit packaging, including magnetic shielding for Josephson junction and SQUID (superconducting quantum interference device) circuits;
- low thermal conductance signal, control, and power input/output (I/O) lines;
- small, efficient, long life cryocoolers;
- cryocooler in-flight control electronics;
- thermal and mechanical interface between the HTS package and the cryocooler;
- spacecraft thermal, mechanical, electrical, signal, and data interfaces;
- space qualification of all components and of the integrated system;
- an in-space test plan.

The high temperature superconductor space experiment (HTSSE-II) [1] offered an opportunity to demonstrate an HTS JJ circuit integrated with a dedicated cryocooler in space. We developed and space-qualified an integrated, small cryocooler and HTS JJ digital MUX circuit package. We report our successful approach in developing the HTS digital MUX space experiment. Our space-qualified experiment package was delivered to NRL and successfully integrated in the HTSSE-II payload which is scheduled to be orbited in 1996. This experiment will demonstrate the feasibility of operating HTS JJ circuits in space. Special attention was provided to meet the requirements for magnetic shielding, thermal management, space-qualification, and HTS circuit electrical I/O.

II. Experiment Description

We packaged two HTS chips containing four (4) HTS 2:1 digital multiplexer (MUX) circuits in a single hermetically-sealed alumina package. Three of the four MUX circuits utilized the nonlinear I–V characteristics of HTS SQUID's and operated over a large temperature range. The fourth digital MUX circuit utilized the magnetic transfer characteristics of the HTS SQUID and operated over the small temperature

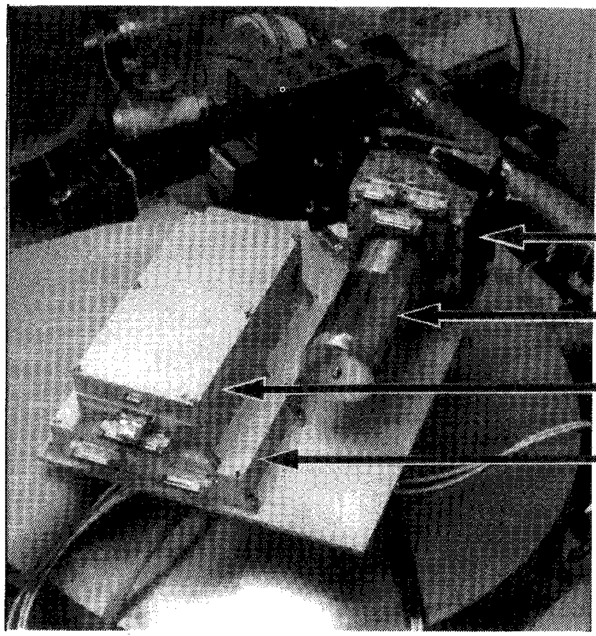


Fig. 1. Photograph of the integrated HTS digital MUX experiment hardware taken during final thermal vacuum testing.

range between 68–72 K. Magnetic shielding was required to reduce the local magnetic fields produced by the cryocooler motor and other sources below the HTS JJ and SQUID device noise level. We achieved this shielding by placing the hermetically sealed alumina package in high permeability magnetic shields.

TRW has developed small, efficient Stirling and pulse-tube cryocoolers for space applications [3]. The Stirling cryocooler and drive electronics was integrated with the HTS package and tested under thermal vacuum and flight vibration conditions. The cryocooler achieved a minimum temperature of 57 K when rejecting heat at 273 K. The cryocooler is projected to operate over the temperature range of 65–75 K.

Fig. 1 is a picture of the small integrated cryogenic package containing four HTS 2:1 digital MUX circuits cooled by TRW's small Stirling cryocooler taken during final qualification testing at TRW. It includes:

1) HTS MUX cold package;
2) ambient spacecraft interface electronics and temperature measurement;
3) cryocooler and cryocooler drive electronics;
4) associated magnetic shields.

The experiment was designed to match the spacecraft capability and requirements with that of the HTS and supporting electronics with respect to size, telemetry data rate, EMI, and environmental temperature. The entire package was delivered in November 1994. In order to meet this schedule, the selection of the HTS devices was completed in January 1994 using components fabricated before 1994. The Stirling cryocooler was chosen for this experiment because of its proven performance and maturity more than one year earlier.

III. HTS Devices and Circuits

The HTS devices were dc SQUID's incorporating grain boundary step-edge JJ's. These were fabricated in $YBa_2Cu_3O_7$

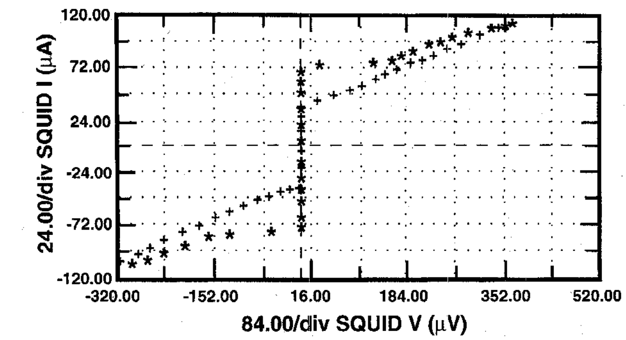


Fig. 2. The superposition of two YBCO SQUID current-voltage curves. The curve with a larger critical current corresponds to no flux bias, the curve with a smaller critical current corresponds to a $\Phi_0/2$ flux bias.

(YBCO) thin films deposited on $LaAlO_3$ substrates by pulsed laser deposition. Multiple, planar, washer type dc SQUID's were fabricated on each chip using single YBCO films. Fig. 2 shows the current-voltage (I–V) characteristics of a YBCO SQUID, demonstrating the suppressed supercurrent when a magnetic flux equal to 1/2 flux-quantum is applied. Fig. 3 shows the resulting voltage response of a YBCO dc SQUID as a function of the applied magnetic flux.

Grain boundary step-edge junctions were fabricated by depositing a thin YBCO film across a small but sharp step in a substrate as described by Luine *et al.* [4]. The step was produced by ion milling the substrate through a thin film Nb stencil. We produced the straight walled stencil by depositing a 150 nm thick Nb film on a $LaAlO_3$ (100) substrate and patterning the Nb film using high contrast AZ5214E photoresist. In order to obtain the desired step-edge profile, it was necessary to have both a straight-wall mask and a low ratio of mask-to-substrate etch rate (1:3). The Nb film was reactive-ion-etched with CF_4 (12.5 mT and 100 W), producing a sharp (approximately 88°) profile which was aligned to either the $LaAlO_3$ (010) or (001) crystal axes. We then stripped

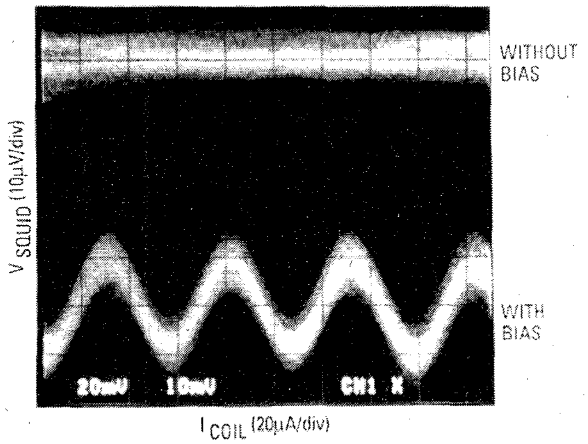


Fig. 3. YBCO SQUID voltage modulation measured on a Stirling cryocooler with the circuit packaged in a magnetic shield identical to the one used for the HTSSE-II deliverable. The operating temperature is 59 K.

the photoresist and ion milled the sample in an argon/oxygen atmosphere at a rate of 4 nm/min. The substrates were attached to a water-cooled stage by a high thermal conductivity paste. Ion milling was performed with the ion beam normal to the substrate which was rotated about an axis normal to the substrate. The Nb film was then chemically stripped, leaving the sharp step in the substrate. A 200 nm thick YBCO film was deposited using pulsed KrF excimer pulsed laser deposition at 780°C in a 25 Pa oxygen atmosphere. An ex-situ silver layer was then deposited for contacts and annealed at 400°C in oxygen.

It is desirable to use the magnetic transfer characteristics of SQUID's as MUX logic gates (e.g., SAIL [5], [6]). However, HTS SQUID devices in late 1993 had acceptable operating margins only over a very small temperature range. Since the space-qualified cryocooler control electronics developed for this experiment will not provide temperature control over the orbital temperature excursions of the spacecraft, we predict large temperature variations on orbit. This restricted the selection of HTS MUX circuits to those which had lowest temperature sensitivity.

Fig. 4 is an electrical block diagram of the HTS MUX experiment. Each MUX circuit consists of two YBCO dc SQUID's. To maximize the chance for successful operation and minimize the risk of inoperability in space, four identical MUX circuits were included in the space experiment package. Each of the four redundant MUX circuits were tested independently of the others and will be measured independently in space. Three of the YBCO digital MUX's operate on the nonlinear I–V characteristics of the SQUID's with directly injected Data and Select currents. The fourth MUX operates on the SQUID magnetic modulation characteristics and uses planar silver coils integrated with the SQUID's to effect this magnetic flux modulation.

The direct injection MUX circuits exploit the SQUID nonlinear current-voltage characteristic, which for these devices is consistent with the simple resistively shunted junction (RSJ) model [7], given by

$$V = 0 : \quad \text{for } I < I_c, \tag{1}$$

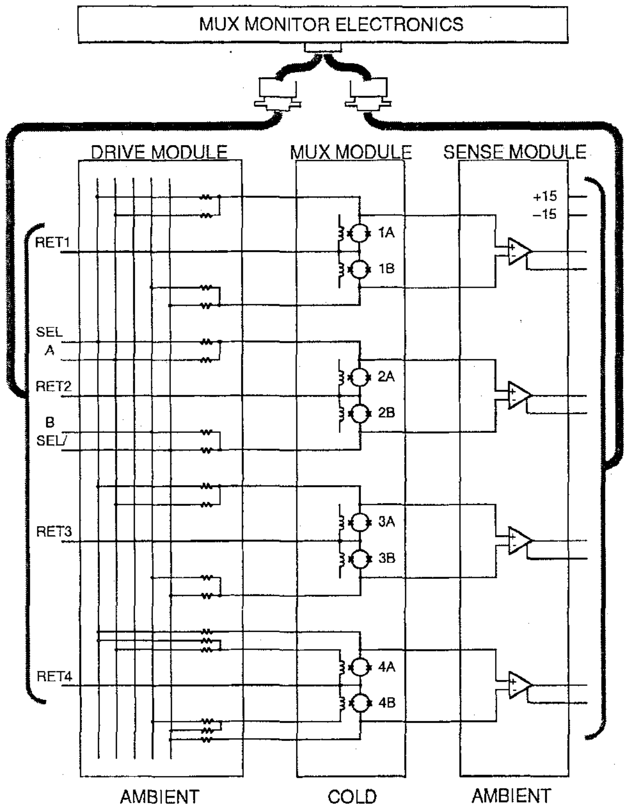
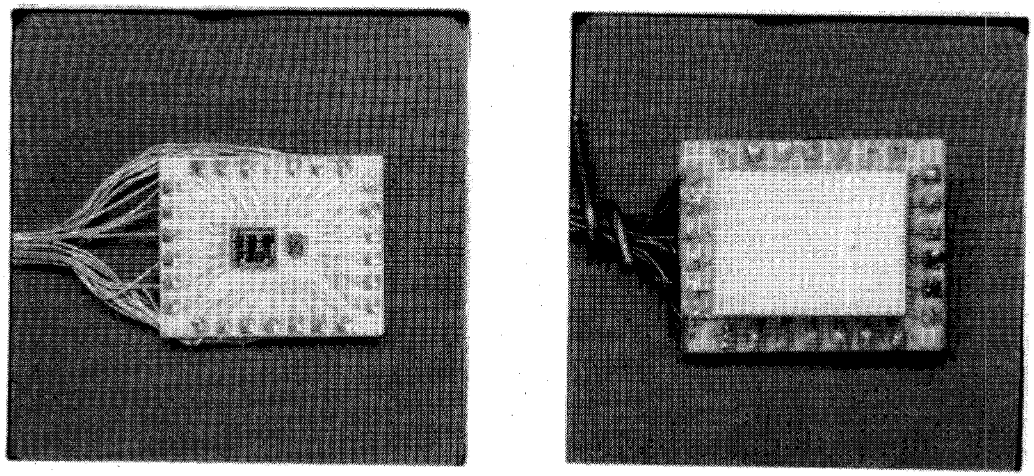


Fig. 4. The HTS digital MUX circuit implementation.

$$V = I_c R_n \left[\left(\frac{I}{I_c} \right)^2 - 1 \right]^{1/2} \quad : \quad \text{for } I \geq I_c. \tag{2}$$

I_c is the SQUID critical current ($\sim$500 μA) and the $I_c R_n$ product is about 300 μV. Each of the two SQUID's in each MUX circuit is used as a gate to either block or pass its data to the output terminals. One of the SQUID's is biased in the OFF state so that the total current through it is below I_c independent of what data is presented to it. The other SQUID is biased in the ON state so that when a "0" appears in its data channel, its total current is below I_c and the output is zero, but when a "1" appears in its data channel, I_c is exceeded and a voltage appears across the output terminals. Biasing both SQUID's in the ON state simultaneously produces an illegal condition.

The magnetically modulated MUX circuit is similar to the direct injection circuits, except the data is applied to the SQUID's via their magnetic flux control lines. Fig. 2 shows two superimposed SQUID I–V characteristics; the curve with a higher I_c corresponds to no magnetic flux, and the curve with lower I_c corresponds to 1/2 magnetic flux quantum. Biasing the SQUID midway between the two values of I_c places it in the ON state. Under these conditions it will pass data applied to its magnetically coupled input. Biasing the SQUID well below the lower value for I_c places it in the OFF state. Under these conditions the SQUID will remain at zero voltage for both values of input data, blocking that data channel. The SQUID's selected in late 1993 showed small magnetic modulation of I_c. This limited the operating margins, output voltage, and temperature range of the resulting MUX circuit.



(a) (b)

Fig. 5. (a) HTS chips bonded on the alumina substrate and (b) the hermetically sealed HTS flight package. The Al bond wires have been tested to 2 gm pull strength.

Each YBCO MUX was fully characterized over the expected operating temperature range. From these data we determined the optimum Data and Select currents for that MUX. Discretionary resistors were selected and mounted on the drive module board to set the operating condition for each HTS MUX.

IV. MUX Fabrication, Packaging, Encapsulation, and Magnetic Shielding

A. Electronics

Fig. 4 is an electrical block diagram of the HTS MUX experiment. Each MUX circuit consists of two YBCO dc SQUID's. Each of the three modules which operate the MUX circuits in space was fabricated on a separate printed circuit board. The first module (MUX monitor) generates the signal for digital multiplexing and performs test pattern generation, drive level generation, and spacecraft interface functions. This module is completely outside the cryogenic and magnetically shielded package. The MUX drive and sense modules perform the input and output level translations required between the MUX monitor unit and the HTS circuits. The MUX drive and sense modules were located physically near the HTS circuits and within a large two-layer magnetic shield described below. The MUX monitor signal is routed to the cooled HTS circuit through a MUX drive board which contains a resistor network to produce the current levels compatible with the HTS circuits selected. The MUX output signals are routed to a sense board which amplifies the voltage signal 8000 times to a level compatible with room temperature electronics. The signal is then sent back to the main MUX monitor module.

B. Packaging

In order to enhance the reliability of the HTS MUX during space qualification, storage, and flight, a flight-qualifiable package was developed to protect the circuits from potentially damaging environmental influences. To isolate the HTS circuits from deleterious chemical environments, we encapsulated and hermetically sealed the HTS chips. Many SQUID die were screened to select the best candidates for the flight package. As a result, two die were selected and bonded to a metallized alumina substrate with silver-filled epoxy as shown in Fig. 5(a). The chips were connected to the traces on the substrate with aluminum wire bonds that were nondestructively pull-tested to 2 gm. We fabricated the substrate lid from alumina rings which were epoxied to an alumina cap. The HTS chips were encapsulated at room temperature in an oxygen atmosphere by sealing the lid to the substrate with a dielectric-film epoxy as shown in Fig. 5(b). To the limit of our testing capability, the packages were all measured to be hermetic. We soldered phosphor-bronze twisted-pair wires to the substrate through plated-through holes to make the electrical connections.

C. Magnetic Shielding

We were required to shield the HTS SQUID's to isolate them from the ac and dc magnetic environments expected on the spacecraft. In particular, the dc field due to the cryocooler compressor motor at the cold tip was measured to be 9 gauss, and we expected the ambient ac fields to be a noise source. Therefore, we enclosed the cryocooler compressor and the device volume around the cold finger in cylindrical mumetal (high permeability metal) shields. Shielding factors at the cold tip were calculated to be 7 using MAGGIE, Version 4.1, an approximate 2D magnetostatic simulation program from Macneal–Schwendler Corporation. This shield also reduced the stray fields generated by our cooler at the other positions on the spacecraft. These mumetal shields, intended primarily to reduce static and low frequency magnetic fields at the HTS circuits, also provided effective attenuation of electromagnetic interference (EMI). Confining all low-level signal lines immediately connected to the HTS circuits within the shields minimized external EMI.

We further enclosed the hermetically sealed HTS package in a small rectangular mumetal box which provided an additional magnetic shield for the HTS JJ circuits. The sealed packages were silver-epoxied into the mumetal housing to provide good thermal contact. We calculated the shielding factor for the rectangular box at 1700 using MAGGIE. Fig. 3 shows the measured magnetic response of an HTS dc SQUID which was mounted in these magnetic shields on an operating Stirling cryocooler similar to the one in the final package. The measured magnetic field noise was <3 mG, and the compressor motor frequency component was below the noise level of the room temperature amplifier.

Because the mass of the HTS package, including the rectangular mumetal box, was sufficiently small (approximately 5 gm), we were able to mount it directly on the cold finger with an aluminum mounting plate. This avoided a separate mechanical support for the HTS package, which would have produced additional thermal load. The entire assembly on the cold tip was wrapped in multilayer insulation (MLI). Phosphor bronze twisted pair wires were used to connect the HTS circuits to first stage low noise amplifiers and bias resistors which were located within the outer layers of mumetal shielding. Placing the first stage amplifiers and bias resistors in the mumetal shield provided extra noise immunity for the HTS circuits. Signals amplified by a second stage are fed directly into the HTSSE A/D converters provided by NRL. The temperature of the cold finger was measured with a GaAs diode thermometer, which is permanently located in the cold tip, through the cryocooler control electronics and supplied to the HTSSE electronics. All wires and cables were tacked down with dielectrically loaded epoxy to provide the mechanical stability required to survive vibration and pyro-shock testing and launch.

D. Cryocooler and Thermal Management

We selected an integral Stirling cryocooler produced at TRW for this experiment. It was provided to this project by NRL for the purpose of performing this space experiment.

A photograph of the integral, vibrationally balanced flight-qualified Stirling cooler is shown in Fig. 6. The compressor is driven by a moving-coil, linear motor with the moving coil supported by flexure springs that also provide and maintain alignment for the attached noncontacting piston which oscillates and compresses gas into the displacer/regenerator. A small clearance between the cylinder and piston seals the compression space. The compressor operates at its 67 Hz resonance frequency. The single vibration balancer contained in the compressor pressure vessel is used to cancel the force imbalance, created by the collinear compressor and displacer motions. A small linear motor drives the balance mass, which is supported by flexure springs that provide the stiffness necessary to achieve resonance at the fundamental drive frequency. The balancer position is measured by a position sensor whose output is used to control its stroke. The displacer/regenerator is integrated with the compressor and is suspended from its own flexure spring stacks, which maintain the small clearances required in the cold finger for this moving element. The miniature integral Stirling cooler weighs 1.4 Kg and was developed to cool IR sensors on lightsats to temperatures as low as 50 K. Although we have built and tested several

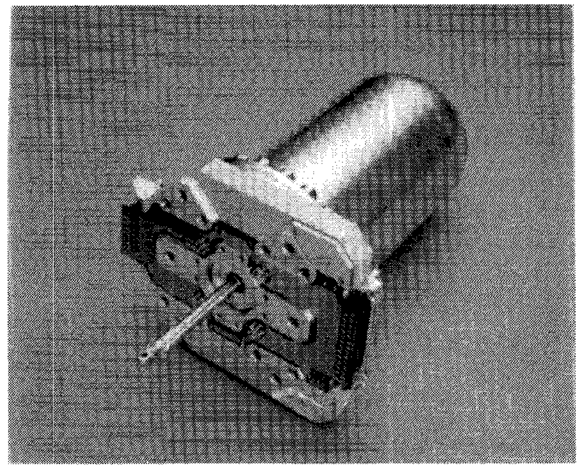


Fig. 6. Photograph of the assembled cryocooler.

of these vibrationally-balanced, nonwearing design Stirling coolers, and two coolers are currently in extended life test, this cooler will be the first of its design which will be flown. The cooler is controlled by its drive electronics and operates in a free (rather than driven) displacer mode. No provision was made in the control electronics for active vibration control despite the inherent capability of the mechanical cooler.

The cryocooler produces 250 mW cooling capability at approximately 60–65 K. Combined power consumption of the cooler and its control electronics is 20 W. Approximately 3 h is required to cool the HTS package from 290 to 65 K. The temperature of the cold finger is determined by the stroke of the compressor piston, the temperature of the heat rejection plate, and the thermal load. The stroke of the compressor piston is controlled remotely through the cryocooler control electronics. The stroke amplitude is adjusted during cool-down to avoid overdriving the piston (maximum stroke can only be used when all mechanical parts are close to their operating temperature) and during steady state operation to achieve crude temperature control. No active electronic control was provided to compensate for the expected temperature variations of the heat rejection plate on-orbit.

The cryocooler and the two electronic control units (Cryocooler control and MUX control) are heat sunk to the base plate shown in Fig. 1. All power dissipated in the experimental payload must be conducted away through this plate and its heat sink to the spacecraft, and eventually radiated to space. The efficiency of the radiators is determined by the orbital attitude and position with respect to the nearby hot bodies: sun, earth, and moon. Orbital and thermal analysis was performed to ensure that the thermal management was adequate to maintain proper operating temperature of all parts of the experiment.

V. Performance

Fig. 7 compares the data for YBCO MUX no. 2 taken at TRW just prior to delivery and at NRL during integration onto the HTSSE-II flight deck using NRL's HTSSE-II spacecraft interface. The similarity between the two sets of data demonstrates the successful transfer of the integrated system

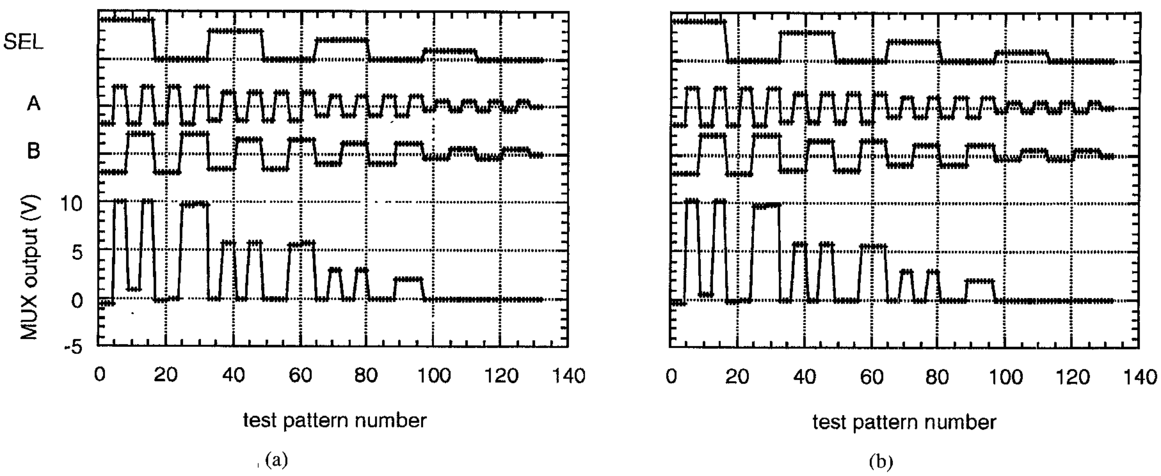


Fig. 7. (a) HTS MUX output data taken just prior and (b) just after delivery to NRL. The SEL, A, and B drive signals are offest and shown for reference.

from the laboratory/development environment to the spacecraft/integration environment. The data show the output being switched between the two data inputs, A and B, through the application of the select (SEL). The switching is repeated for four drive levels and shows the correct output for the first three drive levels. Testing at four drive levels will accommodate temperature variations in flight as well as reduce the risk of inoperability due to changes in the junction I_c. The amplitude of the output for the four drive levels will also enable us to measure changes of SQUID I_c.

One of the direct injection MUX's and the magnetically modulated MUX were damaged in packaging and/or space-qualification testing. The two remaining HTS MUX's appear to be robust and we are confident that they will operate successfully in space.

During final testing in preparation for delivery, the loaded cryocooler achieved a minimum temperature of 57 K when rejecting heat at 273 K and when driven at maximum stroke level. The cryocooler was closely monitored during this laboratory test. The maximum stroke amplitude to be used in flight is somewhat lower. Since the heat rejection temperature in space is expected to vary between 273–307 K, the HTS circuits are projected to experience a temperature range from 65–75 K while driven at the maximum flight levels. In addition to the temperature variations due to changes in rejection temperature, we plan to use the stroke level command to cycle the MUX circuits through the superconducting transition temperature. Fig. 8 shows the expected temperature profile of the controlled temperature variations. In-flight testing will demonstrate the long term operation of the system (one year) over many thermal cycles and investigate the effects of aging and flux trapping. An extended space evaluation period may be used to demonstrate the longer term (three years) operation of the cryocooler.

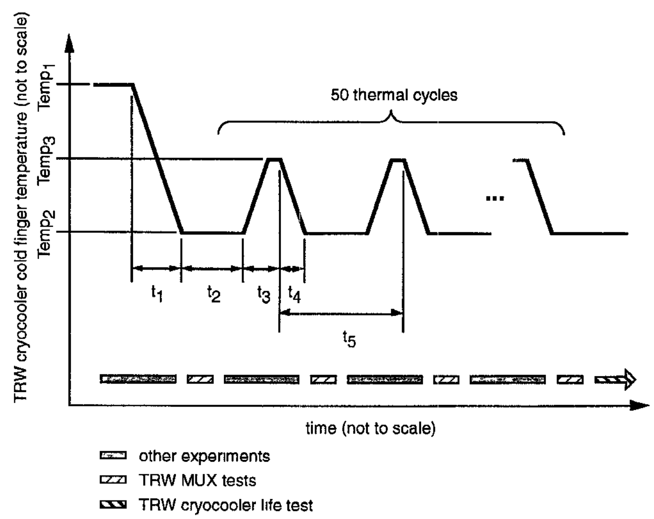


Fig. 8. Temp1 is ambient, temp2 is the MUX operating temperature (65–75 K), and temp3 is above the superconducting transition temperature (~100 K). The MUX tests are performed in the first year and extended cryocooler tests may be performed in the second and third years.

VI. Space-Qualification

This HTS MUX experimental payload was fully space-qualified through a combination of tests and verifications to ensure the reliability of the payload for its intended storage and deployment environments at minimum testing costs. All units were tested and demonstrated their ability to withstand the vibration and thermal ranges expected during launch and space flight. Three electronics units (Cryocooler control, MUX control, and MUX Drive/Sense) provide the required signal conversion and power conditioning to support all the electrical interfaces between the cryocooler, HTS circuits, and spacecraft. At the electronic component level, all parts selected meet MIL-STD-883 Class B requirements. Radiation hardness of the payload was ensured by selecting only rad-hard designated parts.

Selected standard hybrid assembly tests were performed as applicable to the HTS MUX module which contains the critical technology for this space experiment. These include bond pull tests and hermeticity tests. At the electronic box level, the acceptance tests include functional and active temperature cycling tests. Once the boxes were integrated into units, they were subjected to the full space qualification tests, including EMI, vibration (pyroshock, quasistatic vibration, and random vibration), and thermal vacuum tests.

The test level for each unit depended on the number of units available. We produced two cryocooler/MUX units. One was designated as a qualification unit and went through qualification-level testing. The second one was designated as the flight unit and was tested at the acceptance level. Only one control electronics unit was available. It was tested at the proto-flight level. Finally, the qualification unit was integrated onto the qualification deck and went through a complete set of tests and a magnetic survey. After successful completion of the qualification tests, the flight units were integrated into the flight deck and a full set of acceptance level tests were again repeated.

VII. Summary

This HTS digital MUX space experiment met all performance and qualification requirements and was accepted as part of the HTSSE-II experiment payload. This demonstrates that HTS Josephson junction circuits can be packaged with a dedicated cryocooler and space-qualified. After HTSSE launch, we will receive the data which will determine on-orbit performance of the self-contained HTS/cryogenic experiment.

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G. Akerling joined TRW, Redondo, Beach, CA, as a Member of the technical staff in 1990. He has 23 years of experience in developing electronic and hybrid packaging, including 20 years experience in all areas of microelectronics assembly. In 1981, at AMPEX Corp., he developed a wafer scale solder bump process. Currently he is involved in low temperature superconducting flip chip and multichip module packaging development.

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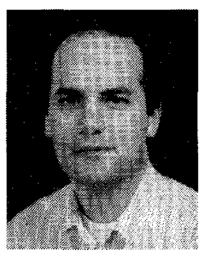

D. Durand received the B.S. degree in physics from the University of Washington, Seattle, in 1984, and the M.S. and Ph.D. degrees in physics from the University of Illinois, Urbana-Champaign, in 1985 and 1989, respectively. He was a Post-doctoral Associate at the University of Illinois in 1989.

He joined TRW, Redondo Beach, CA, in 1990, where he worked on the design and evaluation of microwave and analog-to-digital low temperature superconductive circuits. Prior to joining TRW, he performed experimental nuclear magnetic resonance work on the electronic properties of high dispersion metal particles and high temperature superconductors.

J. Godden, photograph and biography not available at the time of publication.

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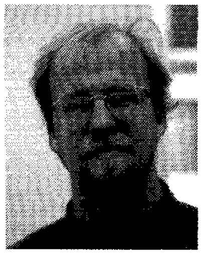
K.-F. Lau received the Ph.D. in applied physics from the California Institute of Technology, Pasadena, in 1976.

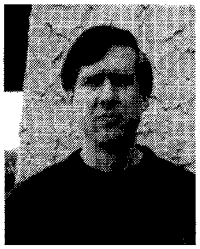
He is currently the program manager of a key high temperature superconductor development program at TRW, Redondo Beach, CA. Prior to his current assignment, he was the deputy program manager of the TRW MIMIC Program. Dr. Lau has 20 years of experience in advanced technology development, transition of advanced technology into production and program management. He was responsible for improving GaAs MMIC chip wafer processing yield and for the space-qualified production of GaAs and surface acoustic wave (SAW) components.



J. Murduck received the B.S. degree in physics from Rose-Hulman Institute of Technology, Chicago, IL, and the Ph.D. degree in physics from Northwestern University, Evanston, IL, in 1988.

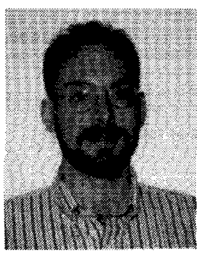
In 1988, he joined the staff of TRW's Superconducting Electronics Organization, Redondo Beach, CA, where he developed their NbN junction process. In 1993, he became the Leader of the high temperature superconductor fabrication group. Recent research has focused on step-edge junction and multilayer process development in YBCO.

R. Orsini, photograph and biography not available at the time of publication.



J. Raab received the B.S. degree in mechanical engineering from the California Polytechnic State University, San Luis Obispo, in 1980.

In 1980, he joined TRW, Redondo Beach, CA, as a Member of the Technical Staff in the advanced materials and technology section. In 1987, he moved to the cryogenics area at TRW where he has been Lead, Systems, and Project Engineer, and Program Manager on various IRD, technology, and flight programs delivering Stirling and pulse tube coolers.



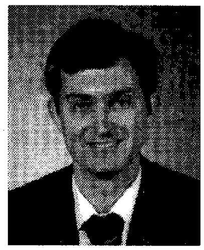
S. Schwarzbek received the Ph.D. degree in physics at the University of Notre Dame, South Bend, IN, in 1990.

Since then, he has been working primarily on the applications of high temperature superconductors (HTS) to digital applications at TRW, Redondo Beach, CA. His current work also includes the statistical analysis of our HTS process control measurements, as well as design and layout of the test structures themselves. The applications oriented work is focused on "SAIL" gates as a simple way to do high speed digital gates with generally available HTS processes. Other interests include the design and layout of high speed low impedance circuits in general.

Dr. Schwarzbek is a member of APS, AAAS, and the American Statistical Association.

E. Tward received the B.Sc., M.A., and Ph.D. degrees in physics from the University of Toronto.

He joined TRW, Redondo Beach, CA, in 1988. Since that time he has been Manager of the TRW cryogenics program and Project Manager for a number of cryocooler development projects. He has been Project Manager for development of a miniature pulse tube cryocooler for their Brilliant Pebbles project, the miniature Stirling cooler for LLNL, the 150 K PSC cooler for Phillips Laboratory and a 10 K cryocooler development project also for Phillips Laboratory. Prior to joining TRW, he was Chief Executive Officer of SpectroSonex, Inc., a start-up company that was developing a novel medical ultrasound imager. From 1969 to 1986, he was at the Jet Propulsion Laboratory, Pasadena, CA, where he was Supervisor of the Low Temperature Physics Group. While there, he was active in the development of long-lived cryocoolers for spacecraft, advanced coolers for Josephson junction devices, superconducting cavity oscillators, and the Infrared Astronomy Satellite cryogenic system. From 1969 to 1979, he was active in research in magnetic resonance and the development of cryogenic gravity wave detectors while a Professor of physics at the University of Regina, Regina, Saskatchewan, Canada.



M. Wire received the B.S. degree in physics in 1977 from the University of California, Los Angeles, and the Ph.D. degree in physics from the University of California, San Diego, in 1984. He completed his graduate research at Los Alamos National Laboratory.

From 1984 to 1986, he held a postdoctoral position at the Universitat zu Koln. His interests include superconducting and magnetic materials and their properties. In 1987, he joined TRW's Superconducting Electronics Organization, Redondo Beach CA, where he participated in thin film Josephson device and circuit development. Most recently he has been involved in cryogenic packaging and integration of these devices and circuits.