# The NRL Josephson Junction Monitoring Experiment on HTSEE-II

John H. Claassen, Robert G. Skalitzky, and Robert J. Soulen, Jr.

*(Invited Paper)*

*Abstract*— **An experiment designed to ride on the high temperature superconductor space experiment (HTSSE-II) satellite package is described, which monitors the current-voltage characteristics of two high temperature superconductor (HTS) Josephson junctions. The junctions are typical examples of the state-of-the-art at the time of incorporation, and were obtained from two industrial laboratories: TRW and Conductus. Stringent requirements on shielding the devices from rf interference and dc magnetic fields are necessary to ensure that the measurements are meaningful. An additional constraint is imposed by the necessity to minimize flow of heat into the device package. Engineering solutions to these problems, and the resulting performance of the measurement system, are described. The package and associated electronics have been integrated into the flight satellite.**

## I. Introduction

THE initial uses proposed for high temperature superconductor (HTS) technology in space involved passive elements such as RF filters. It is important to be able to advance to more sophisticated applications that involve active devices on the same chip. HTS Josephson junctions represent the most promising candidate for such a device. These are now being produced in several laboratories by various technologies, but have not reached a level of maturity to be routinely integrated into a complicated microwave circuit. One of the high temperature superconductor space experiments (HTSSE-II), the TRW experiment, discussed in a companion article, does incorporate a small number of Josephson junction devices as part of a low-speed digital circuit. Widespread use of HTS technology in space hinges on development of an advanced generation of devices that can be fabricated in large numbers on the same chip as passive microwave devices.

A first step in qualifying active HTS microwave circuits for space applications is to qualify the basic active device, the Josephson junction. There are several issues to be addressed: how the devices age in a space environment, what sort of electronics is needed to monitor device characteristics, what kind of shielding, both against magnetic and EMI fields, is required. Additional complications are imposed by the fact that such devices need to be protected from humidity and there is no widely used packaging technology analogous to the TO cans of the semiconductor industry.

Manuscript received October 16, 1995; revised February 27, 1996.

The authors are with the Naval Research Laboratory, Washington, DC 20375 USA.

Publisher Item Identifier S 0018-9480(96)04798-9.

The basic goal of this experiment then is to monitor the current-voltage characteristics of individual Josephson junction devices supplied from two different industrial laboratories. Data will be taken at various stages before and after launch, and compared to see if any changes occur. We expect some differences between initial laboratory measurements and those on the cold bus, since the operating temperature will be somewhat different. However any changes observed once the devices are mounted on the cold bus can be ascribed to changes in the devices themselves.

The current-voltage curve is the single most important means of evaluating a Josephson junction; in a more complicated circuit it would probably be impossible or impractical to extract this information. The parameters of interest are the critical current (the current at which a voltage just starts to appear), the resistance of the device at currents above critical, the effective noise level (which determines the degree to which the characteristic near the critical current is "rounded"), and any asymmetry between positive and negative currents.

## II. Requirements

The experiment was designed with the following requirements in mind:

1) The devices must be shielded from external electromagnetic interferences. Josephson junctions have a broadband sensitivity to rf currents much greater than any semiconductor device, and the stringency of this requirement is of a higher order than normally encountered.
2) Magnetic fields must be attenuated. Laboratory tests of one device showed that fields as low as 0.1 G could modify the current-voltage characteristic. Initial estimates of the ambient field in the satellite ranged as high as 10 G, and this was the assumed level for testing purposes. Subsequent measurements of the field produced by the cryocooler (the dominant on-board magnetic source) suggest external fields at the sample position closer to the 1 G level.
3) The devices must be protected from humidity.
4) The heat load from 300 K electronics should be minimized.

## III. Cooled Package Design

Two devices; one fabricated by Conductus (dev.1) and the other by TRW (dev.2) are mounted in the flight package. The

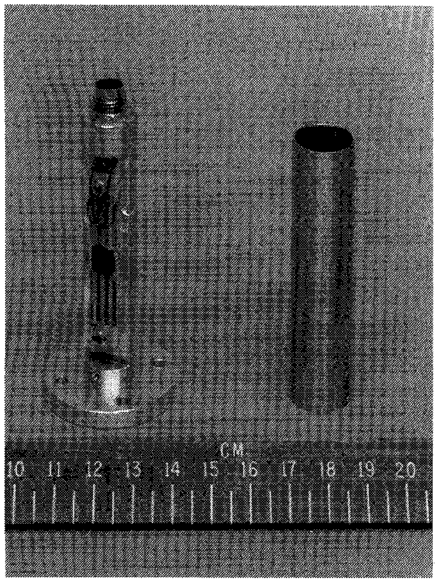



Fig. 1. Photograph of the device mounting package and shield prior to assembly, showing one of the chips and carrier.

Conductus Josephson junction is of the SNS type with the $N$ layer being CaRuO and the superconductor being YBCO. The fabrication technique for these devices is given in [1]. The TRW device also uses YBCO as the superconductor, and is fabricated by the step-edge technique. Here the barrier yielding Josephson efffects consists of a grain boundary. This device was fabricated as described in [2], with the addition of a passivation layer of $SrTiO_3$ to improve stability. Both device chips were glued to a carrier patterned with 4 solder/bonding pads (gold-plated copper). In one case (dev.1) the carrier was fiberglass PC board, and in the other (dev.2) it was alumina. The pads in turn were wire-bonded to the device on the chip.

Fig. 1 shows the NRL device package design. The chip carriers are attached with "long-lock" screws to an aluminum mounting surface that locates the devices near the center of a cylindrical $\mu$-metal shield, 0.75 in. OD and 3 in. long. The shield is a commercially available unit, meant for use with photomultiplier tubes, from which the paint was stripped. The carrier solder pads were used to make connections to the miniature connector (Microtech LF series) at the end of the package. This connector was found to work reliably after shake tests and repeated cycling to 78 K. A hermetic version is available but was not used since these often involve magnetic materials. Rather, an adequate seal was obtained by filling the region behind it with an epoxy that is known to work at reduced temperature (see below).

## IV. Electronics Design

In the flight electronics, all control functions are established via standard command pulses derived from the main processor. These include sweep current direction, digital resolution (8 bits or 10 bits), and an overall reset. Selection of the device to be measured is accomplished with relays which are switched via command pulses. The current to the device selected is swept via a series of pulses sent to a counter whose output is sent to a 10-bit DAC (AD 561). The output of the DAC ($\pm 5$ V range) is sent to the device via a resistor to define the current. (The resistance of the devices is small enough that the current is accurately determined with an external resistor). An appropriate current-limiting resistor is selected for each device prior to installation of the electronics in the satellite. The voltage across a device is amplified first with an instrumentation amplifier (INA101), with the overall gain tailored to the specific device to yield an output voltage range approximately $\pm 5$ V. Several outputs are available to be read with the onboard 12-bit ADC's, which have an input range of $\pm 5$ V. These include the amplified device voltage, the output of the DAC, and a pair of outputs which contain information about the state of the digital portion of the electronics.

To maximize rf isolation between the experiment electronics and the external environment, the command pulses were transmitted through optical isolators. Output voltages and power supply lines passed through EMI filters.

Because of the accelerated timing of the experiment development, the flight electronics were not available for testing until late in the overall development period. It was thus initially necessary to build a much simplified laboratory version of the electronics to test devices and procedures. This used the same basic current drive and voltage detection IC's, but acheived computor control via a digital word generator and switched between devices with a semiconductor analog switch (AD 7512).

The 50 cm cable between the cooled device package and the 300 K connector panel used a 12-pin Microtech connector at the cold end (of which eight were used) and a conventional connector at the warm end. The leads consisted of two sets of "Quad-twist" wire assemblies from Lake Shore, Inc., shielded by a nominal 1/16" ID stainless steel braid. The leads are insulated #36 phosphor-bronze alloy and have total resistance $\sim 5\ \Omega$. The estimated heat load from the leads and shield were 14 and 11 mW, respectively, representing approximately 4% and 3% of the total cryocooler load.

## V. Testing

In addition to the standard vibration and environmental testing of the components of the experiment, additional tests were required to ensure that the specific requirements mentioned above for a meaningful measurement of a Josephson junction are met. These are detailed in the following:

## VI. Magnetic Shielding

The $\mu$-metal shield, which is designed for use at room temperature, was tested at 78 K. The axial shielding was tested using a commercial gaussmeter and a copper wire solenoid to generate fields, and found to give a shielding factor $\sim 100$, almost as good as the room temperature value. A more important parameter is the shielding against transverse fields, since fields in this direction couple most strongly into the Josephson junctions. The transverse shielding properties were tested at 78 K using a Hall effect detector (model GH600 sensor from F. W. Bell, made from GaAs). A large permanent magnet placed tens of cm from the shield was used to generate an approximately uniform external field. For

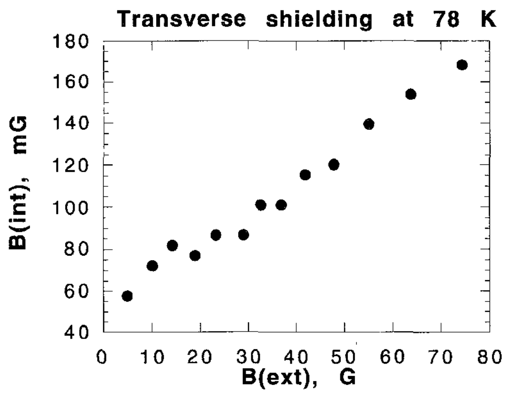



Fig. 2. Test of shielding performance of the $\mu$-metal shield at 78 K.

each measurement the detector was rotated 180 deg., and the readings subtracted, to remove the offset voltage. The uncertainty in the internal field measurements is ~10 mG. Fig. 2 shows the results at 78 K, which are not much different than those at 300 K. For this shield, which had been previously exposed to fairly large external fields, a remnant field would be expected. Shields used for the actual flight package were protected from large field excursions. We conclude that with an external field of 10 G the shielding is adequate to avoid modification of the characteristics of the Josephson juncion.

## VII. EMI Shielding

Since the Josephson junction is more sensitive to high frequencies than any alternative testing device, we must use the samples themselves to establish that EMI levels are adequately low. To do this, the current-voltage characteristic should first be measured in an environment known to have a low level of rf noise. Deviations of the characteristic in the actual environment of the experiment from this benchmark measurement would suggest excessive rf interference. In general, rf noise will have the effect of lowering the apparent critical current of the junction, and may increase the degree of "rounding" in the vicinity of the critical current [3]. It must be stressed, however, that other explanations of differences in the characteristics should also be considered: first, the critical current of the devices used is a strong function of temperature, and there are many well-known difficulties in knowing the temperature of a site without a thermometer being placed exactly there. Second, it was found that some of the devices to be tested underwent significant drifts over time.

There are additional signatures of interference, at least in a typical urban context. One follows from the fact that rf noise levels are rarely constant either in time or space. Thus a critical current that seems to be fluctuating is often a signature of inadequate shielding. Likewise, if the device is moved around the room while monitoring its critical current, a dependence on position or orientation suggests that it is coupling to external rf signals. Rapid rise time pulses, which may be considered a particular class of rf interference, lead to a characteristic result: such pulses often facilitate the entry of trapped flux vortices into the active region of the Josephson junction. Trapped fields generally result in an asymmetry between the positive and negative critical currents. The specific trapping configuration may persist indefinitely, or may change to a different one upon arrival of a new pulse of sufficient magnitude.

Extensive testing of devices in a relatively noisy laboratory environment gave convincing evidence that external noise was not a problem when the "lab" version of the electronics package was used. There are important differences between this electronics and the flight version which could affect rf immunity: the use of pulses to control functions of the latter, and use of mechanical relays. Further, the ultimate rf noise environment is difficult to simulate in laboratory experiments. The time constraints of integrating the experiment with the satellite left little opportunity to monitor the devices with the flight electronics, in the actual noise environment to be ultimately encountered. While some interim testing phases did show clear indications of excessive rf noise, the final thermal-vacuum test of the flight unit was much more reassuring. Any differences between the "baseline" current-voltage curves and those of the tests could be accounted for by possible small differences in operating temperature or drifts in junction properties. These conclusions, however, are based on a small statistical base. Only experience in flight will make it clear whether shielding of the junctions was adequate.

## VIII. Protection from Humidity

The flight package was assembled in a glove box with an atmosphere of dry nitrogen, then sealed with epoxy. The epoxy used (Stycast 2850 FT) is well established for use in cryogenic applications, with a coefficient of expansion much closer to that of metals than most alternatives. Nevertheless, there is no guarantee that small leaks will not appear after the rigors of launch and cool-down. However leaks at that point are irrelevant, since presumably water vapor will no longer be present. The only purpose of the seal is to protect the devices from humidity during their wait on the ground.

During the laboratory testing phase, the device package was not sealed, and was cooled simply by immersion in liquid nitrogen. To avoid condensation of water on the devices during warmup, the whole package was quickly transferred to a vacuum desiccator, and pumped while warming up. While one of the devices did show changes in its characteristics over time, it is doubtful that this could be ascribed to chemical degradation due to humidity.

## IX. Temperature Control

The temperature sensitivity of the current-voltage characteristics of the devices has not been measured, but is expected to be large. It is thus important that the temperature of the devices in flight be accurately known. We presume that the temperature of the cold bus, to which the device package of Fig. 1 is attached, will be accurately monitored. The issue is then whether the temperature of the devices themselves is the same as the cold bus. The primary source of heat that could raise their temperature is via the wires leading to the 300 K electronics. To test this, a cold package without the epoxy seal was bolted inside an indium wire sealed can which was immersed in liquid nitrogen. Connection to the lab electronics

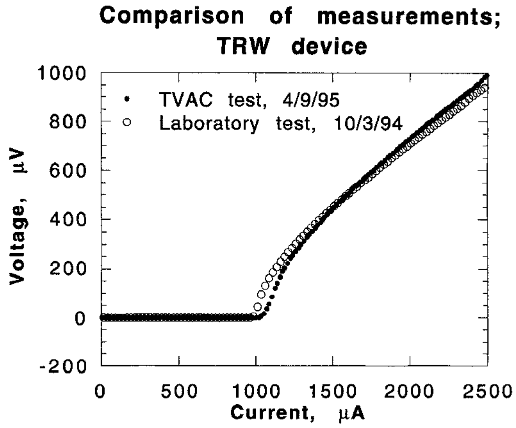



Fig. 3. Comparison of the current-voltage characteristics of the TRW device measured first with laboratory electronics, immersed in liquid nitrogen; then approximately 6 months later in the thermal-vacuum test of the satellite, using on-board electronics and telemetry, nominally at 78 K.

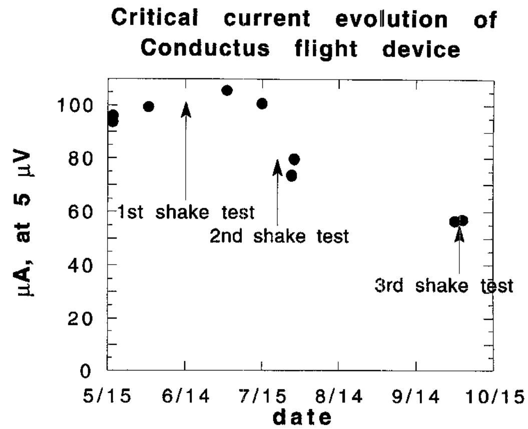



Fig. 4. Evolution of the critical current of the Conductus device during the testing period prior to delivery for integration.

was via leads identical those to be used in the spacecraft. The can was pumped to a high vacuum, ensuring that heat conducted down the leads is not carried away by cold gas. This thus approximates the thermal environment to be encountered in flight. After recording the current-voltage characteristics of the devices, nitrogen gas was admitted to the can. This should ensure that the device temperatures are precisely at that of the liquid nitrogen bath. For both devices, changes in the critical currents were observed, suggesting that their temperatures were raised by heat coming down the leads. In the case of dev. 2, from TRW, the change was quite small (0.5%), probably due to the relatively high thermal conductivity of its alumina chip carrier which helps shunt heat carried by the wires toward the cold bus. In the case of dev. 1, from Conductus, the change was rather larger: ~8%. This is most likely a consequence of the poorer conductivity of the fiberglass chip carrier.

At the time that the sensitivity to heat influx via the leads was observed, it was too late to incorporate substantial changes in the design. One difference between the above experiment and the flight package is that the latter includes an epoxy seal of the leads as they enter the package, which should provide some additional thermal shunting. Another favorable point is that we are primarily interested in changes in the device characteristics over time; the most important requirement then is that the temperature of successive measurements be the same. There is no reason to believe that the temperature offsets noted above should change over time.

## X. Current Status

The flight package containing two devices has passed all relevant vibration/environmental tests and has been integrated into the satellite. Fig. 3 shows data for the TRW device obtained in the laboratory just prior to delivery for integration, as well as data generated in a "Thermal-Vacuum" test of the satellite six months later. No asymmetry between positive and negative branches of the current-voltage characteristics was noted in the latter case, suggesting that trapped flux was not a problem. There are some noticeable differences in the two measurements: the slope of the curve at high currents (the differential resistance) is slightly greater as measured in the satellite, while the critical current is larger by ~7%. Changes of this magnitude could be the result of aging of the device, or more likely can be explained if the temperature was slightly lower in the satellite than in the case of the laboratory measurements. Generally, we are confident that the satellite data is a correct representation of the characteristics of the devices.

The laboratory and on-board measurements of the Conductus device differ significantly. In this case the explanation is almost certainly drift in its characteristics. It was observed that this device changed considerably over time. Fig. 4 shows the evolution of its critical current (measured in the laboratory) over several months prior to integration into the satellite. There were also smaller, random shifts following individual thermal cycles.

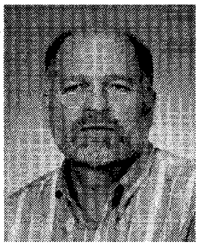
## XI. Summary

Two Josephson junctions will have their current-voltage characteristics monitored before and during the space flight. Various issues involved in obtaining a meaningful measurement have been addressed and solved. An important remaining one is the intrinsic drifts in the characteristics of the devices selected, independent of exposure to a space environment. These changes probably have to do with some sort of slow physical relaxation or chemical change in the junction region. Either process would be effectively frozen once the cold bus reaches its operating temperature, so observations of changes during the cooled duration of the flight should be meaningful. However, changes between measurements on the ground and just after launch will be hard to interpret. By contrast, the characteristics of the TRW device over the same period represented in Fig. 4 changed by a negligible amount. Thus this may prove to be a more useful indicator of the utility of HTS Josephson devices in space applications.

## References

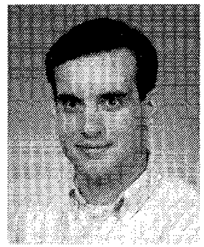
[1] K. Char, M. S. Colclough, T. H. Geballe, and K. E. Myers, "High $T_c$ superconductor-normal-superconductor Josephson junctions using $CaRuO_3$ as the metallic barrier," *Appl. Phys. Lett.*, vol. 62, p. 196, 1993.

[2] J. Luine, J. Bulman, J. Burch, K. Daly, A. Lee, C. Pettiette-Hall, S. Schwarzbek, and D. Miller, "Characteristics of high performance $YBa_2Cu_3O_7$ step-edge junctions," *Appl. Phys. Lett.*, vol. 61, p. 1128, 1992.
[3] K. K. Likharev, "Superconducting weak links," *Rev. Mod. Phys.*, vol. 51, p. 101, 1979.



**John H. Claassen** received the Ph. D. degree in physics from Cornell University, Ithaca, NY, in 1972.

He worked as a post doctoral fellow in the Department of Physics, University of California, Berkeley, concentrating on applications of Josephson junctions as high frequency detectors and mixers. He moved to the U.S. Naval Research Laboratory, Washington, D.C., in 1977, and has worked there to the present. His experience includes development of a step-edge technique for fabricating Josephson junctions and SQUID's in NbN (later used in HTS), growth of ultra-clean epitaxial films of refractory metals, and a first observation of universal conductance fluctuations in ultra-fine wires of Nb. He has developed a novel technique for quantifying the proximity effect in normal/superconductor bilayer films. Since the advent of high critical temperature oxide superconductors, he has participated in MBE growth of films, and development of inductive techniques for measurement of the critical current density and superconducting penetration depth. He was the manager of one of the NRL experiments to be flown on the HTSSE-II satellite project.



**Robert G. Skalitzky** received the B.S. degree in electrical engineering from Northwestern University, Evanston, IL, in 1990.

Since 1987, he has worked for the U.S. Naval Research Laboratory's Naval Center for Space Technology in the Power and Instrumentation Section, Washington, D.C. He is currently the Electical Lead on the Power Subsystem of the Microelectronics and Photonics Test Bed, a radiation effects space flight experiment on various electronic parts. His other work has included the first spaceflight Common Pressure Vessel $NiH_2$ Battery Experiment, radiation dosimeters and power system support for the Clementine spacecraft, the first spaceflight Sodium Sulfur Battery experiment and a next generation nonexplosive ordnance experiment. He designed and built the control electronics for the Josephson Junction experiment.

**Robert J. Soulen, Jr.** received the B.S. and Ph.D. degrees from Rutgers University, New Brunswick, NJ, in 1962 and 1967, respectively.

He was a Researcher in superconductivity and thermometry at the National Bureau of Standards, Gaithersburg, MD, from 1966 to 1982, where he developed an absolute temperature scale below 1 K based on noise thermometry. He was also coinventor of the NBS Superconductive Fixed Point Devices, SRM 767 and 768. He was subsequently Chief of the Temperature and Pressure Division at NIST from 1982 to 1987. He then became head of the Superconducting Materials Section, U.S. Naval Research Laboratory, Washington, D.C., where he leads a group in R & D of high temperature superconductivity.

Dr. Soulen received the NBS Condon Prize in 1976, the U.S. Department of Commerce Gold Medal in 1979, and was Elected Fellow of the American Physical Society in 1990.