NASA/TM—2001-211129

Electronic Components and Systems for Cryogenic Space Applications

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August 2001

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Prepared for the
2001 Cryogenic Engineering Conference (CEC) and
International Cryogenic Materials Conference (ICMC)
sponsored by the Cryogenic Society of America
Madison, Wisconsin, July 16–20, 2001

National Aeronautics and
Space Administration

Glenn Research Center

August 2001

Acknowledgments

This work was supported by NASA Glenn Research Center base R&T Program, and Contract Number NAS3–00145, GESS Task 0020. Support was also provided by JPL NASA Electronic Parts and Packaging Program (NEPP).

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ABSTRACT

Electronic components and systems capable of operation at cryogenic temperatures are anticipated in many future NASA space missions such as deep space probes and planetary surface exploration. For example, an unheated interplanetary probe launched to explore the rings of Saturn would reach an average temperature near Saturn of about –183 °C. In addition to surviving the deep space harsh environment, electronics capable of low temperature operation would contribute to improving circuit performance, increasing system efficiency, and reducing payload development and launch costs. Terrestrial applications where components and systems must operate in low temperature environments include cryogenic instrumentation, superconducting magnetic energy storage, magnetic levitation transportation systems, and arctic exploration. An on-going R&D program at the NASA Glenn Research Center focuses on the development of reliable electronic devices and efficient power systems capable of surviving and operating in low temperature environments. An overview of the program will be presented in this paper. A description of the low temperature test facilities along with selected data obtained from in-house electronic component and small system testing will also be discussed.

INTRODUCTION

In many future NASA missions such as planetary exploration, space probes, and communication satellites, high power electrical components and systems must operate reliably and efficiently in very cold environments. Electronic instrumentation and power systems deployed near Pluto will encounter temperatures as low as –229 °C [1]. TABLE 1 shows typical temperatures of spacecraft heated only by the sun.

Power electronics capable of low temperature operation will not only survive the harsh environments, but will reduce system size and weight by eliminating the need for radio-active heating units and associated equipment, thereby reducing launch cost, improving reliability and lifetime [2], and increasing energy densities. Low temperature electronic components will also have a great influence in many terrestrial applications such as cryogenic medical instrumentation, superconducting magnetic energy storage and distribution systems for the power industry, magnetic levitation transportation systems, as well as NASA's Arctic and Antarctic missions.

Commercial-off-the-shelf components are usually limited in their temperature handling capability due to limitations in the materials being used or due to the inherent design and manufacturing processes and techniques. New materials and advanced components capable of providing more efficient and reliable operation at low temperatures coupled with improvement in design topologies, therefore, constitute a major challenge in the development of advanced power systems suitable for use in deep space and other harsh environments.

The Low Temperature Electronics Program at the NASA Glenn Research Center (GRC) focuses on research and development of electrical components and systems suitable for applications in deep space missions. Research is being conducted on devices and systems for use down to cryogenic temperature (–230 °C). The goal of the GRC Low Temperature Electronics Program is to develop and demonstrate reliable, efficient power systems capable of surviving and exploiting the advantages of low temperature environments. The targeted systems are mission-driven and include converters, inverters, power controls, digital circuits, and special-purpose circuits. Initial development efforts have produced the successful demonstration of low temperature operation and cold-restart of several DC/DC converters (with outputs from 5 to 1000 Watts) utilizing different design topologies [3–5]. Some of these circuits employed superconducting inductors.

In support of system development, device and component research and development efforts are underway in critical areas of passive and active components, opto-electronic devices, and energy generation and storage. Initially, commercial-off-the-shelf (COTS) devices and components are characterized in terms of their low temperature performance.

TABLE 1. Temperature of spacecraft, without internal heat generation, at various distances from the sun

Distance from Sun	Solar Intensity (W/m^2)	Unheated Spacecraft Temperature (°C)
Mercury	9149.0	175
Venus	2620.0	55
Earth	1371.0	6
Mars	591.0	–47
Jupiter	51.0	–151
Saturn	15.0	–183
Uranus	3.7	–209
Neptune	1.5	–222
Pluto	0.9	–229

When viable commercial devices fail to meet mission requirements, efforts are then undertaken to develop advanced low temperature components. A description of the GRC Low Temperature Test Facilities, along with selected data obtained from in-house component and circuit testing are given below.

LOW TEMPERATURE FACILITIES

At NASA Glenn Research Center, facilities exist for the testing of electrical power, control, and other circuits operating from DC to several Megahertz over a wide temperature range. These facilities consist of several liquid nitrogen cooled environmental chambers in which a circuit can be operated with controlled temperature in the range of 200 °C to –196 °C. The chambers have built-in controllers that allow selecting the desired temperature rate of change as well as soak times. Computer-controlled instrumentation is interfaced with the environmental chambers via IEEE GPIB-488 for data acquisition. Measurement equipment include a digital signal analyzer, pattern generators, precision digital RLC meters, high speed storage oscilloscopes, precision temperature controller and recorder, and various electronic and resistive loads for handling power levels from milliwatts to kilowatts.

A unique computerized control system is used in conjunction with a cryopumped vacuum chamber containing a cryocooled sample holder for the characterization of commercial and developmental semiconductor devices and components. This facility is capable of in-situ I-V and C-V characterization of semiconductor devices from 23 °C to –248 °C.

GRC has designed computer-controlled facilities for low-temperature long term thermal cycling and characterization of electrical and physical properties of dielectrics and capacitors. In addition, facilities have been built at GRC for reliability studies and life testing of passive and active devices in space-like environments under multi-stress conditions. Typical studies that can be carried out using these unique facilities include dielectric material characterization, DC and AC breakdown voltages, resistivity measurements, switching characteristics, and power system output regulation and efficiency.

Other on-site supporting research facilities include physical, chemical, and mechanical test chambers and diagnosis stations. Characterization of materials and evaluation of systems and components under space-like environment, such as vacuum, plasma, ultraviolet radiation, and atomic oxygen, can be achieved in multi-stress aging test rigs and facilities.

LOW TEMPERATURE R&D ACTIVITIES

On-going research includes characterization of commercial-off-the-shelf, as well as newly developed components and circuits for potential use in low temperature applications. Results of some of the investigations follow.

FIGURE 1 shows the output voltage and efficiency of a DC/DC converter versus temperature for four conditions of input voltage and output load levels. These conditions included minimum input voltage under light and heavy loads, and maximum input voltage under light and heavy loads. The converter showed relatively good output regulation down to –120 °C, as depicted in FIGURE 1. Beyond that temperature, the output voltage seemed to increase slightly as the temperature was decreased further. Its efficiency, however, exhibited a gradual decrease as temperature was decreased. For a given temperature, the efficiency was higher at heavy load than that at light load conditions. Under the same loading, the efficiency was higher as the input voltage was decreased. Although this module ceased to operate for temperatures below –180 °C, it regained operation once its temperature rose above –180 °C.

The functionality of a pulse-width-modulation (PWM) controller chip at low temperature was evaluated by observing the waveforms of its internal voltage reference and the PWM outputs in the temperature range of 20 °C to –140 °C. The performance of the controller chip at room temperature and at –140 °C is shown in FIGURES 2a and 2b, respectively. It can be clearly seen that the reference voltage remained relatively stable, but the output frequency and duty ratio changed considerably. The dead time, however, did not exhibit much change with temperature.

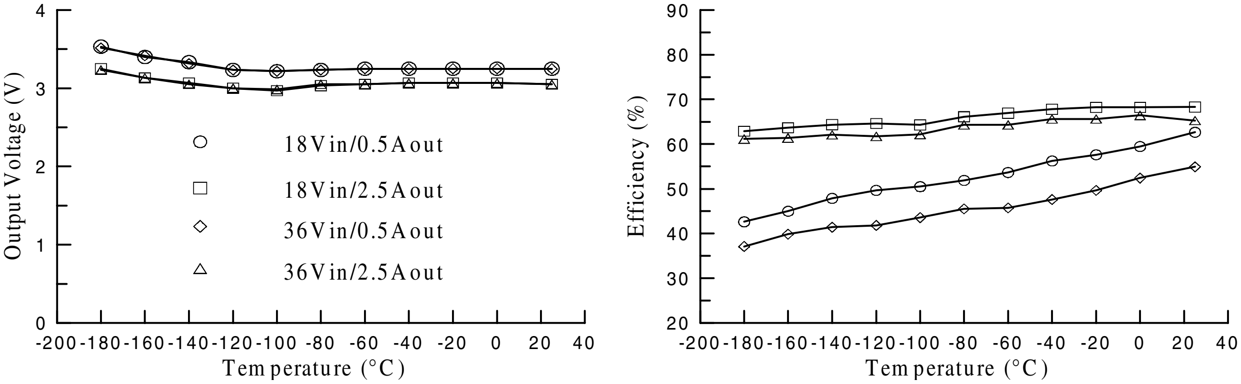

FIGURE 1. Output voltage and efficiency of a DC/DC converter as a function of temperature.

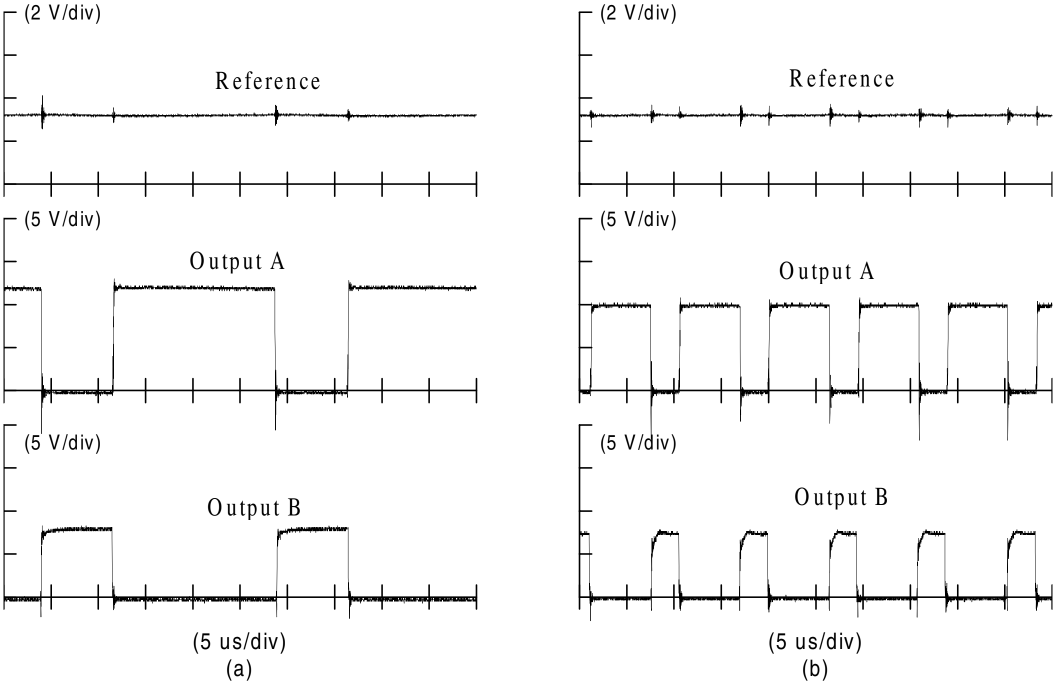

FIGURE 2. (a) Performance of a PWM controller chip at room temperature and (b) at –140 °C.

Several oscillator circuits designed for low temperature operation were built and evaluated as a function of temperature in the range of 20 °C to –190 °C. The dependence of the oscillator output frequency of three circuits utilizing different components is shown in FIGURE 3. It can be clearly seen that a drop in the output frequency, for all circuits, occurred as the temperature was decreased. The frequency drop is attributed to and is consistent with crystal behavior at lower temperatures. For frequency-stable operation under extreme temperatures, some compensation must be incorporated into the circuit design in order to counteract the effects of low temperature on the oscillator output behavior.

FIGURE 4 shows the change in capacitance for three types of capacitors in the temperature range of 25 °C to –190 °C at a frequency of 20 kHz. It can be seen clearly that while the mica capacitor exhibited excellent stability with temperature, the electrolytic tantalum capacitor underwent a significant decrease in capacitance when the test temperature dropped below –25 °C. In fact, at temperatures below –80 °C the capacitance dropped to zero. Unlike its electrolytic counterpart, the solid tantalum capacitor exhibited only a slight decrease in capacitance as temperature was decreased. This reduction in capacitance amounted to only about 10 percent even down to –190 °C.

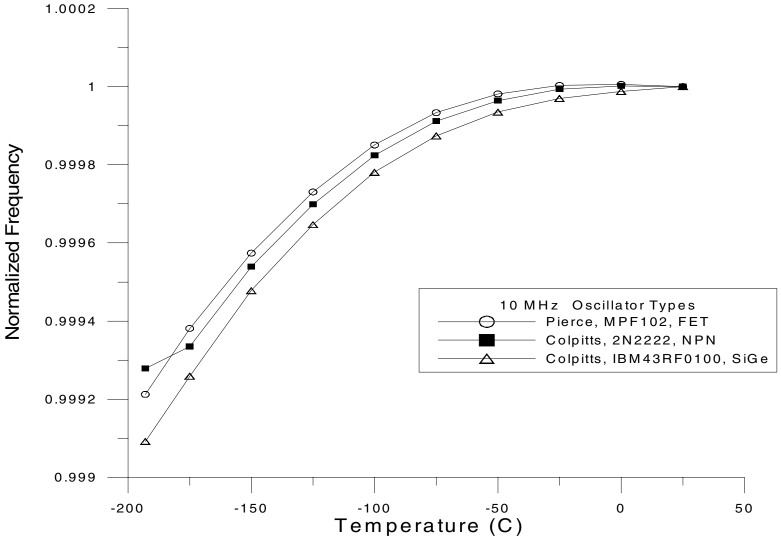

FIGURE 3. Output frequency of three oscillator circuits as a function of temperature.

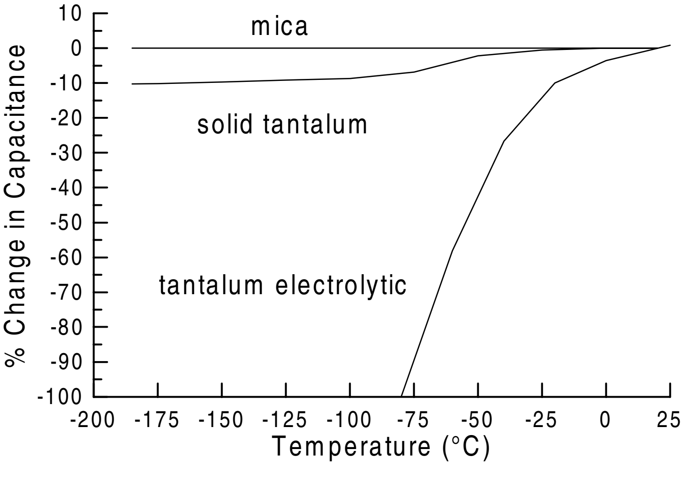

FIGURE 4. Change of capacitance as a function of temperature for three types of capacitor.

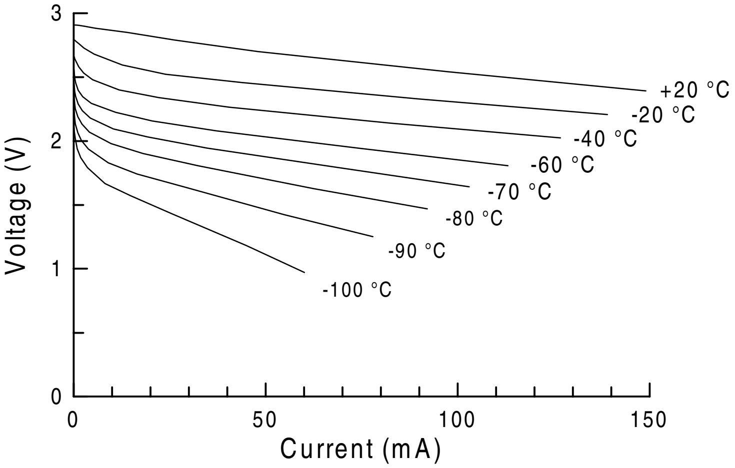

FIGURE 5. Current-voltage characteristics at various temperatures for a lithium carbon monofluoride battery.

Energy storage is an area of major importance in power systems for space applications. Efforts are being performed to develop energy storage devices that can operate reliably and efficiently under extreme temperatures. Lithium-based batteries are considered as good candidates for low temperature short-term space missions. The effect of temperature on the current-voltage characteristics of a lithium primary battery is depicted in FIGURE 5. The characterization of this lithium primary battery was performed at various loads at a given test temperature. It is quite evident that the battery underwent a drop in its voltage/current performance with decreasing temperature. The reduction in the battery capacity with decreasing temperature was more noticeable at higher load levels.

It is important to note that the effect of low temperature exposure on a particular device varied from minimal to being detrimental to its performance depending on several parameters that included the device internal structure, material constituents and compatibility under extreme temperatures, and packaging topologies.

CONCLUSION

An overview of the Low Temperature Electronics Program at NASA Glenn Research Center was given. The research efforts are focused on developing selected, mission-driven, power systems and supporting technologies for low temperature operation. The on-going activities include dielectric and insulating material research and evaluation, development and testing of low temperature power components, and electronic system integration and demonstration. Other supporting research investigations comprise long term reliability assessment of power devices and integrated circuits and the effects of low temperature exposure on device interconnect and packaging.

A description of the in-house low temperature test facilities for material testing and characterization, and component and system evaluation along with some preliminary experimental data were also presented. Coordination of the various research and development efforts with other agencies, academia, and the aerospace industry as well as the utilization of test facilities with the proper diagnostic and analytical tools will certainly contribute to meeting the needs of future space power and other electrical systems.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2001	Technical Memorandum

4. TITLE AND SUBTITLE

Electronic Components and Systems for Cryogenic Space Applications

5. FUNDING NUMBERS

WU–755–A4–12–00

6. AUTHOR(S)

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S. Gerber, M.E. Elbuluk, and E. Overton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–12978

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2001-211129

11. SUPPLEMENTARY NOTES

Prepared for the 2001 Cryogenic Engineering Conference (CEC) and International Cryogenic Materials Conference (ICMC) sponsored by the Cryogenic Society of America, Madison, Wisconsin, July 16–20, 2001. R.L. Patterson, J.E. Dickman, and E. Overton, NASA Glenn Research Center; A. Hammoud, QSS Group, Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142; S. Gerber, ZIN Technologies, Inc., 3000 Aerospace Parkway, Brook Park, Ohio 44142; and M.E. Elbuluk, University of Akron, Department of Electrical Engineering, 302 Buchtel Mall, Akron, Ohio 44325. Responsible person, R.L. Patterson, organization code 5480, 216–433–8166.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS

Cryogenics; Electronics; Low temperature; Space missions

15. NUMBER OF PAGES

13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102