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# Assessment of electronics for cryogenic space exploration missions

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## Abstract

Space exploration missions require electronics capable of efficient and reliable operation at low temperatures. Presently, spacecraft on-board electronics are maintained at approximately 20 °C through the use of radioisotopes. Cryogenic electronics would enhance efficiency of space systems, improve reliability, and simplify their design. A Low Temperature Electronics Program at the NASA Glenn Research Center focuses on research and development of electronics suitable for space exploration missions. The effects of cryogenic temperature and thermal cycling are being investigated for commercial-off-the-shelf components as well as for components specially developed for low temperature operation. An overview of this program along with selected experimental data is presented in this paper.

*Keywords:* Cryoelectronics (D); Space electronics (F); Semiconductors (A); Power applications (F)

## 1. Introduction

Electronic components and systems capable of low temperature operation are required for many future NASA space exploration missions where it is desirable to have smaller, lighter, and less expensive spacecraft. These include Mars orbiters, landers and rovers, Europa oceanic exploratory instrumentation, and outer planetary exploration and deep space probes. Table 1 shows typical cold environmental temperatures for spacecraft and surface probes in the solar system. For example, an inter-planetary probe launched to explore the rings of Saturn would experience a temperature of about −185 °C.

Presently, spacecraft operating in the cold environment of deep space carry on-board a large number of radioisotope heating units (RHUs) to maintain an operating temperature for the electronics of approximately 20 °C [1]. This is not an ideal solution because the radioisotope heating units are always producing heat, even when the spacecraft may already be too hot, thus requiring an active thermal control system for the spacecraft. In addition, RHUs are very expensive and require elaborate containment structures. Electronics capable of operation at cryogenic temperatures will not only tolerate the hostile environment of deep space but also reduce system size and weight by eliminating radioisotope heating units and associated structures. The exclusion of heating elements will result in reduced system development and launch costs, improved reliability and lifetime, and increased energy densities.

In addition to deep space applications, low temperature electronics have potential uses in terrestrial applications that include magnetic levitation transportation systems, medical diagnostics such as magnetic resonance imaging (MRI) that uses superconducting magnets, cryogenic instrumentation, and super-conducting magnetic energy storage systems. The utilization of power electronics designed for and operated at low temperature is expected to result in more efficient systems than room temperature systems. This improvement results from better electronic, electrical, and thermal properties of materials at low temperatures [2,3]. In particular, the performance of certain

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Table 1
Typical cold environmental temperatures for spacecraft and surface probes

| | | |
|---|---|---|
| Mercury | Slow rotation, minimum surface temperature | −180 °C |
| Earth | Minimum temperature | −75 °C |
| Moon | Minimum temperature | −230 °C |
| Mars | Windy and dusty, surface temperature | −140 °C to +20 °C |
| Jupiter | Cloudtops | −140 °C |
| Moon Europa | Icy surface temperature | −188 °C to −143 °C |
| Saturn | Cloudtops mean temperature | −185 °C |
| Moon Titan | Surface temperature | −180 °C |
| Uranus | Cloudtops temperature | −212 °C |
| Neptune | Mean temperature | −225 °C |
| Pluto | Mean temperature | −236 °C |

semiconductor devices improves with decreasing temperature down to liquid nitrogen temperature (−196 °C) [3,4]. At low temperatures, majority carrier devices demonstrate reduced leakage current and reduced latch-up susceptibility. In addition, these devices show higher speed resulting from increased carrier mobility and saturation velocity [3–5]. An example is the power MOSFET that has lower conduction losses at low temperature due to the reduction in the drain-to-source resistance RDS(on) resulting from increased carrier mobility [4,6,7].

## 2. NASA Glenn Research Center Low Temperature Electronics Program

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 (−196 °C). The goal of the 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, 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 W) utilizing different design topologies [1,4,7]. Some of these circuits employed inductors made of superconductor material.

In support of system development, device and component research and development efforts are underway in critical areas of passive and active components, optoelectronic devices, and energy generation and storage. Initially, commercial-off-the-shelf (COTS) devices and components are characterized in terms of their performance at low temperatures. When viable commercial devices fail to meet mission requirements, efforts are then undertaken to develop special cryo-tolerant components. In addition to the development efforts to fill the technology gaps in low temperature power electronics, thermal issues relating to packaging, integration, and cycling are being explored.

## 3. Low temperature R&D activities

Some of the components that are being characterized include semiconductor switching devices, pulse width modulation controllers, high frequency oscillators, DC/DC converters, sensors and transducers, and passive and active devices. Results of some of the investigations follow.

### 3.1. Oscillators

The performance of two similar solid-state resistor-tunable oscillators was investigated in the temperature range of 25 °C to −193 °C. These tunable devices have good accuracy and can be driven with a single 2.7–5.5 V power supply providing a 50% duty cycle square wave output. These units, which were industrial grade with a specified operating temperature range from −40 °C to +85 °C, have a CMOS output driver that insures fast rise/fall times and rail-to-rail switching. The output frequency of device 1 and 2 was set to 10 and 11 MHz, respectively, via the selection of external precision resistors.

The output frequency of the two oscillator circuits is shown as a function of temperature in Fig. 1. Both devices exhibited a gradual decrease in output frequency as temperature was decreased. At −100 °C, for example, this decrease in frequency amounted to 1.7% and 1.2% for device 1 and device 2, respectively. At the extreme lowest test temperature, namely −193 °C, the output frequency of device 1 decreased by 5.6% while that of device 2 decreased by 3.5% from their room temperature values. The change in frequency with temperature in the range of 25 °C to −40 °C seems to agree with that of the device specifications as these integrated circuits are specified by the manufacturer to have a ± 40 ppm/°C temperature stability with operating temperature range of −40 °C to +85 °C. It can be speculated that the decrease in the output frequency

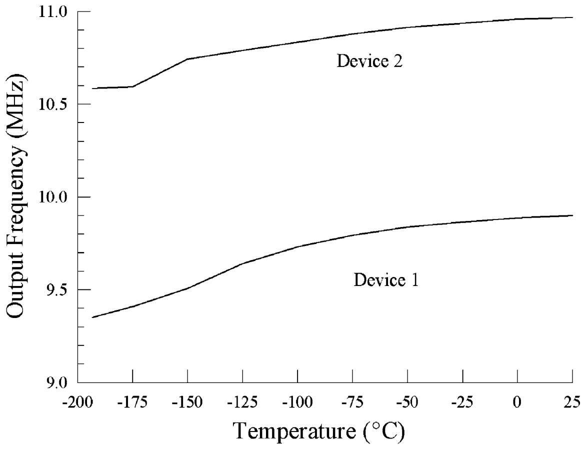

Fig. 1. Output frequency for two oscillator devices as a function of temperature.

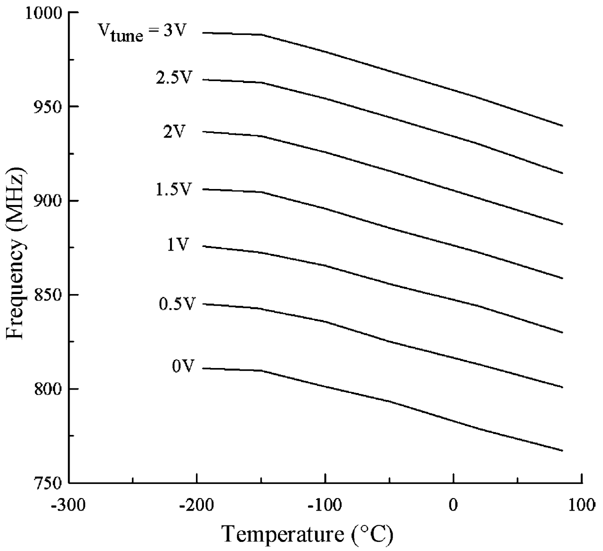

Fig. 2. Oscillator frequency versus temperature of a silicon germanium oscillator for various tune voltages.

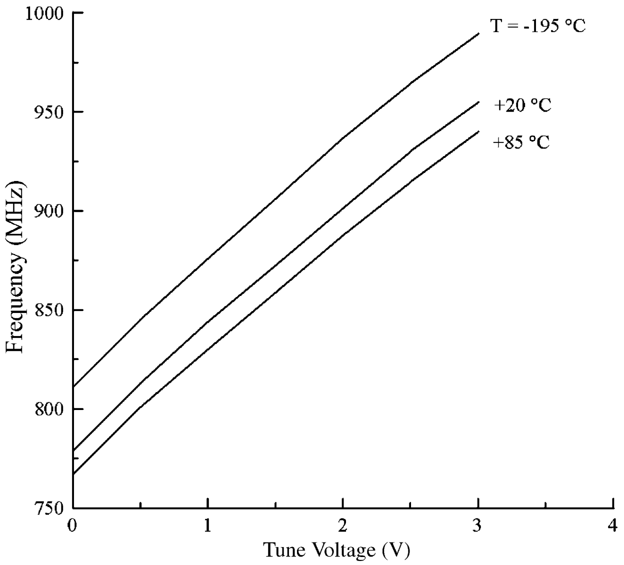

Fig. 3. Frequency vs. voltage of silicon germanium oscillator (pre-cycling).

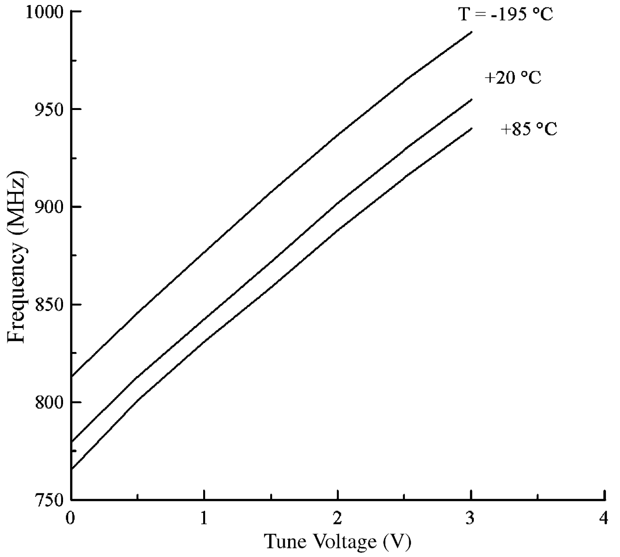

Fig. 4. Frequency vs. voltage of silicon germanium oscillator (post-cycling).

of the oscillator at very low temperatures may be associated with drift in the values of external tuning resistors or variation in the operation of internal transistors or amplifiers.

The output frequency at various tune voltages of a silicon germanium (SiGe) voltage-controlled oscillator (VCO) is shown as a function of temperature in Fig. 2. For any given test temperature, the output frequency increases with increase in the external control tune voltage. It can be also seen that the frequency increases, almost linearly, as the temperature is decreased from +85 °C to −150 °C. This trend is observed at all levels of the applied tune voltage. As the temperature is further decreased beyond −150 °C, i.e. to −195 °C, the oscillating frequency experiences insignificant increase. The effects of thermal cycling under a wide temperature range on the operation of this SiGe voltage-controlled oscillator were investigated by subjecting the device to a total of 12 cycles between −195 °C and +85 °C at a temperature rate of 10 °C/min. Measurements of the output frequency and supply current of the cycled devices were then taken at +20, +85, and −195 °C. A comparison of the output frequency of the oscillator as a function of tune voltage at test temperatures of +20, +85, and −195 °C for pre- and post-cycling conditions are shown in Figs. 3 and 4, respectively. It can be clearly seen that the post-cycling frequency/voltage curves at any given temperature were the same as those obtained prior to cycling. Similar results were obtained on the supply current of the oscillator chips. This limited thermal cycling also appeared to have no effect on the structural integrity of these parts as no structural deterioration or packaging damage was observed.

### *3.2. DC/DC converters*

Several DC/DC converters have been built and characterized, in-house, at low temperatures. The converters were designed or modified to operate from room temperature to −196 °C using commercially available components such as CMOS-type (Complementary Metal-Oxide-Semiconductor) devices and MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) switches. These systems had output power range from 5 W to 1 kW with switching frequencies of 50–200 kHz. Pulse width modulation technique was implemented in most of these systems with open-loop as well as closed-loop control. The topologies included buck, boost, multi-resonant, push-pull and full-bridge configuration [8–11]. In addition, several commercially available DC/DC converter modules were investigated for potential use at low temperatures. The output voltage of a commercial DC/DC converter at various load levels, for example,

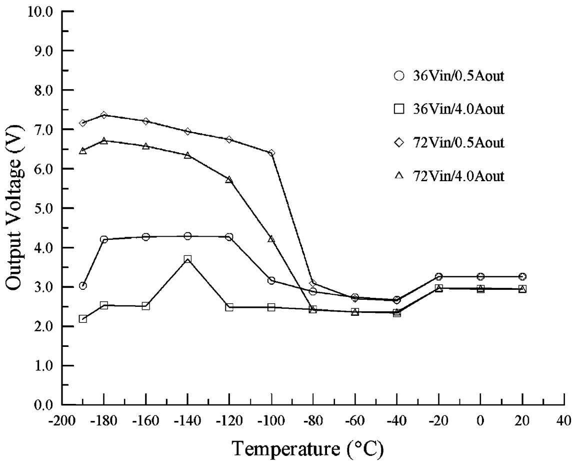

Fig. 5. Output voltage of an unstable DC/DC converter module as a function of temperature.

is shown as a function of temperature in Fig. 5. It can be seen that the output voltage of this particular module tends to be steady only between +20 °C and −20 °C. A slight reduction occurs in voltage regulation as temperature is further decreased to −80 °C. Beyond that temperature, the converter tends to become unstable in terms of voltage regulation. This behavior occurs regardless of the levels of the applied input voltage and connected output load. The output voltage of another commercial converter module under the same test conditions is depicted in Fig. 6. At low load levels, this converter exhibits excellent stability in its voltage regulation throughout the temperature range from 20 °C to −120 °C. At heavy loads, however, the converter output voltage tends to decrease with decreasing temperature. This decrease becomes more evident at temperatures lower than −40 °C. It is important to note that although this converter ceases to operate beyond −120 °C it does, however, recover when the temperature is raised above that level. The low temperature-induced effects on the operation of either converter could not be specifically identified as the converters were modular units and access to internal test points was not feasible. However, it can be speculated that the unstable converter used silicon bipolar transistors that significantly dropped in current gain as temperature decreased and rendered the converter useless at low temperatures. The more stable converter likely used MOSFETs and CMOS devices that would be more expected to produce better low temperature operation.

### 3.3. Transistors

An SOI (Silicon-On-Insulator) MOSFET and a standard MOSFET device were characterized in the temperature range of +20 °C to −190 °C. Performance characterization was obtained in terms of their gate threshold voltage (VGS(th)) and drain-to-source on-state resistance (RDS(on)). These properties were obtained using a digital curve tracer. The test temperatures at which these devices were investigated were: 20 °C, −50 °C, −75 °C, −100 °C, −125 °C, −150 °C, −175 °C, and −190 °C. Limited thermal cycling testing was also performed on the devices. These tests consisted of subjecting the devices to a total of five thermal cycles between +20 °C and −190 °C. A temperature rate of change of 10 °C/min and a soak time at the test temperature of 10 min were used throughout this work. Fig. 7 shows the gate threshold voltage (VGS(th)) versus temperature for both devices. The gate threshold voltage for each device was measured at very small values of drain currents. These values of drain current (i.e. 250 μA for the standard and 100 μA for the SOI) were selected from each of the manufacturer's specification. As can be seen from Fig. 7, both devices exhibit an increase in gate threshold voltage with decreasing temperature. The standard MOSFET device, which has a maximum specified gate voltage of 20 V, registered a gate threshold voltage in the range of 3.03–3.92 V from 20 °C to −190 °C. This corresponds to a normalized gate threshold voltage (VGS(th)/VGS(max)) range of 0.152 –0.196.

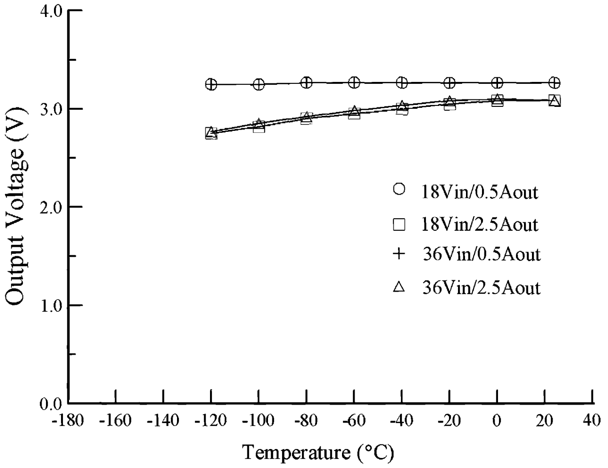

Fig. 6. Output voltage of a steady DC/DC converter module as a function of temperature.

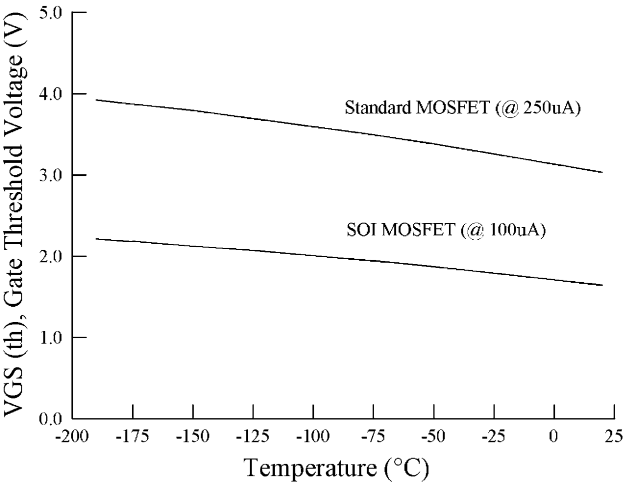

Fig. 7. Gate threshold voltage for SOI and standard MOSFET devices vs. temperature.

The SOI MOSFET device, which has a maximum specified gate voltage of 10 V, required a gate threshold voltage in the range of 1.64–2.21 V from 20 °C to −190 °C. This corresponds to a normalized gate threshold voltage range of 0.164–0.221. Both devices are concluded to display comparable changes in their gate threshold voltage with change in temperature. Fig. 8 shows the drain-to-source on-state resistance (RDS(on)) versus temperature for the two devices. It can be clearly seen that both devices show similar behavior in their on-state resistance with temperature. The on-state resistance of either device seems to decrease with decrease in temperature till about −170 °C. This trend, however, is reversed as the test temperature is decreased further as reflected by the slight increase in the on-state resistance of both devices. At any temperature, the SOI device exhibits a slightly higher on-state resistance than its standard counterpart.

Fig. 9 shows the forward voltage–current characteristics of an NPN transistor at room temperature (20 °C). These output characteristics are defined as collector current ($I_C$) versus collector-to-emitter ($V_{CE}$) voltage family of curves at various base currents. As the transistor was exposed to a temperature below room +20 °C, the base current had to be increased to maintain the collector current at a predetermined value. The increase in the base current continued as the test temperature was lowered further. Thus, the decrease in temperature resulted in a downward shift or significant compression of the transistor's characteristic curves. These effects of cryogenic temperature on the characteristics of this transistor at the extreme temperature of −195 °C are shown in Fig. 10. It is important to note that in addition to the downshift of the switching curves at the extreme temperature, larger step size was used in the base biasing current. This behavior can be attributed to the fact that this bipolar junction transistor relies on minority charge carriers in their base region, and their concentration drops as temperature is decreased [12]. Thus, these devices tend to exhibit significant loss of current gain when cooled.

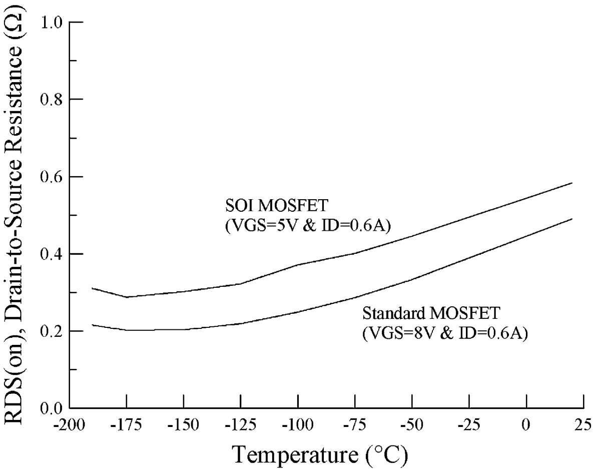

Fig. 8. Drain-to-source on-resistance for SOI and standard MOSFET devices vs. temperature.

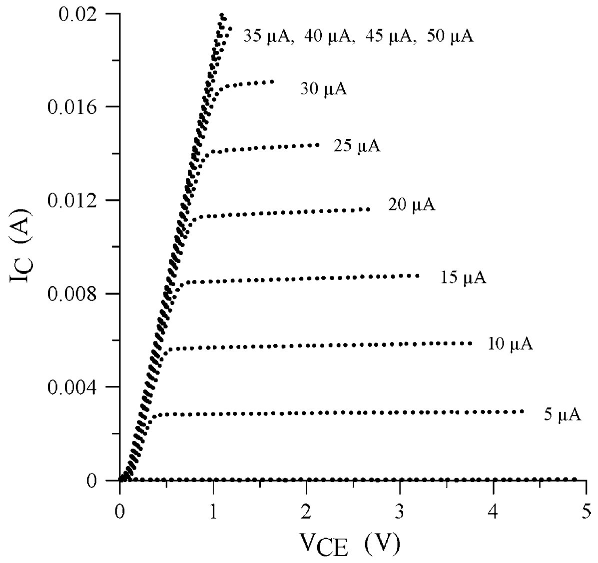

Fig. 9. Forward voltage–current characteristics of an NPN transistor at +20 °C.

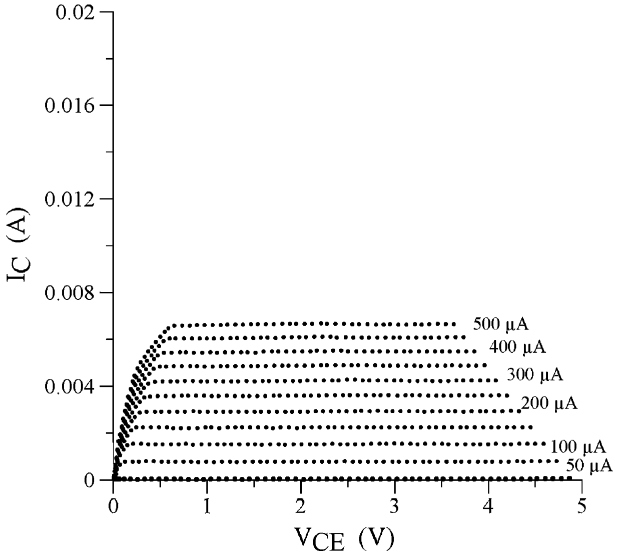

Fig. 10. Forward voltage–current characteristics of an NPN transistor at −195 °C.

## 4. Summary

An overview of the Low Temperature Electronics Program at the 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. For example, there are developments of silicon germanium (SiGe) and also germanium switching transistors and diodes for low temperature power circuitry. Other supporting research investigations comprise long-term reliability assessment of power devices and integrated circuits and the effects of low temperature exposure and thermal cycling on device interconnect and packaging. Preliminary experimental data were obtained for the evaluation of crystal and silicon germanium oscillators, DC/DC converters, and transistors under cryogenic temperatures. The effects of thermal cycling under wide temperature range on the operation of these devices were also determined. The findings of this work were also presented in this paper. NASA Glenn Research Center collaborates with other agencies, academia, and the aerospace industry to develop and investigate electronic components and circuits that will operate at low temperature for future space exploration missions.

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