

Temperature Controlled Measurement System for Precise Characterization of Electronic Circuits and Devices

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Abstract—A temperature controlled oven, with provisions for easy connection of instruments to the device under test, was designed and built. This paper describes the oven, its thermal model and control system and presents measurement results with different temperature profiles. An NTC thermistor measures the system temperature and a modified Steinhart & Hart equation is used to convert resistance readings to temperature. The system is capable of setting its temperature from just over ambient temperature up to 375 K (around 102 °C). Temperature stability is ultimately limited by the resolution of temperature measurement to ± 2 mK.

I. INTRODUCTION

Measurement of electronic devices and circuits is often affected by the temperature of the device under test (DUT) which therefore needs to be controlled. This is especially critical in circuits for current and voltage references and temperature sensors. In these and other cases, it is paramount that measurements are performed at a stable, known temperature.

Standard laboratory ovens and test chambers have many drawbacks for precise temperature measurements on circuits whose signals may be very low level, in particular ultra low power circuits. These instruments often present a temperature uncertainty around ± 1 °C down to ± 0.3 °C [1]. Moreover, the heaters are sometimes connected to the mains AC supply and controlled in an on/off fashion while the system may include electric fans for air circulation. These features imply lack of enough temperature stability for some applications together with a risk of contaminating the DUT with electromagnetic interference (EMI).

The need for a temperature stable, electromagnetically clean measurement environment prompted the design and construction of a temperature controlled oven incorporating assorted connectors for easy access of measurement instruments to the terminals of the DUT. Although temperature controlled systems are ubiquitous, there is scarce previously published work on comparable systems [2]–[4]. The main novelty of our work is precisely that combination of high temperature stability, low EMI, and availability of specialized connectors for measurements in ultra low power circuits together with an affordable cost.

This paper starts by describing a prototype of such a system in Section II. Section III gives further detail regarding the thermal model and Section IV describes the control system that was implemented. Section V shows measured temperature profiles and the high stability achieved while Section VI concludes the paper.

II. DESCRIPTION

The oven consists of a thermally insulated, electrically heated chamber and a top panel with connectors (Fig. 1).

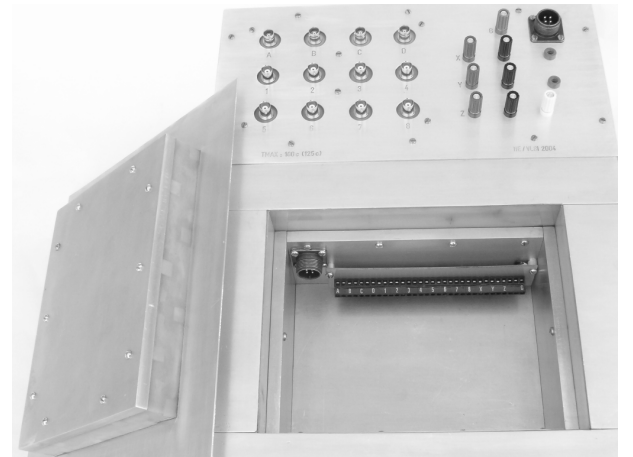


Figure 1. Photograph of the oven showing the measurement chamber (from [5])

The measurement chamber (210 mm $\times$ 160 mm and 80 mm high) consists of a 10-mm thick aluminum box. The chamber lid is also a thick slab of aluminum. The 3.9 kg aluminum mass helps to achieve temperature stability. The closed metallic design contributes to avoid external EMI.

Several assorted connectors are included on the top panel for easy access to the terminals of the DUT. Teflon insulated wires route the signals from the connectors to a strip of screw terminals inside the chamber. The connectors include 7 banana jacks, 8 BNC sockets and 4 triaxial BNC sockets for low current measurements.

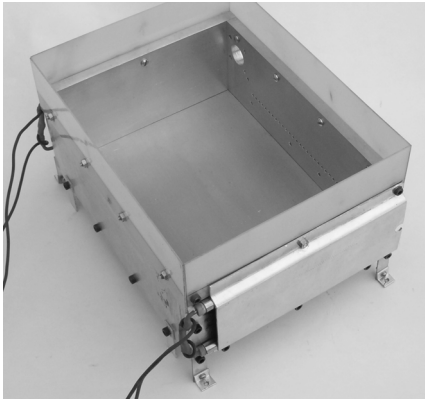


Figure 2. Photograph of the measurement chamber showing the heaters and support strips

A couple of custom made, tubular, sealed industrial-grade heaters are fixed to the outer surface of the chamber which is surrounded by stone wool thermal insulating material. The insulation is protected by an outer thin aluminum box. The heavy chamber is supported and held into position by strips of fiberglass board in order to minimize heat transfer (Fig. 2).

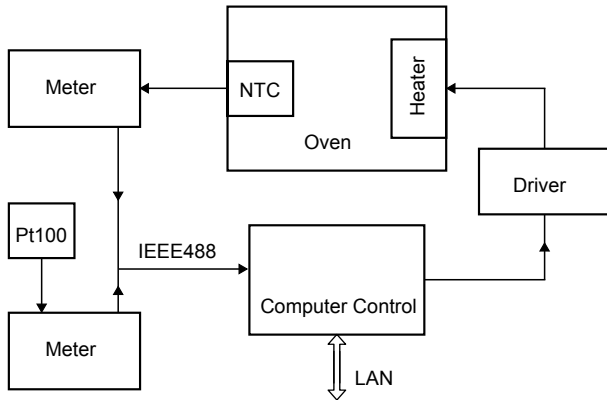


Figure 3. Block diagram of the system

Fig. 3 shows a block diagram of the whole measurement system. It consists of the electrically heated, insulated chamber, probes that measure the temperature inside the chamber and the outside ambient temperature, a computer (PC) that implements a control loop and the heater driver. The following paragraphs describe these elements in further detail.

The heaters are driven by a DC current source controlled by an analog voltage signal from the PC. In turn, the driver is supplied by a standard lab DC source. This arrangement avoids EMI introduced by the heating circuit.

The temperature control (described in further detail in Section IV) is implemented in a PC. A probe senses the temperature in the chamber, close to the DUT. It consists of a long term stability thermistor (YSI 46007) encased in a custom tooled aluminum sheath (Fig. 4). Its resistance is measured by a Fluke 45 multimeter which sends measurements to the PC through an IEEE 488 bus. Ambient temperature is recorded by a Pt-100 probe which is rigged to a second multimeter, also connected through the IEEE 488 bus.

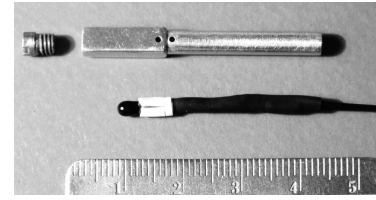


Figure 4. NTC long term stability thermistor outside its aluminum sheath

The control system in the PC computes the power to be applied to the heater while logging internal and ambient temperatures. A D/A card is used to output an analog voltage signal that controls the heater driver. Both the setpoint and the temperature logs can be accessed through the Internet.

III. THERMAL MODEL OF THE SYSTEM

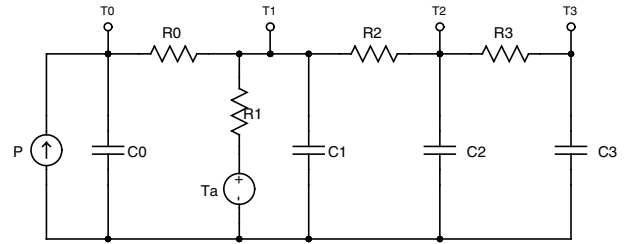


Figure 5. Equivalent circuit of the thermal model of the system

Fig. 5 shows a thermal model for the oven. Electric power P is delivered to the heater elements. Their thermal capacity is C_0 and their temperature is T_0 . The heaters deliver power to the aluminum chamber through a thermal path with thermal resistance R_0 . This power leaks to ambient temperature T_a through insulation resistance R_1 . C_1 is the thermal capacity of the chamber at temperature T_1 .

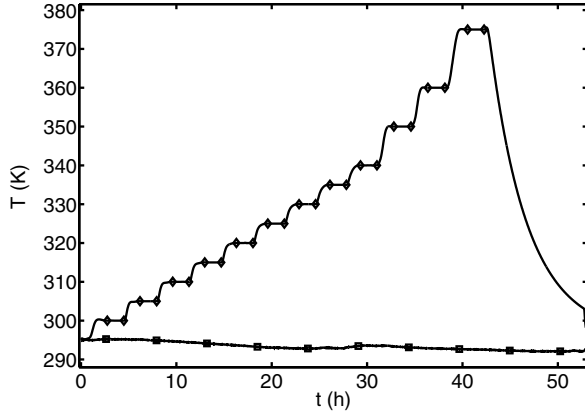
The chamber walls heat the air inside (thermal capacity C_2 , temperature T_2) through thermal resistance R_2 . Finally T_3 is the temperature of the probe with thermal capacity C_3 and R_3 is the thermal resistance between the probe and the internal ambient air.

The system has a dominant pole determined mainly by R_1 and C_1 , two non dominant poles and a fourth fast pole which can be neglected. The transfer functions from the input power and ambient temperature to the temperature of the probe can be simplified as shown on Eq. 1 and Eq. 2.

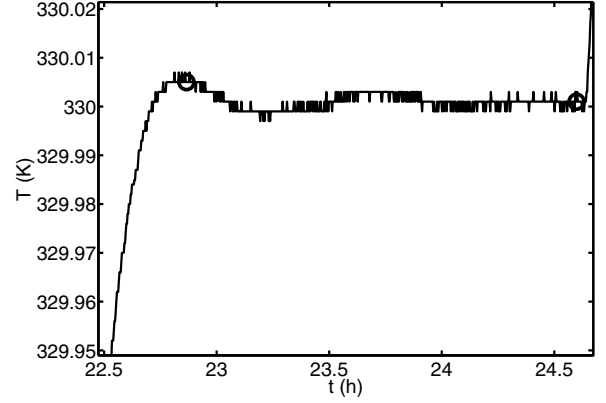
$$\frac{T_3}{P} = \frac{R_1}{(1 + \tau_1 s)(1 + \tau_2 s)(1 + \tau_3 s)} \quad (1)$$

$$\frac{T_3}{T_a} = \frac{1}{(1 + \tau_1 s)(1 + \tau_2 s)} \quad (2)$$

The values for the parameters on the equations have been experimentally determined through system tests as shown on Table I.



(a) Across the complete experiment. ($\diamond$): temperature inside the measurement chamber. ($\square$): ambient temperature



(b) Zoom of one of the temperature steps

Figure 6. A typical temperature profile during an experiment to test a temperature sensor

Table I. EXPERIMENTALLY DETERMINED PARAMETERS FOR THE TRANSFER FUNCTIONS

Parameter	Value
R_1	3.15 K/W
τ_1	13975 s
τ_2	522 s
τ_3	281 s

IV. CONTROL OF THE OVEN

The temperature inside the chamber is measured by a multimeter through the resistance of an NTC thermistor (Section II). The conversion from resistance to temperature is performed using a novel modified Steinhart & Hart [6] formula:

$$\frac{1}{T} = c_0 + c_1 \log(r) + c_2 \log^2(r) + c_3 \log^3(r), \quad (3)$$

where the measured resistance R is offset corrected by R_{off} and normalized as:

$$r = \frac{R - R_{off}}{1 \Omega}. \quad (4)$$

The thermistor was calibrated in a calibration bath and the coefficients in Eq. 3 were thus obtained by interpolation [7]. The control system converts resistance readings to temperature through Eq. 3 and uses this value to determine the power to be delivered to the oven.

The control architecture is a PID controller with anti-windup. Parameters for the PID were optimized through a simulation with Simulink(TM). A feedforward control compensates variations in the ambient temperature.

The control system was implemented in Labview. Fig. 7 shows the control panel of the virtual instrument. The panel allows to choose several parameters including a safety maximum temperature, the sampling time for the control system and a temperature error band to determine if the setpoint has been attained. The graph on the left displays the time evolution of the setpoint, internal chamber temperature and ambient

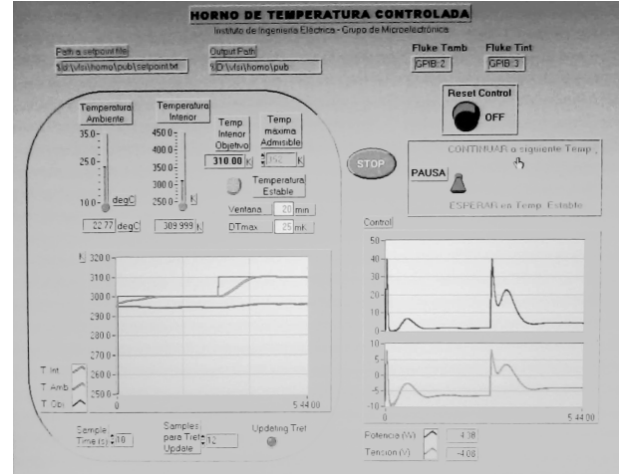


Figure 7. Front panel of the LabView virtual instrument that controls the temperature in the oven

temperature. The graphs on the right depict the power delivered to the oven and the corresponding control voltage applied to the driver. The stable status is logged in a file together with the temperature inside the chamber and the ambient temperature.

V. MEASUREMENT RESULTS

The control system proved to be very robust. The measurement system has been used for several tests of simple blocks in integrated circuits: bias current generators, voltage generators with both PTAT and arbitrary slopes and temperature sensors [8]–[11].

Examples of some typical temperature profiles are shown in Fig. 6 and Fig. 8.

Fig. 6 shows a temperature profile from an experiment together with the evolution of ambient temperature. Steps of 5 K, 10 K and 15 K were produced up to 375 K (near 102 °C). The zoom shows detail of the settling to 330 K. The electrical measurements were carried on between the symbols (circles). Temperature stability during the measurement was better than ± 10 mK.

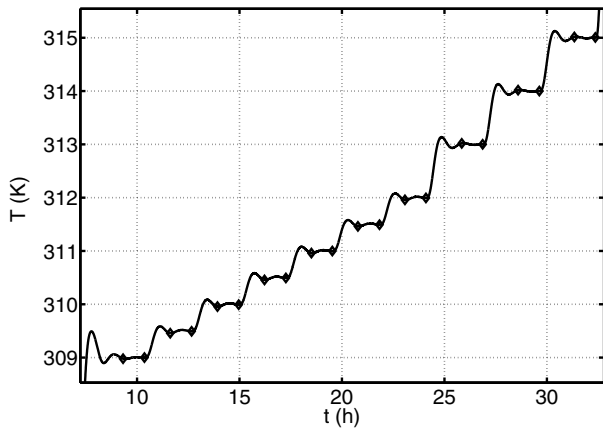


Figure 8. Example of a temperature profile with several fine steps

Fig. 8 depicts the temperature profile in another experiment showing the ability to produce fine resolution temperature steps of 0.5 K and 1 K. The steps range from 309 K (near 36 °C) to 315 K (approximately 42 °C).

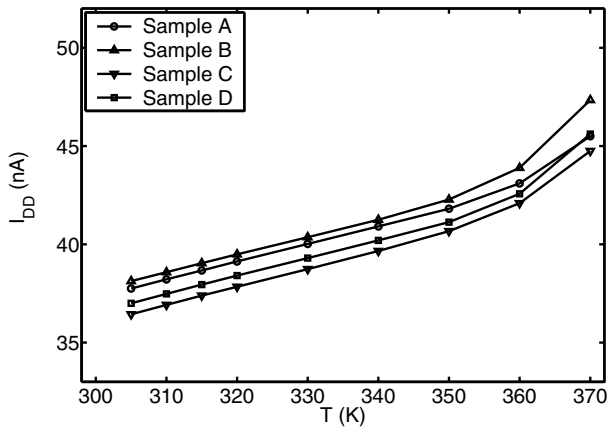


Figure 9. Current consumption of a temperature sensor at several temperatures [8], [9]

Fig. 9 shows an example of application of the described system: measurement of the consumption of four samples of an ultra low power temperature sensor [8], [9].

VI. CONCLUSIONS

A versatile lab instrument for measurement of electronic circuits and devices at controlled temperature was designed and built. The temperature range extends from just over ambient temperature up to 375 K (almost 102 °C). Temperature stability better than ± 20 mK was routinely achieved in daily use. Ultimate stability approaching the resolution of the internal temperature probe (± 2 mK) is achievable if the system is allowed enough time to settle down.

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