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PERFORMANCE OF A FLIGHT QUALIFIED, THERMOELECTRICALLY TEMPERATURE CONTROLLED QCM SENSOR WITH POWER SUPPLY, THERMAL CONTROLLER AND SIGNAL PROCESSOR.

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ABSTRACT

A thermoelectrically temperature controlled quartz crystal microbalance (QCM) system has been developed for the measurement of ion thrustor generated mercury contamination on spacecraft. Meaningful flux rate measurements dictated an accurately held sensing crystal temperature despite spacecraft surface temperature variations from -35 °C to +60 °C. A thermal control system was developed which held the sensing crystal at 25 °C ± 1°C over the flight temperature range.

An electronic control unit was developed with magnetic amplifier transformer secondary power supply, thermal control electronics, crystal temperature analog conditioning and a multiplexed 16 bit frequency encoder.

INTRODUCTION

Operation of Ion Thrustors for spacecraft propulsion raises the question of potential spacecraft surface contamination by mercury from the thrustor beam. NASA Lewis Laboratories' Ion Thrustor experiment on the P80-1 Space Shuttle program is contracted to Hughes Aircraft Company which plans to monitor contamination using QCMs (quartz crystal microbalances). Two QCMs (operated by a single electronics control unit) will be placed at right angles to the thrustor beam.

In order to make relatable contaminant flux rate measurements, the collecting surface temperature, i.e. the QCM sensing crystal temperature, must remain at a constant temperature. This temperature was specified to be 25 °C ± 1°C. The orbiting spacecraft QCM attachment surfaces however are expected to vary between -35 °C and +60 °C. This requirement led to a contract with Berkeley Industries to develop a QCM sensor with an active thermal control system which would accurately hold the 25 °C set point temperature, would have minimal frequency temperature coefficient in the two degree temperature region around the set point, would be operated by an electronics unit with single point ground system power supply, and would have crystal analog temperature outputs, a

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multiplexed QCM 16 bit parallel frequency encoder and would not consume over 5 watts of power. This QCM system was developed, flight qualified and delivered to Hughes Aircraft Company in March 1980.

This paper presents some of the unique design problems encountered in this new QCM system, their solution and the system performance.

NOMENCLATURE

The following nomenclature is used in this paper:

T	Temperature -°C.
T_C	Sensing Crystal Temperature
T_{HS}	Heat Sink Temperature at QCM Attachment Point
I	Current - Amps
V	Voltage - Volts
PRT	Platinum Resistance Thermometer
R	Resistance - Ohms
R_T	PRT Resistance at Measuring Temperature
R_0	PRT Resistance at 0 °C
R_{100}	PRT Resistance at 100 °C
α, β, δ	Coefficients of Callendar-Van Dusen equation
k	Thermal Conductivity
L	Length
A	Area
f	Beat Frequency - Hertz
τ	Time - Seconds
P	Power - Watts
Q	Heat Flux - Watts
m	Mass - Grams
C_p	Specific Heat - joules/gram -°K
SC	Solar Constant - 1353 w/m^2
TE	Thermoelectric Peltier Element

SYSTEM DESIGN

The contamination system, termed the Berkeley Industries MK 10 QCM System, consists of two thermoelectrically temperature controlled QCM sensors with a common electronics unit. The system is shown in Figure 1 and the functional schematic in Figure 2. The active elements of the QCM sensor include 10 MHz sensing and reference crystals, a platinum resistance (PRT) temperature sensing element, a thermoelectric heater/cooler and a dual oscillator/mixer hybrid chip element. The electronics unit has a power supply unit, a frequency encoder and a thermal control/temperature readout section. These various elements will be discussed separately.

Power Supply

The power supply is required to regulate the incoming 28 volt ±6 volt power, applying the proper EMI line filtering and to supply isolated secondary voltages for the QCM oscillator/mixer, the thermoelectric heater/coolers and the various signal processing electronic circuitry while using only 5 watts of power.

A magnetic amplifier transformer type secondary power supply with a 22 KHz oscillator was chosen after computer optimization studies. The high conversion efficiency and isolated secondary features were paramount factors in this choice. Thermoelectric elements have high amperage, low voltage operating characteristics which normally lead to very inefficient power converters. However, optimized mag-amplifier design can achieve 75 to 80% efficiency.

The secondary power supplied is ±11.5 volts, +10V and ±6 volts for the thermoelectric elements.

Frequency Encoder

The QCM beat frequency is digitally encoded using 16 bit counters and a quartz crystal clock to gate the frequency. The encoded parallel output is TTL/CMOS compatable. The QCM to be interrogated is selected by external signal, with a select verify signal returning. A count omplete signal terminates the frequency output cycle.

Thermal Control/Temperature Readout

The purpose of the thermal control system is to hold the absolute temperature of both QCM's sensing crystals at 25° ± 1°C. Conceptually, a platinum resistance element (PRT), thermally locked to the crystal, generates a voltage proportional to the crystal temperature. This voltage can be compared to a set point voltage (calculated for the desired 25°C) and either a positive or negative voltage supplied to the thermoelectric element which is thermally locked to the crystal and PRT. Thus the crystal is either heated or cooled until the setpoint is reached. The block diagram in Figure 2 illustrates the concept.

The dynamic thermal control elements in this system are the QCM crystal package, consisting of the sensing and reference crystals with the PRT sandwiched in between, the thermoelectric heater/cooler to which the crystal package is attached, and the electronic comparator circuit. Crucial to stable crystal temperature operation is the matching of the thermal time constants of the crystal package and the thermoelectric element and the dynamic response of the mag-amplifier/comparator circuit. As illustrated in Figure 3, the slope of the comparator response curve can be adjusted from a step change heating to cooling response for a detected temperature error (the so called "bang-bang" response) to a very "soft" response. This response must be tailored to the thermal time constant of the crystal package. This time constant involves the mass of the sense crystal, reference crystal and PRT mount and the overall thermal conductivity (including joint resistance) from the TE element to the PRT and sense crystal.

If long time constants exist in the crystal package, temperature overshoot may result at the crystal before the correcting signal has time to respond. Uncontrolled temperature oscillations can then occur. Analysis and experiment determined stable operation to exist for short crystal package time constants and comparator response which delivered maximum current at the limits of allowable temperature excursion, i.e. ±1°C.

From

$$\frac{\Delta T}{\Delta \tau} = \frac{Q}{C_p m} \qquad (1)$$

short time constants result from minimum mass and maximum positive or negative heat flow. Additionally, transient and steady state temperature gradients must be minimized if the PRT temperature is to represent crystal temperature. From

$$\Delta T = \frac{Q\,\Delta L}{k\,A} \qquad (2)$$

the thermal conductivity of the assemblage must be high and length dimensions minimized for a low temperature gradient.

QCM Sensor Design

The QCM sensor assembly is shown schematically in Figure 4.

The thermoelectric heater/cooler is a 72 element low aspect ratio single stage unit designed for approximately 1/4 amp current at ±4 volts. The TE was soldered to the heat sink and the crystal package with high temperature eutectic solder. The low aspect ratio design gave the element greater shear strength for the vibrational launch environment.

The crystals are 10 MHz, AT cut optically polished 12.4mm diameter crystals with outward facing surfaces fully aluminum coated to reduce solar insolation effects. The crystal's aluminum electrode is overcoated with a quarter wave length thickness of magnesium fluride to avoid aluminum deterioation due to mercury yet at the same time optimize the surface reflectivity.

All metal parts, with the exception of the TE, are machined aluminum for high thermal conductivity. The aluminum is plated with 1 μm of nickel eliminating mercury corrosional effects. The crystals are spring loaded into mounting rings which are bolted with high screw loading to the PRT mounting ring thus minimizing temperature gradients. The PRT unit is mounted in its mounting ring with high thermal conductivity epoxy.

Lead wires to the crystals and PRT are #30 Teflon coated Constantan wire for low heat leak to the TE.

The heat sink is designed for less than 1°C temperature gradient with maximum heat sink to crystal temperature differential.

QCM PERFORMANCE

Crystal Temperature Analog Output

The crystal temperature is determined from an analog voltage which is scaled for approximately 0 to 5 volts corresponding to -50° to +65°C. The crystal temperature is assumed to be identical to the PRT temperature thus the emphasis in the sensor head design on structural features which minimize temperature gradients. The final accuracy of the temperature determination is actually a matter of voltage resolution in the telemetry signal and the linearity of the voltage-temperature curve. In this application, the linearity was specified to be ±1% of full scale or better.

The resistance-temperature characteristics of the PRTs was accurately determined at the temperatures of boiling and freezing points of distilled water (100°C and 0°C) and at liquid nitrogen boiling point (-196°C). Points in between were measured with a calibrated thermocouple. A bridge circuit was used to minimize PRT selfheating. The resistance ratio curve, R_T/R_O was found to match very closely the NBS curve for pure, strain free platinum. The PRTs were then tested with the heat dissipation produced by the 0.973 ma circuit current and coefficients found for a best fit of the Callendar-Van Dusen equation,

$$\frac{R_T}{R_O} = 1 + \alpha\left[T - \delta\left(\frac{T}{100} - 1\right)\frac{T}{100} - \beta\left(\frac{T}{100} - 1\right)\left(\frac{T}{100}\right)^3\right] \tag{3}$$

The coefficients are $\alpha = 0.003900$, $\beta = 0.09997$ and $\delta = 1.2031$. Minor differences are observed between these results and the values reported by Glassford (Ref. 1) for similar PRTs. These differences are due to the current flow in the PRT and evidently the availability of higher quality platinum.

Using Eqn 3, a reading accuracy of ±0.01 Ω PRT resistance results in ±0.02°C accuracy in inferred temperature.

A test to determine the linearity of the analog voltage output with crystal temperature was performed in vacuum over a temperature range of -45°C to 65°C. The analog voltage was measured with an accuracy of ±1 mv and the temperature to ±0.02°C using the PRT resistance. The resultant data is shown in Figure 5 for both QCM circuits. The data is seen to be well within the desired ±1% linearity requirement.

Crystal Temperature Control

The primary intent of this QCM system design was the maintenance of the crystal temperature at 25°C ± 1°C while the heat sink temperature varies from -20°C to +50°C (survive -35°C to +60°C). A test in vacuum was performed on the complete system, i.e. two QCMs and the Electronics Unit, over the survival temperature range, using the analog voltage output for crystal temperature indication and a separate PRT thermally attached to the QCM heat sink mounting plate for the heat sink temperature. The results shown in Figure 6 demonstrate the ability of the thermal control system to maintain the crystal temperatures well within the desired ±1°C range. The voltage outputs of the two QCMs were identical within the ±1 mv accuracy of the measuring instrument.

QCM Frequency Stability

The measurement of contaminant mass by a QCM assumes that frequency changes occur only as a result of mass deposited on the sensing crystal. In actuality, a small frequency shift may occur as a result of temperature gradients between the sensing and reference crystals. A crystallographic cut (35° 12') was chosen for the crystals in this program to reduce the frequency temperature coefficient to near zero. A test was performed in a vacuum bell-jar to confirm the clean crystal QCM stability with the thermal control system maintaining the crystals at 25°C ± 1°C as in Figure 6. The results, shown in Figure 7, indicate some minor thermal gradients do exist in the crystal package. However, considering the fact that a 30 Hz change in frequency is equivalent to a single monoloayer of mercury molecules, the QCM frequency stability is quite acceptable.

Solar Radiation Effect

During orbiting flight, the QCMs will at times be exposed directly to solar insolation which has been shown earlier in Reference 2 to have an effect on the sensing or exposed crystal's frequency. In the present QCM design, an effort was made to minimize this effect by limiting the radiant flux absorbed by the crystal and by using a zero temperature coefficient crystal unit. The results, shown in Figure 8, indicate that these efforts were only partially effective. The heat absorbed by the crystal which is not reradiated must either effect a rise in the bulk temperature of the crystal or create a heat flow and resultant temperature gradient in the quartz plate. Either effect would result in a frequency shift but for different reasons. The uniform bulk temperature rise would alter the frequency by the quartz temperature coefficient relationship depending upon the crystal cut, while a temperature gradient in the plate produces physical stresses which result in a change in frequency. In this present QCM design, the thermal locking of the PRT and the sensing crystal for temperature reading accuracy resulted in a crystal mount design in which it would be unlikely for the crystal bulk temperature to change because of the high conductivity crystal edge mount but would result in temperature gradient induced stress. The frequency shift is quite repeatable and can be removed in the data reduction.

System Power Requirement

Tests in vacuum were performed to determine the required system power which was specified to be less than 5 watts. The power curve, shown in Figure 9, indicates that although the specified maximum power was exceeded when the heat sink was at -20 °C, the average power usage was considerably less than 5 watts.

CONCLUSIONS

A QCM system with thermoelectrically temperature controlled contaminant flux sensing crystals has been developed and successfully flight qualified. The thermal control system is capable of holding the mass sensing crystals at a precise temperature (± 1°C) despite widely varying spacecraft temperatures.

ACKNOWLEDGEMENTS

This program was made more enjoyable by association with the witty personality of George Thomas, Hughes Aircraft program manager.

REFERENCES

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2. Wallace, D.A., "Transient Frequency Effects in Piezoelectric Quartz Crystals Caused by Incident Thermal Radiation" NASA SP-336, 7th Conference on Space Simulation, November 12-14, 1973.

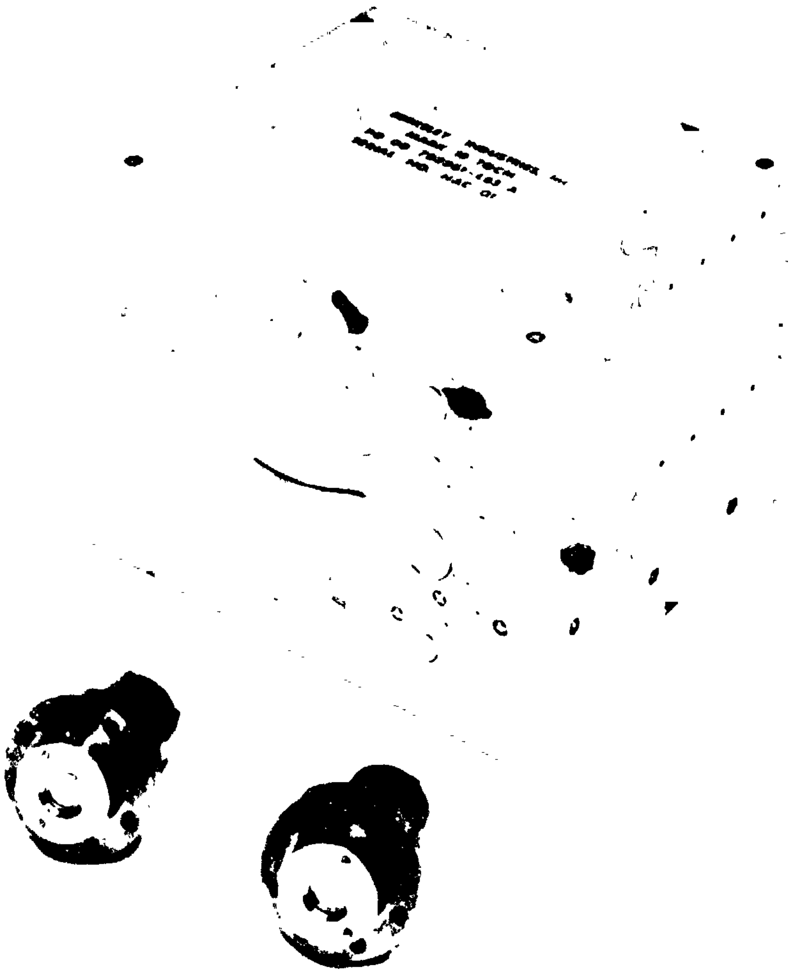


Figure 1 MK12 Thermoelectrically Temperature Controlled QCM Sensors and Electronics Unit

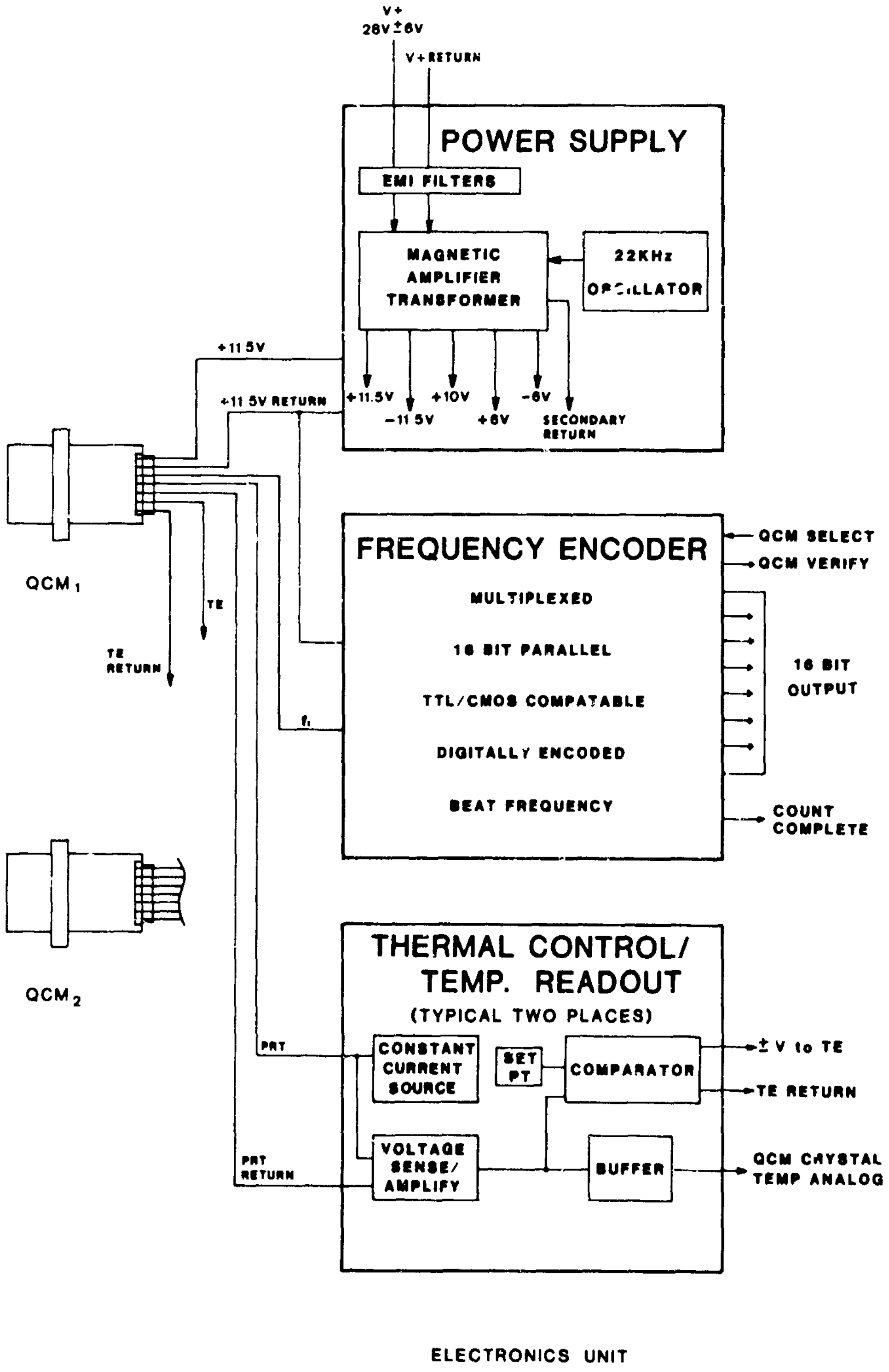
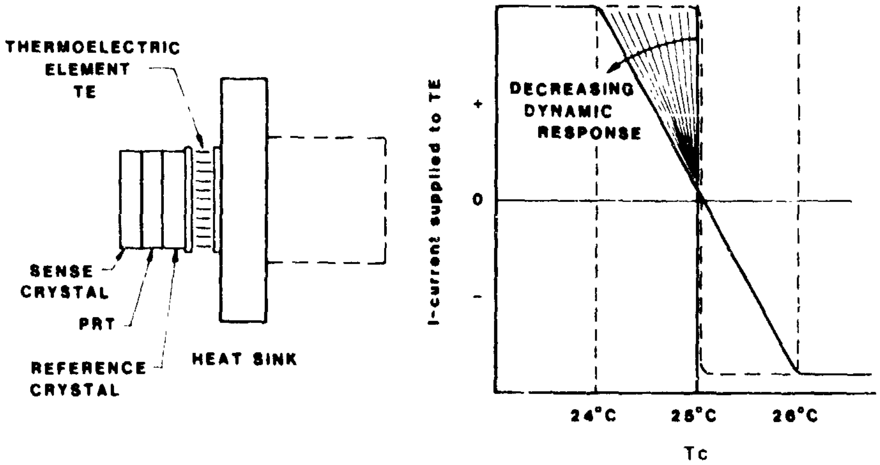


Figure 2 QCM System Functional Block Diagram



QCM

COMPARATOR

Figure 3 Dynamic Temperature Control Elements

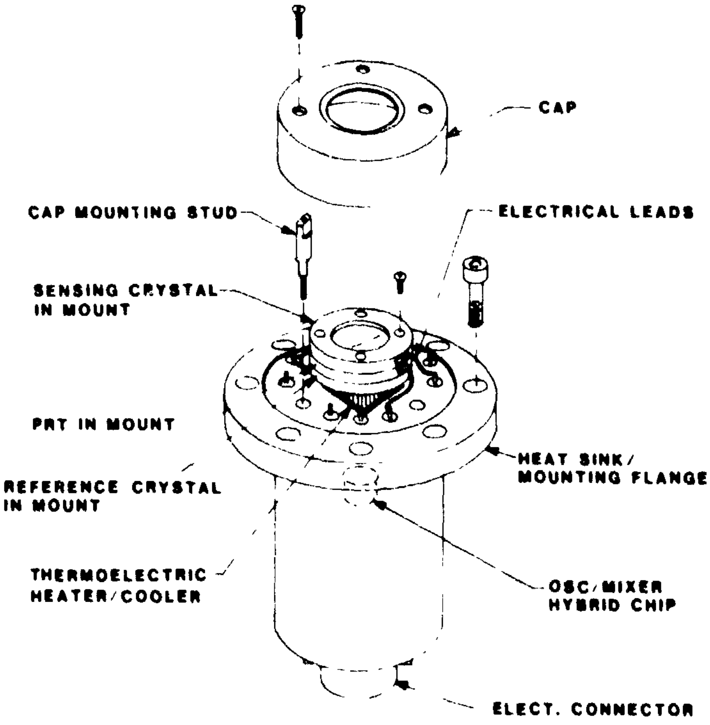


Figure 4 QCM Sensor Head

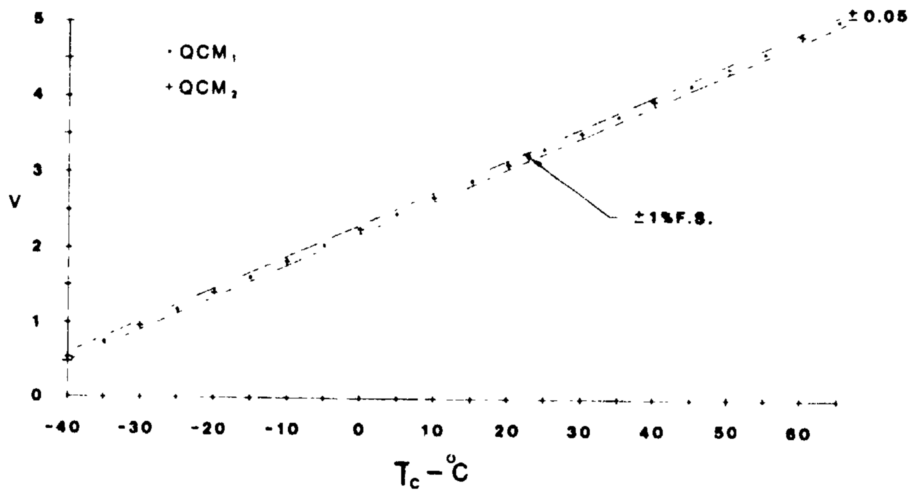


Figure 5 Crystal Temperature Analog Voltage

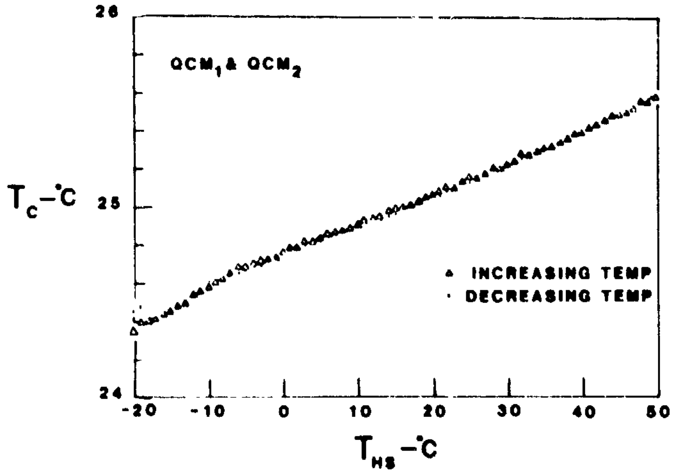
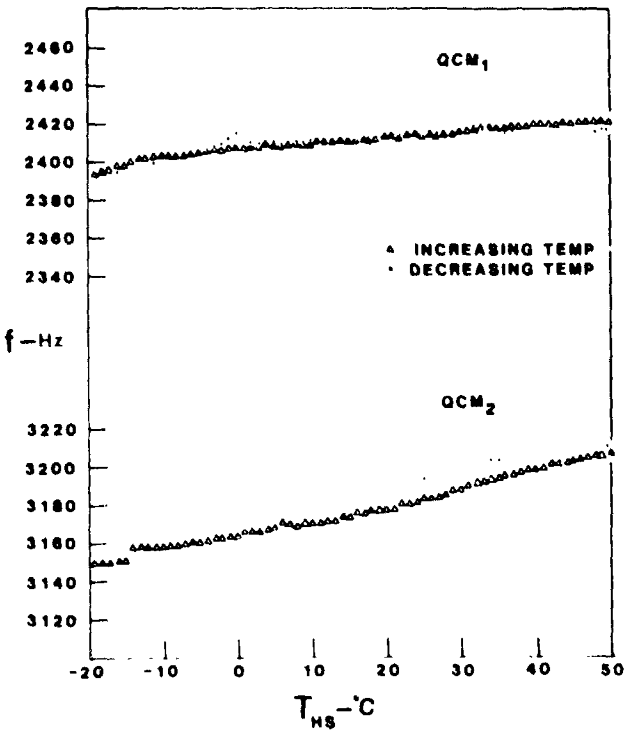


Figure 6 Crystal Temperature Control at 25°C Set Point



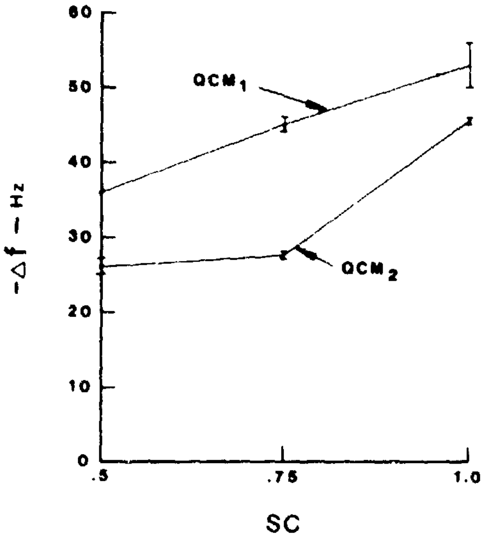


Figure 7 Crystal Frequency Stability with Thermal Control

Figure 8 Solar Insolation Induced Frequency Effects

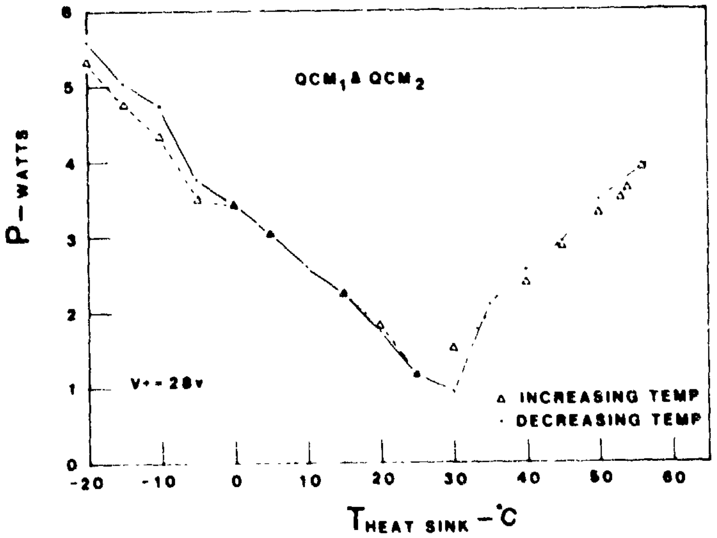


Figure 9 QCM System Power Requirement