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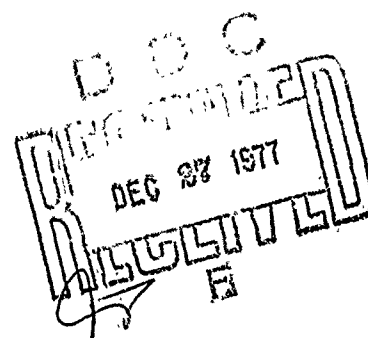
STUDY OF RADIATION-HARDENED QUARTZ
PRODUCTION PROCESSES

IRT Corporation

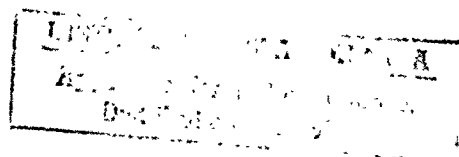Approved for public release;
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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

DEC 27 1977

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This technical report has been reviewed and approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of an initial program performed by IRT Corporation in support of the RADC/DNA program "Radiation Hardened Quartz Process Investigations" are presented. Included are calculated depth-dose profiles in the resonator assuming 10-MeV electrons incident on the oscillator package to be used in the resonator evaluation program. Also presented are the results of irradiations of the oscillator package at the RADC facility. Effectiveness of a collimator in protecting oscillator and oven control electronics has been assessed and the

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20. ABSTRACT (Continued)

results of dose mapping throughout the electronics is presented. Scaling relationships relating dose in the resonator to the dose at an external reference point were developed. Irradiations of a working oscillator were performed to assess the extent of possible experimental anomalies that would impact the actual RADC measurements.

The results of the above tasks were evaluated in light of their impact on the RADC program and used to formulate working procedural and/or equipment choice suggestions. In addition, a preliminary study has been made of the hardness assurance requirements for quartz used in quartz crystal filters.

FOREWORD

Contributions to this report were made by W. H. Hardwick, D. P. Snowden, M. J. Treadaway, and T. F. Wrobel of IRT Corporation. In addition, T. M. Flanagan of Frequency and Time Systems, Incorporated developed the initial program (while at IRT) and subsequently served as a consultant on the program. The RADC personnel involved in these investigations were P. W. Pellegrini, F. K. Euler, and A. Kahan.

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CONTENTS

SECTION 1

INTRODUCTION

High quality crystalline quartz devices are required by modern military communication and navigation systems. Since these systems must face the possibility of exposure to nuclear and/or space radiation, radiation tolerant quartz devices are needed. The requirements for quartz devices in systems where nuclear or space radiation can be encountered have led to investigations of radiation response of various types of quartz materials. In general, it is found that pure Z-growth swept synthetic quartz is the material of choice. Z-growth quartz can be obtained in several grades: electronic, optical, high Q and premium Q, and each grade can be swept. Quartz bars are graded by the manufacturer on the basis of process and performance specifications which have been written without consideration for the effects of radiation, and some latitude in processing and performance is allowed within each grade. In radiation tests, considerable variability in response has been seen for devices manufactured from the same grade of quartz. Both acceptable and grossly unacceptable performance has been observed within most grades. At the time of initiation of this program, the procedure for obtaining quartz for application to systems with radiation specifications was to:

(1) determine the grade of swept quartz which met system needs,

(2) order material and have devices fabricated,

(3) perform radiation tests on finished devices to determine acceptability or nonacceptability of the device.

This procedure is both costly and time consuming with six to ten months taken up by processing. In recognition of the need for an established and documented procedure for processing by the manufacturer and procuring by a systems builder, a hardness testing program was initiated for quartz or crystal devices. The goals of this program are (1) to produce specifications for growth and procurement of quartz which will consistently yield state-of-the-art performance when exposed to radiation, and (2) to make available

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for other system use quartz bars found acceptable under this program. In addition, it is anticipated that recommendations for possible improvements in processing will result from this program.

The RADC/DNA "Quartz Radiation Hardness Assurance" program has been divided into various phases. This report describes the first phase of a hardness assurance program during which IRT Corporation has provided support to RADC primarily in the definition of the radiation-testing program. In addition, possible process requirements, process controls, and quality conformance tests have been suggested.

Recommendations on test geometry effects, critical to successful radiation tests have been made. IRT in cooperation with RADC personnel has carried out test irradiations at the RADC linear accelerator facility in order to characterize dose deposition in the oscillator package and provide RADC with input data to formulate an appropriate experimental configuration for use during oscillator measurements.

Finally, performance characteristics of quartz crystal filters have been surveyed by IRT in order to ascertain whether there exist any radiation hardness problems unique to filters. The latter effort was to identify if an additional program beyond the scope of the present program is necessary in order to provide hardness assurance guidelines for crystal filters.

SECTION 2

PROGRAM PLANNING

The processes involved in growing and sweeping quartz were reviewed in meetings at RADC and at Sawyer Research Products. As a result of these discussions, candidate controls can be postulated as a first step toward a hardness assurance specification for growth and sweeping.

Growth and Processing Requirements

Low aluminum impurity content

Slow growth rate

Vacuum deposited sweeping electrodes

Controlled atmosphere during sweeping

High-temperature sweeping

Process Controls (sliced from 100 percent of the bars)

IR absorption scan across Z-axis

Irradiation of slices after sweeping and optical examination

Quality Conformance Tests

Q^{-1} versus temperature

Lot sampling of resonators

The above listing is preliminary and other tests and inspections have been suggested for inclusion in each of the above categories. The list can be expected to change and become more specific as test data is evolved.

SECTION 3

EXPERIMENTAL GEOMETRY

The oscillator assembly chosen by RADC as the vehicle for resonator irradiation was Frequency Electronics Incorporated (FEI) model FE 2037B. As originally configured, this model contained the quartz resonator in an orientation such that the normal to the resonator disk was along the major axis of the oscillator package as illustrated in Figure 1. In order to avoid major irradiation of the oscillator circuits and oven-control electronics, it is necessary to irradiate the resonator along a diameter of the resonator disk. However, a simple one-dimensional energy loss calculation based on the Berger and Seltzer tables[1] indicates that it is likely that electrons incident on the package with an energy of 10 MeV will be stopped before traversing the entire resonator disk. Table 1 summarizes this calculation. Consequently, energy deposition in the resonator would be highly nonuniform, increasing rapidly at the end of the electron range. This would cause uncertainties in the interpretation of the frequency and Q changes. In addition, dose variations across the disk of the resonator can also be caused by scattering of the incident beam. Although detailed calculations of this effect were not made, it seems intuitively reasonable that these effects would be considerably greater for irradiation along the diameter of the disk than normal to it.

Several possible modifications were discussed with RADC such as: (1) use of higher energy radiation source, (2) removal or modification of part of the oscillator package which is responsible for degradation of beam energy, (3) use of a different oscillator for radiation testing, (4) irradiation with package axis at an angle ($\simeq 26$ degrees) to the electron beam, and (5) 90-degree rotation of the resonator in the package. Discussions between RADC and FEI personnel indicated that recommendation (5) was feasible, allowing irradiation of the resonator disk in the direction of its thickness.

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PREFERRED
DIRECTION
FOR
IRRADIATION

QUARTZ
RESONATOR

ELECTRONICS
PACKAGE

ELECTRONICS
PACKAGE

RT-15215

OVEN
CAVITY

DEWAR
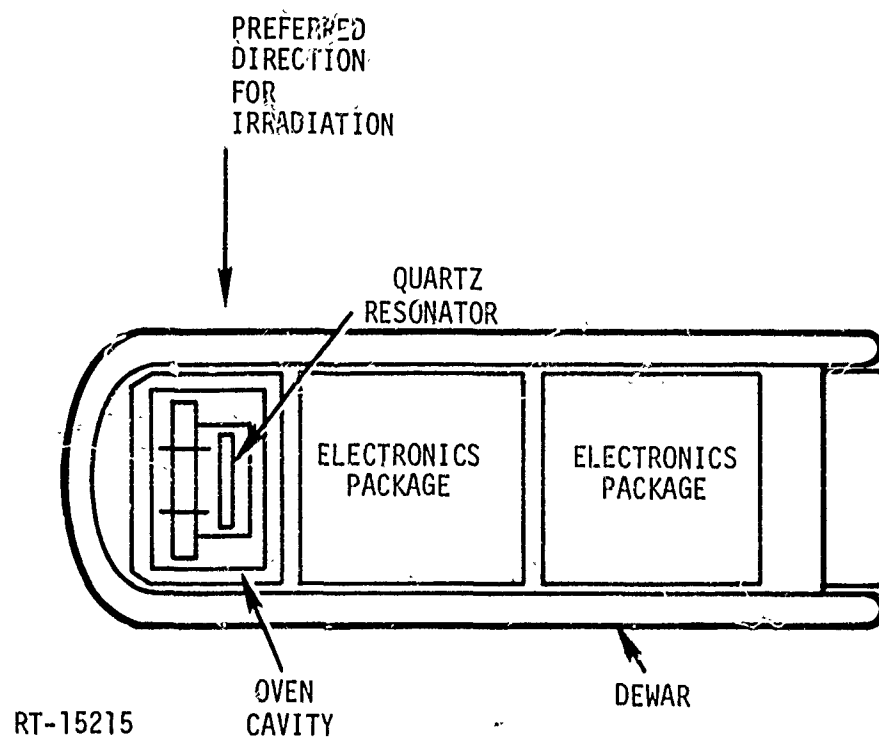
Figure 1. Oscillator package layout showing orientation of quartz
resonator disk as originally mounted[2]

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Table 1. Summary of Energy Degradation Calculation Through Oscillator Package

Material	Thickness (cm)	Density (gm/cm^3)	Electron Energy (MeV)
			10
Aluminum	0.0508	2.70	
			9.78
Pyrex	0.159	2.23	
			9.21
Vacuum	0.3175	0	
			9.21
Pyrex	0.159	2.23	
			8.65
Aluminum	0.533	2.70	
			6.34
Styrofoam	0.541	0.056	
			6.29
Copper	0.0254	8.92	
			5.93
Nitrogen	0.12	0.00125	
			5.93
Quartz	1.50	2.65	
			a

[a]Electrons are stopped in quartz.

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SECTION 4

EXPERIMENTAL MEASUREMENTS

During test planning and coordinating meetings held in the early stages of this program, it became apparent that a number of questions relating to the test dosimetry could be best answered emprically. One such question is the relationship of the dose per pulse at some point external to the oscillator package to the dose at the resonator. Another is the impact of scattering, machine tuning and alignment on the dose ratio. In addition, the proximity of electronic components to the resonator required verification of the effectiveness of the collimation and shielding in order to optimize the life of the electronics.

The following is a description of the experiments performed by RADC and IRT personnel at the RADC Linac facility. These experiments were to examine the sensitivity of the dosimetry to geometry and tuning, to optimize the shielding of electronics and to work out test procedures which minimize the requirements for positioning the oscillator.

4.1 DOSIMETRY MEASUREMENTS

4.1.1 Silicon Calorimeter Dosimeters

Primary dosimetry was performed using silicon calorimeter dosimeters. These dosimeters are made of single-crystal silicon chips to which chromel-alumel thermocouples have been attached. The silicon chip measures 3.2 x 3.2 x 0.25 mm. In the center of one face of the chip, a 0.25-mm-diameter gold dot is alloyed. To this gold dot, a 25-μm chromel-alumel thermocouple is attached with a very small amount of indium alloy solder. The silicon chip is supported in the fixture by small blocks of styrofoam which also serve as thermal isolation.

Several factors were taken into account in the design of the silicon calorimeter. It is suspended by sytrofoam blocks, and the thermocouple was made from small-diameter wire for thermal isolation. The small amount of indium solder on the gold dot

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is such that its mass is only a small perturbation on the silicon absorber (the mass ratio is 2 percent). Silicon is also a relatively good thermal conductor and will reach thermal equilibrium rapidly (< 0.1 second).

Radiation incident upon the silicon block results in a temperature rise which can be converted to energy deposition (dose) by the specific heat of silicon. The measurement is a direct determination of the average dose in the sample, independent of the type of radiation particle or its energy, and is traceable to NBS standards (NBS Circular 500, Part 1, 1952). The specific heat capacity for silicon is 0.169 ± 0.001 cal/g-$^{\circ}$C at 25°C. This can be directly converted to 7.08×10^{4} rad(Si)/$^{\circ}$C by using the conversion factor 4.19×10^{7} erg/cal and 10^{-2} g-rad/erg. The response of the chromel-alumel thermocouple at room temperature is 40 μV/$^{\circ}$C ± 1 μV/$^{\circ}$C. Therefore, the response of our silicon calorimeter is 1757 rad(Si)/μV ± 3 percent.

The largest source of error in using this type of calorimeter arises in the reading of the appropriate signals. The reading accuracy of the calibration is about 5 percent, and calorimeter response reading accuracy is approximately 10 percent (worst case); therefore, assuming that the errors propagate independently and that the remainder of the system has accuracies of approximately 3 percent, the total error in dose measurements becomes about 16 percent.

An analysis of the heat transfer characteristics between the silicon calorimeter and its environment has been performed on previous calorimeters constructed by IRT[3], and the dominant heat loss path was found to be conduction through the trapped air of the styrofoam. The calculated time constant agreed well with experimental values of about 10 seconds and is of sufficient duration to allow accurate reading of calorimeter deflection to be performed easily without the need for high-speed recording equipment.

One silicon dosimeter was mounted in an empty resonator package and was used to determine resonator dose. Other calorimeters were mounted at the input and output sides of the oscillator package. A multichannel dosimeter amplifier and recorder were used to display the output of these dosimeters simultaneously.

4.1.2 TLDs

Thermoluminescent dosimeters (TLDs) were used for measurement of total deposited dose at various locations in the package and its surroundings. RADC CaF$_2$-filled Teflon TLDs were used for most measurements and were read out immediately after being irradiated. In addition, in a few instances, IRT CaF$_2$ TLDs were also used

and read out approximately five days after irradiation. It had been determined previously that negligible bleaching of these dosimeters will occur over this time period. The largest difference noted between an IRT and RADC TLD was 30 percent and most differences were smaller than this. All TLDs were wrapped in aluminum foil prior to irradiation for equilibration of the dose deposited in the TLD.

4.1.3 PIN Diodes

The RADC PIN diode with a tantalum shield was routinely used to monitor the pulse shape of the Linac output. The diode was mounted behind the oscillator package for these measurements. In addition, the possibility of use of this diode in this location for routine dosimetry was evaluated. It was found that the diode signal did not track the resonator dose as measured with the internal Si calorimeter. When the dose was varied by insertion of a scattering plate at the Linac output, the PIN signal varied sublinearly with resonator dose. This effect is a direct result of the large energy loss in the oscillator package. As a result, a PIN is not suitable for routine dosimetry measurements.

4.2 RESONATOR POSITION

Measurements were made of the resonator location in the oscillator package in order to determine the optimum position of the package for irradiation.

In order to facilitate alignment, the center of the resonator was marked on the inner oscillator package.

4.3 COLLIMATION AND SHIELDING

Two collimator structures were evaluated experimentally. Collimator 1, provided by IRT, consisted of 5 cm of Aℓ backed by 2.5 cm of Pb and had a 2.5-cm-diameter collimation hole. Collimator 2, available at RADC, had 1.3 cm of Aℓ, 0.6 cm of Pb, and 0.6 cm of Aℓ and had a 1.3-cm-diameter collimation hole.

Using collimator 1 it was determined that dose deposited in the oscillator electronics nearest the resonator was 6 and 10 percent of the value at the resonator on the irradiating-beam-input side and output side, respectively (positions A and B, respectively, of Figure 2). The letters in this figure indicate the locations of the TLDs.

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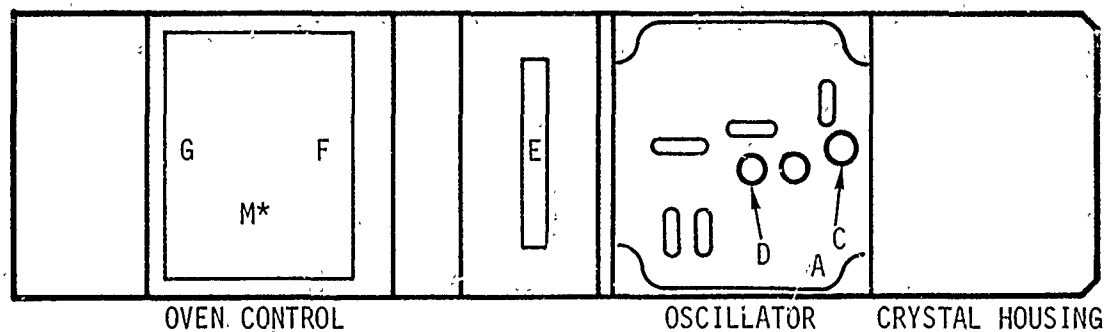
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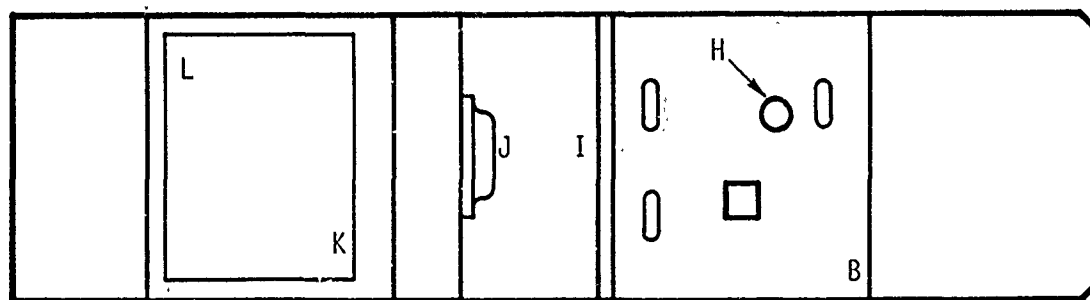
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Figure 2. Schematic figure showing locations of electronics dose map.
2a: input side; 2b: output side

In an attempt to reduce this dose, collimator 2 was used. The dose at positions A and B was approximately the same with this collimator, ~7 percent of the value at the resonator.

Using collimator 2 it was determined that the dose at the resonator was independent of the position of the resonator within a circle of 6 mm diameter around the resonator center. It was therefore concluded that resonator alignment was not critical; adequate positioning can be obtained by visual alignment of the oscillator package with reference marks on the collimator plate.

Measurements of the transmitted dose behind both collimators were made by exposing TLDs on the back of the collimator with ~5 x 10^6 rads incident. For Collimator 2, dose at the back was ~1 percent of the incident dose; for collimator 1, it was ~0.3 percent.

Based on the above measurements, it is recommended that the collimator to be built for RADC's resonator measurements be comparable in thickness to collimator 1, but utilize a collimation hole similar to that of collimator 2.

4.4 DOSE SCALING FACTORS

The ratio of dose at the resonator position to that at the input side of the oscillator package was determined by simultaneous measurements of the dose at these locations using silicon calorimeter dosimeters. These measurements were made with the resonator located at 10 cm and 40 cm from the output port of the Linac.

At 10 cm, this ratio was found to be 0.220 ±0.009 and at 40 cm was 0.290 ±0.011. The average dose per pulse in the resonator at the 10-cm position was 3.9 krads and at 40 cm was 260 rads for normal Linac operation using the 1.3-cm-diameter collimator.

In order to verify that the silicon calorimeter at the input was not affecting the dose deposited in the resonator, a series of measurements was made with TLDs at the input location for measurement of the input dose. To within the accuracy of the measurements, no difference was seen in the ratio of input to resonator dose.

The difference in the scaling factors at the two locations is explained by the $1/r^2$ dependence of the Linac output dose measured from a virtual focus point 5 cm behind the output point. (The internal and external dosimeters were separated by 3-cm.)

The calculated ratio should differ by a factor of 1.36 while the measured ratio differs by 1.32. The difference between these values is ~3 percent, less than the standard deviation of either of the scaling factors.

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4.5 OSCILLATOR PACKAGE DOSE MAPPING

Dose deposited in the electronics package was measured with the oscillator at both 10- and 40-cm positions using TLDs. Figure 2 shows an outline diagram of the oscillator package and indicates the location of the points at which the dose was measured.

Table 2 summarizes the dose deposited at each of the locations defined in Figure 2 for unit dose deposited in the resonator.

It is noted that the dose at locations in the electronics well removed from the resonator is lower at the 10-cm position than at 40 cm. This indicates that not all of this dose is due to scattering from the resonator location, but that transmission through the stopping block also contributes. At the closer position, fewer electrons will be incident at any given off-axis position than at 40 cm. Consequently, use of the thicker stopping block as recommended above should further reduce the dose at 40 cm in the electronics.

Table 2. Dose[a] Deposited in Electronics Package at Locations Defined in Figure 2

TLD Position Location	Normalized Dose (10-cm position)	Normalized Dose (40-cm position)
A	1.4×10^{-1}	7.3×10^{-2}
B	4.9×10^{-2}	7.3×10^{-2}
C	4.3×10^{-2}	5.5×10^{-2}
D	2.3×10^{-2}	3.1×10^{-2}
E	8.4×10^{-4}	8.8×10^{-3}
F	8.4×10^{-4}	3.4×10^{-3}
G	$< 3 \times 10^{-4}$	2.1×10^{-3}
H	1.3×10^{-2}	3.4×10^{-2}
I	1.1×10^{-3}	1.1×10^{-2}
J	8.4×10^{-4}	9.2×10^{-3}
K	2.8×10^{-4}	3.5×10^{-3}
L	$< 3 \times 10^{-4}$	1.7×10^{-3}
M	$< 3 \times 10^{-4}$	2.1×10^{-3}

[a]Dose is relative to unit dose in the resonator using 1.3-cm-diameter collimator.

SECTION 5

RECOMMENDED EXPERIMENTAL SETUP

As a result of the tests at the RADC Linac, the following general guidelines were established for the experimental setup.

In order to obtain reproducibility, a 1.3-cm-thick aluminum base plate could be mounted on the fixed and movable tables at the irradiation locations and pinned to both tables. Reference to the Linac output port will be obtained by "pinning" to the fixed table and the movable table will be immobilized by "pinning" to the plate.

A stopping block collimator structure should be fabricated of 5 cm of aluminun backed by 2.0 cm of lead. A 1.3-cm-diameter collimator should be used. Standard locations at the 10 and 40-cm positions can be obtained either by pins in the aluminum plate which mate with holes in the collimator or by brackets or angles attached to the plate against which the stopping block is positioned.

The oscillator should be mounted "lying on its side" with the frequency adjustment screws pointing away from the axis of the Linac in a position in which they can be easily adjusted. The oscillator can rest on a shelf attached to the stopping block or to a separate stand mounted in a standard position behind the block.

After the Linac is initially tuned, final steering adjustments should be made by steering the beam through the collimator. This steering can also be checked during the day by sliding the oscillator away from the collimator so that it is completely behind the stopping block. A PIN diode attached to the stopping block and behind the oscillator when it is in the irradiation position can be used as a detector when the steering adjustments are made. The oscillator package can be moved manually, which would be entirely adequate. If more frequent adjustments will be needed, motorization of the oscillator position should be considered.

During initial tuning of the Linac at the beginning of the day, it will be feasible to leave the oscillator in the radiation room if necessary. The total dose in a location on the floor, near the end of the beam tube and behind lead bricks was found to be <200 rads during initial machine tuning.

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Primary dosimetry can be made using a silicon calorimeter dosimeter fixed at the output side of the collimator. The dosimeter scaling factors given in paragraph 4.4 above would then be used to determine resonator dose.

Another possibility is to mount a silicon calorimeter inside the oscillator package at the position originally intended for a PIN diode. This will require a specially constructed calorimeter, and appropriate scaling factors for resonator dose as a function of position would have to be determined experimentally.

Although not absolutely mandatory, it is recommended that the dose scaling ratios and dose received in the electronics package be remeasured in the final experimental setup. This would verify the data presented here and also indicate any differences caused by the final experimental arrangement.

SECTION 6

INITIAL RESONATOR IRRADIATION

Initial measurements were made of the frequency offset induced by electron irradiation of a quartz resonator mounted in the FEI package used for the dosimetry characterization discussed above. The resonator was mounted in the package with the disk rotated 90 degrees as described above. The purpose of these tests was to check out the system and to uncover possible experimental problems.

Oscillator frequency was measured using the system previously set up and tested by RADC. The oscillator output was mixed with the output of the Hewlett-Packard Cesium Beam Frequency Standard, Model 5060A, and the frequency shift was determined with an FEI Frequency Error Analyzer and Digital Phase Comparator. The output of the error analyzer was displayed on a chart recorder. The response time of this system is such that frequency offset data is lost for the first several seconds after irradiation.

The behavior of the radiation-induced offset in this resonator was different than that usually seen where an initially large offset decays back to a smaller "steady-state" offset in about 15 to 20 minutes.[4] Instead, for this resonator, except for the first pulse of ~ 200 rads, the frequency offset was negative when the frequency error analyzer recovered (~ 5 seconds after the pulse) and continued to increase in a negative sense for 10 to 15 minutes before reaching a steady-state value. The offset caused by the first pulse was positive and decayed with time to a smaller positive value.

The magnitude of the oscillator offset during a Linac pulse, caused by other than radiation effects in the resonator was investigated. With a stopping block (5 cm aluminum backed with 2.5 cm of lead) in front of the collimator, the frequency offset was positive and varied from 1.0 to 2.2 parts in 10^{11} for a pulse which would have delivered ~ 150 rads without the stopping block (40-cm position). This offset was probably due to pickup in power supply leads, or possibly signal leads, which connected the oscillator to equipment in the measurement room. It is likely that this small frequency

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offset could be reduced by use of low-pass filters on each of the power supply lines at the input to the oscillator package.

One pulse was also taken with the oscillator positioned behind the collimator so that the electronics package, at a position of ~2 cm from the resonator, would be irradiated. For this shot, $\Delta f/f = 2.8 \times 10^{-11}$ for a 150-rad pulse. Direct irradiation of the electronics in this position evidently contributes a small addition to the "spurious" frequency shift. However, since the dose to the electronics is reduced by a factor of 100 to 300 when the oscillator is positioned normally behind the collimator, this contribution should be entirely negligible.

One important consideration in the assessment of the long-term behavior of the oscillator after an irradiation pulse is the behavior of the oven and dewar assembly after the temperature excursion caused by the energy deposition of the pulse. A rough calculation of the thermal recovery time indicates it to be about 20 minutes and to be dominated by conduction down the dewar walls and the support structure of the internal electronics. Measurement by RADC of the oven current during and after an irradiating pulse tends to confirm this recovery time since the oven current was seen to change for at least this long.

Temperature shifts of a few millidegrees can cause frequency shifts of a few parts in 10^{11}, depending, of course, on the resonator temperature and frequency-temperature characteristics. Consequently, at least part of the oscillator frequency recovery may be affected by recovery of the resonator temperature. Additional data will be required to clarify this point.

SECTION 7

QUARTZ CRYSTAL FILTERS

Crystal filters have found many applications in analog and digital space systems and their radiation hardness has been investigated;[5] however, the question of how a user orders crystal filters which have radiation response comparable to filters used previously is a problem of hardness assurance. The question addressed here is whether the specifications used to ensure the hardness assurance of quartz resonators is sufficient to ensure the hardness of crystal filters. To address this question, it is necessary to identify those specifications used in the design of crystal filter networks which relate to the basic parameters of the bulk crystal material from which the filters are manufactured. The specifications include attenuation characteristics, phase and/or delay characteristics, bandwidth, spurious response, insertion loss, etc. It is then necessary to determine if the basic parameters of the bulk crystal material will be affected by radiation enough to adversely affect the filter response.

It must be recognized that circuit configurations of crystal filters are varied and often highly complex. Relating the change in the basic crystal parameters to a change in crystal filter response will be complicated by the circuit configuration, and therefore, an analysis on each configuration will be necessary in order to assess the response. Such an analysis is beyond the scope of this effort. However, in order to perform the analysis of an overall filter response, it is necessary to be able to predict the shift in the operation of each crystal element.

The response of the crystals can be analyzed in terms of the equivalent circuit shown in Figure 3, where C_p is the capacitance of quartz between electrodes; C_s is proportional to the elastance of the quartz; L_s is proportional to the mass of the quartz; R_s is proportional to the dissipation in the quartz. At series resonance, the crystal looks primarily resistive with a magnitude of R_s and the Q of the circuit is given by:

$$Q = \frac{X_{L_s}}{R_s} . \tag{1}$$

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The value of Q is quite large for most quartz materials (1×10^3 to 3×10^6 for 5 MHz fifth overtone resonators) and depends upon the quality of the quartz material.
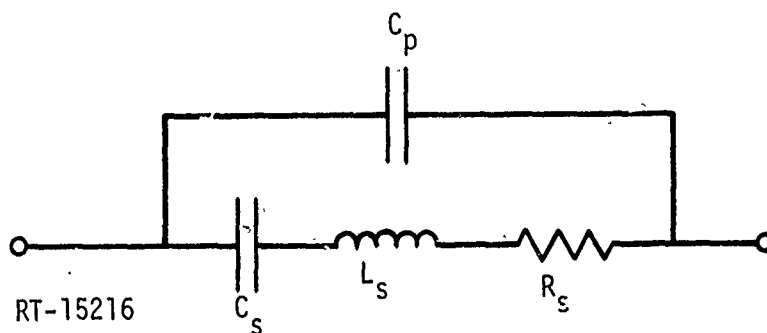

RT-15216

Figure 3. Electrical circuit equivalent of quartz resonator

Using the above information and a simplified filter circuit shown in Figure 4, the effect of inserting the crystal filter in the circuit may be analyzed.

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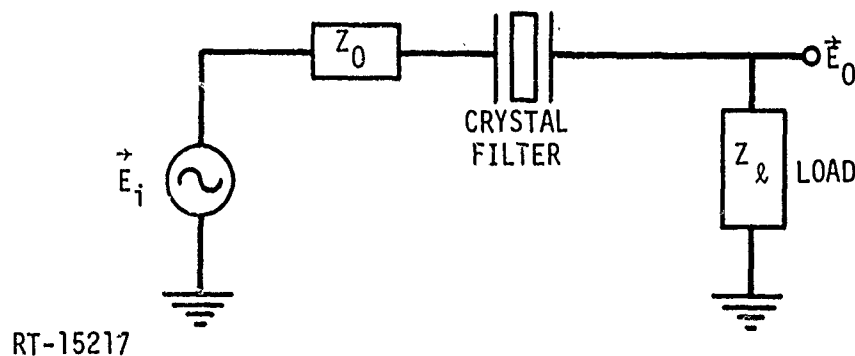
Figure 4. Simplified electrical circuit diagram for quartz filter

In order to realize maximum power transfer at resonance from the driver stage to the load, the load should be designed to be the complex conjugate of the source output impedance. This will put the loop current in phase with the source voltage which implies that the circuit looks resistive. The output voltage can be expressed as

$$\vec{E}_0 = \frac{\vec{E}_i \, \vec{Z}_\ell}{\vec{Z}_0 + \vec{Z}_\ell + \vec{Z}_{xtal}} \qquad (2)$$

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The denominator of this equation, at the resonant frequency, is composed of only the real portions of the impedances. Therefore,

$$\vec{E}_0 = \frac{\vec{E}_i \, \vec{Z}_\ell}{R_0 + R_\ell + R_s} \ .$$ (3)

Without the crystal in the circuit, the output voltage, $\vec{E}_0'$, would be

$$\vec{E}_0' = \frac{\vec{E}_i \, \vec{Z}_\ell}{R_0 + R_\ell} \ .$$ (4)

The insertion loss in dB of the crystal filter may now be calculated using Equations 3 and 4 as

$$\text{Insertion Loss (dB)} = 20 \log_{10} \left| \frac{\vec{E}_0}{\vec{E}_0'} \right| = 20 \log_{10} \frac{R_e}{R_e + R_s}$$

$$= 20 \log_{10} \frac{1}{1 + \dfrac{R_s}{R_e}} \ .$$ (5)

where $R_e = R_0 + R_\ell$. From Equation 5, it can be seen that if the insertion loss is to remain low, then the ratio of R_s to R_e must be kept small. Radiation data on quartz resonators indicate that at very modest ionizing dose levels, the value of R_s may vary significantly for some types of quartz crystals.[6] Annealing does occur over a time period of approximately one second; however, in the case of natural quartz, some permanent changes may occur.

The consequences of the increase in the insertion loss will be a decrease in the signal level, thus reducing the signal-to-noise ratio in the circuit. Another detrimental effect (seen from Equation 1) is the reduction of Q as R_s increases, resulting in a broadening of the signal passband.

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Also,

$$Q = f_0/\Delta f \quad , \tag{6}$$

where f_0 is the center frequency and Δf is the 3-dB bandwidth. This may result in an increase in the noise level which will reduce the signal-to-noise ratio further. Whether or not this decrease in the signal-to-noise ratio will be detrimental to circuit operation, will depend upon circuit application and design margins.

There are other radiation effects on quartz that can contribute to the reduction of signal-to-noise ratio. A shift in the resonant frequency of the resonators after exposure to ionizing radiation has been observed.[5] This is manifested as an initial transient offset which generally anneals at least partially and a residual permanent offset. For crystal filters designed with very high Q crystal requirements, this shift in resonant frequency may cause an out-of-tolerance shifting in the overall bandpass character- istics. This shift in the frequency response will cause the signal to operate on the edge of the bandpass characteristic curve which will result in a phase shift in the output voltage. In timing applications, this phase shift may result in significant timing error by the time the transient shift has annealed to the post-irradiation value.

The above-mentioned radiation effects are of concern for the circuit designer when there is need for very narrow band crystal filters (BW = 10's to 100's Hz) or if a wide band filter is designed using a number of narrow band units. The swept synthetic quartz crystals used in the construction of hardened quartz resonators are a better choice for those critical applications in which very narrow bandpass is needed in the design.

From this study, we see that the same parameters which affect the performance of quartz resonators also control the behavior of crystal filters. Consequently, hardness assurance criteria for resonators will, in general, be valid for filters, although limits on parameter shifts may be somewhat different. Detailed analysis of specific critical filter circuits would be necessary to determine the precise requirements on quartz hardness. It seems likely, however, that these requirements will not be more stringent than those for resonators.

One area on which we have not found specific experimental or analytical work is the relationship between the radiation-induced changes in Q and R_s for fifth harmonic

AT-cut resonators used in oscillators and those in the fundamental mode resonators used for filters. This relationship could have important consequences on the radiation hardness of filters and should be addressed further.

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METRIC SYSTEM

BASE UNITS:

Quantity	Unit	SI Symbol	Formula
length	metre	m	...
mass	kilogram	kg	...
time	second	s	...
electric current	ampere	A	...
thermodynamic temperature	kelvin	K	...
amount of substance	mole	mol	...
luminous intensity	candela	cd	...

SUPPLEMENTARY UNITS:

Quantity	Unit	SI Symbol	Formula
plane angle	radian	rad	...
solid angle	steradian	sr	...

DERIVED UNITS:

Quantity	Unit	SI Symbol	Formula
Acceleration	metre per second squared	...	m/s
activity (of a radioactive source)	disintegration per second	...	(disintegration)/s
angular acceleration	radian per second squared	...	rad/s
angular velocity	radian per second	...	rad/s
area	square metre	...	m
density	kilogram per cubic metre	...	kg/m
electric capacitance	farad	F	A·s/V
electrical conductance	siemens	S	A/V
electric field strength	volt per metre	...	V/m
electric inductance	henry	H	V·s/A
electric potential difference	volt	V	W/A
electric resistance	ohm		V/A
electromotive force	volt	V	W/A
energy	joule	J	N·m
entropy	joule per kelvin	...	J/K
force	newton	N	kg·m/s
frequency	hertz	Hz	(cycle)/s
illuminance	lux	lx	lm/m
luminance	candela per square metre	...	cd/m
luminous flux	lumen	lm	cd·sr
magnetic field strength	ampere per metre	...	A/m
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m
magnetomotive force	ampere	A	...
power	watt	W	J/s
pressure	pascal	Pa	N/m
quantity of electricity	coulomb	C	A·s
quantity of heat	joule	J	N·m
radiant intensity	watt per steradian	...	W/sr
specific heat	joule per kilogram-kelvin	...	J/kg·K
stress	pascal	Pa	N/m
thermal conductivity	watt per metre·kelvin	...	W/m·K
velocity	metre per second	...	m/s
viscosity, dynamic	pascal·second	...	Pa·s
viscosity, kinematic	square metre per second	...	m/s
voltage	volt	V	W/A
volume	cubic metre	...	m
wavenumber	reciprocal metre	...	(wave)/m
work	joule	J	N·m

SI PREFIXES:

Multiplication Factors	Prefix	SI Symbol
1 000 000 000 000 = 10^{12}	tera	T
1 000 000 000 = 10^{9}	giga	G
1 000 000 = 10^{6}	mega	M
1 000 = 10^{3}	kilo	k
100 = 10^{2}	hecto*	h
10 = 10^{1}	deka*	da
0.1 = 10^{-1}	deci*	d
0.01 = 10^{-2}	centi*	c
0.001 = 10^{-3}	milli	m
0.000 001 = 10^{-6}	micro	μ
0.000 000 001 = 10^{-9}	nano	n
0.000 000 000 001 = 10^{-12}	pico	p
0.000 000 000 000 001 = 10^{-15}	femto	f
0.000 000 000 000 000 001 = 10^{-18}	atto	a

* To be avoided where possible.

MISSION
of
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