INITIAL RESULTS ON 5 MHz QUARTZ OSCILLATORS EQUIPPED WITH BVA RESONATORS

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ABSTRACT

The techniques of fabricating BVA resonators have yielded greatly improved performance in terms of aging, amplitude-frequency effect, and acceleration sensitivity.

Preliminary results have been recently obtained including Q factor of 3.5×10^6, short-term stability of 5×10^{-13} at 1 second and aging of 5×10^{-12} per day measured at NBS. In addition, the frequency shift under acceleration (measured at ONERA) was found to be as low as 2×10^{-10} per g for AT-cut quartz, and a factor of 10 smaller for SC-cut, with no residual frequency shift after static g loading, to within a few 10^{-11}.

In this paper are presented new results on 5 MHz resonators concerning aging versus drive level, reduced amplitude-frequency effect, frequency and phase stability performance, and frequency retrace following power interruption.

The conclusion from aging and level of drive investigations is that a zero aging rate is possible at a drive level which depends on the quartz material used. For natural AT quartz, a level of 70 to 90 μW appears to be optimum, and for SC quartz approximately 160 μW.

Measurements of short term frequency stability and of the phase noise were performed using crystals mounted within a modified commercial oscillator model, FTS 1000. A 5th overtone crystal exhibits S_ϕ (f) = -127 dB at 1.5 Hz from the carrier with close-in phase stability

being degraded very little as the drive level is increased. The white noise floor improves with drive level, as expected.

A stability $\sigma(\tau) < 5 \times 10^{-13}$ for averaging times of 1 to 30 seconds was measured for an SC, 3rd overtone resonator at 37 μW drive level. This is the square root of the Allan variance and represents the noise from both test and reference sources.

I. Introduction

New resonators have recently (1) (2) (3) (4) been developed in Besancon, France. Research type resonators have been developed covering approximately 10 different types or versions according to various goals of frequency range, type of mounting, size, environment, etc. At this point, some types are close to the industrial preproduction stage (5).

Results have been obtained at various frequencies including 100 MHz and ultrahigh frequencies (6). However the BVA_2 5 MHz type resonator has been the most extensively studied.

In this paper, the most interesting results previously obtained are reviewed and some new results concerning oscillators and resonators are given. Particular attention is given to drive level capabilities and aging versus drive level questions. Frequency and phase stability performance and frequency retrace following power interruption are discussed. Of importance is the fact that BVA units have already been used in a modified commercial oscillator, FTS 1000; initial results with this configuration are presented and discussed.

This paper deals only with resonators of the BVA_2 design. Basically, BVA_2 resonator construction includes:

1. An "electrodeless" design. All problems of damping, stresses, contamination, ions migration, etc., which relate to electrode deposition are removed.

2. A crystal mounting made of quartz. Small "bridges" connect the vibrating part of the crystal to the dormant part. Key advantages are:

   - no discontinuities nor stresses in mounting points

   - very high precision in shape and location of "bridges"

- symmetry and reproducibility when needed

- design of bridges very versatile according to goals.

3. Additional parameters. (when compared to classical designs). The design exhibits additional construction parameters:

   - the electrode (and thus the electric field) can have a radius of curvature different from the radius of curvature given to the vibrating crystal.

   - heaters and sensors can be placed in a vacuum close to the crystal without contacting the vibrating crystal.

   - connecting "bridges" can have a great variety of shapes, locations and various other features.

4. Provision for any material, crystal cut or frequency (including very high frequencies).

5. Use of technological means (i.e. ultrasonic machining) which allow reproducibility or versatility (for example the external shape of the crystal does not need to be circular or rectangular).

II. Brief Review of Previous Results

In this section, only results dealing the 5 MHz AT or SC cut units will be discussed, to point out interesting figures already available. Very roughly speaking, the BVA design is capable of an order of magnitude improvement in short term stability (7), long term drift and acceleration sensitivity (8). More precisely, the following features can be listed from previous results:

1. Higher Q factor: A 5 MHz fifth overtone AT resonator (made at Oscilloquartz, Switzerland, ref. 3) yielded $Q = 3.5 \times 10^6$ together with

   $R_1 = 80.7\Omega$
   $C_1 = 1.02\ 10^{-4}\,\text{pF}$
   $C_0 = 4.1\,\text{pF}$

2. Better frequency adjustment (by a factor of 2 to 5 depending on technology).

3. Better short term stability. 5.9×10^{-14} for 128 s has been achieved (7) and 10^{-13} (for integration time in the order of 100 s) has been reproduced since.

4. Lower drift rate. 5×10^{-12}/day drift has been measured at NBS Boulder and at ENSMM Besancon as well. Also important is the fact that final aging is established within days and remains constant (4) (9). Results recently obtained will be discussed in the next section.

5. Lower g sensitivity (8). A maximum sensitivity of the order of 10^{-10}/g can be achieved in the case of AT cut units. A sensitivity lower than 5×10^{-11}/g can be achieved in the case of SC cut single crystals. There is no residual frequency shift after static g loading, to within a few parts in 10^{11}.

6. Reduced amplitude frequency effect: Reduction by a factor of 2 to 15 (9).

III. Recent Advances

1. Extremely high drive level:

The usual drive level for conventional units ranges from 0.1 μW to some 20 or 30 μW, at least in ultrastable 5 MHz oscillators. Precision oscillators with an aging rate lower than 10^{-10}/day usually operate at less than a few μW. In the case of high spectral purity oscillators, the crystal can be driven slightly harder but this causes the aging rate to increase by an order of magnitude or two. If the crystal is driven harder, non-linear effects (10) occur and with still higher levels the crystal can even fracture.

On the contrary, BVA_2 resonators withstand drive levels in the mW range at 5 MHz. For instance, the BVA_2 2-77, 5 MHz, natural quartz, AT cut fifth overtone unit has now been running for 11 months at a 1600 μW drive level. The oscillator and the single oven are of very simple design. Nevertheless, the drift remained very constant at $3.3 \pm 0.2 \; 10^{-10}$/day after 72 hours. Another similar resonator of artificial unswept material (BVA_2 2-119) has been driven at 2.8 mW with an aging of approximately 10^{-9}/day.

2. Aging versus drive level:

The aging rate for BVA_2 resonators is a non-monotonic function of drive level. Although aging experiments require long time periods, preliminary results on 7 resonators, using various oscillator electronics, have been obtained. These data plus theoretical considerations show that the resulting aging, a_r, may be modeled by the following formula:

$$a_r = a_i + kP \left[1 + a \exp\left(- \sqrt{P/P_0}\, t/\tau\right) + \cdots \right]$$

where: a_i is an intrinsic aging depending on material and cut

k is a constant depending on material and cut

P is the power dissipated in motional resistance R

P_0 is a reference power level

τ is a time constant; t is time

This formulation is valid for a first operation; there is some evidence that the exponential part decreases for further operations. At this point, it is premature to quote precise figures for each parameter. However, orders of magnitude can be given for AT cut natural-quartz fifth overtone crystals:

$a_i \rightarrow$ parts in 10^{11} per day (negative)

$k \rightarrow$ parts in 10^{13} per day, per μW (positive)

$a \rightarrow$ order of 10 to 100

$\tau \rightarrow$ several days

The numbers obtained with various units fabricated from the same material are consistant.

For these units the aging is predictible. Moreover it is possible to change the aging rate by changing the drive level. In particular it is possible to obtain, by slight changes of drive level, slightly positive or slightly negative aging. There is a drive level P_1, called "zero aging drive level", since it yields an aging rate crossing zero. Three oscillators operating at this "zero aging drive level" were constant in frequency to within 2×10^{-10} over 3 months. For AT cut, natural quartz, 5 MHz, fifth overtone, four bridge units a drive level of 70 to 90 μW appears to be optimum. For SC cut, natural quartz, 5 MHz third overtone four bridge units a level of 160 μW is suitable for the so called "zero aging".

3. Internally heated crystals (11):

Using very high drive levels, it is possible to directly heat the crystal by energy dissipation in the motional resistance R_1. Units specially devoted to internal heating have been designed (12). These special units are of special construction and will not be described here. However, if a regular BVA unit is used at mW drive level, it is easy to see, through the mechanisms involved that important changes will occur. In particular, the internally applied energy can no longer be ignored; in other words, the energy exchange with the external environment will no longer uniquely go through the surface. As a consequence (11) the whole bulk crystal participates "in situ" in its own temperature control, and its sensitivity to external temperature fluctuations decreases.

4. Frequency retrace following power interruption:

Extensive retrace experiments have been conducted with resonator BVA_2 2-77 already mentioned. This resonator retraced to within 2 or 3 x 10^{-10} following power interruption ranging between 12 and 48 hours. Some other experiments with similar resonators but different drive levels have been conducted yielding similar results. Nevertheless, one particular resonator has shown a frequency versus temperature hysteresis effect which at this point seems to be related to the old mounting structure and packaging of prototype BVA_2 units. If so, this is one more reason to use the low g design (8) which also carefully avoids mounting thermal stresses.

5. Results using commercial oscillator:

Several BVA_2 resonators have now been operated within modified commercial oscillators (FTS-1000 of Frequency and Time Systems, Inc., Massachusetts). Results have been obtained with both AT and SC cut, operated at various drive levels.

It has been verified that low aging rates are established quickly (in a few days), and that a "zero aging" drive level exists. However, since the first oscillator was operated for less than 200 days, more data must be collected for a more complete picture on aging versus drive level.

Figure 1 shows results for an SC-cut 3rd-overtone resonator (BVA 2-125) for which the drive level was progressively increased up to 284 µW, over an elapsed time period of 135 days. The aging rate changed from positive to negative in going from 124 µW to 284 µW. When the drive level was set to 160 µW approximately zero aging resulted and this is as predicted for SC-cut natural quartz.

This same resonator has yielded short term stability measurements shown in Figure 2. In one case the drive level is 37 µW and the reference is a standard FTS 1000 oscillator. The square root of the Allan variance for the two sources is better than 3.7 x 10^{-13} over 3 to 30 seconds averaging time.

Results for an AT-cut, 5th-overtone resonator (BVA 2-28) at 72 μW drive level are also shown. Figure 3 shows S_ϕ (f) phase noise results for this resonator versus the reference S/N 165. At 3 μW drive the phase noise floor is -142 dB (spectral density in 1 Hz bandwidth); for 72 μW the phase noise floor is -144 dB which is essentially the noise floor of the reference. At the same time, the close-in phase noise is degraded by not more than 1 dB for the higher drive level (indicating that a flicker floor of a few 10^{-13} is maintained). It should be noted that 72 μW is close to the theoretical "zero-aging" power level for this AT cut resonator.

Phase noise spectral density results for two other resonators are shown in Figure 4. Here two BVA resonators are directly compared, and assumed to contribute equally. A SC-cut, 3rd overtone resonator (BVA 2-131) is driven at a rather high power level of 265 μW. The other resonator (BVA 2-52) is an AT-cut, 5th overtone at 84 μW. Close-in phase noise in characterized as -118 dB at 1.5 Hz from the carrier, and -140 dB at 10 Hz. At 100 Hz, S_ϕ is -152 dB; at 5000 Hz, -154 dB. In this region the observed result is limited by the system noise floor shown as the dashed line.

IV. Conclusion

Initial results using a commercial modified oscillator have shown that is is possible to take practical advantage of the BVA resonator features. Especially the high drive level can provide extremely good spectral purity without degrading time domain stability. In contrast to results with conventional resonators, the aging of BVA resonators remains comparatively small even at high drive levels. Moreover, there are good hopes that the BVA technique can yield resonators with an aging modelable and settable through drive level.

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APPROX. DRIVE LEVEL (MICROWATTS)	AGING RATE $\Delta f/f$ (per day)	TIME ELAPSED FROM 1st TURN-ON (DAYS)
10	$+ 4 \times 10^{-10}$	8
37	$+ 9 \times 10^{-11}$ (45 day avg.)	70
124	$+ 3 \times 10^{-11}$	120
284	$- 9 \times 10^{-12}$	135
160	approx. zero	165
Oscillator OFF 12 hours		
160	$+ 4 \times 10^{-10}$ (after 1 day)	167
Oscillator OFF 12 hours		
160	$+ 2 \times 10^{-10}$ (after 4 days)	173
160	zero	177

Figure 1. BVA Resonator Aging Versus Drive Level

RESONATOR B V A	DRIVE LEVEL	REFERENCE OSCILLATOR	$\tau =$ 1 sec	3	$\sigma_y(\tau)$ in units 10^{-13} 10	30	100
2-125 SC, 3rd	37 μw	1000 s/n 12	*6.5	3.6	3.5	3.7	5.1
	285 μw	B5400 s/n 165	*8	6.5	5.2	7.4	
2-28 AT, 5th	72 μw	1000 s/n 12	*8	6.0	6.4	6.8	

*Uncorrected for 50% dead time, at 1 second only

Figure 2. Time Domain Stability – Allan Variance (Two Sources)

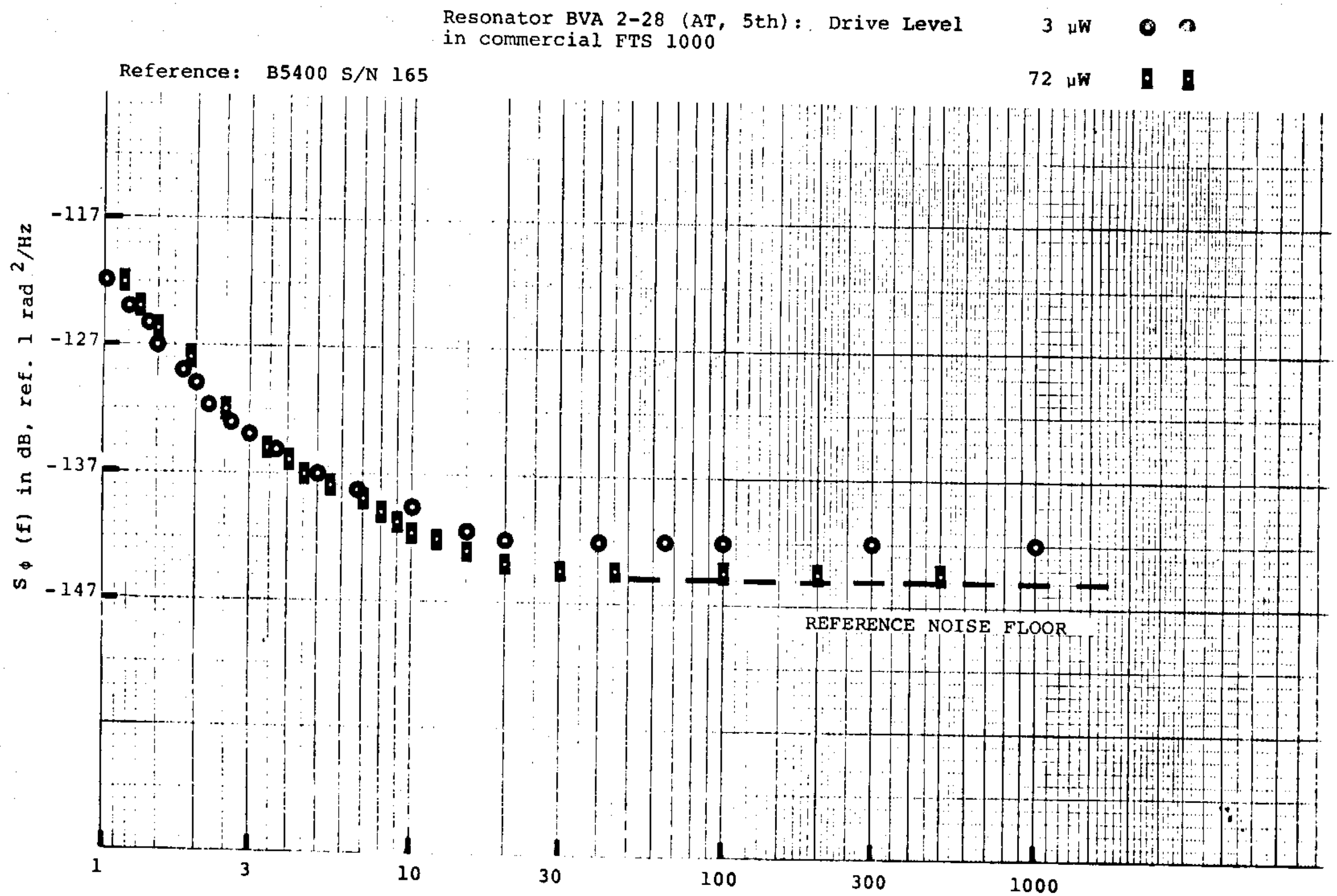

FIGURE 3

Figure 3. Phase Noise Spectral Density, S_ϕ (f), in 1 Hz BW

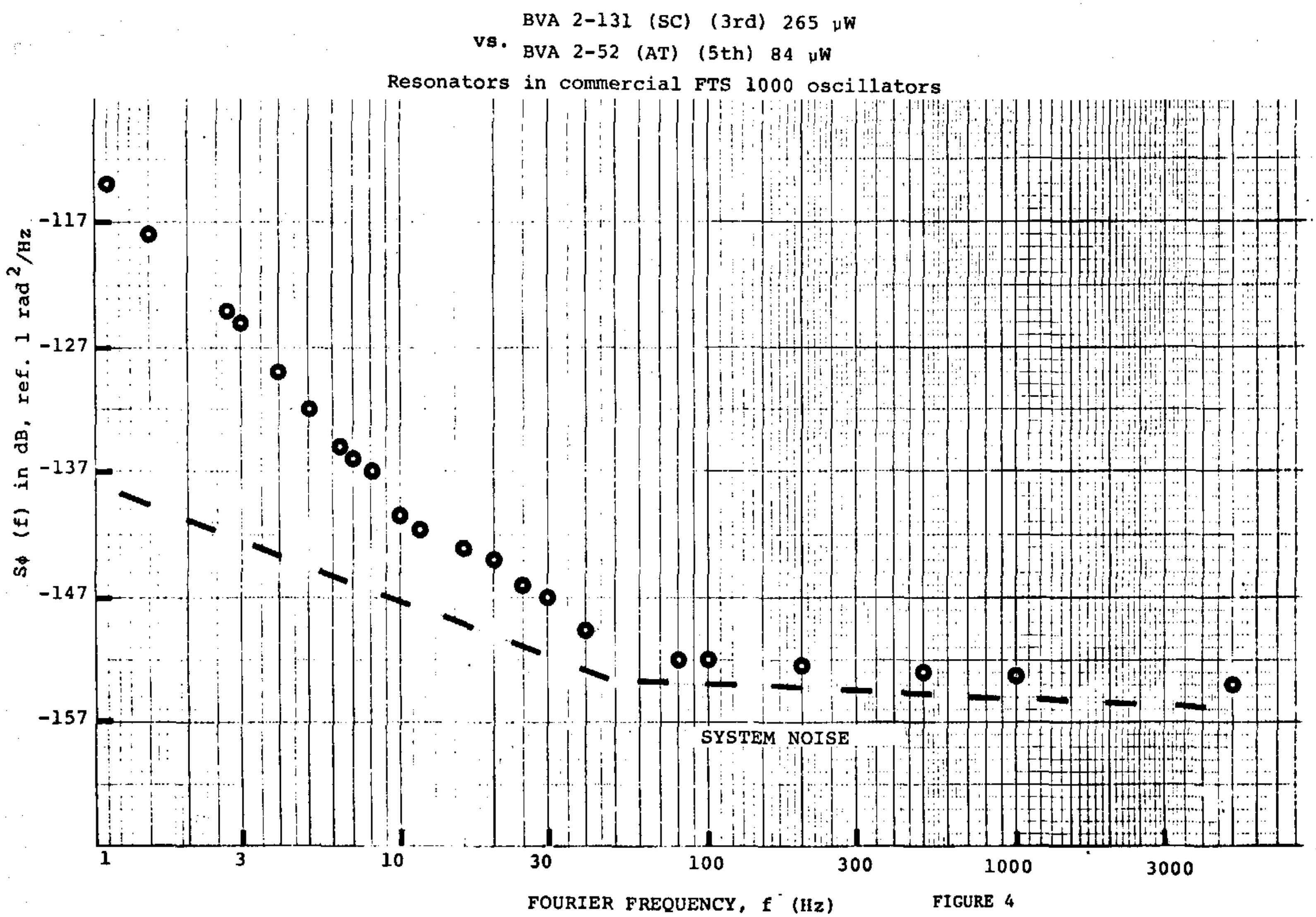

FIGURE 4

Figure 4. Phase Noise Spectral Density, S_ϕ (f), in 1 Hz BW

QUESTIONS AND ANSWERS

QUESTION:

Could you comment on the partial availability of and the quantities that they are available?

DR. BESSON:

You are talking about the resonators or oscillators or what?

QUESTION:

Resonators.

DR. BESSON:

Well, I don't believe I could, myself, answer that question, but however I believe that the resonator will be available with the oscillator.

DR. HAMMOND:

These three papers on quartz resonators, if you will pardon a few comments, in the thirty-some years that I have been following quartz, it has been interesting to track the progress of stability. If you go back to 1930, it was probably a part in 10 to the 5th, by 1950, a part in 10 to the 8th. Today we are looking at a part in 10 to the 12th. And watching that over the last 30 years that I have observed it, it has been an order of magnitude improvement in quartz about every 7 years and it looks like it is on track and it looks like, also, that the next order of magnitude is also possible. That that extrapolation-- It is always very dangerous to extrapolate into the future, but I agree with Arthur Ballato in his first comments that this is an exciting time in quartz. I know of no time that I have observed it when so many things have been coming together that showed so much promise.

Remember, you heard it here first.