QUARTZ PRESSURE TRANSDUCER TECHNOLOGIES

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INTRODUCTION

The past several years have seen a proliferation of pressure transducers that use quartz as the pressure sensing element. However, there exists considerable confusion among some pressure transducer users regarding the terms *quartz pressure transducer* and *quartz crystal pressure transducer.* (To add confusion, at least one company calls their silicon strain gauge a “crystal” sensor.) This paper explains the technology involved in quartz pressure transducer sensor elements on the market today.

For the purposes of this paper, the term *transducer* means the sensor with its associated electronics and its mechanical housing. The term *sensor* means the element that exhibits a change in its properties in response to changes in pressure.

NON-RESONANT QUARTZ SENSORS

Three types of quartz pressure sensors are *non-resonant* (as opposed to *resonant,* or *vibrating* devices)— the *dynamic piezoelectric quartz sensor,* the *fused quartz capacitance sensor,* and the *fused quartz Bourdon tube.* [Authors' aside: To the quartz *crystal* engineer, the use of the term *quartz* to refer to *fused quartz* is nearly a sacrilege! Indeed, Sosman [1] in 1927 wrote: "The use of the single word "quartz" to refer to vitreous silica can not be too strongly condemned. It has arisen through carelessness or ignorance and is already causing troublesome confusion." Sosman suggests the use of *quartz glass* or *fused quartz* for this material.] Non-resonant sensors are inherently analog, since their fundamental output is a voltage or capacitance; while resonant sensors are inherently digital, since their output is a frequency.

(Since the silicon strain gauge is single-crystal silicon, ***not*** single-crystal quartz, it will not be discussed in this paper. Calling a silicon strain gauge a “crystal” sensor appears to be an attempt to capitalize on the reputation of quartz crystal sensors.)

DYNAMIC PIEZOELECTRIC SENSORS

Dynamic piezoelectric sensors utilize the principle of the *direct piezoelectric effect.* That is, when a force is exerted upon a piezoelectric element, a voltage is generated. (The *inverse* piezoelectric effect is used in resonant sensors, as discussed below.) The generated voltage is amplified and measured to determine the applied pressure. However, since this voltage rapidly decays due to self-discharge, the circuitry of the dynamic sensor must capture and process the peak of the voltage generated by the applied force. Because of the self-discharge effect, dynamic transducers are not usable for steady-state or slowly changing pressures. However, for rapidly changing pressures (100s of psi/s [tens of bar/s]) the dynamic piezoelectric sensor is the preferred technology—the analog (voltage) signal of the dynamic sensor can be captured much more quickly than the digital (frequency) signal of the resonant sensor, which must be counted for a brief period of time (typically <1s), during which time the signal is averaged. The piezoelectric element can consist of crystalline quartz, or the man-made piezoelectric ceramics PZT and PLZT, depending upon the sensitivity, resolution, and temperatures required.

CAPACITANCE SENSORS

The most common capacitance sensor uses one or more metal diaphragms to form a capacitance capsule that changes capacitance when a pressure is applied to one or both sides of the capsule. The capacitance change is usually converted to a frequency with the capsule in the feedback loop of an LC or RC oscillator. Counting the frequency determines the pressure applied to the capsule. At low pressures, the capsule can be large, resulting in low hysteresis, low creep, and good resolution. However, for high pressures and temperatures, as encountered in oil and gas wells, the capsule becomes small and stiff, resulting in the need to have well-behaved materials and controlled manufacturing techniques to maintain low hysteresis, low creep, and good resolution. Some manufacturers use *fused quartz (silica glass)* to improve the performance of their capacitance sensors.

The improved performance of the fused quartz capacitance sensor is based upon its extremely low coefficient of thermal expansion—much lower than all standard glasses. In addition, fused quartz has excellent elastic behavior (low hysteresis and creep), and is relatively chemically inert. These properties make fused quartz a nearly ideal material for the manufacture of small capacitor modules for exposure to temperatures up to 200°C in the oil and gas field. However, any sensor element used to sense pressure (or any other parameter, for that matter—except for temperature itself) must be temperature compensated or temperature corrected in order to achieve an accuracy better than a few percent over the temperature range of interest to the oil field. Thus, the need for temperature compensation over this large temperature range negates the advantage provided by the low temperature coefficient of expansion of fused quartz. Indeed, well-designed metal-plate capacitance transducers are strong competitors in the precision downhole market.

Some manufacturers have added to the *quartz* confusion by advertising their metal plate capacitance sensors as *quartz* pressure sensors, simply because they use an insulating layer of *fused quartz* in their capacitance sensor.

The Transducer Technologies Incorporated (TTI) (now defunct) transducer was a true fused quartz capacitance pressure sensor. This device used a coaxial cylinder fused quartz capacitor to provide the stiffness required to operate up to 15,000 psi [1034 bar]. An RTD attached to the sensor element determined the temperature. Extremely sensitive electronics converted the very small percentage change in capacitance into indicated pressure changes. The main downfall of this sensor was its tendency to fail mechanically from shock and vibration, due to the cantilever mounting of the sensor. TTI made transducers for both the down-hole and general-purpose markets.

BOURDON TUBE SENSORS

Due to the near perfect elasticity and low temperature coefficient of expansion of fused quartz, it has been used for about 50 years to make Bourdon tube pressure sensors and gravity meters. The fused quartz Bourdon tube pressure sensor typically is a helical coil of fused quartz glass with dimensions of about 2.5 cm diameter by 3-6 cm long. Pressure applied to the helix causes the coil to unwind. Common practice is to use a *force-balance feedback* technique to apply an opposing force to prevent the coil from unwinding. The current required to maintain equilibrium is a measure of the applied pressure. Due to the size and fragility of this sensor, it is used mainly in the laboratory as a secondary pressure standard or in a pressure controller. Mensor and Ruska make Bourdon tube sensors.

RESONANT PIEZOELECTRIC SENSORS

Although there are numerous *resonant* devices used as sensors (metal cylinders, stretched strings, silicon beams, etc.), the one most used and most familiar in the oil field is the resonant quartz crystal sensor. The main reason for the desirability of quartz resonators for pressure sensor applications lies in the chemical inertness and high elasticity of quartz. (High elasticity means that the mechanical behavior of a material is highly repeatable from cycle to cycle, and that it is free from hysteresis.) Quartz is soluble mainly in fluoride-containing acids and salts (hydrofluoric acid and ammonium bifluoride); quartz is nearly perfectly elastic up to its breaking point.

There are two basic types of resonant (digital) quartz sensors: the thickness-shear mode (best characterized by the Hewlett-Packard design) and the vibrating beam (made popular by Paroscientific). The thickness-shear device is a hydrostatic pressure sensor, since the sensing element is totally surrounded by the pressure media; while the vibrating beam device is a force sensor—the pressure must be converted to a force by means of a Bourdon tube, or by a combination of bellows, hinges, and levers. Each type has its strengths and weaknesses.

QUARTZ VIBRATING BEAM PRESSURE SENSORS

• PAROSCIENTIFIC/WELLTEST

Paroscientific, Inc.'s quartz pressure transducers are based upon two similar resonant (typically 10-50 kHz) quartz crystal force sensors—the single-beam flexure-mode crystal [2] and the double-ended quartz tuning fork (DETF) [3]—depending upon the pressure range and the application for the transducer. For low pressures, the quartz beam is attached to a small hinged metal lever (to control the force-input axis and to scale the full scale force to the design load for the beam). A bellows is attached to the opposite end of the lever. As the bellows is pressurized, it pushes on the lever, thereby loading the quartz resonator. For high pressures, the resonator is attached across a metal Bourdon tube, which is sized for the load carrying capability of the beam and the full-scale pressure of the design. The similar WellTest Inc. (WTI) transducer is based upon the double-ended tuning fork and the metal Bourdon tube. WTI transducers are rated to 15,000 psia and 177°C. Crouzet also manufactures a similar device.

The DETF has a negative parabolic frequency-temperature response (similar to the Hewlett-Packard, below). The temperature at which df/dt=0 for the DETF used in the Paroscientific and WTI transducers is around room temperature. A quartz torsional tuning fork (TTF) [4] temperature sensor located near the DETF provides temperature compensation.

Paroscientific transducers work exceptionally well at low pressure (<1000 psi [69 bar]). However, where the Bourdon tube must be used, the adhesives and the Bourdon tube contribute to creep and hysteresis. Quartz beams are inherently rugged (being similar in size and manufacturing techniques to the quartz tuning forks used in all quartz wristwatches today). Unfortunately, the large size of the attachment mechanisms for the beams (flexures or metal Bourdon tube) causes these sensors to be somewhat prone to breakage due to shock and/or vibration, thereby requiring that the transducers be properly shock mounted. Since the quartz resonator force sensor is not directly surrounded by the pressure fluid, it is not subject to nonadiabatic transient errors. Any pressure or temperature transient effects are due to mechanical effects in the metal system (lever and bellows or metal Bourdon tube), the adhesives used to attach the quartz beam, and differences in the thermal time constants of the pressure and temperature sensing resonators.

Since there is essentially no displacement in the Paroscientific designs, and the bellows/Bourdon tube is so small that there is little fluid movement, a buffer tube or an additional bellows is not needed to isolate these transducers from the harmful effects of well fluid. However, because of the transducer's shock sensitivity, a buffer tube is often used as part of the resilient mounting of these transducers.

QUARTZ THICKNESS-SHEAR MODE SENSORS

The thickness-shear mode quartz sensor is based upon the well-known *force-frequency effect* of precision quartz resonators: if force is exerted upon the circumference of a quartz resonator, its frequency will shift in proportion to the applied force.

• HEWLETT-PACKARD

The use of the thickness-shear mode quartz crystal for pressure applications was popularized by Hewlett-Packard Co. in the late 1960's/early 1970's [5,6]. The HP 2813 (originally the 2811) Quartz Pressure Probe immediately became the industry standard for precision pressure measurements in the oil field. (Its first application was in oceanographic detection of Tsunami waves.) The 2813 is rated to 11,000 psia and 177°C. (HP ceased the manufacture of the 2813 in 1993.)

The HP design is a precision resonator integrally surrounded by a continuous quartz shell that is hermetically sealed, Figure 1. HP's pressure sensor is quite large—1 in (2.54 cm) diameter by 3.35 in (8.51cm) long—which contributes to its cost, tool size, and transient performance: it takes several minutes to change and stabilize the temperature of such a large piece of quartz.

The HP sensor is made of BT-cut quartz. The BT-cut has a negative-parabolic frequency versus temperature response. HP positions the BT-cut's turning point (where df/dt=0) at 65°C, which results in a frequency/temperature slope at 0°C and 130°C equivalent to about 20 psi/°C, increasing to 30 psi/°C at 177°C. To reduce this effect, HP incorporates a matched BT-cut reference crystal into their design, which reduces this error at 177°C to about 3 psi/°C. However, since the BT reference crystal is several inches away from the pressure sensing crystal, and is outside the pressure media, large thermal transient errors result from any non-adiabatic pressure or temperature event.

Due to the technology available in the late 1960's, HP did not supply the 2811 with temperature measurement capability, thereby creating problems for the tool user. Unless the actual (quartz) temperature was determined by an ancillary temperature measurement, the probe's stated accuracy could not be assured. The lack of temperature compensation dictated that precision pressure measurements could be made only at thermal equilibrium. This, combined with the poor transient response (to both pressure and temperature transients) of the large quartz sensor, increased the time required to make precision pressure measurements.

Several companies have incorporated RTD's into the HP 2813 to improve its accuracy and transient performance. Several custom modifications to the thermal coupling between the tool housing and the reference crystal also improve the thermal transient response of the HP 2813.

Since the HP design (and all the other thickness-shear mode designs described below) requires the sensor to be surrounded by the pressure media, and since the electrodes on the outside of the sensor element must be protected from corrosive effects, it is normal for the pressure crystal to be surrounded by an inert liquid, such as Dow Corning 200 silicone fluid. Due to the relatively large "dead volume" of oil around the sensors, it is not feasible to design a soft bellows to isolate these sensors. Therefore, all of the thickness-shear mode designs have used one or more silicone-filled buffer tubes to protect the crystal's electrodes. This approach has been more or less successful, depending upon how skilled and conscientious the field technicians have been in servicing the buffer tubes.

- **QUARTZTRONICS**

The HP design was modified by Quartztronics, Inc., [7-11] by using an AT-cut resonator with a non-cylindrical shell geometry (provided by the use of external flats on the cylinder walls) to reduce the transducer's temperature coefficient of scale-factor, and to make a smaller, higher pressure range, lower cost pressure transducer. The use of the AT-cut, which is less temperature sensitive than the BT-cut, eliminates the need for precision matching of the temperature versus frequency curves of the pressure and reference crystals required by the HP design. Quartztronics manufactures a line of laboratory transfer standard quartz crystal pressure transducers that use a pressure sensor crystal based upon the same general design as the HMR, below, except the Quartztronics pressure sensor crystals are somewhat smaller than the HMR's. Also, Quartztronics places a torsional-mode tuning fork (TTF) [4] temperature crystal and an SC-cut [12] reference crystal outside the pressure media. By positioning the temperature and reference crystal in the high pressure electrical feedthru, and by using an oversize housing to thermally isolate the three-crystal assembly from external temperature change, the transducer maintains excellent thermal and pressure transient performance over a narrow laboratory range of 0-40°C. Quartztronics ceased manufacturing their unit in 1993.

- **HALLIBURTON**

The Quartztronics' design is licensed to Halliburton for downhole oil and gas field use [and to Fisher Controls International (now Rosemount) for process control applications]. The design uses a torsional tuning fork (TTF) [4] temperature sensing crystal and an SC-cut reference crystal [12] located with the pressure crystal. These temperature and reference crystals are designed to have the same thermal time response as the pressure sensor, thus providing greatly improved pressure and temperature transient response when compared to the HP design. Halliburton uses the Quartztronics pressure transducer in the Halliburton Memory Recorder (HMR) [13]. The HMR pressure crystal design is significantly smaller than HP's (see Figure 1), resulting in faster thermal response with more shock resistance. Hence, the HMR exhibits rapid response to pressure and temperature transients—similar to the CQG (below). The HMR is rated to 16,000 psia and 175°C.

- **SCHLUMBERGER**

The information that Schlumberger has published [14,15] about the new *Compensated Quartz Gauge* (CQG) (also being called the *Crystal Quartz Gauge*) shows an SC-cut [12] pressure sensing crystal operating simultaneously in two modes—one that is pressure sensitive and somewhat temperature sensitive, and another that is temperature sensitive and somewhat pressure sensitive. This combination allows the CQG to 'take its own temperature,' which is the ultimate for minimizing thermal transient effects. However, since the size of the CQG is relatively large—1 in (2.54 cm) diameter by 1.5 in (3.81cm) long (see Figure 1), it still takes a minute or two to reach thermal equilibrium. Until then, it still will exhibit a small thermal error due to a transient. From the published data, it appears that the CQG has the best thermal transient response of any quartz gauge on the market today under conditions of low pressure at high temperature or high pressure at low temperature, However, the CQG and the HMR probably exhibit similar performance under normal conditions encountered in real-world wells—increasing temperature with increasing pressure. The CQG is rated to 15,000 psia and 175°C.

- **QUARTZDYNE**

Quartzdyne is the latest entrant to the quartz crystal pressure transducer field. The Quartzdyne pressure transducer, as used in the QUARTZDYNE® Series QU, QS, TMC, and 1XP, utilizes a thickness-shear mode quartz sensor element. The Quartzdyne pressure crystal is considerably smaller than the HP, HMR, or CQG designs (see Figure 1). The pressure crystal is hydrostatically squeezed by the pressure media, just like the other thickness-shear mode designs. The small size further reduces the cost of the sensor, while improving its thermal transient response, at the expense of absolute accuracy—Quartzdyne specifies its products at 0.02% of full-scale accuracy, as opposed to better accuracy specifications for the competing resonant quartz technologies. The small size also allows the use of a bellows to isolate the sensor crystal from harmful effects by the well fluid—unlike other thickness-shear designs that have a large "dead-volume" due to the size of their sensor crystals. The Quartzdyne design has a quartz crystal temperature sensor (proprietary design) and an SC-cut [12] reference crystal thermally mounted in the high pressure electrical feedthru, resulting in excellent thermal matching of the three crystals. As a result, the transient response of Quartzdyne downhole transducers, in normal well conditions, approaches that of the CQG and HMR; while the TMC matches the transient response of the CQG and the HMR. Quartzdyne's product line for downhole use is rated up to 25,000 psi at 177°C. Quartzdyne's Laboratory Transfer Standards provide 0.02% F.S. performance to 40,000 psi from -20 to 60°C and 0.01% F.S. from 0 to 40°C.

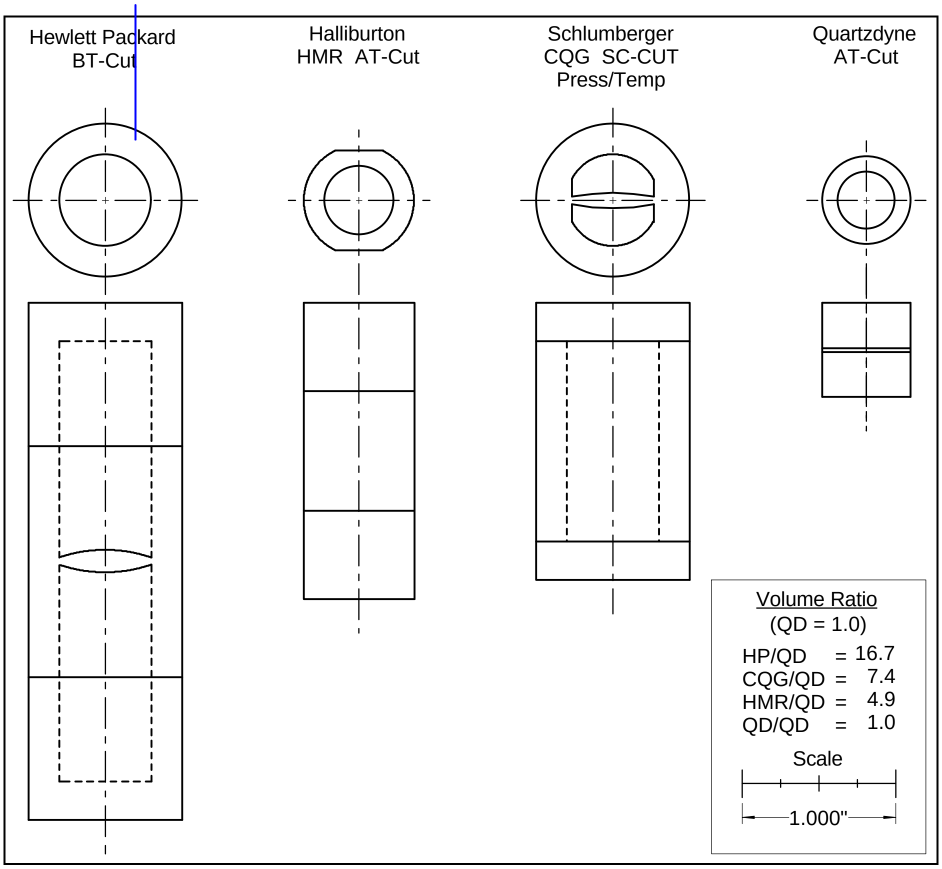

Figure 1: Approximate sizes and shapes for the thickness-shear mode sensors.

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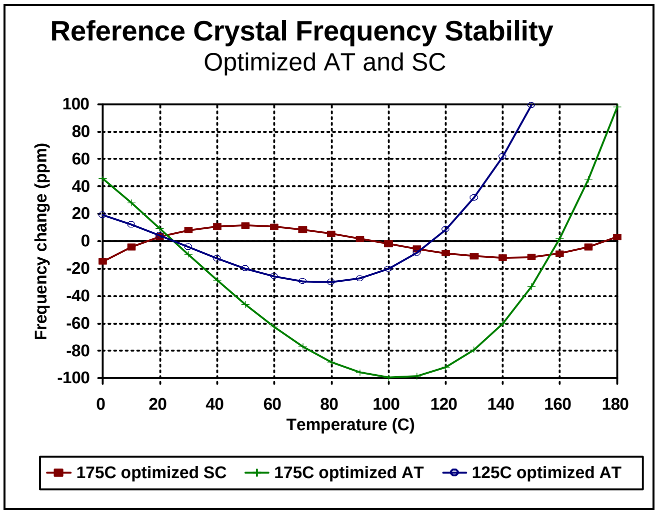
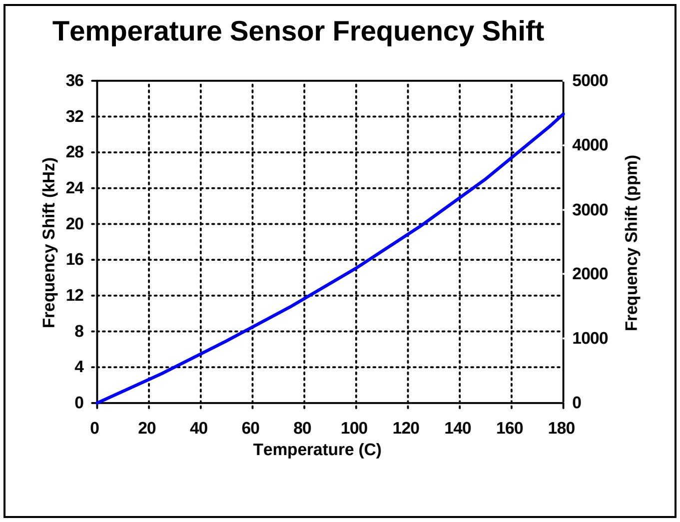
SERIES QR

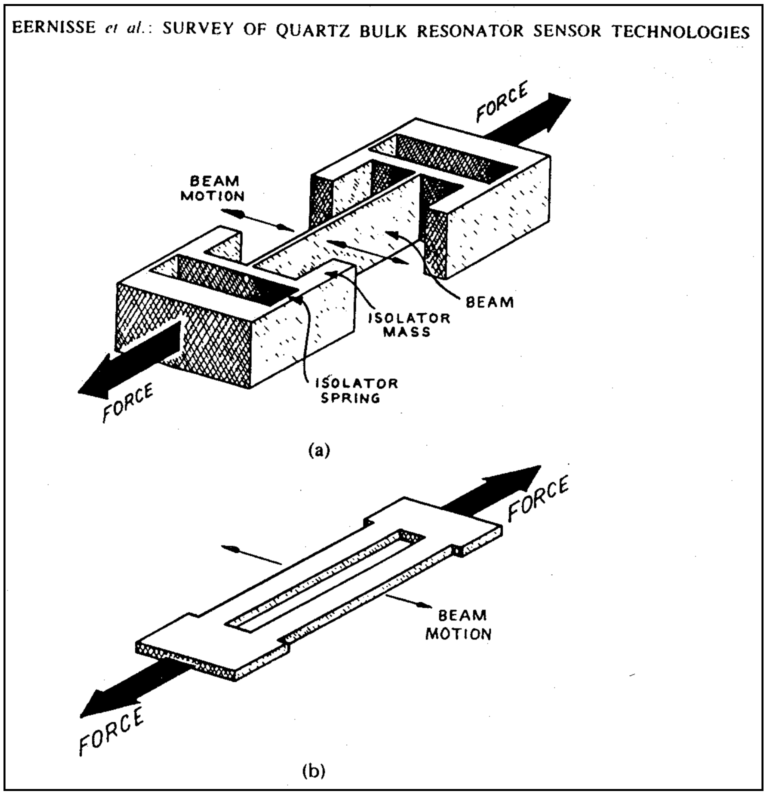


(Nominal) Frequency vs. Temperature
Frequency stability versus temperature for Series QR (175°C optimized SC) and AT. Note that crystals which are not optimized for these temperature ranges will show much more variation in frequency.

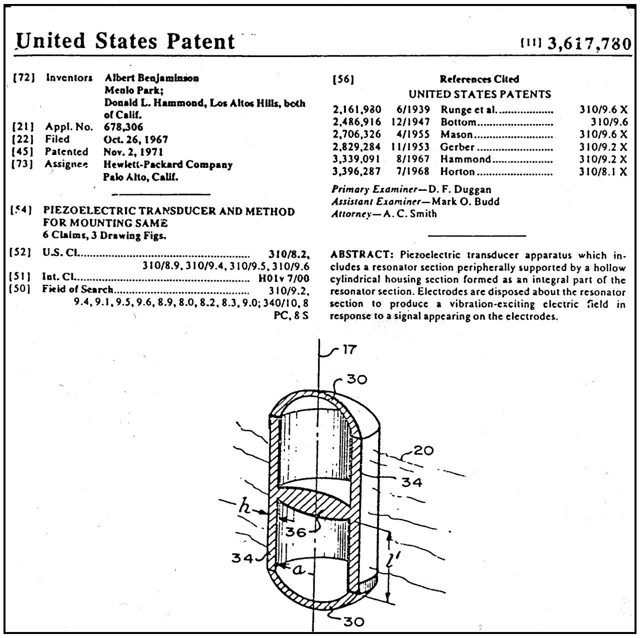
SERIES QT



(Nominal) Frequency vs. Temperature



Paroscientific/Welltest



United States Patent [11] 3,617,780

[72] Inventors Albert Benjaminson
Menlo Park;
Donald L. Hammond, Los Altos Hills, both
of Calif.
[21] Appl. No. 678,306
[22] Filed Oct. 26, 1967
[45] Patented Nov. 2, 1971
[73] Assignee Hewlett-Packard Company
Palo Alto, Calif.

[54] PIEZOELECTRIC TRANSDUCER AND METHOD
FOR MOUNTING SAME
6 Claims, 3 Drawing Figs.

[52] U.S. Cl. 310/8.2, 310/8.9, 310/9.4, 310/9.5, 310/9.6
[51] Int. Cl. H01v 7/00
[50] Field of Search 310/9.2, 9.4, 9.1, 9.5, 9.6, 8.9, 8.0, 8.2, 8.3, 9.0; 340/10, 8 PC, 8 S

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Primary Examiner—D. F. Duggan
Assistant Examiner—Mark O. Budd
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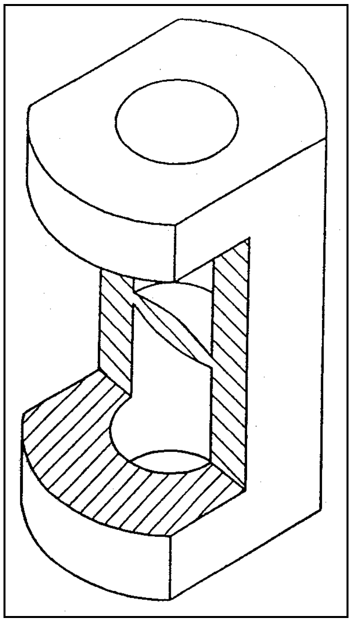
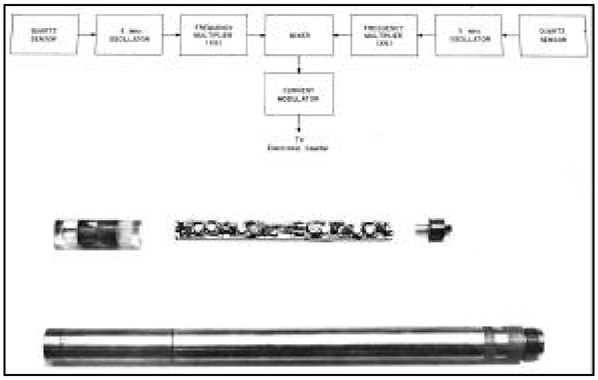
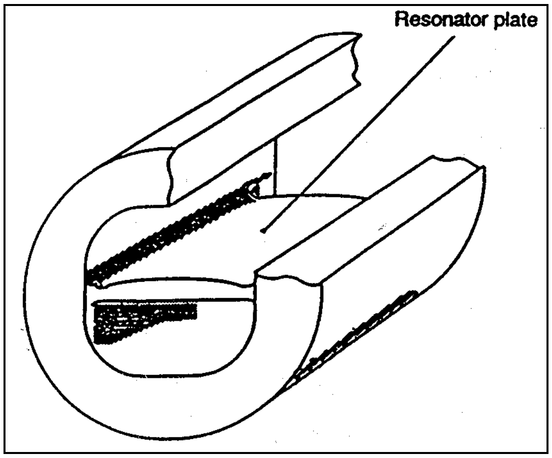
ABSTRACT: Piezoelectric transducer apparatus which includes a resonator section peripherally supported by a hollow cylindrical housing section formed as an integral part of the resonator section. Electrodes are disposed about the resonator section to produce a vibration-exciting electric field in response to a signal appearing on the electrodes.



Halliburton's HMR



Hewlett Packard's 2813



Schlumberger's CQG

	INTRODUCTION YEAR	SENSOR SIZE (OD X OAL)	VOLUME RATIO	PRESSURE RANGE (PSI)	TEMP RANGE (C)	ACCURACY	RESOLUTION (PSI)	TRANSIENT RESPONSE	TEMPERATURE COMPENSATION?	ISOLATION METHOD	1993 PRICE (US$)
HEWLETT PACKARD 2813D/E	**1970**	**1.0"x3.4"**	**16.7**	**11,000**	**177**	**±(1 PSI+0.01% READING)**	**0.001**	**POOR**	**NO**	**BUFFER TUBE**	**27,700 21,600***
HALLIBURTON HMR	**1988**	**0.72"x1.9"**	**4.9**	**16,000**	**180**	**±(1 PSI+0.01% READING)**	**<0.01**	**EXCEL-LENT**	**YES**	**BUFFER TUBE**	**NFS**
SCHLUMBERGER CQG	**1992**	**1.0"x1.5"**	**7.4**	**15,000**	**175**	**±(1 PSI+0.01% READING)**	**0.004**	**EXCEL-LENT**	**YES**	**BUFFER TUBE**	**NFS**
PAROSCIENTIFIC/ WELLTEST	**1983**	**0.12"x0.6"†**	**N/A**	**15,000**	**177**	**<±0.01%F.S.‡**	**<0.01**	**FAIR TO GOOD**	**YES**	**BOURDON & BUFFER TUBE**	**6,800**
QUARTZDYNE QU16K-B	**1991**	**0.58"x0.6"**	**1**	**16,000**	**177**	**±0.02%F.S.**	**<0.006**	**VERY GOOD**	**YES**	**BELLOWS**	**7,900**
QUARTZDYNE TMC16K-B	**1993**	**0.58"x1.2"**	**2**	**16,000**	**177**	**±0.02%F.S.**	**<0.006**	**EXCEL-LENT**	**YES**	**BELLOWS**	**10,795**

***1992 PRICE--HP STOPPED PRODUCTION 3/93**
NFS=NOT FOR SALE; N/A=NOT APPLICABLE
†WIDTH AND LENGTH OF SENSOR
‡NOT SPECIFIED; ESTIMATED FROM OTHER SPECIFICATIONS

COMPARISON OF QUARTZ PRESSURE SENSORS