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roceedings

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A QUARTZ LIQUID-LEVEL SENSOR

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Introduction

Utilizing some basic principles of geometrical optics, a device can be constructed that is very useful in monitoring and controlling the level of a liquid in a vessel. Although such sensors are commercially available, a glassblower and an electronics technician can design a customized unit for a specific need.

This paper begins with a review of those basic principles of light and optics and applies them in a design for a liquid-level sensor of clear fused quartz. An ensuing discussion of the sensor's practical application, particularly in conjunction with a benchtop computer offers some insight into the possible means for automating certain laboratory or industrial processes, as well as into the inherent limitations of the device.

A Review of Some Fundamental Principles of Geometrical Optics

The velocity of light waves through a particular medium is a constant.* However, the velocity of light varies between different media. The denser the medium, the lower the velocity. Thus, the speed of light is greatest in a vacuum (3×10^8 meters per second), less through quartz, and still less through diamond. The ratio of the velocity of light in a vacuum to its velocity in a particular medium is that material's index of refraction:

$$\text{Refractive Index} = n = c/v > 1$$

where, c = velocity of light in a vacuum

v = velocity of light in the medium

Consider Figure 1. In this illustration, the light waves are passing through a medium (N_1) having an index of refraction n_1 to a LESS DENSE medium (N_2) with an index of refraction n_2. Thus, the speed of light in medium 1 is less than that in medium 2. Similarly, the distance travelled by a wave front in a given time interval through medium 1 (d_1) is less than the distance travelled in the same interval through medium 2 (d_2). Because the velocity of light varies between different media, a ray of light will bend (i.e., be refracted) as it passes from one medium to another. In this case, the light ray is bent away from the normal or a line drawn perpendicular to the boundary surfaces. If the light ray were passing into a denser medium, then the figure would be inverted and the ray would be bent toward the normal.

In 1621, Willibrod Snell discerned a constant proportional relationship amongst certain elements of this construction. This discovery was subsequently refined by Descartes in 1637 by means of the mathematical expression:**

$$n_1 \sin I_1 = n_2 \sin I_2$$

where, n_1 = the refractive index of medium N1

n_2 = the refractive index of medium N2

I_1 = the angle of incidence

I_2 = the angle of refraction

This equation (Snell's law), which relates the angles of incidence and refraction for two transparent media, is the fundamental law that dictates the passage of a light ray through an optical system.

Throughout this review emphasis has been placed on the passage of light from one medium to another of less density. It has been indicated that in so doing, the light ray is bent away from the normal. The significance of this becomes apparent if the terms of Snell's Law are rearranged:

$$\sin I_2 = n_1/n_2 \sin I_1$$

Note that if the angle of incidence ($\sin I_1$) is increased, the angle of refraction ($\sin I_2$) will increase at a geometric rate. When the sine of the angle of incidence reaches the value of n_2/n_1, then the sine of the angle of refraction will equal 1.0 and the angle of refraction will be 90°. At this point, and for any light ray having an angle of incidence greater than this point, the ray will be reflected back into the medium N_1. This is known as total internal reflection and occurs only if N_1 is denser than N_2. The angle of incidence at which this occurs is known as the critical angle:

$$\text{Critical Angle} = I_c = \arcsin n_2/n_1$$

Taking advantage of Snell's Law and its corollary concepts of the critical angle and total internal reflection, a piece of quartz rod can be fashioned to create a liquid level sensor. Consider the following critical angles:

N_1/N_2	$I_c = \arcsin n_2/n_1$
CFQ/AIR:	arc sin (1.0000/1.4585) = arc sin .6856 ≈ 43° 17'
CFQ/WATER:	arc sin (1.3330/1.4585 = arc sin .9140 ≈ 66° 4'
CFQ/ACETONE:	arc sin (1.3587/1.4585) = arc sin .9316 ≈ 68° 41'
CFQ/METHYLENE CHLORIDE:	arc sin (1.4241/1.4585) = arc sin .9764 ≈ 77° 32'
CFQ/CARBON TETRACHLORIDE:	arc sin (1.4601/1.4585) = TOTAL TRANSMITTANCE
CFQ/BENZENE;	arc sin (1.5011/1.4585) = TOTAL TRANSMITTANCE
CFQ/1,2,4-TRICHLOROBENZENE:	arc sin (1.5717/1.4585) = TOTAL TRANSMITTANCE

Observe the relatively large disparity between the critical angle of clear fused quartz/air and that of the other media. In fact, for those media that are denser than CFQ, there exists no critical angle and therefore virtually any light ray, regardless of its angle of incidence at the boundary, will be transmitted on through them. Thus, in general terms, the likelihood of internal reflectance for a set of rays decreases dramatically as the refractive index of the second medium increases relative to CFQ.

Because of the rather slight critical angle between CFQ and air (< 45°), a quartz rod acts as a conduit for light — i.e., as a "light pipe" (See Figure 2). Not all of the light rays travelling down the rod will be internally reflected, but a substantial and useful amount will be. And if the end of the rod is annularly ground at 45° and firepolished (Figure 3), a substantial and useful amount of light will be internally reflected back up the rod. If the tip of this rod is suddenly surrounded by a fluid medium other than air, and thereby radically increasing the critical angle between the two media, a majority of the light rays will not be reflected back up the rod, but will simply pass into the second medium. Note how the beveling of the quartz rod at 45° enhances the advantageous utilization of Snell's Law.

It becomes apparent that if a light source and a detector could be mounted in some way on the opposite end of the rod, then the functional basis for a device which can "read" the difference in light intensity caused by the presence or absence of a liquid at the end of the rod could be had (See Figure 4). This can be accomplished by first cutting a 90° step, 8-10 mm in depth and firepolishing the cut. An LED and a photodetector are then mounted on the lower and upper steps, respectively, with plastic shrink-tubing and a plastic block clamp. The electronic circuitry required for a demonstration model of a liquid-level sensing system has been appended to this paper.

Some Applications and Limitations of the Device

Because the glass blower can be directly involved in the fabrication of a sensor, the interface between it and the vessel can be customized to meet the demand of a particular application. For example, an Ace-Thred and Bushing† can be employed in many instances. In situations where the purity of the liquid is essential or where the chemical environment is harsh (e.g. acids and organic solvents; exclusions: hydrofluoric acid and alkalis), elastomers can be avoided by fusing the rod through a CFQ standard taper joint or ball joint. In this case, it is of course desirable to avoid any bubbles or other occlusions in the seal. Therefore, use of a maria in the rod for fabricating the seal is an assured, effective means for maintaining the optical integrity of the light path.

There can be any number of uses for the sensor. The precise control of a fluid level such as in surface chemistry experiments is an example. Here, better resolution of the sensor seems to be gained by using a 6 mm CFQ rod rather than a larger diameter rod. Other examples would include overflow prevention, automatic liquid dispensation or introduction, and boil-off prevention.

A somewhat detailed consideration of a specific application will lend some further insight into the sensor's capabilities and limitations. In certain areas of radiation chemistry research, it is necessary to use extremely pure deuterium oxide or heavy water. To accomplish this, the water must be specially triple-distilled in a borosilicate and CFQ apparatus (Plate 1). Also, because of its cost ($400-$650 per liter for feedstock), the handling of the water and its distillation must be conducted with care to minimize any loss. In fabricating the triple still, it was apparent that it would be desirable to automate the process in order to avoid such losses and to avoid subjecting a technician to the tedium of manually operating it. Therefore, it was decided to employ the liquid level sensors in conjunction with a benchtop computer.

In Plate 2, the sensors are located at socket joint side necks of each of the three pots. A simple computer program can be written to control the feedstock pump and the three heating mantles. Figure 5 consists of two flowcharts of basic programs capable of handling the three elements of the still.

In this particular application wherein the sensor is immersed in the vapor-rich environment of a boiling pot, it was found that condensate on the sensor could provide the program with an erroneous signal. It appears that this can be overcome by "bleeding" the sensor — i.e., for example, by allowing the side of the rod close to the tip to come in contact with the sidewall of the vessel. Also, boiling stones must be added to the pots to minimize bumping and oscillation of the product. Once these impediments are overcome, the still can operate with minimum attention.

Conclusion

Considering recent developments in automating even some of the most complex processes, there is ample evidence that man's motivation toward eliminating tedious, repetitive work continues unimpeded. By combining well-known principles first discovered and formulated during the 17th century, it is possible for the glassblower and electronics specialist to help reduce the researcher's labor in the laboratory.

Acknowledgments

We are very grateful to Mr. Ralph Steinback, Notre Dame Radiation Laboratory Electronics Shop Supervisor, for his invaluable support and advice with regard to the electronics design. We thank Messrs. Paul Deranek and Michael Pecina for their preparation of the photographs and graphic materials, respectively.

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Footnotes:

* In order to simplify this discussion, assume that the light is monochromatic and that the media are at standard temperature (20° C).

** For an excellent explanation of the derivation of this formula, see Warren T. Smith's *Modern Optical Engineering: The Design of Optical Systems*, McGraw-Hill Book Comp N.Y. 1966, pp. 4-5.

† Products of Ace Glass, Incorporated.

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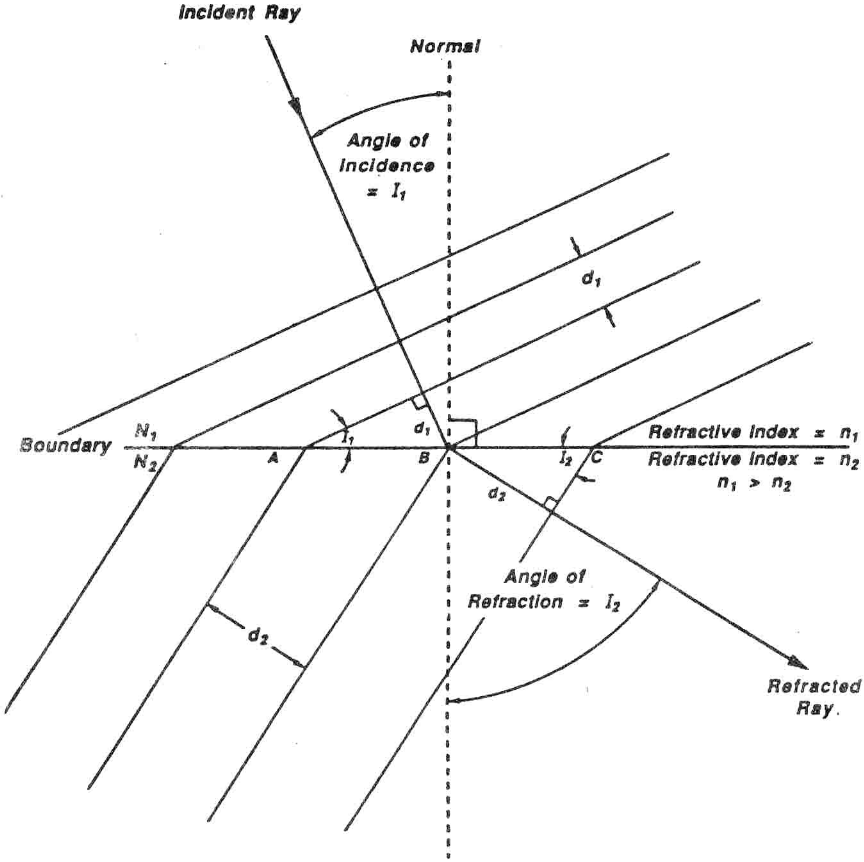


Figure 1

(Adapted from Figures 1.4 and 1.5, Warren J. Smith, *Modern Optical Engineering: The Design of Optical Systems*, McGraw-Hill Book Company, New York, 1966, pp. 4-5.)

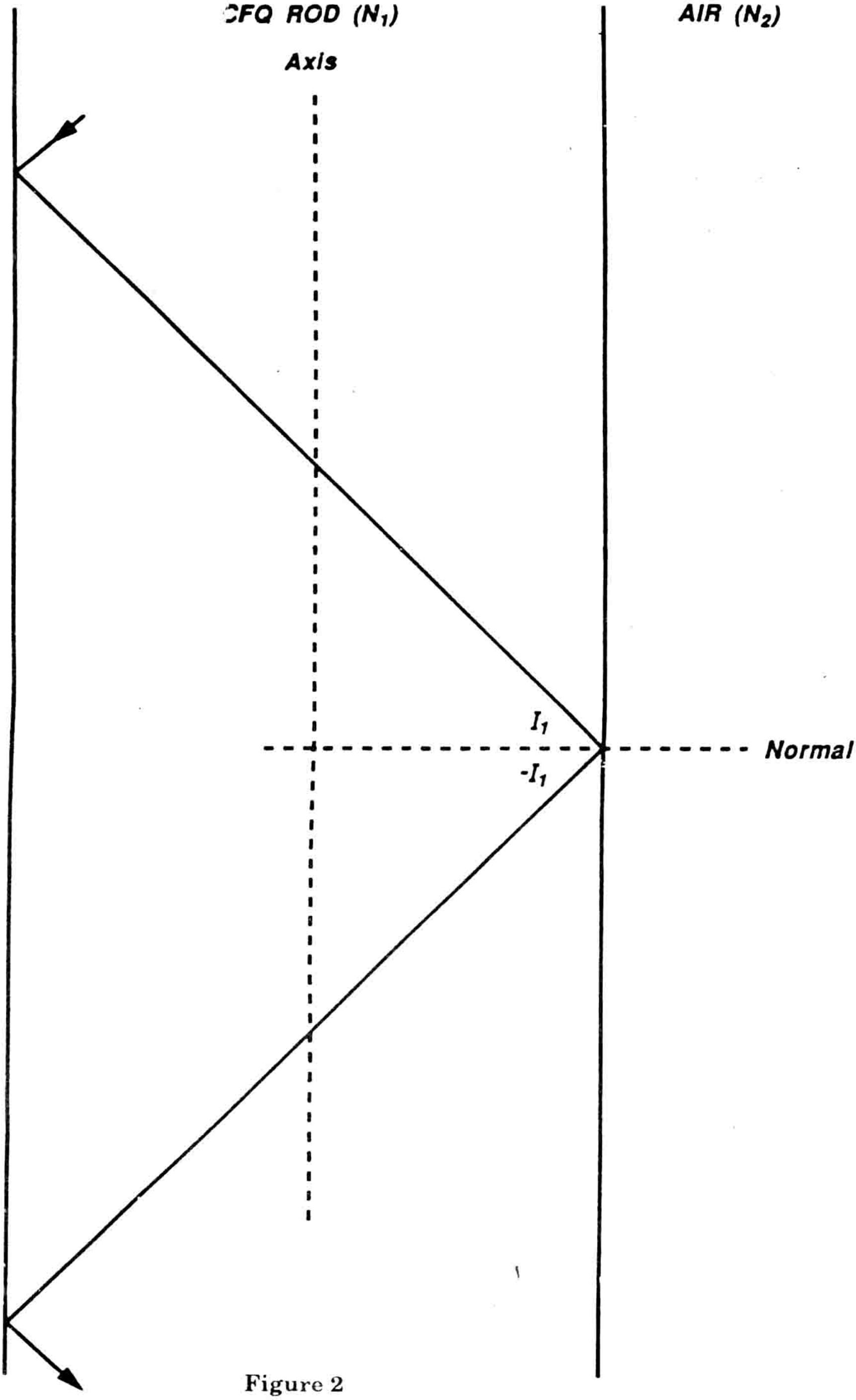


Figure 2

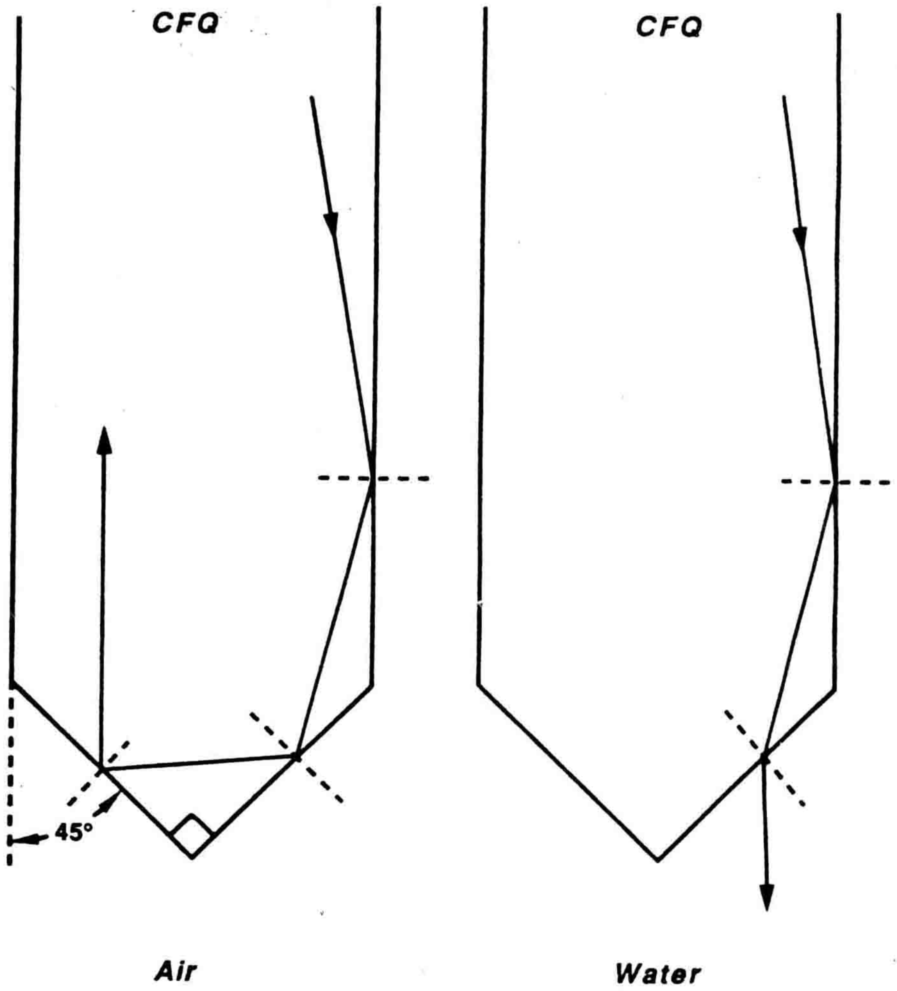


Figure 3

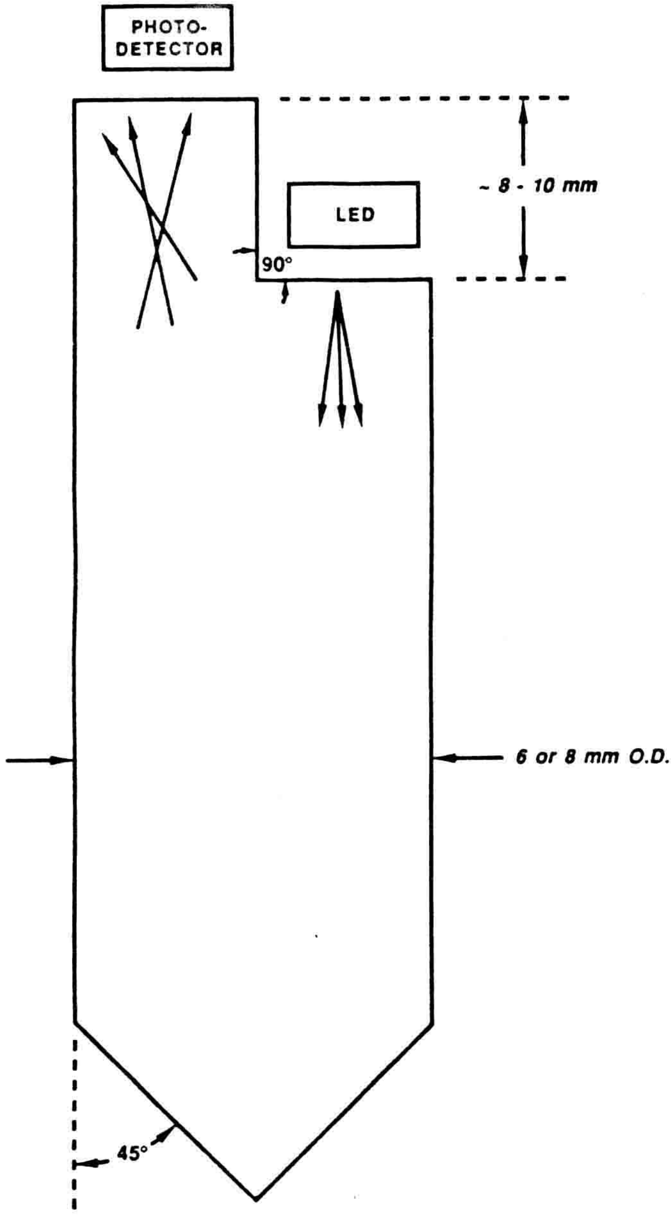


Figure 4

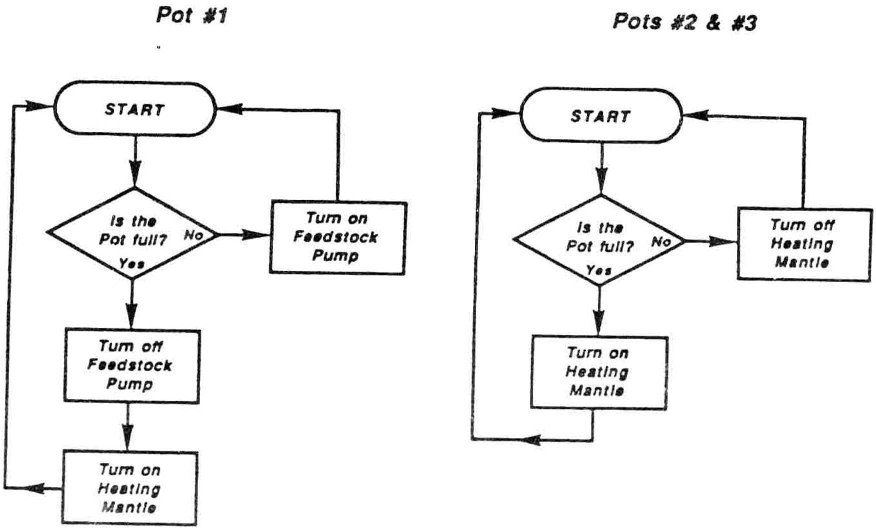


Figure 5

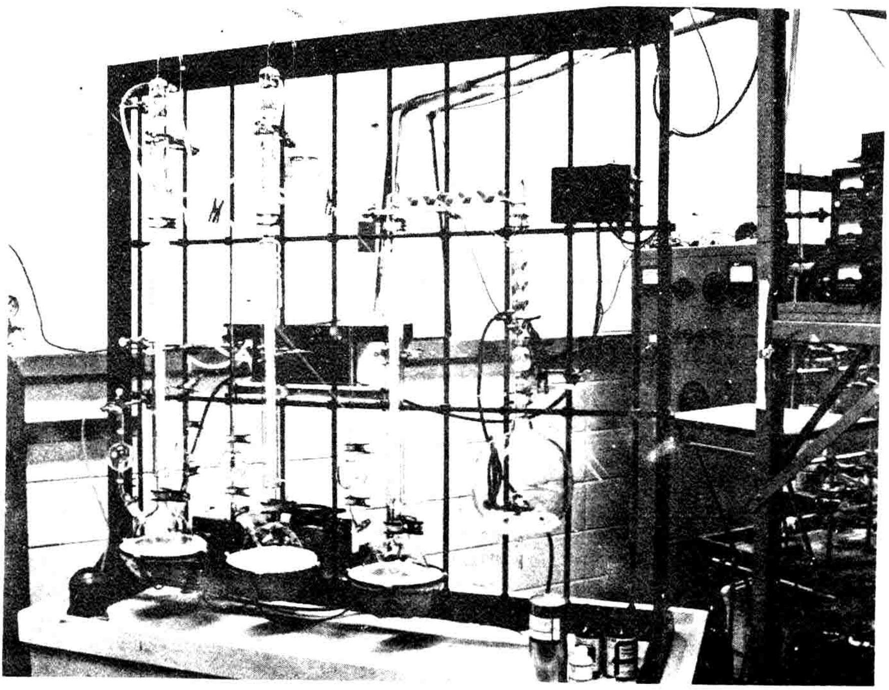


Plate 1

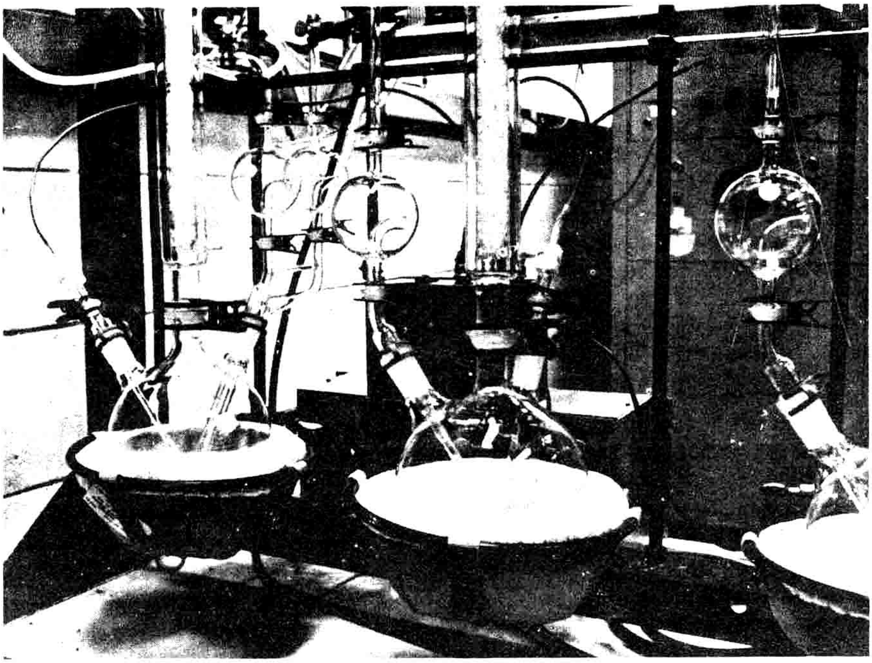
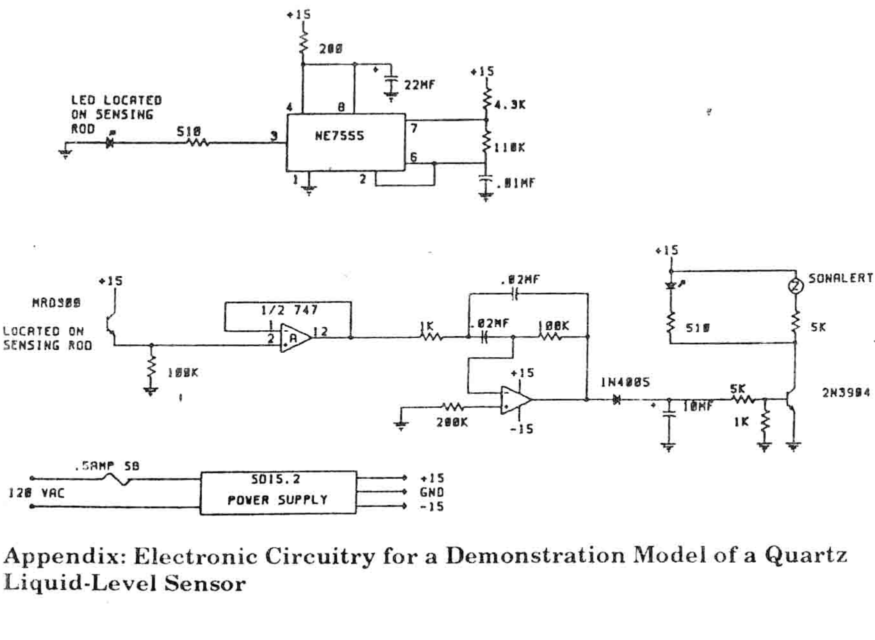


Plate 2



Appendix: Electronic Circuitry for a Demonstration Model of a Quartz Liquid-Level Sensor

"DETERMINATION OF THERMAL EXPANSION HOMOGENEITY OF CORNING CODE 9600 GLASS-CERAMIC BY SEAL TESTING"

Henry E. Hagy
Consultant

Corning Code 9600 Glass Ceramic is a transparent, near-zero expansion material for use in ring laser gyros, optics, and other applications demanding negligible expansion in a quality structure. Expansion homogeneity is also very important. This seal testing study evaluates homogeneity of cast Code 9600 in two sampling modes: firstly, by cutting specimens for test before ceramming to assess *chemical homogeneity*; secondly, by cutting specimens after ceramming to assess *thermal homogeneity*. Expansion differences determined are less than 20 ppb/°C at room temperature with *thermal* showing tighter values.

1. Introduction

Corning Incorporated recently introduced a remarkable glass-ceramic with special physical properties. Code 9600 glass-ceramic is a near-zero thermal expansion material characterized by a fine-grained crystalline structure and high homogeneity. It is an ideal material for ring laser gyros, optical components, and any other application requiring near-zero expansion and a stable, high quality body.

Code 9600 glass-ceramic is melted as a glass, cast into large blocks, and then heat treated (ceramming) to convert the glass into a transparent glass-ceramic. In many cases the original casting is cut into smaller pieces, like a ring laser gyro blank, before ceramming. One of the required properties for ring laser gyros is low helium permeability, which Code 9600 glass-ceramic easily meets.

The thermal expansion characteristics between -100 and 100° C are shown in Figure 1. Note the greatly expanded thermal expansion scale and that near-zero expansivity is attained at room temperature. The initial expansion determination shows hysteresis of 0.6 ppm, which is essentially gone in the second run. Competitive glass-ceramics also exhibit this type of hysteresis of about the same magnitude. However, recent developmental research at Corning Incorporated has essentially eliminated this hysteresis in Code 9600 glass-ceramic.

The near-zero thermal expansion is important to maintain critical dimensions as temperature changes are experienced. High homogeneity of thermal expansion is equally important, else stresses will develop upon temperature change and warp the body through thermal strain.

A plan was developed to measure thermal expansion homogeneity using end-tied sandwich seals. This approach is an easy, straightforward technique for evaluating expansion differences with high precision.

2. Experimental Method

2.1 Material, Geometry

It was decided to use a ring laser gyro blank, 4-1/4" x 4-1/4" x 1-1/2" in size, as the starting geometry. Two such blocks were cut from the same casting. One of these blanks was cerammed and then subsectioned. This blank was termed the thermal homogeneity blank. The second blank was first subsectioned and cerammed along with the *thermal homogeneity* blank. This second blank was termed the *chemical homogeneity* blank. Subsectioning was done by diamond saw cutting, mill grinding, and polishing, producing thirty-six small blocks 1-1/4" x 1-1/4" x 0.140" in size.