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Measuring Underwater Explosions

Transducers and Their Application

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Abstract

This work provides a brief explanation of the physics associated with underwater explosions along with a historical record of the development of transducers to measure these explosions. Its principal focus is on tourmaline transducers. Last, application guidance is provided on the commercial PCB Model 138 series transducer.

Sequence of Events in Underwater Explosions

Underwater explosions occur due to reactions in materials whereby chemical energy is rapidly transformed into thermal energy. As a byproduct, gases result at high temperatures and pressures. A supersonic pressure wave is then initiated, which moves outward from the contact boundary between the explosive charge and the surrounding water. The water encountering the pressure wave becomes compressed causing the boundary to expand further with resultant flow. The high pressure of the entrapped gas behind this boundary begins to decay as a sphere (bubble) is created due to the boundary expansion. At a distance of no more than 10 times the explosive charge diameter[1] the velocity of propagation of the pressure wave becomes sonic (~ 4900 feet/second in sea water depending on salinity, temperature, and depth[2]).

Even though the gas pressure continues to decrease, the bubble grows for awhile due to the inertia of the outward moving water. When the gas pressure in the bubble falls below the combined effects of the atmospheric and hydrostatic pressure acting on it, the bubble begins to contract. This contraction continues until the compressibility of the entrapped gas increases its pressure enough to abruptly reverse the inward motion of the water flow. This process is cyclic resulting in an oscillating system in which subsequent bubbles expand and then contract. Each bubble is of lesser size, lesser amplitude, longer duration, and possesses progressively less energy until an equilibrium state is again obtained. Other effects, such as bubble surface contact, water turbulence, and more can contribute to make the overall process more complicated than was just described[3].

Early Sensing Attempts

Early sensing attempts (circa 1918 to 1919) to measure underwater explosions used mechanical indicators. In one design an explosively loaded piston compressed a confined copper ball to provide a crude indication of peak pressure in the traveling wave. Subsequent modifications to this piston/ball design attempted to equilibrate the deformation of the copper ball to the momentum associate with the explosive charge. Another mechanical measurement technique used the plastic deformation of explosively-loaded, thin, circular plates to provide a relative comparison of the effects of different explosives[4].

D. A. Keys[5] first used the piezoelectric material tourmaline as a sensing material to acquire an analog representation of the pressure-time history of underwater explosions. This work occurred in the U.K. in 1921. With the advent of World War II, the U.S. devoted significant effort towards quantifying the effectiveness of underwater military explosives. Further development of tourmaline transducers by the U.S. Navy, much of it at the Taylor (later David Taylor) Model Basin, enhanced this effort. Concurrently, work progressed on transducer cables, signal conditioners, and data recorders, all of which had their own technical challenges in the early 1940s. As a result, significant advancements were made during this period towards enhanced characterization of underwater explosions. Today the Navy still manufactures tourmaline transducers at the David Taylor Model Basin, an activity of the Carderock Division of the Naval Surface Warfare Center. In 1982 a report[6] was written by R. B. Tussing on Navy tourmaline transducer design and application. While this report is frequently referenced in literature, a subsequent condensed version of it was also written by Mr. Tussing in 1991[7]. While other sensing technologies have been employed in underwater explosions[1], based on its electromechanical properties and application history, tourmaline continues to be the sensing technology of choice.

Why Tourmaline?

Tourmaline is a naturally occurring piezoelectric material in nature. That is, when employed in underwater sensing, an electrical charge is generated in tourmaline whose magnitude depends on the hydrostatic pressure applied to it and the area over which this pressure acts. Twenty-one of 32 crystal classes, identified by their Miller indices, have no center of charge symmetry. Twenty of these classes possess piezoelectric properties. Tourmaline is one of these classes and is unique in several of its properties.

Piezoelectric materials are anisotropic. That is, they have different electromechanical properties in different directions. The d_{mn} coefficient of a piezoelectric material relates the charge generated in the crystal to a directional force stimulus.

The magnitude of the piezoelectric effect can be identified by the polarization vector

$$\boldsymbol{P} = P_{xx} + P_{yy} + P_{zz} \qquad [1]$$

where x, y, and z are an orthogonal axes set within the crystal. In terms of normal (σ) and shear (τ) stresses the P vector components can be written as:

$$\begin{aligned} P_{xx} &= d_{11}\sigma_{xx} + d_{12}\sigma_{yy} + d_{13}\sigma_{zz} + d_{14}\tau_{yz} + d_{15}\tau_{zx} + d_{16}\tau_{xy} \\ P_{yy} &= d_{21}\sigma_{xx} + d_{22}\sigma_{yy} + d_{23}\sigma_{zz} + d_{24}\tau_{yz} + d_{25}\tau_{zx} + d_{26}\tau_{xy} \\ P_{zz} &= d_{31}\sigma_{xx} + d_{32}\sigma_{yy} + d_{33}\sigma_{zz} + d_{34}\tau_{yz} + d_{35}\tau_{zx} + d_{36}\tau_{xy} \end{aligned} \quad [2]$$

The d_{mn} piezoelectric coefficients comprising the 3 by 6 matrix of tourmaline are of the form[8]:

$$\begin{matrix} 0 & 0 & 0 & 0 & d_{15} & -2d_{22} \\ -d_{22} & d_{22} & 0 & d_{15} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & d_{15} \end{matrix} \quad [3]$$

as they relate to Eq. 2. Since water and fluids in general support no shear stress, the stresses applied to tourmaline under hydrostatic loading, in 3 by 3 matrix form, are:

$$\begin{bmatrix} -p & 0 & 0 \\ 0 & -p & 0 \\ 0 & 0 & -p \end{bmatrix} \quad [4]$$

If we substitute the stress matrix components in Eq.4 into Eq. 2 using the d_{mn} matrix for tourmaline in Eq. 3 we get:

$$\begin{gathered} P_{xx} = P_{yy} = 0 \\ P_{zz} = 2d_{31}(-p) + d_{33}(-p). \end{gathered} \quad [5]$$

Eq. 5 is pivotal in that it identifies that tourmaline can respond to hydrostatic pressure if electrodes are applied in its z-axis direction. By contrast, if the d_{mn} coefficients for quartz were substituted in Eq. 2, it would show that quartz does not possess a hydrostatic response in its x, y, or z-axes ($P_{xx} = P_{yy} = P_{zz} = 0$). It is this unique property of tourmaline that lead to its early application in measuring underwater explosions.

Tourmaline Transducers

The early, successful transducers that the U. S. Navy built used varying sizes of tourmaline discs up to ¼ or ½ inch diameter. These discs were often stacked mechanically in series with one another with the electrodes on their faces electrically connected in parallel. This parallel connection (1 – 8 discs) enabled the generation of enough charge (Q) or voltage (V) that, depending on the total cable and circuit capacitance (C), an acceptable level signal (V=Q/C) could be acquired at the recording location over hundreds of feet of cable. Both charge and voltage sensing circuits were utilized.

The tourmaline sensing element obviously had to maintain a high electrical insulation value and also remain water tight during and after the explosion. Rubber molding, rubber tape, rubber cement layers, and various lacquers were all early coating attempts[9]. An operational challenge was, and still is, that any completed tourmaline transducer appears as a reflective object to an incoming pressure wave. The impedance of a fluid (e.g., water) is:

$$Z_f = \sqrt{B}_\rho \quad [6]$$

where B is the fluid bulk modulus and ρ is the fluid density. The impedance of a linear-elastic material (e.g., tourmaline) is:

$$Z_e = \sqrt{E}_\rho \quad [7]$$

where E is the elastic modulus and ρ is the material density. Since the impedance of a rubber booted stack of tourmaline doesn't match that of water, there is always going to be some initial period of very short duration (between a few and 10s of microseconds) until the tourmaline material equalizes with the water pressure. Navy studies in 1972[10] revealed that a Tygon boot filed with silicon oil best minimized these early reflections. Both the Tygon and the silicon oil were a better impedance match to the water than the earlier mentioned coatings. The physical impedance mismatch between water and the tourmaline can't be avoided.

Figure 1 illustrates such a booted configuration[7]. Figure 2 shows the physical implementation of this configuration in a number of the Navy transducers.

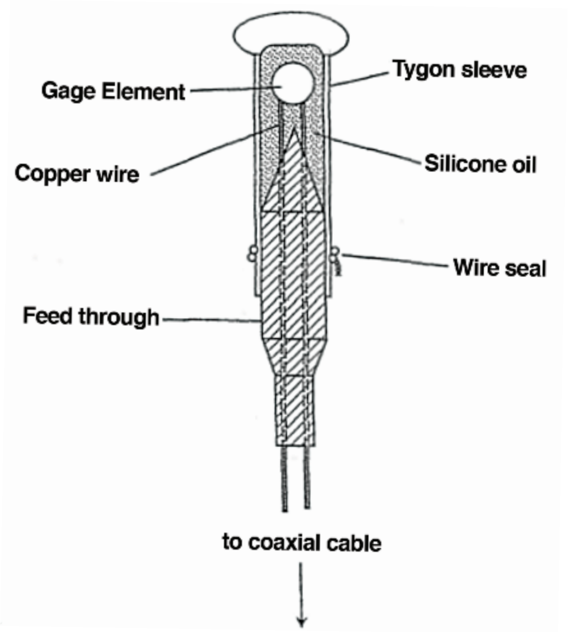


FIGURE 1: U.S. NAVY TOURMALINE TRANSDUCER DESIGN

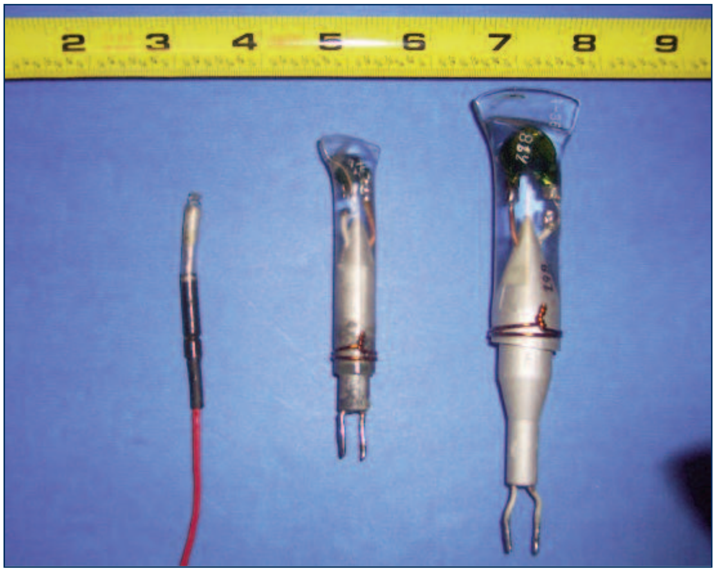
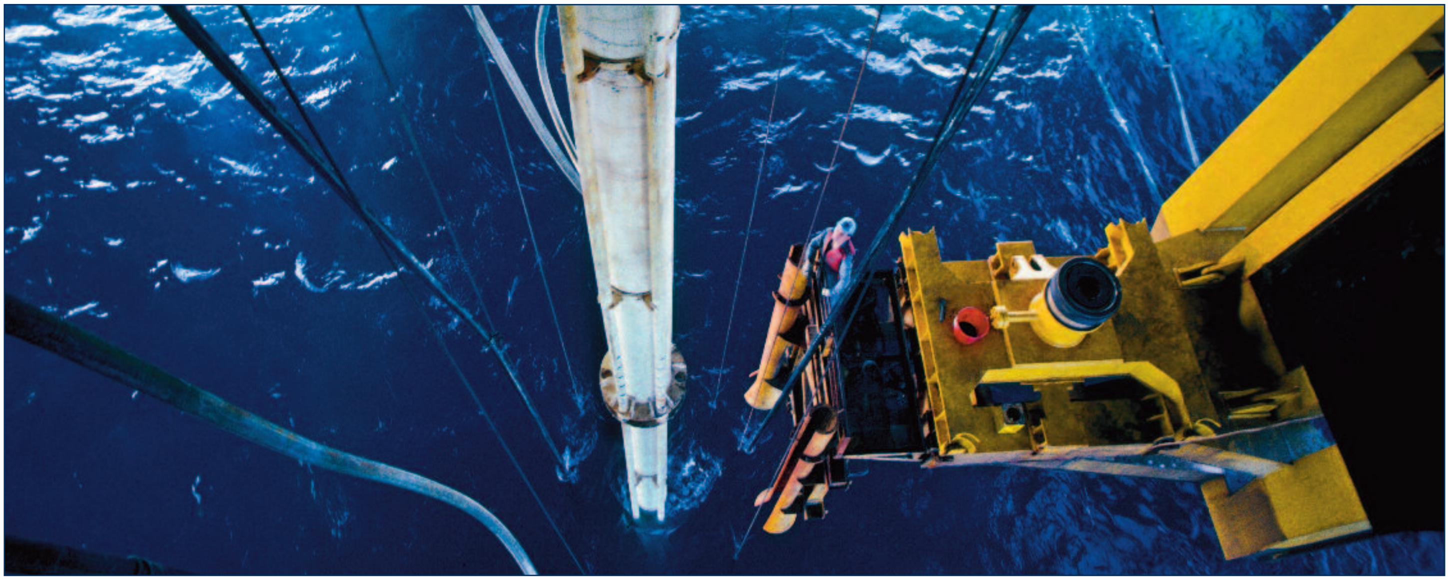


FIGURE 2: ASSORTED NAVY TOURMALINE TRANSDUCERS

The Navy transducers used today retain much of this same configuration. One reason for adhering to this configuration, aside from successful performance, is that a large data base has been built up over the years using these transducers. The upper operating range of tourmaline transducers seems to be limited by both the material and the housing design. Multiple shots on individual transducers at levels to 50,000 psi have been reported[11].

In the 1960s time frame, a small, commercial industry developed in the U.S. incorporating tourmaline transducers in its product line.



Susquehanna Instruments was founded by Mr. Ben Granath in Havre de Grace, MD. Among the transducers he commercialized was a slender, booted, charge-mode, tourmaline transducer. One pragmatic reason for its diametric size reduction from the earlier Navy transducer design was that pieces of crack-free tourmaline were becoming increasingly rare so that only smaller pieces were readily available in commercial quantities. A resultant disadvantage of the smaller pieces of tourmaline was lower signal levels. However, in the 1963-1965 timeframe, the concept of incorporating a two-wire integrated circuit (a field effect transducer (FET)) within a piezoelectric transducer was developed. After the formation of PCB Piezotronics in 1967 this concept was trademarked ICP®. Shortly after PCB's formation, using an adaptation of this technology, Susquehanna incorporated a PCB in-line source follower in the cable close to the transducer thereby lessening concerns about signal level.

Susquehanna Instruments joined PCB Piezotronics, Inc. in October of 1982. Along with the unique Susquehanna sensor line there was transferred an inventory of sensor grade tourmaline. PCB immediately incorporated hermetic sealed ICP® amplifiers in the connector housing of the tourmaline transducers[12]. The resultant low output impedance of the transducer offered significant advantage in the use of long cables compatible with underwater applications. Figure 3 below is a 3-D drawing of a current PCB Model 138 underwater tourmaline transducer. Figure 4 is a photograph of a 2nd configuration for this Model type.

FIGURE 3: MODEL 138XXX; 4.7 IN. LENGTH, 0.38 IN. DIAMETER

FIGURE 4: MODEL 138XXX: 7.6 IN. LENGTH, 0.38 IN. DIAMETER

The models shown in Figures 3 and 4 both contain ICP® amplifiers and, depending on the XXX suffix specified after the model number, operate over pressure ranges from 1,000 to 50,000 psi.

Application Considerations:

These application considerations apply to the PCB Model 138XXX as the sole commercial U.S. manufactured tourmaline transducer model available to consumers in the marketplace.

1. Since, as contrasted to the Navy configuration, the traveling wave associated with the underwater explosion will diametrically encompass the smaller, tourmaline crystal faster, the transducer's high-frequency performance is enhanced. Its resonant frequency is specified as > 1 MHz.

2. Incorporation of the ICP® amplifier (preferred option) in the Model 138 housing minimizes noise and enables a 5-volt full scale signal for recording. When driving long lines the current supply to the ICP® amplifier in the transducer may have to be increased to compensate for frequency attenuation due to the capacitance of the cables[13]. As with all cables at extremely high frequencies, significant cable inductance may require impedance matching[13].

3. The time constant governing the low-frequency roll-off of the Model 138 is specified as 0.2 seconds. This value provides flat frequency response within 5% to frequencies as low as 2.5 Hz. For large charges in deep water explosions, where the goal is to record the pressure wave associated with the supersonic shock, along with the ensuing bubble-time history, this low-frequency response limitation may not be adequate. It will not allow the amplitude of the negative pressure phase between events to be adequately recorded. However, for any pressure event of duration less than 20 milliseconds, it will both accurately record the peak and allow for integration of the pressure-time record for total impulse.

4. The Model 138 should always be fielded with its longitudinal axis orthogonal to the direction of propagation of the incident pressure wave. This assures that the wave traverses the transducer diametrically providing the fastest "ring up" time due to acoustic impedance mismatches between the transducer and the water. Some models are designed with an attachment location (Figure 4) for weights as high as 5 pounds when needed on the end opposite the connector to accommodate mounting the transducer in a pendulous manner. If greater than a 5 pound weight is required, the transducers must be affixed to a line containing this weight. This line must be as thin as possible so as not to act as a reflecting object. See Figure 5 for a typical installation.

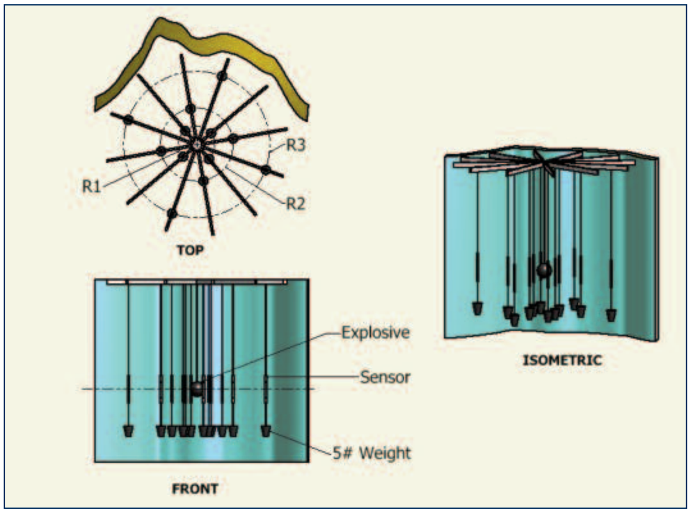


Figure 5: One Illustration of a Test Configuration

5. Once the mechanical (e.g., waterproofing interconnects) and electrical challenges associated with properly fielding the transducer have been satisfied, the resultant data interpretation can proceed. The influences of the incident wave, resultant bubble pressures, surface and reflected waves, and the bottom transmitted wave eventually all reach the transducer. A brief but appropriate document to assist in interpreting these effects is available from the US Army Corps of Engineers, CECW-EG, Engineering Technical Letter No. 1110-8-11, 15 July 1991[14]. Reference 15 is an even more recent and comprehensive interpretive document.

Performance Comparison:

A series of tests were performed by Mr. Kent Rye at the Carderock Division of the Naval Surface Warfare Center comparing the performance of the U.S. Navy and PCB underwater transducers[16]. Recall in application the Navy uses a much larger piece of tourmaline operating into long, low-noise cables terminating in laboratory type electronics on the surface while the PCB transducers use a much smaller tourmaline sensing element with an insitu ICP® amplifier eliminating the requirement for treated low-noise cables when transmitting the signal to the surface. A representative test result follows in Fig. 6. The time or x-axis amplitude is in milliseconds and the y-axis amplitude is in psi. The entire test series resulted in a measured mean peak value difference between the PCB transducers and the Navy transducers of -2.1 percent and, when integrated, a mean calculated total impulse difference of -10.7 percent. The peak pressure range encompassed in testing was 1,000 to 18,000 psi. Considering the physical differences between the transducers, their cabling, and their conditioning circuits, perhaps this less than perfect agreement has to be expected and its source can only be conjectured.

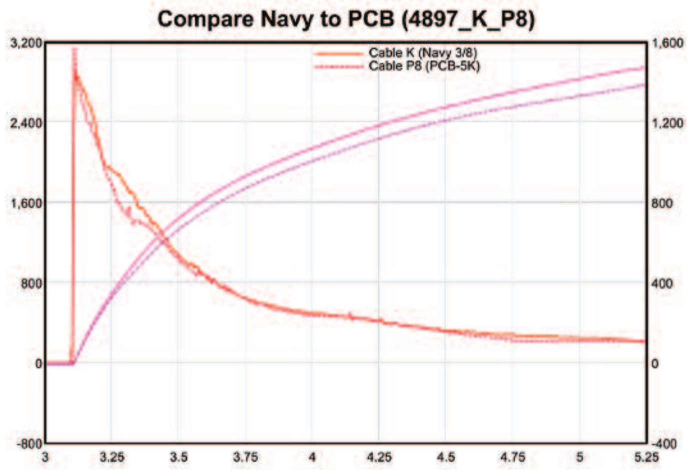


FIGURE 6: NAVY AND PCB UNDERWATER GAGE TEST COMPARISON WITH INTEGRATION

Conclusions:

The unique piezoelectric properties of tourmaline that enable its application in transducer design for the measurement of underwater explosions have been presented. Of primary importance is its ability to respond to hydrostatic pressure when electrodes are placed in its z-directional axis. A brief but comprehensive history of the development of transducers for measuring underwater explosions, along with a relatively complete bibliography, has been provided. Guidance has been provided for field application of the PCB Piezotronics, Inc. Model 138XXX tourmaline underwater transducer. Finally, a typical comparison of a representative U. S. Navy and PCB transducer, along with an overall test series summary, has been presented.

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