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A study of published literature and information from piezoelectric ceramic vendors and underwater sound transducer designers has been undertaken to establish mechanical and electrical operating limits for transducers. It appears that operation up to 3.9–5.9 kV/cm (10–15 V/mil) rms and 69–103 MPa (10–15 kpsi) peak compression is achievable in practical sonar transducers.

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INTRODUCTION

An extensive study has been conducted to determine the safe upper operating electrical and mechanical stress limits for piezoelectric ceramics, specifically on U.S. Navy type I and III piezoelectric ceramics[1] under high mechanical stress and electrical drive conditions. This piezoelectric ceramic survey takes on particular importance with the advent of newer high-power materials such as the magnetostrictive material Terfenol-D and electrostrictive material PMN. In this letter we summarize essential information from an earlier reported work[2] of limited distribution that included a study of published literature and information from piezoelectric ceramic researchers and underwater sound transducer designers. Unless stated otherwise, voltage is in rms and compression is in peak value. Note that some authors use the trademark PZT-4 and PZT-8 designations while others use the Navy generic types I and III, respectively.

I. PUBLISHED STUDIES

Among the works which we have read and summarized, we identify several key references, which are presented here with quoted (" ") or paraphrased (' ') information related to electrical or mechanical stress limits. This abstracted electrical and mechanical stress information is presented here as a convenience for the reader. The results are further summarized in Sec. III.

Berlincourt:[3] 'The history of compositional studies with ferroelectric ceramics is reviewed and the types of characteristics achieved are summarized. The compositional additives and some general principles to explain their behavior are discussed.'

Ugryumova and Golyamina:[4] Strength characteristics of barium titanates and lead titanate-zirconates as a function of structure and chemical composition are given. Fatigue curves are shown for rods excited at their resonance frequency for longitudinal oscillation, ~20 kHz. The lead titanate-zirconate compositions had static strengths of 19 and 30 MPa (or 2.76 and 4.35 kpsi, respectively). The longitudinal dynamic strengths were 25 and 20 MPa (3.63 and 2.90 kpsi, respectively) for 10^8 cycles, while the flexing dynamic strengths were 26 and 28 MPa (3.77 and 4.06 kpsi, respectively) for 10^8 cycles.

Woollett:[5] "The available data on piezoelectric ceramic properties is very meager compared with what is needed for proper design of high power projectors. Building a comprehensive database requires measurements of the dielectric piezoelectric, and elastic properties of projector-type ceramics as a function of static stress, alternating stress, alternating electric field, and temperature. The information on these ceramic properties is needed with all these excitations simultaneously impressed."

Browder and Meeks:[6] Navy type III is slightly more resistant to one-dimensional stress than type I but both exhibit similar trends. This is, however, dependent on the manufacturer. For hydrophone use and based on the change in the peak of the κ_{33}^T dielectric curve, the maximum stress is 100 MPa (14.5 kpsi) for type I, and 125 MPa (18.1 kpsi) for Type III.

Ehrlich:[7] A PZT–lucite ring composite transducer was driven at electrical stresses up to 5.6 kV/cm rms (14 V/mil rms). 'Nondestructive breakdown was experienced at the highest voltage, which was an attempt to reach the design goal, although it exceeded the intended rating of 5000 V across the Navy type III ceramic. The linearity of the transducer was very good up to the maximum drive voltage employed, and the ceramic, as expected, proved to be peak-voltage limited.'

LeBlanc:[8] 'A compilation of the nonlinear characteristics of polarized ferroelectric ceramics in environmental conditions representative of operational situations is presented. The effects of high-ac E fields, large static and/or dynamic stresses, and combinations of field and stress on the electromechanical parameters of several ceramic compositions are discussed.' This is a very useful and detailed review of old and new information (up to 1972) on high-drive characteristics of PZT-4 and PZT-8 ceramics.

Berlincourt:[9] "So long as the electric field and mechanical stress are of very low amplitude the piezoelectric ceramics may be considered linear. Thresholds for deviation from linearity vary widely for the various piezoelectric ceramics... ." PZT-4 data from Table XIII.C: static tensile strength=76 MPa (11 kpsi), rated dynamic tensile strength=41 MPa (6 kpsi); ac rms depoling field at 25 °C: ⩾10 kV/cm; ac field rms for tan δ_E=0.04: 3.9 kV/cm at 25 °C; and 3.3 kV/cm at 100 °C; Curie temperature=328 °C, Q_E=250, Q_m=500.

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Smith:[10] Moisture, ceramic defects, and poor surface cleaning and preparation lead to various breakdowns: corona, high voltage stress leading to arc over. Check for ceramic defects, use good surface preparation and cleaning, use moisture-free gas in the transducer, and use sealant (e.g., Humiseal™) on ceramic electrode free surfaces for reliability.

Krueger:[11] Measurements on PZT-4 and PZT-8 are described for which a stabilizing heat treatment has reduced the change in permittivity. Several mechanical stress cycles to 69 or 138 MPa (10 or 20 kpsi) also stabilize these ceramics; however, stabilization with stress for stress cycles to 69 MPa (10 kpsi) is not permanent. The measurements were made over an aging range from 1 day to 6 months.

Krueger:[12] Measurements of changes in permittivity, tan δ, and d_{33} versus compressive stress parallel to the polar axis for PZT-4 and PZT-8. The ceramics PZT-4 and PZT-8 show large changes of properties for stresses to 20 kpsi, but have good recovery on release of stress. Permittivity and tan δ of these ceramics increase with increase of ac electrical field. For the soft ceramics, the increase in tan δ is enough to eliminate their consideration for uses where efficiency and cool operation are needed. Hard ceramics remain far superior for high-power high-stress use, with PZT-8 being superior to PZT-4.

Brown and McMahon:[13] Two-dimensional (or planar) stress is applied to PZT-4. The stress effects on effective piezoelectric constants, elastic modulus, coupling factor, and high-field dielectric loss were studied. Planar stress was established by subjecting thin, hollow ceramic spheres to external hydrostatic pressure.

Gerson *et al.*:[14] 'The dynamic tensile strength of PZT-4 lead zirconate titanate was tested by electrically driving small bars at their longitudinal resonance until they fractured. The measured dynamic tensile strength of small specimens of good quality ceramic was about 90 MPa (13 kpsi). This value was very drastically reduced for ceramic that was not of optimum quality.'

Krueger and Berlincourt:[15] The authors present the results of a study that determines the effects of static compressive stress on the piezoelectric properties of PZT-4. The permanent effects of stress exposure, determined at zero stress after exposure to a given stress, were found to be more severe with stress parallel to the polar axis than with perpendicular stress. Under maintained stress, however, the effects of perpendicular stress are more severe. PZT-4 shows effects dependent upon stress exposure time but independent of the number of stress cycles. PZT-4 was affected little by static stress, exposure to as high as 15 kpsi.

Berlincourt and Krueger:[16] Now a Morgan Matroc reprint. Covers some of the effects of high static and dynamic stress and E field on the characteristics of ceramics such as PZT-4 and PZT-8. Results are very similar to those given in Woollett's thesis.[17] Stresses from 0 to 138 MPa (20 kpsi) both parallel and longitudinal, and ac rms E field from 0 to 5 kV/cm (12.7 V/mil).

II. SONAR TRANSDUCER DESIGNERS

The summaries here are written without listing the exact company or company source of the transducer designers, to avoid any potential proprietary difficulties. Each paragraph is from a particular individual. Unless otherwise specified, the comments usually refer to type III ceramic because it can typically be driven harder than type I. Some notes given below are paraphrased rather than exact quotes.

'Assuming good ceramic: (i) Static undriven maximum precompression stress parallel to polarization on a transducer: 10 kpsi (69 MPa) type I, and 16 kpsi (110 MPa) type III. (ii) Maximum E-field drive on transducer at resonance: "Somehow inversely proportional to Q. A better number is maximum strain. This is in the range 3×10^{-4} in poling direction; 50% of this is perpendicular to poling. Maximum E field is much higher with loaded transducer Q of 10 than 100." (iii) Maximum allowed tension stress in transducer when driven at resonance at maximum E field: 2 kpsi (13.8 MPa) for both type I and III. General comments: for low duty cycle drive, heat really is not a problem; for high duty cycle drive, watch out, heat sneaks up on you very quickly. High-Q, high-E-field drive could cause trouble; low-Q, high-E-field drive not as bad as high-Q case.'

'The performance of the ceramic is dependent on the dielectric loss factor at the operating drive level. We generally recommend certain safety factors for type I and III. For CW use, 1.2 kV/cm and 0.008 dissipation factor for type I, and 3.0 kV/cm and 0.008 dissipation factor for type III. For pulsed operation, 3.0 kV/cm and 0.016 dissipation factor for type I, and >5.0 kV/cm and 0.016 dissipation factor for Type III.'

'We have not used type I ceramics for full power applications. For type III, we use the 3.9 kV/cm (10 V/mil) as the maximum E field. We have also found that precompression at 69 or 138 MPa (10 or 20 kpsi) both work well, we do not experience any substantial creep, and we find that the properties of the ceramic change very little at both of these stress levels. We have also heard stories of getting up to 9.8 kV/cm (25 V/mil) E field using a low duty cycle. We have tested materials up to these levels but the results depend on the material processing.'

'We have driven actual designs up to 7.8 kV/cm (20 V/mil) for type III materials, in 33 and 31 drives both for cylindrical transducer ceramics. The ceramics were encapsulated, and the pulse lengths were up to 200–300 ms.'

'For type I ceramic transducers, we drive at between 2.4 and 3.9 kV/cm (6 and 10 V/mil), and use 55–69 MPa (8–10 kpsi) prestress. We adopt the parameters for ceramic drive and stress from Wilson's book.[18]'

'In one particular transducer design using PZT-4 (type I), we have run up to 3.5 kV/cm. For long-term use we allow for up to a 20% duty cycle.'

'For type III ceramics, we drive up to 2.8 kV/cm (7 V/mil), but we could drive at higher levels if needed. Using a stress bolt, we apply about 34 MPa (5 kpsi) prestress on the ceramic. We have also experienced cracking in the ceramic for higher prestress values. I have also seen drive levels used of up to 5.9 kV/cm (15 V/mil) at another firm.'

'On one design, we have driven up to 4.7 kV/cm (12

V/mil) E field. In the past 3.9 kV/cm (10 V/mil) has been the customary limit, and 2.7 kV/cm (7 V/mil) has been a typical working value.'

'For type III ceramic transducers, we had to be very careful with the electrodes. The max drive level was about 3.9 kV/cm (10 V/mil), and we were very comfortable with 3.1 kV/cm (8 V/mil). We also experienced corona problems around the connectors at higher drive levels.'

'We drive some transducers up to 3.9 kV/cm (10 V/mil) and can possibly allow 4.7 kV/cm (12 V/mil) with manufacturing process control. Compressional stress is typically around 6.9 MPa (10 kpsi), but possibly up to 83 MPa (12 kpsi). Compression stress needs to be high enough to allow for long-term creep effects in the transducer. We assume that the dynamic ceramic stress will be approximately between 20% to 30% of the static precompression in the ceramic. We have also gone to 207 MPa (30 kpsi) compression prestress in certain transducer designs.'

'For type I ceramic, our limit is 2.0 kV/cm (5 V/mil). For type III ceramic, the limit is 3.9 kV/cm (10 V/mil). For precompression, at ambient conditions, we use 55 MPa (8 kpsi) max for type I and 69 MPa (10 kpsi) max for type III. We also avoid tensile stresses above 14 MPa (2 kpsi) in the ceramic.'

'For low duty cycles we allow 3.9 kV/cm (10 V/mil) for PZT-4 and 5.9 kV/cm (15 V/mil) for PZT-8. For CW use we use half of these values. We also compress PZT-4 up to 83 MPa (12 kpsi).'

'We use Ralph Woollett's 1979 data as a guide: up to 3.9 kV/cm (10 V/mil) for the E field, and maximum compression stress of 69 MPa (10 kpsi). We also allow for 21 MPa (3 kpsi) dynamic stress under driving conditions. I think that 4.7 kV/cm (12 V/mil) is certainly possible with "clean room" manufacturing conditions.'

'Several designs have been driven to 4.7 kV/cm (12 V/mil) E field without problems, and some have been tested to about 5.9 kV/cm (15 V/mil) when arc-over and/or corona occurred; the ceramic can certainly handle up to 5.9 kV/cm (15 V/mil) for type III. The big problems associated with high E field are corona and arc-over, and these are mostly due to manufacturing-related difficulties. These drive levels also assume that the duty cycle is sufficiently low to avoid dielectric heating and thermal runaway. If the arc-over and corona were not issues (i.e., using excellent transducer construction) then type III might be able to withstand 5.9–7.9 kV/cm (15–20 V/mil). Mechanically, the compressive prestress used are order-of-magnitude 69 MPa (10 kpsi), and we always try to avoid any tension in the ceramic.'

'For pulsed operation, we use up to 3.9 kV/cm (10 V/mil) on one particular design. Beyond that, we have experienced cable failure at high fields. We allow 83 MPa (12 kpsi) for the maximum combined static and dynamic stress.'

'Up to 3.9 kV/cm (10 V/mil) has been used for PZT-8 (type III), and we have not seen PZT-4 (Type I) used in several years! A recent specification said we could use up to 5 kV/cm (12.7 V/mil), but we considered that this was too high a value to use. We allow dynamic peak stress up to 41 MPa (6 kpsi), and static compression up to 83 MPa (12 kpsi). We have also found that bender transducers can go negative (will safely allow a small amount of tension stress).'

'E field limitation of 3.9 kV/cm (10 V/mil) is too conservative; type III can be driven at higher E fields than 3.9 kV/cm (10 V/mil) without substantial problem. General rules and comments: never let transducer ceramic go into tension; we have never *crushed* any ceramic, *but* depolarization due to strictly compression is severe above (roughly) 552 MPa (80 kpsi), so avoid compressive stress above 276 MPa (40 kpsi) (e.g., mechanical assembly) using a factor-of-2 rule.'

'As an upper limit, we impose 3.9 kV/cm (10 V/mil) on our E fields.'

'Several years ago, and for a PZT-8 design, we allowed up to 2.4 kV/cm (6 V/mil).'

'In one design using PZT-4, we have used a 62 MPa (9 kpsi) static compression preload. Typically we will exceed 2 kV/cm (5 V/mil) by a bit for PZT-4, but this leads to a short life for the transducer.'

'In our designs we typically use maxima of 3.2 kV/cm (8.2 V/mil) for Type I and 4 kV/cm (10 V/mil) for Type III.'

'For a PZT-8-based transducer design, we have run up to 6 kV/cm (15 V/mil), and we also use the Brush–Vernitron data as guidelines for stress limits: 86 MPa (12.5 kpsi) precompression in maximum static conditions, and dynamically we allow for about 50% of static.'

TABLE I. Summary of relevant electrical and mechanical stress references.

Reference	Stress E or T with comments or notes
Berlincourt[3]	T: 69 MPa (10 kpsi) (I), 110 MPa (16 kpsi) (III); 14 MPa (2 kpsi) tension
Ugryumova[4]	T: 30 MPa (4.4 kpsi) static tension, 2.5 MPa (3.6 kpsi) dynamic
Browder[6]	T: 96 MPa (14 kpsi) (I), 124 MPa (18 kpsi) (III)
Ehrlich[7]	E: 5.5 kV/cm (14 V/mil), staved ring transducer
Berlincourt[9]	E: 3.3 kV/cm (8.4 V/mil), tan δ=0.04 at 100 °C (I)
	E: 6 kV/cm (15.2 V/mil), tan δ=0.03 at 100 °C (III)
	T: 41 MPa (6 kpsi) dynamic tension 25° (I)
	T: 48 MPa (7 kpsi) dynamic tension 25° (III)
Woollett[17]	E: 1.8 kV/cm (4.6 V/mil) 33 drive, tan δ=0.015 (I)
Krueger[12]	T: to 138 MPa (20 kpsi) prestress (I) and (III)
Brown[13]	E: 2 kV/cm (5.1 V/mil) planar stress, aging, etc.
	T: 248 MPa (36 kpsi)

III. DISCUSSION

A feature that emerges from study of the literature is that there was a high level of activity and publication during the 1960s in driving ceramics at high voltage levels. The activity appeared to nearly cease after 1973. It is also noteworthy that much more of the published work explored type I ceramic rather than type III, even at drive levels up to 9.8 kV/cm (25 V/mil) rms. Chronologically the study of the mechanical strength of both ceramic types has progressed in a fairly steady manner. Some of this data is summarized in Table I and suggest that electric fields as high as 5.9 kV/cm (15 V/mil) and compressive stress as high as 138 MPa (20 kpsi) are possible. An important point to note is that this data is often either from small pieces of ceramic or from small, nonproduction transducers.

The data shown in Fig. 1 comes from transducer design engineers' comments, with an emphasis on production trans-

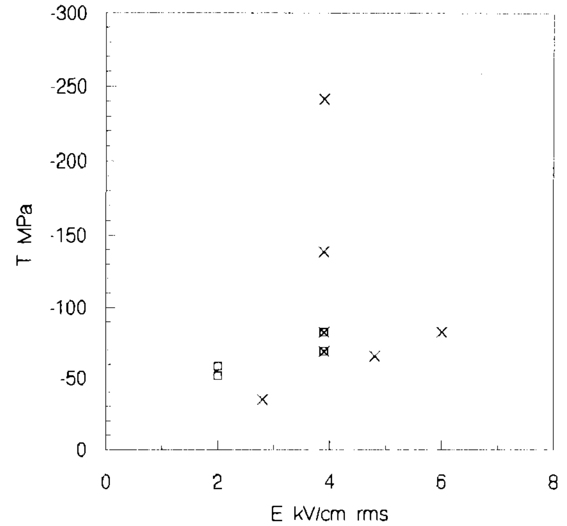

FIG. 1. Transducer designers mechanical and electrical stress limits for U.S. Navy type I (□) and type III (×) piezoelectric materials.

ducers. Because they are production oriented, they have experienced lower, more conservative values for mechanical and electrical stress. A few designers have used very high values of precompression, up to 241 MPa (35 kpsi), but this is usually done to offset compression loss due to transducer hydrostatic loading (such as in a flextensional transducer). A major feature in this graph is that the manufacturers drive type III ceramic at higher E fields and to higher precompression values than type I ceramic. The manufacturers data also appear to be more conservative for both field and stress than the levels the ceramic alone can handle, especially in the case of high electric fields. This suggests that the manufacturing and design of sonar transducers might not be up to par with the capability of the material.

IV. CONCLUSIONS

The data presented suggest that, under certain conditions of operation, high values of mechanical stress may be imposed [over 172 MPa (25 kpsi) in construction, 69–103-MPa (10–15-kpsi) compression in operation] and high values of E field may be applied 3.9–5.9 kV/cm (10–15 V/mil). Our study also suggests that higher values of field and stress are possible in sonar transducers. However, we note, as Woollett[5] did in 1981, that the results are largely single-point findings and fail to define the full mechanical, electrical, and endurance envelope for any given transducer design.

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