Morgan Electro Ceramics

POWER CAPACITIES OF PIEZOELECTRIC CERAMICS IN SONAR-TYPE ACOUSTIC TRANSDUCERS

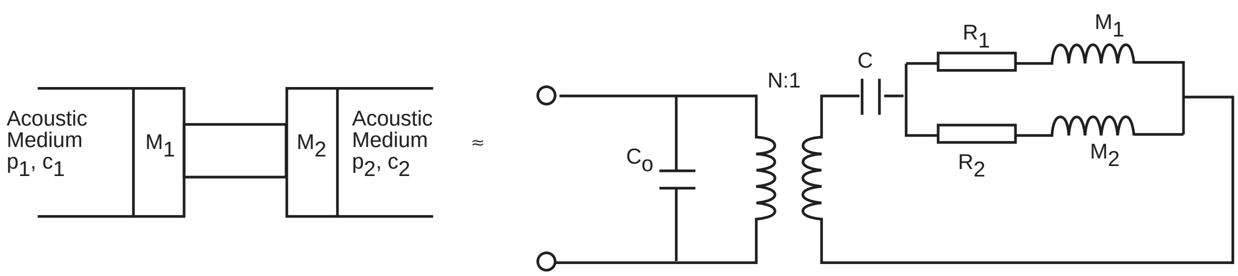
One of the most common and at the same time one of the most difficult questions asked about piezoelectric ceramic materials concerns their power handling capabilities. It is the purpose of this memorandum to explain some of the difficulties in giving a specific answer in watts per cubic metre as well as to give a simple analysis which may serve as a proper means of comparing different materials.

The equivalent circuit for a piezoelectric acoustic transducer was derived first by Mason and various equivalent circuits for specific transducers have been used. Felix Rosenthal worked out equivalent circuits especially for sonar-type transducers and showed in addition that the equivalent circuits, which assume lumped circuit elements, give results which differ relatively little from a rigorous solution so long as the dimensions of the end masses are large with respect to a wavelength.

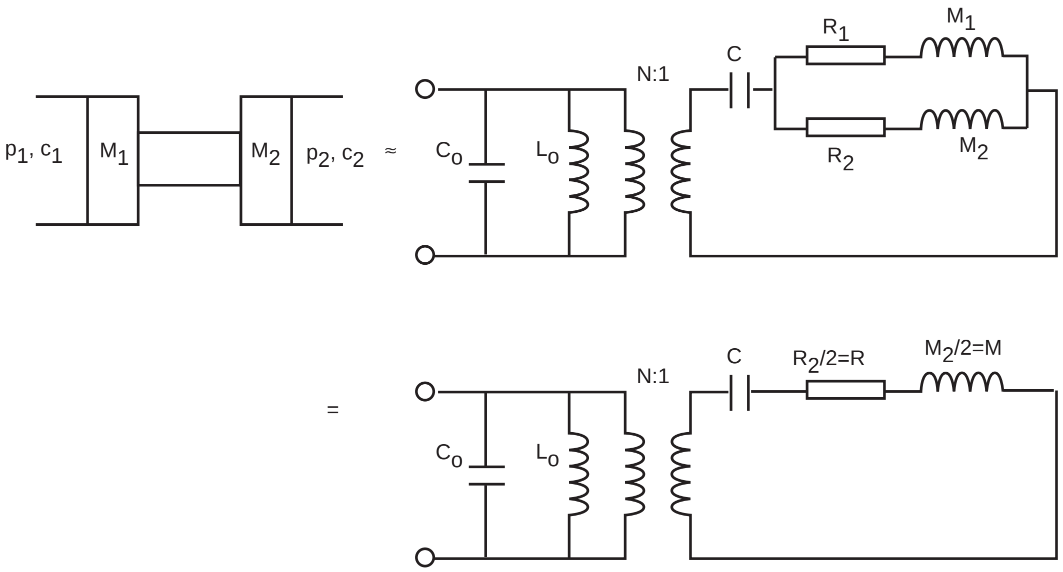
The general equivalent circuit for a sonar transducer loaded with end masses is given below.

It is possible, as Rosenthal noted, to "optimize" a transducer which is limited by allowable electric field applied to the ceramic by adjusting the relative magnitudes of masses M_1 and M_2 If the medium to the left of M_1 is air ($R_1 \approx 0$), then one may make M_1 small and M_2 large in order to maximize the power into the fluid medium (R_2). If the transducer is stress-limited rather than electric field-limited, this approach cannot be used. In practice one is usually field-limited due to dielectric losses at high amplitude, and high tensile stresses may be prevented by precompression of the transducer assembly.

One can readily see, however, that use of the above "optimizing" method, particularly in view of the necessity for compromise (relatively high - Q_M and reduced bandwidth as one increases M_2 at the expense of M_1), makes a specification of a certain power capability of the ceramic per unit volume impossible; too much depends on transducer design.



If we limit ourselves to a simpler transducer configuration, a basis for comparison of various ceramic materials is readily derived. This configuration is as - follows:



The inductor L_o is added to increase the bandwidth of the transducer. It resonates with the static capacitance of the transducer, and increases the bandwidth from $k^2/(1-k^2)$ to $\sqrt{(k^2/1-k^2)}$ for a matched transducer.

For a transducer using the lateral mode the bandwidth is $\sqrt{(k_{31}^2/1-k_{31}^2)}$ (32% for PZT-4); for a transducer using the parallel mode the bandwidth is $\sqrt{(k_{33}^2/1-k_{33}^2)}$ (83% for PZT-4). When no end masses are used, the effective or mode coupling factor is somewhat smaller (by about 25%) with a corresponding decrease in bandwidth. In the case here discussed, with end masses, the bandwidth is related to the resonance and antiresonance frequencies as follows:

(1) BW (matched Transducer)

$$\frac{k_{33}}{\sqrt{1-k_{33}^2}} \text{ or } \frac{k_{31}}{\sqrt{1-k_{31}^2}} = \sqrt{\frac{f_a^2 - f_r^2}{f_r^2}}$$

We can consider a transducer utilizing the lateral (d_{31}) or parallel (d_{33}) mode. Consider first one utilizing the parallel mode. The ceramic has a cross-sectional areaA_c cemented or bolted to identical masses M_2 , with the radiating area of each end mass equal to A_2. The ceramic consists of n plates or rings of total length l, all connected in parallel. The equivalent circuit parameters are:

$$Co = \frac{n^2 A_c \varepsilon^T_{33}(1-k_{33}^2)}{l},$$

$$C = \frac{S^E_{33} l}{A_c},$$

$R_2 = \rho_2 C_2 A_2$, and

$$N = d_{33} A_c n / l S^E_{33}$$

For this transducer, maximum power occurs at the resonance frequency given by:

$$2)\ \omega_R = 2\pi f_R = \frac{1}{\sqrt{MC}} = \sqrt{\frac{A_c}{M S^E_{33} l}}$$

The velocity through the load $R = R_2/2$ at ω_R is given by:

$$3)\quad v(\omega_R) = VN/R$$

The power is given by:

$$4)\quad P(\omega_R) = V^2N^2/R = 2E^2 d_{33}^2 A_c^2 / S^{E\,2}_{33} \rho_2 C_2 A_2$$

where V and E are RMS values.

The power per unit volume of ceramic per ω_R^2 of the transducer is given by:

$$5)\ p/\omega_R^2 = (E^2 d_{33}^2 / S^E_{33}) M_2 / \rho_2 C_2 A_2$$

$$= E^2 k_{33}^2 \varepsilon T_{33} M_2 / \rho_2 C_2 A_2$$

Now consider the case of the transducer utilizing the transverse mode of the ceramic material. Here the ceramic consists of n plates or bars connected in parallel, with total cross-sectional area (n t w) of A_c . The length of the bars is l . The plates each have thickness t between electrodes and width w. The equivalent circuit parameters are:

$$C_o = n\varepsilon^T_{33}(1-k_{31}^2) wl/t$$

$$C = S^E_{11} l / A_c$$

$R_2 = \rho_2 C_2 A_2$, and

$N = d_{31} A_c / t S^E_{11}$

The resonance frequency is given by;

6) $\omega_R = 2\pi f_R = \sqrt{(A_c / M S^E_{11} l)}$

The power at ω_R in given by:

7) $P = V^2 N^2 / R = 2E^2 d_{31}{}^2 A_c{}^2 / S^E_{11}{}^2 \rho_2 C_2 A_2$

where V and E are rms values.

Thee power per unit volume of ceramic per $\omega_R{}^2$ of the transducer is R given by:

8) $$p/\omega_R{}^2 = \frac{E^2 d_{31}{}^2}{S^E_{11}} \frac{M_2}{\rho_2 C_2 A_2} = E^2 k_{31}{}^2 \varepsilon^T_{33} \frac{M_2}{\rho_2 C_2 A_2}$$

Comparison of equations 8) and 5) indicates that for a given limitation in electric field and for a given value of loading masses M_2 and acoustic load $\rho_2 C_2 A_2$ the power per unit volume of ceramic per W^2_R is different only by a factor $(d_{33}{}^2/d_{31}{}^2)(S^E_{11}/S^E_{33})$. A potentially even greater lever on the power capabilities of the transducer is the electric field limitation on the ceramic material. If one arbitrarily sets a limit of 4% on the allowable dissipation factor in order to obtain high transducer efficiency, the electric field limitations for PZT-4 and Ceramic B are respectively 390 and 170 volts/mm rms, a ratio of 5.3 for the squares. When one considers the ratios of d_{33}-constants, 270 to 149 x 10^{-12} m/v, and the ratios of elastic compliances, 14.9 to 9.1 the overall power radiating capabilities differ by a factor

$$5.3 \times \frac{270^2}{149^2} \times \frac{9.1}{14.9} \approx 10.7$$

A similar ratio for PZT-4 and PZT-5 is 37:1 in favour of the former. At 75°C the advantage of PZT-4 over Ceramic B rises to 55:1. The advantage of PZT-4 over the Mason composition (80w%$BaTiO_3$, 12w% $PbTiO_3$) 8w%$CaTiO_3$) is 13:1 at 25°C and 77:1 at 75°C. Comparison of several compositions in both modes is made in Table I.

The effective mechanical Q-factors for the parallel and transverse mode transducers of the type discussed here are given by:

9) $$Q_M = \frac{1}{\rho_2 C_2 A_2} \sqrt{\frac{2 M_2 A_c}{l s^E}} = \frac{2}{\rho_2 C_2 A_2} \sqrt{\frac{M A_c}{l s^E}}$$

where s^E is s^E_{11} for the transverse and s^E_{33} for the parallel mode.

In order to make use of the full bandwidth potentiality of the transducer material and therefore obtain high energy conversion and high efficiency over the bend, it is desirable to properly match the transducer to the electrical generator or vice versa and to match the impedance of the fluid to the transducer. This is discussed thoroughly by Mason in his book Electromechanical Transducers and Wave Filters, pages 230 through 238.

Using a shunt coil L_0 to increase bandwidth, the output resistance of the transmitting amplifier should be:

10) $$R_G = \frac{1}{\omega_R C_o} \sqrt{\frac{1-k_{33}{}^2}{k_{33}{}^2}} = \frac{1}{\varepsilon^T_{33} n^2 k_{33} \sqrt{(1-k_{33}{}^2)}} \sqrt{\frac{M s^E_{33} l_3}{A_c{}^3}}$$

for a parallel mode transducer or:

11) $$R_G = \frac{1}{\omega_R C_o} \sqrt{\frac{1-k_{31}{}^2}{k_{31}{}^2}} = \frac{1}{\varepsilon^T_{33} n^2 k_{31} \sqrt{(1-k_{31}{}^2)}} \sqrt{\frac{M s^E_{11} t^4}{A_c{}^3}}$$

for a transverse mode transducer. The matching mechanical impedance in the radiating side is given by:

12) $$R_T = N^2 R_G$$

$$= \frac{1}{\omega_R C_o} \frac{k_{33}{}^2}{\sqrt{1-k_{33}{}^2}} = \frac{k_{33}}{\sqrt{(1-k_{33}{}^2)}} \sqrt{\frac{M A_c}{s^E_{33} l}}$$

for a parallel mode transducer, or:

13) $$R_T = \frac{1}{\omega_R C_o} \frac{k_{31}{}^2}{\sqrt{1-k_{31}{}^2}} = \frac{k_{31}}{\sqrt{(1-k_{31}{}^2)}} \sqrt{\frac{M A_c}{s^E_{11} l}}$$

for a lateral mode transducer.

The product $R_T R_G$ is given by:

14) $$R_T R_G = \frac{1}{\omega_R{}^2 C C_o} = \frac{M\, l}{A_c \varepsilon^T_{33}(1-k_{31}{}^2)}$$

or

15) $$R_T R_G = \frac{1}{\omega_R{}^2 C C_o} = \frac{M\, t^2}{A_c l \varepsilon^T_{33}(1-k_{31}{}^2)}$$

For a perfect match on the mechanical side the acoustic impedance $\rho_2 C_2 A_2 /2$ must equal R_T as follows:

16) $$R_T = R = \frac{R_2}{2} = \frac{\rho_2 C_2 A_2}{2} = \frac{1}{\omega_R C} \frac{k}{\sqrt{(1-k^2)}}$$

If equations 12) and 16) do not hold, the transducer Is not matched, and the bandwidth and energy conversion are reduced.

If the fluid match is perfect, the mechanical Q is given simply as follows using 12), 13), and 16) in 9):

(17) $QM_{(matched)} = \sqrt{((1-k^2)/k^2)}$

= 1.2 for PZT-4 in the parallel mode and 3.12 in the lateral mode.

Considering the bandwidth of the matched transducer (equal to $k/\sqrt{(1-k^2)}$), the following relationship holds:

(18) $(BW)(Q_M) = 1.$,

for a matched transducer.

Another relationship may be derived for a matched transducer:

(19) $k2 = 1/(1+Q_M Q_E)$

where $QE = \omega_R C_o R_o$

For the general case where the transducer is not matched, the relationship becomes:

(20) $k^2 = 1/(1 + Q_M Q_E R/R_o N^2)$

where, again $R = R_2/2 = \rho_2 C_2 A_2/2$

We can now consider the power at resonance for a matched transducer. In this case, substituting 16) in 5), the power per unit volume of ceramic (p) per ω_R for the parallel mode transducer is:

21) $p/\omega_R = E^2 d_{33}\sqrt{(1-k_{33}^2)}.\sqrt{(\varepsilon^T_{33}/S^E_{33})}$

$$E^2\, k_{33}\varepsilon_{33}^{s3=0}/\sqrt{(1-k_{33}^2)} \quad = \quad E^2\varepsilon_{33}^{s3=0}\, BW$$

For the transverse mode transducer it is:

(22) $p/\omega_R = E^2 d_{31}\sqrt{(1-k_{31}^2)}.\sqrt{(\varepsilon^T_{33}/S^E_{11})}$

$$E^2\, k_{31}\varepsilon_{33}^{s1=0}/\sqrt{(1-k_{31}^2)} \quad = \quad E^2\varepsilon_{33}^{s1=0}\, BW$$

For matched transducers, therefore, one gains by only a factor of 1.7 in power at mid-band using a parallel rather than a transverse mode in PZT-4, but one gains by a factor $(k_{33}/k_{31})(\sqrt{(1-k_{31}^2)}/(\sqrt{(1-k_{33}^2)})$ or 2.6 in bandwidth.

In comparing various ceramic materials for power potentiality in matched transducers, one must again consider the field limitation. If, as before, we limit the field to the value which gives a dielectric dissipation of 4%, the advantage of PZT-4 over ceramic B (parallel mode) is 7:1. The advantage in bandwidth is 1.5 for PZT-4. Comparison on this basis is given in Table 2 for several compositions for both modes. The fourth column of this table gives absolute power output in watts/cm^3/kcps for a limitation of 0.04 on tan∂. A Figure of this type can be given only for a matched transducer, with $\sqrt{Ac} > \lambda$.

The true equivalent circuit must contain a parallel resistance R_o across C_o to account for dielectric losses. Strictly speaking, R_o must be a function of both the frequency and the amplitude of the electric field, the former because the dielectric dissipation is relatively independent of frequency, and the latter due to dielectric hysteresis. The dissipation factor (tan ∂) is given by (tan ∂ is measured at low frequencies and therefore the capacitance includes motional capacitance):

(23) $$\tan\partial = \frac{1}{\omega R_o(C_o + N^2C)}$$

Since tan ∂ is relatively frequency independent R_o must be inversely proportional to frequency. One can define a specific dielectric loss resistance $r_o = R_o A_c/1$, and in this case:

(24) $\tan\partial = \quad 1\ /\ \omega R_o\varepsilon^T_{33}$

The power per cubic metre p_D dissipated in the ceramic by dielectric heating is then given by:

(25) $p_D = E^2/r_o = \omega E^2\varepsilon^T_{33}\tan\partial$

Were E is rms field.

Since R_o varies with electric field it may not be desirable to consider it part of R_G the generator impedance. If, however, R_G for match is less than R_o It may be possible to make the generator impedance R_G' such that at a given electric field:

(26) $$R_G = \frac{1}{\omega RC_o}\sqrt{\frac{1-k^2}{k^2}} = \frac{R_G' R_o}{R_o + R_G'}$$

In this case the bandwidth of the transducer will not suffer. It should be noted, however, that dielectric losses in general do reduce bandwidth as well as efficiency.* It is of some interest for this ideal case to determine an efficiency at ωR, assuming no losses except the dielectric losses in the ceramic and the acoustic power P_a delivered to the acoustic medium. In this case, ignoring losses in the generator (R_G'):

(27) Efficiency in presence of dielectric loss

$$= \frac{P_a}{P_a + P_d} = \frac{\omega_R E^2\varepsilon^T_{33}(1-k^2)BW}{\omega_R E^2\varepsilon^T_{33}(1-k^2)BW + \omega_R E^2\varepsilon^T_{33}\tan\partial}$$

One can readily see that the value of coupling does not have a pronounced effect on transducer efficiency. The efficiencies of matched transducers operating at an electric field such that tan∂=0.04 are shown in Table II.

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*It is also important to note that C is dependent upon electric field, and a change in C_o lowers Sandwidth because it disturbs the L_o C_o tuning of the transducer.

**One might think from this equation that for a given value of tan ∂ there is a certain value of k which will give maximum efficiency. This is of course, not true. The occurrence of the term $\tan\partial/\sqrt{(1-k^2)}$ is merely due to the standard use of the free (low frequency) value of tan∂. If the clamped (in this case S_1 or $S_3 = 0$) value could be measured, it would occur in the denominator of 27) as $(\tan\partial)\sqrt{(1-k^2)}$ and the efficiency then increases with k for all values of k.

It is possible also to determine the effect of mechanical losses in the transducer material. For the purpose a resistance R_c is placed in series with R, the acoustic load resistance. If $R_c + R$ is equal to R_T, the image impedance, the transducer is still matched. The mechanical Q of the ceramic is given by:

(28) $Q_{MC} = 1/\omega_R C R_c$

The reduction in efficiency due to Rc is by a factor $(R_T\text{-}R_c)/R_T$, and using 16) and 28) we obtain:

(29) $(R_T\text{-}R_c)/R_T = \dfrac{k - \sqrt{(1-k^2)/Q_{MC}}}{k}$

The overall efficiency of the matched transducer neglecting all losses other than those in the ceramic is then the product of equations 27) and 29):

(30) $\text{Efficiency} = \dfrac{k - \sqrt{(1-k^2)/Q_{MC}}}{k + \tan\partial/\sqrt{(1-k^2)}}$

just as $\tan\partial$ is a function of E, Q_{MC} is a function of mechanical stress. R. Gerson however, found that variations of Q_{MC} with stress are less pronounced than variations of $\tan\partial$ with electric field. He found that Q_{MC} decreased from about 400 or 500 to about 100 for Ceramic B and PZT-4 with stress increasing from zero to about 2,000 psi, with relatively little further change to 3,500 Psi, the limit of his tests. Similar behaviour was noted with PZT-5, but in this case Q_{MC} decreased from 75 to 25. Since we are generally interested in the transducer efficiency under relatively high drive, the values of Q_{MC} at 3,500 Psi stress were used in calculating overall transducer efficiency in the last column of Table II. It should also be noted that R.Gerson found that the compliance of the ceramic increases at high stress amplitudes, near 5% for PZT-4 and Ceremic B and about 20% for PZT-5 at 3,500 Psi. This change is, of course, most serious for compositions providing low bandwidth.

It is clear from equation 30) that dielectric loss $\tan\partial$ and mechanical loss $1/Q_{MC}$ decrease efficiency with approximately equal effectiveness. In practical cases, however, l/Q_{MC} is considerably lower than $\tan\partial$. One can in general neglect l/Q_{MC} in comparison to $\tan\partial$, but there are in addition other-mechanical losses in the transducer, especially at glue joints, and these enter in the same way as l/Q_{MC} in equation 30). A total mechanical loss of 10%, will, for instance, reduce the efficiency of the matched PZT-4 transducer from 92.5% (Table II) to 82.5%

It is a very simple matter to calculate the stress and strain in the ceramic at resonance by use of the equivalent circuit. For the sake of completeness the results are given below:

(31) $S\ (\text{strain}) = \dfrac{2dE}{A_2\rho_2 c_2}\sqrt{\dfrac{MA_c}{S^E l}}$

TABLE I

Relative Power at Resonance for Same Acoustic Load ($A_2\rho_2c_2$) Loading Mass, and Resonance Frequency for Given Volume of Ceramic

Material & Mode	Temperature, °C	Relative Power
PZT-4, Parallel	25	100
" "	100	65
PZT-4, Transverse	25	23
" "	100	12.5
PZT-5, Parallel	25	2.7
" "	100	3.2
PZT-5, Transverse	25	0.5
" "	100	0.6
Ceramic B, Parallel	25	9.3
" "	75	1.8
Ceramic B, Transverse	25	1.6
" "	75	0.3
Mason Comp., Parallel	25	7.5
" "	75	1.3
Mason Comp., Transverse	25	0.8
" "	75	0.2

*Assuming electric field limited to that which gives $\tan\partial$=0.04.

(32) $T\ (\text{stress}) = \dfrac{2dE}{S^E A_2\rho_2 c_2}\sqrt{\dfrac{MA_c}{S^E l}}$

where appropriate subscripts are used for s^E and d.

For the <u>matched</u> transducers, these equations are simplified as follows:

(33) $S = Ed\sqrt{\dfrac{1-k^2}{k^2}} = \dfrac{Ed}{BW}$

(34) $T = \dfrac{Ed}{S^E}\sqrt{\dfrac{1-k^2}{k^2}} = \dfrac{Ed}{S^E BW}$

where appropriate subscripts are again used.

The stress, for instance, in a matched PZT-4 -parallel mode transducer operating at 390 v/mm rms ($\tan\partial$ = 0.04) is 1230 psi rms. The strain is 1.26 x 10^{-4} rms. For the same transducer operating in the lateral mode, 1/BW is up by a factor of 2.6 and d is down by a factor 117/270 = 0.434, so the strain is 1.42 x 10^{-4} rms and the stress is 1680 psi rms. This brings out another advantage of the parallel mode. In a matched PZT-4 parallel mode transducer the strain and stress are less at a given driving electric field, but the bandwidth is up by a factor of 2.6 and the power by a factor of 1.7 compared to a matched PZT-4 lateral mode transducer.

At this point it might be informative to consider the factors which limit the power-handling capabilities of a transducer. We shall limit ourselves to factors which depend upon the piezoelectric ceramic. These may be summarized as follows:

1) Mechanical strength of the ceramic.
2) Reduction in efficiency due to dielectric losses.
3) " " " " " internal mechanical losses.

TABLE II

Power/Unit Volume at Resonance for Matched Transducer.*

Material & Mode	Temp.°C	Relative Power	Bandwidth %	Watts/cm³ at 1 kcps	Efficiency, tan∂=.04 Ideal Case %	Efficiency, tan∂=.04 Corrected for Q_{MC} of Ceramics at 3500 psi
PZT-4, Parallel	25	100	83	5.6	92.5	91.5
“	100	77	72	4.3	91.5	-
PZT-4, Transverse	25	59	32	3.3	88	86.5
“	100	40	29	2.2	87	-
ZTW-5, Parallel	25	2.3	91	0.13	92.5	88.5
“	100	3.0	80	0.17	91.5	-
PZT-5, Transverse	25	1.5	33	0.08	88	83
“	100	1.8	31	0.10	88	-
Ceramic B, Parallel	25	14.3	55	0.80	92	90
“	75	3.8	44	0.21	90	-
Ceramic B, Transverse	25	6.3	20	0.35	82	80
“	75	1. 6	16	0.09	79	-
Mason Comp., Parallel	25	14.5	36	0.81	88	-
“	75	1.9	34	0.11	87	-
Mason Comp., Transverse	25	5.0	11	0.28	73	-
“	75	0.7	10	0.04	71.5	-

*Assuming electric field limited to that which gives tan∂ = .04

**Bandwidth = $\frac{f_2-f_1}{\sqrt{f_1 f_2}}$ where f_2 = upper cutoff frequency, f_1 = lower cutoff frequency

*** To obtain power/cm³ at any other frequency f multiply by f/1000 cps.

4) Depolarization of the ceramic due to electric field.
5) Depolarization of the ceramic due to temperature rise.
6) Positive feedback between 5) and 2). Instability due to temperature rise in ceramic resulting from internal heating, and subsequent rise in tan∂ at the same level of electric field with higher temperature.

Of these, we eliminate 1) through mechanical bias, as mentioned previously. We can, in general, eliminate 3) on the basis of preceding discussion, even though there may be significant losses in the transducer housing as distinct from the active piezoelectric element. An electric field which will cause depolarization would create extremely high dielectric losses and resulting very low efficiency, and we therefore need not consider 4). We may for practical purposes confine ourselves to 2) and 5) and feedback between these (6). The heat dissipated due to dielectric loss may be removed by conduction through the transducer masses and housing. The efficiency of heat removal is important, since this determines the temperature rise. This depends upon the thermal conductivity of the ceramic and upon the design of the transducer. The temperature rise will be less for a pulsed than for a continuous duty transducer, so limitations are much less severe for a low-duty-eycle transducer.

It is, strictly speaking, possible to have the power rating of a transducer efficiency-limited or temperature-rise-limited. For instance, with a matched PZT-4 parallel mode transducer, the power capability with a limit of 0.04 on tan∂ is 5.6 watts/cm³ kcps with an efficiency of 92.5%. In this case the heat power is 0.4.6 watts/cm³ kcps. The resulting temperature rise may or may not be sufficient to cause serious trouble, depending on transducer design and frequency. Under similar circumstances the power capability of a <u>matched</u> Ceramic B parallel mode transducer is only 0.8 watts/cm³ kcps with an efficiency of 92%. The heat power is then only 0.07 watts/cm³ kcps. We thus see that with the same limitation of 0.04 on tan∂, the actual heat rise is less with Ceramic B. It must be noted, however, that PZT-4 is much more able to withstand severe heat rise. If we allow a value of 0.10 for tan∂ in Ceramic B the power at 1 kcps will be up to 3.2 watts/cm³, but the efficiency will be only 80%, giving a heat power of 0.6 watts/cm³ kcps . The point to be made here is that we may limit each ceramic by setting an arbitrary minimum efficiency or a maximum value on generated heat power. The PZT compositions can withstand higher temperature rise than the $BaTiO_3$ ceramics, so a limitation on heat power suitable for the latter would be unrealistic for the former.

If we now extend the data of Table II to 100 kcps, we find that a matched PZT-4 parallel mode transducer can radiate 560 watts/cm³ with an internal heat power of 46 watts/cm³, still with an efficiency of 92.5%. This is, of course, ridiculous for a continuous-duty transducer without very efficient forced cooling, but realistic for one with a 1% duty cycle. It is safe to say that a high-f requency- continuous -duty-transducer will in general be heat-rise rather than efficiency limited, and for this case a specific limit on tan∂ for all materials may make sense. A low-frequency-continuous-duty-transducer may also be efficiency limited, and a low-frequency-low-duty-cycle transducer will certainly be efficiency limited.

As mentioned previously, a limit on tan∂ is not the same as a limit on efficiency, since equations 30) and 27) also involve the coupling factor. Table III gives power ratings for the various ceramic compositions for 80% efficiency excluding all losses other than dielectric losses in the ceramic. On this basis values of tan∂ are 0.12, 0.12, 0.107, and 0.077 for PZT-4, PZT-5, Ceramic B, and the Mason composition for the parallel mode, and 0.075, 0.077, 0.05, and 0.025 in the lateral mode. Allowable driving fields are those which give these values for tan∂ and power ratings were calculated from equations 21) and 22).

Table IV gives power ratings for the same compositions in matched transducers where in each case the power dissipated due to dielectric loss is 0.5 watts/cm^3 kcps. The outstanding advantage of PZT-4 on this basis is the resulting efficiency compared to that for the other compositions. Even PZT-5 here shows up to advantage over the barium titanate compositions, especially at the higher temperature. It is clear that. PZT-4 operating in the parallel mode is optimum whether the transducer is efficiency limited (Table III) or heat-power-limited (Table IV).

SUMMARY

The values of acoustic power output for a given volume of Piezoelectric ceramic in a sonar-type transducer can be given only for a matched transducer (Table II), for very specific limiting conditions, and for cases in which the dimensions of the radiating area are large compared to a wavelength. The term matching is applied to the process of adjusting the acoustic load so that it corresponds to the image impedance of the transducer considered as a band-pass filter, and with an inductor equal to $1/\omega R^2 C_o$ connected across the transducer. This leads to maximum bandwidth when the impedance of the driving electric generator also equals the image impedance.

For the case of an unmatched transducer an absolute value for the power capability of the ceramic material cannot be given even for specific limiting conditions, but comparison may be made between various piezoelectric ceramics for a condition of equal acoustic load and end masses (Table I).

It is important to note that a matched transducer does not radiate the most acoustic power for a given volume of ceramic. One can actually get more power by undermatching (equations 5 and 8), but in this case the bandwidth is reduced. In this case also mechanical strength of the ceramic may become a limiting factor, unless very high precompression is used.

Mechanical losses in the ceramic and the transducer housing and dielectric losses detract from efficiency. In general the mechanical losses in the ceramic may be neglected, but dielectric losses may not. For a given value of tan∂ or $1/Q_{MC}$ the reduction in efficiency is less for a composition with high piezoelectric coupling than for one with low piezoelectric coupling (equation 30) and Table II.

One may choose an optimum transducer material as one which radiates the most acoustic power for a given efficiency or for a given dissipated heat power. Most pulsed transducers are efficiency limited; high frequency, continuous duty transducers are likely to be heat-power-limited. In either case PZT-4 operating in the parallel mode gives the highest allowable acoustic power (Tables III and IV).

TABLE III

Acoustic Power per Unit Volume of Ceramic at Resonance for Matched
Transducer at 80% Efficiency, Excluding All
Losses Except Dielectric Losses in Ceramics

Material and Mode	Temp. °C	Power, watts/cm^3 at 1 kcps
PZT-4, Parallel	25	23.6
"	100	20.4
PZT-4, Transverse	25	7.8
"	100	6.4
PZT-5, Parallel	25	3.1
"	100	3.0
PZT-5, Transverse	25	0.32
"	100	0.40
Ceramic B, Parallel	25	4.4
"	75	1.5
Ceramic B, Transverse	25	0.64
"	75	0.15
Mason Comp., Parallel	25	2.1
"	75	0.34
Mason Comp., Transverse	25	0.11
"	75	0.014

TABLE IV

Acoustic Power per Unit Volume of Ceramic at Resonance for Matched Trans:
ducer, for 0.5 watts/cm3 kcps Dissipated Power Due to Dielectric Loss

Material and Mode	Temp°C	Acoustic Power, watts/cm^3 kpcs	Efficiency,%
PZT-4, parallel	25	6.1	92.5
"	100	5.3	91.5
PZT-4, transverse	25	3.6	88
"	100	2.7	84.5
PZT-5, Parallel	25	2.2	81.5
"	100	2.3	82
PZT-5, transverse	25	1.3	72
"	100	1.4	74
Ceramic B, parallel	25	2.6	84
"	75	1.2	71
Ceramic B, transverse	25	1.5	75.
"	75	0.65	56.5
Mason Camp., parallel	25	2.2	81.5
"	75	1.0	67
Masoll Comp., transverse	25	0.78	61
"	75	0.35	41