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Compact Piezo-Based High Voltage Generator - Part II: Quasi-Static Measurements

Contents

Abstract

This paper presents the results of an effort to develop and test a piezo-based high voltage generator (HVG). A theoretical model was developed and, in order to verify this model, quasi-static measurements were conducted using a 15 mm diameter and 20 mm long cylindrical PZR-5A piezoelectric element and an electric press driven by a rotating screw. Measurements were made using various load capacitances and resistances and using single and multiple piezo elements. The results of these measurements will be presented. A prototype piezo-based HVG with a diameter of 65 mm and a length of 275 mm was also built and tested and the results will be presented in a follow-on paper. This generator produced almost 400 kV with 3 J of energy stored in the generator.

1. Introduction

Using the quasi-static test results described in [1], a prototype high-voltage generator (HVG) was designed based on the 15 mm diameter, 20 mm long PZT-5A element used during those tests. The photo of the HVG is shown in Fig. 1, together with a photograph of the assembled system. Note that the high-voltage generator could later incorporate a dipole antenna for generating high-power RF radiation directly. The diameter of the generator shown in Fig. 1 is 65 mm, with length 275 mm not including the electrical connector for the gas generator. In principle, the generator is simple. A small pyrotechnic gas generator at one end of the generator produces a pressure in the small gas volume in front of the piston of up to 200 bar, increasing linearly over 10 ms. During this time, the piston transmits a force of up to 40 kN to the four piezo elements, thus compressing them. The force is contained by a robust fiberglass housing. This system is a compact replacement for the electromechanical press used for the tests described in [1]. It has an added advantage in that the force is applied to the piezo approximately 1000 times faster. This much shorter time scale means that the output current from the piezo elements will be about 1000 times higher, counteracting the effects of charge leakage through resistive paths which could prevent high voltages from being attained.

The generator contains 4 or possibly 6 piezo elements split into two groups. According to the results discussed in [1], the limitation on the

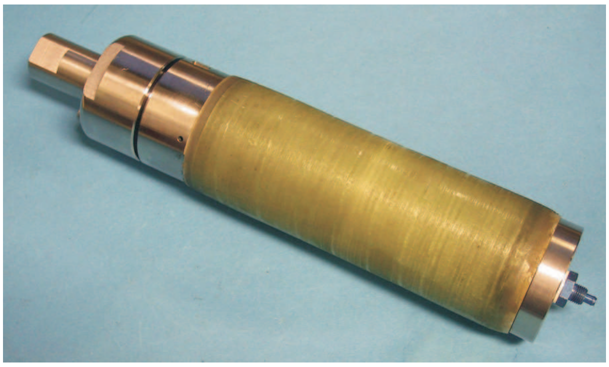


Fig. 1. Prototype of a piezo HVG.

achievable voltage from the generator will not be the piezo, but rather the voltage that can be sustained both inside the generator and across the exterior of the housing without electrical breakdown. The generator can be filled with either oil or SF6 gas to inhibit breakdown, but outside the generator the breakdown voltage is limited by the atmosphere. This is particularly true of slow, or quasi-DC, charging of the antenna. When the electric field on the housing attains 3 MV/m, a discharge can form, which can short-circuit the antenna. Since the charging current provided by the piezo elements is small, of the order of 1 mA, even a highly resistive path will be sufficient to discharge the antenna. In the event that the exterior of the source housing is wet or when the air humidity is higher than 60 %, the problem will be even more serious. Therefore, the antenna must be pulse charged as quickly as possible in order to attain the maximum possible charging voltage. This is especially critical for small sources where even modest voltages of 100 kV can produce electric fields of more than 1 MV/m.

An additional consideration in favor of pulsed charging is that in order for a compact source to radiate, it must produce high-frequency, or alternatively short-pulse, radiation. This means that the antenna spark gap should be as small as possible to minimize the switch closure time, that is, on the order of 1 mm for slow charging. However, with realistic gas pressures or with oil, the breakdown voltage with such a small antenna spark gap will not exceed 100 kV. To achieve higher voltages, a larger gap must be used. To maintain the required switch closure time, pulsed charging should be used to over-volt the antenna gap as much as possible. Therefore, pulsed charging of the antenna is essential to obtaining efficient radiation from the piezo generator.

The simplest technique for implementing the required pulse charging is to arrange the two groups of two piezos so that the polarizations are in opposite directions. This means that when pressure is applied, the total voltage across the antenna will remain at approximately 0 V. The metal connecting rod in the centre of the generator between the piezos will be charged to two or three times the voltage on each piezo depending on the number of piezos used. Based on the results presented in [1], a voltage of at least 200–300 kV should be achievable in this manner. When the voltage is sufficiently high, a spark will form between one of the antenna elements and the connecting rod. It is irrelevant from which antenna element the spark forms. This charging spark gap switch short-circuits one of the groups of piezos, reducing the voltage across these piezos to zero. The voltage across the antenna therefore increases approximately to the voltage across the two remaining undischarged piezos. This process can be expected to occur over about 10–30 ns.

When the voltage across the dipole antenna increases rapidly, a voltage will be applied to the antenna spark gap switch. When the voltage has attained the breakdown threshold, the antenna switch fires and produces a radiated impulse. Since the antenna charging is fast, significant over-volting of the antenna gap is expected. This will assist in achieving the necessary subnanosecond switch closure time. Even though half of the energy stored in the generator will be lost, the advantages of this configuration for efficient nanosecond pulse switching and suppression of exterior breakdown are important characteristics for a practical source concept.

2. Gas Generator Pressure Tests

The gas generator chosen for the piezo HVG was the DM82 cartridge, which has been produced in large quantities by DIEHL. In its standard configuration, the DM82 is charged with 200 mg of P 806 smokeless powder propellant. For the pressure tests, it was not necessary to use the piezo elements. Instead, the source was assembled according to the setup shown in Fig. 2. A disc was inserted immediately after the piston, locking it in place without requiring the piezo elements or, in fact, the remainder of the source to be installed. An added benefit was that the housing was not stressed during these tests. This was important since the pressure could not be accurately predicted prior to the tests. For its usual application, the DM82 is used to produce 40 bars of pressure in a larger volume and extrapolation to a pressure of 200 bars was not simple due to the effects of gas cooling caused by the relatively large ratio of surface area to volume in the piezo generator. Because of this difficulty in predicting the actual pressure generated by the DM82, the gas generator was designed so that up to 4 each 50 mm diameter, 1.5 mm thick washers could be installed inside the gas volume as shown in Fig. 2. A pressure transducer was connected to the system using the mounting hole indicated in Fig. 2 to allow the pressure to be measured against time for various numbers of washers, corresponding to different gas chamber

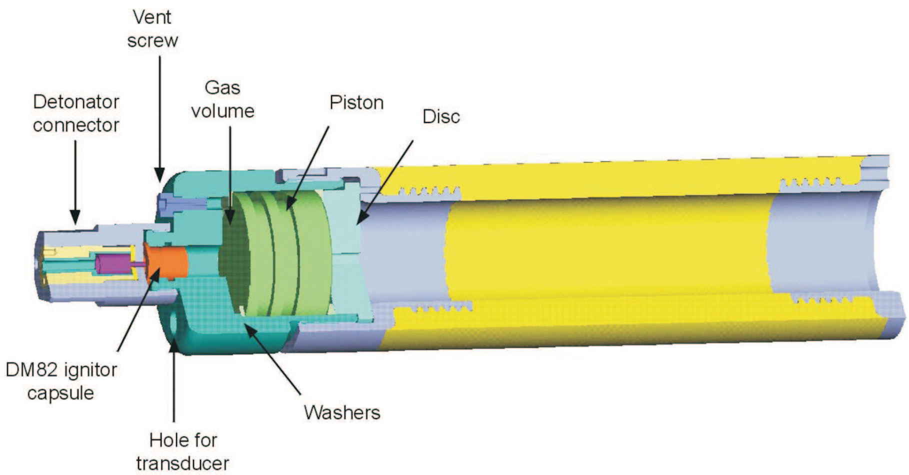


Fig. 2. Source configuration for gas generator pressure tests.

volumes. Note the vent screw in Fig. 2, which had a 1 mm diameter hole drilled on-axis to allow the chamber to be rapidly vented. Although this was expected to reduce the maximum pressure, the advantage of this vent is that the 200 bar pressure, corresponding to 40 kN of axial force on the housing, need only be maintained for approximately 20 ms. The vent screw could be replaced with a standard M5 screw to seal the gas chamber if desired.

The measured pressure is plotted against time in Fig. 3 for various gas chamber volumes and with the 1 mm diameter vent either open or closed. In all cases, after a small initial step immediately following detonation, the pressure increases approximately linearly up to the maximum in about 10 ms. This is satisfactory for the requirements of the piezo compression. After maximum pressure is attained, the pressure decreases rapidly initially due to the effects of cooling of the gas by the walls of the chamber. At later times the pressure drop is due to venting of the gas from the chamber. The two top plots show the pressure obtained with 4 and 2 washers in the gas chamber and the vent open. The vent caused the chamber pressure to drop approximately exponentially with a time constant of about 20 ms. The maximum pressure obtained with 4 and 2 washers was 56 and 67 bar, respectively. This is approximately a factor of 3 less than the desired value of 200 bar. Therefore the vent was closed for subsequent tests in order to obtain the maximum possible pressure.

The effect of closing the vent can be seen in the lower four plots in Fig. 3. After attaining the maximum, the pressure decreases to 35–40 bar and remains there for the duration of the data collection window. The maximum pressure for each gas chamber volume is shown in Fig. 4. The highest value of 142 bar was obtained with the minimum gas chamber volume, as expected. This value was still lower than the target of 200 bar. As shown in Fig. 4, the pressure and volume were related by

$$P = \frac{901}{V}, \tag{1}$$

where P is the pressure in bars, and V is the volume in cm^3.

In order to increase the pressure to the target value, the P 806 powder charge in the DM82 was increased from the standard value of 200 mg up to the maximum of 310 mg. The pressure waveforms are shown in Fig. 5. Initially, the vent screw was closed and the general shape of the waveform is the same as that in Fig. 3. The desired maximum pressure of 200 bars was attained with 1 washer in the gas chamber. However, a pressure of about 75 bars was present even long after the pressure had attained the peak value. In order to avoid this and since the gas chamber volume could be further reduced, it was decided to open the 1 mm diameter vent. With the vent open, the maximum pressure was 161 and 212 bar with one and no washers in the gas chamber, respectively. The pressure decreases rapidly with a time constant of about 15 ms after the maximum value has been attained. Note that the bottom two plots in Fig. 5 show two shots conducted with the same chamber conditions to show the excellent repeatability of the system.

The maximum pressure obtained for each volume with the vent either open or closed is shown in Fig. 6. The pressure and volume for the case when the vent closed are related by

$$P = \frac{1680}{V}, \tag{2}$$

where P is the pressure in bars and V is the volume in cm^3. The pressure is a factor of 1.86 higher than for the standard DM82. Note that the amount of powder has been increased by a factor of 1.55.

Due to the acceptable maximum pressure of 212 bars, the almost linear rate of voltage increase, and

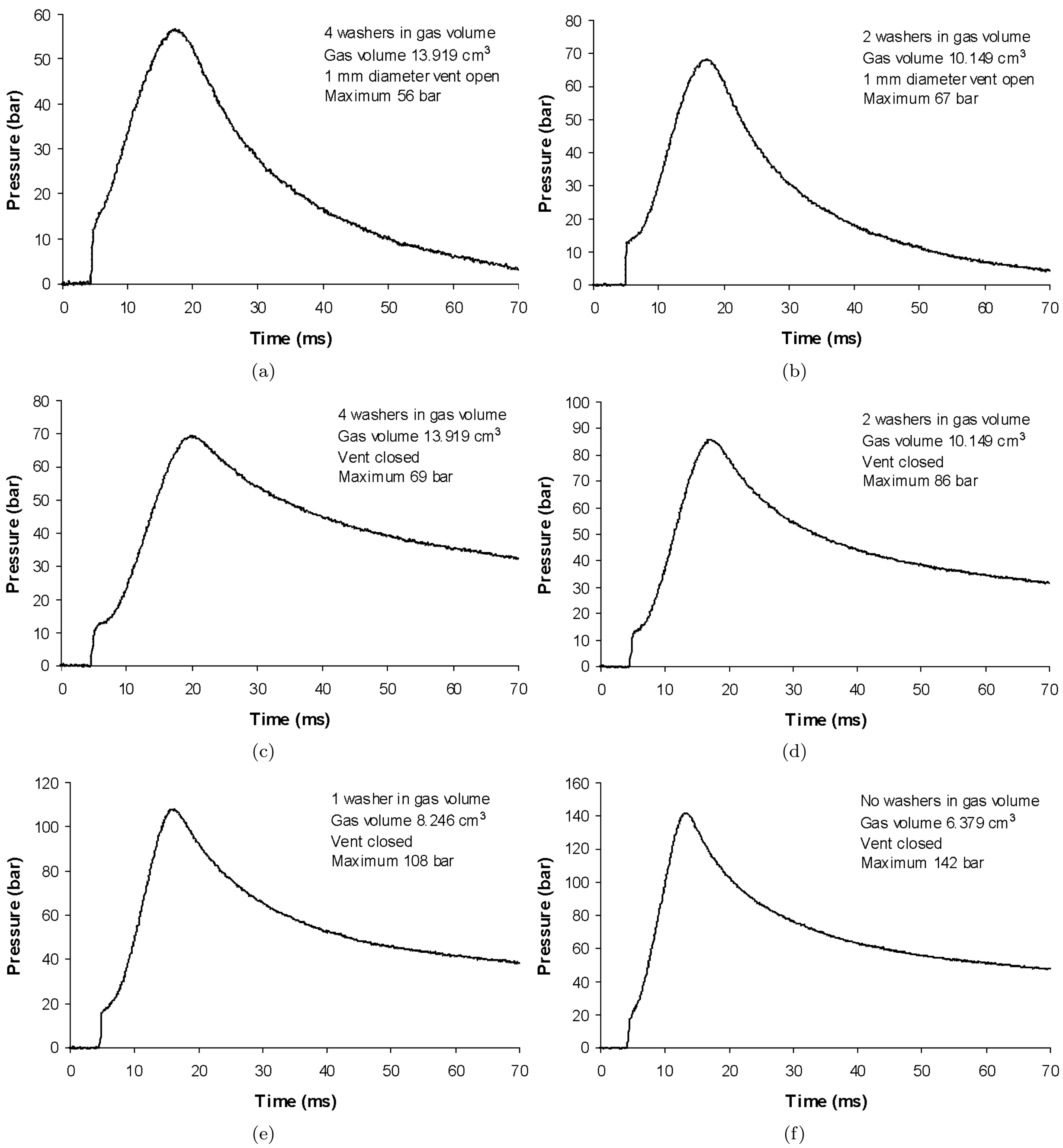


Fig. 3. DM82 pressure for various gas volumes.

the rapid fall time of the chamber pressure, the configuration with no washers in the chamber and a 310 mg powder charge in the DM82 was adopted as the standard configuration for further testing.

3. Single-Piezo Voltage Tests

To verify the voltage generation capability of a single PZT-5A piezo element, the test system shown in Fig. 7 was assembled. The complete housing was used, but with a steel rod used to fill the space available for the additional piezos. A single piezo element was installed at the opposite end of the HVG to the gas generator. The ball joint shown at one end of the piezo element is used to ensure that the piston force is applied uniformly over the end surfaces of the piezo. The plastic rings are used to ensure that the force is applied only in the axial direction without bowing of the steel rod and that the piezo is correctly located. Soft annealed copper discs were placed under the piezo to account for any tolerance in the surface flatness of the piezo or the other components.

Initial tests were conducted to find the maximum voltage that could be tolerated across the PZT-5A element. The piezo elements were cleaned with alcohol

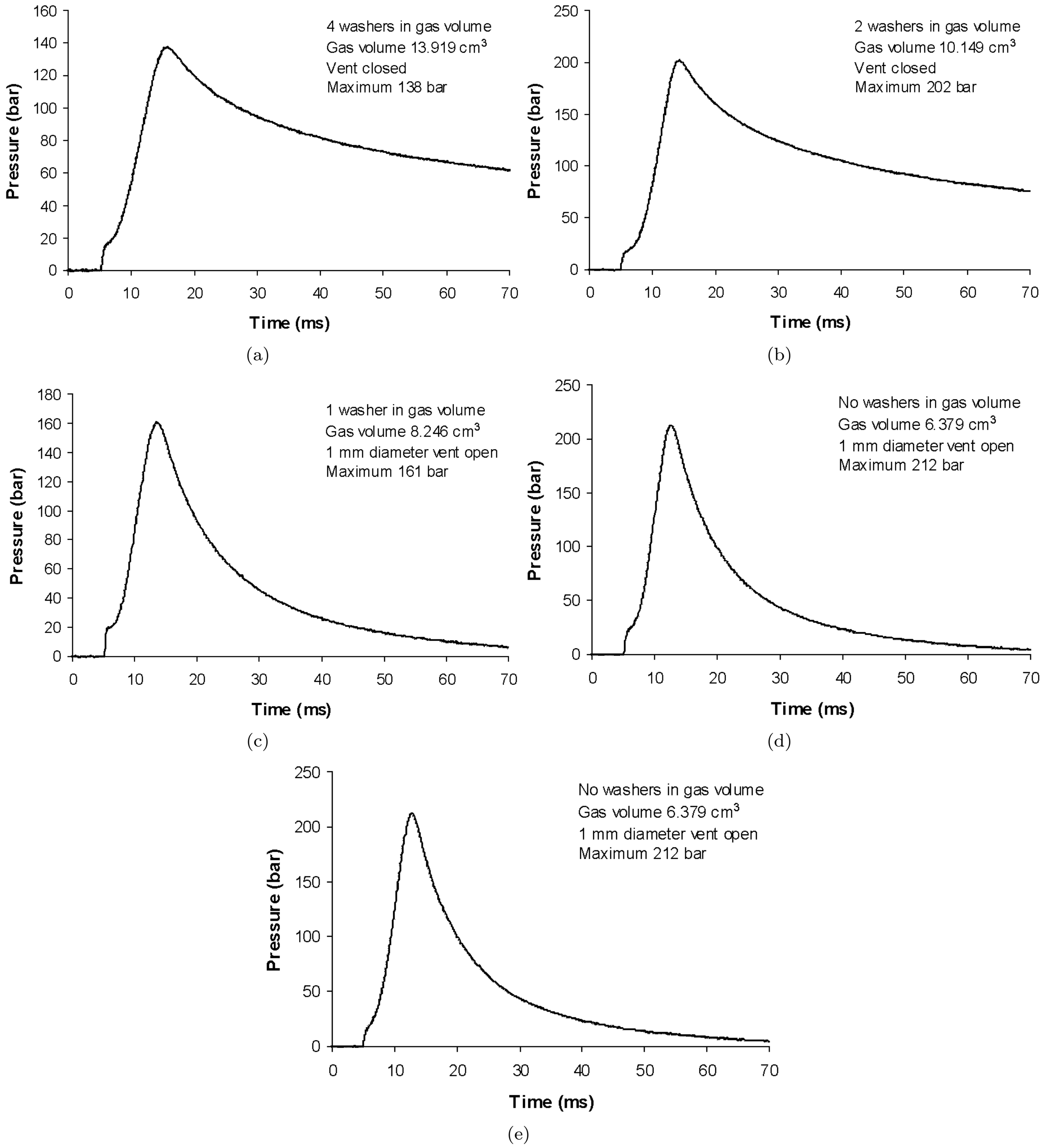


Fig. 5. Modified DM82 pressure for various gas volumes with vent open or closed.

before installation into the HVG. The open-circuit voltage produced across the metal ends of the HVG was measured using a Tektronix P6015A high-voltage probe connected to a TDS3032 300 MHz real-time oscilloscope. The results of three shots with this configuration are shown in Figure 8. Note that a new piezo was used on every shot and a gas pressure of approximately 10 bars was used to insulate the system. A P806 powder charge of 310 mg was used in the igniter for every shot. A maximum voltage of 60–75 kV was attained in each case. The voltage limit is clearly related to a "breakdown" process in the piezo element itself, as varying the gas pressure was found to have no effect on the voltage limit. Figure 9 shows the discharge track observed on the surface of the piezos following the breakdown effect.

Since the breakdown effect was obviously the limit on the achievable voltage, some effort was devoted to understanding the cause of the problem. In Fig. 8, it can be seen that at early times, there is a step in the pressure, and hence output voltage, which occurs when the thin metal foil covering the DM82 powder charge ruptures. Normally a 0.1 mm thick aluminum foil is used in the DM82. The results shown in Fig. 8

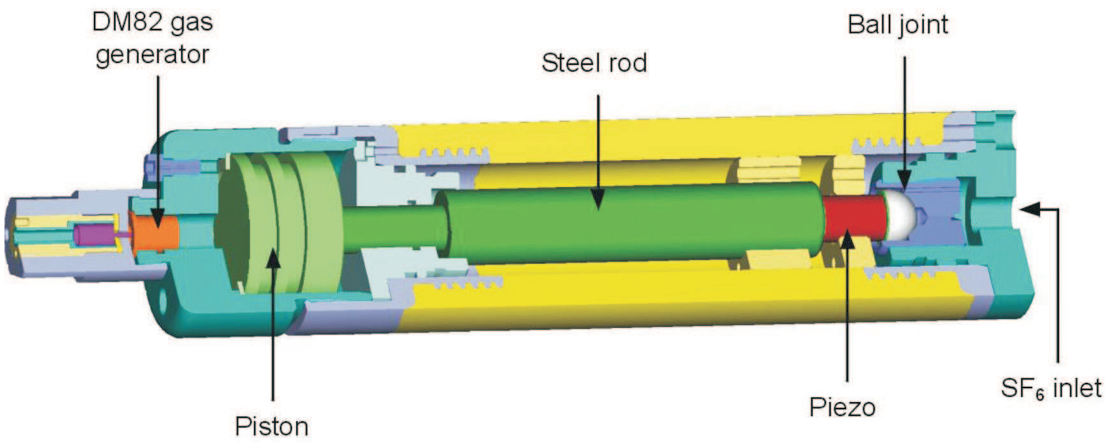
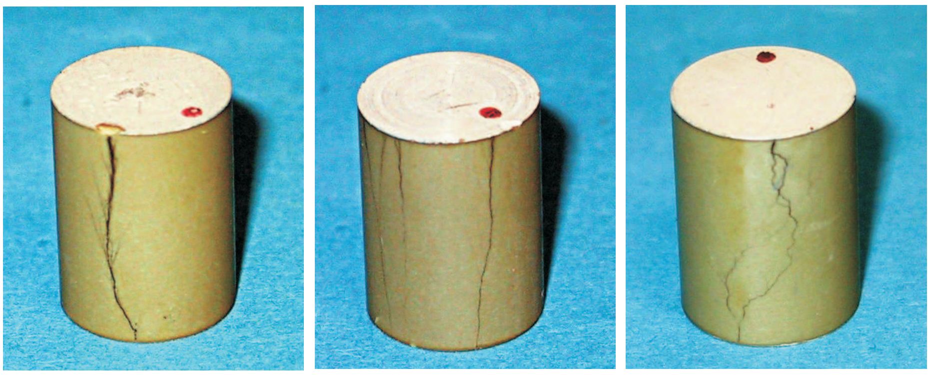


Fig. 7. Piezo HVG with single piezo element installed.



(a) (b) (c)

Fig. 9. Damage to piezos from breakdown effect.

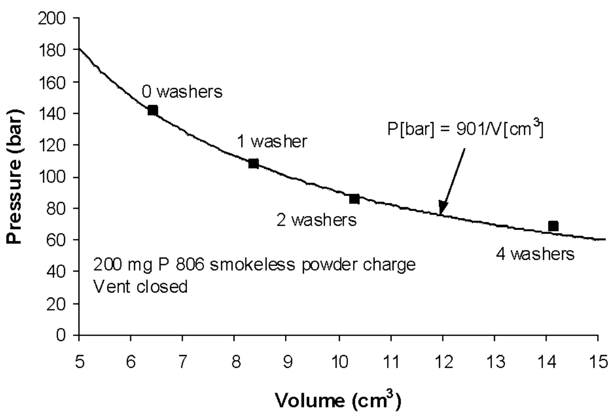


Fig. 4. DM82 maximum pressure versus gas volume with vent closed.

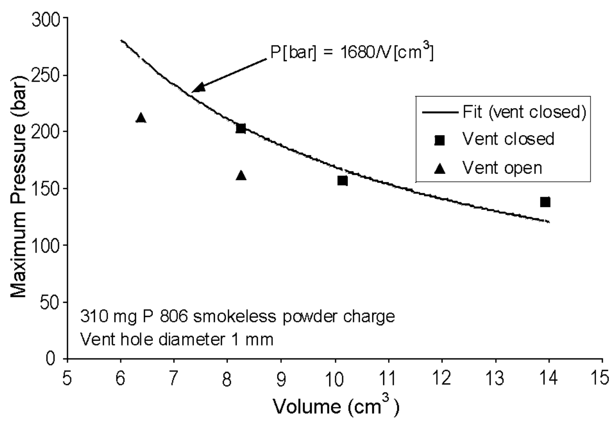


Fig. 6. Modified DM82 maximum pressure versus gas volume.

suggest that the worse this initial shock, the earlier the breakdown effect occurs, and therefore the lower the maximum voltage.

For the next test, an 80 pF capacitive load was connected across the piezo generator. If the breakdown effect observed with the open-circuit case was voltage-related, then a capacitive load should reduce the output voltage according to

$$V_{out} = \frac{C_0}{C_0 + C_L} V_{oc}, \quad (3)$$

where C_0 and C_L are the piezo and load capacitances and V_{oc} and V_{out} are the open-circuit and output voltages, respectively. Because the voltage is lower,

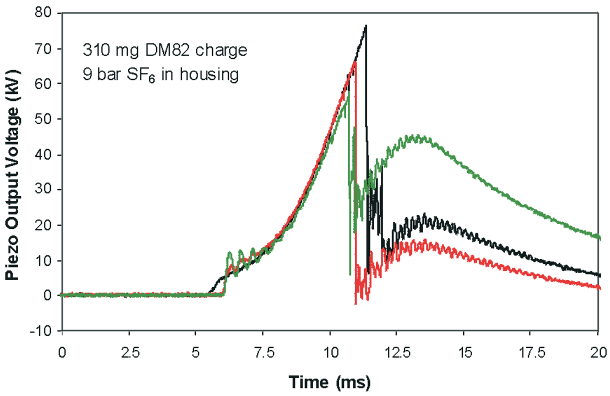


Fig. 8. Output voltage for single piezo element for three shots.

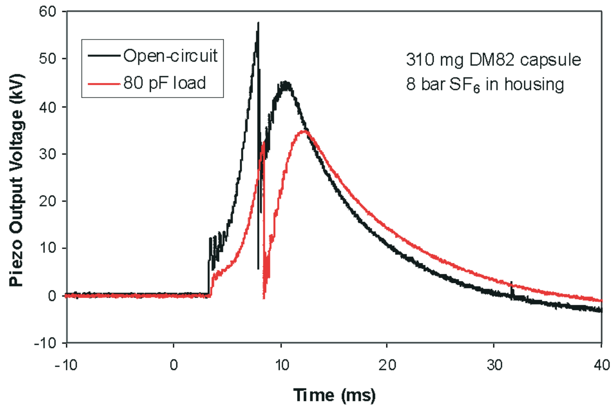


Fig. 10. Output voltages for single a piezo element with capacitive load.

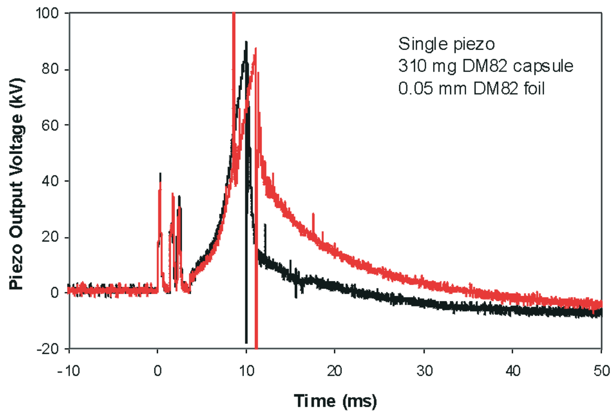


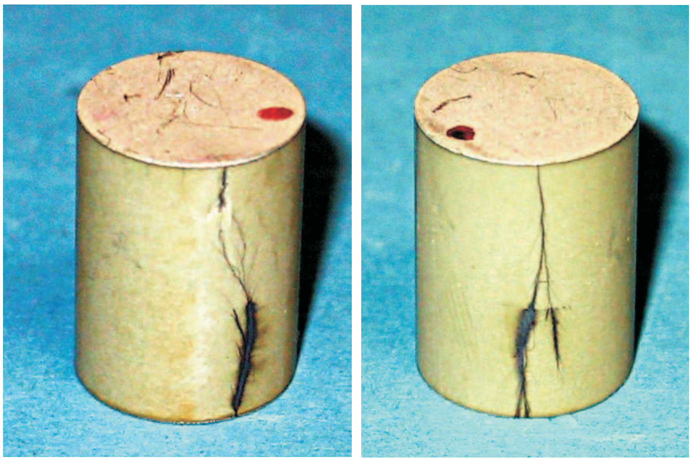
Fig. 11. Output voltage for single piezo element with 0.05 mm foil in the DM82.

the breakdown level could be avoided. On the other hand, if as suspected, the breakdown was related to mechanical stressing, then the effect would be observed at the same time regardless of the voltage. As seen in Fig. 10, this second case is exactly what was observed. The voltage was reduced according to Eq. (3), but the breakdown effect occurred at the same time. This means it is clearly related to mechanical stressing of the piezo. Presumably, the piezo should be squeezed slowly relative to the electro-mechanical resonance. This resonant frequency separates the quasi-static and dynamic timescales for the piezo. Shocking the piezo may result in the stress not being uniformly distributed along the length of the piezo, producing localized overstressing and electrical breakdown long before the maximum static stress of about 100 kN is attained. Note that the quoted electromechanical resonant frequency of a single piezo is 67 kHz, which suggests that the 5 ms stressing period is definitely longer than the resonant period of 15 μs and that the piezo was quasi-statically stressed as intended. However, this frequency only applies in the low stress and voltage regime. The resonant frequency inferred from the oscillations visible in Fig. 8 and Fig. 10 is a few kHz. Therefore, it appears that the resonant frequency in the high stress and voltage regime is significantly lower and that it is necessary to stress the piezo over a longer time period than was originally expected.

The next test was performed with modified DM 82 cartridges, which used a 0.05 mm aluminum foil rather than the usual 0.1 mm foil. Two shots were performed using the new cartridges with the piezo generator open-circuited. The results from these shots are shown in Fig. 11. A maximum voltage of over 85 kV was obtained for both shots. This provided clear evidence that the initial pressure step was responsible for the voltage limit. Note that the 3 initial spikes seen before the voltage increases in Fig. 11 were stray pick-up from the ignition system. For these measurements, a resistive probe was used rather than the Tektronix P6015A probe, due to the higher voltages expected. This probe was accurate at lower frequencies, but susceptible to high-frequency pick-up.

Figure 12 shows the breakdown track across the surface of the piezos after the two shots corresponding to Figure 11. It appears as though the initial overstressing occurred over the lower half of the piezos. Flashover in this region then led to total breakdown over the entire length of the piezo. This is consistent with the hypothesis that the piezo was not stressed uniformly over the entire length.

To further reduce the initial pressure step, DM82 cartridges were prepared with a 0.04 mm polyethylene (PE) foil over the exit aperture. This is the weakest material that was available. The results from this test for a single piezo are shown below in Fig. 13. The maximum voltage obtained was about 80 kV, which is similar to that for the 0.05 mm aluminum foil. It was concluded that no further improvement was obtainable from reducing the foil thickness. Figure 13 shows that the initial pressure step has been eliminated, and so the PE foil was adopted as the standard from this point on. Note that the large spike observed when the breakdown effect occurred is due



(a) (b)

Fig. 12. Damage to piezos from breakdown effect with 0.05 mm foil in the DM82.

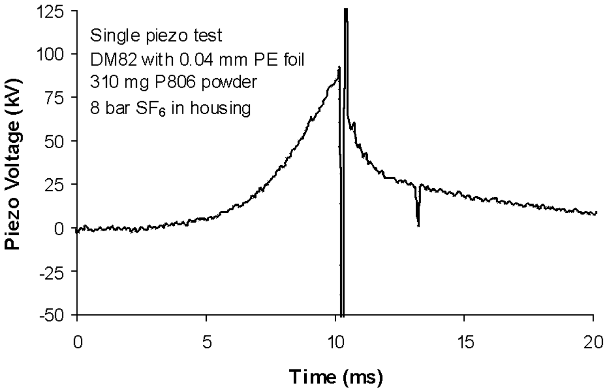


Fig. 13. Output voltage for single piezo element with 0.04 mm PE foil in DM82.

to the probe sensitivity to high-frequency interference and is not genuine voltage.

The next step in the optimization process was to reduce the burn rate of the powder to slow the rate of stressing as discussed previously. This was expected to produce more uniform compression over the length of the piezo. The results obtained with two different types of powder, R903 and the even slower K525, are shown in Fig. 14, along with results from the much faster-burning P806 powder tried initially. The vent in the gas chamber was open and no additional washers were used, so the volume of the chamber was 6.4 cm^3. The measured voltage with one piezo is shown for each case. Various weights of powder were used as indicated in the plots. Voltages in excess of 100 kV were now obtainable without the undesired breakdown effect with K525 powder. Note that the plots on the left are directly measured from the resistive voltage probe. The plots on the right have been corrected for probe droop, since the 700 MΩ probe loads the piezo output slightly. Equation (26) in [1] has been applied using a piezo capacitance of 130 pF. Note that this correction can only be used up until breakdown occurs. The maximum voltage of 130 kV was obtained with 390 mg of K525 powder, at which point an internal breakdown inside the generator probably occurred. There was no visible breakdown track on the piezo, so it is unlikely to be the piezo breakdown effect discussed previously. In any case, it was apparent that maximum voltage had been almost attained before the breakdown occurred.

The maximum pressure attained inside the generator was measured for each of the powder charges used in the single piezo tests. These values are shown in Table 1. The time-dependence of the pressure was as measured previously with P806 powder and as shown in Fig. 5. Note that the maximum pressure of 258 bars for 390 mg of K525 powder corresponds to 52 kN of force, or over 5 tons. Comparing the results in Fig. 14 with the pressures listed in Table 1, the maximum voltage for a single piezo is proportional to the maximum pressure. To a reasonable approximation

$$V_{\max} = 0.55 p_{\max}. \qquad (4)$$

This is consistent with Eq. (26) in [1] given a piston diameter of 50 mm. Therefore it was concluded that the voltage obtained is consistent with the simple theory presented previously.

Figure shows the results of pressure tests conducted with the new propellants R903 and K525 under conditions corresponding to the voltage measurements in Fig. 14. The rate of pressure increase with these propellants is at least 2–3 times slower than for P806. The shape of the voltage waveforms shown in Figure 5, after correction for the voltage probe response, is clearly similar to the pressure waveforms shown in Fig. 14, as expected. Note that the pressure measurements shown in Fig. 15 correspond to no additional spacer washers in the hot gas chamber and with the vent closed, as for Fig. 14.

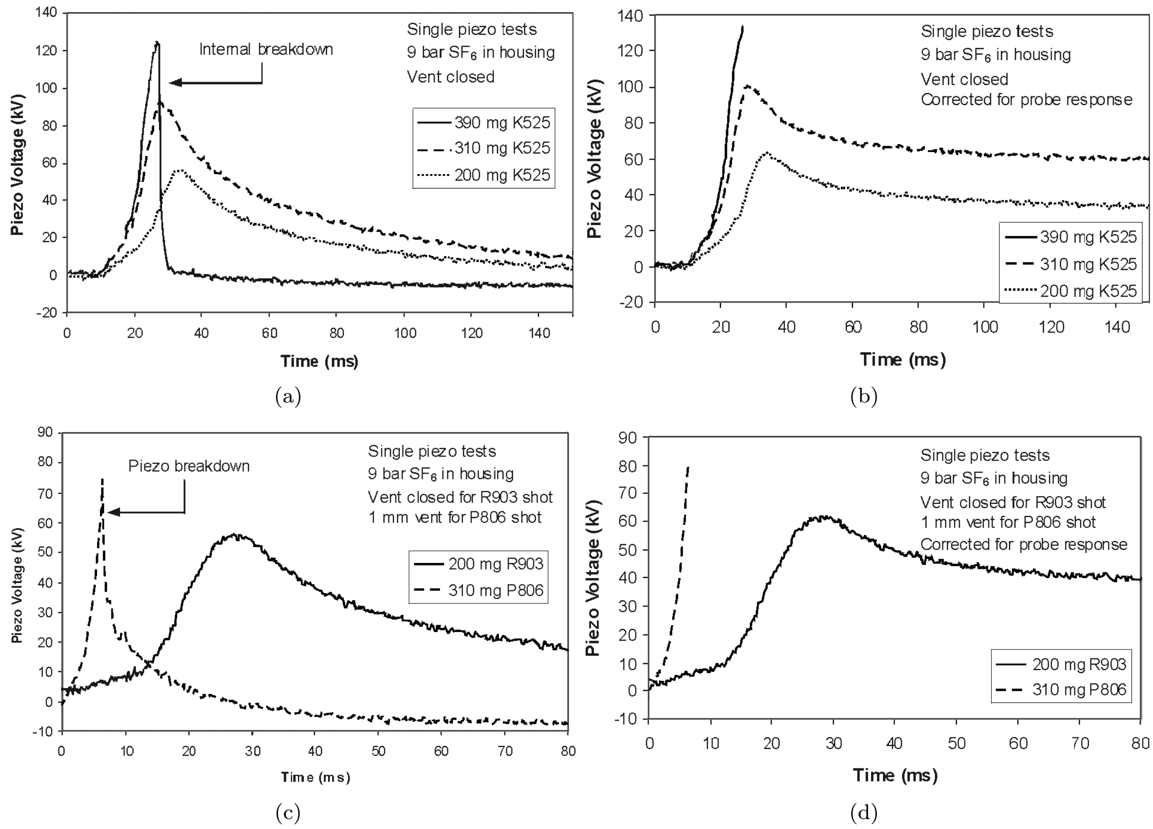


Fig. 14. Output voltage for single piezo element with various powder charges.

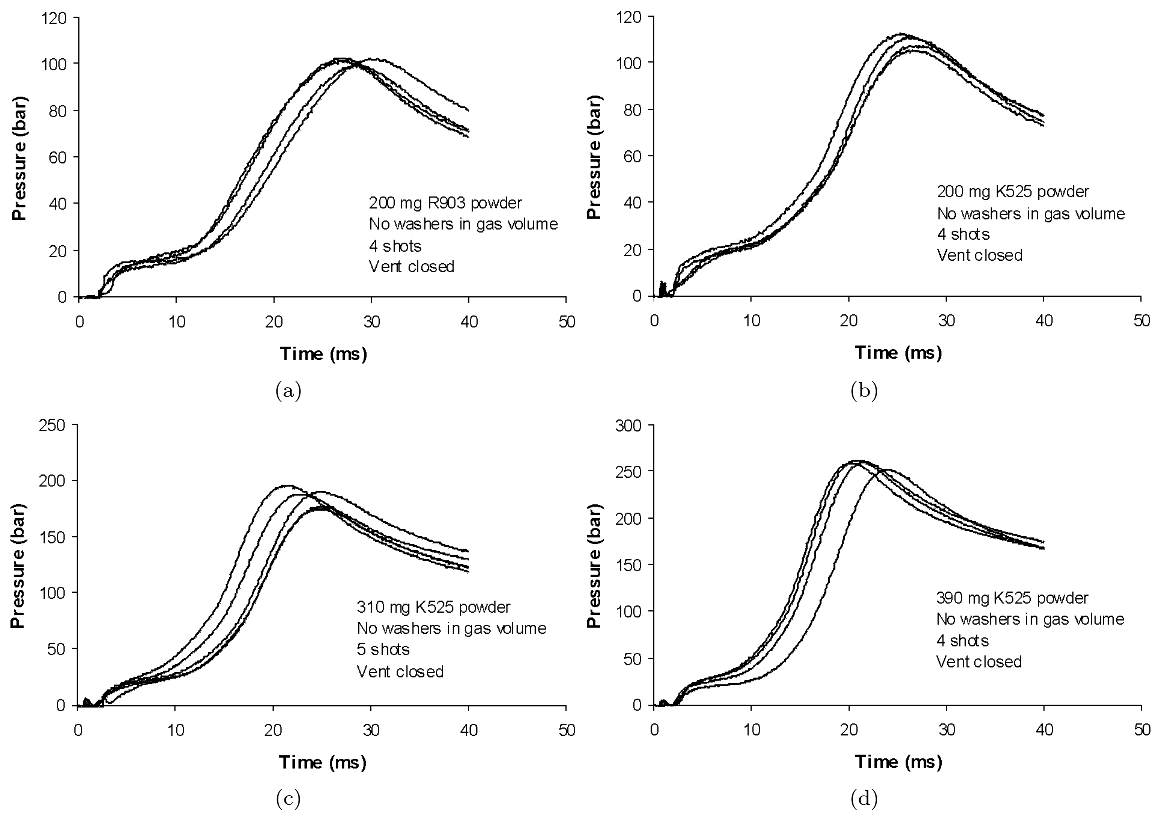


Fig. 15. Pressure test results for R903 and K525 propellant powder.

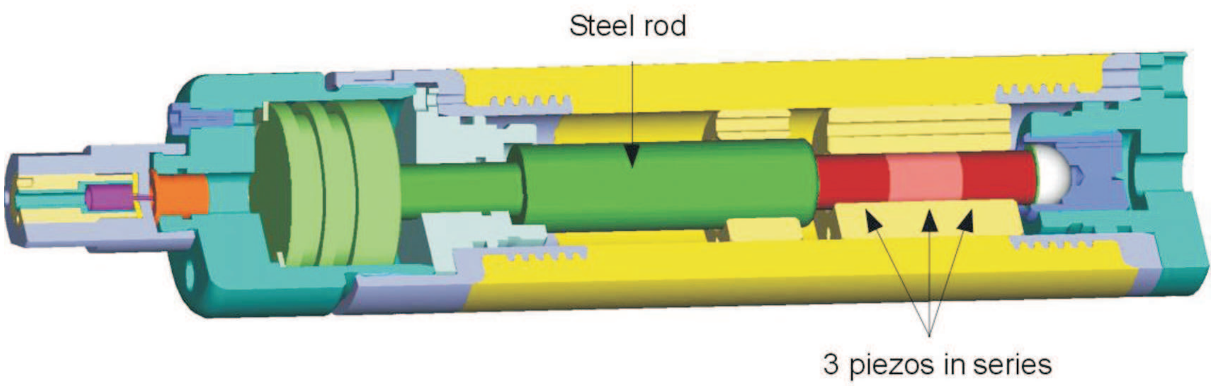


Fig. 16. Piezo HVG with 3 series piezo elements installed.

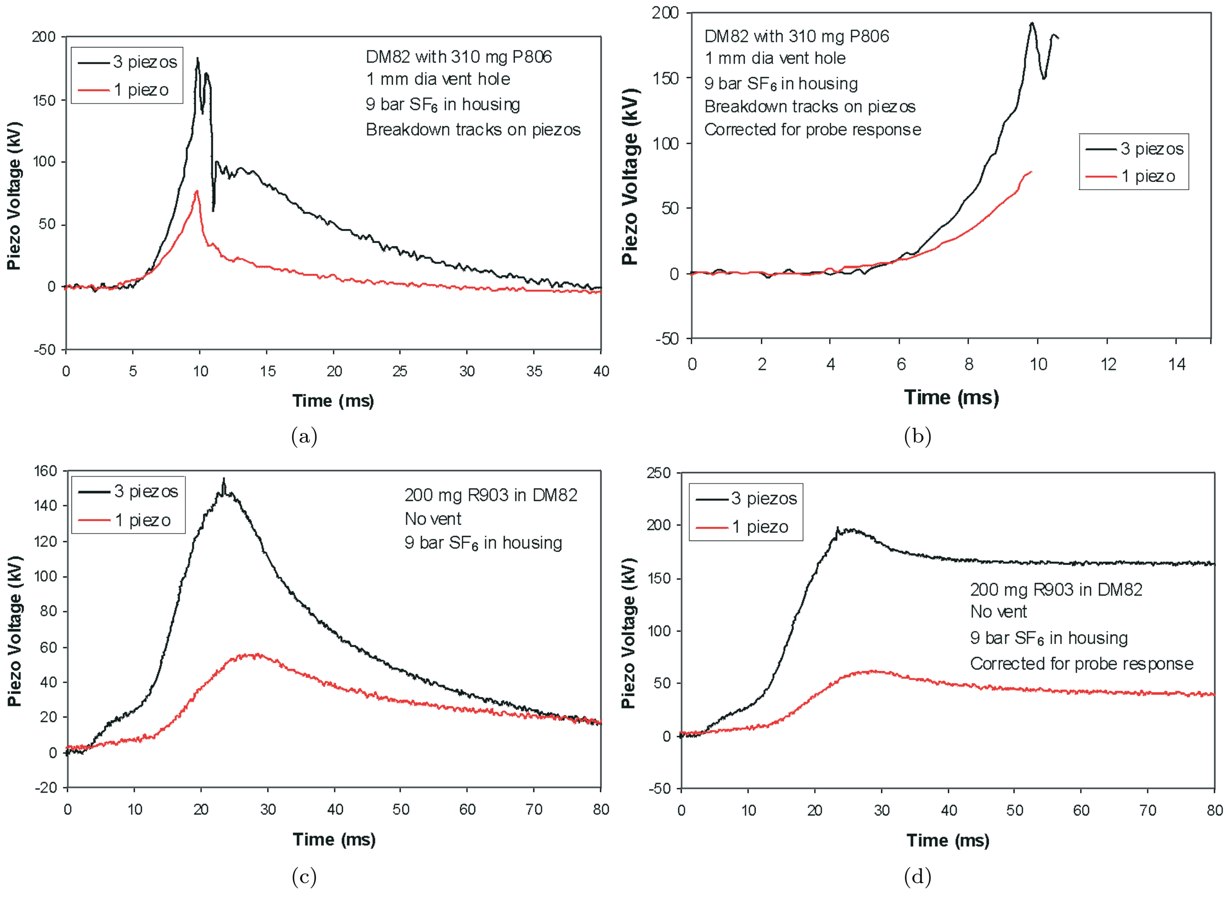


Fig. 17. Output voltage with three piezo elements for P806 and R903 powder.

4. Three-Piezo Voltage Tests

The next step was to demonstrate that higher voltages could be attained through simple series cascading of piezo elements. This is an advantage of the quasi-static stressing approach. If the piezos are shocked, reflections from interfaces between the piezo elements considerably complicate the situation. The test configuration for the generator is shown in Fig. 16. This configuration represents half of the system shown in Fig. 1. In Fig. 1, two groups of up to three piezos in series can be used. The polarization of each group is opposite, so that the total voltage across the generator only appears when the spark gaps in the antenna fire and is zero during the long charging time. This is essential to avoid breakdown along the exterior of the generator. For the tests discussed in this section, it is necessary to measure the voltage during piezo compression. Therefore the generator was placed in a bucket containing transformer oil to prevent breakdown during the measurement. This exterior insulation is only necessary for test purposes. The

Table 1. Maximum pressure for various DM82 powder charges

Powder	Weight (mg)	Pressure (bar)
R903	200	101
R903	310	181
K525	200	109
K525	310	185
K525	390	258

complete piezo generator concept has been explicitly designed to avoid the requirement for any exterior insulation.

Figure 17 shows the output voltage obtained from the generator for various DM82 powder charges. Both the three-piezo and single piezo voltages are shown to show that the voltage obtained with three piezos is indeed three times the voltage obtained from one piezo. As for Figure 4, the plots on the left were measured directly from the resistive voltage probe. Since the total capacitance of the three piezos in series is about 42 pF, the loading of the generator output by the probe is more noticeable. Note that the very slow decrease in voltage is consistent with the fact that the vent in the hot gas chamber was closed so as to maximize the pressure given the slower burn rate of the propellant powder.

The maximum voltage measured with three piezos was 240 kV using 310 mg of K525 powder (Fig. 18). Note that this was limited by external breakdown in the voltage probe and is not the maximum voltage attainable in the generator. Since the voltage obtained with three piezos is clearly three times the voltage from a single piezo, it can be reliably inferred that the maximum voltage that would have been obtained with three piezos and 390 mg of K525 powder would have been about 390 kV. Since further modification of the test setup was not convenient in the pyrotechnic test chamber available at DIEHL and since the original voltage target was stated to be 100–300 kV, it was decided to stop the testing at this point. It was concluded at this point that the principle of the piezo high-voltage generator had been proven.

A final point for demonstration was that the generator could be used to charge a capacitive load such as an antenna. The capacitance of three piezos in series should be about 42 pF. At a voltage of 390 kV, this corresponds to a maximum energy of about 3 J. To confirm this, a short length of high-voltage coaxial cable was connected across the output of the generator. The capacitance of the open-circuit cable was 80 pF. Figure 19 shows the voltage measured across the output of the generator both with the cable and open-circuit (no load). The maximum voltage with the capacitive load was about 80 kV. Breakdown occurred at close to this value, probably across the end of the coaxial cable, however it was clear that the maximum voltage was almost attained at this point.

With no load, the measured output voltage was about 200 kV. Ideally, Eq. (3) predicts that the open-circuit voltage should be about three times the voltage with an 80 pF load. The measured result agrees reasonably well with this prediction, with the voltage for the capacitive load being slightly higher than the expected value of 66 kV. This discrepancy could be accounted for by variations in the pressure from shot to shot as indicated in Figure 5. This test showed that the piezo generator was producing both voltage and significant energy, with about 250 mJ stored in the coaxial cable. Note that for the source concept shown in Figure 1, it is anticipated that the antenna capacitance will be less than 5 pF, so the charging voltage will be close to the open-circuit voltage as presented previously.

5. Conclusions

The results presented in this paper show that a compact high-voltage generator (HVG) based on piezo compression are feasible for generating voltage and energy output consistent with realistic loads. The tests described in this paper have shown that simple quasi-static compression of the piezo elements is adequate to charge a low-capacitance load such as a high-power wideband antenna to a voltage of about 400 kV. The charging voltage can be increased by cascading more piezos in series. Alternatively, to increase the energy in the generator for a given voltage, more piezos could be cascaded in parallel. This effectively increases the capacitance of the generator and the amount of charge generated.

One of the results from this study was to show that a small fibreglass housing can withstand the large force required for quasi-static piezo compression. Over 50 kN was repeatedly applied to the housing used for the tests described in this paper. In principle, even larger forces can be considered with such housings, especially if the diameter of the sources increases.

The main limitation on the achievable output voltage from a compact piezo generator will be electrical breakdown inside or outside the generator, rather than a limitation of the piezos themselves. For this reason, more complicated schemes such as shock depolarization or dynamic compression of the piezo elements are not warranted. In principle, a voltage as high as 1 MV could be attained in a reasonably compact system and energy as high as 100 J could be attained by cascading up to 100 piezos in series and parallel. The volume of the high voltage generator itself would be about 100 mm in diameter

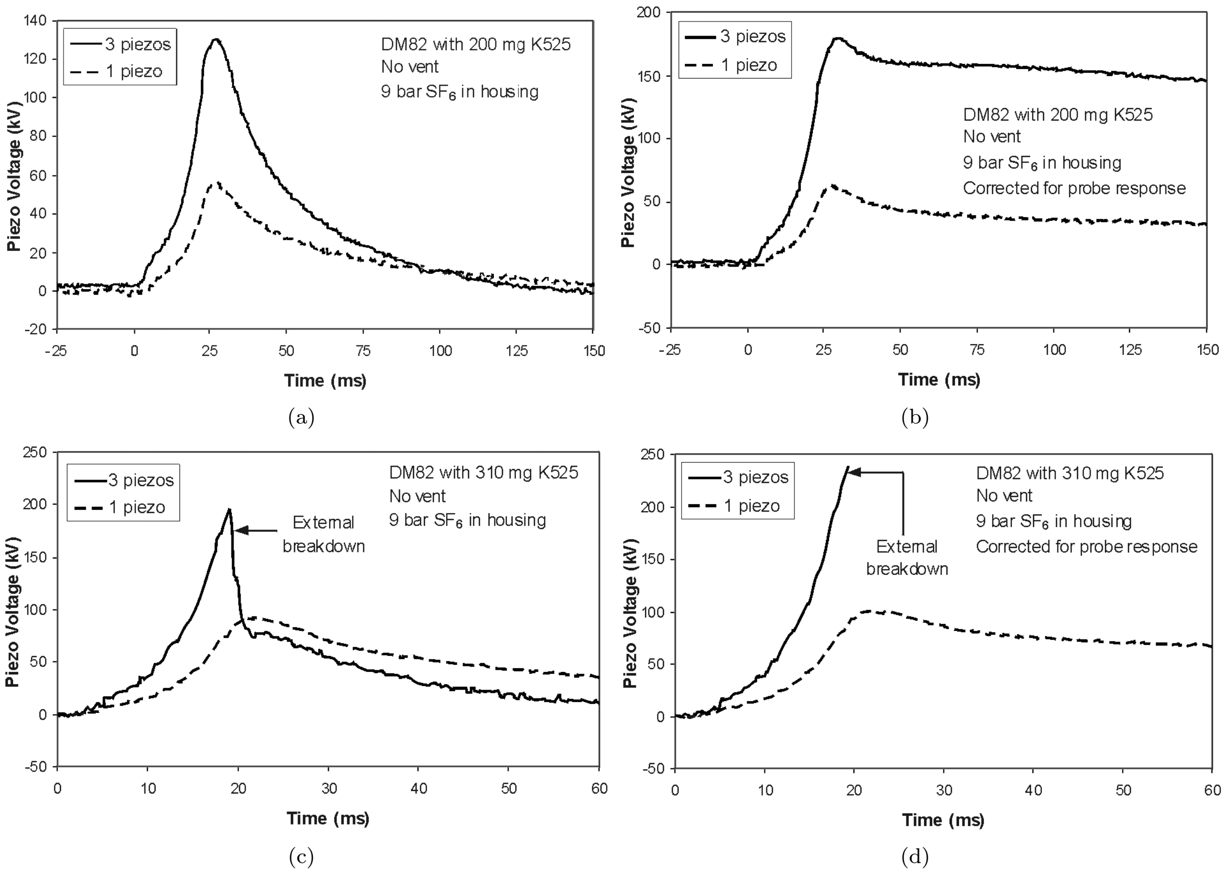


Fig. 18. Output voltage with three piezo elements for K525 powder.

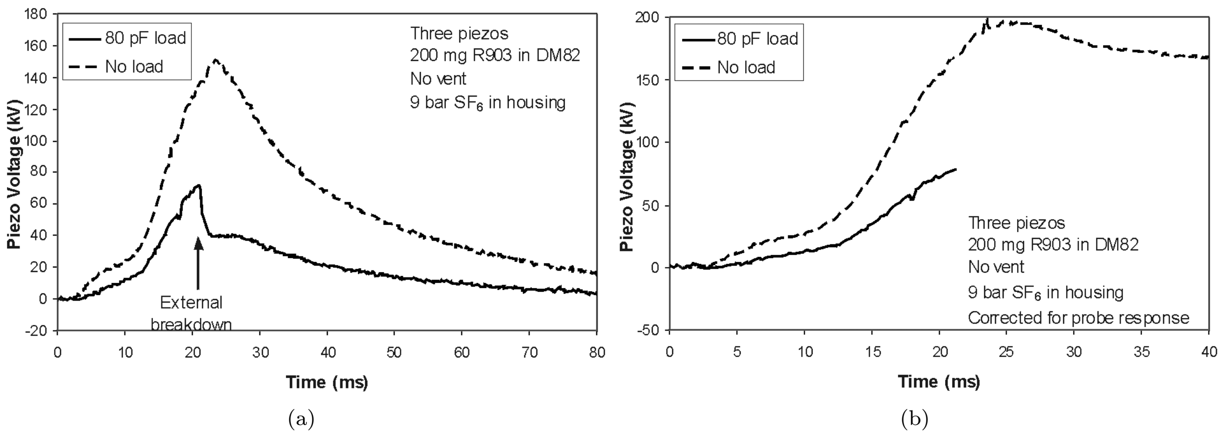


Fig. 19. Output voltage with three piezo elements with capacitive load.

and 250 mm long to achieve these specifications. Even higher energy could be attained in a larger system, but the number of piezos may become impracticably high. The piezo generator would then be used to charge a high-energy antenna which in turn produces a RF pulse. Alternatively, there may be sufficient energy to drive a microwave source. Such a piezo generator could also be used as a general purpose single-shot charging system for general pulsed power applications. The advantages of this type of system are its compact size, direct high-voltage output and virtually unlimited maintenance-free storage time.

A concept has been prepared in which a piezo-based HVG is integrated with a pulse-charged dipole antenna. A fast spark gap switch discharges the antenna and generates a wide-band high-power RF pulse. An antenna charging voltage of 400 kV has been shown to be achievable. This system is designed to ensure that the voltage across the exterior of the housing during the relatively slow piezo stressing time is zero. This avoids the possibility of breakdown, especially in the typically dirty environments often encountered in practical scenarios. The voltage only appears across the source when the antenna element is pulse charged from the piezos. Future development can be directed at developing and proving a prototype RF source based on this design concept.

A further possibility for future development is to miniaturize this source concept. The existing prototype is 65 mm in diameter and 275 mm long. The length of the system cannot be reduced significantly due to breakdown constraints when the antenna switches fire. However, there is considerable scope to reduce the diameter of the generator. The 15 mm diameter piezos used for the tests discussed in this paper were chosen in order to be conservative regarding the amount of energy which could be lost to charge leakage during piezo compression. This proved not to be a problem during testing. If the antenna has a capacitance of less than 5 pF, then it may be possible to reduce the diameter of the piezos by as much as 50 %. This would mean that the required compression force would be reduced to only 25 % of the force used in the present tests. The reduced force requirement would lead to a reduction in the required strength of the fibreglass housing, which currently has to hold approximately 5 tons. A total system diameter of as low as 25 mm may be achievable in such an optimised system, with a length of possibly 200 mm.

The tests described in this paper clearly show the feasibility of developing a non-explosive piezo generator with moderate energy and very high voltage output capability. The generator is small, autonomous, and safe. A piezo system of this type is also much more cost effective to develop than an explosive system since only the piezo and gas generator cartridge need to be replaced after every shot, rather than the complete generator. The use of even the 200–500 g of explosive required for small flux compression generators (FCGs) may be undesirable. In addition, FCGs require an initial current source, inductive storage, and an opening switch to produce high voltage. A piezo system based on the principle discussed in this report requires no explosive and no initial energy supply and produces high-voltage directly. While the energy of a practical piezo system may be limited to 100 J, these advantages could be very useful for potential compact pulsed power applications.

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