Electrical Weapon Charge Delivery with Arcing

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Introduction: Human electronic control with the Conducted Electrical Weapon (CEW) has gained widespread acceptance as the preferred law enforcement force option technology due to its dramatic injury and fatal shooting reduction. However, with bulky or baggy clothing, a CEW probe may fail to make direct skin contact and thus arcing is critical to complete the circuit. The goal of the study was to evaluate the ability of modern CEWs to deliver their pulse charges across typical required arcing distances.

Methods: Popular TASER® CEW models X26E (open-loop output), and the X2 and X26P (with closed-loop outputs) were activated using a cartridge connected to a custom polymer air-gap fixture. For each model 5 units were tested. The raw and normalized charge delivery were evaluated according to ANSI-CPLSO-17.

Results: All 5 units of each model satisfied ANSI-CPLSO-17 even at maximum arcing length. The X26P CEW had the greatest arcing gap capability.

Conclusions: The stabilized closed-loop charge output feedback of modern electrical weapons (X2 and X26P CEWs) provides a significantly improved output consistency under arcing conditions. With arc lengths of 10-20 mm per probe, the X2 CEW normalized output charge exceeds that of some units of the older higher output X26E CEW model.

Key Words: ANSI, CEW, charge, ECD, electrical weapon, TASER

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INTRODUCTION

Human electronic control with the Conducted Electrical Weapon (CEW) has gained widespread acceptance as the preferred law enforcement force option technology due to its dramatic injury and fatal shooting reduction. Large prospective studies have consistently found subject injury rate reductions of about 65%.[1] Of the 310,000 annual CEW field uses, only 1 in 3500 is temporal to an Arrest-Related Death (ARD) vs. the baseline force-involved ARD rate of 1:1000 (or 1:71000 law enforcement officer (LEO)-civilian encounters). This reduction in temporal-fatality rate is consistent with prospective published data, which showed that 5.4% of CEW uses "clearly prevented the use of lethal force by police."[2] It is also consistent with a 2/3 reduction in fatal police shootings where CEW usage is not overly restricted.[3] Brandishing, including drawing, pointing, LASER painting, and arcing (without probe deployment or direct contact) comprises about 71% of CEW-involved force incidents; with subject compliance increasing to 81% with special officer training.[4]

The short-duration electrical pulses applied by Axon Enterprise, Inc. (Axon), formerly TASER International, Inc. (TASER), CEWs are intended to stimulate Type A-α motor neurons, which are the nerves that control skeletal muscle contraction, but with minimal risk of stimulating cardiac muscle. This typically leads to a loss of regional muscle control and can result in a fall to the ground to end a potentially violent confrontation or suicide attempt.[5, 6] The present Axon CEWs meet all relevant electrical safety standards.[7]

Axon's CEW cartridges deploy probes using inert compressed gas. The top probe deploys straight to the target, while the bottom probe deploys at a 7 or 8° downward angle. This deployment method provides increased spread between the probes as the distance between the CEW and the target increases. With 2 probes with increasing spread over distance, the risk of a direct connection failure (with skin on both probes) increases. Additionally, with bulky or baggy clothing, a CEW probe may fail to make direct skin contact and thus arcing is critical to complete the circuit.[8, 9] The purpose of the Axon CEW high voltage (arcing) phase is to mitigate or reduce the risk of a "clothing disconnect" or failed electrical connection with the skin by allowing arcing to complete the circuit.

The goal of the study was to evaluate the ability of modern CEWs to deliver their pulse charges across typical required arcing distances. The charge delivery was evaluated according to ANSI (American National Standards Institute)-CPLSO-17.[10] This standard requires that a minimum charge of 40 μC (microcoulombs) be delivered. The charge is also normalized to a standard 100 μs duration to correct for shorter pulses being more efficient at stimulation than longer pulses.[11] The ANSI standard requires a minimum normalized charge of 60 μC.

A typical CEW pulse is shown in Figure 1. By convention, the "main" phase is defined as being positive. The initial brief negative phase serves to establish an initial arc in case of a connection gap. The creation of the arc allows the lower-voltage main phase to flow through the circuit. The duration of the pulse is defined as the time from the 1st downward transition below –100 mA (-60 V with the 600 Ω load) up until the last downward transition below a value of +100 mA (60 V) according to the ANSI standard. The raw charge is the integrated value throughout the duration of the pulse. Note that the raw charge is always less than that of the main phase since the arc phase contributes a *negative* charge, thus cancelling some of the main phase charge.

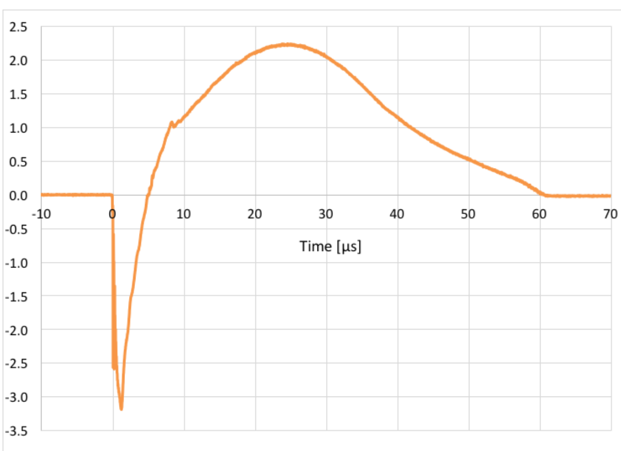

Figure 1. Typical X2 CEW pulse with current in amperes.

The most common CEW is the single-shot X26E model introduced in 2003 as the X26 and discontinued in 2014. It is now referred to as the X26E to distinguish from the present X26P model. It operates open loop and thus has more output variability than newer generation CEW models. It also has a much longer — and hence less efficient — waveform. For these reasons, its typical raw charge is about 35 μC greater than the newer models. Note: the manufacturer initially rated the X26E CEW charge using the main-phase charge and this artificially provided another 10 μC of apparent difference.[8] The newer single-shot X26P "Smart" CEW (introduced in January 2013) has a feedback loop allowing a feature referred to as "charge metering" to stabilize the output. The X2 "Smart" CEW (introduced in April 2011) is a 2-shot CEW, also with a feedback loop to stabilize the output charge. The X26P and X2 CEW have high voltage modules designed with the same pulse and feedback technology. However, due to differences in the physical design of the cartridge bays and cartridges themselves, they exhibit different circuit interactions and charge delivery when delivering charge into different size arc gaps.

METHODS

The TASER brand models X26E, X26P, and X2 CEWs were the subject of this study. Five samples of each model, spanning a serial number range to represent a manufacturing interval greater than 4 years were selected for the test. The non-inductive 600 Ω resistive load used was the Ohmite® LN100J600 resistor.[12] A Tektronix® DPO3034 oscilloscope was used with a Tektronix TCP-202A current probe. The oscilloscope was set to acquire data sampling at a rate of 500 megasamples/second, averaging the last 8 samples (of the 5-second delivery) to reduce the influence of high voltage noise on the measurement equipment.

To maintain the natural air gaps of the CEW systems, the CEWs were activated using a previously deployed cartridge connected to a custom air-gap fixture. The air-gap fixture was machined from polyvinyl chloride and is shown in Figure 2. The air-gap fixture allows the cartridge probes to be "zeroed" out and secured in place. The air gap can then be manually adjusted in or out while arcing by the turn of a non-conductive Lexan® knob.

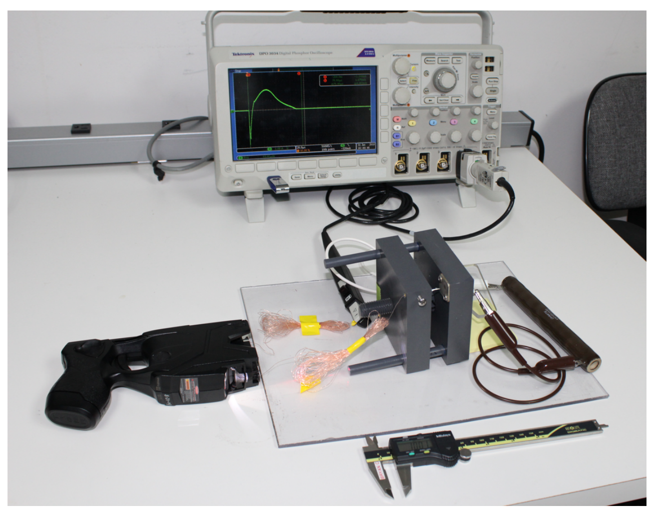

Figure 2. Test setup with X2 CEW.

The wires of the deployed cartridges were wrapped up and separated to minimize any capacitive coupling effect on the arcing distance results, and to minimize the risk of erroneously discharging into anything other than the load-gap fixture. Two details were noted during the setup calibration; (1) the portion of the wire placed in the current probe must have an additional layer of insulation, otherwise there could be a discharge through the thin wire insulation into the current probe when the arc distance is reaching its maximum, and (2) the arc fixture needs to be elevated above any work surface to prevent the arc from "riding" the along the surface, resulting in longer than expected arc distances. A small length of electrical tape was wrapped around the cartridge wire where the current probe was clamped to prevent arcing through the thin wire insulation to the probe. The gap fixture, resistive load, and cartridge wires were insulated from the conductive electrostatic discharge work surface by placing them on top of a 6 mm thick sheet of plastic. The gap fixture was further elevated by a 6 mm stack of dry paper between it and the plastic sheet. The cartridge probes were inserted into the gap fixture with the probes pressed against the electrode plates and tightened down to prevent movement. The fixture's gap was adjusted by manually turning the knob to move the probes closer or further from the fixture's electrode plates. Mitutoyo® CD-6" CSX digital calipers were used to validate the correct arcing distance for each test gap.

For all the "zero" gap, or contact activations, the 600 Ω load was connected directly to the cartridge probes to collect baseline values. For all the gapped tests, the load was connected to the arc-gap fixture's coated copper landing plates. After acquiring the contact data, the arc testing began with both the top and bottom probes arcing. The arc fixture was set for a 2.5 mm gap (5.0 mm cumulative), the oscilloscope set to trigger on the current pulse, the CEW was armed, and then triggered. A typical arc is shown in Figure 3.

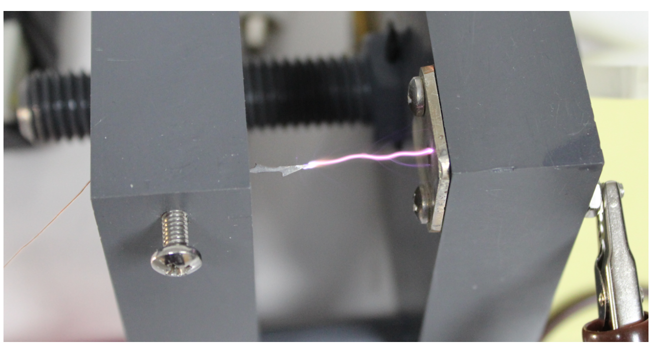

Figure 3. Typical arc.

After the data were saved, the arc fixture's gaps were increased to 5.0 mm (10 mm cumulative), oscilloscope set to trigger, CEW armed, and then triggered. This was repeated in 5 mm increments until there was no arc connection when the CEW was triggered. The fixture gap was then slowly reduced and adjusted while constantly activating the CEW until a consistent discharge could be achieved at the maximum distance. The same process was repeated for the top probe arcing, with the bottom probe directly connected to the load, in 5 mm increments, and again for the bottom probe arcing with the top probe directly connected to the load, also in 5 mm increments.

The effectiveness normalized charge (QNE) was calculated according to the ANSI standard formula to normalize to a standard 100 µs (microsecond) duration:

$$Q_n = Q_r \frac{100 + 140}{duration + 140}$$

This normalization is based on the chronaxie of 140 µs for motor-neuron stimulation.[13-15] This normalization is illustrated in Figure 4. For example, a waveform with an 80 µC raw charge with 100 µs duration will have a normalized charge of 80 µC. However, if the 80 µC was delivered by a 60 µs duration waveform then the normalized charge is 96 µC. The specific data shown are for the 15 mm bottom dart gap using data measured in our study.

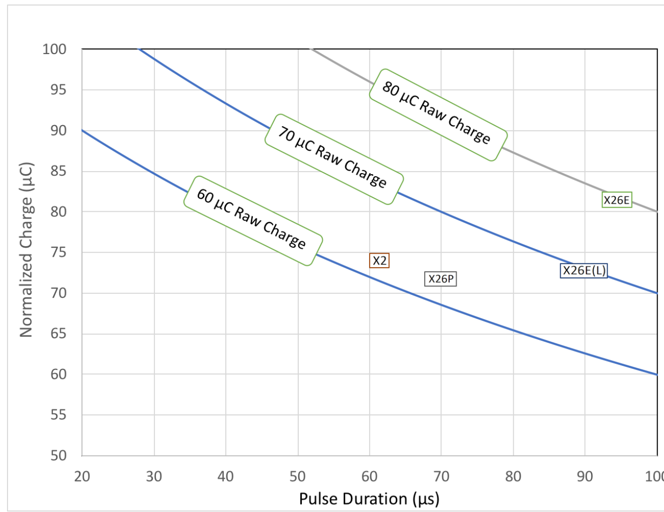

Figure 4. Normalized vs raw charge. Examples given are with 15 mm bottom dart gap.

Note: This paper uses Q_r and Q_n for the raw and normalized effectiveness charge respectively; the ANSI standard uses Q_0 and Q_{NE}. For our measurements, we used ± 50 V limits for historical comparisons instead of the ± 60 V limits in the ANSI standard.[8] The resulting differences are immaterial, being 0.3% and 0.01% (direct contact and maximum arcing respectively) in the normalized charge for the X26E CEW, for example.

RESULTS

The baseline results are given in Table 1. As expected, the X26E CEW has more variability in its output than the newer X26P and X2 models which have output charge feedback stabilization. The lowest output X26E is shown as X26E(L) in order to illustrate the effects of the variability of outputs with this model. The X26E mean values includes X26E(L). Since the pulse durations of the X26E CEW are > 100 µs, the normalized charge is *reduced* from the raw charge.

Table 1. Baseline outputs with direct contact.

CEW Model	Qr=Raw Charge (µC)	Duration (µs)	Qn=Normalized Charge (µC)
X26E	99.5 ± 6.5	131.4 ± 6.2	86.6 ± 4.1
X26E(L)	88.5	123.6	79.4
X2	63.8 ± 1.7	69.3 ± 1.6	74.6 ± 2.0
X26P	65.9 ± 1.8	94.8 ± 3.0	67.4 ± 2.0

X26E(L) is the lowest output X26E CEW of the 5 tested.

The opposite is true for the X26P and X2 CEWs since they have pulse durations < 100 µs. The charge stabilizing effect of the output charge feedback and the newer charge control method is clearly seen with the raw charges of the X2 and X26P CEWs having standard deviations < 2 µC compared to the 6.5 µC of the X26E.

Table 2. Maximum gap for continuous arc.

CEW Model	Top (mm)	Both (mm)	Bottom (mm)
X26E	23.5 ± 1.2	22.7 ± 0.9	30.8 ± 1.8
X2	20.1 ± 0.3	18.3 ± 1.6	26.6 ± 0.3
X26P	24.4 ± 1.3	24.6 ± 0.5	33.8 ± 1.0

The maximum arc capabilities are shown in Table 2. The maximum arc gap was always with the bottom probe since that is the positive polarity probe during the arc phase. In an arc, electrons carry charge from the cathode (-) to the anode (+) while positive ions carry charge in the opposite direction.[16-18] Since the electrons move more rapidly, they arrive at the anode before the positive ions arrive at the cathode. This implies that the initial, transient current density is highest at the point, on the cathode, where the arc initiated and launched the electrons.[18]

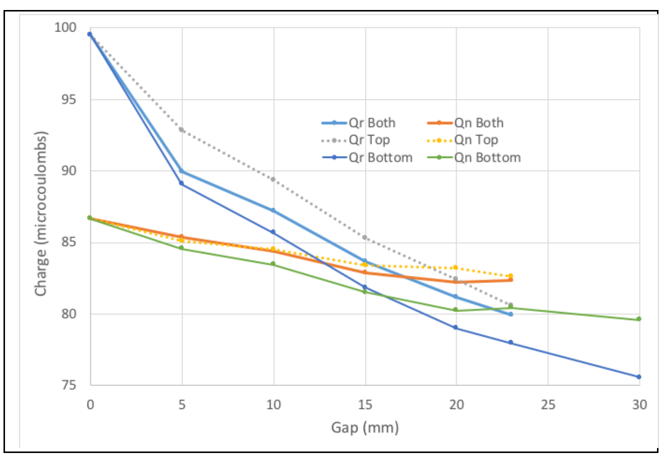

Figure 5. Results for X26E CEW.

Figure 5 depicts the performance for the X26E CEW averaged over all 5 tested units. For the bottom probe arcing the raw charge Qr decreased from 100 µC to 76 µC. Because the X26E CEW pulse duration is nominally > 100 µs, the normalized charge is less than the raw charge. However, with an increasing arc gap, the pulse duration decreases and at about 15 mm equals 100 µs. Thus, at this gap the normalized charge equals the raw charge. For the bottom probe arcing the normalized charge (Qn) decreased from 87 µC to 80 µC. Similar changes are seen for the top gap and for both probes arcing.

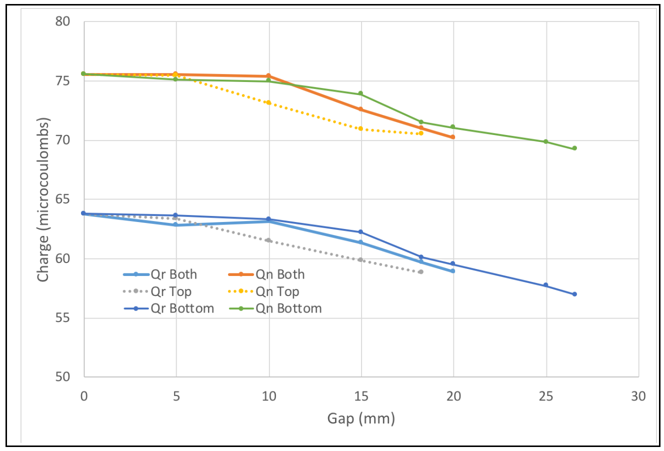

Figure 6. Results for X2 CEW.

Figure 6 shows the performance for the X2 CEW averaged over all 5 tested units. For the bottom probe arcing the raw charge Qr decreased from 64 µC to 57 µC. Because the X2 CEW pulse duration is always < 100 µs, the normalized charge is *greater* than the raw charge. For the bottom probe arcing the normalized charge (Qn) decreased from 76 µC to 69 µC. Similar changes are seen for the top gap and for both probes arcing.

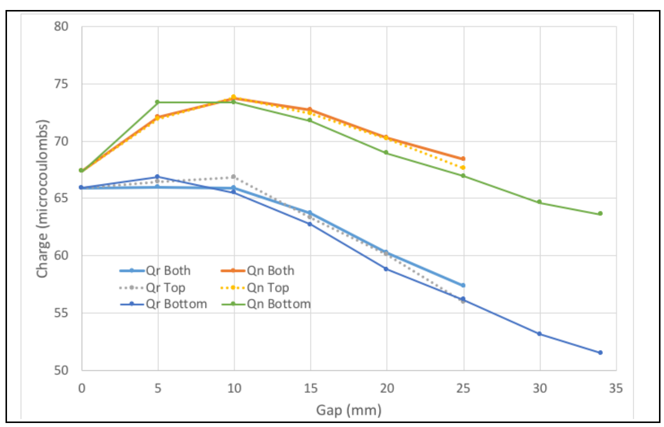

Figure 7. Results for X26P CEW.

Figure 7 depicts the performance for the X26P CEW averaged over all 5 tested units. For the bottom probe arcing the raw charge Qr decreased from 66 µC to 52 µC. This is somewhat of an exaggerated decrease as the X26P CEW is capable of much longer arcs than the X2 CEW. For consistent comparisons at a 25 mm arc, both deliver a raw charge of ≈ 57 µC. Like the X26P CEW, because the X2 CEW duration is also always < 100 µs, the normalized charge is again greater than the raw charge.

The X26P CEW has the greatest arcing capability for both the top and bottom probes. For clarification, the arc gap measurements for "both" probes meant that each probe was spaced at an identical gap and continuous current was passed. In other words, the measurement of 24.6 mm for the X26P CEW means that the length of the arcs was 12.3 mm for each probe, giving a total cumulative arc distance for the 2 probes of 24.6 mm.

The X26P CEW model has a significant pulse shortening with typical gaps (5-20 mm). This leads to an *increase* in the normalized charge compared to a direct connection. This interesting feature is clearly seen in the top curves. For the bottom probe arcing the normalized charge Qn *increased* from 67 µC to 74 µC before slowly decreasing to 63 µC. Similar changes are seen for the top gap and for both probes arcing.

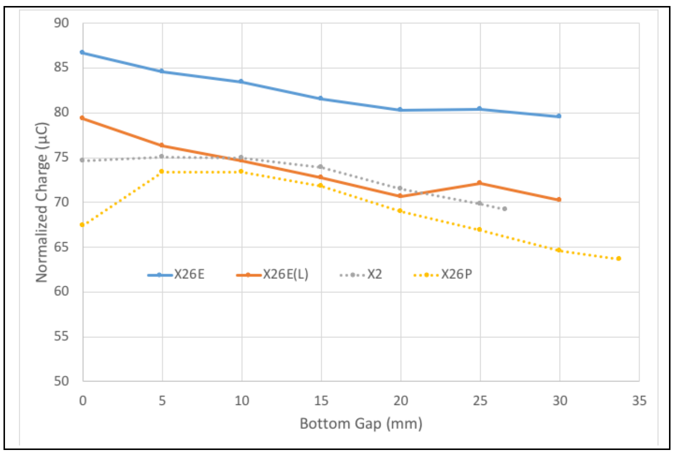

Figure 8. Normalized charge vs. bottom gap.

Figure 8 compares the normalized charge for all CEW models for the bottom probe arcing. We have included the X26E(L) CEW which was the lowest output unit of the X26E CEW models tested. The average X26E model output is, of course, greater than the other models for any arc gap. What is striking about this plot is how consistent the normalized charges are for the X26E(L), X2, and X26P CEWs for all gaps between 5-25 mm.

DISCUSSION

We believe that this paper represents the first systematic measurement of the performance of modern electrical weapons under various arcing conditions. Our results appear to be consistent with those of Reilly who tested a single X26E CEW arcing into a 5 cm sphere and a 500 Ω load.[19]

The most interesting finding is the improved effectiveness of the X26P CEW under arcing conditions. The high voltage technology in all of these weapons is called Shaped Pulse™. The patented technology uses separate arc- and main-phase capacitors connected to a common high voltage output transformer. The circuit generates first an arcing voltage of up to around 50 kV by discharging the arc capacitor through the transformer primary windings, followed by the positive polarity main pulse created by discharging the main phase capacitors through the transformer secondary windings. As the output transformer passes the main capacitor current through its secondary winding into the load, it stores some of the capacitor energy in its magnetic core. After the main capacitor is sufficiently discharged, the energy that was stored in the output transformer's magnetic core is released as electric charge into the load. This happens during the last portion of the waveform's main phase. The energy needed to drive a given electric charge into the load is in proportion to the load impedance. As the load impedance increases, the load voltage will be higher, and more energy will be needed to drive the same amount of charge. Because only a certain amount of energy can be stored in the output transformer's magnetic core, as the output voltage increases, the faster the stored magnetic energy will be depleted, As the magnetic energy depletes faster, the output waveform duration becomes shorter, while the charge feedback regulation keeps the delivered charge consistent.

In order to charge the main capacitors between pulses there needs to be air gaps present between the main capacitor and transformer circuit and the electrodes in front of the weapon. The circuit that generates the high voltage is physically very small, on the order of 6 x 3 x 3 cm and in order to contain the very high voltages the circuit is potted in a high voltage potting compound; Hence, the required circuit air gaps must be placed *outside* the potted module assembly. The natural location for the required air gaps is as part of the handle assembly. Due to different body designs, the air gaps in the 3 weapons are different. In addition, there are air gaps present from the weapon electrodes to the cartridge electrodes. Due to the physical construction of the weapon and the cartridge, the X2 weapon has longer air gaps from the high voltage circuit to the cartridge wire connections than the X26P which has equivalent high voltage circuitry. Because of the X2's longer air gaps, the X2 has an overall shorter waveform. But since the X26P has shorter air gaps connecting the high voltage circuit to the cartridge electrodes, the output waveform can jump a slightly longer distance to connect a circuit. If the X26P must arc to create a circuit connection, the charge regulation circuit keeps the output charge constant, while the increased circuit impedance leads to a shorter waveform, At the same delivered charge, the shorter waveform thus becomes more effective.

Our results appear to confirm the manufacturer's use of closed-loop feedback to stabilize upper charges for the X2 and X26P CEWs.

The ANSI CPLSO-17 electrical weapons standard does not have requirements for arcing performance and all testing is done with direct connections.[10] Nevertheless, it is tempting to compare the arcing performance to the ANSI standard output requirements. They require a normalized charge Qn > 60 μC. All units tested exceeded this 60 μC requirement for all gaps. For bottom gaps of 10-20 mm, the X2 CEW had the highest normalized charge, slightly exceeding that of the X26P and the X26E(L) CEWs.

LIMITATIONS

Our testing used an air gap constructed with probes and metallic landing section mounted in PVC. This is different from the field situation where the arc landing is human epidermis. For a direct skin connection, there is human data showing an inter-probe resistance of 602 ± 77 Ω for inserted probes, hence consistent with the use of a 600 Ω non-inductive resistor.[12] The arcing distances found were consistent with earlier results using moist bovine tissue yielding arc distances of ~ 25 mm.[20] While dry skin has a high initial resistance it is highly nonlinear and begins to break down at 15-40 V.[21, 22] Skin obtains a very low resistance at 200-500 V which is far less than our 50 kV arcing voltages.[23] Arcing quickly desiccates and eventually burns the tissue and thus our model provided superior repeatability over tissue.

The testing was performed by product compliance manager BDC independently from R&D and manufacturing staff which staff had no input into either the study design or data analysis.

CONCLUSIONS

The stabilized closed loop charge output feedback of modern electrical weapons (X2 and X26P CEWs) provides a significantly improved output consistency under arcing conditions. With arc lengths of 10-20 mm per probe, the X2 CEW normalized output charge exceeds that of some units of the older higher output X26E CEWs.

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