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Humidity and Ventricular Fibrillation: When Wet Welding can be Fatal

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Abstract:
Introduction: Arc welding is generally considered very safe electrically. There have been electrocution cases with welders in high humidity environments. When dry, the flux coatings tend to have sufficient electrical resistance to limit the current below that required for the induction of VF (ventricular fibrillation).
Methods: We tested 4 welding electrodes for resistance in both dry and wet conditions. To estimate the cardiac current density — in a worst-case scenario — we used a 20k element finite-element bioimpedance model with 1 cm of skin and fat along with 1 cm of muscle before the heart of 5 cm dimensions. Between the heart and a metal plate we assumed 5 cm of lung and 1 cm of skin and fat.
Results: Welding electrode flux is highly resistive when dry. However, when saturated with moisture the resistance is almost negligible as far as dangerous currents in a human. The FEM model calculated a current density of > 7 mA/cm^2 on the ventricular epicardium with a source of 80 V at the welding rod.
Conclusion: In conditions of high humidity, a supine operator, in contact with a coated welding electrode to the precordial region of the body can be fibrillated with the AC open-circuit voltage. Most reported DC fatalities were probably due to pseudo-DC outputs that were merely rectified AC without smoothing.

INTRODUCTION

Arc welding is generally considered very safe electrically. The voltages are limited to 80 VAC RMS and 100 VDC by US OSHA regulations and other countries have similar limitations. The vast majority of welders have experienced a painful shock, without injury, from arc-welding.[1] Factory electrocutions, while welding, are almost never reported but maintenance welding, using flux coated rods (Manual Metal Arc Welding or MMAW) welding has led to some fatalities. Most of the fatalities have involved breaches of safety regulations such as a welder standing in water with wet gloves and providing a low impedance hand-to-feet pathway.

There have also been fatalities with welders in high humidity environments. When dry, the flux coatings tend to have sufficient electrical resistance to limit the current below that required for the induction of VF (ventricular fibrillation). Many coatings are cellulose with very high resistivity or iron powder which — depending on compression and oxidation — has a resitivity of 100 kΩ•cm - 1 MΩ•cm.[2]

Peng reported 7 deaths in Chinese welders of which 5 were working on ships in high humidity and temperature.[3] Notably, 3 were confirmed to be using DC and all 3 of these were welding inside a ship. In a USA case of possible electrocution by DC welding, a 43-year old welder with 22 years of experience was found dead with the rod across his chest. [4] He was lying supine on a wet, metal screen deck in the high humidity of a mine with outside temperature of 36° C.

These cases are puzzling as DC current is known to be far safer than AC current for the induction of VF. Ferris' sheep data suggest using a DC/AC VF threshold ratio of around 4.4 (where VF obtains) or 4.17 (highest currents without VF) for 3-second exposures to 60 Hz AC.[5] Knickerbocker reported on 1000s of dog tests using both AC (20 Hz) and DC.[6] For durations of 1 and 2 seconds he reported a DC/AC ratio of about 3.65.

The goal of this study was to investigate the VF risk of DC and AC welding in situations of very high humidity.

METHODS

We procured 4 electrodes for resistance measurements. These represented both titania sodium and low-hydrogen iron powder coating. For the resistance measurements they were tightly wrapped in aluminum foil of 30.5 cm width as shown in Figure 1.

Figure 1. Welding electrode wrapped in aluminum foil.

The resistance measurements were done using a 4-terminal technique with separate contacts for driving the current and sensing the voltage drop. The system was excited with a 44 V AC transformer output in series with a 200 Ω current limiter as seen in Figure 2.

The electrodes were stabilized in a laboratory with a 21% relative humidity before their dry measurements. After

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that they were soaked in distilled water for 90 minutes and then wiped down for excess water for their wet measurements. This was to simulate a maximum-moisture content from operation in extreme humidity.

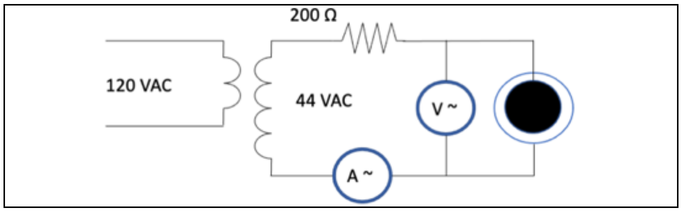

Figure 2. Resistance measuring circuit

We assumed a worst-case situation of an electrode laying on the precordial (over the heart) region. In that case, the critical value is the current density on the right ventricular epicardium. We also assumed that the welder's shirt was saturated in sweat and thus offered no electrical resistance.[7] Finally, we assume that the welder was supine on a conductive metal surface as shown in Figure 3.

To estimate this current density we used a 20k element finite-element bioimpedance model with 1 cm of skin and fat along with 1 cm of muscle before the heart of 5 cm dimensions. Between the heart and the metal plate we assumed 5 cm of lung and 1 cm of skin and fat.

RESULTS

The results of the electrode testing are given in Table 1. The flux resistivity was calculated from:

$$Z = \frac{\rho}{2\pi L} ln\left[\frac{r_o}{r_i}\right]$$

where ρ = resistivity, L = length, r_x = outer and inner radii.

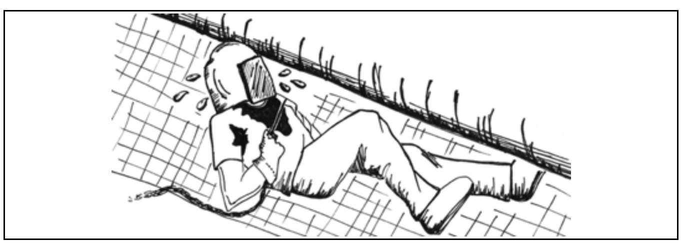

Figure 3. Welder in worst-case scenario on metal surface.

The immediate and obvious conclusion is that the flux is highly resistive when dry. However, when saturated with moisture the resistance is almost negligible as far as dangerous currents in a human.

The voltage maps for the FEM model are given in Figure 4 with a source of 80 V at the rod. The current-density maps for the FEM model are given in Figure 4 and Figure 5 with a source of 80 V at the welding rod. They predict a current density of > 7 mA/cm² on the ventricular epicardium.

The FEM assumed a welding rod with 0 Ω resistance and a 5 x 5 mm square cross-section. The resulting impedance seen by the welding rod was 80 Ω according to the finite element analysis modeling. Our flux-testing found that the full-circumference resistance varied from 40.5 to 122 Ω in the moisture-saturated electrodes evaluated. Those values are doubled (2x) to a *bottom* resistance for the contact with the skin as shown in Table 2. That resistance value can be used to calculate a voltage divider with the 80 Ω from the FEM. That, in turn, can then be used to calculate an expected current density at the epicardium.

Sharma was able to consistently induce VF in humans via a 9 V battery connected to a 3 mm diameter electrode in the right ventricle.[8] At that voltage the impedance of the electrode is approximately 200 Ω giving a current of 45 mA.[9] The surface area of the coil is ~5 cm². Ignoring the higher current density at the end of the coil, the average current density can be estimated at ~ 9 mA/cm². Sharma was able to induce VF in 96% of attempts with application durations averaging 3.8 ± 1.4 seconds. Assuming a Gaussian distribution, a 96% success rate implies a current density of 1.75 standard deviations above the mean. Animal VF threshold studies show that the standard deviation is about ¼ of the mean. Using that, we can estimate that the mean DC VF threshold was about 6 ± 2.5 mA/cm².

Watson measured the human AC (50 Hz) VF threshold at 1-8 mA (2.8 ± 2.0 mA) using epicardial discs of 1.8 cm diameter.[10] He did not disclose the distribution of patient receiving surgery for coronary artery disease vs. valvular disease. Since coronary disease reduces the VFT by about 50%, we estimate that Watson demonstrated an average VF threshold of 4 mA.[11] In the Sharma study, 78% of the patients had coronary artery disease. Correcting for coronary disease, we estimate that Sharma's data predicts an average VF threshold of 9 mA/cm² DC in normal subjects.[11]

A common error in calculating such a current density is to assume that all of the current flows away from the disc in a perpendicular direction. In fact, the current density from a *monopolar* disc, over a semi-infinite resistive body, is given by:[12]

$$J = \frac{I}{2\pi R\sqrt{R^2 - r^2}}$$

where R is the disc radius and r is the distance from the center of the disc.

Table 1. Electrode resistance and calculated flux resistivity.

Rod type	Wire D (mm)	Outer D (mm)	V dry (V)	I dry (mA)	R dry (kΩ)	rho calc (Ω•cm)	V wet (V)	I wet (mA)	R wet (Ω)	rho calc (Ω•cm)
8018	3.2	5.5	43.5	0.711	61	2.E+07	17.1	140	122.1	43637
7018	3.2	5.8	43.7	0.082	533	2.E+08	10.1	165	61.2	19715
6022	4.0	5.8	43.6	0.085	513	3.E+08	5.5	181	30.4	16038
Fusion E	3.4	8.5	33.2	0.052	638	1.E+08	7	173	40.5	8568

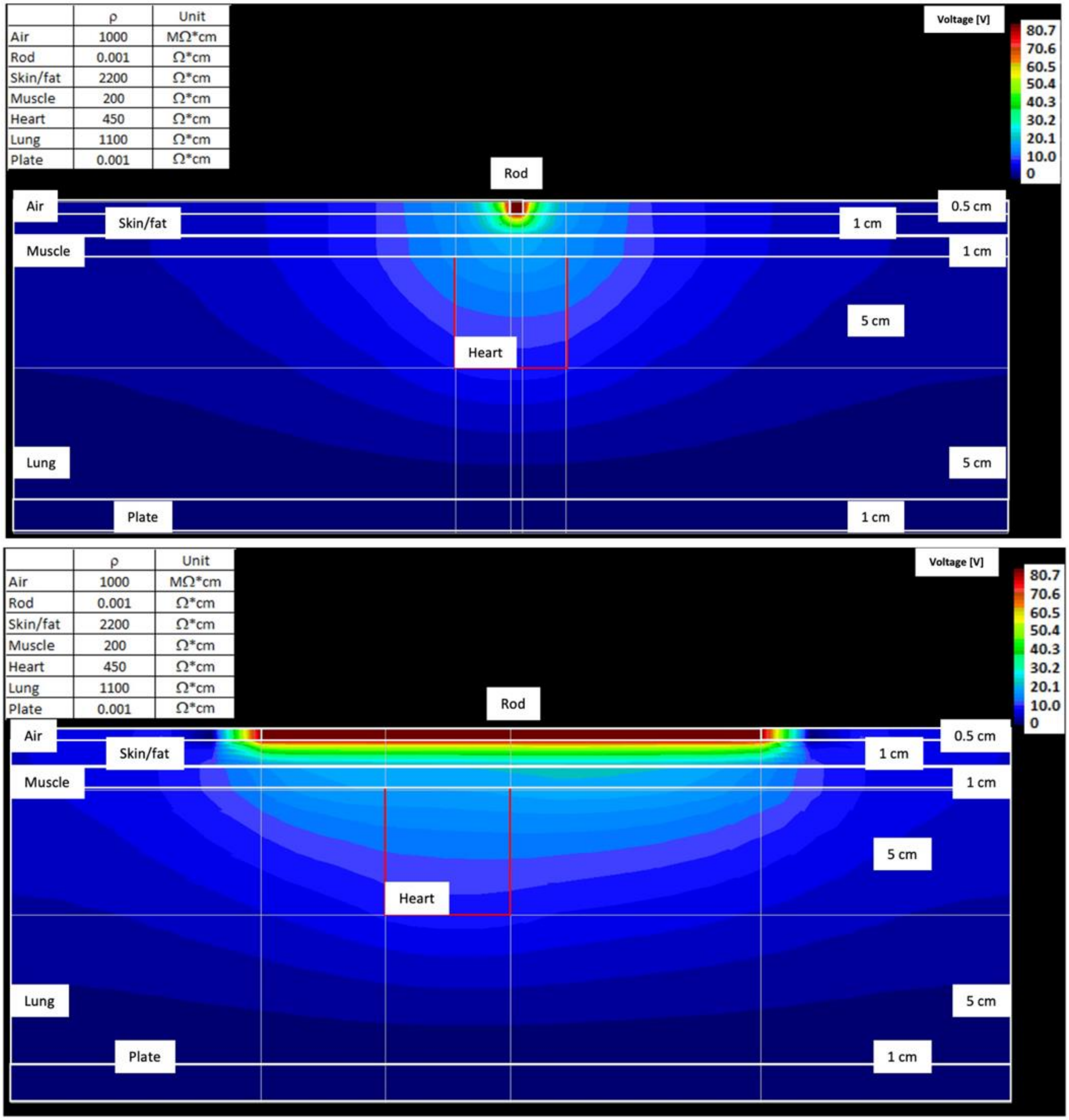

Figure 4. Radial and longitudinal axis voltage maps of finite element analysis model.

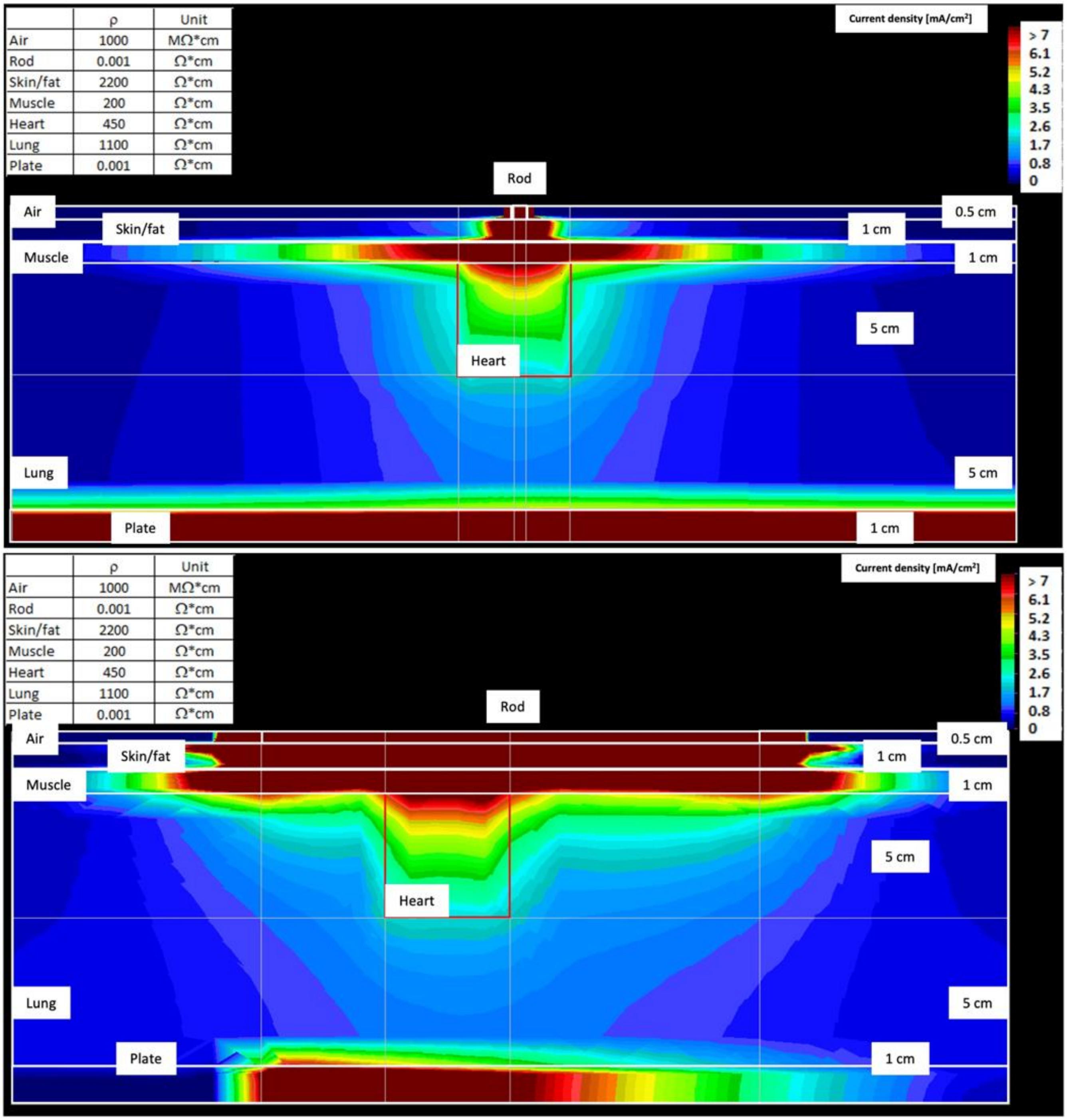

Figure 5. Radial and longitudinal axis current-density maps of finite element analysis model.

Table 2. Expected epicardial current density from saturated welding rods with 80 VDC potential.

Rod type	Outer D (mm)	R circum. (Ω)	R bottom (Ω)	Expected current density (mA/cm2)
8018	5.5	122.1	244.2	1.73
7018	5.8	61.2	122.4	2.77
6022	5.8	30.4	60.8	3.98
Fusion E	8.5	40.5	81	3.48

The outer 15% of the disc radius delivers 50% of the current and 30% of the current is delivered from the outer 2% of the disc radius. We estimate that the current density on the edge of the disc, for Watson's patients, would have been 2.5 mA/cm^2 for a monopolar disc. However, the disks were fairly close, with only 0.5 cm edge to edge spacing, and thus the surface current density between the disks was larger and had less penetration.

Our expected current densities in Table 2 appear to be consistent with human data for a high risk of VF induction for at least some of the welding rod types when fully saturated of moisture when delivering AC. For DC, the predicted densities are lower than the estimated mean VF threshold.

DISCUSSION

We believe that this is the first paper to demonstrate a risk of VF induction with welding rods through the flux coating in a worst-case high-humidity situation.

Knickerbocker showed that the VF risk of an offset AC current was basically predicted by the amplitude of the AC component.[6] Consider the output of the older welding unit shown in Figure 6 set to a "direct current" output. It is delivering essentially a rectified AC with a peak-to-peak component of nearly 140 V. Therefore this would have the VF risk of a 70 V AC base-to-peak (~ 100 V RMS) source.

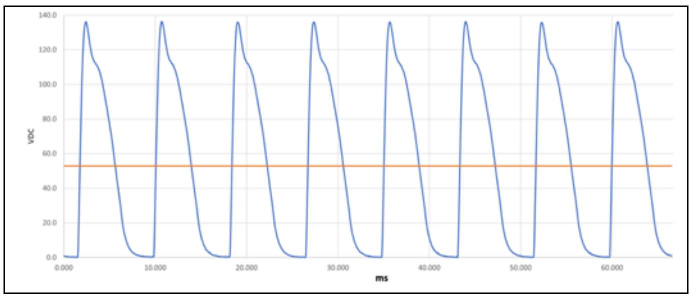

Figure 6. Open circuit voltage with "DC" setting on an older model.

The more modern welding unit, with output shown in Figure 7 was also set to a direct current output. It is delivering essentially an unsmoothed rectified AC with a peak-to-peak component of about 54 V. Therefore this would have the VF risk of a 27 V AC base-to-peak (~ 38 V RMS) source.

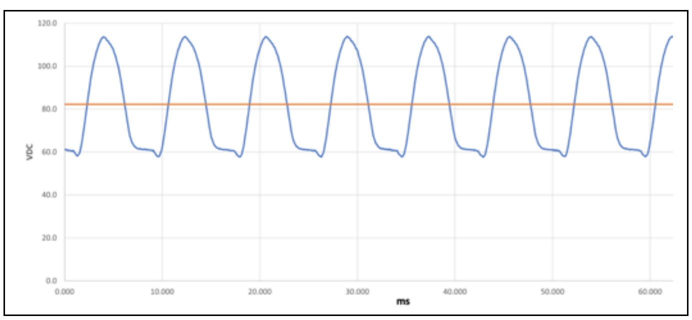

Figure 7. Open circuit voltage with "DC" setting on a current model.

Since a true direct current does not appear reasonably likely to induce VF in a welding accident, we believe that most such reported fatalities were due to pseudo-DC outputs that were merely rectified AC without smoothing.

Recently, a Voltage Reducing Device (VRD) is often designed in or added as an aftermarket device. Unfortunately, many welding machines come to the end user with the VRD intentionally defeated. The VRD is designed to deliver no current unless a specified low resistance is detected. This is often set at 200 Ω as that is typically below the impedance presented by the human body. Severe shocks were seen in Canadian potash mines with a VRD set at 100 Ω but these stopped after the VRDs trigger impedance was reduced to 40 Ω. This result supports our modeling predicting a resistance of 80 Ω across the chest with worst-case humidity conditions since $40\ \Omega < 80\ \Omega \leq 100\ \Omega$.

Coffin is credited with inventing the arc welding machine in 1890, in a novel approach to join iron and steel to replace the riveting process. Welding machines have been involved in the electrocutions of operators ever since.[1] Early welding machines were AC output as they were designed for controlled high current output before the advent of high-current rectifiers.

An example fatality (1969) involved a 73-volt output most likely alternating current (AC). As is typical for these types of fatalities, the victim was working in a hot, high humidity and damp confined location. The workspace was so confined that the investigators mention that it would have been difficult to tighten the 13-inch electrode into the electrode holder in the space the victim was working in as it was a spin-to-tighten electrode holder. The report mentions that several spent electrodes lay nearby and that a new electrode had been installed.

Hisey (International Institute for Welding Commission 2019 meeting in Bratislava), reported that out of 24 fatalities from contact with welding current, 6 could be identified as AC current and 8 as DC current. AC welding is primarily suited for aluminum although many hobbyists still have old inexpensive AC-only units. With an estimated 5-20% of manual electrode welding being done with AC, Hisey's case series suggest that DC is far safer than AC.

A non-precordial pathway fatality case illustrates the risk from saturated electrodes.[13] The welder set up his process with the welding machine de-energized complete with a new electrode. Even though the welder was standing in water, the first electrode was used without incident. The fatal act was inserting the new electrode with a wet-gloved hand which allowed sufficient current to flow through the hand, arm body and out through the welders' legs and feet. The ship-hold water provided a high humidity level, possibly damp gloves and certainly wet boots and feet. In this case the current flow was most certainly through the electrode, the flux coating, and the gloves.

LIMITATIONS

We only tested 4 types of welding rods.

CONCLUSIONS

In conditions of high humidity, a supine operator, in contact with a coated welding electrode to the precordial region of the body can be fibrillated with the AC open-circuit voltage. Most reported DC fatalities were probably due to pseudo-DC outputs that were merely rectified AC without smoothing.

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