Electrical Contact Accident With A Welding Machine

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1. ABSTRACT

In 1991, a Bonneville Power Administration (BPA) worker suffered severe injury during an electrical contact accident involving a welding machine. This incident occurred during a complete station outage at a BPA substation. Injuries to the employee consisted of muscle, tissue, and bone damage to one of the worker's shoulders.

Tests simulating the accident were performed at BPA's High Voltage Laboratory and at the substation where the accident originally took place in order to determine why the electrical shock occurred and how this type of accident can be prevented in the future.

It was concluded from testing and analysis that the injuries occurred to the worker because he came in bare handed contact with a grounded steel structure and a riser that was being welded. In such a situation, the 60 Hz voltage output from the welding machine had the capability of generating enough current to tetanize the muscles in the worker's arms and chest, probably leading to the muscle, tissue, and bone damage to his shoulder.

2. INTRODUCTION

In February 1991, a BPA employee suffered injury during an electrical contact accident involving a welding machine. The accident occurred at BPA's Spearfish Substation, and injuries consisted of muscle, tissue, and bone damage to the left shoulder.

2.1 Events Leading Up To The Accident

Spearfish Substation taps into the Chenoweth/Goldendale 115-kV line, and then feeds out at 125kV to Klickitat County PUD (Figure 1). A complete station outage was taken at Spearfish to tie expansion work that Klickitat County PUD had been doing into BPA. Disconnect switches to the 12.5-kV regulators were CLOSED.

Figure 1 - Spearfish Substation One-Line Diagram

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Figure 2 shows the circuit configuration at the time of the accident. One worker was in the bucket of a welding truck just above the regulators. Two other workers were up in the 125-kV side of a grounded steel rack. One of the workers in the rack removed his work gloves to bolt an aluminum riser to an insulator. He then steadied the riser with one hand while the riser was to be welded into an oversized bracket (bracket located on top of the regulator). With the other hand the worker held on to the rack. Next, the following sequence of events occurred:

1) The first welding arc was struck.
2) The bucket of the welding truck shifted, extinguishing the first arc.
3) A second welding arc was struck.

Injuries to the worker holding on to the riser and steel rack occurred during step 2 or 3. The injuries are believed to have resulted from severe muscle contractions during an electrical shock.

2.2 Initial Questions Concerning Cause Of The Accident

Initially, there was some question about whether a malfunction in the welding machine caused this accident. Testing performed by BPA showed that the welding machine was functioning properly and that the accident was not due to an equipment malfunction.

Next, the integrity of the ground mat at Spearfish Substation was investigated. Tests performed by BPA in April 1991 uncovered no problems with the ground mat connections that would have accounted for this accident.
Questions concerning an inductive kick from one of the regulators as well as questions about ground link between the welding machine and truck chassis have also come up. Since the answers to these questions are dependent upon data presented later in this paper, the answers will be presented at that time.

The primary purpose of this paper is to document:

1) Why the electrical shock and injuries occurred to the worker, and
2) How this type of accident can be prevented in the future.

3. POSSIBLE SCENARIOS FOR THE ACCIDENT

3.1 "Inductive Kick" Scenario

In this scenario, the first welding arc struck causes a current to flow in the regulator. When the arc is extinguished, the regulator tries to continue forcing current through the circuit. This scenario assumes the following (Figure 3):

1) The welding machine ground lead is hung on the bracket. The riser is isolated from the bracket due to an oversize fit. The first arc is struck on the bracket with no incident. Current flows back to the welding machine through the welding machine ground (see Circuit Return Path - 1).

2) The bucket of the welding truck shifts, and the arc extinguishes:
   a) Just before the bucket shifts, the bracket and riser are tacked together.
   b) The shifting of the bucket disconnects the welding machine ground from the bracket while the arc remains. Now current flows back to the welding machine though the regulator (see Circuit Return Path - 2).
   c) The stinger is pulled away and the arc extinguishes.
   d) A voltage develops at the high side of the regulator, generating an "inductive kick", briefly forcing current to flow back to the welding machine through the worker (see Circuit Return Path - 3).

3) The second arc is struck.

Figure 3 - Inductive Kick Scenario

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The "inductive kick" scenario depends completely upon the connection being broken between the welding machine ground lead and oversized bracket. This is unlikely for two reasons:

1) The first arc was struck without incident, indicating a solid connection between the welding machine ground and bracket.
2) There was no indication that the welding machine ground had been disturbed at any time during the incident.

![Diagram of Welding Machine Voltage Scenario]

**Figure 4 - Welding Machine Voltage Scenario**

3.2 "Welding Machine Voltage" Scenario

A more likely scenario is that the worker becomes the only path back to the welding machine when an arc is struck on the riser (with the riser isolated from the bracket due to an oversize fit). This scenario is explained in Figure 4, with the sequence of events as follows:

1) The first arc is struck on the bracket with no incident (see Circuit Return Path - 1).
2) The bucket of the welding truck shifts, extinguishing the arc without incident.
3) The second arc is struck on the bracket and the stinger is moved to the riser -OR- an attempt is made to strike the second arc directly on the riser. Once the arc or stinger comes in contact with the riser, the electrical isolation between the bracket and the riser forces current through the worker as shown in Circuit Return Path - 2.
4. TEST SETUPS AND PROCEDURES

4.1 Test Setup at the BPA High Voltage Laboratory

Initial tests were performed at the BPA High Voltage Laboratory. In order to simulate the Spearfish circuit as closely as possible, a regulator identical to the one at Spearfish Substation was loaned to BPA by Klickitat County PUD. In addition, a Trailblazer 44D welding machine was used.

The Trailblazer 44D welding machine simultaneously puts out a 60 Hz voltage and a high frequency voltage pulse. The high frequency pulse occurs several thousand times per second, and has a ring down time of approximately 2 MHz. The purpose of the high frequency pulse is to clean off oxide and maintain the arc when welding aluminum, while the 60 Hz output provides heat for making the weld. During welding, the 60 Hz output is 32 V-rms, while the high frequency output is approximately 4 kV-pk.

4.1.1 60 Hz Laboratory Test Circuit

The 60 Hz laboratory test circuit is shown in Figure 5. Output from the welding machine was applied to a salt water resistor (used to simulate human body impedance). One moderately-soiled but dry leather workglove was placed in series with the salt water resistor to test for possible insulating effects at 60Hz. Testing was also performed to see if the regulator generated an inductive kick when the arc was extinguished.

Figure 5 - Laboratory Circuit For Measuring 60 Hz Output From Welding Machine
4.1.2 High Frequency Laboratory Test Circuit

The high frequency laboratory test circuit is shown in Figure 6. Protective and static grounds were attached in an attempt to short out the high frequency pulse. As with the 60Hz configuration, testing was performed to see if the regulator generated an inductive kick when the arc was extinguished.

4.1.3 Electrical Tests On Leather Work Gloves

Megger tests were performed on dry pigskin leather workgloves that were relatively new and moderately soiled. Sixty hertz tests were performed on these gloves in dry, slightly moist, and saturated wet conditions. No tests were performed to determine the amount of high frequency insulation provided by the leather workgloves.

4.2 Measurement Circuit Used At Spearfish Substation

Circuitry used to measure the 60 Hz and high frequency output from the welding machine during an October 1991 outage at Spearfish Substation is shown in Figure 7.
During an electrical contact accident, the primary concern involves the flow of current through the human body. In order to calculate current at a given voltage and frequency, an accurate impedance model of the human body must be established.

Figure 8 details a simple human body impedance model used in analyzing the Spearfish accident:

1) Skin impedance of each hand is represented by a parallel combination of skin capacitance \( C_{\text{skin}} \) and skin resistance \( R_{\text{skin}} \), and
2) Internal body resistance is represented by \( R_{\text{body}} \).
The impedance equation for the human body is as follows:

$$ \text{Human Body Impedance} = (X_{C_{\text{skin}}} || R_{\text{skin}}) + R_{\text{body}} + (X_{C_{\text{skin}}} || R_{\text{skin}})$$  \hspace{1cm} (Eq. 1)

This equation yields a human body impedance of about 1200 Ω for 60 Hz, and 500 Ω for high frequency.

6. TEST RESULTS

Unless noted otherwise, test results refer to bare hand-to-hand contact with the riser and the grounded rack structure.

6.1 60 Hz Test Results

Sixty hertz test results are listed in Table 1. From the results, the following observations can be made:

1) The worst 60 Hz current measured at Spearfish was 54 mA-rms at 65 V-rms. This occurred when:
   a) The connection between the bracket and riser was FLOATING, and
   b) An arc was struck on the riser -or- the stinger was touched directly to the riser.
2) Bonding the bracket and riser together significantly reduces the 60 Hz current down to about 3.5 mA-rms, but this is not considered a safe level.
3) With the bracket/riser connection FLOATING, one dry leather workglove in series with the human body reduces the 60 Hz current down below 0.5 mA-rms.
4) The regulator generates no measurable inductive kick, and regulator tap position is insignificant.

Table 1
60 Hz Tests With Ground Link Installed And Welding Machine Ground Hung On Bracket
Bare hand contact assumed (unless otherwise noted)

<table>
<thead>
<tr>
<th>Test Location</th>
<th>Regulator Position</th>
<th>Between Bracket &amp; Riser</th>
<th>Arc Struck On Riser</th>
<th>Ground Link Installed</th>
<th>Voltage (V)</th>
<th>RMS Current (mA)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>Neutral</td>
<td>Floating</td>
<td>Y</td>
<td>Y</td>
<td>1.70</td>
<td>1.40</td>
<td>Data questionable</td>
</tr>
<tr>
<td>Substation</td>
<td>Neutral</td>
<td>Floating</td>
<td>Y</td>
<td>Y</td>
<td>62.23</td>
<td>51.38</td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Raise-3</td>
<td>Floating</td>
<td>Y</td>
<td>Y</td>
<td>65.05</td>
<td>53.72</td>
<td></td>
</tr>
<tr>
<td>Laboratory</td>
<td>Neutral</td>
<td>Floating</td>
<td>N</td>
<td>Y</td>
<td>59.40</td>
<td>49.05</td>
<td>Stinger touching riser (NO ARC)</td>
</tr>
<tr>
<td>Substation</td>
<td>Neutral</td>
<td>Floating</td>
<td>N</td>
<td>Y</td>
<td>62.23</td>
<td>51.38</td>
<td>Stinger touching riser (NO ARC)</td>
</tr>
<tr>
<td>Substation</td>
<td>Raise-3</td>
<td>Floating</td>
<td>N</td>
<td>Y</td>
<td>59.40</td>
<td>49.05</td>
<td>Stinger touching riser (NO ARC)</td>
</tr>
<tr>
<td>Laboratory</td>
<td>Neutral</td>
<td>Bonded</td>
<td>Y</td>
<td>Y</td>
<td>2.97</td>
<td>2.45</td>
<td>Dry workglove used</td>
</tr>
<tr>
<td>Substation</td>
<td>Neutral</td>
<td>Bonded</td>
<td>Y</td>
<td>Y</td>
<td>4.53</td>
<td>3.74</td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Raise-3</td>
<td>Bonded</td>
<td>Y</td>
<td>Y</td>
<td>4.31</td>
<td>3.56</td>
<td></td>
</tr>
<tr>
<td>Laboratory</td>
<td>Neutral</td>
<td>Bonded</td>
<td>Y</td>
<td>Y</td>
<td>0.18</td>
<td>0.15</td>
<td>Dry workglove used</td>
</tr>
</tbody>
</table>

60 Hz human body impedance: 1211 Ω
Table 2
High Frequency Tests With Ground Link Installed
And Welding Machine Ground Hung On Bracket
Bare hand contact assumed (unless otherwise noted)

<table>
<thead>
<tr>
<th>Test Location</th>
<th>Regulator Position</th>
<th>Connection Between Bracket &amp; Riser</th>
<th>Arc Struck On Riser</th>
<th>Ground Link Installed</th>
<th>Peak Voltage (kVp)</th>
<th>Peak Current (Amps)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory</td>
<td>Neutral Floating</td>
<td>Y Y</td>
<td>4.90</td>
<td>9.8</td>
<td>Static ground attached to riser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laboratory</td>
<td>Neutral Floating</td>
<td>Y Y</td>
<td>3.80</td>
<td>7.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Neutral Floating</td>
<td>Y Y</td>
<td>2.00</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Raise-3 Floating</td>
<td>Y Y</td>
<td>1.00</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Neutral Floating</td>
<td>N Y</td>
<td>2.00</td>
<td>4.0</td>
<td>Stinger touching riser (NO ARC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substation</td>
<td>Raise-3 Floating</td>
<td>N Y</td>
<td>1.60</td>
<td>3.2</td>
<td>Stinger touching riser (NO ARC)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

High frequency human body impedance: 500 Ω

6.2 High Frequency Test Results

High frequency test results are listed in Table 2. The following observations can be made from the results:

1) High frequency data measured at Spearfish Substation was approximately 60 percent lower than measured in the laboratory. These lower levels are caused by stray capacitance between the riser and the adjacent steel rack (see Figure 9), and this capacitance was not taken into account during testing at the laboratory. Stray capacitance increases as conductive objects come closer together. Capacitive impedance $X_C$ goes down as frequency increases so that stray capacitance provides a low impedance path for high frequency current to flow along. In this way stray capacitance shorts out some of the signal that would otherwise appear across the human body. At 60 Hz, the effects of stray capacitance between the riser and steel rack is insignificant.

2) The largest high frequency current measured at Spearfish was 4.0-Amps pk at 2.0-kV pk. This occurred when:
   a) The ground link between the welding machine and truck chassis was CONNECTED,
   b) The connection between the bracket and riser was FLOATING, and
   c) An arc was struck on the riser.

3) Bonding the bracket and riser together reduces the high frequency current, but not to a safe level.

4) Use of a protective or static ground DOES NOT reduce the high frequency current down to a safe level because of inductance in the ground lead (Figure 9). Inductive impedance $X_L$ in a ground lead goes up as frequency increases. Thus, ground lead inductance appears as an open circuit to the high frequency pulse. At 60 Hz, the effect of ground lead inductance is insignificant.

5) The regulator generates no measurable inductive kick, and regulator tap position is insignificant.
In a bare hand-to-hand contact situation, there appears to be no way of protecting the worker from the high frequency output from the welding machine. Since this is the case, we must investigate the relative hazards associated with this high frequency output and compare them with the 60 Hz output from the welding machine.

6.3 High Frequency Current Referenced To 60Hz Current

Let us begin with the following situation: an adult male has hold of an energized conductor while at the same time being grounded somewhere along his upper arm. The current that will flow between the hand and upper arm has a frequency of 60 Hz. There is a large area of skin in contact with conductor (i.e., palm of the hand). This subject has an "average" response to 60 Hz current, and will react as follows:

1) **Nerve Stimulation Threshold:** For 60 Hz current, the threshold for nerve stimulation is about 1 mA-rms. At this point, the subject will experience a mild tingling sensation. Slightly above this sensory threshold, the subject may anticipate mild responses in the small muscles of the hand.

2) **"Let-Go" Threshold:** As 60 Hz current increases, the subject will reach a point where he cannot let go of the energized conductor. This threshold where a subject cannot release an energized conductor is known as the "let-go" threshold. To explain this phenomenon, we must understand that muscles in the forearm consist of flexors and extensors. During hand grip electrical contact, current flowing in the forearm stimulates the stronger flexors and weaker extensors. Since the flexors are a more powerful muscle group than the extensors, the subject cannot release the gripped conductor. Above the "let-go" threshold, it is likely that the muscles in the forearm will go into a state of tetanus and lock up. Experimental data shows that the average 60 Hz "let-go" threshold for adult males is 16 mA-rms.
3) **Above "Let-Go" Threshold:** Above the 16 mA "let-go" threshold, the subject will experience involuntary muscle reactions.

Recall that in measurements made at Spearfish Substation, the highest 60 Hz current was found to be 54 mA-rms; nearly 3.5 times the 60 Hz "let-go" threshold. It is safe to conclude that the 60 Hz current alone would have been enough to tetanize the muscles in the forearm and upper arm.11

### 6.3.2 Effects Of High Frequency Current On The Human Body

Analysis has shown that in the Spearfish Substation accident, the amount of continuous high frequency current required to produce the same effect as a given 60 Hz current is 400 times as much. Recall that the 60 Hz "let-go" threshold is 16 mA-rms, (23 mA-pk12). Thus, the high frequency current required to produce the same "let-go" effect on the human body would be 23 mA-pk * 400, or 9.2 Amps-pk.

This factor of 400 is conservative because we have assumed that the high frequency current waveform is continuous. Since the welding machine output is not continuous, but rather a decaying sinuswave, the high frequency current required to produce the same effect as the 60 Hz current will be greater than 400 times as much - but we will use 400 as a conservative estimate.

Recall that the largest high frequency current measured at Spearfish Substation was about 4.0 Amps-pk. Taking into account the factor of 400, this high frequency current would produce the same results in the human body as a 60 Hz current of 10 mA-pk, or 7 mA-rms13.

### 6.3.3 Comparative Effects

The worst case high frequency current measured has the equivalent effect of a 60 Hz current equalling 7 mA-rms. Recall however that the actual worst case 60 Hz current level measured was 54 mA-rms. From this we conclude that the 60 Hz current put out by the welding machine was the primary source of nerve stimulation in the Spearfish Substation accident.

### 6.4 Removal of Ground Link Between Welding Machine and Truck Chassis

The question came up about whether or not the worker would have suffered injury if the ground link between the welding machine and the truck chassis had not been present. The reasoning is that, with the ground link removed, the welding machine would have been electrically isolated. This in turn would have eliminated any return path back to the welding machine through the worker.

In the Spearfish Substation circuit, removal of this ground link does not eliminate all paths back to the welding machine (Figure 10). Tests performed in the laboratory investigating the effects of ground link removal are shown in Table 3. From these tests, the following observations are made:

1) The absolute worst case high frequency current measured at the laboratory was 12.0-Amps pk at 6.0-kV pk. This occurred when:
   a) The ground link between the welding machine and truck chassis was **REMOVED**,
   b) The connection between the bracket and riser was **FLOATING**, and
   c) An arc was struck on the riser.

2) Even with the bracket and riser bonded together, removal of the ground link **INCREASED** the amount of high frequency current applied to the worker (as compared with the case where the ground link was installed).
The ground link between the welding machine and truck chassis is installed on BPA trucks for convenience. With the link in place, welding can be performed on a small workpiece by simply attaching it to the truck chassis, eliminating the need of uncoiling and attaching the welding machine ground lead to the workpiece. Also, with the truck chassis grounded to a tower during field work, welding can be performed on the tower without having to use the welding machine ground lead.

In summary, removal of the ground link between the welding machine and truck chassis is not recommended because:

1) It increases the risk of injury to the worker from a high frequency standpoint, and

2) It generates more work for people doing the welding.
6.5 Tests On Work Gloves

Pigskin leather work gloves were found to provide some degree of electrical insulation:

1) Both slightly soiled and moderately soiled DRY gloves have Megger readings in excess of 2000 MΩ.
2) Sixty hertz tests showed that DRY gloves had a resistance of more than 8 MΩ. However, they provide no insulation from a 60 Hz standpoint if they become wet.

7. SAFETY ISSUES

7.1 Miller Safety Literature

The literature that the Miller Company puts out with the 44D welding machine warns against workers coming in direct contact with the stinger or workpiece being welded. Warnings from the literature are as follows:

1) "Never touch the electrode and any metal object unless the welding power source is off."14 This statement implies that a worker should NEVER touch the hot end of the welding circuit while touching another metal object, (especially if the other object is grounded).
2) "WARNING: ELECTRIC SHOCK can kill... Do not touch live electrical parts."15
3) "...high frequency arcing through the electrode holder can seriously injure the operator."16 This implies that the high frequency output is dangerous, thus workers must avoid contact with any object that may be subject to high frequency output.
4) "Wear dry [electrical] insulating gloves... Keep body & clothing dry."17

7.2 Miller Safety Sticker

Warning stickers have been issued by Miller to be placed on welding machines (Figure 11). Notice in particular the electrical safety precautions:

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ELECTRIC SHOCK can kill.

- Do not touch live electrical parts.
- Install according to Owner’s Manual and applicable codes.
- Keep all panels, covers, and guards in place.
- Wear dry insulating gloves and body protection.
- Stop engine before touching electrode, welding wire, or any metal parts in weld circuit unless wearing proper insulating gloves and clothing.
- Stop engine, and disconnect negative battery cable from battery before making any connections or servicing.

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From test results and analysis of how the human body responds to electrical current, we conclude that the primary cause of injuries to the BPA worker was the 60 Hz output from the welding machine. The injuries occurred as a result of three factors, all of which had to be present:

1) Electrical isolation due to an oversize fit between the grounded bracket and riser that the worker was holding on.
2) Working bare handed.
3) One hand gripping the riser and the other hand gripping the grounded steel rack structure.

This type of accident has never occurred at BPA before. Probable reasons for this are:

1) The pieces being welded have been solidly bonded together so that the worker is not the only return path back to the welding machine.
2) The worker has worn dry leather workgloves that provide some amount of electrical insulation from the output of the welding machine.
3) The worker has steadied a workpiece using both hands or using only one hand (with the other hand not touching a grounded object). In this type of situation, the possible path through the worker includes the worker's footwear. Footwear having a large resistance would provide a small amount of insulation to the worker (helping to eliminate a good conductive path back to the welding machine through the human body).
7.4 Leather Workgloves And Electrical Protection

Mention has been made throughout this paper that dry, pigskin leather work gloves may have helped prevent this type of accident from happening in the past. However, the following precaution must be noted:

Although DRY pigskin leather work gloves provide a worker with some degree of electrical insulation, leather work gloves should not be used as a means of providing a worker with electrical protection!! Dry leather workgloves have probably kept electrical contact accidents involving welding machines from happening in the past, but any electrical insulation has been by chance and not by design. Pigskin leather workgloves should never be used as a means of providing workers with electrical protection!

7.5 Summary Of Physical Impact On The Worker

1) **Muscle Tetanization:** Under the “worst-case” scenario for the Spearfish Substation accident, the 60 Hz current of 54 mA-rms was high enough to tetanize muscles in the arm, and possibly the chest of the worker. One hypothesis for the traumatic shoulder injury is that tetanizing muscle forces caused by electrical stimulation may have been enough to cause the damage. To be more confident of this hypothesis, we would need to extend our evaluation to account for muscle forces, position of the limbs during the accident, and the strength of bone.18

2) **Thermal Damage:** The currents associated with the Spearfish accident would not have been large enough to generate any injuries due to thermal effects because the duration of current flow only lasted a few seconds.19

3) **Cardiac Dangers:** The 60 Hz output from the welding machine cannot be ruled out as having a possible influence on cardiac function during the exposure, although fibrillation does not appear to have been a credible hazard. The high frequency component postulated for the Spearfish accident was not likely to have affected cardiac function.20

7.5 Prevention Of Future Accidents

To prevent this type of accident in the future, BPA's Safety Office has issued the following precautions covering work situations similar to those encountered at Spearfish Substation:

1) Preparations for welding high voltage circuit parts will include electrically bonding such parts.

2) If the parts being welded need to be steadied, [or] supported, this should be done using some type of insulating device or material (hotstick, rope, etc.).

3) As part of the switching process for clearances which include voltage regulators, the regulators will be placed on manual, neutral, and the high side disconnects opened.

Test results presented in this paper indicate that Precautions (1) and (2) are the most significant. If followed, these two precautions eliminate the need for Precaution (3).
8. CONCLUSIONS

1) Injuries to the BPA worker occurred because he came in bare handed contact with a grounded steel rack and a riser that was being welded.

2) The primary cause of the injuries was the 60 Hz output from the welding machine. The 60 Hz voltage output had the capability of generating enough current to tetanize the muscles in the worker's arms and chest, probably leading to the muscle, tissue, and bone damage to his shoulder.

3) Testing has shown that, for a worker who comes in bare hand-to-hand contact with a piece being welded and a grounded tower, neither the 60 Hz nor the high frequency output from the welding machine can be reduced to a safe level. Although a great deal of high frequency current is required to produce a given effect on the human body, we cannot say that the high frequency output from the welding machine is harmless. The effect of 4.0 Amps-pk at high frequency (if the high frequency is continuous) will be the same as 7 mA-rms at 60 Hz, and this level is slightly less than half of the "let-go" value of 16 mA-rms. Even 7 mA-rms of 60 Hz current will cause enough discomfort for a person to jerk their arm out of the circuit.

4) Although workpieces should be bonded together and grounded, this does not safely guard the worker against either the 60 Hz or the high frequency output from the welding machine for bare, hand-to-hand contact with a piece being welded and grounded structure!

5) Literature from the Miller welding machine company warns against coming in direct contact with the stinger or a workpiece being welded.

In short, all who work around welding machines should observe to this warning:

Workers must not, under any circumstances, come in contact with a piece being welded unless some type of electrical insulating device is placed between the worker and workpiece!

9. REFERENCES & NOTES

6 $X_{C_{\text{skin}}}$ (capacitive impedance of skin) is calculated as follows: $X_{C_{\text{skin}}} = 1/(2\pi f C)$, $f=$frequency of signal (Hz), $C=$skin capacitance (in farads).
7 $X_C$ (capacitive impedance) $= 1/(2\pi f C)$.
8 $X_L$ (inductive impedance) $= 2\pi f L$.
12 For a sinusoidal waveform: peak current $= \text{rms current} \times \sqrt{2}$.
13 For a sinusoidal waveform: $\text{rms current} = \text{peak current} / \sqrt{2}$.