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Forensic Engineering Analysis of Electric Shock From Failed Ground Fault Circuit Interrupter (GFCI)

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Abstract

Many electrical wiring systems include Ground Fault Circuit Interrupters (GFCI) as protective elements. The application is for avoidance of electric shock injuries to a person in the event that their body becomes part of an electrical circuit path from a live wire and ground. The theory behind the device is that if there is a difference in electrical current flowing through the live (120 volt ac) wire and the Neutral wire, then the difference current is flowing to ground and is potentially hazardous to a person. Functionally, the GFCI should automatically open the electrical circuit above a certain ground current value. This paper explores how the circuit may fail to provide the protection for which it is intended, and result in an electric shock.

Introduction

There have been instances where electrical shock, and even electrocution, were the direct result of a GFCI not opening the electrical circuit when it should have. A European version is called RCD, and it operates with 220 volt circuits. This paper specifically addresses the 120 volt GFCIs used in USA, and presents graphic results of tests on 120 volt units. In some cases, the circuit-opening mechanism developed some mechanical retardation which made it slow in opening the circuit, and the slowness exacerbated the fact that some internal electrical components will fail catastrophically because they are under-rated for prolonged energizing. In other cases, repeated electrical over-stress of another component will cause it to fail catastrophically and burn-up adjacent electrical components which comprise the protective circuit. The latter was discussed previously in Journal of NAFE[6], Vol. XVII, No. 1, on Metal Oxide Varistors (MOV). Results are summarized in this paper, along with two other principal component failures which result in inoperative circuit protection from shock.

Background

Electrical current affects the human body. But there are variations from person to person, of the specific effect of various current levels, related to age, sex, health, and other factors. References to literature on electric shocks[1, 3. 4] are

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included at the end of this paper. Typical human body reactions to a range of currents is listed in Figure 1. The sketch at left represents a current flowing from a hand, through the body and down to a foot, which would be typical of someone grabbing a defective power tool while standing on wet earth. The two columns at the right show the physiological effect at some representative current ranges. GFCIs are designed to operate at approximately 5 milliamps (0.005 amps), so that current higher than the specified trip current should reliably and automatically open the electrical circuit. Opening the circuit removes power from the "load" where the victim may have contact, and also eliminates the difference current which had caused the device to act in the first place.

The issue of electrical shock from a circuit which includes a GFCI arises when the GFCI fails to respond to the stimulus of an excessive difference current. The failure to respond may be result of internal component specifications, past history, or mechanical problems in the un-latch mechanisms. This paper explains that failures may not be visible from an outside view and that internal inspection may be necessary to determine the exact cause of GFCI failure to interrupt the electrical power flow through it.

References to publications relating to human body resistance and electrical shock are available in the literature[2, 5].

Outside and Inside Views of Typical GFCI

Outside views of a typical GFCI are shown in A and B of Figure 2. Units that had internal failures did not look any different outside – no blackening, char, or burning. Photos C and D show the dis-assembled GFCI, with labels indicating the MOV (Movistor, Metal Oxide Varistor), SCR (Silicon Controlled Rectifier), and COIL (the solenoid which should pull a plunger and mechanical assembly to mechanically open the power contacts).

Electrical Circuit and Basic Operation

Schematic of the circuit is shown in simplified form in A of Figure 3. Toroids (ceramic toroidal cores) sense the difference current between the line (120volts) and Neutral line. In normal state, the relay contacts are closed (making contact) so that there is electrical power flow through the GFCI. The SCR within a diode bridge will energize the coil when a difference current is sensed, and should cause the relay contacts to open (shut off power flow). Lower right of figure shows the victim being provided a shock current from the 120 volt line and Ground. The current flowing to Ground does not pass through the toroid, which thus senses the current imbalance.

In B of that drawing, the pulses are shown being delivered to the gate terminal of the SCR because a current difference has been detected, and arrows show the current flow delivered through the relay coil. For simplicity of presentation, only the one direction of current flow is shown, whereas this is an ac circuit and would have current flowing in either direction, depending upon the voltage polarity at that time. From an operational point of view, unless all components are functioning, the relay contacts will not open as they should. Through Circuit Analysis and testing of GFCIs, it was observed that prominent modes of GFCI failure, that is the component failures which make GFCI inoperative, are SCR, Relay COIL, and MOV. Examples of these failures are shown in this paper. Photographs were taken by the author.

SCR Failure – Photo Group

For convenience in displaying the SCR failure mode, the relay coil was removed from the circuit and externally wired next to the circuit board. Relay contacts were physically removed from the circuit and electrically bypassed, which is equivalent to mechanical friction or foreign matter inclusion into the mechanism preventing or slowing the contact opening. The SCR rating makes it suitable only for short time operation, and if the operation extends to one or more seconds, the SCR may fail. Figure 4 sequence A, B, and C shows coil overheating, followed by the SCR blowing out, and finally a massive flash as the SCR destroys itself. Photo D shows the hole blown in side of case for the test shown above. Photo D shows a SCR from another test, where part of the case was blown off.

In an actual case, a service person came into contact with an outdoor illuminated sign and received a fatal electrical shock. The sign had an internal electrical problem which energized the sign’s frame, and its power cord was plugged into a GFCI outlet. The GFCI did not prevent his shock and was found to be non-responsive to ground currents. Dis-assembly and examination of the GFCI revealed that the SCR case was blown open, much like Photograph E in Figure 4.

COIL Failure – Photo Group

The same test display setup was used in this test as was used in the above SCR test. Figure 5, A, B, and C show the COIL overheating, smoking, and eventually failing with bright flash and flying metal sparks. Photo D is the coil from this test, with beading on separated ends of coil wires, indicating that there was an electrical arc, consistent with the observed flash. Photo E is of a coil in another test, where the bead is also shown.

An explanation for the two different component failures (SCR or COIL) in tests which were similarly set-up, appears to be that there is variation in the precise SCR, where some SCR’s fail quickly. And if the particular SCR holds on for a longer time, the COIL fails. In either case, whether it is the SCR or the

COIL which explodes, the result is the same. The GFCI becomes non-functional to any subsequent current imbalance, and therefore offers no protection.

MOV Failure – Curves and Photos

Metal Oxide Varistors (MOV) are included in the GFCI package to capture surges, and prevent circuit damage from those surges. Problem is that the knee of the curve for a MOV shifts toward the lower breakdown voltages as a result of repeated surges or sustained over-voltage for a period of time. This is the effect of whatever comes in on the power line such as high voltage surges or voltage spikes from inductive circuits or lightning. This catastrophic failure of MOVs was discussed in more detail in the NAFE Journal[6] article listed in the Introduction to this paper. When the MOV fails, it does so catastrophically, and burns up nearby components which are necessary for the proper functioning of the GFCI.

In Figure 6, curve A shows degradation of MOV by successive voltage pulses over the lifetime of the device. Curve B shows this in a different way, that the knee of the curve moves to lower voltages, as a reaction to degrading influences on the device. The curves were derived from manufacturer's data. Photos C and D show the burned circuit board and burned components (Compare it to unburned unit in Figure 2, C and D.) with an arrow pointing to the MOV. In Figure 6 C, the device is burned and the case is split open, allowing the flash to burn nearby components. Figure 6 D shows where the MOV totally blew up and only one of its wire leads remains in the circuit board. The component victim of an exploding MOV appears to be the SCR, but fatal damage to other components like the IC (Integrated Circuit) is also possible, with the same end result, that the GFCI becomes inoperative and non-functional to any subsequent current imbalance, and therefore offers no protection.

An actual case was in a boat yard, where one worker was using an electric tool inside the steel hull boat which was out of the water on a boat cradle. A second worker received a fatal electrical shock when his body touched the outside of the boat's hull, while he stood in wet ground. The GFCI supplying power to the electric tool was examined and found to be non-responsive to ground currents. The MOV had blown up, detonated, and caused failure of electronic components related to the protection circuitry components which were near-by. Four additional GFCI's from the same boat yard were examined and found to also have blown MOVs, and they were also non-functional.

Conclusion and Recommendation to FE Investigator

By way of summary, the following observations are offered for the reader's consideration:

- After failure of SCR, COIL, or MOV, the GFCI becomes totally non-functional, and can deliver fatal electrical shocks to the victim.
- Investigator can not identify failure mode externally by simply looking at the outside of the case, because failures are inside case and typically produce virtually no external clues.
- In order to determine the actual cause of GFCI failure, the investigator must open the case after putting all interested parties on notice. X-Rays can be made prior to opening, but may not reveal aberrations of electronic components because the steel and brass internal elements are more dense and tend to mask the electronic components, which are less dense than the solid metal elements.
- Identification of the actual cause of the failure can generally be achieved by observing visual signs inside the case, without any electrical testing. Examples of prominent failure modes and their physical appearances were presented in this paper.
- If following visual signs does not reveal the cause, electrical testing and removal of components from the circuit board may become necessary to identify other component failures.

This paper has attempted to provide insight into the operation and principal modes of GFCI failure to protect a victim from electrical shock injuries. Results are based upon circuit analysis and tests, and are intended as a guide in investigation and evaluation of electrical shock injuries, where the point of victim contact is down-stream from a GFCI.

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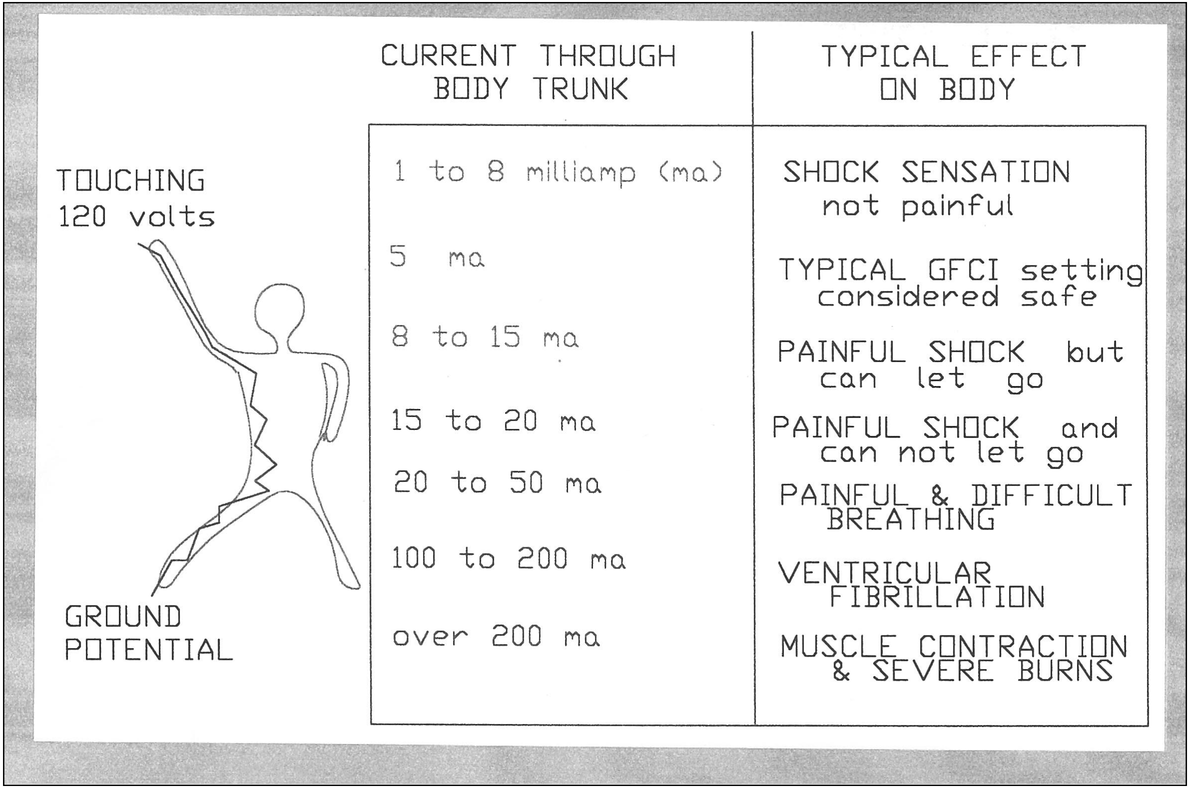

CURRENT THROUGH BODY TRUNK	TYPICAL EFFECT ON BODY
1 to 8 milliamp (ma)	SHOCK SENSATION not painful
5 ma	TYPICAL GFCI setting considered safe
8 to 15 ma	PAINFUL SHOCK but can let go
15 to 20 ma	PAINFUL SHOCK and can not let go
20 to 50 ma	PAINFUL & DIFFICULT BREATHING
100 to 200 ma	VENTRICULAR FIBRILLATION
over 200 ma	MUSCLE CONTRACTION & SEVERE BURNS

Figure 1

Chart showing currents through body trunk, and typical effects on body

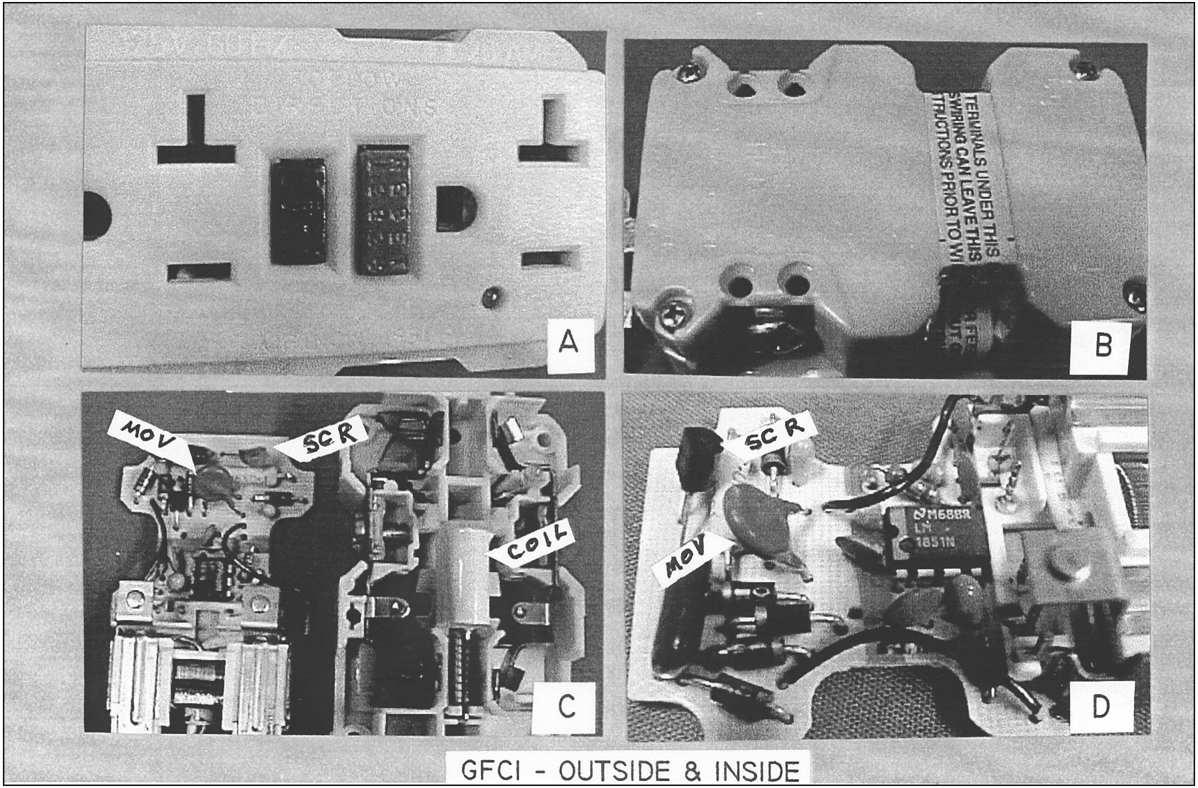

Figure 2
External views and internal views of GFCI, with internal components tagged

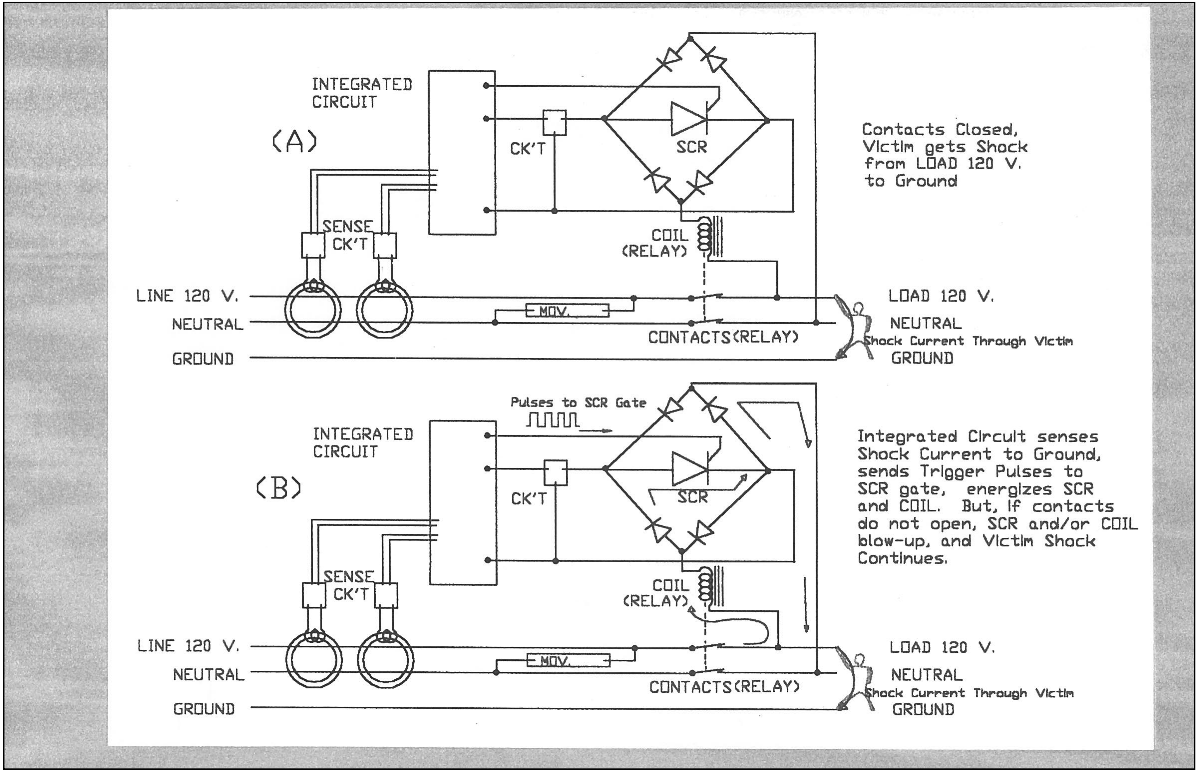

Figure 3
Schematics, showing (A) typical circuit, with body contact from load 120 volt line to ground and (B) Circuit response, with current path through SCR and relay coil.

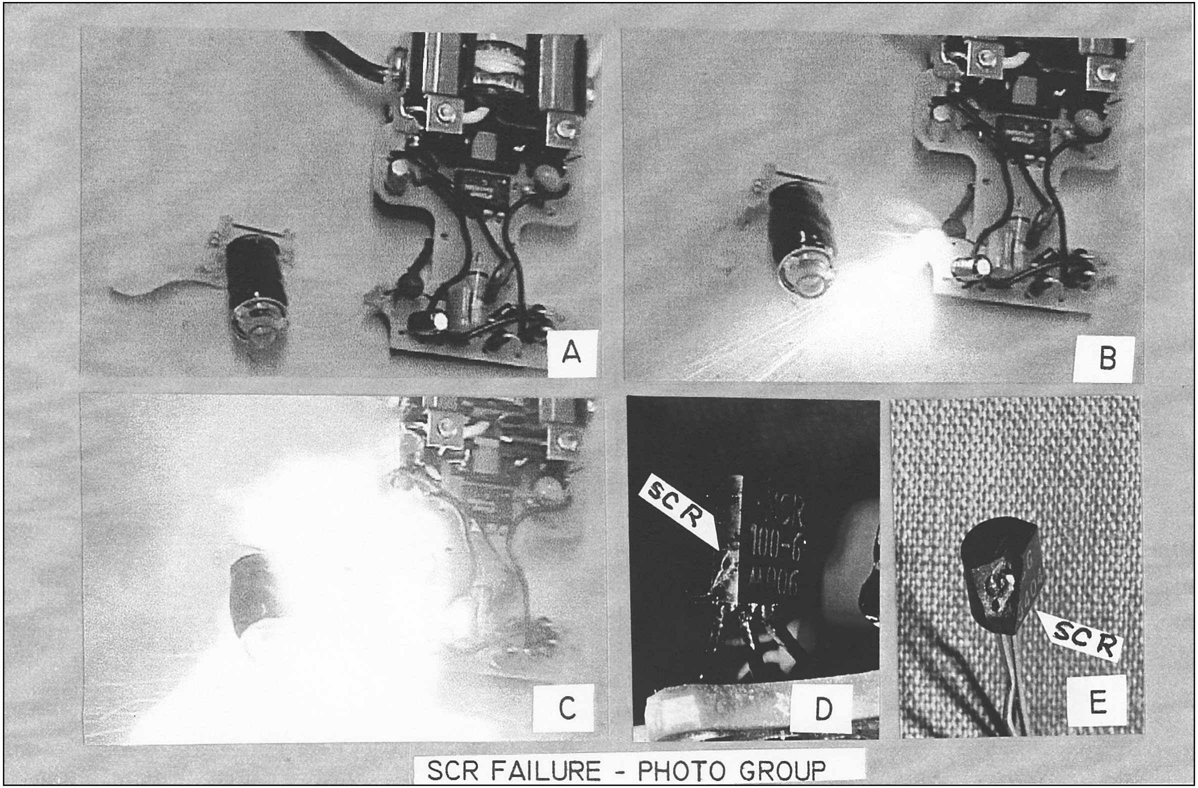

Figure 4
Photo group showing SCR failure when relay contacts fail to open quickly enough

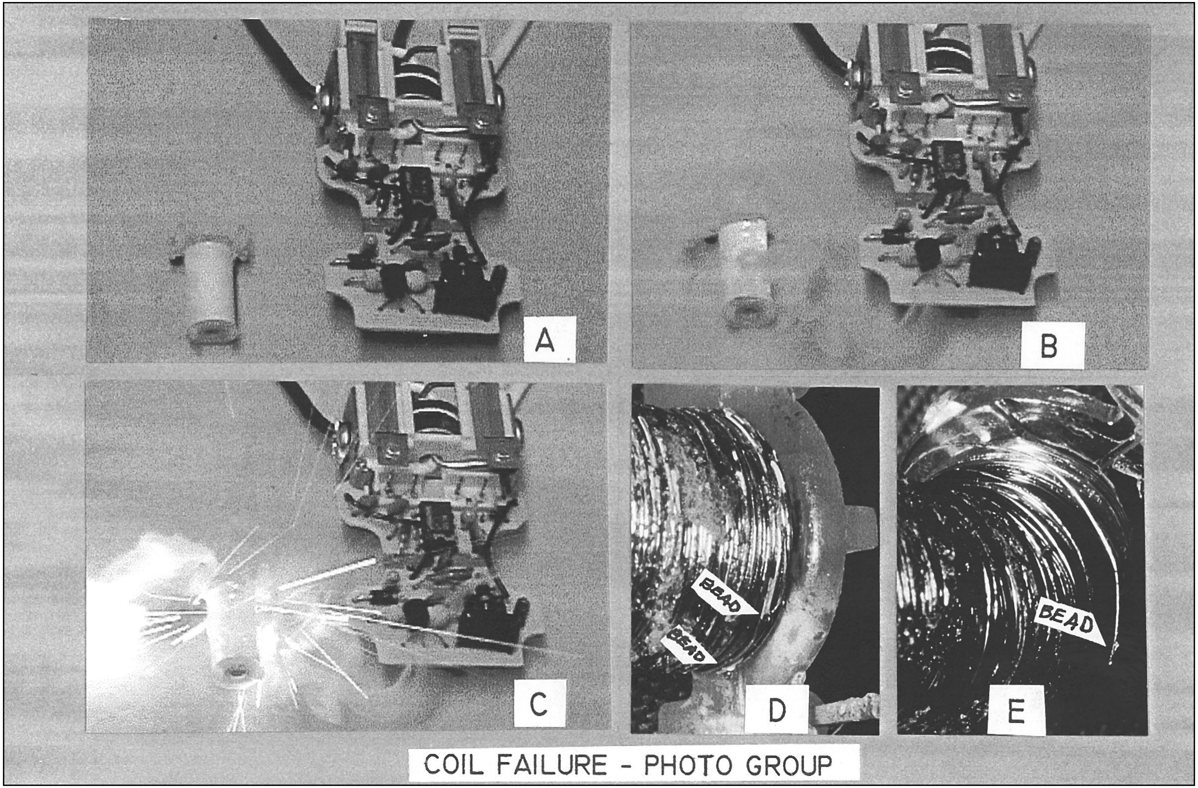

Figure 5
Photo group showing Coil failure when relay contacts fail to open quickly enough

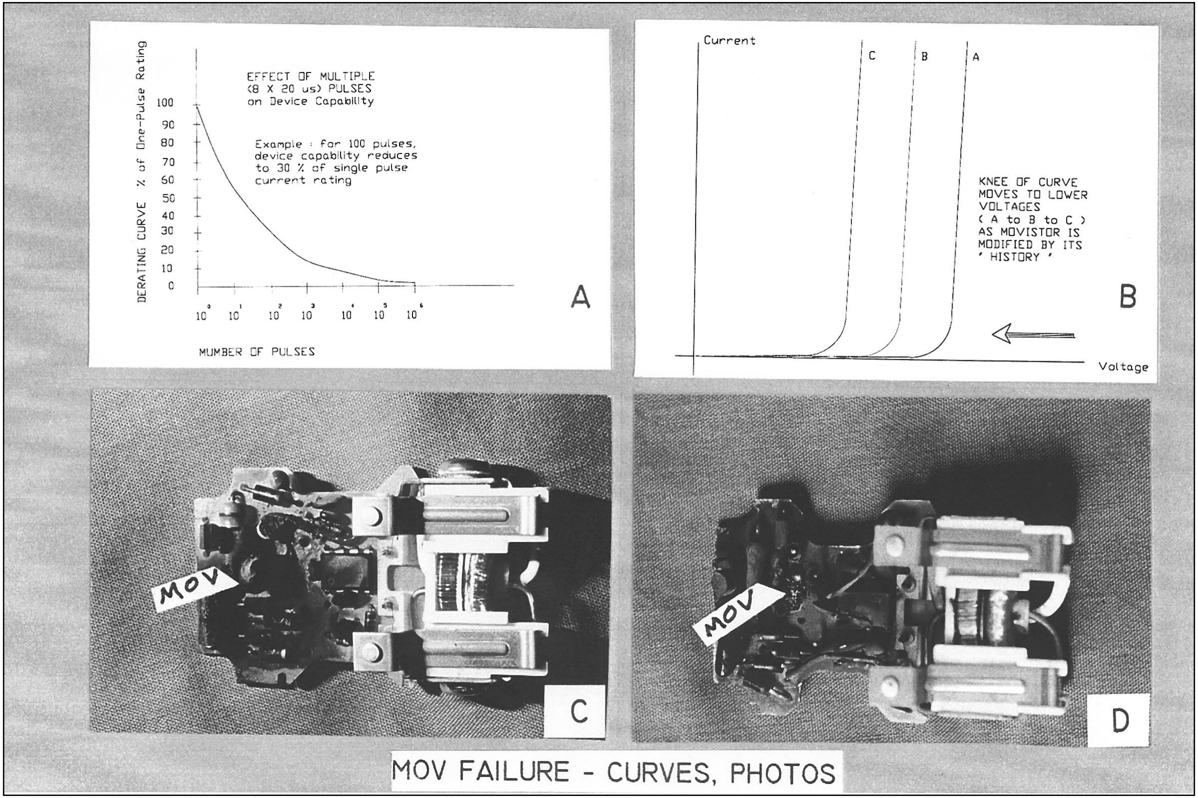

Figure 6

Photo group showing MOV failure due to history of electrical stresses on MOV