Electric Shock

Electric shock is the reaction of the human body to an unnatural passage of electric current through its tissues.

There is no doubt that the passage of electric current through the human body can cause severe injury, and may lead to death. However, there are many myths about the true dangers of electricity, some of which have no basis in reality.

Background

Electricity is an invisible form of energy which flows along conductive paths (often metal 'wires'). This flow results from the movement of sub-atomic, electrically charged particles called electrons.

Definitions

Various terms and definitions are used in the field of electricity.

Conductor - a substance or object through which electricity will flow readily.

Insulator - a substance or object through which electricity will not flow (to any normally measurable extent).

Voltage [V] - the 'pressure' which causes electricity to flow. Measured in Volts. [V]

Current [I] - the rate at which electricity flows. Measured in Amperes or Amps. [A]

Resistance [R] - the property of a conductor to limit the flow of current and convert electrical energy into heat. Measured in Ohms.[Ω]

Charge [Q] - the amount of electricity which flows in a given time, or which may be held in a storage device. Measured in Coulombs, or in Amp-Hours. [C], or [Ah]. One electron holds a charge of 1.6×10^{-19} C.

Energy [E] - the amount of electrical energy which flows in a given time, or which may be held in a storage device. Measured in Joules. [J]

Power [P] - the rate at which electrical energy flows. Measured in Watts. [W]

Direct current [DC] - a current which flows in one direction only.

Alternating current [AC] - a current which alternates between flowing in one direction and the other.

Frequency [f] - the rate at which AC alternates. Measured in Hertz [Hz] (1 Hz = 1 alternation per second).

Capacitance [C] - the ability of an object to store electric charge. Measured in Farads. [F]
A degree of capacitance allows the passage of AC but not DC.

Inductance [L] - the property of a conductor, when carrying a current, to convert electrical energy into magnetic force. A degree of inductance resists the flow of AC (but not DC). Measured in Henries. [H]

Impedance [Z] - the combination of conductor resistance, capacitance, and inductance, and thus the total property of a conductor to resist the flow of current. Impedance is normally dependent on the frequency of alternation of the current flowing. Measured in Ohms.[Ω]

Generator - a device which converts mechanical energy into electrical energy. Generators usually produce AC. By nature, the output voltage follows a mathematical 'sine' waveform.
A dynamo is a generator designed to produce DC - although the output is pulsed, usually with a single-directional half 'sine' voltage waveform.

Battery - a device which converts chemical energy into electrical energy. Batteries only produce DC.

Inverter - an electronic device which creates AC from DC.

Rectifier - an electronic device which converts AC into pulsed DC.

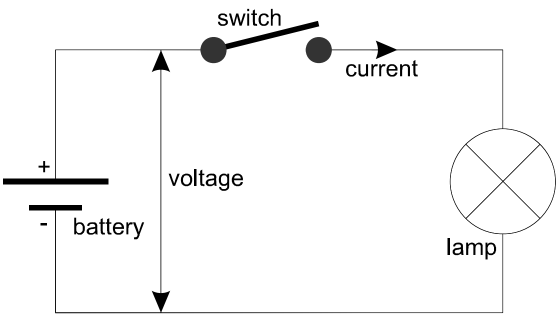
Static electricity - a build-up of electric charge on an object. The charge is classed as either positive or negative. Electrostatic charge will move along any available conducting path, to reduce the opposing charges.

Earth - the planet Earth is considered to be able to absorb infinite amounts of electrical energy; it thus is also considered as being the zero voltage reference point for many electrical systems. Connections are commonly made to Earth to provide protection against electric shock.

Electrical circuits

For a continuous electrical current to flow, conductors must be formed into a closed loop, or circuit, starting and ending at the source of energy - battery or generator.

The diagram below shows a simple circuit. When the switch is closed, current flows from the battery, through the switch, through the lamp, and back to the battery.



The flow of current moves stored energy from the battery to the lamp, where it is given off as heat and light.

Opening the switch breaks the circuit, prevents current flow, and halts energy movement.

The current in the circuit is proportional to the voltage and the resistance, according to the simple formula: $I=V \div R$. This is known as Ohm's Law.

The energy transferred to the lamp is proportional the applied voltage, the current, and time: $E=V \times I \times t$. The power, or rate of flow of energy, is given by: $P=V \times I$.

Static electricity

Static electricity results from a build-up of electric charge on two objects (usually insulators, or surrounded by insulators) which have become separated after having been in contact or close proximity.

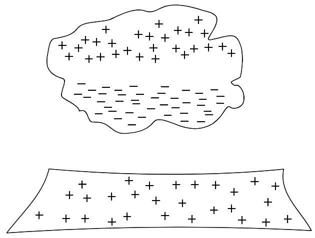
The act of a person walking across a carpet may lead to an electro-static charge build-up of 10kV, or more.

An electrostatic discharge (ESD) occurs when static electric charge moves from one charged object to another. This movement of charge (which constitutes a current) does not require a circuit - just a single conducting path. It may occur over a period of time, or may be almost instantaneous, depending on the resistance of the path between the objects.

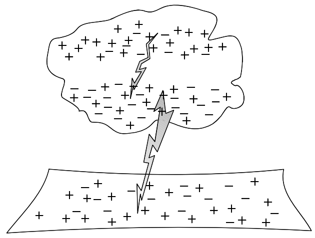
Much electrostatic discharge occurs imperceptibly through the air, conducted via humidity.

If an electrostatically charged object is brought near another object, charge will move in this other object according to the rule 'like charges repel; opposing charges attract'. As a result of this action, a small mechanical force will build up between the two objects - attracting them together.

Lightning



Lightning is a natural phenomenon which occurs following a massive buildup of electrostatic charge in cloud formations - particularly cumulo-nimbus clouds.



As ice particles form within the clouds, positive and negative charges build up in the upper and lower levels of the cloud formation. The negative charge in the cloud base creates a corresponding buildup of positive charge on the ground underneath.

If the charges build up a high enough voltage (which may exceed 1000MV), charge will begin to flow through the cloud, and in the air down to Earth. This initial movement of charge is almost invisible, but it is followed by a sudden 'flash-over', which gives a visible lightning flash.

A typical lightning flash dissipates 500MJ of energy with a discharge current of 40kA, and heats surrounding air to a temperature of around 10,000ºC.

This vast amount of dissipated energy leads to massive movements of air, and to shock waves which may be heard as thunder.

The rolling or crashing thunder sound occurs as the time-delayed sound reaches the listener from different points along a long discharge path.

The Passage of Electricity through the Human Body

The human body will conduct electricity if it becomes involved in a current path or circuit.

The actual current which will pass is determined by the voltage applied and the impedance of the body.

The impedance of the human body

Body tissue contains a significant proportion of water, in which salts are dissolved. This solution conducts electricity relatively well. Conversely, the skin, through which any electric current must normally pass, has a fairly high resistance - especially when dry.

The overall impedance of the human body varies widely, and is almost unpredictable. It varies from person to person, and depends on many factors such as contact area, moisture, voltage, and the path through the body.

Total body impedance

The total body impedance is measured either from one hand to the other, or from a hand to a foot. The two routes give the same approximate value. The total body impedance is the sum of the impedance of the skin and the internal body impedance.

The impedance of the skin

The impedance of the skin varies according to several factors, including the applied voltage and its frequency; contact area, moisture, and the duration of current flow.

Dry skin has a relatively high resistance - over 10MΩ per square millimetre. However it has considerable capacitance and is thus able to conduct AC more readily than DC, with a decreasing impedance as the frequency increases. The impedance of the skin is directly inversely proportional to the contact area, thus the resistance for 1 square centimetre is approximately 100kΩ.

The resistance of wet skin is very much less than that of dry skin. The resistance falls even lower if the skin is wetted with a conductive solution. Additionally, breaking or abrading the skin further lowers its resistance.

The impedance of the skin is affected by the voltage applied - for voltages over 50V, the impedance falls significantly with increasing voltage, reaching almost zero at around 200V, when the skin begins to break down.

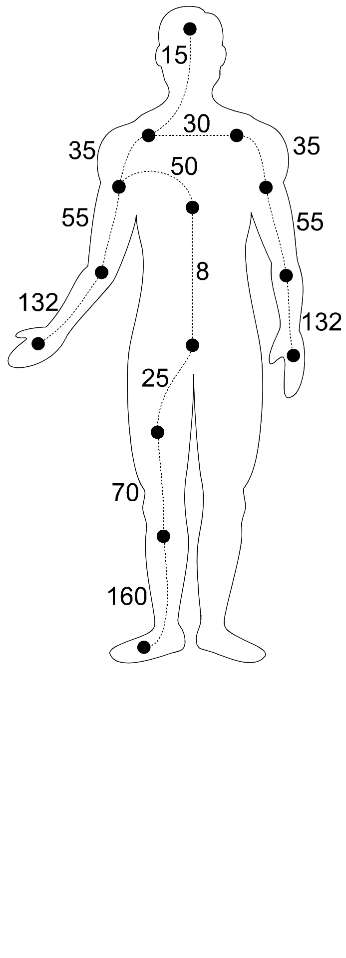
The internal body impedance

The internal body impedance depends mainly on the route of the current path; the shorter the path, the lower the impedance. eg. the impedance from one hand to the forehead is 50% of the impedance from one hand to the other.

The impedance varies depending on the types of tissue involved: muscles and blood vessels readily conduct electricity, whereas bone tissue and fat tissue do not.

The diagram below indicates values, in Ohms, for the impedance between various internal areas of the body, taking an average value of 500Ω for the impedance from the right hand to the right foot.

The impedances of the wrists and ankles are relatively high. This is because these areas consist of multiple bones with little other tissue.

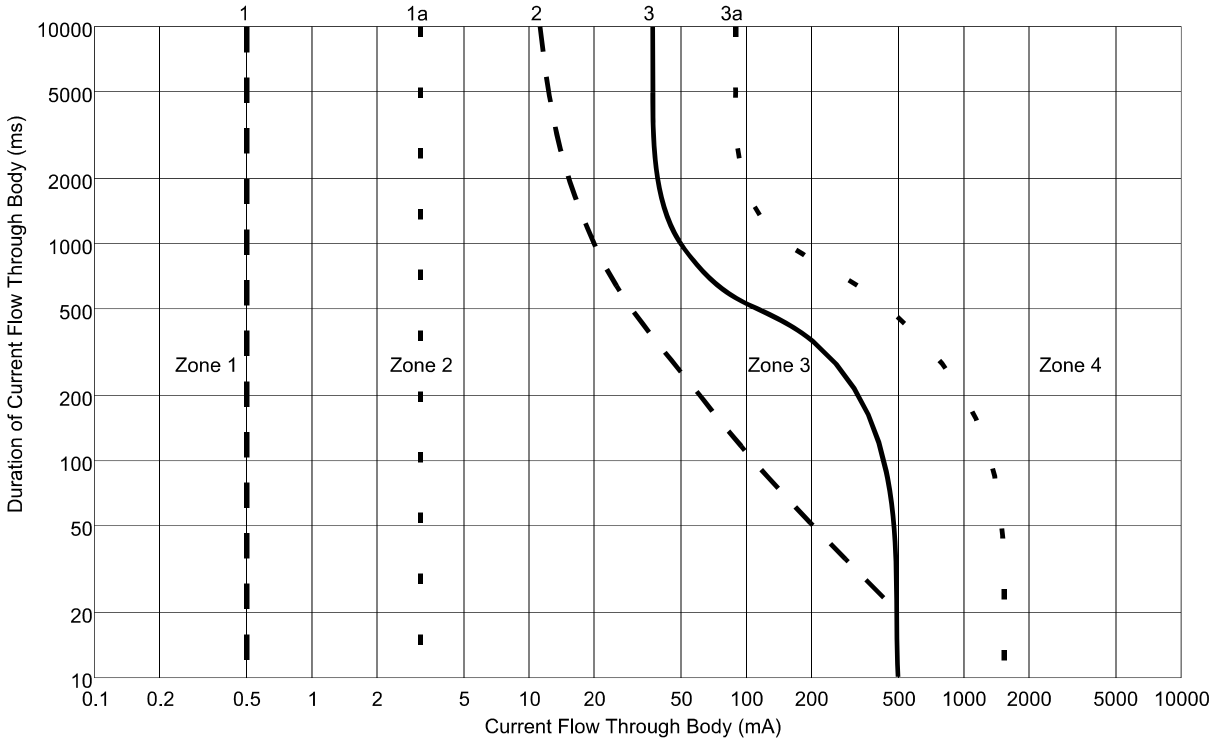


The Effects of Current passing through the Human body

The severity of any effects caused by electric current flow through the human body depends on the amount of charge passed - ie. the combination of the current and the duration of the flow. The main effects are sensation, muscular action, cardiac arrhythmias, tissue cell damage, and burning. Apart from sensation, all effects worsen as the duration of the current flow increases.

The following chart indicates the possible effects on a person passing an alternating electric current. The current path is assumed to be from the left hand to both feet (ie. across the heart).

The effects of DC are similar for currents above 500mA, but the effects are considerably less than for an equivalent AC at lower current levels.



Zone	Likely Effects of Current Flow
Zone 1	no sensation
Zone 2	increasing sensation, reaching pain at line 1a; no permanent harm
Zone 3	muscular contractions, including disturbances to respiration and heartbeat; disturbances to cardiac rhythms; no tissue damage
Zone 4	ventricular fibrillation, increasing in probability to 50% by line 3a; as current and time increase: tissue damage, burns, respiratory and cardiac arrest

Sensation

Electric current stimulates sensory nerves through which it passes.

With AC, the sensation varies with the current, from tingling at 0.5mA, through discomfort at 2mA, to pain at 3mA and above.

With DC, only the making or breaking of the current causes actual pain. An increasing sensation of warmth is felt for any steady current above 2mA.

The agonising sensations caused by the long term passage of high currents tend to be masked by other effects such as cardiac arrest.

Muscular action

Electric current stimulates motor nerves and muscle tissue through which it passes.

The muscles of respiration and of the heart are affected as well as the muscles of the limbs, thus giving the risk of respiratory or cardiac disturbances, or even arrest, at all but the lowest current levels.

With AC the muscular action varies with the current, with mild twitching at 1mA, spasms at currents towards 10mA, uncontrollable contraction above 15mA, and total muscular tetanus at 35mA (this usually results in respiratory arrest). Severe muscular action can damage the muscles themselves, tendons and ligaments, or even bones. Also, sudden muscular action may cause a person to fall, or to collide with other objects, thus leading to injury.

With currents above 10mA, it becomes very difficult to 'let go' of an electrical contact held in the hand; this may well be impossible above 15mA.

DC has less effect on the muscular system than AC, causing significant contraction only when the current is made or broken, although currents above 300mA tend to inhibit normal muscular action and prevent 'let go'.

Cardiac arrhythmias

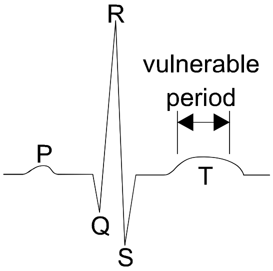
The heart is controlled by electrical discharges. These may be disturbed or masked by an electric current flowing through the heart, in addition to any direct effects on the heart's muscular action.

The effects caused depend on both the current magnitude and the duration of current flow.

12mA AC, over more than a few seconds, can lead to extrasystoles, atrial fibrillation, and actual temporary cardiac arrest, although permanent damage is not likely.

50mA AC can cause ventricular fibrillation (VF) if applied for more than 1 second.

As the current increases towards 500mA, the duration of a shock likely to cause VF shortens towards 100ms.



With shock durations below 100ms, the likelihood of VF is much less if the shock falls outside the vulnerable period of the cardiac cycle. This period occurs as the ventricles repolarise - during the T wave of the ECG.

Currents of several Amps (AC or DC), for longer than 1 cardiac cycle, tend to cause total contraction of all cardiac muscle, and cardiac arrest. If significant tissue damage does not occur, cardiac function may well return to normal following removal of the current. This phenomenon is known as defibrillation.

The effects of shocks from steady DC of less than 500mA are considerably less than those of an equivalent AC.

Cell damage

Tissue cells are surrounded by membranes which act as electrical insulators (except to high frequency AC). Low levels of current - DC or low frequency AC - pass around the cells, leaving them unharmed.

At current levels above 100mA, the electric field developed around a cell begins to draw water molecules into the cell, disturbing its pores. If too much water is drawn in, the pores expand too far and rupture the membrane, damaging, or destroying, the cell. This effect is known as electroporation.

Electroporation is reversible for currents up to 200mA applied for less than 5 seconds; above these levels, it can cause permanent tissue damage.

Burning

If human tissue is heated to over 45°C for any length of time, damage is likely. The passage of current through body tissue produces heat. 200mA passing for 5 seconds can heat body tissue to 45°C, 70°C after 5 seconds of 500mA - causing severe damage. Electroporation adds to the damage at higher current levels.

As the majority of damage tends to occur in deep tissues rather than in superficial layers, the full extent of an electrical burn may not become apparent until several days after the injury.

High voltage, high energy sources are capable of passing currents of many Amps through the body. The high voltage forces the current through all types of tissue, generating intense heat, evaporating water from the tissues, and resulting in almost total destruction of tissue along the current path.

Contact burns

The points of contact with an electrical source are common sites for skin tissue damage.

The extent of the damage depends on the current flow per area of skin, and on the duration of flow.

Effects vary from reddening at current densities of 10 - 20 mA/mm^2, through discoloration and blistering at 20 - 50 mA/mm^2, to actual tissue destruction and carbonisation at current densities above 50mA/mm^2.

Flash burns

An electric arc is produced whenever electric current jumps through air. This produces heat; that produced by a large arc will be sufficient to cause instantaneous burning of any nearby body tissue.

Electric arcs can damage the eyes, as they produce intense light levels which can harm the corneas or retinas. Such injuries are known as arc eye.

The Risks

Batteries

Small batteries used in household appliances pose no measurable risk of electric shock.

High power batteries used in electrical vehicles may be of high enough voltage to pose significant risk of shock, and are capable of delivering massive amounts of energy.

Domestic mains

Domestic mains (230V AC in the UK) is capable of causing significant harm. The risks vary, depending on contact area, current path through the body, moisture, and the susceptibility of the casualty. Likely injuries vary from small painful shocks with no after effects, through to cardiac arrest and extensive burning if contact is prolonged.

Industrial mains

Industrial mains in the UK varies from 110V, to 400V, and up to several kV.
For voltages much above 230V, any contact is likely to lead to significant current flow through the body and severe injury.

Power distribution systems

The high voltages (up to 100's of kV) and immense amounts of available energy in overhead or underground main distribution cables mean that the consequences of any shock are likely to be severe, and will nearly always be fatal. Even where death does not result, extensive burning and tissue destruction will almost certainly occur.

Static electricity

Small build-ups of static electric charge may cause momentarily painful shocks, but otherwise are harmless.

Lightning

Being 'struck by lightning' almost always causes either death or serious injury, but it is well known that some persons have survived lightning strike virtually unscathed.

Electrical accidents

Electrical accidents may lead to injury. Other consequences of electrical accidents include equipment and appliance damage, and subsequent effects - including the risk of fire and explosion.

Almost all electrical injuries occur either through a lack of care, through ignorance, or through failure to abide by safety rules or good practice.

Apart from lightning strike, electric shocks only occur through contact with, or arcing from, a live electrical conductor; this can happen when:

- A live conductor is wrongly believed to be 'dead'.
- A system which had been switched off to allow safe working is wrongfully re-energised.
- A lack of care or knowledge leads to contact with, or proximity within arcing distance of, a live conductor.
- Degradation and/or lack of maintenance allows failure of insulation or barrier devices.
- Malicious or ignorant action has over-ridden or disabled protective devices, and a hazard arises from faulty equipment.

Potential injuries

The injuries and other effects which may result from an electrical accident may include:

- Pain and discomfort, which may last for some time, but which usually subside without further complications.
- Respiratory problems, ranging from momentary breathlessness to respiratory arrest.
- Cardiac problems, ranging from mild arrhythmias to cardiac arrest.
- Burning, ranging from mild contact burns, through to full thickness, extensive electrical burns. These may be made worse if the contact has been via a ring, bracelet, or similar article.
- Arc eye.
- Disturbances of consciousness, ranging from momentary faintness through to long term total unresponsiveness.
- Injuries resulting from muscular action and sudden impulsive movement, ranging from mild discomfort, through strains and/or sprains, to fractures, internal injuries, and injuries associated with falling.

Protection against Electric Shock

To reduce the risks of electric shock, various measures are taken, both in product and system design, and in working practices.

Use of low voltages

Many modern appliances operate from voltages below 50V - a voltage level which poses minimal risk of dangerous shocks. Power is supplied either from batteries, or from the mains supply via a voltage-reducing power supply, constructed so as to prevent accidental contact with the mains power.

Insulation

Human contact with conductors or parts of equipment carrying hazardous voltages is prevented by a covering of insulating material such as rubber or plastic.

In many appliances, insulation is ‘doubled’, offering protection against electric shock without the need for additional measures such as earthing.

Protective earthing

Hazardous electrical parts are enclosed in a conductive housing which is then connected to Earth by a separate conductor.

The connection to Earth prevents the housing becoming ‘live’ should a fault occur which might otherwise cause this.

Separation

Human contact with conductors is prevented by physical separation, enforced by physical barriers, such as is the case with overhead distribution lines, distribution switching centres, and sub-stations.

Fuses and overcurrent devices

Fuses are intended as ‘weak links’ in a system. They overheat, melt, and break the circuit when an abnormally high current flows - such as may occur through an overload or fault condition.

Overcurrent devices are switch devices, but they include mechanisms to sense the amount of current passing through them, and automatically break the circuit should that current exceed a pre-determined level. Thus they give protection in a similar manner to fuses, but they are re-usable.

Residual current devices

Residual current devices (RCDs) operate by monitoring the current in both flow and return conductors of a circuit; they break the circuit if a fault condition (and thus shock hazard) causes the flow and return to be unequal.

Note: An RCD does not guarantee protection from injury should the fault condition cause current to flow through the human body.

Regulations

Health & Safety regulations require electrical installations and appliances used in places of work to be set up, maintained, and used such as to prevent injury.

Although domestic wiring installations are covered by regulation, workplace regulations do not apply to domestic electrical appliances, although it is good practice to follow similar guidance.

New appliances

EU law requires all electrical appliances for sale within the EU to meet basic safety standards. The presence of the “CE” mark on a product indicates a declaration from the manufacturer that the appliance meets these standards.

Caution is required, however, if purchasing second-hand items, or purchasing items other than via reputable sales outlets, as there is then no guarantee that the items are in ‘new’ and safe condition, or that they actually meet the required standards.

Safety precautions

Basic checks for safety require no special training or equipment. An appliance should not be used if:

> Its casing is damaged such that internal parts are exposed or accessible.

> Its power cable is damaged, frayed, or no longer properly retained.

> Its power plug is damaged or incomplete.

> It shows signs of ‘non-professional’ repair.

> It fails to operate correctly, or abnormal sounds or smells occur when it is used.

Any of the following should be a trigger for an investigation and checks by a suitably trained person:

> Repeated blowing of a fuse, or operation of an overcurrent or residual current device.

> Abnormal sounds or smells occurring from electrical equipment.

> Visible damage, or signs of overheating or burning, to electrical fittings and appliances.

First aid for Electrical Accidents

Ensure safety!

The absolute priority in any case of electric shock is the prevention of further casualties through careless rescue attempts. It is essential that the casualty is disconnected from the power source before any attempt is made to touch them. Ideally, the source of power itself should be safely and securely ‘turned off’.

Low voltage

In situations where the voltage is known to be relatively low (eg. domestic mains power at 230V AC), it is usually possible to unplug or turn off an appliance or circuit. Alternatively, a connection may be pulled away from a casualty using the protection given by the insulation of the appliance or its cable (where these are obviously undamaged). Otherwise it may be possible to use insulating barriers such as dry heavy-duty rubber gloves, or an item such as a broom (preferably made from plastic), to lift a connection away from a casualty.

Higher voltages

In situations where the voltage is either unknown, or is suspected as being high (several thousand volts, or more), the only safe course of action is to remain at least 20 metres from the casualty, and hold bystanders and other would-be rescuers at this distance, until the power has been turned off and declared safe by a suitably knowledgeable person.

Approach and treatment

Once it is safe to approach and touch the casualty, they should be treated as indicated by any conditions or injuries present.

The possibility of other injuries and potential after-effects must always be considered in a casualty who has suffered an electric shock. They should be checked thoroughly, and monitored for some considerable time afterwards.

Initial first aid treatment for electrical burns is as for any other burn - cool with water.

First aid treatment for arc eye is to cover the eyes.

Special notes

Arc eye may take some time (up to six hours) to develop.

Casualties must be referred for hospital treatment in all cases of:

> Electrical burns - however slight they may initially appear to be.

> Arc eye.

> Unconsciousness - however brief - resulting from an electric shock.

> Chest pains, pulse irregularities, breathing difficulties, reduced consciousness or reduced levels of ability following an electric shock.

The cause of an electrical accident will almost certainly require action if further accidents are to be prevented:

> A faulty appliance must be withdrawn from service.

> A faulty electrical installation must be de-energised.

> If the accident has occurred in a workplace or to a person at work, a formal report may well be required, together with a formal investigation into the circumstances of the accident.

The duty of initiating any follow up action may not fall directly to the first aider, but they are very likely to be involved.