Topic 17: ELECTRICITY

This *Topic* (dated April 2017) is an updated version of *Topic 17*, which appeared in the 3rd edition of *Topics in Safety* (ASE, 2001). Some parts need updating, particularly the section on batteries, and on portable appliance tests where the Health and Safety Executive has moved to a more proportionate risk-based approach.

17.1 Electrical hazards

The principal electrical hazards are injury or death by electric shock (electrocution[1]), burns from currents flowing through body tissues, fires from overloaded cables or devices, and burns from hot components and conductors. The risks from electric shock are reduced by using low voltages where practicable, insulation of the electrical conductors, an earthed conducting cover, and physical barriers to keep people away from the conductors. The risks from electric shock, electrical burns and fires are reduced by using suitably-sized conductors, and current-overload devices - normally fuses and circuit breakers.

17.1.1 Electrocution and electrical burns

An electric current flowing through a human body interferes with the electrochemical mechanisms of the nervous system and produces the effects known as electric shock. A large current, in addition, causes serious burns. If the current is high enough, it can cause heart fibrillation leading to cardiac arrest. The effect of a current passing through the body depends upon many factors, including the person's age and health, so there is not a precise safe current level. For adults in good health, currents through the body below 5 mA at 50 Hz are regarded as unlikely to cause direct injury. At higher currents, one that flows, say, from one finger to another on the same hand is unlikely to prove fatal, although a serious burn could result. A current which flows through the brain, or which interferes with the heart or breathing, may easily be fatal. In any accident where a current passes from one hand to the other or via the trunk to a foot, it is likely that breathing and the heart could be arrested and first aid will be required while an ambulance is called. Note that before first aid is applied, it is imperative that the electrical supply is switched off, or the electrocuted person is moved well away from the power conductors using an insulated device, otherwise the first-aider could be electrocuted too[2].

The skin of adults provides a layer of insulation which is effective when hard and dry. The soft skin of a child, especially when wet, provides a much lower resistance. If the skin is cut and in contact with a conducting liquid (such as salt water), the resistance becomes low and dangerous currents can flow at quite low voltages. Because of the variation of electrical resistance among persons (and for the same person under different conditions), it is difficult to define a dangerous voltage. While lower voltages can be dangerous in exceptional circumstances, only supplies greater than 40 V dc (or 28 V ac rms) are normally regarded as sufficiently dangerous in schools to warrant protection[3].

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[1] Electrocution originally meant execution by an electric shock, but its meaning has changed over time and is now also defined as injury or death (accidental or otherwise) caused by an electric shock.

[2] HSE has produced a poster - *Electric shock: First aid procedures*. (ISBN: 9780717664337; 2011) This poster gives basic advice on first-aid procedures if someone has been electrocuted, but it is not a substitute for first-aid training.

[3] The definition of 'hazardous live' used in British (and other) Standards is much more complicated than this, allowing for the differing effects of ac, dc and capacitive sources. While a physicist should have no difficulty with such detail, other science teachers could find it confusing and the simpler approach adopted here is likely to be accessible to all.

17.1.2 Overheating, fires

If cables are overloaded, they become excessively hot and can catch fire. An internal fault in equipment could cause an excessive current to flow so that an equipment lead becomes hot. This condition should be prevented by the fuse in the plug, but all too often one finds a standard mains plug fitted with a 13A fuse when a 3A one would be correct. (See section 17.7.3 for advice on fuses.)

The maximum continuous current rating of a cable is usually specified in free air at a particular ambient temperature. If the actual temperature is much higher, or the cable is coiled or running through material that is not a good heat conductor, the maximum current needs to be derated or the cable may overheat. Coiled drum extension cables can catch fire if they are used at the maximum rated current without being fully uncoiled. Appliances often have vents to allow cooling of the internal circuits. If the vents are obstructed, the equipment can overheat and catch fire without the fuse or circuit breaker interrupting the current.

17.2 Batteries

A cell is a single unit containing an anode and cathode in an electrolyte for generating a voltage. (The voltage generated by a cell is also called an electromotive force, or emf. The term voltage is more general, it can refer to an emf and also to the potential difference between different points of an electrical circuit.) Strictly, a battery is a number of separate cells connected together; so for example, a 12 V car battery comprises six 2 V cells in series. However, for most users, it is irrelevant whether the source of electrical power contains a number of cells or only one and the term ‘battery’ is now used generically for both a battery and a cell. 'Battery' is used here to mean both cells and batteries; the term ‘cell’ is only used where it is necessary to identify the single electrochemical unit.

Batteries transfer energy by an electrochemical process. This is a reduction-oxidation (redox) reaction involving an anode and cathode in an electrolyte, where oxidation takes place at the anode and reduction at the cathode. When an external circuit is connected across the anode and cathode, electrons flow through the external circuit from the anode to cathode to cause an electric current. The particular electrochemical process is governed principally by the anode material, the cathode material, and the electrolyte, but the specific detail of the electrochemical designs of commercial batteries is often a trade secret. Confusingly, there is no consistent naming convention for the types of electrochemistry. Some are referred to by the anode and cathode materials, eg nickel-cadmium (nicad), some by the anode and electrolyte, eg lead-acid, some by just the electrolyte, eg zinc chloride.

A characteristic of a particular electrochemical design is the emf. This is the open-circuit voltage - the voltage across the battery terminals with no current flowing. For example, a zinc-manganese dioxide cell has a characteristic emf of about 1.5 V, while a nicad cell is about 1.2 V. The actual emf is temperature dependent and depends on other factors such as the purity of the battery materials. The emf also falls as the battery is used. When choosing a battery, keep in mind the differences in emf among the types of electrochemistry; for example a PP3-size battery, nominally 9 V, may be as low as 7.2 V for NiMH versions. Whatever the electrochemistry, a cell voltage is typically no more than a few volts so a battery is unlikely to produce a voltage high enough to give shocks unless very large numbers of cells are placed in series.

A few types of cell have a very stable characteristic emf and were once used to design voltage references, eg the Weston standard cell. The Weston cell is obsolete for good reason: it was easily damaged and it contained mercury and cadmium. If any are still held in a science department they should be disposed of as hazardous waste. Voltage references have been superseded by cheaper and more-reliable semiconductor devices.

The energy stored in new batteries is reflected in their capacity. This is usually stated in ampere-hour (Ah) or milliampere-hour (mAh) for smaller batteries. It is the current the battery can theoretically deliver through a circuit for an hour before the battery terminal voltage falls below a specified level. The actual conditions at which the rated capacity applies should be stated by the manufacturer, often at a discharge current one-fifth of the value of the capacity. For example, one manufacturer states its 2000 mAh battery is at a discharge of 400 mA which the battery can maintain continuously for five hours.

All batteries have an internal resistance. This causes the voltage across the terminals to fall when a current flows, and the greater the current, the greater the fall. The internal resistance is not constant, and generally it becomes greater as the battery ages through use. The current through the internal resistance causes internal heating and consequently the battery temperature will rise. Excessive gas can also be evolved at high currents. If a battery delivers a sustained current beyond its specification, the pressure may build inside it, causing seals to fail and consequent leakage of electrolyte. Batteries often have vents to release excessive pressure, but the venting can still be relatively violent, particularly with larger capacity batteries. In severe cases, the battery can explode. The electrolyte in many battery designs is corrosive and if it enters the eye from a violent venting, it must be washed out thoroughly to prevent injury.

The term 'dry battery' or ‘dry cell’ is still sometimes used. Batteries were originally designed with liquid electrolytes. This is not useful for applications where the battery is to be used in any orientation, so the battery electrolyte is modified to a paste or gel form. This is called a dry battery. There are few 'wet battery' designs now, the classic one being the 12 V lead-acid car battery.

When a completely discharged cell is subjected to a current in the direction which would tend to discharge it further, it causes damage and the cell can leak, causing damage to the equipment. To avoid this, do not continue to use a battery (here meaning several cells connected in series) when its voltage becomes low. By the same argument, it is better not to connect in series, batteries of different types, or mix new batteries with old. Doing so risks cells leaking, or explosion in severe cases, when the non-discharged batteries drive a current through the completely-discharged ones.

17.2.1 Battery nomenclature

Unfortunately manufacturers do not all use the same system for designating battery size and type. Many use their own system so it can be troublesome finding equivalent batteries from other manufacturers. There is an international IEC system, but this is often ignored. An obsolete ANSI terminology is still in regular use for the small cylindrical household batteries: AAA, AA, C, and D, but this gives information just on the battery size, not the electrochemistry. When finding an equivalent, it is not just the physical size that needs to be the same; the battery electrochemistry and voltage also need to be suitable. Equipment manufacturers often specify what batteries are suitable for their equipment.

17.2.2 Non-rechargeable batteries

Non-rechargeable batteries (also called primary batteries or disposable batteries) are designed for single use and are disposed of as waste when they become discharged.

The oldest type of non-rechargeable consumer battery is based on the Leclanché cell. It has zinc and carbon electrodes, hence it is usually called a zinc-carbon battery even though the electrochemical process is actually between zinc and manganese dioxide. The electrolyte is a paste of aqueous ammonium chloride (or ammonium chloride and zinc chloride) with manganese dioxide. Zinc-chloride batteries are similar, but are usually constructed from higher purity materials and a higher proportion of zinc-chloride in the electrolyte than zinc-carbon ones. If a zinc-carbon or zinc-chloride battery is short-circuited or required to produce a large current, the electrolytic effects cause the battery to ‘polarise' as hydrogen is produced. This causes the voltage to drop and the current to fall to a low level (or even to zero). If the battery is disconnected and left for a while, it normally recovers and will work again. Consequently, zinc-carbon and zinc-chloride batteries are very unlikely to explode and are suitable for use by students under conditions where short-circuits are likely. A disadvantage is that zinc-carbon and zinc-chloride batteries generally have a shorter shelf life compared to, for example, alkaline batteries, and it is best not to buy large stocks a long time ahead of use. The terms ‘Heavy Duty’, ‘Extra Duty’ and so on are often used by suppliers to describe their zinc-carbon and zinc-chloride batteries, but the terms are not useful because they are a comparison to zinc-carbon battery capacity decades ago.

Alkaline-manganese dioxide batteries (often just called alkaline batteries) use zinc-manganese dioxide electrodes but with potassium hydroxide electrolyte. They also have a very different construction to the zinc-chloride battery. For the same size battery, alkaline types have a lower internal resistance than zinc-carbon and zinc-chloride batteries, making them suitable for higher currents such as operating cameras and toys with small motors. However, if alkaline batteries are subjected to sustained short-circuits, they are likely to produce high currents that may cause insulation to burn; in extreme cases they can vent. This makes them less suitable for general circuit work where short-circuits are likely. Alkaline batteries are sometimes labelled 'long life' to distinguish them from the other zinc-manganese dioxide type batteries. The shelf-life of alkaline batteries is around several years.

Lithium non-rechargeable batteries (lithium-manganese dioxide electrochemistry, not to be confused with rechargeable lithium-ion batteries) are superior to zinc-chloride and alkaline batteries in energy capacity. They have a shelf-life of up to ten years, and they work at low temperatures. However, if the battery is short-circuited it could fail catastrophically. Lithium-manganese dioxide AA batteries made by Energizer feature a resettable fuse that limits the current under short-circuit conditions. When the short-circuit is removed and the battery returns to normal temperature, the protective device resets and the battery is usable again. However, it is not wise to rely on this, so this type of battery should not be used for general circuit work where short-circuits are likely.

There is a range of non-rechargeable button-style (or coin-style) batteries of various electrochemical design, for example lithium batteries, silver oxide and alkaline. These are designed for fitting into equipment and are enclosed during normal use. These batteries are not suitable for experimentation or bench circuit work. They should not be used with very young children (who are likely to put them in their mouths) unless closely supervised.

It is unwise to attempt to charge a non-rechargeable battery of any sort; to do so may cause a build-up of pressure and consequent violent venting or explosion.

17.2.3 Rechargeable batteries

Rechargeable batteries (also called secondary batteries, or rarely, accumulators when referring to lead-acid batteries) are designed so that the electrochemical reaction is reversible, and the battery may be re-energised many times by passing an electric current through it in the direction opposite to that which flows when the battery is delivering power, a process called battery 'charging', and the device for doing it a 'charger'. These are now well-established terms but they are misnomers to an extent because batteries do not store charge: they store energy.

Some rechargeable batteries such as nickel-metal hydride (NiMH) can give over 1000 recharge cycles if used and charged correctly. For any rechargeable battery, the charging current needs to be controlled during the charging cycle or the battery’s working life will be reduced and its capacity impaired. In extreme cases, if the charging current is too great, the battery could rupture. It is important to use a charger designed for the particular type and capacity of the rechargeable battery. Do not, for example, use a 12 V car battery charger to charge a 12 V NiMH battery pack.

It is not wise to leave lead-acid batteries in a discharged state for any length of time; irreversible chemical changes take place on the lead plates and the battery loses capacity and, if left discharged for long enough, the battery may be ruined. When charging lead-acid batteries, ensure there is good ventilation so that any hydrogen and oxygen gases which may be evolved during the charging are dispersed. A hydrogen and oxygen gas mix can easily explode if ignited by a spark or naked flame.

Rechargeable batteries lose their stored energy over time even if they are not used. This is called self-discharge. In the manufacturers' drive for higher-capacity batteries, some, notably high-capacity NiMH, would completely self-discharge in just a month or so. Low self-discharge NiMH batteries are now available that retain 90% of their energy even if unused for a year or longer. Since most battery-operated equipment in school science tends to be used intermittently, if rechargeable batteries are used it makes more sense to choose low self-discharge types. Check the specification, don't assume all NiMH brands of battery are now low self-discharge.

Rechargeable batteries generally have a much lower internal resistance than equivalent-sized non-rechargeable zinc-carbon and alkaline batteries. Consequently, they can supply really large currents; for example, it is possible to make an AA 1.2 V NiMH rechargeable battery drive a current of 20 A through a low-resistance circuit for a short time. Such batteries should never be used by children who are likely to create short-circuits accidentally. Some rechargeable batteries such as lithium-ion can catch fire when short-circuited if the battery has no internal protection device. Rechargeable batteries are best used for battery-operated devices in which they are completely enclosed with no access to the circuit, eg, torches and cameras.

A type of alkaline battery was developed to be recharged, using a special charger. One type was aimed at schools under the brand name *Schoolcell*. This type of battery is not common now, the NiMH being superior in most aspects, particularly the number of times the battery can be recharged.

17.2.4 Cutting open batteries

Zinc-carbon cells can be cut open with care, wearing eye protection and disposable gloves. It is unwise to cut open alkaline batteries because of the very corrosive electrolyte. Cutting open other batteries such as lithium types should not be done; the materials released could react violently. It may be instructive to open, carefully, the casing of, for example, a 6 V zinc-carbon lantern battery or a 9 V PP3 zinc-carbon battery to show how they are actually made up of multiple cells and are ‘batteries’ of cells in series.

17.3 Electrostatic machines

There are several designs of machine which produce electrostatic charges at very high potentials and which have been used in schools. Among these are friction-charging (triboelectric) machines and the electrostatic induction type, eg the Wimshurst machine. All of these can produce hundreds of thousands of volts but the quantity of charge on a well-designed school-sized machine is small enough that the electric shock from a single discharge is not harmful to a healthy person.

The most common electrostatic machine in schools is the Van de Graaff generator. The energy stored on the sphere capacitor should be no more than about 500 mJ. Above this, the shock becomes very unpleasant; at 1 J, the shock from a discharge affects everyone severely. The size of the charged sphere should be limited to less than 25 cm to limit the discharge energy to well under 1 J. Do not increase the capacitance of the charged conductor because of the severe electric shock hazard. When doing the hair-standing demonstration, only one person should be charged at a time.

Keep sensitive equipment such as laptop computers and mobile phones at least 2 metres away. Persons participating in experiments with a Van de Graaff generator should, so far as is known, be in good health. People with electrical and electronic medical implants should keep well away from Van de Graaff generators and other devices that generate extremely high electrostatic voltages; a conservative estimate for a school Van de Graaff is at least 6 metres distance[4].

17.4 Low-voltage power supplies

The term ‘low voltage' (or low tension) in schools is used to describe those sources of electrical power which are safe in normal use and cannot drive a current through a human body large enough

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[4] This safe distance is being reviewed by CLEAPSS (Feb 2017).

to produce an electric shock or any other dangerous effect[5]. For general circuit practical work where not all the accessible conductors are insulated, we recommend an output of no more than 40 V dc or 25 V ac. (This accords with CLEAPSS guidance. SSERC has a different level: not more than 70 V smooth dc or 33 V ac or unsmoothed dc in dry conditions; not more than 35 V smooth dc or 16 V ac or unsmoothed dc in wet conditions.) Pupils rarely need power supplies beyond 25 V dc output at about an ampere or so maximum current. High-current output power supplies are not suitable for general circuit investigations by pupils. It is very useful to be able to lock the maximum voltage output to a particular value, otherwise the result will be a very high failure rate of lamps etc. The power supply should be able to withstand indefinite short-circuits, preferably by internal current-limiting circuitry, or by an overload current trip; using a low-voltage power supply that cannot withstand short-circuits will result in serious, and expensive, problems.

A low-voltage power supply usually takes power from the mains at 230 V ac and converts it directly with a transformer to a low voltage. In an alternative design called switch-mode, the mains voltage is first converted to dc, then to a high-frequency ac before being converted with a transformer to a low voltage. This has the advantage of a physically much smaller transformer being needed, but at the cost of increased circuit complexity and greater difficulty of having it repaired should the power supply fail. Be careful when purchasing power supplies; there are examples of poor-quality power supplies that are not robust enough for school use. There have been switch-mode supplies that have failed in use, producing a hazardous high-output voltage.

17.5 High-tension or HT power supplies

High-tension (HT) or high-voltage power supply units supply significant currents, perhaps up to 150 mA or more, at voltages of more than 40 V dc and up to about 500 V dc. These HT units are needed for Millikan's experiment, certain discharge tubes, some Teltron tubes, and for high-voltage electrophoresis. HT power supply units can have low-voltage auxiliary output terminals, particularly 6.3 V ac which was the common heater voltage for thermionic devices. HT power supply units can cause electrocution, so they should be handled only by authorised staff and post-16 students under supervision, and then with extreme care. They should never be used by more-junior students even if only the auxiliary low-voltage outputs are to be used. The HT connections must be made using shrouded connectors so accidental contact with live conductors is unlikely. No attempt to change the circuit should be made without first switching off the supply, and students using such supplies must be instructed not to switch on initially until the circuit has been checked by staff. Older HT supplies may need the output terminals converted for shrouded connectors.

Electrophoresis apparatus for high-voltage use should have suitable interlocks to prevent access to solutions or any other parts at dangerous voltages.

17.6 Extra-high-tension (EHT) power supplies

EHT power supplies for normal school-science practical work should have a maximum output of 5000 V dc (5 kV dc) and current-limited to 5 mA or less. The current limit is essential, not optional, otherwise the electric shock would be severe, feasibly fatal. There are EHT supplies designed for research and industrial applications that have output currents in excess of 5 mA. If such a power supply could be justified in school science, it would need to have a key lock to avoid unauthorised use, and the users would need specific training on using it safely.

The EHT output terminals should be the shrouded type, and the connecting leads similarly with mating shrouded connectors. The insulation of the leads should be suitable for voltages up to 5 kV.

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[5] On the other hand, to an electrical engineer, ordinary household mains voltage, nominally 230 V ac, is referred to as 'low voltage' compared with those used for power transmission namely, 66,000 V up to 400,000 V on the Supergrid. The electrical engineer would refer to our 'low voltage' as 'safety extra-low voltage' or SELV.

At high voltages much above 5 kV and significant currents, there is a risk of X-ray production, particularly in vacuum discharges.

The power supply for a GM tube is sometimes referred to as an EHT power supply, although it produces probably less than 500 V, because its output current is usually limited to less than a milliamp.

17.7 Mains supplies

The most common instance of a hazardous high voltage is, of course, the 230 V ac mains supply. The room power supply is referred to as the fixed electrical installation and comprises the fixed components of the electrical power supply that come with the building. It includes the distribution boards, room electrical isolators, the light sockets and 13 A mains sockets and the electrical cabling going to them. In a correctly installed and maintained fixed installation, an overload is unlikely because the installation is protected by current-overload devices, usually fuses or miniature circuit breakers (MCBs). The Institution of Engineering and Technology (the organisation that publishes the UK wiring regulations) recommends the fixed installation is formally inspected by an electrician at least every five years. This inspection would normally be arranged by whoever is responsible for the school estate/facilities management.

A standard ring main system is considered by the HSE to provide an appropriate laboratory installation in most cases. The neutral wire remains close to earth potential, while the live (or line) wire voltage alternates between a positive potential and a negative potential. A 30 A fuse or 32 A MCB at the distribution board protects the ring main from overload.

Fixed electrical installations in laboratories often have a residual-current device (RCD) installed. This breaks the circuit should there be a difference in current flowing in the live and neutral conductors, i.e. if there is a current flowing through earth. There is a dangerous misconception that an RCD can protect a person against electrocution. **No safety device can protect the user against electrocution by contact with both the live and neutral conductors.** Even for contact between live and earth, a dangerous current could flow through the body until the RCD trips out.

Some school laboratories are fitted with what is called a Blakley unit. This is a combined centre-tapped isolation transformer and sensitive RCD, 5 mA or less. In this unit, a transformer is used to isolate the supply from the normal earth-referenced mains, and the mid-point (centre-tap) of the secondary of the transformer is connected to earth through a resistor, giving two lives - live 1 and live 2 - instead of live and neutral. Live 1 and live 2 are both 115 V ac with respect to earth, and 230 V ac with respect to each other. Under normal (no-fault) conditions, the resistor carries no current and the centre tap is at earth potential. If there is a low resistance leak to earth from either live, current flows through this resistor and, since it has a value of 12,000 ohms, most of the 115 V is developed across it. The leakage current is no greater than 115/12000 A, i.e. 9.6 mA, during the fraction of a second before the RCD operates. The risk of injury from electric shock to earth is greatly reduced by the use of such devices. However, instead of one line at 230 V there are two lines each at 115 V ac with respect to earth. The chance of an earth leakage is therefore doubled but two chances of lesser shocks are safer than one chance of a serious one! However, Blakely units do not protect against electric shock between direct contact with both live 1 and live 2. The HSE suggests that this sort of installation may be helpful where the situation is abnormal such as in special schools or where the rate of vandalism defeats the rate at which the system can be repaired. Provided that the nominal tripping current of the RCD is not more than 5 mA, standard plugs and sockets may be used with this system, i.e. in which the centre tap of the isolating transformer is connected to earth through a resistor of at least 12000 ohm.

Many items of electrical equipment used in schools have metal cases for robustness. If a live wire inside one of these were to become loose and make contact with the metal, the case would also become live. If the user were then to make good electrical contact with the case, there is the strong possibility of an electric shock provided the circuit is completed.

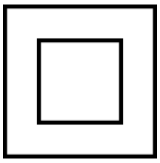
To protect against this, it is common practice in the UK for the neutral wire to be connected to earth where the supply enters the building at the meter. A low-resistance connection is made from the metal case (or other external metal parts of the appliance) to earth. Should the live conductor make contact with the case, a large current will flow through this earth wire which should cause a fuse (or other device) to break the circuit and protect the user.

The earth connection to the external metal parts of an appliance needs to be checked periodically, because there is no warning if it fails - the appliance still works normally. If there is a failure and the live wire comes into contact with the external metal parts, if the user is connected to earth through the feet or a hand, the circuit will be completed and a shock will result.

In a bathroom, the mains supply for shavers, electric toothbrush chargers and similar appliances is fed through a transformer which isolates both sides of the mains from earth. In this case, a fault which allows the user to make contact with a live wire will not give rise to an electric shock even if the user is well-earthed through wet skin and plumbing because there is no circuit involving earth: the supply is `floating'. However, contact with both live and neutral will still cause an electric shock.

17.7.1 Double-insulated equipment

This is mains equipment designed so it does not need an earth connection for electrical safety. It is also called Class 2 equipment. There are at least two layers of insulating material between live parts and the user. Often, the equipment casing is completely plastic and counts as one of the insulating layers. The equipment is marked with a double square logo (one square inside another) to indicate it is double-insulated. See the diagram left.



However, some domestic equipment with metal exterior parts, such as table lamps, is marked double-insulated by counting the outer cable protective sheath inside the equipment as the second layer of insulation. This sort of equipment is not suitable for the harsher laboratory environment.

17.7.2 Choice of fuse

The preferred mains plug fuses are 3 A and 13 A. However, 5 Amp fuses are still used in some older equipment and such fuses can still be purchased. For equipment power ratings up to 720 W, use a 3 A fuse, and any equipment over 720 W, a 13 A fuse. Some appliances, particular those with large motors, draw much more current on being switched on than when in normal use and may require a higher current fuse than the power rating would indicate.

Some equipment may also have an input fuse inside as well as a fuse in the mains plug. The input fuse is to prevent (to some extent at least) damage to the equipment resulting from misuse or internal faults. The fuse in the mains plug may help in this (particularly if there is no input fuse in the equipment) but the plug fuse is essentially there to protect the mains lead between the equipment and the plug, not the equipment.

17.7.3 Additional notes on protection by Residual-Current Devices

These devices have been given various names, for example, earth-leakage circuit-breakers and residual-current circuit-breakers. The preferred term is now residual-current device, RCD. It is a device that breaks a circuit when there is a current imbalance between live and neutral conductors, nearly always because of a fault current flowing through earth. If you happen to be the fault connection to earth, the RCD takes some time to trip, it could be 200 ms, and in that time you will be connected to 230 V ac. This is enough to give a considerable shock, but you are likely to survive it. However, if you touched the live and neutral conductors and you were not touching anything earthed, and you were on flooring that was a good insulator, to the RCD you would be a normal electrical load and the RCD would not trip at all; you would receive a severe electric shock.

One mode of equipment failure is a progressive insulation breakdown. Under a partial breakdown, the live conductor may be in contact with the metal casing of the equipment, but the current flowing through may not be enough to blow the fuse, but at 30 mA it would trip the RCD, indicating a fault.

The disadvantage of fitting an RCD is nuisance tripping. RCDs rated at 30 mA tend not to cause so much nuisance tripping, but at 10 mA and below it becomes more of a problem. Nuisance tripping arises because some insulating materials, if left for long periods, become damp and permit leakage from live to earth even when in good condition. Electric motors can suffer too, with dampness on the motor winding contacts. Further, switching on devices containing large electric motors, such as refrigerators and floor polishers, can produce transient electrical ‘noise’ on start-up that trips the RCD. If a refrigerator/freezer causes nuisance tripping at 30 mA, and assuming the equipment is in good condition, an electrician may advise that it is connected to an RCD-unprotected socket, the justification for this being that the device plugged in is not handled by students. Unprotected sockets should be suitably labelled if the other room sockets are RCD-protected.

17.8 Portable appliance inspection and electrical tests (PAT)

A safety inspection of a portable electrical device combined with an electrical test (with a portable-appliance tester) is commonly termed a ‘PAT test’ (PAT meaning portable appliance test, so the phrase ‘PAT test’ has an element of tautology, but it is widely used.)

Electrical safety of portable electrical equipment depends on a suitable scheme of inspection and testing. However, more faults in school equipment are found by inspection than by the portable appliance tester. Consequently, it is recommended that there should be two levels of inspection: informal and formal. Informal inspection is done each time the equipment is used; the user should take a few moments to check that there is no visible damage to the plug, the mains cord and the equipment itself. The formal inspection is more thorough and often combined with the appropriate electrical test.

The electrical tests have a key part to play in electrical safety, but the appropriate tests depend on the class of equipment. The two classes most likely to relate to school science equipment are Class 1 and Class 2. Class 1 is equipment that has exterior metal parts that must be electrically earthed for safety; Class 2 (see 17.7.1) is equipment that is double-insulated and does not require an electrical earth. The Institute of Engineering and Technology, IET, has produced useful guidance on appropriate inspections and tests for the classes of equipment in the latest edition of its *Code of Practice for In-service Inspection and Testing of Electrical Equipment.*

Class 1 equipment needs a low-resistance earth connection (often called the earth bond) to the metal exterior parts to ensure the fuse blows quickly if there is a live to earth fault - a simple continuity test is inadequate to check this. Secondly, the electrical insulation needs to be tested. This is done by applying a higher voltage than normal to the live and neutral conductors, and checking there is insignificant leakage current through the earth connection. Both of these tests are performed by most portable appliance testers.

Class 2 (double-insulated) equipment is fitted with a two-core mains lead. An earth connection test is not relevant. Secondly, if there are no exposed metal parts it is impractical to subject this equipment to a meaningful insulation test with the portable test equipment available to schools. Consequently, in most cases an inspection to check that the case and lead are undamaged is all that is really necessary to ensure its safety.

Electrical testing (PAT) of electronic instruments and IT equipment needs careful consideration. Passing large earth test currents through them can damage printed circuit boards and components and ruin the instruments. See section 17.8.3.

17.8.2 Frequency of inspection and electrical tests (PAT)

The present regulations require that electrical equipment and systems are maintained in a safe condition. It is down to employers to choose how to do that, who does it, and how often. Many schools chose to schedule a combined formal inspection and electrical test (PAT) of all portable electrical equipment yearly, but the regulations do not make it a legal requirement to do it in that way. The formal inspection and electrical tests can take place at periods based on the risk, so that the items least at risk are only formally inspected yearly and electrically tested, perhaps, every four years, while others that are high risk undergo a combined inspection and electrical test every six months. The HSE latest guide HSG107 *Maintaining portable electrical equipment* (free to download) and the IET *Code of Practice for In-service Inspection and Testing of Electrical Equipment* give helpful advice on frequencies of inspection and electrical testing. The testing and inspection scheme is commonly a whole-school arrangement and if so, you should follow your school's arrangements. If the testing and inspection scheme for portable electrical science equipment is delegated to your department, it is important that you decide which testing and inspection scheme best suits your department, and then implement it and keep to it.

17.8.1 Who may do the inspection and electrical tests (PAT)?

The *Electricity at Work Regulations* require the employer to set up a system to ensure that the fixed electrical installation and the equipment powered by it are maintained in a safe condition. For portable equipment, a simple pass/fail test using a portable appliance tester along with an inspection can be done by anyone with suitable training on what to look for, and how to use the particular tester available. Some employers use a contractor to inspect and test both. Others use a contractor for the fixed installation and their own employees to test and inspect the portable equipment. It is up to the employer to decide and to provide any training which may be required as a result of that decision. As with all safety training, the employer must see that it takes place, while employees have a legal duty to attend it.

17.8.3 Testing IT equipment and instrumentation

IT equipment and some instrumentation may be damaged by normal earth tests (arising from the electrical test) particularly if the earth pathway goes through printed circuit boards. Such equipment should not be tested with the standard portable appliance testers - it is advisable to find the equipment manufacturer's recommendation for testing. Laptop computers are usually low-voltage, around 19 V dc, and do not require electrical testing, just a visual examination. The laptop external power supplies are normally double insulated and do not require electrical testing, just inspection. (Some laptop external power supplies have an earthed screen to reduce electrical noise from the power supply, not for electrical safety.)

If no written guidance on testing is available, have the equipment examined by someone competent and, where necessary, follow the IET recommendations for reduced current test in the latest edition of its *Code of Practice for In-service Inspection and Testing of Electrical Equipment.* SSERC and CLEAPSS may be able to offer advice on old, but popular, school-science instrumentation.

Older computers may fail the insulation test, part of the electrical test, because there are mains interference filters built into them which allow small currents to flow between the line and earth. The computer should not be regarded as unsafe just because of this.

17.9 Special items

Many of the following items are for teacher demonstrations only because of their hazardous nature but teachers must remember that they have a duty to look after their own safety as well as that of students. Showing students how safety can be achieved in such cases is an important part of their education.

17.9.1 Induction coils

School induction coils supplied by reputable firms since about 1970 cannot produce a current above 5 mA and so are electrically safe. Older induction coils or induction coils obtained from other sources should be regarded as potentially hazardous and not used.

17.9.2 Demountable transformers

When using this equipment, keep the voltage to the primary coil below 28 V ac (except for the mains coil) and make sure the output voltage across the secondary coil does not exceed 28 V ac.

Be careful not to step up the voltage to over 28 V ac by using a secondary coil with many more turns than the primary coil. For demonstrations showing stepping down of mains voltage, use a primary coil specifically designed for connection to the mains. It should be double-insulated with the coil and connections fully enclosed by substantial insulation, and an integral mains lead. Older mains coil designs with exposed windings, or unsafe connectors for high voltage, such as spade terminals and 4 mm sockets, are not safe to use and should be taken out of service. (CLEAPSS members should refer to Guide GL112.). Mains coils are often not designed for use with an open iron core for more than a few moments because they overheat and may burn out. Eye protection is needed for activities showing induction heating and melting nails.

17.9.3 Power-line demonstration

In 1987, a Health and Safety Executive (HSE) letter to local authorities expressed concern about the ac power-line demonstration and reminded them of the dangers of high voltages to both the demonstrators and their students. It said:

> “The experiments may continue if one of the following precautions, or other equally effective precautions, is taken:
>
> a) the voltage of the transmission line is limited to 50 V ac rms or 120 V dc;
>
> b) the demonstration as a whole is located within an enclosure constructed, for example, of clear polycarbonate so that live conductors operating above 50 V ac rms or 120 V dc cannot be touched; or
>
> c) all conductors and terminations etc operating above 50 V ac rms or 120 V dc are fully insulated so that live conductors cannot be touched.”

Most would agree that these are very reasonable precautions and support the HSE policy of allowing potentially hazardous demonstrations to continue with appropriate precautions. Alternative ways of taking these precautions (and those in sections 9.5, 9.6 and 9.7) are described in detail in, SSERC *Bulletin* 158[6] and on the CLEAPSS web site[7]. There are power-line demonstration kits from equipment suppliers that work at high voltages, but with the conductors suitably insulated.

17.9.4 Variac

This is a trade name, but it has become a generic name for a variable autotransformer. It allows the mains ac to be varied from 0 to about 240 volts ac. This is useful for testing and repairing mains equipment by allowing a slow increase in the applied ac voltage. The ac output is not isolated from the mains input and can give a severe electric shock. This equipment should be treated as an HT supply, i.e. it should be handled only by authorised staff who know how to use it safely, and then with great care. The output connections must be made using shrouded connectors so accidental contact with live conductors is unlikely.

17.9.5 Teaching students to wire 13 A plugs

This becomes hazardous if the students can insert their plugs into a live socket and there are bare wires on the end of the practice lead; or if the plug has been wired incorrectly and there is some item on the end of the lead.

There are three precautions, all of which should be taken to protect the students.

- The plug should be made incompatible with the sockets in the room either because it is 'off-standard' (not quite the standard pin arrangement) or because it has been modified in school (by bending the earth pin or by fitting the earth pin with, for example, a pop-rivet).
- The power to all sockets should be switched off in such a way (e.g. by using a switch which is out-of-reach) that it cannot be accidentally restored.

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[6] SSERC *Bulletin* 158 (1987) Ring-main models.

[7] CLEAPSS *Laboratory Handbook*, Chapter 6. Available to members of CLEAPSS.

- The unused end of the practice lead should be sealed with insulating tape or another secure method so that no conductors are accessible.

17.9.6 Ring-main models

If you demonstrate a ring-main model, use a safe low voltage, e.g. 12 V. Do not use standard 13 A plugs and sockets in case someone mistakenly applies 230 V mains. The best way to avoid this is to use off-standard plugs and sockets for the model[8], i.e. ones which look like 13 A ones to a casual inspection but have a small difference which prevents interconnection with the proper mains ones. (See the CLEAPSS web site or SSERC *Bulletin* 158.)

17.9.7 Conductivity of glass

There is no longer any need to do this demonstration at high voltages. High-efficiency LEDs require small currents to produce relatively bright light. If a piece of glass rod has two conductors wrapped around it, spaced about 10 mm apart, and the glass is heated, the current flowing at 30 V pd across the glass is several milliamps, enough to make a high-efficiency LED glow brightly. Some form of current limiting is needed to prevent the LED being overloaded; CLEAPSS members can access Guide SRA23 which explains in detail how to construct the relatively simple circuit.

17.9.8 Radiant heaters

No electric fire or mains-operated radiant heater with an exposed element is now considered sufficiently safe for use in schools. Types where the element is surrounded by a silica sheath are suitable. In some applications, high-power incandescent lamps can be used in place of heating elements with exposed conductors. CLEAPSS members can find further information in the Position Statement PS028 *Radiant heaters in physics*.

17.9.9 Teltron tubes

Teltron tubes are a range of cathode ray tubes used to demonstrate the properties of electrons. Older Teltron tubes do not have shrouded connectors on HT and EHT terminals. These should be converted using special adapters so that the connections are shrouded. Connections to the tube should not be made or removed while the HT and EHT supplies are switched on.

17.10 Repairs by staff

Students must not repair mains-operated equipment; staff should do so only if permitted by their employer. However, simple repairs such as the replacement of broken terminals or sockets are usually permitted.

17.10.1 Simple repairs

Even the simplest repairs usually require the case of the equipment to be opened, and it is important to check that the equipment has been disconnected from the supply before opening it. Output terminals can be replaced or their connections repaired and the cover must then be replaced before testing the unit.

17.10.2 Repairs to the input or mains connections

In this case, obvious faults can be dealt with if repairers are confident in their ability to do the job correctly - but after the repair the equipment should be tested for earth-bonding and insulation with a proper test set. Then the functioning of the equipment can be confirmed.

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[8] Such plugs and sockets are available from MK Electric (available through distributors such as RS Components, Farnell, and Newey & Eyre.

17.10.3 Repairs involving live testing

Some colleges and schools may have staff qualified to find more-obscure faults which require taking meter or oscilloscope readings while the equipment is live and exposed. Working on live mains is very hazardous and should only be undertaken by competent people with the permission of the employer. If this is to be done, a special area must be prepared. This requires the use of a separate supply via an isolating transformer so that it is not earth referenced. The work bench should also be earth-free and an insulating mat should be provided for the repairer to stand on.

When the repairs have been completed, the equipment should be subjected to a full electrical safety test before being returned to use.