watts = 110 x amps

Appliances are usually marked with their power requirements in watts. If you want to figure out how many amps they take, just divide the power by 110 V.

USA household amps = watts/110

A bright light bulb that uses 110 W takes 1 amp. A heater that uses 550 W takes 5 amps. Amps add (they represent the number of electrons per second), so if you have both the light bulb and the heater, then you will have a total of 1+ 5 = 6 amps coming into your home. If you use more than 15, your fuse might blow. (By "blow" I mean that the wire inside the fuse melts, stopping all further current from flowing.)

In Europe, the typical house voltage is 220 V rather than 110 V. That means that for typical power, the voltage is higher and the current is less. Higher voltage makes the electricity more dangerous than in the U.S., but lower current means that there is less energy lost in the wires that deliver electricity to the outlet. (Or, alternatively, it means that they can use cheaper wires without getting too much heating.)

If you want to keep a 15 amp fuse from blowing, then you should limit the power of your electric appliances to 15 amps x 110 V = 1650 W. One electric heater can use this much. Appliances such as toasters tend to use high current for short periods, but that is enough (when used together with a heater) to blow a fuse.

High tension power lines

Most long-distance transmission of electricity is done at extremely high voltage, several tens of thousands of volts. At these high voltages, you can sometimes hear the crackle of small sparks coming from the wires. Sometimes people refer to these lines as "high tension" lines. That's not because people who live near them get tense, but because "tension" is an old synonym for voltage. It is still used in the UK.

There is an important reason that we use high voltage for such lines. Recall that power = voltage x current. So high-voltage lines have less current (for the same power delivered) than do low-voltage lines. But heating from resistance depends only on the current, not on the voltage. So if we use high-voltage lines, then we can reduce the amps, and that reduces the loss of power from resistive heating.

Since high voltage can make electricity dangerous, there are special devices that raise the voltage V and lower the current I, while keeping the power P unchanged (i.e. V times I remains unchanged). Such a transformer is called, aptly, a "transformer." We'll talk about how they do their work after we have discussed magnetism. Some transformers are near homes, so they don't lower the voltage until they are as close as possible. Many of these transformers are filled with an insulator known as PCBs.[7] When it was discovered that PCBs can cause cancer, an ongoing campaign began to

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[7] PCB stands for "polychlorinated biphenyl." Polychlorinated means the molecule contains multiple molecules of chlorine. Biphenyl means that the organic molecule has two "phenyl" groups attached, each consisting of a benzene ring with one hydrogen removed. Even most physicists don't know this kind of chemistry. (I had to look it up too.)

eliminate these liquids and replace them with something that was less carcinogenic.

Electric forces at different distances

Near the beginning of this chapter, we considered the force between two electrons a centimeter apart. I said that the electric force was stronger than the gravity force by a factor of 4.17×10^{42}.

Now suppose we put the electrons 2 cm apart. The force of gravity is then 4 times weaker (because gravity is an inverse square law). And so is the electric force!

If, instead of 1 cm separation, you put the electrons 1000 cm apart, then both forces are weaker by a factor of $1000 \times 1000 = 1$ million.

This similarity in the distance behavior has intrigued a lot of people. It means, for example, that an electron orbiting a proton bears a lot of similarity to the Earth orbiting the Sun. That's why you'll often hear people describing atoms as little solar systems. The analogy is not perfect, however, because when you get to the small dimension of an atom, quantum physics becomes important. We'll talk more about that in Chapter 10.

Magnets

You're probably familiar with magnets, such as those used to stick messages on refrigerators. Magnets are truly strange, and I strongly recommend that you play with several. A magnet will attract a piece of iron, but it can either attract or repel another magnet, depending on the orientation of the two.

According to the ancient author Pliny (who lived from 23-79 AD), the word "magnet" in Latin comes from Magnes, the name of a shepherd who noticed that his iron staff and nails from his boots were attracted to certain rocks.

The simplest magnets have two ends, one of which is called N or the "north pole" (because if you hang it from a string, it will orient itself to face the North Pole of the Earth), and the other called S or the "south pole." Play, and you'll discover that two north poles repel each other, that two south poles repel each other, but that a north pole will attract a south pole. The repulsion seems particularly mysterious, because it is so unlike gravity. But it is very similar to electricity because the like charges repel and opposite charges attract.

Permanent magnets are materials that keep their magnetism. But every time that electric current flows it creates magnetism. A magnet made with electric current is called an electromagnet. You can turn its magnetism on and off by changing the current.

Lodestones , kissing stones, and compasses

The first known magnets were natural rocks containing iron ore, known as lodestones. A magical feature of these stones is that if you suspend them (by a string, or by floating them on a piece of wood), they tend to rotate until one end is pointing north. This became an enormously important discovery, since it could be used to tell direction. It was called a "compass" and was so valuable that it was originally a deeply held military secret. Even on a completely cloudy day, far out at sea, you could tell which direction was north. The word lodestone derives from the Old English word "lode" which means way or path; a lodestone helps you find your way. The impact that the magnetic compass had on history is difficult to know. In 1620, Francis Bacon ranked it with gunpowder and the printing press as the three inventions that had revolutionized the world. (He must have meant the "recent" world, since he didn't include earlier inventions such as the wheel, or controlled fire.)

For hundreds of years, nobody understood why one end of the lodestone points north. Some people assumed that the lodestone felt some attraction towards the North Star. The secret turned out to be that the Earth itself is a large magnet, and the north pole of the lodestone was being rotated by the magnetism of the Earth.[8] The "north pointing pole" of the lodestone was referred to as simply "the north pole" of the magnet. The other end was called, naturally, the "south pole" of the magnet.

Another major discovery was that you could make new magnets from iron. You can do this yourself by rubbing a needle on a magnet; be careful to rub only one direction, and not back and forth. The needles made into magnets this way could then be used for compasses.

A second magical feature of lodestones is their force of attraction to each other. Because of this property, the Chinese called them *tzhu shih*, which means "loving stone." The French word is similar: *aimant*, literally, "stones that like each other." Of course, the attraction depends on the orientation. Lodestones, placed N to N, or S to S, dislike each other.

Magnetism from moving charge

We now know that the force of magnets--what we call magnetism--is really another aspect of electricity. It is a force between electric charges that occurs only if the electric charges are moving. For that reason you can think of magnetism as a force that occurs between electric *currents* rather than between stationary charges.

The magnetic force law[9] is similar to the electric force law, and to the gravity force law. It states that if you have two short lengths of wire, each carrying current, then the force between them is inverse-square. That means if you double the distance, the force will weaken by a factor of four. It is more complicated, however, because the force is not a simple one of attraction or repulsion, but can be in a different direction that depends on the orientation of both segments.

To calculate the force between long wires, you have to add together all the forces between each pair of wire segments. For long wires, there are a huge number of such pairs, and that makes the problems complicated. For simple cases (e.g. two long straight wires) the total force can be worked out mathematically; the result is that two parallel wires carrying current in the

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[8] There are records of magnets being used in China in the first century. The first records in Europe date from a manuscript written in 1187 by Alexander Neckam. In 1600, William Gilbert (the physician to Queen Elizabeth I) figured out that the Earth was a giant magnet. He wrote, in Latin, "Magnus magnes ipse est globus terrestris." That can be poetically translated as, "A magnificent magnet is the terrestrial globe."

[9] It is usually called the Biot-Savart Law.

same direction will attract each other. For more complicated cases, such as wires wrapped in large loops, the calculation is usually done on a computer.

Permanent magnets

Modern permanent magnets are used for refrigerator magnets, for magnetic compasses, and for door latches. They certainly don't *seem* to have any electric current. Moreover, they don't *seem* to have anything to do with electricity.

But now we know that permanent magnets do get their magnetism from electric currents. But the electric currents are extremely well hidden. The electric currents for permanent magnets are inside the electrons!

It was discovered in the 20th century that all electrons spin. That means that the charge within the electron is also spinning, and that is an electric current. This makes every electron into a tiny magnet.

It is hard to detect this magnetism if a nearby electron is spinning in the opposite direction, because then the magnetism tends to cancel. This is the case for most materials. But in a few materials, known as ferromagnets (iron is the most prominent example), the electrons from different atoms tend to line up and have the same spin direction. Then the magnetism adds. These are the materials from which we make permanent magnets. They are permanent, because they retain their magnetism without any need for additional power.

You can imagine why it was hard to discover this. Who could have suspected that electrons--all electrons--spin? In fact, we now believe that it is impossible to stop this spin. Electrons always spin. We can change the direction of their spin, but we cannot stop it.

Magnetic monopoles?

As I mentioned above, in some ways magnets behave like electric charges. North poles repel, just as like electric charges repel, and opposites attract. This has led many people to speculate that there must be magnetic charges, similar to electric charges. These hypothetical objects are called "magnetic monopoles." Permanent magnets behave as if they have a concentration of such charges at their ends.

Yet we know this is not really true. All present permanent magnets actually work because of currents flowing within their electrons.

If you take a magnetic needle, one end will be the north pole, and the other end will be the south pole. You might think that you can break off the north pole by cutting the needle, but if you do that, new poles form at the broken ends--so each piece continues to have one north and one south pole each. Magnets appear to always have both north and south poles, no matter how they are made. That's because a broken magnet still consists of rotating electric currents, and those always produce north and south poles.

Some physicists have speculated that even though all known magnetism comes from currents, that doesn't mean that magnetic monopoles are impossible. Many projects have been made to search for them, or to try to make them. Some theories (e.g. superstring theories) predict that they should exist, or at least, it should be possible to make them. Searches have been made in materials that have been exposed to extremely energetic collisions, since those may have created monopoles. Materials studied have included lunar rock (exposed to energetic cosmic rays for billions of years) and metals placed at the end of large particle accelerators ("atom smashers").

If magnetic monopoles could be made, they would be valuable. They could be accelerated to very high energy by ordinary magnets, and this could be a convenient way to create radiation (which would have applications in medicine and elsewhere).

The short range of magnetism

Because magnets (until monopoles are discovered) have both north and south poles, once you get a reasonable distance away from one, the two forces cancel. This cancellation tends to make the net magnetic force fall off faster, not with an inverse square law but with an inverse cube law. That means that if you go twice as far away, the force is reduced by a factor of $2^3 = 8$. So when twice as far away, the force is 2x2x2 = 8 times less. If you are three times as far away, the force is 3x3x3 = 27 times weaker.

The result is that magnets are very useful for short distances, but don't work very well for larger distances. You may have noticed this, if you tried to pick up an object with a magnet. Unless the magnet is close to the object, it has very little net force on it. Contrast that with what you see in cartoons, where magnets are depicted as being able to lift things at great distances.

Electric and magnetic *fields*

It was once thought that one electric charge put a force directly on other electric charges. Now we know that there is something intermediate that happens. The electric charge creates something that we call an **electric field** that fills up space. It is this field that puts the force on the second charge.

Gravity works the same way. Mass creates a gravitational field. When a second object is in that gravity field, it feels a force from the field. In other words, there is no direct force between the two masses. Rather, one mass creates a field, and the other mass feels that.

The situation is similar to two people pulling on ends of a rope. One person pulls on the rope, and the rope pulls on the other person. The two people don't directly touch each other.

The way we know electric fields really exist is from the behavior when you suddenly remove one of the charges. The force on the other charge is still there, if only for a short time.

We also know that the field can be made to vibrate, a phenomenon that gives rise to something known as an electromagnetic wave. (This is analogous to shaking the rope.) It turns out that light, radio signals, and x-rays are all examples of electromagnetic waves.

The key idea here is that charge produces an electric field, and this electric field can produce a force on other charges. Likewise, moving charges (currents) produce a magnetic field, and this field can exert a force on other moving charges.

Magnetic fields can be visualized by sprinkling iron filings near a powerful permanent magnet. In the image a piece of glass was placed above the magnet, and the filings were sprinkled on the glass.

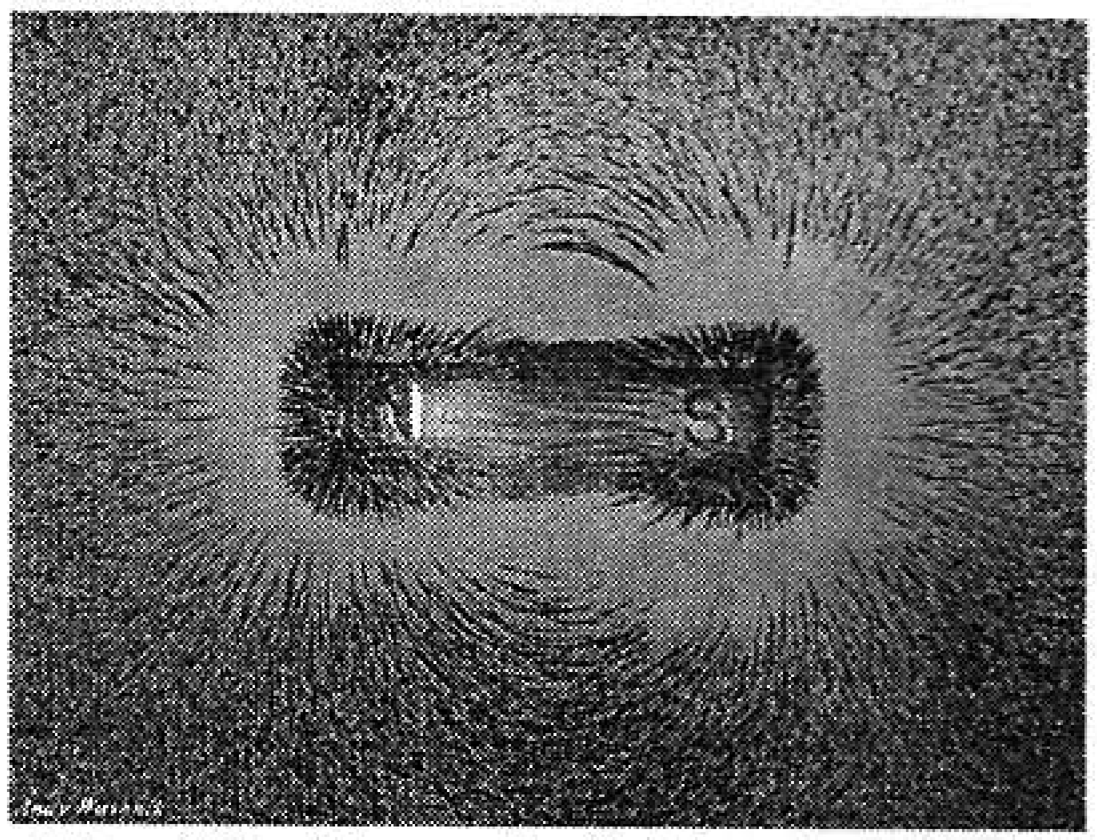

Fig. 6.2 Magnetic fields visualized by their effect on iron filings (NASA).

If there is a magnetic field in a vacuum, is it still a vacuum? That is partly a matter of definition. There are no particles there, but the magnetic field does contain energy. Is space really empty if it contains energy? Normally we define a vacuum to be a region of space with no (or few) particles, and we don't worry about whether a field is present.

The magnetic field is easy to visualize because of the way it lines up iron filings. It is possible but much harder to "see" strong electric fields since they tend to produce sparks, and when that happens the charges move in such a way to reduce the field.

Electromagnets

If you put a wire into the right geometry, you can arrange it to exert a very strong electrical force on other currents, or on a permanent magnet. A common geometry to do this is called a solenoid. It is just wires wrapped around a cylinder. Turn on the electricity, and you have a strong magnet. Turn it off, and the magnet is turned off. Reverse the current, and the magnetism is reversed (i.e. the north pole becomes a south pole).

Electromagnets have lots of uses. In automobiles, they are used to lock and unlock doors. (If you click the door switch, a solenoid electromagnet pulls a permanent magnet.)

Small electromagnets are used in speakers and earphones to create sound. Typically such devices have a small permanent magnet, and an electromagnet. Electric current goes through the electromagnet and that causes an attraction between it and the permanent magnet. Then the current is reversed, the magnetism of the electromagnet is reversed, and now the two magnets repel. Usually, the electromagnet is made very lightweight and it can move back and forth in response to these reversing forces. The electromagnet vibrates in a way that follows the oscillations of the current. In an earphone or speaker, a piece of paper attached to the electromagnet oscillates along with it, and that pushes against the air, making the air vibrate. Air vibrations reach the human ear, and we hear them as music. (We'll discuss this further in Chapter 7 "Waves.")

Superconducting electromagnets

Large strong electromagnets require high currents, and that means that a lot of power is wasted in resistive heating. For that reason, many such devices are now made using superconducting wires. Although some energy must be used for the refrigerators that keep the wires cool, that turns out to be much less than you would lose from the resistance of ordinary wires. The image on the right shows a large superconducting magnet used at a particle accelerator (commonly known as an atom smasher) at Fermilab in Illinois.

Superconducting magnets are also widely used in medicine to provide the strong magnetic fields needed for MRI

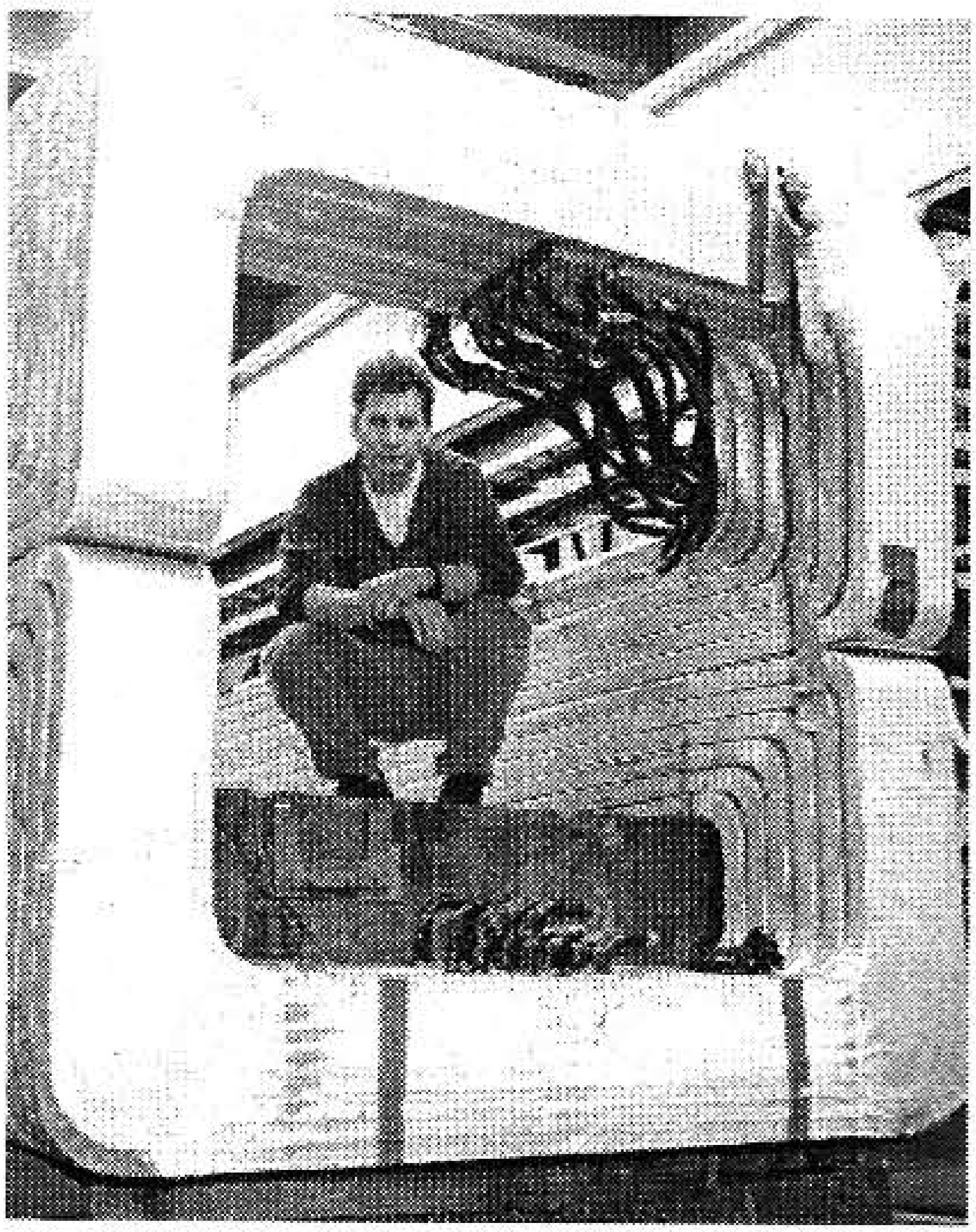

Fig. 6.3 Superconducting magnet at Fermilab (Dept of Energy)

imaging. The magnetic field of such magnets provide a force on the nuclei of hydrogen atoms that makes them wobble around the direction of the field. This wobble can be detected, to create an image of the distribution of hydrogen. (We'll discuss MRI further in Chapter 9.)

The electromagnet in the Earth

We believe that the magnetism of the Earth comes from large currents flowing in the liquid iron core. (We know the core is liquid from seismic data, discussed in Chapter 7.) The flow is complicated, so the Earth's field is complicated. A recent computation of the Earth's magnetic field lines is shown below.

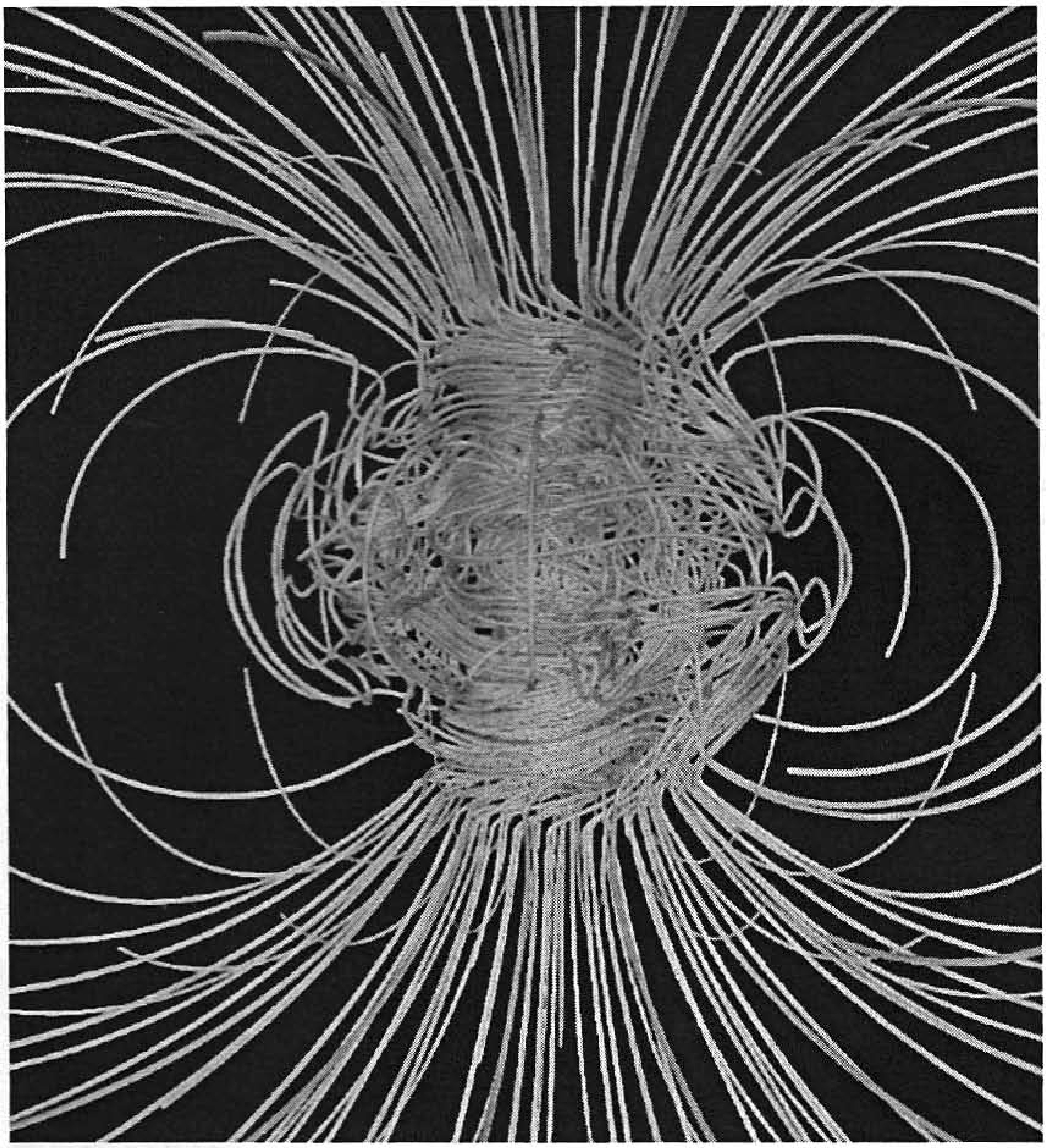

Fig. 6.4 The magnetic field lines of the Earth, as computed by physicists Gary Glatzmaier and Paul Roberts. Deep inside the Earth the field is very tangled and complex, but on the surface it is relatively simple.

Magnetic materials -- the special role of iron

I said earlier that permanent magnets are made from materials in which a large number of the electrons are spinning in the same direction. Ordinary iron is not normally a permanent magnet because its electrons, even though they are spinning, are all spinning in different directions.

But if you apply an external magnetic field, e.g. by an electromagnet, then that puts a force on these spinning electrons. For iron atoms, it tends to make the electrons all spin in the same direction, and that makes the iron into a magnet, as long as there is current flowing in the external electromagnet. We say that magnetism is *induced* in the iron.

That's why a permanent magnet can pick up a paperclip. When you bring the permanent magnet near the paperclip, magnetism is induced in it, and then the permanent magnet and the paperclip attract each other.

Here is how an electromagnet can lift a piece of iron, as in a junked car. The electromagnet is turned on, and it makes a strong magnetic field. This magnetism aligns the electron spins in the iron of the car, turning it into a magnet. It is an induced magnet. For iron, the two magnets (the electromagnet and the induced iron magnet) attract each other.

Induced magnetism can also be used to make magnetic fields that are much stronger. If you place iron inside the cylinder of an electromagnet, then the weak magnetism of the current is strongly enhanced by the induced magnetism of the electron spins. And it doesn't stop there. The induced magnetism of some of the atoms induces even more electrons to spin in the same way. The strength of the magnetism grows dramatically, until the magnetism is hundreds of times stronger than it would have been without the iron. This kind of magnetic amplification is so useful that most electromagnets use iron cores.

Remnant magnetism

Imagine that you have an electromagnet that is applying its field to a piece of iron. When the electric current is turned off, and there is no externally applied magnetic field, then most of the induced magnetism goes away. But usually some of the electrons remain lined up with each other, so there is a small *remnant* (that means remaining) magnetism.

Remnant magnetism can be very useful, e.g. to make permanent magnets, or it can be a real nuisance. If you bring an iron screwdriver close to a strong magnet, it becomes magnetized; when you take it away, there may be some remnant magnetism left. If that is true, the screwdriver may attract screws or little bits of iron, and that can be useful or annoying. Old watches (in pre-electronic days) would become magnetized if brought close to a magnet, and then the pieces within the watch would attract each other, and that was usually enough for the watch to stop working. Watch repair experts would fix the watch by putting it back in a changing magnetic field that would slowly reduce the magnetization to zero.

Magnetic recording

Induced magnetism is also the basis behind magnetic recording, and that includes videotape, computer hard drives, and MP3 players. In these devices, a very small electromagnet induces magnetism in a small region of a magnetic material. In the adjacent region, it can induce similar magnetism or a reversed magnetism. The signal is stored in the magnetic material by these small regions. For example, if adjacent regions have the upward direction induced in a series of north and south magnetic poles: N, N, S, S, N, then this could be a way of recording the digital signals 1, 1, 0, 0, 1. This is the basic principle for all magnetic recording.

Some magnetic recording devices record this pattern on flexible tape, e.g. cassette players and videotape recorders. The tape has a very thin layer of magnetic material deposited on its surface. To get a lot of information on the tape, the magnetic regions must be very small. A computer hard drive has magnetic material distributed on the surface of a rotating disk. As the disk moves under the electromagnet, different places have different induced magnetism. These days, these regions are typically a micron or smaller in size. That's the kind of drive used in many iPods.

The magnetic recording can be "read" by another wire. When a moving magnet passes a wire, it makes a small amount of electric current flow, and that current can be detected. In modern hard drives the wire is a special material in which the resistance of the wire depends on the magnetic field. By measuring that resistance, the wire gives information about the magnetic field.

Heat destroys magnetism: Curie temperature

If you heat a permanent magnet, the atoms and electrons bounce around faster and faster. This can cause the atoms to change their orientation, and the electrons within them to change the direction of their spin. Pierre Curie, the husband of the more famous Madam Marie Curie, discovered that at a certain temperature all permanent magnetism disappears (since the electron spins get mixed up).Every material has its own "Curie temperature" at which this happens.

Remember this: if you heat up a permanent magnet to its Curie temperature, then its magnetism goes away.

Rare earth magnets

In the last few decades, a particularly strong type of permanent magnet was invented. The first was made out of a compound called samarium cobalt. Samarium is an element known as a "rare earth." Since its discovery, other similar compounds have been found, and these magnets are often called "rare earth magnets."

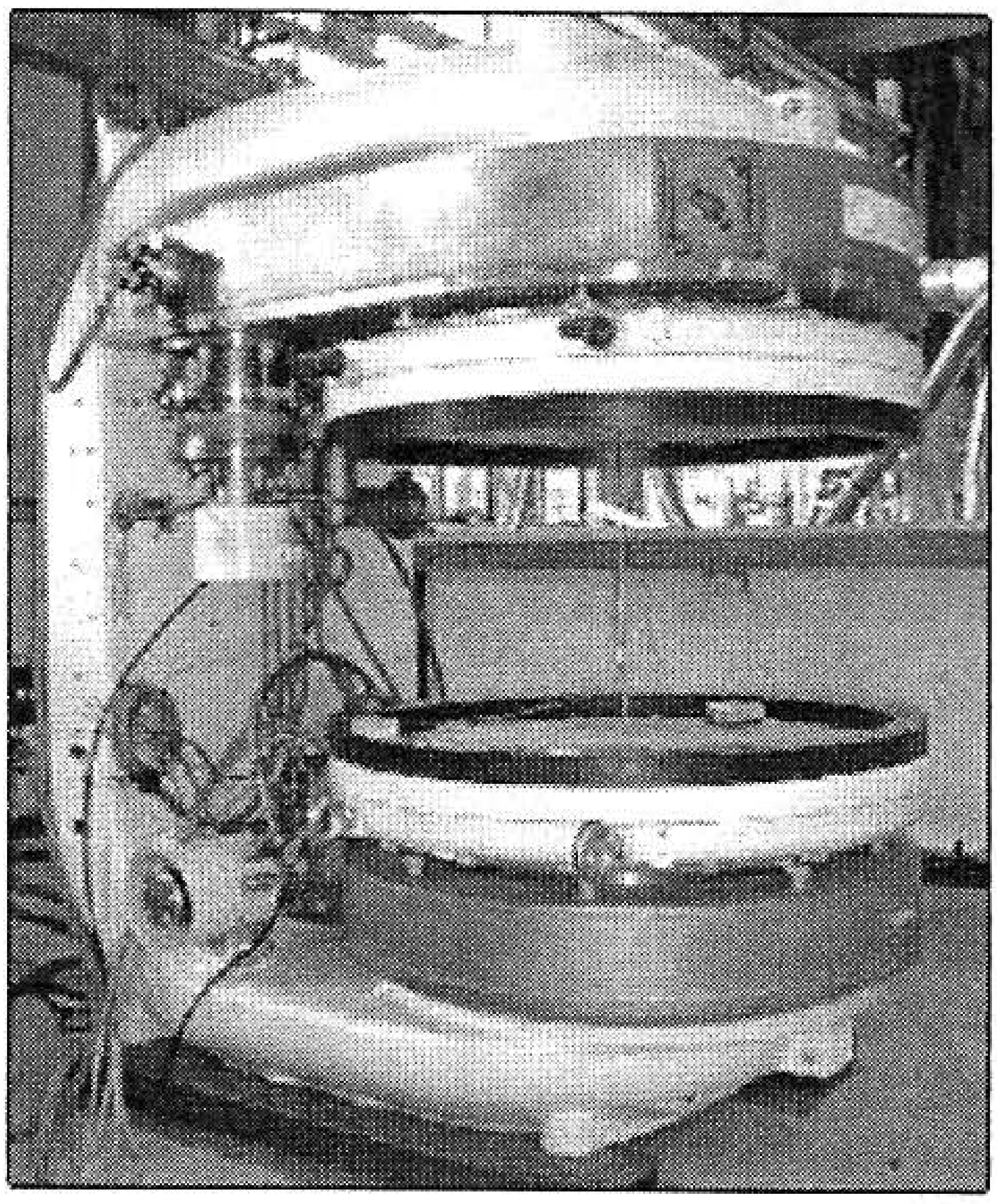

Fig. 6.5 Rare-earth magnet used for Magnetic Resonance Imaging (DoD photo)

These magnets are so strong that they can be dangerous. If you break one (maybe by dropping it) and it breaks in such a way that the two pieces repel each other, then pieces can go flying apart at such high velocities that they can hurt someone. When used in earphones, they are packaged in such a way as to prevent the magnet from being struck with a shattering blow.

The earphones once used by your grandparents were big and bulky. Now, thanks to rare earth magnets, high quality earphones can be small and light; similarly for loudspeakers and motors.

The image on the left shows a large rare-earth magnet used for a kind of medical imaging called MRI. We'll discuss this further in Chapter 9. For now, it is useful to know that rare earth magnets are very useful ways to create large magnetic fields without having to have large electric currents.

Finding submarines

A submarine is made of steel, and when it sits in the Earth's field, it becomes a big magnet. During World War II, scientists realized that you might be able to find submarines deep under water by detecting this magnetism. Because magnetic fields get weak at large distances (by a factor of $1/r^3$), this method doesn't work for very deep submarines, but it is still used when submarines are within a few hundred meters of the surface.

Because this method works so well, submarines are specially treated every time they come to port to remove any remnant magnetism they may have picked up.

Electric motors

Electric motors are really based on magnetism. In an electric motor, the wires are wound in such a way as to create a strong magnetic field. In the simplest version of a motor, this magnetism is used to pull or push on a permanent magnet. If the current is periodically reversed, then the alternating pushes and pulls can be made to move the magnet in a circle. That is how an "electric" motor works – by magnetic forces.

It is not necessary to use a permanent magnet. Many electric motors use two electromagnets, one which is stationary and one which rotates. The electric current is switched in such a way that the force of one magnet on the other pushes the rotating magnet in circles.

As long as thick wires are used, the electric resistance can be small, and electric motors can be very efficient, i.e. they can turn the electric power into mechanical motion with very little loss to heat. Hybrid automobiles use the electricity stored in batteries to drive the wheels with electric motors.

Electric generators

The most effective way to make electricity for commercial use is by moving a wire through a magnetic field. When this is done, it is called an electric generator. Essentially all the electricity that you use is made this way. You also use some electricity from batteries (in flashlights and in your auto), but that is only a very little bit compared to the rest.

A wire made of metal has electrons in it that can move. When you move this wire through a magnetic field, then the electrons move with the wire. Moving electrons, just as with any current, feel a force from the magnetism. If you move the wire perpendicular to the length of the wire, then the force of the magnetism will be along the wire, so the electrons will be pushed along the wire--that is, current will flow along the wire.

At nuclear power plants, the nuclear chain reaction is used to produce heat, and that turns water into steam. The steam drives propellers (technically called a turbine) and those are used to drive wires through a magnetic field, producing electricity.

In a coal burning power plant, the coal is burned to produce heat--and from there on, the power plant works the same way, ultimately producing electricity by pushing wires through a magnetic field.

In a gasoline burning power plant, or one that uses natural gas, the fuel is burned to produce heat, and from there on the process is the same.