RECENT ADVANCES IN SCIENTIFIC RESEARCH

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ATOMIC ENERGY*

FOR practical purposes power or a supply of energy is usually obtained by burning coal, oil, or natural gas or from water power.

The heat from burning gas, for example, is used to raise high-pressure steam in a boiler. The steam from the boiler drives a turbine and the turbine drives an electric generator. The current from the generator is distributed through a network of wires to factories and houses. The electrical power furnishes heat and light and mechanical power wherever they are needed over a wide area. The energy distributed to the consumers comes from the gas and oxygen in the air, which combine when the gas burns. No energy is created or lost. The total amount of energy remains the same. But the chemical energy of the gas and air is changed into heat energy and then into mechanical energy and then into electrical energy. The electrical energy is distributed and changed into heat energy or light energy or mechanical energy in the factories and houses.

When coal is burned, it combines with oxygen forming carbon dioxide gas. This chemical reaction may be represented by the chemical equation

$$C+O_2 \longrightarrow CO_2$$

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*A public lecture delivered on October 27, 1946, by H. A. Wilson, F.R.S., Professor of Physics of the Rice Institute.

Here C represents an atom of carbon, O_2 a molecule of oxygen consisting of two atoms, and CO_2 represents a molecule of carbon dioxide consisting of one atom of carbon and two atoms of oxygen combined together. The energy in the carbon dioxide is less than the energy in the carbon and oxygen; so when the carbon and oxygen combine, the energy difference appears as heat energy and the carbon dioxide formed has a high temperature. The chemical reaction when natural gas is burned may be represented in the same way by the chemical equation

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

Here CH_4 represents a molecule of natural gas consisting of one atom of carbon combined with four atoms of hydrogen, and H_2O represents a molecule of water consisting of one atom of oxygen and two atoms of hydrogen.

In such chemical reactions the atoms remain unchanged. They are merely rearranged. The numbers of carbon, hydrogen, and oxygen atoms in the carbon dioxide and water formed are the same as in the gas and oxygen which disappear. The heat energy produced by such reactions comes from the attractive forces between the atoms.

To start coal and natural gas burning, it is necessary to heat them to a high temperature. The gas does not burn until lighted with a match. Raising the temperature increases the velocity with which the molecules in a gas move about, and the natural gas and oxygen molecules do not react chemically unless they collide with velocities above a critical value.

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Radioactivity was discovered by Becquerel in 1896, and radium by Madame Curie a few years later. Radioactivity is found to be due to a new kind of reaction quite different from ordinary chemical reactions.

Radium is a metallic element similar to silver with chemical properties analogous to those of barium. Radium atoms are unstable, and after an average life of about two thousand years radium atoms explode or split up into helium and niton atoms. This reaction may be represented by the equation

$$\mathrm{Ra} \rightarrow \mathrm{He} + \mathrm{Nt}$$

where Ra represents a radium atom, He a helium atom, and Nt a niton atom. Helium is the chemically inactive, very light gas used for filling balloons, and niton is another chemically inactive but very heavy gas. Atoms consist of a very small particle called the nucleus and a number of electrons which move about near the nucleus. The radium nucleus breaks up into a helium nucleus and a niton nucleus. Such reactions are called nuclear reactions. The energy released in many nuclear reactions is enormously greater than that released in ordinary chemical reactions.

In 1919 Rutherford discovered a new kind of nuclear reaction, in which helium combines with an element to form an unstable element which immediately breaks up into hydrogen and another element. For example:

$$\mathrm{Al} + \mathrm{He} \rightarrow \mathrm{P} \rightarrow \mathrm{Si} + \mathrm{H}$$

Here Al represents an atom of aluminum, He one of helium, and P an unstable atom of phosphorus. The phosphorus atom breaks up into an atom of silicon, represented by Si, and an atom of hydrogen, H. A great many different nuclear reactions have since been discovered.

In nuclear reactions, the elements reacting disappear and new elements are formed, usually with a great release of energy. This energy is called nuclear energy, or atomic energy, to distinguish it from energy of ordinary chemical reactions, which is called chemical energy.

A nuclear reaction in which hydrogen reacts with lithium, forming helium, has been carefully studied. Lithium is a rather rare metal similar to sodium. It is used in medicine and in Edison batteries. The reaction equation is

$$\mathrm{Li} + \mathrm{H} \longrightarrow 2\mathrm{He}$$

It is found that 700 pounds of lithium react with 100 pounds of hydrogen, forming helium, but only 798 pounds of helium are obtained, so that there is a loss of two pounds. It is supposed that the two pounds lost is the mass of the energy released. Two pounds of energy, according to Einstein, is enough to drive a 100,000 horsepower engine for about 36 years.

According to Einstein's theory, the energy in foot-pounds in a mass of one pound is equal to the square of the velocity of light in feet per second divided by 32. The velocity of light is one billion feet per second; so the energy in one pound is one billion billion foot-pounds divided by 32.

The enormous energy of the atomic bomb is the energy of a nuclear reaction.

To understand Einstein's theory of the energy in matter, it is necessary to consider the fundamental principles of mechanics.

The weight of one pound is often used as a convenient unit of force. Thus, for example, the force required to lift a 100-pound weight is 100 such units of force. The work required to lift a pound weight up one foot is called a foot-pound and is a convenient unit of work. Energy is power of doing mechanical work, and so energy may be expressed in terms of foot-pounds. Thus, for example, if a car weighing 3000 pounds goes up a hill 100 feet high, the work done raising the car is 3000 x 100 or 300,000 foot-pounds.

When a body is allowed to fall freely, it is found that it moves faster and faster as it falls and its velocity increases at the rate of 32 feet per second every second. That is, after falling for one second its velocity is 32 feet per second, and after falling for two seconds its velocity is 64 feet per second, and after three seconds 96 feet per second, and so on.

When a force acts on a body, the rate at which the force changes the velocity of the body is taken to be proportional to the force. Thus, for example, a force equal to one half of the weight of the body would make the velocity of the body change 16 feet per second every second, since a force equal to the weight of the body changes its velocity 32 feet per second every second.

These relations may be expressed by the equation

$$\frac{\text{Force on body in pounds weight}}{\text{Weight of body in pounds}} = \frac{\text{Change of velocity in feet per second per second}}{32}$$

For example, if a car weighing 3000 pounds gets up a speed of 60 miles per hour in one minute, the force on it may be calculated as follows:

Sixty miles per hour is equal to 88 feet per second; so the rate of change of the velocity of the car is 88/60 feet per second every second. Therefore,

$$\frac{\text{Force on car in pounds weight}}{3000} = \frac{88/60}{32}$$

so that the force on the car is $\frac{3000 \times 88}{32 \times 60}$ or 137½ pounds weight.

The momentum of a moving body may be defined as the number of pounds in the body multiplied by its velocity in feet per second. The rate of change of the momentum is therefore equal to the number of pounds multiplied by the rate of change of the velocity. The above equation therefore gives

$$\text{Force on body in pounds weight} = \frac{\text{Rate of change of momentum}}{32}$$

When a large force acts on a very small mass, the rate of velocity increase is very large. It is found that when the velocity gets very large, the rate of increase becomes smaller and the velocity finally becomes constant when it is equal to that of light or one billion feet per second. This has been shown experimentally with the betatron, a machine in which electrons move round a circular path in a magnetic field and are accelerated by an electric field produced by increasing the strength of the magnetic field. It is found that the electrons move faster and faster until their velocity gets practically equal to that of light, but then remains constant although the force driving them round the circular path is still acting.

If then a force acts on a body moving with the velocity of light, the velocity remains constant. The momentum of the body is equal to its mass in pounds multiplied by its constant velocity. The force increases the momentum; so, since the velocity is constant, the force must increase the mass of the body. The rate of increase of the momentum will be equal to the velocity of light multiplied by the rate of increase of the mass. The equation giving the rate of increase of the momentum therefore becomes

$$\begin{array}{c}\text{Force on body in}\\ \text{pounds weight}\end{array} = \frac{\begin{array}{c}\text{Velocity of light}\\ \text{in feet per second}\end{array} \times \begin{array}{c}\text{rate of increase}\\ \text{of mass in pounds}\\ \text{per second}\end{array}}{32}$$

If we suppose the initial value of the mass very small, the mass after the force has been acting will be equal to the rate of increase of the mass multiplied by the time during which the force has been acting. This gives

$$\text{Force} \times \text{time} = \frac{\text{Velocity of light} \times \text{mass}}{32}$$

The work done by the force or the energy given to the body is equal to the force in pounds weight multiplied by the distance the body moves in feet. This gives the energy in foot-pounds. The distance is equal to the velocity multiplied by the time; so, multiplying the above equation by the velocity of light, we get

$$\begin{array}{c}\text{Energy in foot-pounds}\\ \text{given to the body}\end{array} = \frac{\text{Velocity of light} \times \text{velocity of light} \times \text{mass}}{32}$$

The velocity of light is one billion feet per second; so the energy is equal to one billion billion foot-pounds divided by 32 times the mass in pounds. This is Einstein's result.

This result has been verified experimentally by measuring the energy released and the loss of mass in nuclear reactions.

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A new element with atoms called neutrons was discovered about 1930. Neutrons are formed in several nuclear reactions, for example:

$$\text{beryllium} + \text{helium} \longrightarrow \text{carbon} + \text{neutrons}$$

and

$$\text{deuterium} + \text{deuterium} \longrightarrow \text{helium} + \text{neutrons}$$

Deuterium, often called heavy hydrogen, is hydrogen of atomic weight two, twice that of ordinary hydrogen. Neutrons have an atomic weight nearly equal to that of hydrogen but have quite different properties from those of hydrogen atoms. Neutrons pass very freely through all kinds of matter, so that it is not possible to get any kind of container from which they do not escape very quickly.

A new kind of nuclear reaction was discovered in Germany in 1939. It was found that uranium reacts with neutrons, producing many different elements. The atomic weight of uranium is 238, and an atom of uranium combines with a neutron forming an atom of atomic weight 239.

If the neutron is moving very rapidly when it combines with the uranium atom, the atom formed is unstable and breaks up into two nearly equal atoms and several neutrons. This is called atomic fission. The elements formed by uranium fission have atomic weights between 80 and 140. For example, barium, cæsium, iodine, strontium, and bromine are formed besides others.

If the neutron is at rest or only moving very slowly when it combines with the uranium atom, the atom formed does not break up into two nearly equal atoms but it emits two electrons and becomes an atom of a new element, plutonium. Plutonium is one of the elements used to make atomic bombs. It has quite different chemical properties from uranium and so can be easily separated chemically from uranium. It fissions with neutrons like uranium.

It is found that uranium contains about one per cent of uranium atoms of atomic weight 235. These atoms have the same chemical properties as uranium atoms of atomic weight 238 and so cannot be separated chemically from uranium 238.

Uranium 235 breaks up into two nearly equal atoms and several neutrons when it reacts with a neutron which is either at rest or moving rapidly, and so differs from uranium 238, which only fissions with a fast neutron.

If a fast neutron goes into a piece of uranium 238 or uranium 235 or plutonium, then if the neutron hits an atomic nucleus, fission occurs and several neutrons are emitted. These neutrons then may hit nuclei and produce more fissions. Each fission produces more neutrons; so the number of fissions increases very rapidly, and in a small fraction of a second a large part of the piece may undergo fission. This is called a chain reaction.

There is a loss of mass in the fission reaction. One thousand pounds of uranium give only about 999 pounds of reaction products. This loss of mass is the mass of the energy released by the reaction. As we have seen, 32 pounds of energy is equal to one billion billion foot-pounds. The fission chain reaction therefore produces an explosion of enormous power.

It is found that a piece of uranium does not explode when neutrons go into it unless the piece is greater than a critical size. If a neutron goes into a small piece and hits a nucleus, causing fission of that nucleus, the neutrons emitted may escape from the piece without hitting another nucleus. Suppose, for example, that on the average a neutron goes a distance of one inch in the uranium before it hits a nucleus. Then with a small piece, say, half an inch across, neutrons emitted in the piece would nearly all escape without causing fission and a chain reaction could not be produced. With a larger piece, say, twelve inches across, a neutron emitted inside would be very unlikely to get out without hitting a nucleus and so a chain reaction could be started.

It is found that the critical size for uranium 238 is very large, very much larger than for uranium 235 or plutonium. Uranium 238 is therefore not used for atomic bombs, which have to be small enough to be carried in an airplane.

To make an atomic bomb, it is therefore necessary to obtain either pure uranium 235 or pure plutonium.

Plutonium is manufactured by exposing uranium 238 to slow neutrons. The plutonium formed in the uranium can be obtained pure by dissolving the uranium and other elements present in it in acid, and precipitating the plutonium by adding suitable chemicals to the solution.

Pure uranium 235 can be obtained by separating it from ordinary uranium. This is a complicated and very expensive process which would take too long to describe here.

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