Energy Resource Series for Youth and Adult Energy Programs

7. Nuclear Fission

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Preface

Nuclear power is one of the leading sources in our search for energy. One source of nuclear power is nuclear fission, an energy-releasing process in which the nuclei of atoms are split. The energy produced is close kin to chemical energy. Similar basic laws, rules and reasoning apply.

Perhaps the best means of gaining an overall understanding of nuclear energy is to examine three of the known force fields in nature. Because of the importance of these basic concepts, this publication will concentrate on descriptions of these force fields and how they are harnessed for our use.

In addition, the publication will examine the familiar concept, mass equals energy, as described in the Einstein formula, E=mc².

Although the subject matter in this publication is presented in some detail, a person not familiar with nuclear terms should find meaningful information to support many kinds of energy-related programs.

This is the seventh publication in a 12-part energy resource series designed for the adult and student with a serious interest in the energy situation. Each publication in the series examines a different energy source and considers the advantages and disadvantages associated with its use.

When necessary, diagrams and/or tables are used to clarify or elaborate upon information found in the text. Questions with answers are included at the end of each publication so that you can test what you have learned.

The author wishes to thank Joseph Taraba and Linda Bach of the Department of Agricultural Engineering, University of Kentucky, for reviewing the text.

The Energy Resource Series for Youth and Adult Energy Programs includes the following publications:

AEES-21 Energy Overview
AEES-22 Definitions
AEES-23 Oil and Gas
AEES-24 Coal
AEES-25 Solar
AEES-26 Wind
AEES-27 Nuclear Fission
AEES-28 Nuclear Fusion
AEES-29 Wood
AEES-30 Water
AEES-31 Geothermal
AEES-32 Alcohol
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Magnet Force Fields</td>
<td>4</td>
</tr>
<tr>
<td>Electricity and Force Fields</td>
<td>5</td>
</tr>
<tr>
<td>Other Force Fields</td>
<td>6</td>
</tr>
<tr>
<td>Atomic Parts and Forces</td>
<td>6</td>
</tr>
<tr>
<td>Atom Smashers</td>
<td>8</td>
</tr>
<tr>
<td>Heart of Nuclear Energy</td>
<td>8</td>
</tr>
<tr>
<td>Matter Into Energy</td>
<td>10</td>
</tr>
<tr>
<td>Mass Difference</td>
<td>10</td>
</tr>
<tr>
<td>Determining the Mass</td>
<td>10</td>
</tr>
<tr>
<td>Energy From Fission</td>
<td>12</td>
</tr>
<tr>
<td>The Critical Mass</td>
<td>15</td>
</tr>
<tr>
<td>Fuel Element Design</td>
<td>15</td>
</tr>
<tr>
<td>Uranium: From Element to Fuel</td>
<td>17</td>
</tr>
<tr>
<td>Prospecting</td>
<td>17</td>
</tr>
<tr>
<td>Mining</td>
<td>17</td>
</tr>
<tr>
<td>Milling</td>
<td>18</td>
</tr>
<tr>
<td>Enrichment</td>
<td>18</td>
</tr>
<tr>
<td>Fuel Pellet Manufacturing</td>
<td>19</td>
</tr>
<tr>
<td>Worker Safety</td>
<td>19</td>
</tr>
<tr>
<td>Fuel Reserves and Breeder Reactors</td>
<td>19</td>
</tr>
<tr>
<td>Spent Fuel and Radioactivity</td>
<td>20</td>
</tr>
<tr>
<td>Spent Fuel Management</td>
<td>21</td>
</tr>
<tr>
<td>Nuclear Reactor Safety</td>
<td>21</td>
</tr>
<tr>
<td>Ash Disposal</td>
<td>22</td>
</tr>
<tr>
<td>Questions</td>
<td>23</td>
</tr>
<tr>
<td>Answers</td>
<td>25</td>
</tr>
</tbody>
</table>
Permanent Magnet Force Fields

One of the quickest ways to "see" a portion of a magnetic force field is to perform a simple demonstration. The equipment required includes a permanent magnet (bar or U-shape), iron filings (these may be purchased or obtained by using a file on some metal object); and one sheet of typing paper.

There are many things you can do with these items to illustrate the magnetic force field around the permanent magnet. With the magnet on a table, lay the paper on the magnet and lightly sprinkle some iron filings evenly about the paper. You will immediately notice that the outline of the magnet becomes apparent, especially around the ends or poles. The result will be similar to the illustration in Figure 1.

Look very carefully at the iron particles near the poles. The use of a magnifying glass would help. Notice that those filings directly above the poles are standing on end. If you sprinkled them carefully, some may appear to be sticking together end-to-end and pointing straight up. At the edge and corners of the poles they stick out at an angle of about 45°. This is shown in the drawing of the 'U' magnet in Figure 2.

Fig. 2.—At the corners of the permanent magnet the iron particles follow the lines of force at 45° angles. In (a) the U-magnet is placed in a horizontal position. In (b) the U-magnet is held vertically. This shows that the force field extends outward into space in all directions from the source.

Close observation shows that the lines of force radiate from the poles in all directions. If the iron particles were not so heavy, or if the magnet were stronger, more would cling together and climb farther out from the pole.

The fact that the iron particles do not climb very far from the pole demonstrates one extremely important fact about magnetic force fields. The strength or intensity of the magnetic force field decreases inversely as the square of the distance. But the field extends to a very great distance though it is too minute to be detected by existing instruments.

Figure 3 illustrates the effect of like poles (North-North or South-South) and unlike poles (North-South) on the force field. With unlike poles...
the force field flows from one to the other; with like poles the force fields oppose each other at the midpoint. (It is essential that you be aware of this to understand the descriptions of the charged particles in Figure 7.)

One way to check for the existence of the magnetic field at much greater distances than with the iron filings is to use a compass (Figure 4). A small, inexpensive type will work. Hold it just above the paper near one pole. Note that while you move the compass in a large circle around the pole the needle remains pointed toward the pole. You can move the compass away several inches, and the needle will still point toward the pole. But the farther away you move the less sensitive it is. This tests the reality of the inverse square law. Note also, that the needle always aligns itself parallel to the lines formed by the iron filings.

Next, remove the paper from the magnet and put the iron filings back in their container. Hold the magnet above the table and investigate the presence of the field in all directions and distances around the magnet with the compass. Tip the compass when above or below the magnet to keep the needle from hanging in the case. You will find the field radiates in all directions from the poles and is the same strength at the same distance.

Electricity and Force Fields

Next, the similarity of the field around the permanent magnet and the field that surrounds moving electrons, that is, an electric current, will be illustrated. Figure 5 shows one of the tests that can be performed.

Support a rather rigid sheet of paper so that a wire can be run vertically through its center. Connect the ends of the wire to a flashlight battery for a few seconds. While the wire is in contact with the battery and the electrical current is flowing, sprinkle iron filings thinly on the paper around the wire. Concentric circles will appear in the iron particles. If the compass is placed on the paper while the current is flowing, the needle will align itself with these circles.

Reverse the ends of the wire at the battery and note how the compass needle reverses itself. Examine the iron filings through the magnifying glass, both when the current is on and when it is off. You will note that the field exists only when the current flows.

The investigations so far illustrate the effects of an electromagnetic force field, whether produced by a permanent magnet or an electric current. The
electromagnetic field is composed of photons (see AEES 21, Energy Overview and AEES-2S, Solar). At various frequencies the photon field gives rise to 60 cycle AC electric current, electromagnets, radio and television bands, radar, microwaves, infrared heat, visible and ultraviolet light, laser beams, X-rays and gamma rays. It may be difficult to realize that the same photons which bring information to our eyes also make up the radiation field of devices, such as heaters that can heat a large auditorium, or microwave ovens that can cook a large roast in a few minutes. These photons also comprise the strong field of a large electric magnet that can pick up many tons of scrap metal.

**Other Force Fields**

At the present time, physicists are actively examining three kinds of force fields. The one already discussed is called the electromagnetic or photon field. The other two are the gravitation field and the internucleon field. Physicists are searching for two more. One is a relatively weak internucleon force causing radioactivity, and the other is a field within nucleons.

Most scientists agree that all force fields are caused by exchange of radiation particles. The broad photon field spectrum has probably been predicted and proven more thoroughly than any other physical phenomenon. The internucleon field, composed of particles called mesons, has been quite thoroughly examined in the last 20 years. It was predicted in the early 1930s by a Japanese physicist, Hideki Yukawa, and results of experiments since high energy equipment has become available have borne out his predictions. The principal part of the meson field that seems to cause the strong nuclear bonding force is particles called pions.

The gravitation field is thought to be composed of radiation particles called gravitons that are exchanged between any particles of mass. Much is known about this force. The mathematical laws that have been derived concerning it have been thoroughly tested in practice, as witnessed by the achievements in space. Photon and pion particles have been isolated and studied, but so far the graviton has not.

The prediction of such particles and forces is similar to other physical phenomena. Take the solar system for example. At one time in history man was conscious only of the fact that "lights" were in the heavens. Gradually man became aware that the sun was the center of a great system of orbiting planets. Still later, with the aid of better instruments, these curved orbits could be carefully analyzed and accurate predictions could be made of relative positions at future times. Small, seemingly eccentric changes in the orbital paths, led scientists to predict undiscovered objects out in space whose gravitational field caused the seemingly erratic changes in the path. By greatly narrowing the space to be scrutinized by their instruments many large and small objects have been pinpointed.

Physicists use similar clues to locate and isolate minute forces and particles within the atom. Each affects neighboring atoms causing movement in such ways as to accurately predict masses, velocities and electric changes of unseen new objects.

**Atomic Parts and Forces**

Figure 6 is a schematic drawing illustrating what physicists now know about the atom. The helium atom is chosen for illustration because it has enough parts in the nucleus to show the various interactions but is still uncomplicated enough to draw a reasonable diagram. A description of the lettered parts follows.

The symbol $e^-$ represents the electron with its negative electric charge. Figure 7a illustrates a point of negative charge with the force field, composed of photons moving toward it from all directions.

The curved line $e_0$ represents the orbit of the two electrons of the helium atom. The concept now is that the electron covers a relatively wide area rather than a point. This does not affect the mathematics.

The lines $P_1$ indicate the photon field of electrostatic force between the electron in orbit and the protons ($P^+$) in the nucleus (see Figure 7b).

The large circles $P^+$ represent the proton particle with its positive charge. Actually all four large circles in the helium nucleus should touch. They are shown apart so that the interacting force can be drawn between them.

The symbol $N^0$ represents the neutron with no electric charge. The neutron is thought to be similar to a hydrogen atom, that is, a proton particle with the electron smeared evenly over its surface and near the surface rather than at ordinary orbit distance. This accounts for its mass being slightly greater than a proton and also for the neutral charge.
Fig. 6.—A schematic drawing of the helium atom. The relative size and distance are not drawn to scale.

Fig. 7.—In (a) the circle represents an isolated negative charge with the force field moving toward it. In (b) the circle is an isolated positive charge, and the field is moving in the opposite direction. The opposite charged particles in (c) are shown close together, and the field agents (photons) are interchanging between the two causing them to be attracted to each other.

The symbol $M_f$ represents the meson particle force field. It consists of three separate types of particles whose mass is roughly one-seventh to one-half that of the proton. The lightest of these, the pions, apparently are the agents responsible for the strong interaction force between the nucleons (protons and neutrons). These force field particles, moving at nearly the speed of light, exist for only $4 \times 10^{-24}$ second. This means that two nucleons must be within one nucleon diameter of each other before the pion particle fields can interact (Figure 8). At this distance or less, the large nucleon particles are strongly attracted and will remain together like the north and south poles of two magnets until a stronger force breaks them apart.

The strong nuclear force can be likened to a hoisting rope with a hook on the end that is to pick up a load that also has a hook. Only when the hooks meet can the two objects, the hoist and the load, be brought together by the rope. If the load is outside the length or range of the rope, the tension force capability of the rope cannot be effective. The pion force field causing the strong nuclear force has a similar definite limit. It reaches out to only $1.5 \times 10^{-13}$ cm before returning to the nucleon or disintegrating. Some also have likened the strong nuclear force to adhesive tape. The tape and object only
adhere when they come extremely close together. Outside this distance there is no attraction.

Thus, the nuclear binding force field is different in two ways from the electromagnetic and gravitational fields. It has a definite limit while the others extend to infinity, and the nuclear binding force is stronger, about 130 times the force of the electromagnetic.

The symbol Q stands for quarks. Within the last 10 years mathematical calculations have predicted their existence. These calculations show that each of the particles in the nucleus, the proton and neutron, are composed of three quarks. Each quark has slightly different characteristics. These account, at least in theory, for all the different particles and forces between them. An extremely large accelerator near Batavia, Illinois was built to attempt to break apart the nucleon particle and test the quark theory.

The heavy dashed lines Qf indicate a probable extremely strong exchange particle field holding the three quarks together, thus forming a proton or neutron. The name alvion has been proposed. If the nucleons are broken into quarks, the parts will be much more massive by themselves than when combined. This follows the E = mc² law. The loss of mass, when combined, appears as energy in the strong Qf field holding the quarks together. Is there super energy concentrated here? Man may know within the next decade or so.

**Atom Smashers**

To break up the nucleus of an atom, a high speed particle (bullet) is used to hit the nucleus with enough force to break the strong nuclear bond. This means the nucleon particles are forced far enough apart so that the pion exchange particles or gluions cannot reach each other.

To get a particle to move at a great enough velocity a particle accelerator is used, similar to a slingshot using stones for the bullet. A proton, which is the hydrogen atom with the electron stripped away, is held at the end of a long arm by a negatively charged electromagnet. The arm rotates at a high velocity; then the electromagnet is switched to positive, which pushes the proton off, and it goes flying down a tube (barrel) to the target nucleus. This proton is guided down the tube by negatively charged magnets all around the tube forcing the positively charged bullet to stay at the center. In practice, many positively charged particles are fired at many nuclei at the same time so the chances of a hit are greater.

**Heart of Nuclear Energy**

Since the nuclear bond or pion exchange field is extremely strong, it takes a force equal to it or just slightly greater to break the bond. But when it is broken, all this pent up energy is released. This is the source of the vast amount of nuclear energy. While chemical energy comes from breaking electrostatic bonds between electrons and protons (Pf in Figure 6), nuclear energy comes from breaking the stronger nuclear binding force (Mf in Figure 6).

But there is a problem. The method used to split the nucleus requires more energy than is recovered. Some way was needed to make the nucleus break down automatically.

During the 1930s and the early '40s the search for the right combination for a self-sustaining chain reaction finally determined that the very heavy element, uranium, offered the only possible access to a sustained chain reaction. Mathematical theory supports this also.

At this time Europe was being engulfed by war. A group of scientists fled from Germany and other European countries, to the United States. They were concerned that Germany would develop this chain reaction and discover a way to unleash the vast potential energy held in the atomic nucleus. This group explained their theories and fears to Dr. Albert Einstein; he was confident that the theories would lead to actuality.
However, another big problem arose. It was discovered that the easily broken down common uranium 238, which is very scarce in the United States, was not appropriate. The need was for uranium 235 and not 238, which was even more critical, because U^{235} makes up only 0.7 percent of all uranium.

This group of scientists realized they needed outside help. They composed a letter to President Franklin Roosevelt which Dr. Einstein signed; they felt the President would respect his scientific views on this critical matter. Roosevelt was impressed, and as a result, the Manhattan Project was started. Several large uranium refining and enriching plants were constructed in various parts of the United States.

While these were under construction, common U^{238} in the shape of bricks was tested in a large stack, commonly called a pile, about 25 feet square and 20 feet tall under the stadium seats of the University of Chicago. This large stack did support a self-sustaining chain reaction, and energy from the atomic nucleus was released and controlled by man for the first time. The date was December 2, 1942, nearly one year after Pearl Harbor.

With enriched uranium (containing high concentrations of U^{235}), from the refining plants the critical size was decreased from the first very large stack. On July 16, 1945, near Alamogordo, New Mexico, two pieces of this material, each about half the size of a basketball, were fired together resulting in the first "atomic" explosion set off by man on earth.

The chain reaction discovered by these scientists is illustrated in Figure 9. The breakthrough came when it was discovered that when very slow neutrons hit the nucleus of U^{235} the nucleus would "absorb" them (Fig. 9a). (If the neutron is too fast it will glance off.) Instantly, a reshuffling of particles takes place, apparently trying to make a place for the new neutrons (Fig. 9b). During this reshuffling, the quivering nucleus probably forms a dumbell shape (similar to a cell dividing). It very quickly breaks at the narrow point into two parts (Fig. 9c). The wavy arrows illustrate energy photons leaving because of loss of mass of each nucleon, and two surplus neutrons are shown being expelled. They will be slowed by moderating material and go on to enter neighboring U^{235} nuclei. The radiation (photons) is utilized as heat.

The U^{235} nucleus does not always break at the same point. If it broke exactly in half there would be half the original protons in each new part. Since the uranium nucleus has 92 protons, the two new halves
would each contain 46 protons. This element is palladium (Pd). Note that only one neutron is needed to keep the chain reaction at an even rate. On the average, the moderating material throughout the pile must absorb one neutron from the fission at each atom.

The nuclear reaction illustrated in Figure 9 is actually transmutation, the changing of one element into another. The smaller nuclei require fewer neutrons to assist in holding them together than do larger ones. When the large uranium nucleus splits into two smaller nuclei there are always two or three unneeded neutrons expelled. These neutrons, moving out and colliding with other U235 atoms, sustain the chain reaction. This chain reaction releases many times more energy than is required to start the reaction.

Matter into Energy

Mass Difference

The mass of a nucleus is always less than the mass of the separate parts (protons and neutrons) that comprise it. In other words, the mass of the product is always less than the original mass. This difference or loss of mass is energy according to \( E = mc^2 \). The mass of one proton, out by itself, is 1.00728\( \mu \) and the mass of a neutron, also by itself, is 1.00866\( \mu \). If two protons and two neutrons are forced together to form helium (Figure 6) the mass of this nucleus, as measured by tests, is 4.0026\( \mu \). The results of this arithmetic are as follows:

- Mass of proton as individual particle = 1.00728\( \mu \)
- Mass of proton as individual particle = 1.00728\( \mu \)
- Mass of neutron as individual particle = 1.00866\( \mu \)
- Mass of neutron as individual particle = 1.00866\( \mu \)
- Total mass of individual particles = 4.03188\( \mu \)
- Total mass of particles compacted together in nucleus = 4.0026\( \mu \)

\[
\text{Mass difference} = \frac{4.03188\mu - 4.0026\mu}{4} = 0.02928\mu
\]

Determining the Mass

The mass of minute particles, such as nucleons can be precisely determined. The instrument and method to do this are shown in Figure 10. Positive ion particles are generated at the source and directed at a known velocity in a straight line through a barrel which is perpendicular to a negatively charged plate. When the positively charged particle speeds through the slit, it immediately comes under the influence of the flat, negatively charged plate, causing the particle to travel in a curved trajectory until it intersects the plate. The less massive particles curve in a shorter radius than do more massive ones. The spots where particles hit the photographic film indicate precisely the mass. Thus, the mass of single protons and neutrons and of the nucleus of each of the elements, as well as the isotopes of the elements, have been documented. To get the mass of the negatively charged electron particles, the charges in the barrel and on the plate are changed to positive. By this method, the relative masses of the particles and nucleus in the previous example have been established.

By dividing the mass difference of 0.02928\( \mu \) by four (the number of nucleons involved in the helium nucleus), the average difference (loss) per particle is 0.00732\( \mu \). Figure 11 shows the result of applying this method or arithmetic to each of 100 elements. The results, when plotted as loss in mass (\( \Delta \) mass) per nucleon particle versus the atomic number (specified element), closely follow a smooth curve. Examination of this curve reveals the source of the vast potential energy in the nucleus of some of the atoms. This curve tells at a glance what kind of nucleon combinations will give energy and about how much.

Thus, Einstein's theory that energy and mass are interchangeable has been proven true.
Fig. 11.—Loss of nucleon mass upon combining.
Energy From Fission

Physicists know that objects under internal stress, such as a stretched wire or spring, contain internal energy; this internal energy causes the objects to have more mass than unstretched objects. This change in mass is too minute to measure in the usual physics laboratory, but when it comes to internal energies within the nuclei of atoms it is a different story. The energy contained in the strong binding forces that hold the nucleons together is so great that the masses of the nuclei are measurably different from the masses of the separate parts.

By using proper conversion factors, Einstein's equation becomes useful in translating the change of mass into energy units that are familiar. Proper ratio and proportion can be set up to find the energy of any amount of mass change or electron volts (eV) emission in the units best understood. The first conversion is:

\[
1 \text{MeV (one million electron volts)} = 1,000 \text{ amu (atomic mass units)}
\]

or

\[
1,000 \text{ eV} = 1 \text{ amu}
\]

This equation gives the energy in electron volts which may not be familiar. A change into other units can be as follows:

one million electron volts = 1.666 ergs

or

\[
1 \text{ MeV} = 1.666 \text{ ergs}
\]

If energy, in ergs, is not familiar, another conversion which may make the answer easier to understand is:

one Btu = 10,500,000,000 ergs

or

\[
0.00000000095 \text{ Btu} = 1 \text{ erg}
\]

When considering the energy of only one atom, the answers become infinitesimal. But when one gram or an ounce or pound of material is considered, the number of atoms is so great that the energy liberated is quite significant.

Now what happens when a large atom splits? Consider U\text{235} that the researchers found so effective in releasing energy. Assume that in this case the U\text{235} atom splits into two equal parts. Since U\text{235} is element number 92, the new elements would be number 46, palladium (Pd).

Notice from the curve in Figure 11 that the element Pd is much higher, vertically, on the curve than the element U. The vertical distance from U up to Pd represents the amount of mass lost by each nucleon.

A common breakdown of U\text{235} is into krypton (Kr) number 36, and barium (Br), number 56. These atoms are not the same size but each one is higher up the curve. The two vertical distances represent the mass lost by each of the nucleons involved.

There is a great difference in phenomena on the left end of the curve. Suppose the atom helium, number 2, is split. It can only split into two equal parts, each being hydrogen, number 1. From this curve it is seen that the particle, a proton, making up the atom hydrogen gained mass because the vertical distance is downward. In other words, it took a great deal of external energy to break up the helium atom. Much more must be put in than is received from it.

Obviously, the nature of things is different on this side of the curve. Here the atoms should combine to move up the scale vertically so that each nucleon can lose mass.

Consider the hydrogen atom again. If two atoms of hydrogen can be forced together to form helium, a giant step in mass reduction can be made. Instruments indicate that within the sun it takes temperatures of 15,000,000°C, or agitation of the hydrogen atom equal to that temperature, to speed up the particles and effect the combination. Vastly greater energy is given in return.

If three helium atoms can be made to join, they form a carbon atom with six protons and accompanying neutrons. The vertical distance up from helium to carbon is the mass lost per nucleon and converted to energy. A temperature of 150 to 200 million°C is required for helium to fuse together. This extremely high temperature is necessary because the three positively charged helium nuclei require higher velocities to come together. These steps are what is happening within the sun.

Thus, the method for energy liberation among the heavy elements on the right hand side of Figure 11 is fission—breaking apart; that on the left side with the lighter elements, is fusing—joining together. The great difficulty with the joining process or fusion is the extremely high temperature necessary to force the light atoms together. This is the reason that nuclear energy for peaceful uses has been by the fission process. Nuclear bombs have employed the fusion process by using a small fission bomb to supply the very high temperature to fuse hydrogen into helium. The words, thermonuclear bomb, have been applied to this process because of the high temperature required. This all takes place in a few millionths of a second and affects space for miles around. In the future, researchers may develop ways to tone down and control the fusion process. The control of the fusion
process would allow an even, or steady output of energy rather than the rapidly increasing runaway chain reaction resulting in explosions.

As mentioned in AEES-22, Definitions, the harnessing of energy is a big engineering problem area. Harnessing of nuclear energy is no exception. One must remember that the difference between an explosion and a regulated flow of energy is that in the explosion of nuclear devices the chain reaction runs away, and a vast number of nuclei are split in an extremely short time (Figure 12); or at least until the explosion blows all the material apart or melts and vaporizes it. In nuclear bombs only a small fraction of the total amount of fuel actually undergoes splitting.

In a nuclear device designed for producing energy for peaceful purposes, the chain reaction is closely controlled so that it never passes a certain level (Figure 13). Then a constant rate of neutrons is allowed to contact new fuel (unsplit atoms, U$^{235}$) and the constant rate of energy generation is provided.

The schematic diagram in Figure 14 shows one way nuclear energy is harnessed. Actually this diagram can be broken into three parts or distinct steps forming the complete system. The first part is the reactor circuit or loop (heavy lines). The second part is the steam circuit, and the third part is the generator. The third part will not be discussed because many different things could be attached to the rotating turbine shaft to do useful work.

In a nuclear reactor, radiation in the form of heat from U$^{235}$ fission within the fuel elements, heats the water within the steel vessel; this in turn heats water in the heat exchanger, turning it into steam that drives the turbine.

The water within the reactor circuit is at such high pressure that it does not turn to steam, thus the physical size of the reactor can be at a minimum. The water temperature around the fuel is usually designed to be between 500 and 550 °F with accompanying pressure of 600 to 1,200 pounds per square inch. Some systems operate with partial steam in
Fig. 14—A schematic diagram of a nuclear reactor.
the reactor circuit. This keeps the temperature the same but lowers the pressure; at the same time the physical size of the pressure vessel increases.

The control rods are made of material that stops or absorbs the expelled neutrons and does not pass them on. When these rods are lowered into the fuel elements the chain reaction ceases. One, at the center, is shown lowered part way, thus slowing reaction of that element.

The Critical Mass

The fuel element is the heart of the reactor. Fuel elements must be precisely shaped because the geometry drastically affects the opportunity or probability of expelled neutrons finding new fuel (unsplit nuclei) or just passing into unfissionable material and stopping.

For instance, researchers have found that a golf ball size quantity of nuclear fuel will not sustain a chain reaction. Neutrons escape through the outer surface into the air before contacting a new nucleus of fuel, and so the process dies and stays dormant. Even with an external source of neutrons beamed at it to start the process, the golf ball size chain reaction stops as soon as the source is turned off. But if material containing fuel (U\textsuperscript{235}) is gradually added in thin layers to the surface of the golf ball, a spherical size will be reached so that the ejected neutrons find enough new fuel, in an extremely short time (millionths of a second). With many billions of nuclei being split in this short time (a total of a hundred or so generations), the huge quantity of energy cannot help but cause an explosion which blows the mass of material apart. Each of these small bits is then again too small to sustain a chain reaction, and the whole thing stops. But in between was the terrific explosion produced by expansion of heated air and material, and accompanied by energy release in the form of heat, light and of gamma radiation. The minimum size sphere that will cause the uncontrolled chain reaction to occur is called the "critical" mass.

Fortunately, the critical mass in spherical shape can be calculated precisely. The amount of uranium fuel that can become critical is about the size of a softball. The exact size depends on the richness of the mixture. The size can be super critical, that is, a much larger amount than is required for a runaway chain reaction. But so far as explosions are concerned, everything over the critical mass is blown away and does not enter into the energy production.

The shape of the mass is as important as the quantity. One situation, which was publicized, concerned uranium fuel in a solution. It was held in a shallow flat pan but was being slowly poured into a cylindrical container. The mistake was caught just before this quantity went on to critical size. The cylindrical shape of the receiving container much more nearly approached a critical size sphere than did the flat shape where ejected neutrons simply shot out in the air.

Fuel Element Design

The main thing to grasp so far in the discussion of reactors is that both quantity and shape are very important; that is, the geometric arrangement of the fuel elements. The fuel particles must be arranged so that each splitting nucleus will send at least one expelled neutron to an adjacent nucleus, causing it to split. The fuel particles also must be arranged so that control rods can be inserted as desired to intercept the neutrons and reduce or stop the chain reaction, thus keeping it under control.

Figure 15 is an end view of one method of designing a fuel element. The circles labeled F are tubes containing the fuel, uranium dioxide (U\textsubscript{2}O\textsubscript{2}). The larger crosshatched circles are control rods. The fuel element may be 4 to 6 feet in length. This depends on the design of the reactor.
Many of these elements can be placed in a reactor, separated by just a few inches of supporting material. The larger the reactor, the longer the elements must be, and more of them are placed side by side.

Some kinds of structural support must be present to hold the fuel tubes in place and to allow the control rods to move up and down. Water circulates through each fuel element picking up heat from the fuel tubes. Note the symmetry of the design. When the control rods are removed, each fuel tube F is exposed about equally to another. When the control rods are lowered or pushed into the fuel element each tube is shaded or protected so much from the others that fission stops.

Even in a chemical energy system, such as the burning of woods, much thought and management of the arrangement of the fuel must be practiced.

Figure 16 illustrates the importance of geometry in initiating and maintaining both chemical energy (a wood burning fireplace) and nuclear energy. In Figure 16a a match started by heat from friction, ignites small pieces of paper which in turn furnish enough heat to vaporize adjacent fuel; this fuel then unites with the oxygen in the air because of the high temperature. About 15 percent of the energy given off in combustion is used to vaporize and ignite adjacent fuel. As anyone knows who has operated a fireplace or built a campfire, some planning must go into the geometry or placement of the various pieces of wood.

Similarly, nuclear fuel must be arranged precisely to start and maintain the fission process. In Figure 16b one slow neutron is directed toward a U^{235} nucleus. This is comparable to the match in Figure 16a. The fuel nucleus fissions and gives off energy in the form of gamma rays which eventually produce heat; at the time of fission two or three neutrons are also expelled. The expulsion of these neutrons takes some energy, about 20 percent of the total, but they are used to strike other U^{235} atoms which in turn release energy, as heat plus other neutrons. The geometric placement of the nuclei is critical in a similar way to the placement of wood in the fire.

It is important to realize that photosynthesis was the source of energy input (boosting electrons to higher levels) into the wood. This stored energy is given up in the combustion or recombining process involving the electrons and their electrostatic forces, as the electrons fall to lower energy levels. Nuclear energy (fission) comes from the fact that protons were forced together by great forces, velocities and temperatures to form large nuclei (uranium, number 92). When man controls the splitting or breaking up of these binding forces this energy is released. Thus, nuclear energy is similar to chemical energy in that similar forces are involved, but the nuclear forces are approximately 130 times as strong.

The first step in the construction of a fuel element is to compact uranium dioxide (UO_2) into cylindrical pellets, each about 1/2 inch in diameter and 1 inch long. These fuel pellets are then loaded into thin-walled stainless steel cladding tubes. An inert gas, such as helium is then pumped into the tubes, and the ends are sealed. The gas serves as a heat conductor between the fuel pellets and the stainless steel cladding. Several of these tubes are placed in a geometrically designed cluster similar to that in Figure 15 and held in place by spacers.

This group of fuel tubes with the control rods is known as a fuel element. They are about 8 inches square and are from 4 to 6 feet in length, depending on the size of the reactor. Many such fuel elements (in large reactors there may be several hundred), held side by side by means of grid plates, make up the reactor core.

At the present time the construction of fuel elements is the most costly step in nuclear fuel production. But these precise steps are necessary to attain a high degree of fuel decomposition (burning up), which means the fuel can stay in the reactor longer, thereby giving greater efficiencies.
Water circulates through each fuel element and is in contact with the outside surface of the cladding tube. The heat from the fission of the uranium atoms inside the tube is conducted to the helium gas by the fuel pellet itself. The helium conducts the heat to the thin stainless tube wall which in turn conducts it to the water. This high temperature water in the reactor loop, in turn heats water in the turbine loop but does not come in contact with it.

The water also serves another purpose, that of a moderator. As neutrons are expelled from fissioning uranium atoms they are moving too rapidly to be absorbed by neighboring uranium atoms. They simply glance off. The water serves as a moderator of this velocity and slows the fast neutron so that in approaching another nucleus, as in Figure 9, it will be absorbed and cause fission. The distance through the water is very critical so that the expelled neutron will be going within close limits of the correct velocity from tube to tube. Hence the size of the tubes and the distance between them (the geometry) are dictated.

This water must be chemically pure to prevent any corrosion of the fuel cladding or spacers. Purity also prevents mineral deposits that would cause hot spots. In addition to the heavy water, that is, water containing special hydrogen called deuterium, the hydrogen atom that has a neutron in the nucleus, is added in controlled amounts to make the moderating ability of the water perform effectively. For these reasons, this water is kept physically separated from the water in the turbine loop and is known as the reactor water loop.

**Uranium: From Element to Fuel**

**Prospecting**

Uranium is not a rare element. Rock deposits containing uranium are scattered over the earth's surface. The richest ore containing the element is called pitchblend. The color ranges from black through brown to green; shade is dark, and its name is derived from the similarity to shiny pitch. Pitchblend's composition varies but the elements in it are always combined with oxygen. Radium, polonium and activium as well as uranium are obtained from pitchblend.

Uranium is not an unfamiliar element. In its combination with oxygen it has been used to color chinaware and ceramic products. The steel manufacturing industry has used uranium in various combinations to give its products special properties. In combination with carbide, it is used in the process of manufacturing ammonia.

From these examples uranium is seen to be very chemically active. It will rapidly combine with oxygen in the air, just as magnesium does. The most common combinations with oxygen are as $\text{UO}_2$ and $\text{UO}_3$. Uranium combines easily with other chemically active gases such as chlorine, hydrogen and fluorine. As will be seen, scientists have taken advantage of the importance of uranium's chemical activity.

Before World War II the world's need for uranium was minimal. But when the potential energy of uranium was discovered, military and industrial concerns multiplied.

Prior to its energy discovery, uranium ore was mined at only a few places in the world. High-grade deposits were located in Zaire, formerly the Belgian Congo, and in northern Canada. After its importance increased, prospecting for other deposits took on all the appearance of a gold rush.

Uranium prospectors use Geiger counters rather than pick and shovel and pan. Uranium and some of the other elements, such as radium in the pitchblend ore are mildly radioactive. The gamma rays emitted, in the spontaneous breakdown of these elements, can be detected by one of these small portable instruments.

The Atomic Energy Commission (AEC) was established by Congress in 1946. This official office was given authority over all phases of atomic energy which included buying uranium ores discovered by prospectors. Establishment of the AEC and the cooperation of the U.S. Geological Survey greatly expanded the search for the element. As a result, the United States has been thoroughly searched and now ranks at the top in worldwide uranium production.

In the United States, uranium has been found to be most prevalent in ores called carnitite. Carnotite is similar to pitchblend but the elements found in it are more complex. Most of these deposits are located in western areas of New Mexico, Arizona, Colorado, Utah and Wyoming.

**Mining**

Mining the ore is similar to mining coal. Some ore is located in rock deposits where it is most economical to use large earth moving equipment. Other deposits, deep in the earth, are best mined by shafts and underground equipment.
Milling

The first step in the transformation of uranium found in ore to a fuel element is the mill. The bulk rock ore is delivered by truck or rail car to the mill. The concentration of uranium in these rocks is only a few parts per million. In more familiar terms, this is from 2 to 20 pounds of uranium oxide (black oxide, UO2O6) per ton of ore. The mill reduces the bulk, or in other words increases the richness of the ore, by removing impurities.

At the mill the ore is pulverized by hammer mills. These fine particles are soaked in a reagent which dissolves or leaches out the uranium dioxide. This liquid is then heated to drive off excess moisture. What is left is commonly known as "yellow cake." This is a more concentrated mixture of about 70 percent UO2O6, or an increase of 300 times or more as compared to the raw ore state. There are approximately 20 of these mills operating in the U.S. today.

From these mills the product goes to a refining plant located in St. Louis. Here the concentrate is again dissolved and heated to form uranium trioxide (UO3). This is a very fine, smooth, bright orange colored powder. Before its use as an energy source, uranium, in the form of UO3, was used as a coloring agent. A second step at the St. Louis plant now is to chemically convert the UO3 to UF6 which is also called "green salt." The advantage of the naturally hyperactive ability of uranium to react with fluorine gas (F2) is used in this step.

Enrichment

From the St. Louis concentration plant the green salt is moved to enrichment plants. There are three of these using similar systems of enrichment, located at Oak Ridge, Tennessee; Paducah, Kentucky, and Portsmouth, Ohio. Kentucky is, and has been for some time, at the center of nuclear fuel manufacturing.

These plants are of tremendous physical size. They have to be because they operate on the gaseous diffusion process. This system requires miles and miles of separation membranes. Recall that in the very early stages of research on fissionable elements it was discovered that U235 rather than U238 more easily and economically (from an energy particle standpoint) split. Recall also the fact that U235 makes up only 0.7 percent of uranium. This means that only seven atoms out of 1,000 uranium atoms are U235. The job of these three enrichment plants is to separate the U235 from the U238 and gather them together in whatever increased concentration is desired. For instance, the reactor core size used in small ships like submarines must of necessity be of minimum size. The fuel pellets in these reactors are richer (about 90 percent) in U235 atoms than is needed for land based reactors which may operate on as low as 15 percent U235.

At these enrichment plants the green salt, newly arrived from St. Louis, is reacted with fluorine gas to form a volatile compound, UF6. Since UF6 gasifies easily, the compound is vaporized at these plants and is ready for the separating process to begin. Fluorine exists as only one kind (isotope) of atom. The element is adjacent to oxygen in the periodic table and is number 9. It therefore has nine protons in the nucleus. Its mass number or atomic weight is 19, and it therefore has 10 neutrons in the nucleus. For fluorine this never varies. But uranium can have an atomic number of 235 or 238, and an extremely small amount occurs as 234.

U238 has 146 neutrons in the nucleus and is heavier than U235 which has only 143. This is the only detectable difference. They have the same quantity of charge and chemically react the same.

Since UF6 turns into the gas state easily and because it exists in only one isotope, the only difference between a molecule of U238F19 and U235F19 is that the second one is three neutrons lighter. This represents about a 1 percent difference in mass. Contrast this with the difference between hydrogen one and two (H1 and H2) in which the first atom has a single proton while the second has a proton and a neutron. The mass of the second one is double that of the first or a 100 percent increase. It is easy to distinguish between these two atoms.

The small difference in mass between U235 and U238 can be used, however, and is the basis of the design of the gaseous diffusion plants. These plants were designed with long duo-concentric pipes, that is, a small pipe within a larger pipe. The gasified UF6 (uranium hexafluoride) is injected into the inner pipe. This pipe is perforated with many very small holes. The UF6 gas molecules vibrate at a high rate because of the temperature and pressure. The lighter a molecule the faster it must move to equal the kinetic energy of a more massive one. Thus, on a statistical basis only, the faster vibrating gas molecule should find a hole in the pipe more often than the slower one. This process is called gaseous diffusion.

This process of enrichment may not appear to be a very satisfactory way to separate U235 from U238 but it works. The process requires many miles of the dual-type pipe to produce the many tons needed by military and industrial users each year.
The uranium hexafluoride that escapes the center pipe into the outside one contains a higher concentration of U\textsuperscript{235}. The outside pipe can be tapped at any point and this gas removed at whatever concentration is desired. This gas is now ready to move to fuel pellet manufacturing plants.

**Fuel Pellet Manufacturing**

Just before the pellets can be formed, some decisions must be made, based on the reactor design and use. For the water cycle type, the fuel pellet UO\textsubscript{2} has been found most satisfactory. To change the UF\textsubscript{6} to UO\textsubscript{2} is a straightforward chemical process.

First the UF\textsubscript{6} is reacted with water and then with a hydroxide salt. The precipitate is heated for drying and the orange colored uranium trioxide (UO\textsubscript{3}) again appears. This time it is enriched, that is, the compound contains a higher percentage of U\textsuperscript{235} atoms. This is reduced to UO\textsubscript{2} by use of hydrogen gas, a powder ready for compacting into fuel pellets. Many companies in the United States are set up to furnish this service, all under license from the AEC.

**Worker Safety**

The reader may wonder about the danger of radiation to people who work in the plants. Uranium is only slightly radioactive and can be handled by workers in most cases, the only protection being good ventilation of the working space. It takes highly sensitive instruments to detect the low radiation that could be present. However, it is a different story in regard to handling spent fuel elements removed from reactors.

**Fuel Reserves and Breeder Reactors**

Since it is U\textsuperscript{235} that is essential to the fission process and since this isotope is only 0.7 percent as plentiful as common U\textsuperscript{238}, the supply of nuclear fuel could become a limiting factor. However, it was theoretically predicted that a new element could be produced that did not occur naturally.

It was predicted that when U\textsuperscript{235} absorbed a slow neutron and split, two and sometimes three high speed neutrons would be expelled. Only one is needed to continue the steady rate of a chain reaction. The extra neutrons could be used on U\textsuperscript{238}, and the new element could be produced.

It works in this manner. If an atom of U\textsuperscript{238} is nearby it would absorb one of the extra expelled neutrons, but it would not fission. U\textsuperscript{238} then becomes U\textsuperscript{239}. Due to the nature of things, it does not split in the middle and release lots of energy like U\textsuperscript{235} but splits off a tiny fragment (radioactive style) called a beta particle. The beta particle is actually an electron expelled from a neutron in the nucleus. This electron previously was integrally smeared over a proton neutralizing the charge of each, hence the neutron.

Immediately after the electron was jarred loose and expelled the neutron became a proton. The nucleus that was U\textsuperscript{238} now contains 93 protons and is not U\textsuperscript{238} anymore, but up one step to element 93, neptunium (Np). Neptunium turns out to be very weak, radioactively. It emits a beta particle, like U\textsuperscript{238} did, and moves up one step to number 94, plutonium (Pu), which is just slightly more radioactive. It was also found, as predicted, that plutonium when hit by a slow neutron, splits into two nearly equal parts with as much energy released as when U\textsuperscript{238} breaks apart.

Here then is a way to use the excess expelled neutrons from fissioning U\textsuperscript{235} and turn common U\textsuperscript{238} into a new fissionable fuel, plutonium. If one of the expelled neutrons from the U\textsuperscript{238} is used to fission an adjacent U\textsuperscript{239} and keep the chain reaction going, and the second is used on a U\textsuperscript{238} nucleus, maybe the third, which is sometimes expelled, could also be used on still another U\textsuperscript{238} atom. If so, the resulting amount of plutonium from common U\textsuperscript{238} would be greater than the number of U\textsuperscript{235} to run a power plant. This new fuel is separated from the spent fuel when the fuel element has run its course in the reactor—usually a year or more.

It must be emphasized that in the process of utilizing the potential energy in uranium this fuel is used up. Each atom that fissions no longer exists as uranium but as the new lighter elements into which it fissions, such as Ba and Kr. It must also be understood that the fuel, plutonium, comes from U\textsuperscript{239}. Each atom of U\textsuperscript{239} that turns into plutonium is used up and no longer exists.

In each of these cases, the basic element, uranium has disappeared. We may have become complacent and lulled into thinking that nuclear energy, if harnessed sufficiently, could provide for all our energy desires for all time. But since uranium is a finite material, it too, can vanish. It is true that if properly harnessed and used efficiently the small quantity available (in relative comparison to coal) in the earth's crust can generate vast amounts energy. Efficient engineering designs are imperative if nuclear energy is to bear the load of energy production for several decades, and then other sources...
can begin bearing their share of the load. At some-
time in the future people will have to switch from
fission fuel to different sources for their energy, as
we are now being forced to switch from 100 percent
use of fossil fuels.

Spent Fuel and
Radioactivity

The residue or ashes resulting from the fission
process are highly radioactive. The residue is made
up of the new atoms which are formed when
uranium or plutonium break into smaller atoms. The
most common new atoms from this fission of U$^{235}$
are krypton (Kr) with 36 protons and barium (Br)
with 56 protons. Sometimes the residue will be
strontium (Sr) with 38 protons and xenon (Xe) with
54, or rubidium (Rb) with 37 and cesium (Cs) with
55. In each combination, note that the number of
protons adds up to 92, the number of protons in the
parent uranium nucleus.

Remember that smaller atoms need a propor-
tionally smaller number of neutrons to make their
nucleus stable than do larger atoms. When
the combinations of smaller atoms are formed from
the more massive uranium atom, excess neutrons are
contained in the nucleus of each. The new, smaller
nucleus immediately begins to reshuffle its nucle-
on, and the excess neutrons are expelled until a
stable condition exists. This action is what causes
radioactivity.

There are basically three modes of radioactive
decay. These are naturally occurring events, and
humans cannot control them. All that can be done is
to examine and catalog them. Instruments have
been built that detect the kind of radiation being
emitted, and this allows the observer to know the
substance doing the emitting and what the new
substance will be.

The largest piece that is ejected by a reshuffling
atomic nucleus is called an alpha particle. It is
exactly like the helium nucleus. It has two protons
and two neutrons. It must be remembered that when
the alpha particle is emitted as radioactivity, the
remaining nucleus has two fewer protons, thus
moving down two steps in the periodic table of
elements. A second thing to remember is that the
mass number is lowered by four (two protons plus
two neutrons). By knowing this an identification tag

The second kind of radiation, as far as size is
concerned, is the beta particle. It is exactly like an
electron. It is assumed to come from a neutron in
the nucleus; immediately after a reshuffling nucleus
emits a beta particle, it steps up one place in the
periodic table. This indicates the nucleus has
gained one proton (the neutron turning into a
proton), but the mass number stays the same.
Again, by knowing this kind of radiation, the new
substance can be predicted.

The third kind of radiation is called gamma rays.
This radiation is a bundle or short burst of very high
ergy photons. Photons make up all electromagnetic
radiation, such as television and radio bands,
light and x-rays, as well as gamma radiation. This
burst of photons comes from the reshuffling nucleus
and at a much higher frequency than x-rays. As a
result, gamma rays contain high energy and are
therefore much more penetrating than alpha or
beta. Gamma radiation will penetrate several inches
of lead or several feet of concrete in contrast to
x-rays, which will penetrate flesh, but not bone.

We know that when energy is emitted, it is at the
expense of, or in exchange for mass. Some part of a
particle or particles contributed mass (although an
extremely small amount) to make this burst of
intense photons possible. Yet the element number
and the mass number stay the same.

The three main modes of radioactive decay are
briefly summarized here so that later in this publica-
tion the need and methods for radiation protection
will be understood.

Alpha Decay—Same as a helium nucleus. A sheet of
paper will stop these particles. The protection
needed is good ventilation and/or dust goggles, and
a cloth over the mouth and nose. Hands should be
washed carefully so radioactive elements are not
taken in.

Beta Decay—Same as an electron. This particle can
be ejected at extremely high velocities. Thick
wooden doors or heavy gauge metal panels are the
best kind of protection from these particles.

Gamma Decay—An intense burst of photons similar
to x-ray, but of much higher frequency and much
more penetrating. Gamma rays are slowed or
moderated by colliding with the atoms of sub-
tances. Protection is obtained by many feet of
earth, several inches of lead or steel, or several feet
of concrete. Protection adequate for gamma is
sufficient for alpha or beta.
Spent Fuel Management

Within the tubes holding the fuel pellets and within the pellets themselves, are the ashes or residue resulting from fissioning. This residue is intensely radioactive. After a nucleus fissions and liberates energy, the two new parts are of no further benefit to energy production. They actually interfere with the continued fissioning of other nuclei by absorbing or deflecting neutrons. This is called 'drag' on the system. Recall that in a wood burning stove the ashes must be removed from the fire box so that efficient burning can continue.

Because of the natural buildup of residue during the operation of a reactor, nuclear engineers must pack in excess fuel when the elements are fabricated. It is practically impossible to design fuel elements for 100 percent fuel burn up. Normally one and one-half to two years of operating time are to be expected before the chain reaction slows to inadequate rates because of the increased drag. Then the reactor must be shut down, the used fuel elements removed, and new ones inserted. Because of the intense radiation being issued from the used elements, much of it gamma, this removal is done by remote control using overhead hoists which lift the elements from the reactor core and place them in thick lead-lined containers.

The next step is the cooling vat. Here the fuel elements are removed by remote control, from behind thick concrete walls, from the lead container and placed in a large vat of water. Water is a good, economical moderator of the radiation. Many of the radioactive substances in the residue are short-lived. As a general rule, the short-lived ones are more intense. This cooling off period of several months allows this intense radioactivity to run down in the safety of the water.

A final step for the used fuel element is its removal from the cooling off tank and transportation in lead containers, to the spent fuel processing plant. Here the fuel element is again removed from the containers by remote control and placed in a large vat of acid. The stainless steel cladding is dissolved by this acid and is held in solution along with the fuel.

Because of distinct differences between the elements in solution, each can be removed by common chemical methods. Those elements that are highly radioactive are separated and prepared by remote control for safe storage. The unused uranium is recovered (both U^{238} and U^{235}) along with any new fuel (plutonium) and sent to enrichment plants to be mixed with the fuel being processed from raw ores. This recovered fuel is no more radioactive than the fuel from ore and is handled in the same way.

The nuclear industry is managed efficiently as far as uranium utilization is concerned. Even the radioactive residue is stored in such a way that it can be dipped into for elements that are needed in research, medicine, industry and agriculture. For example tiny nuclear batteries make use of the energy of natural radioactive material, yet are safe to handle.

Nuclear Reactor Safety

Nuclear reactor safety is foremost in the news today. One of the purposes of this publication is to acquaint the reader with nuclear reactor operation and nuclear energy in general, so that intelligent decisions can be made about the use of this potential energy source as it relates to our life-style.

Many citizens will undoubtedly have an opportunity to vote on referendums concerning construction of nuclear plants someday. Citizens also may be asked to serve on a board for hearings on licensing of these plants. All the facts a person can gather will be needed.

From the very start of the nuclear industry, the designers have been extremely conscious of safety. Except in cases where considerable pressure was applied to cut costs, safety has never been compromised.

Concerning the reactor itself, the first question asked by people unfamiliar with nuclear energy operations is about the possibility of an explosion. The reason for this question is obvious. Their only acquaintance with nuclear energy has been with dramatic explosions. The results of nuclear explosions have been thoroughly covered in the news media. It must be realized that considerable design and effort must be expended to obtain refined and enriched fuel which is the basis for an explosion. Then too, the mechanics for holding this material together for the required time, so that the chain reaction can progress to explosive force are unique and must be engineered to work.

The construction and fuel used in reactors are just the opposite. The fuel pellets used are greatly diluted compared to weapon fuel, and the geometry of construction is such that an explosion is impossible. In other words if one tried to build a bomb this way you would fail on two counts: the nuclear reactor uses relatively diluted fuel, and the geometry cannot be conformed into the critical mass.
If all of the many safeguards that surround a reactor should fail at the same time the worst accident possible would be the melting of the fuel cladding and its supports. The resulting extreme dilution and moderation of the surrounding water would stop the neutrons and stop the release of energy. The reason for placing the reactor in a round-topped building is not an attempt to contain an explosion, but an attempt to contain radioactive vapor from boiling water if the fuel cladding should melt. Actually, as long as the water surrounding the fuel elements can absorb and carry away the quantity of heat generated within the tubes, no melt down can occur.

The damage done to the reactor at the Three Mile Island, Pennsylvania, electric generation plant apparently could have easily and simply been averted if the indicator instruments had been properly observed. This is similar to an automobile engine heat or oil pressure warning signal being ignored. A severely damaged engine can result.

There are three things that naturally occur if the chain reaction should increase to a rate faster than intended. First, as the temperature of the fuel pellet rises, the expelled neutrons from splitting atoms (the ones that cause new fission) are absorbed preferentially by non-fissioning nuclei. This is just a natural phenomena, and the designer takes advantage of it. In other words, as the chain reaction tries to go faster it causes circumstances that automatically slow it down. This is a natural damping action.

A second natural effect is that as the fuel temperature rises, the pellet material expands. This puts more distance between fuel nuclei, thus causing the neutrons to take more time getting to a new nucleus or missing it all together. This results in an automatic slowdown of the chain reaction.

A third effect is that the surrounding water expands as it is heated, thus becoming a much poorer moderator of neutrons passing through. This results in fewer fissions which automatically slows down the chain reactions.

In addition to these natural safeguards against a chain reaction producing more heat than the system was designed to handle, several controllable safeguards are also designed for the system. One is the control rods system, and the other is the rapid injection of a neutron absorbing substance into the water.

Failure of the water to circulate through the reactor could lead to the overheating of the fuel pellets and their cladding material. One instance where this became a very real possibility was much publicized in the news. In this case the insulation in the control building caught on fire from a candle being used to test for ventilation drafts. The fire quickly spread throughout the building and nearly cut off the electric power to the water circulating pumps. In this case, because of budget constraints, rather than construct two or more control buildings with separate electric power circuits as was originally planned, the circuits were all contained in one. This proved to be a costly decision which will not be repeated. Since this incident, all open flames are forbidden and fireproof insulation is used. The main way to provide safety of the reactor water loop is with the conservative design which is practiced in all phases of engineering and has proven to be successful.

The safety of nuclear reactors is mainly in the area of containing the radioactive material it develops, and not on containing any force of an explosion.

Ash Disposal

There are two vast differences between the ashes from a nuclear plant and those from a coal burning plant. First, the ashes from the nuclear plant are extremely small in quantity (a few pounds per week), while the coal plant produces several hundred tons. Second, although the ashes of the nuclear plant are highly radioactive and require special handling techniques, the ashes stay confined inside the fuel tubes until the fuel tubes are removed.

There is a tremendous amount of gases, as well as any solids not trapped by expensive collectors, in the exhaust from the boiler of fossil fuel plants. In addition, the refuse or ashes collected amount to a great tonnage each year that must be disposed of. In contrast, the nuclear plant has very little exhaust, usually only the ventilation air.

The thermal addition of either type plant to the environment will be the same since they generate the same quantity of heat and convert it into mechanical motion the same way at about the same efficiency.
Questions

To stimulate thought and greater understanding, answer these questions with the best word(s) to make a true statement. Refer to the material when necessary.

1. Can the force of magnetism go through paper? (Yes or No)

2. Explain in your own words what is meant by the inverse square law.

3. Does the magnetic field extend out from the pole of a magnet equally in all directions? (Yes or No)

4. The needle of a compass is a small bar magnet. (True or False)

5. An electric current is actually

6. The magnetic field that surrounds an electric current is the same as the field that surrounds a permanent magnet. (True or False)

7. The magnetic field around a wire conducting an electric current loses strength according to the inverse square law. (True or False)

8. The magnetic field is composed of

9. Name the three known force fields.

10. What do scientists think the force fields are caused by?

11. Why are scientists wanting larger and stronger particle accelerators?

12. What is transmutation?

13. Describe two basic natural facts that are taken advantage of to make a nuclear chain reaction work and release energy.

14. Describe the difference between nuclear fission and fusion processes that produce energy.

15. Describe briefly a nuclear critical mass.

16. What two main things must a designer take into account when designing fuel elements? and
17. What elements compose a nuclear fuel pellet?  

18. What is a fuel element?  

19. What is the purpose of helium gas inside the pellet tubes?  

20. What two purposes does the water in the reactor loop serve?  
   and  

21. What is the first step or operation performed on uranium bearing ore?  

22. What is the need for enrichment plants?  

23. Is there great danger from radiation to workers in plants processing uranium for fuel pellets? (Yes or No)  

24. Is there an infinite amount of uranium bearing ore in the earth? (Yes or No)  

25. Is uranium used up in reactors? (Yes or No)  

26. What is plutonium created from?  

27. Can scientists and engineers devise methods of using uranium so that this fuel will last forever? (Yes or No)  

28. At some future date will humans have to derive energy from some other source? (Yes or No)  

29. What causes an element to be radioactive?  

30. Can man control radioactivity? (Yes or No)  

31. Name the three main modes of radioactivity.  
   and  

32. Which type of radioactivity requires the greatest protection?  

33. Which type of radioactivity steps up the resulting element in the periodic table?  

34. Which kind of radioactivity changes the resulting element to a place two steps lower in the table?  

35. Which kind of radioactivity leaves the element the same and with the same mass number?  

36. Can the used fuel elements be handled by hand after removal from the reactor as they were before? (Yes or No)  

37. What is the purpose of the cooling off vat?  

24
38. Can unused uranium and any new fuel, such as plutonium be recovered and placed in new fuel pellets? (Yes or No) ________

39. Is this uranium and plutonium radioactive? (Yes or No) ________

40. Is the radioactive residue useful? (Yes or No) ________

41. Can a nuclear power plant blow up? (Yes or No) ________

42. What is the worst possible accident that could happen at a nuclear power plant? ____________________________

43. Why is the reactor contained in a strong, round-topped building? ____________________________

Answers

1. yes
2. If the distance between two objects is doubled the attractive force is one-fourth.
3. yes
4. T
5. moving electrons
6. T
7. T
8. photons
9. electromagnetic (photon), gravity, inter-nucleon
10. exchange particles
11. to break up nucleon particles (neutron, proton)
12. changing from one element into another
13. fewer neutrons needed in smaller nucleus; mass of nucleus is less than mass of separate parts
14. In fission the large nucleus breaks up. In fusion two small nucleons come together. (In each case the mass of the end product is less than before the reaction.)
15. a minimum-size sphere that will allow an uncontrolled reaction to proceed until it blows itself apart
16. quantity and shape or geometry
17. compact uranium dioxide
18. a group of tubes which contain the pellets and control rods
19. a heat conductor between pellets and metal tube walls
20. neutron speed moderator and heat conductor
21. pulverized and uranium oxide leached out
22. to separate the sparcce \textit{U}^{235} from \textit{U}^{238}
23. no
24. no
25. yes
26. neptunium after the emission of a beta particle
27. no
28. yes
29. excess neutrons
30. no
31. alpha (helium atom), beta (electrons), gamma (photons)
32. gamma
33. beta (electron emitted causing a proton in nucleus)
34. alpha
35. gamma
36. no
37. The short-lived, intense radiation can run down safely.
38. yes
39. no (If any, it is very mild.)
40. yes (research, medicine, industry, agriculture, etc.)
41. no
42. melt down of fuel elements (only if all of many safety devices fail)
43. prevent escape of radioactive water vapor in case of melt down
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