



Nuclear power for mechanical engineers
by Ralph W Arboe

A THESIS Submitted to the Graduate Faculty In partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at Montana State College
Montana State University
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Abstract:

This thesis was written to be used as a text for M E. 508, Atomic Power Engineering and consists of declassified material released by the Atomic Energy Commission, as well as this student's original ideas and presentation. The presentation is on a level for a graduate student. All of the complicated mathematics and physics have been eliminated and only a straight-forward engineering approach presented.

The introduction starts with the basic concept of the atom and its structure. Also in the introduction are a table of definitions and conversion tables for converting energy, mass and charge units. The brief review in the introduction is then used as a background for the remainder of the thesis.

The discussion then turns to a brief history of the findings of radioactivity, isotopes, isomers, artificial radioactivity, nuclear reactions, neutrons and positrons. Nuclear energy is explained and the type of reactions needed to produce energy by means of nuclear reaction and fission.

Separation of isotopes and the detection of radiation must be understood before a useful reactor may be designed. The types of reactors are discussed showing the advantages of one type over the other.

In conclusion all of the aforementioned material is compiled to use nuclear power for industrial uses. Nuclear power is put to use in aircraft, power stations, locomotives, industrial processes and heating. Calculations show the amount of nuclear fuel required in comparison to coal and oil, as well as a cost comparison.

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FOR MECHANICAL ENGINEERS

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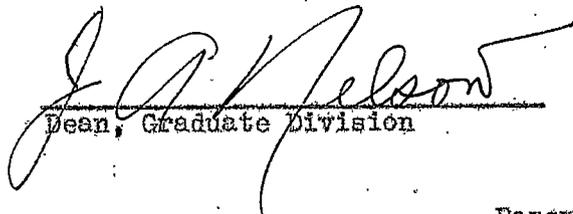
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INTRODUCTION

ANOTHER LOOK INTO THE ATOM

Before the turn of the century (1880-90), the Physicists were content to believe that nothing new could be found and that they had explained every phenomenon. The future technical outlook appeared as if all experimental and research work would have to be along the lines of already existing theories. This belief did not last long, because a series of discoveries starting with Wilhelm Roentgen's discovery of X-rays in 1895, Henri Becquerel's discovery of natural radioactivity in 1896, also the work of the Curie's, J.J. Thomson, Max Planck, Rutherford and Soddy, Einstein, Bohr, Aston, Compton, Chadwick, the Joliot's, Fermi and Oppenheimer, with the final result being the Atomic Bomb. (The above mentioned scientists and their work will be discussed in the following pages.)

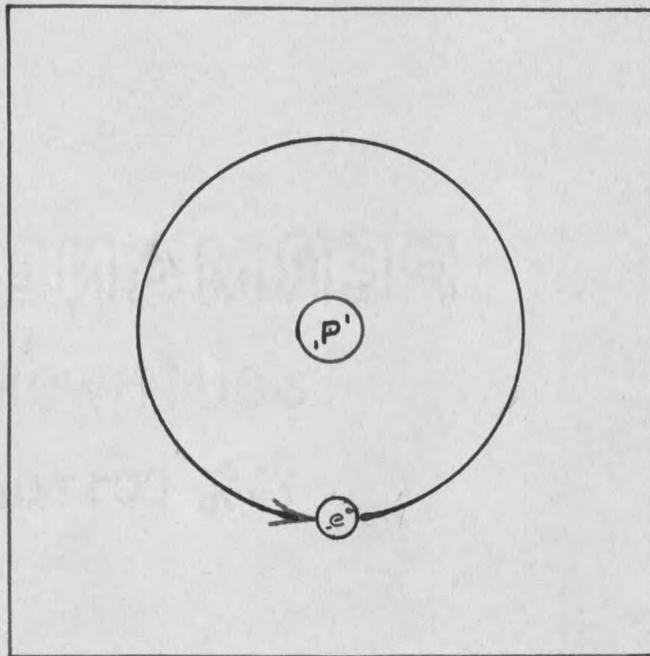


Figure 1 The Hydrogen Atom

Before continuing

with our discussion let us examine the present concept of the atom. According to the present concept every atom consists of a small heavy nucleus approximately 10^{-12} cm in diameter surrounded by a large empty

region 10^{-8} cm in diameter¹ in which electrons move somewhat like the planets about the sun. The nucleus having a positive charge (the amount depending on the individual atom) which is counterbalanced by an equivalent negative charge of the electrons (or electron). The mass of one electron is 2.01×10^{-30} lbs. or 9.1066×10^{-28} gms. Because of these awkward units the physicists have used another unit for the mass of these small particles, being the atomic mass unit (1 amu = 1.66×10^{-24} gms) which is based on the most abundant isotope² of oxygen having a mass of 16 atomic mass units.³

In examination of the smallest and simplest of the atoms, the hydrogen atom, we find that its simplicity is drawn from the fact that it has only one electron. As a result it needs only one positive charge in its nucleus (See Figure 1). The hydrogen atom has an atomic number (Z) of one, the next atom in sequence is the helium atom with an atomic number of two.

The helium atom has two electrons and two positively charged particles in its nucleus and therefore its weight should be twice that of the hydrogen atom. Referring to the mass of the hydrogen atom 1.00813 atomic mass units and the helium atom 4.005 atomic mass units we can see

¹ It is interesting to note that the diameter of the electron orbits is 10,000 times the diameter of the nucleus, and that all matter is made of atoms but only a very small volume of the atom is comprised of the nucleus and electrons, the rest of the volume being empty.

² Isotopes will be discussed later.

³ In chemistry the mass is slightly larger. This is because the unit is established by assigning the value 16,000 not to the predominant ^{16}O isotope, but to oxygen as it occurs in nature. The ratio of the mass of an object on the physical scale to its mass on the chemical scale is 1.00027.

that the mass ratio is approximately four and not two as we assumed. (At the present time the physicists have accurately determined the masses of the atoms and various isotopes). Our assumption was erroneous and there must be something else in the nucleus besides these two positively charged particles (protons). The other particles were found to be neutrons,⁴ a particle with no charge and a mass approximately that of the proton.

Therefore, the helium nucleus is made of two protons and two neutrons with two electrons moving in their orbits (Figure 2). The helium atom has an atomic number of two, an atomic mass number of four, and atomic weight of 4.003 amu. For future reference the atomic number, atomic mass number, and

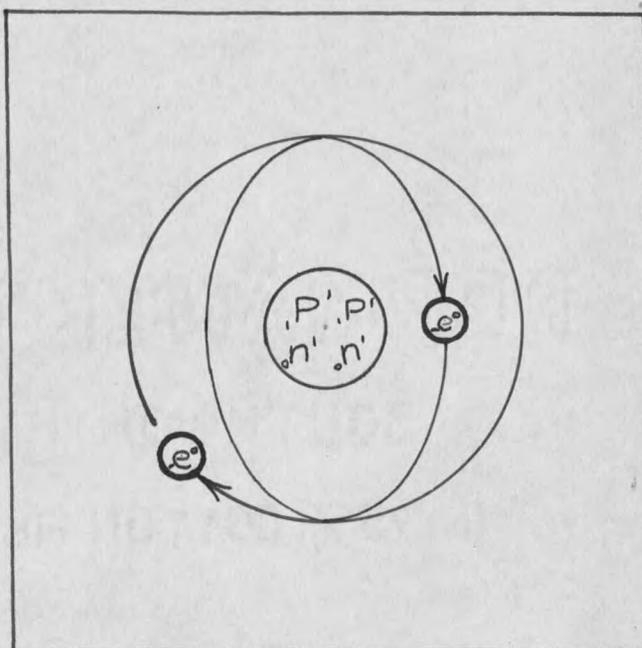


Figure 2 The Helium Atom

atomic weight will be designated by the symbols Z , A and M respectively.

The atomic number (Z) is the number of positive charges in the nucleus. It determines the number of electrons in the extra-nuclear structure, and this in turn determines the chemical properties of the atom.

⁴ The discovery of the neutron will be discussed in detail later.

Thus all the atoms of a given chemical element have the same atomic number, and conversely all atoms having the same atomic number are atoms of the same element regardless of possible differences in their nuclear structure. The electrons in an atom arrange themselves in successive shells according to well-established laws. Optical spectra arise from disturbances in the outer parts of this electron structure; X-rays arise from the disturbances of the electrons close to the nucleus.

If we go back to a fundamental law of physics, Coulomb's Law of Force between electrically charged particles,

$$F = \frac{q_1 q_2}{kr^2} \quad (1)$$

where F is the force in dynes, q_1 and q_2 charge on particles 1 and 2 in coulombs, r distance between particles in cm and k is the dielectric constant. The significance of this law is to calculate the force between charged particles, whether they have the like or opposite charges. As we already know, like charges repel each other and opposite charges attract. The nucleus of the helium atom is comprised of two protons and two neutrons. The charge on a proton is plus 4.805×10^{-10} stat-coulombs. There are two protons both having a positive charge, therefore, from Coulomb's Law, there must be a force of repulsion.

A present analogy is that there are two types of opposing forces in the nucleus, those of attraction and those of repulsion. The electrostatic force of repulsion, (long range force) is due to the like charges of the protons. This force may be fairly large; it has been calculated that two grams of protons placed at opposite poles of the earth would

repel each other with a force of 26 tons. The forces of attraction in the nucleus, called nuclear forces (short range forces) exceed even the electrostatic forces. These forces of attraction exist between protons, between neutrons and between protons and neutrons. These forces are not predominate except at very close range. If we were to graph these two forces against the distance (r) between the charged particles, the long range force would decrease exponentially from a distance of approximately 3×10^{-12} cm to where the force approaches zero at a distance of infinity. The short range forces are only in effect up to approximately 3×10^{-12} cm. (Figure 3). The height of the curve x is generally referred to as the

potential barrier; any positive charged particle moving toward a nucleus must have sufficient energy to overcome this potential barrier to enter the nucleus. But neutrons have no charge and are not effected by this long range electrostatic force, therefore, a neutron moving in the direction of a nucleus will not have to overcome this potential barrier and may move directly within range of the nuclear

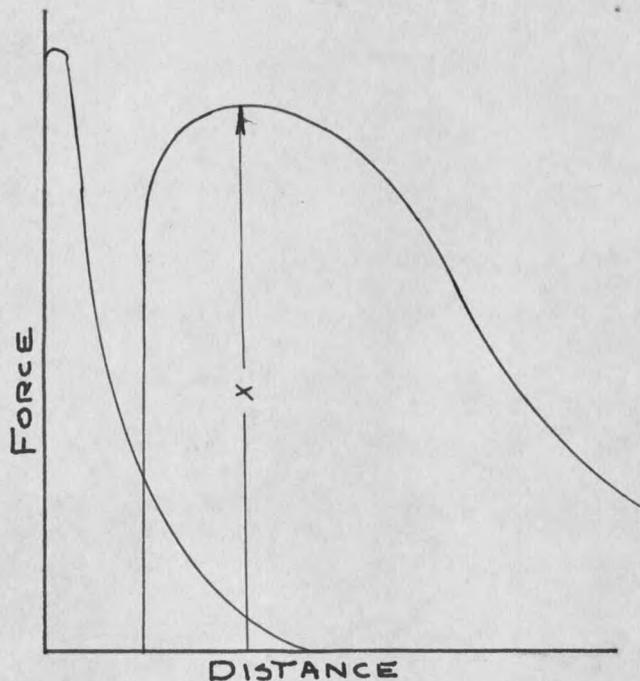


Figure 3 Comparison of Electrostatic Forces to Nuclear Forces as plotted against Distance

forces of attraction (this is the secret to nuclear energy and will be referred to at frequent intervals). However, these short range forces reach a point of saturation depending on the individual nucleus. Two hydrogen atoms attract each other very strongly to form a hydrogen molecule (H_2) and then attract no additional atoms, also two protons and two neutrons tend to unite into the helium nucleus with comparable saturation effects.

in isotope of uranium U^{235} will have in its nucleus 92 protons and 143 neutrons but let us examine the forces acting on these particles. The uranium atom has an atomic number of 92 and an atomic weight of 238.07. The force on a proton in the center of the nucleus is the nuclear force of attraction for any of its adjacent particles (other protons or neutrons, short range forces). But a proton on the outside surface of the nucleus is in contact with less neutrons and protons, and a proton on the opposite side of the uranium nucleus may be beyond the short range and be in the range for the electrostatic forces of repulsion. Taking this into consideration it can be seen that some of these heavier atoms, although stable, may be disrupted very easily; an example of what may happen is easily shown by taking a drop of water and letting it fall from some high point (the gravitational force acting on the drop will be, $F = mg$). The drop will split into two halves.

So far this discussion has two main purposes, first to give a very brief resume of the atom (for a more detailed discussion see any college physics text) and second to give the reader several new things to think about.

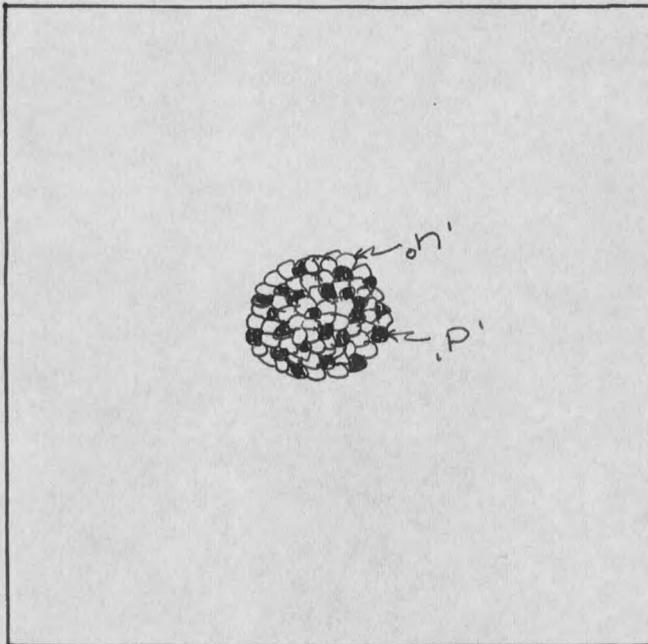


Figure 4 A Typical Heavy Atom (U) showing the Protons and Neutrons

The presentation is only complete enough for a Mechanical Engineer's first study in nuclear power and not intended for a study in nuclear physics. Before going further I believe several definitions and tables should be presented.

TABLE I

Particle	Symbol	Weight (amu)	Change in Stat-Coulombs
Electron	${}_{-1}e^0$.00055	$+4.803 \times 10^{-10}$
Proton	${}_{1}H^1$	1.00758	$+4.803 \times 10^{-10}$
Neutron	${}_{0}n^1$	1.00893	0
Deuteron	${}_{1}H^2$	2.01418	$+4.803 \times 10^{-10}$
Alpha	${}_{2}He^4$	4.00275	$+2.401 \times 10^{-9}$
Neutrino		0	0
Positron	${}_{+1}e^0$.00055	$+4.803 \times 10^{-10}$
Meson		Approx. .1 & .16	$\pm 4.803 \times 10^{-10}$

BASIC DEFINITIONS

Alpha rays - A stream of alpha particles.

Alpha particle - the nucleus of the helium atom (${}_{2}He^4$).

Atom Smashers - devices used to accelerate charged particles to a sufficient energy for nuclear reactions.

Artificial radioactivity - radioactive nuclei produced by means of bombarding stable nuclei with various particles.

Barn - a unit used in measuring cross-section and equal to 10^{-24} cm²/nucleus.

Beta particles - negatively charged high speed electrons.

Beta rays - a stream of beta particles.

- Binding Energy → the amount of energy required to break a nucleus into the fundamental particles (neutrons and protons).
- Compound Nucleus → a nucleus believed to exist instantaneously during nuclear reactions.
- Critical Size → the size for which the production of free neutrons by fission is just equal to their loss by escape and non-fission capture.
- Cross-Section → the probability that an incident particle will cause a nuclear reaction with a nucleus.
- Deuteron → a positively charged particle comprised of one proton and one neutron, being the nucleus of the rare isotope of hydrogen (${}^2_1\text{H}$), the isotope that combines with oxygen to produce heavy water, mass of 2.01418 amu.
- Electrometer → an instrument for measuring an electric current.
- Enriched Fissile → the use of partially separated uranium, i.e., the U^{235} isotope in greater abundance than that of uranium as it occurs in nature.
- Factor-K → the ratio of the number reoccurring fission neutrons to the number of incident neutrons.
- Fission → the process whereby a nucleus, generally a very heavy nucleus, splits into two lighter nuclei. The reaction differs from radioactivity in the fact that there are two product nuclei and not just one product nuclei and a particle.
- Flux → neutron density, number of fissions occurring per second per unit volume.

Gamma rays - electromagnetic radiations, similar to X-rays.

Half-life - the time required for a radioactive substance to decrease its mass by one half.

Ionization - the process whereby an atom, which generally of neutral charge, becomes charged because of the loss of one or more of its planetary electrons. Ionization may be caused by light, X-rays or any charged particle and the ionized atom becomes an ion.

Isobars - atoms of the same mass number (A) but of different atomic numbers, these are atoms of different elements, but have the same number of nucleons.

Isomers - nuclei which are identical in mass numbers and in atomic number but have different radioactive properties.

Isotope - atoms of different weights (mass numbers, A), but of the same atomic number (Z). Different isotopes of the same atom cannot be differentiated by chemical means because they have identical chemical behavior, the only difference being their masses.

K-capture - this process occurs in place of the emission of a positron during the radioactive decay of a nucleus. Actually the nucleus will capture an electron from the K shell, thus forming a product nucleus of an atom in the excited state, it will then return to the normal state by the emission of X-rays.

Meson - a particle with either positive or negative charge found in cosmic rays and having a mass of approximately 200 times that

of the electron.

Neutrino- still a theoretical prediction, not proven experimentally as yet, though there is experimental evidence for belief in their existence (the physicists cannot account for a very small amount of energy or mass during several nuclear reactions and the neutrino is a means of balancing their equations).

Neutrons- nucleons with zero charge having a mass of 1.00893 amu.

Nucleons- the particles comprising the nucleus, protons and neutrons, generally referred as the total number of particles in the nucleus.

Positron- a charged particle with electron mass and charge except the charge is positive.

Proton - positively charged nucleon having a mass of 1.00758 amu, is also the nucleus of the hydrogen atom (${}^1_1\text{H}$).

Radioactivity- occurs naturally in unstable atoms which emit alpha, beta (and), or gamma rays, thereby changing to some other element. (The change depends on the type of emission.

Resonance Energy- the energy of a bombarding particle for which a nucleus is exceptionally reactive. For instance the resonance energy for the absorption of a neutron by U^{238} is 33 ev.

Spectrograph- the mass spectrograph is a precision instrument used in measuring the masses of isotopes.

Thermal Neutrons- neutrons of very low energy.

Transmutation- the changing of one nucleus to the nucleus of another. Generally pertaining to nuclear reactions.

Transuranic- elements of atomic number greater than 92, for instance plutonium and neptunium.

Wilson Cloud Chamber * an instrument used in visibly showing the paths of charged particles.

ENERGY UNITS

The energy of an electron traveling at a velocity of $(3 \times 10^8 \text{ cm/sec})$ would be

$$E = \frac{1}{2} mv^2.$$

$$\begin{aligned} E &= \left(\frac{1}{2}\right) (9.1066 \times 10^{-28}) (3 \times 10^8)^2 \\ &= 40.9 \times 10^{-12} \text{ ergs} \\ &= (40.9 \times 10^{-12}) (2.78 \times 10^{-14}) \\ &= 1.138 \times 10^{-24} \text{ Kw-hrs.} \\ &= (1.138 \times 10^{-24}) (3413) \\ &= 3.885 \times 10^{-21} \text{ BTU} \end{aligned}$$

The basic study will be with very light particles, and as shown above our conventional units (Kw-hrs, BTU) are too large for this study. Therefore, we must use energy units that are very small. The electron volt can be used to advantage in cases of this nature. One electron volt is the energy of one electron as it passes through a potential difference of one volt. With relation to Kw-hrs there are 2.25×10^{25} electron volts in one Kw-hr.

$$\begin{aligned} E &= (1.138 \times 10^{-24}) (2.25 \times 10^{25}) \\ &= 25.6 \text{ ev.} \end{aligned}$$

The proton whose mass is 1840 times as great as the electron the

energy units used will be Mev (Million electron volts).

The following conversion table will prove useful for energy units.

TABLE II

MULTIPLY	BY	TO OBTAIN
Mev	1.07×10^{-3}	amu
	1.60×10^{-6}	ergs
	3.183×10^{-14}	Gm. Cal.
	4.45×10^{-20}	Kw-hrs.
	1.52×10^{-16}	BTU
Amu	9.31×10^8	Mev
	1.49×10^{-3}	ergs
	3.56×10^{-11}	Gm. Cal.
	4.15×10^{-17}	Kw-hrs.
	1.417×10^{-13}	BTU
Ergs	6.71×10^8	amu
	6.24×10^5	Mev
	2.39×10^{-8}	Gm. Cal.
	2.78×10^{-14}	Kw-hrs.
	9.49×10^{-11}	BTU

MULTIPLY	BY	TO OBTAIN
Gm. Cal.	2.81×10^{10}	amu
	2.62×10^{13}	Mev
	4.18×10^7	ergs
	1.16×10^{-6}	Kw-hrs.
	3.96×10^{-3}	BTU
Kw-hrs.	2.41×10^{16}	amu
	2.25×10^{19}	Mev
	3.60×10^{13}	ergs
	8.60×10^5	Gm. Cal.
	3.413×10^3	BTU
BTU	7.06×10^{12}	amu
	6.62×10^{15}	Mev
	1.054×10^{10}	ergs
	2.53×10^2	Gm. Cal.
	2.93×10^{-4}	Kw-hrs.

Table II shows only the conversion of energy units. For units of electric charge mass, etc, refer to Tables III and IV.

TABLE III

MULTIPLY	BY	TO OBTAIN
Statcoulombs (esu)	$1/3 \times 10^{-10}$	Abcoulombs (emu)
Statcoulombs (esu)	$1/3 \times 10^{-9}$	Coulombs
Coulombs	3×10^9	Statcoulombs (esu)
Coulombs	0.1	Abcoulombs (emu)
Volts	1/300	Statvolts (esu)
Volts	10^8	Abvolts (emu)
Statvolts (esu)	300	Volts
Statvolts (esu)	3×10^{10}	Abvolts (emu)
Abvolts (emu)	10^{-8}	Volts
Abampere (emu)	10	Amperes
Ampere	0.1	Abampere
Statvolts/cm	1	Dynes/esu (field)
Volts/cm	300	Dynes/esu
Electron-volts	1.074×10^{-9}	Amu (Phys.)

TABLE IV

Electron charge	$= 4.803 \times 10^{-10}$ statcoulombs
	$= 1.602 \times 10^{-19}$ coulombs
	$= 1.602 \times 10^{-20}$ abcoulombs
Electron, charge/mass	$= 1.7592 \times 10^7$ abs emu/gm.

Electron, rest mass.	$= 9.1066 \times 10^{-28}$ gm.
	$= 5.4862 \times 10^{-4}$ amu (phys.)
	$= 5.4847 \times 10^{-4}$ amu (chem.)
Electron volts	$= 10^{-6}$ Mev
	$= 1.161 \times 10^{-6}$ deg. (ags)
	$= 1.768 \times 10^4$ gm.
	$= 1.768 \times 10^{-33}$ gm.
Amu	$= 1.65993 \times 10^{-24}$ gm.
Velocity of light	$= 2.99776 \times 10^{10}$ cm/sec.

After examination of Tables II and IV it is interesting to note that there are conversion factors for converting mass units to energy units, and vice versa, this is the basis of the energy from nuclear reactions. The name, Atomic Power, has been misused because actually the energy comes from the nucleus and not the atom, this text will refer to it as a nuclear power. This first came about when non-technical men wrote the original publicity directly after the first bomb was dropped on Japan.

As Mechanical Engineers, we are interested in the power available from the nucleus, how it may be obtained, and in what form it exists. Therefore, this text will eliminate the complicated nuclear physics behind this new type of power and only touch the more important issues. This text's primary purpose is to present basic material for Mechanical Engineers so they will be able to discuss intelligently and have a working knowledge of nuclear power. The following material is presented at a level for seniors or graduate students in Mechanical Engineering and

reviews their background in nuclear physics and features some of the uses of nuclear energy as directly related to Mechanical Engineering problems. For a more detailed discussion on the subject of nuclear physics there are numerous texts, but they are beyond the scope of our study and are intended for a student majoring in physics. As Mechanical Engineers we are interested primarily in using this energy for our power plants, steam generation, heating and gas turbines.

RADIOACTIVITY

In 1895 William Roentgen, a German physicist, discovered some new invisible rays with very deep penetrating properties which he called X-rays. This discovery

came about while using a Crookes tube, the rays emitted passed through a variety of things, including his own flesh. For when he placed his hand in the path of these rays a clear outline of the bones of his hand could be seen on a fluorescent screen. A

series of experiments showed these rays easily

passed through substances of low density but were stopped by very dense

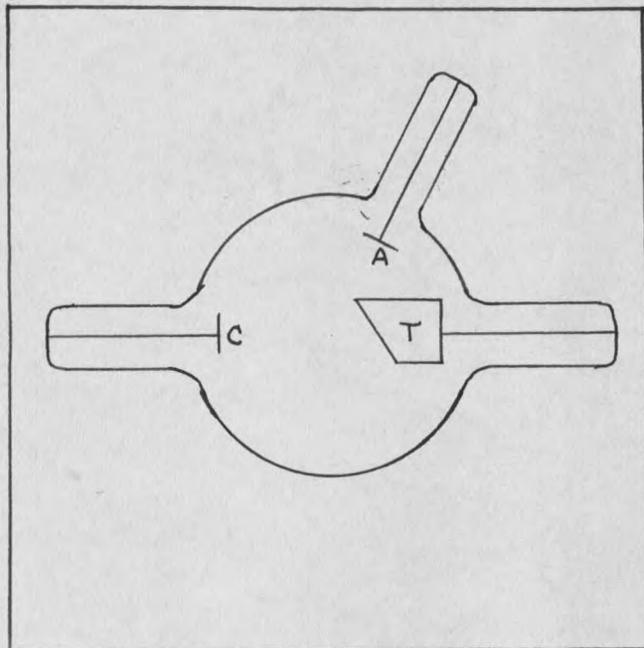


Figure 5 Typical X-ray tube showing position of Anode, Cathode and Target in Vacuum Tube

elements such as lead. The use of photographic plates also played a prominent part in the detection of X-rays. Figure 5 shows a schematic sketch of a typical X-ray tube. X-rays are produced, in this tube, by the bombardment of the target (T) by high speed electrons. A difference in potential (V) between the cathode (C) and the anode (A) cause the electrons emitted from the heated cathode to have an energy in ergs of

$$E = Ve \quad (2)$$

E will be in ergs if V is in statvolts (esu) and e the charge on one electron in statcoulombs (esu, 4.803×10^{-10}), see Tables I, III, and IV. The X-rays produced by these high speed electrons bombarding the target will have a frequency as calculated by the equation:

$$E = h\nu \quad (3)$$

E again being in ergs, h Planck constant (6.624×10^{-27} erg-sec.) and ν the frequency of the produced X-rays in cycles per second. The wave length of these waves may be calculated from the equation:

$$\lambda = \frac{c}{\nu} \quad (4)$$

λ being the wave length in cm, c the velocity of light in cm/sec., and ν the frequency in cycles per second. Under certain conditions it may be necessary to calculate the velocity of the initial electrons by means of the equation:

$$E = \frac{1}{2}mv^2 \quad (5)$$

E again in ergs, m mass in grams, and v in cm/sec. Combining equations (2) and (5):

$$Ve = \frac{1}{2}mv^2$$

$$\text{or } v^2 = \frac{2Ve}{m}$$

$$v = \sqrt{\frac{2Ve}{m}}$$

As the velocity (v) of the electrons approaches the speed of light (see Table IV), the law of relativity, as derived by Einstein must be taken into consideration to determine the mass of the electron at its high speed. The equation for changing rest mass, taking into consideration the inertia at velocity v is:

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (6)$$

where m_0 is the rest mass in grams, v the velocity of the particle in cm/sec., c the velocity of light in cm/sec., m being the corrected mass. For a more detailed discussion of the elementary physics equations consult and study any College Physics text.

Example No. 1. An X-ray tube has a difference in potential of 300 volts between the cathode and anode. Find the energy of the electrons in ergs, the electrons velocity and the frequency of the X-rays.

$$V = \frac{300 \text{ Volts}}{300 \text{ Volts/Stat-Volts}} = 1 \text{ Statvolt}$$

From equation (2)

$$\begin{aligned} E = Ve &= (1)(4.803 \times 10^{-10}) \\ &= 4.803 \times 10^{-10} \text{ ergs.} \end{aligned}$$

From equation (5)

$$\begin{aligned} E &= \frac{1}{2}mv^2 \\ v^2 &= \frac{2E}{m} = \frac{(2)(4.803 \times 10^{-10})}{(9.1066 \times 10^{-28})} \end{aligned}$$

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$$v = 1.023 \times 10^9 \text{ cm/sec.}$$

but we did not insert the relativity correction for the mass.

Equation (6)

$$\begin{aligned} m &= \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{9.1066 \times 10^{-28}}{\sqrt{1 - \frac{(1.023 \times 10^9)^2}{(3 \times 10^{10})^2}}} \\ &= \frac{9.1066 \times 10^{-28}}{\sqrt{1 - .00116}} = \frac{9.1066 \times 10^{-28}}{.9998} \\ &= 9.10662 \times 10^{-28} \text{ gms.} \end{aligned}$$

The difference in this case is negligible. For future work we may say that the relativity correction need not be inserted unless the velocity of the particle is greater than 10% of the velocity of light.

From equation (3)

$$\begin{aligned} E &= h\nu \\ \nu &= \frac{E}{h} = \frac{4.803 \times 10^{-10}}{6.624 \times 10^{-27}} \\ &= 7.255 \times 10^{16} \text{ cycles/sec.} \end{aligned}$$

we may further calculate the wave length of these rays.

From Equation (4)

$$\begin{aligned} \lambda &= \frac{c}{\nu} = \frac{3 \times 10^{10}}{7.255 \times 10^{16}} \\ &= .415 \times 10^{-6} \\ &= 41.3 \text{ \AA} \end{aligned}$$

where one Angstrom unit (\AA) = 10^{-8} cm.

RADIOACTIVITY. Within a year after Roentgen's discovery of X-rays, the French scientist, Antoine Henri Becquerel, while examining various substances for possible fluorescent and phosphorescent effects, found uranium, its various minerals, and compounds emitted invisible radiation capable of affecting photographic plates and ionization of the air. Becquerel then found that several of the other heavier elements have this same behavior and no matter what he did to these substances he could not change this property which he then called radioactivity. He tried compounding uranium with various elements and even running experiments with powdered uranium which led him to believe that this property (radioactivity) must come from the atoms of uranium. Shortly after this time Sir Ernest Rutherford, a British physicist, carried on experiments to determine the penetrating properties of these invisible rays and found them to be of two types. One type was easily stopped by a thin aluminum foil which Rutherford called alpha rays and the other was stopped by aluminum sheet which he called beta rays. Later he found a third type of radiation which had very deep penetrating properties and reacted similarly to Roentgen's X-rays but were finally called gamma rays.

Rutherford used an electrical method to study these radiations based upon the ionization produced by the radiation in its passage through a gas (his later work, of a similar type, caused one of the first nuclear reactions). Professor Pierre Curie and his wife Mme. Curie using a similar method showed that the amount of activity of any uranium compound varied directly with the amount of uranium in the compound, thus showing that this activity must come from the atoms themselves.

The Curies then carried on a series of experiments with all available chemical materials to obtain further evidence of the existence of radioactivity in other substances. In 1898, G. U. Schmidt as well as Mme. Curie found the element Thorium to exhibit radioactive properties both emitting the alpha rays. While experimenting with various uranium-bearing ores and minerals, the Curies found these unrefined uranium minerals exhibited greater radioactivity than the refined uranium metal they had produced in their laboratory. This led to the belief that there must be another radioactive element present in these minerals that has greater activity than pure uranium. After careful study the Curies were able to separate this new radioactive element with bismuth. Its properties were similar to bismuth except for radioactivity. Mme. Curie then named this element after her native home Poland, which she called Polonium in 1898. The Curies with several collaborators discovered and named radium. Work was also done to determine the atomic weight of radium which was found to be 226. In 1899, Debierne discovered another radioactive element which he called actinium. Several scientists were working in all parts of the world on these newly discovered radioactive elements as to their atomic weights, chemical and physical properties. It is interesting to note that every new element had already been determined by Mendelieff's periodic table in approximately 1865. Mendelieff's periodic table had the elements arranged in periods, starting with the lightest element, hydrogen, and that at certain regular intervals elements would appear with similar properties (bismuth and polonium; radium and barium). All of these new elements fell in an open space in this periodic table. Today's Periodic

Chart of the atoms, as designed by Henry D. Hubbard (National Bureau of Standards), shows how all the known elements fall into periods.

By 1903, Rutherford and Soddy in England had studied the emanations from radioactive materials and had formed a theory of radioactive disintegration. As

previously mentioned, the invisible rays emitted by radioactive materials were shown to be of three types and named alpha, beta and gamma. Rutherford found these three types by their penetrating powers and was further established by means of letting these radiations pass through an electromagnetic field,

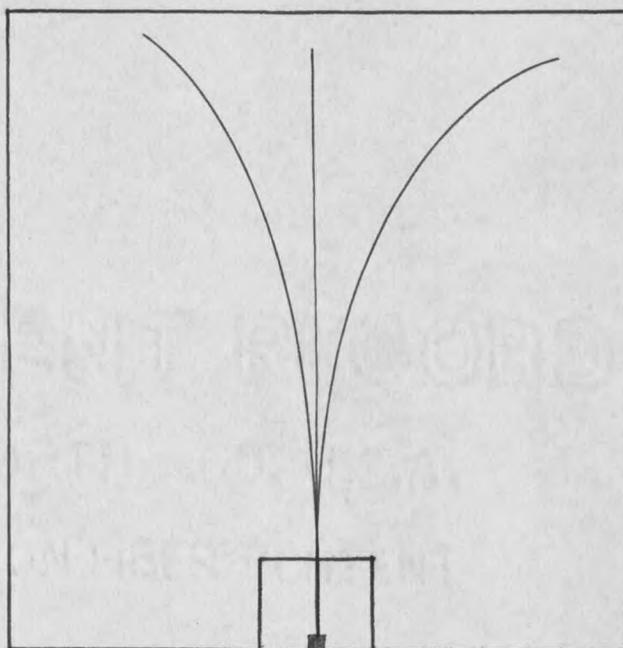


Figure 6 Paths of Alpha, Beta and Gamma Rays in an Electromagnetic Field

Figure 6. This proved that the alpha rays were of a positive charge, that the beta rays had a negative charge and the gamma rays were of a neutral charge. Upon further study, Rutherford and Soddy found that when a radioactive atom emits an alpha particle, its mass decreases by four times the weight of a hydrogen atom and its positive charge decreases by two, thus forming a new element of two less atomic numbers. This also led to the fact that alpha rays consisted of a series of alpha particles and that an alpha particle is actually the nucleus of the helium atom (two protons

and two neutrons). However, when a beta particle was emitted from a radioactive atom, its mass is practically unchanged but the positive charge in the nucleus is increased by one. This fact and that beta rays were negative helped prove that these rays consisted of very small particles (beta particles)

which were essentially electrons. Figure 7 shows graphically the changes that take place during radioactivity. Gamma rays as they occur during radioactivity are found only in connection with beta rays and are never found alone. For this reason we will call radioactive materials either alpha or beta

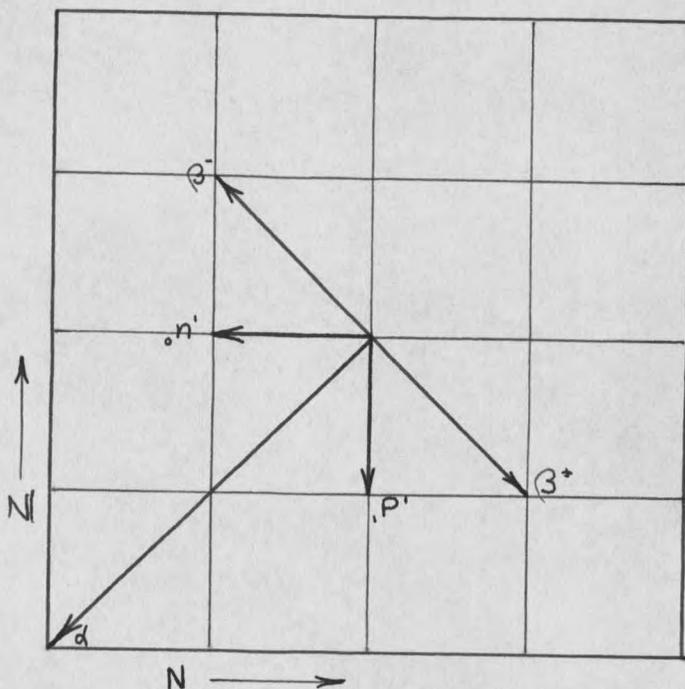


Figure 7 Radioactive Emissions

emitters except for several cases that may emit both (these will be discussed later).

Rutherford and Soddy also found several radioactive series to exist in nature, i.e., uranium emits an alpha particle and becomes thorium, which is also radioactive, etc., until a stable atom is formed. There are four series as shown in Figures 9, 10, 11, and 12. Figure 13 shows the uranium-radium series graphed.

The Neptunium Series (Figure 12) is one that existed in nature but its members had short enough half-lives that they long since have disappeared during the two-billion year history of the earth. This series is called the Neptunium Series because this element is the longest-lived of the Series.

It is now known that various elements emit alpha or beta particles. The Curies found Polonium to be more active than uranium, this also holds true for all other radioactive elements each one having its own rate of emitting alpha or beta particles.

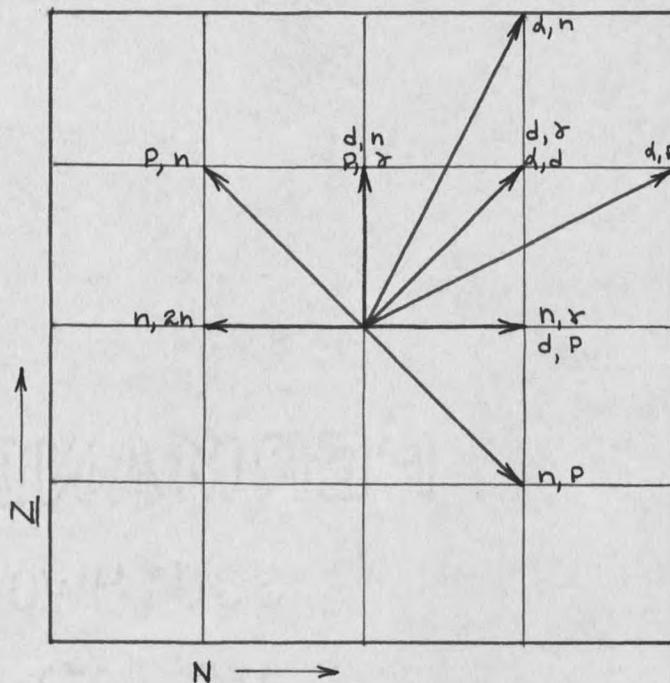


Figure 8 Nuclear Reactions

The rate of emission is generally in terms of half-life of the material, the half-life being the time required for half the number of atoms to change by emitting alpha or beta particles. The number of particles emitted per unit time is inversely proportional to the half-life. Taking one gram of a radioactive element the emissions may be counted and the half-life determined, but if we were to separate one atom from this original gram the time elapsed before emission could not be predetermined because this emission is haphazard and the exact time when each atom is going to change

URANIUM-RADIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Uranium (Uranium I)	238	92	α	4.55×10^9 yrs
Thorium (Uranium X ₁)	234	90	β ⁻	24.1 days
Protactinium (Uranium X ₂) ..	234	91	β ⁻	1.14 minutes
Protactinium (Uranium Z) ..	234	91	β ⁻	6.7 hours
Uranium (Uranium II)	234	92	α	2.3×10^5 yrs
Thorium (Ionium)	230	90	α	3.825×10^4 yrs
Radium	226	88	α	1590 years
Radon	222	86	α	3.823 days
Polonium (Radium A)	218	84	α	3.05 minutes
Lead (Radium B)	214	82	β ⁻	20.8 minutes
Bismuth (Radium C)	214	83	α, β ⁻	19.73 minutes
Polonium (Radium C ^m)	214	84	α	1.5×10^{-4} sec.
Thallium (Radium C ^o)	210	81	β ⁻	1.32 minutes
Lead (Radium D)	210	82	β ⁻	22.3 years
Bismuth (Radium E)	210	83	β ⁻	4.97 days
Polonium (Radium F)	210	84	α	139.5 days
Lead (Radium G)	206	82	Stable	

Figure 9

(Courtesy of Westinghouse Electric Corp.)

THORIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Thorium	232	90	a	1.389×10^{10} years (longest)
Radium (Mesothorium I)....	228	88	β^-	6.7 years
Actinium (Mesothorium 2)..	228	89	β^-	6.13 hours
Thorium (Radiothorium)....	228	90	a	1.90 years
Radium (Thorium X).....	224	88	a	3.64 days
Radon (Thoron).....	220	86	a	54.50 seconds
Polonium (Thorium A).....	216	84	a	0.145 seconds
Lead (Thorium B).....	212	82	β^-	10.6 hours
Bismuth (Thorium C).....	212	83	a, β^-	60.6 minutes
Polonium (Thorium C').....	212	84	a	3×10^{-7} sec. (shortest)
Thallium (Thorium C'').....	208	81	β^-	311 minutes
Lead (Thorium D).....	208	82	Stable	

Figure 10

Note: The traditional names for the disintegration products are given in parentheses. These names were assigned before the products were adequately identified, and they do not, in general, correctly name the element of which the disintegration product is an isotope.

(Courtesy of Westinghouse Electric Corporation)

ACTINIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Uranium (Actinium U).....	235	92	a	7.13×10^8 yrs
Thorium (Uranium Y).....	231	90	β^-	24.64 hours
Protactinium	231	91	a	3.2×10^4 yrs
Actinium	227	89	a, β^-	13.4 yrs
Thorium (Radioactinium)...	227	90	a	18.9 days
Francium (Actinium K).....	223	87	β^-	21 minutes
Radium (Actinium X).....	223	88	a	11.2 days
Radon (Actinon).....	219	86	a	3.92 seconds
Polonium (Actinium A).....	215	84	a	2.1×10^{-3} sec.
Lead (Actinium B).....	211	82	β^-	56.0 minutes
Bismuth (Actinium C).....	211	83	a, β^-	2.16 minutes
Polonium (Actinium C').....	211	84	a	2×10^{-3} sec.
Thallium (Actinium C'').....	207	81	β^-	4.71 minutes
Lead (Actinium D).....	207	82	Stable	

Figure 11

Note: The traditional names for the disintegration products are given in parentheses. These names were assigned before the products were adequately identified, and they do not, in general, correctly name the element of which the disintegration product is an isotope.

(Courtesy of Westinghouse Electric Corporation).

NEPTUNIUM SERIES

ELEMENT	MASS Number	ATOMIC Number	RADIATION	HALF-LIFE
Plutonium	241	94	β^-	Relatively long
Americium	241	95	a	500 years
Neptunium	237	93	a	2.25×10^6 years
Protactinium.....	233	91	β^-	27.4 days
Uranium.....	233	92	a	1.63×10^5 years
Thorium.....	229	90	a	7×10^3 years
Radium.....	225	88	β^-	14.8 days
Actinium.....	225	89	a	10 days
Francium.....	221	87	a	4.8 minutes
Astatine.....	217	85	a	1.8×10^{-2} second
Bismuth.....	213	83	a, β^-	47 minutes
Polonium.....	213	84	a	4.4×10^{-6} second
Thallium.....	209	81	β^-	1 hour
Lead.....	209	82	β^-	5.3 hours
Bismuth.....	209	83	Stable	

Figure 12

Named the Neptunium Series because of the long half-life of Neptunium. The other elements in the series include the new "man-made" elements americium (No. 95) and uranium-233, as well as the recently identified elements, astatine (No. 85) and the francium (No. 87). The series differs from the three found in nature in having an end product other than lead. The final stable product of the neptunium series is bismuth-209.

(Courtesy of Westinghouse Electric Corporation)

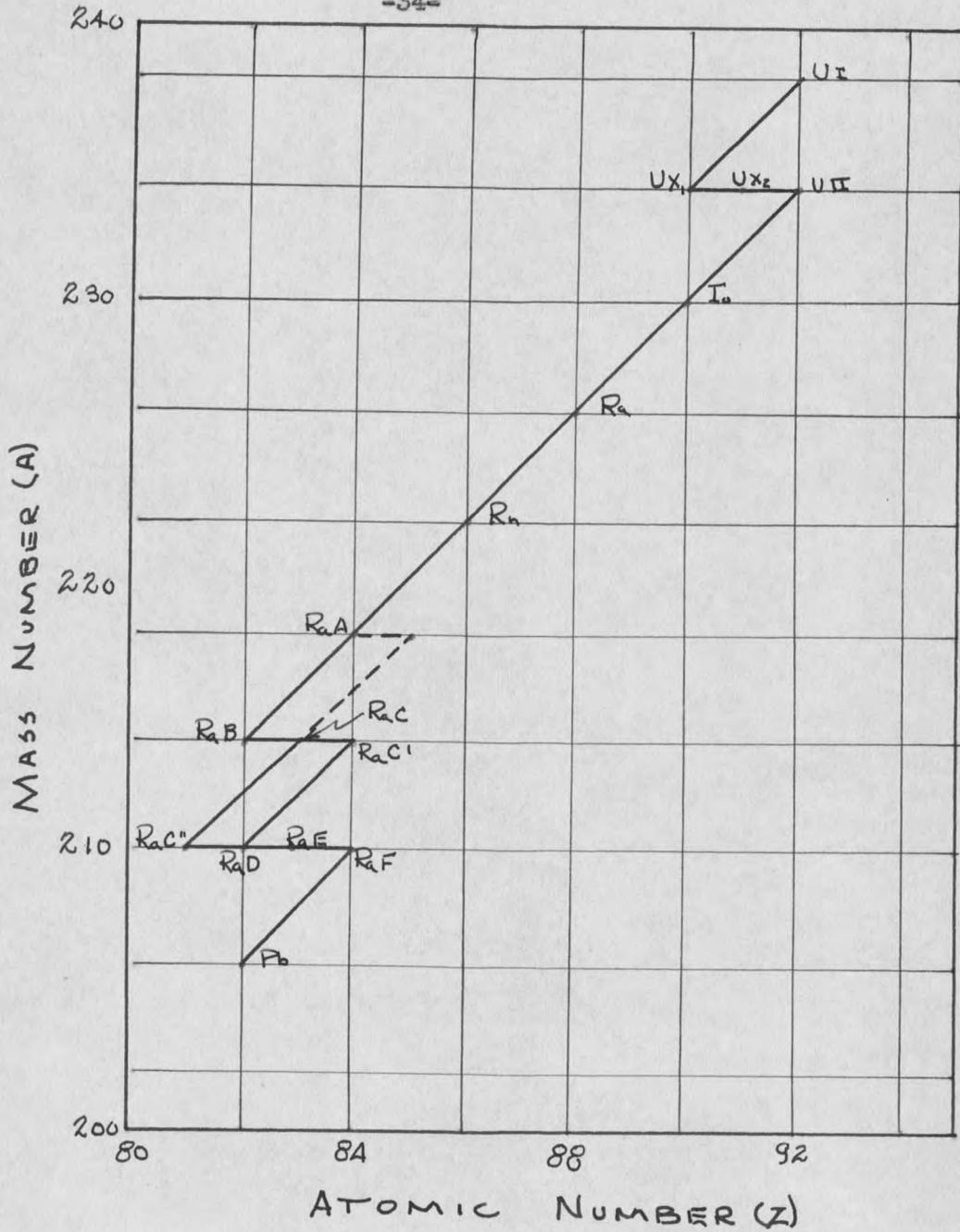


Figure 13 Uranium Series, plotting Mass Number against Atomic Number

is somewhat of a quantum secret. Also the rate of radioactive disintegration is independent of all physical and chemical conditions. Take a sufficient number of radioactive atoms of any one element and during a small interval of time, dt , there will be a certain number of atoms disintegrating, dN ; if the number of atoms present at time t and δ is the disintegration factor, which varies with each radioactive element. The following relation exists:

$$-dN = \delta N dt \quad (7)$$

Separating Variables

$$\frac{-dN}{N} = \delta dt$$

Integrating

$$\text{Log } N = -\delta t + \text{Log } c \quad (7a)$$

c being the constant of integration, to evaluate, when $t = 0$,

$N_1 = c$, where N_1 is the initial number of atoms:

$$\text{Log } N = -\delta t = \text{Log } N_1 \quad (7b)$$

$$N = N_1 e^{-\delta t} \quad (8)$$

Equation (8) shows that the number of atoms present at any time t disintegrates exponentially. The number of atoms present is a direct relation of the mass of the atoms therefore equation (8) may also be written:

$$M = M_1 e^{-\delta t} \quad (8a)$$

where M is the mass remaining after time t and M_1 the initial mass when $t = 0$. Taking equation (7b) and substituting $\frac{N_1}{2}$ for N and T for t , the capital (T) must be the time required for one-half of the initial number of atoms to disintegrate, therefore being the half-life:

$$\text{Log } \frac{N_i}{2} = -\delta T + \text{Log } N_i$$

$$T = \text{Log } 2 = 0.693$$

$$T = \frac{0.693}{\delta} \quad (9)$$

Under certain conditions the average lifetime of a radioactive atom may be desired which will be denoted by T_a and found by integrating the product $t dN$ over the limits of from 0 to N_i and dividing by N_i .

$$T_a = \frac{\int_0^{N_i} t dN}{N_i}$$

from equation (8) by differentiating:

$$dN = -N_i \delta e^{-\delta t} dt$$

combining the two above equations (from page 35):

$$T_a = \frac{-N_i \int_0^{\infty} t \delta e^{-\delta t} dt}{N_i} = \int_0^{\infty} t \delta e^{-\delta t} dt$$

by means of integration by parts:

$$\begin{aligned} T_a &= \delta \left[\frac{-te^{-t\delta}}{\delta} + \frac{e^{-t\delta}}{\delta} dt \right]_0^{\infty} \\ &= \delta \left[\frac{-te^{-t\delta}}{\delta} - \frac{e^{-t\delta}}{\delta} \right]_0^{\infty} \\ &= \delta \left(\frac{1}{\delta^2} \right) \\ &= \frac{1}{\delta} \end{aligned} \quad (10)$$

Taking equations (9) and (10) and equating the half-life may be put in terms of the average life:

$$T = 0.693 T_a \quad (11)$$

Figure 14 shows equation (8) plotted with N as the ordinate, also showing the points of half-life and average life. One method in determining the half-life of radioactive elements is by means of counting the number of emissions per

unit time and then graphing this activity against time. The slope of the curve will be λ , and using equation (9) the half-life may be readily calculated. The counting of emissions may be achieved by means of a Geiger Counter which will be discussed in detail later.

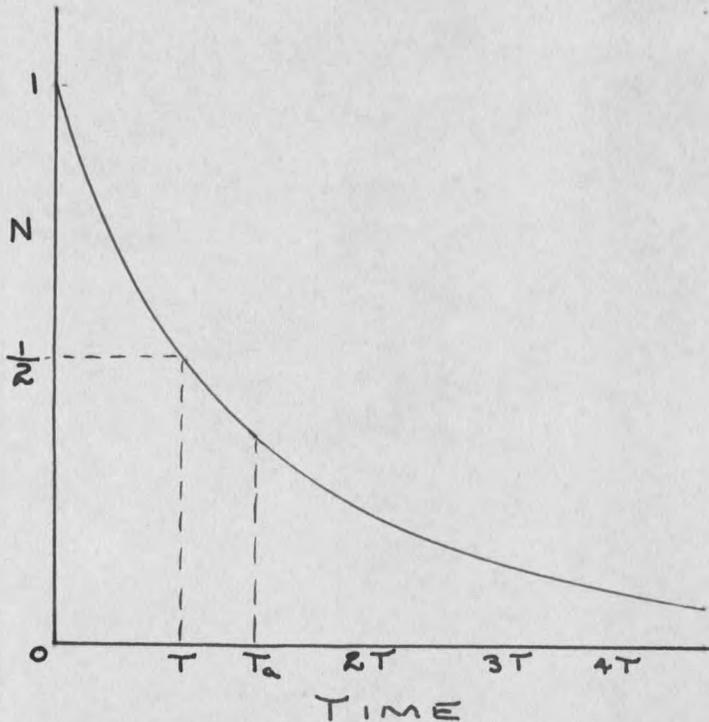


Figure 14 Equation (8), plotting N against Time showing the points of Half-life and T_a

Example No. 2. A radioactive element emitting beta particles was placed within range of a Geiger Counter. Emissions were counted at intervals of one minute and the following counts were tabulated after making corrections for background readings: 626, 508, 416, 354, 290, 240, 198, 164, 133, 111, 90, 76, 63, 52, 43. Calculate the disintegration constant and the half-life.

Using equation (7b)

$$\text{Log } N = -\delta t + \text{Log } N_1 \quad (7b)$$

May be written:

$$\text{Log } N = -\delta t$$

Because we are only interested in calculating δ , which is the slope of an activity ($\log N$) time curve, the term $\text{Log } N_1$ will only shift this curve and not effect its slope.

Figure 15 shows the curve of $\text{Log } N$ plotted against time. The slope of this curve will be calculated by:

$$\begin{aligned} \text{Slope} = \delta &= \frac{\Delta \text{Log } N}{\Delta T} \\ &= \frac{5.87 - 4.14}{13 - 4} = \frac{1.73}{9} \quad (\text{Values taken from graph}) \\ &= .192 \end{aligned}$$

For half-life:

$$\begin{aligned} T &= \frac{.693}{\delta} \quad (9) \\ &= \frac{.693}{.192} \\ T &= 3.61 \text{ minutes} \end{aligned}$$

ISOTOPES:

Figures 9, 10, and 11 showing tables of the Uranium-Radium, Thorium, and Actinium series have one thing in common and that being that they end with stable lead. The Atomic weight of lead had already been established as 207.21 amu but the lead found in connection with the Uranium-Radium series had an atomic weight of approximately 206. At first there seemed to be some experimental error but trial after trial proved the same result. The atomic weight of the lead from the Thorium series was found to

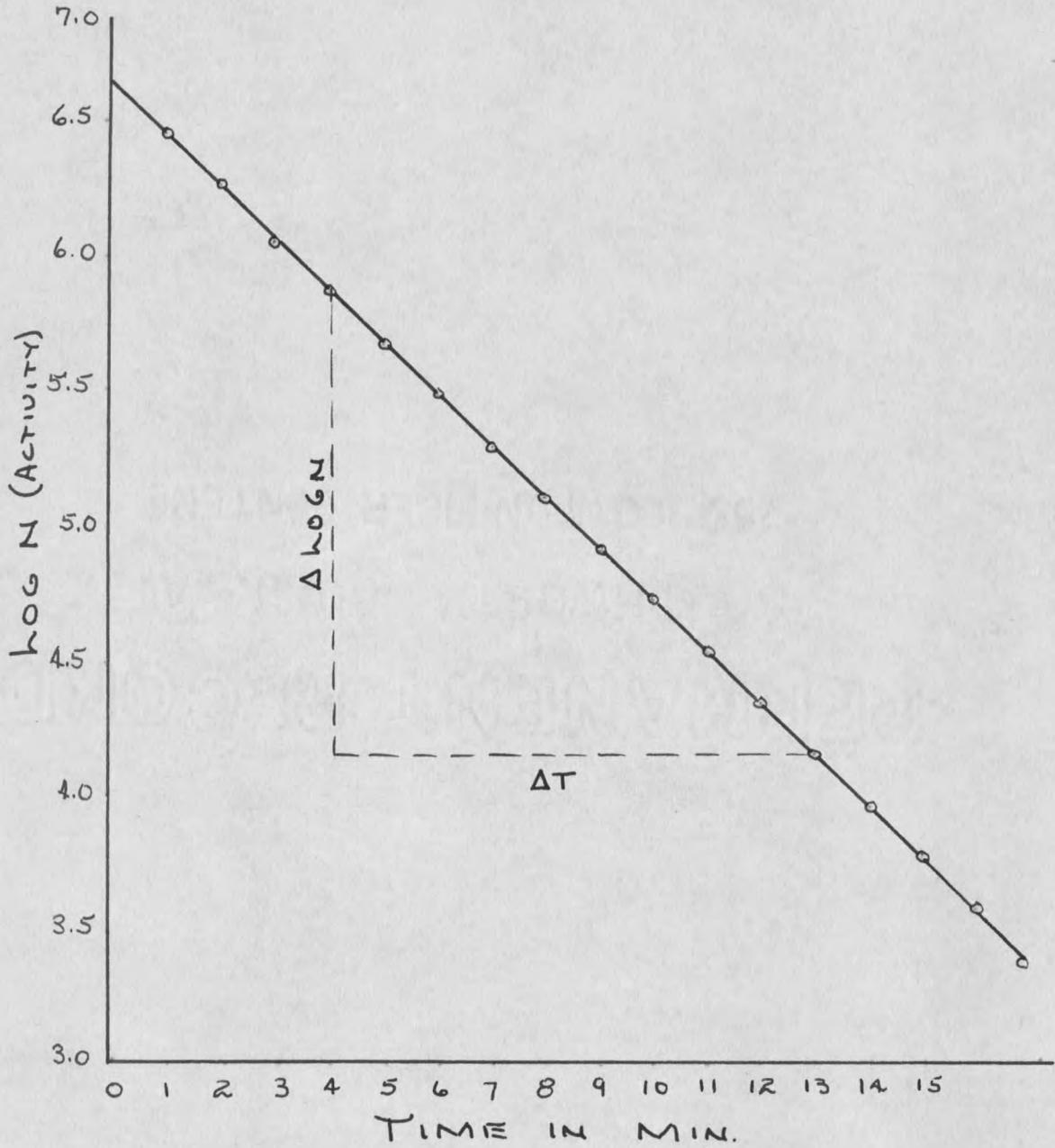


Figure 15 Graph for Example No. 2

be approximately 208, and the lead from the Actinium series was found to be approximately 207. The lead from the Actinium series seemed to be the only one that agreed with the already established atomic weight of lead.

Further experiments and study showed that normal lead was comprised of three different atoms, their chemical properties being identical, the only difference being their mass. This mass difference is taken advantage of when separating these different atoms. The different atoms of one element were named isotopes and much later a fourth isotope of lead was discovered having an atomic mass number of 204.

It has now been shown most known elements have at least two isotopes. Lead has four with the following percentages:

204	1.5%
206	23.6%
207	22.6%
208	52.3%

Lead has an atomic number (Z) of 82, meaning its nucleus has 82 protons with 82 planetary electrons, and 204 minus 82 or 122 neutrons for the lightest isotope of lead and 124, 125 and 126 neutrons for the other three isotopes. This difference in the number of neutrons accounts for the difference in the masses of isotopes of one element, while the same atomic number of the isotopes of any one element accounts for the identical chemical properties. Isotopes of the various elements will be denoted by ${}_{82}^{206}\text{Pb}$ where Pb is the symbol for the element, the number at the lower left is the atomic (Z) and the number at the upper right is the mass number (A).

ISOMERS:

From Figures 9 and 13 in the Uranium-Radium Series, there is a single line of disintegration until Bismuth (Radium C) is reached. At this point the radiation may be either Alpha or Beta particles. In the case of Alpha emission, Thallium (Radium C') is formed while when beta emission occurs, Polonium (Radium C) is formed. However, the distribution of the emission from Bismuth (Radium C) is only 0.04% Alpha particles and 99.96% Beta particles. When dual emissions occur from one isotope, they are known as isomers.

SECULAR EQUILIBRIUM:

Again in the Uranium-Radium Series, uranium (${}_{92}\text{U}^{238}$) emits an alpha particle with a long half-life of 4.55×10^9 years to form Thorium (${}_{90}\text{Th}^{234}$) which has a short half-life of 24.1 days. In cases of this nature, the rate of emission from the uranium may be considered constant and the amount of thorium builds up to steady amount where the same amount of thorium disintegrates as is formed by the activity of the uranium. When this takes place the product is said to be in secular equilibrium and the following equations hold true:

Where S_U, N_U - uranium

S_T, N_T - thorium

$-dN_T$ - rate at which thorium disintegrates

dN_U - rate at which uranium disintegrates
or which thorium accumulates

or

$$\frac{dN_T}{dt} = dN_U - dN_T$$

substituting equation (7)

$$-dN = \delta N dt \quad (7)$$

$$\frac{dN_T}{dt} = \delta_U N_U - \delta_T N_T \quad (12)$$

If secular equilibrium exists N_U is considered constant

$$\frac{dN_T}{\delta_U N_U - \delta_T N_T} = dt$$

Multiplying both sides by $-\delta_T$

$$\frac{-\delta_T dN_T}{\delta_U N_U - \delta_T N_T} = -\delta_T dt$$

Integrating

$$\text{Log} (\delta_U N_U - \delta_T N_T) = -\delta_T t + \text{Log } C$$

$$\delta_U N_U - \delta_T N_T = C e^{-\delta_T t}$$

Solving for the constant of integration C

When $t = 0, N_T = 0$

or $\delta_U N_U - 0 = C \times 1$

$$C = \delta_U N_U$$

$$\delta_U N_U - \delta_T N_T = \delta_U N_U e^{-\delta_T t}$$

$$\delta_U N_U - \delta_U N_U e^{-\delta_T t} = \delta_T N_T$$

$$N_T = \frac{\delta_U}{\delta_T} N_U (1 - e^{-\delta_T t}) \quad (13)$$

As t approaches infinity

$$e^{-\delta_T t} = 0$$

$$t \longrightarrow \infty$$

$$N_T = \frac{\delta_U}{\delta_T} N_U$$

Using the half-life equation (9)

$$T = \frac{0.693}{\delta} \quad (9)$$

$$\frac{N_T}{N_U} = \frac{\delta_U}{\delta_T} = \frac{T_T}{T_U} \quad (14)$$

Example No. 3. In the Uranium-Radium Series, ${}_{92}\text{U}^{238}$ disintegrates through a series of radioactive elements to ${}_{82}\text{Pb}^{206}$. Where a uranium ore is found, the ratio of the amount of lead present with respect to the amount of uranium is 100 grams to 1000 grams respectively.

Calculate the length of time the uranium has been in existence and the radium present per 1000 grams of uranium.

From table on Figure 9

Half-life of Uranium = 4.55×10^9 years

Half-life of Radium = 1590 years

$$N = N_1 e^{-\delta t} \quad (8)$$

$$\delta = \frac{.693}{T} = \frac{.693}{4.55 \times 10^9}$$

The initial number of atoms (N_1) of uranium must take into consideration the loss in mass of the particles emitted.

$$N_i = 1000 + 100 \frac{238}{206} = 1115.6 \text{ grams}$$

$$N = 1000$$

$$e^{\lambda t} = \frac{1115.6}{1000} = 1.1156$$

$$t = \frac{(\text{Log } 1.1156)(4.55 \times 10^9)}{(.693)}$$

$$= 7.17 \times 10^8 \text{ years}$$

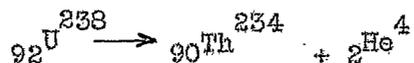
The amount of radium present under conditions of secular equilibrium

$$\frac{T_r}{T_u} = \frac{M_r}{1000}$$

$$M_r = \frac{1590 \times 1000}{4.55 \times 10^9}$$

$$= 3.49 \times 10^{-3} \text{ grams}$$

Radioactive disintegration will be written in equilibrium form for the remaining portion of our study. Taking the disintegration of uranium into thorium by the emission of an alpha may be written:

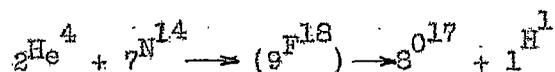


where ${}_2\text{He}^4$ is the nucleus of the helium isotope having the mass number four. Equations of this type will be written for the nuclei of the atoms neglecting the planetary electrons.

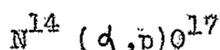
NUCLEAR REACTIONS AND ARTIFICIAL RADIOACTIVITY

In 1919 Sir Ernest Rutherford used the knowledge of Radio-activity to perform a series of experiments. His thoughts were to use these atomic "bullets" from radioactive substances and observe their reactions when bombarding other nuclei. But first he wanted to study the range of alpha particles in air so as to be able to deal with his other work more easily. One of the main reasons for this work was to be able to understand more about the atom as to its construction, which lead to our present day concept (as discussed previously).

Using a closed chamber for his work Rutherford found that while measuring the range of alpha particles in air there would be an amount of hydrogen present. This seemed very strange, so he then tried nitrogen in place of air and again hydrogen was found. No explanation could be given at that time and further experiments showed that when the air or nitrogen was replaced by several other gases such as oxygen, carbon dioxide or carbon monoxide no hydrogen was found. Therefore the hydrogen formed must have some relationship with the alpha particles and the nitrogen nuclei (or atoms). Later the Wilson Cloud Chamber showed this reaction to be the absorption of the alpha particles by the nitrogen nucleus with the formation of a proton and a much heavier particle. Remembering that the proton is the hydrogen nucleus (${}_1\text{H}^1$). (The use of the Wilson Cloud Chamber will be discussed in detail later). The complete reaction may be written in equation form as follows:



the flourine is known as the compound nucleus. There is not any proof of its existence but is believed to exist for a very short period of time. The ${}_{7}\text{N}^{14}$ and the ${}_{8}\text{O}^{17}$ are known as the reacting and product nuclei respectively. Nuclear reactions of this type are also written in a more concise method, for the same equation as above:



In using this condensed method of writing a nuclear reaction, the subscripts may be omitted because the chemical symbol establishes the value of Z. The symbols inside the parentheses designate in order the incident and ejected particles, but they are not the chemical symbols used in the longer method. A proton is designated by the letter p instead of ${}_{1}\text{H}^{1}$. The other symbols used to represent the incident and ejected particles are:

n - neutron

d - deuteron

α - alpha particle

γ - gamma rays

This being the first time that nuclei of one element were converted into nuclei of another. It might be said that this change was the dream of scientists in the past. This change also brought about numerous experiments by new scientists. The majority of this new work was in the form of bombardment with all the known particles on the lighter elements. The bombardment of beryllium, boron and lithium by alpha particles emitted a very penetrating ray. At first this radiation was thought to be gamma radiation although it was more penetrating than any gamma rays known, and the details of experimental results were very different and difficult to

interpret on this basis. The next important contribution was reported in 1932 by Irene Curie and F. Joliot in Paris. They showed that if this unknown radiation fell on paraffin or any other hydrogen-containing compound it emitted protons of very high energy. This was not in itself inconsistent with the assumed gamma ray nature of this new radiation, but detailed quantitative analysis

of the data became increasingly difficult to reconcile with such an hypothesis. Finally (later in 1932) J.

Chadwick, in England, performed a series of experiments showing that the gamma ray hypothesis was untenable. He suggested that the new radiation consisted of uncharged

particles of approximately the mass of the proton, and he performed a series of experiments verifying his suggestion. Such uncharged particles are now called neutrons.

A brief history of the experiments leading to the discovery of the neutron would start with the original gamma ray hypothesis.

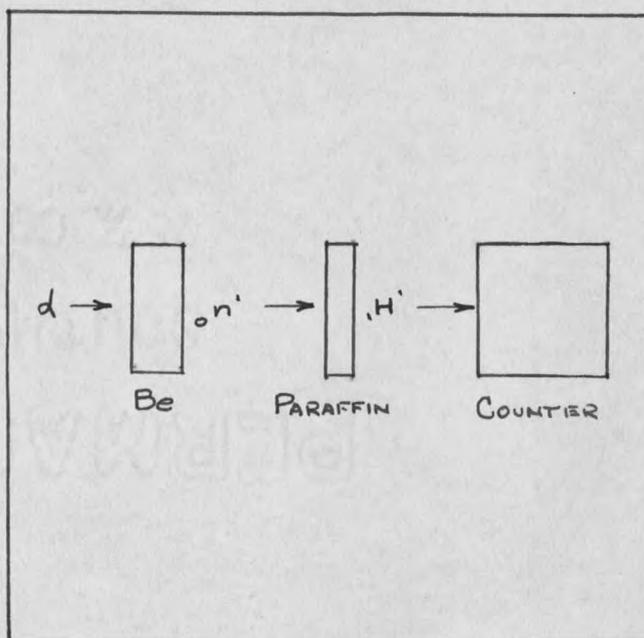
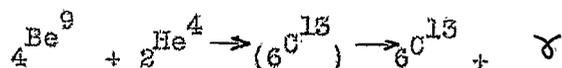


Figure 16 Schematic Drawing of Chadwick's Experiment for the Discovery of the Neutron



Calculations made by Bothe and Becker (1930) showed that the gamma ray protons to have an energy of approximately 6.8 Mev when absorbed in lead. In the Curie-Joliot experiments the assumed gamma rays ejected protons when bombarded into paraffin with an energy of 5.5 Mev (See Figure 16). Other experiments showed the energy to range from 15 to 90 Mev using the conservation of mass, energy and momentum. This inconsistency lead to further study, which showed that omitting the paraffin (Figure 16) the counts were relatively small, then using a thin lead sheet only decreased the number of counts slightly. But when the paraffin is inserted the number of counts increases greatly. The explanation for this is that the paraffin when bombarded by these uncharged particles (neutrons) ejects protons which have a charge and may be counted. When the paraffin was replaced by lead the reason for any counts at all is that the neutrons will collide with parts of the counter and eject nuclei which cause the counts. When the lead is removed and the neutrons move directly into the counter the approximate number of counts are taken showing that these high energy neutrons are not stopped by thin sheets of lead. This is just the opposite as would occur if this radiation were gamma rays. Chadwick then measured the velocity of the ejected protons from paraffin and then used nitrogen to replace the paraffin and measured the velocity of the nitrogen nuclei after the collision. Using the conservation of energy and equation (5)

$$\frac{1}{2} MV^2 + 0 = \frac{1}{2} mv^2 + \frac{1}{2} M(V-v)^2$$

Where M and V are the mass and velocity of the neutron before collision, m and v the mass and velocity of the proton, or nitrogen, nuclei after the collision. Taking the velocity of the proton and nitrogen as zero before collision,

$$MV^2 = mv^2 + M(V^2 + 2Vv + v^2)$$

$$2MV = v(M + m)$$

$$\frac{v}{V} = \frac{2M}{M + m}$$

the velocities Chadwick found were

$$v_H = 3.3 \times 10^9 \text{ cm/sec. for the proton}$$

$$v_N = 4.7 \times 10^8 \text{ cm/sec. for the nitrogen}$$

taking the two experiments and combining in one equation

$$\frac{v_H}{v_N} = \frac{M + m_N}{M + m_H}$$

where m_H and m_N are the masses of the proton (hydrogen) and nitrogen respectively. Taking nitrogen as being fourteen times the mass of the proton ($14 m_H = m_N$)

$$M = 1.16 \text{ amu}$$

After more careful and detailed experiments this value for the mass of the neutron was changed to our present value of 1.00893 amu.

The most important property of the neutron is the fact that it has no charge, which is the main reason for the delay in its discovery. This also makes them very penetrating, it is impossible to observe them directly and makes them very important as agents in nuclear change. An atom in its normal state is also uncharged, but it is ten thousand times

larger than a neutron and consists of a complex system of negatively charged electrons widely spaced around a positively charged nucleus. Charged particles (such as protons, electrons, or alpha particles) and electromagnetic radiations (gamma rays) lose energy passing through matter. They exert electric forces which ionize atoms of the material through which they pass. (It is such ionization processes that make the air electrically conducting in the path of electric sparks and lightning flashes). The energy taken up in ionization equals the energy lost by the charged particles, which slows down, or by the gamma ray, which is absorbed. The neutron, however, is unaffected by such forces; it is affected only by the short-range force, i.e., a force that comes into play when the neutron comes very close to an atomic nucleus. This is the kind of force that holds a nucleus together in spite of the mutual repulsion of the positive charges within it. Consequently a free neutron goes on its way unchecked until it makes a "head on" collision with an atomic nucleus. Since nuclei are very small, such collisions occur but rarely, and the neutron travels a long way before colliding. In the case of a collision of the "elastic" type, the ordinary laws of momentum apply as they do in the elastic collision of billiard balls. If the nucleus that is struck is heavy, it acquires relatively little speed, but if it is a proton, which is approximately equal in mass to the neutron, it is projected forward with a large fraction of the original speed of the neutron, which is itself correspondingly slowed. Secondary projectiles resulting from these collisions may be detected, for they are charged and produce ionization. The uncharged nature of the neutron makes it not only difficult to detect but hard

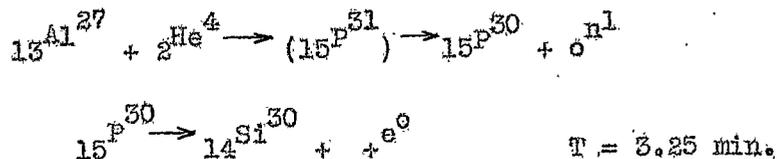
to control. Charged particles can be accelerated, decelerated, or deflected by electric or magnetic fields which have no effect on neutrons. Furthermore, free neutrons can be obtained only from nuclear disintegrations; there is no natural supply. The only means we have of controlling free neutrons is to put nuclei in their way so that they will be slowed and deflected or absorbed by collisions. As we shall see, these effects are of the greatest practical importance. Further experiments showed that the bombardment of a series of elements by alpha particles emitted neutrons. All of these elements being in the first two rows of the Periodic Chart (aluminum, argon, beryllium, boron, fluorine, lithium, magnesium, nitrogen, phosphorus, and sodium).

THE POSITRON

In about 1910, Victor F. Hess found the existence of a penetrating radiation from sources outside the earth called cosmic rays. At first these rays were considered similar to gamma rays, but because of their greater penetration to have a shorter wave length. Later electrostatic and electromagnetic experiments proved the rays to be composed of charged particles. In 1932, C. D. Anderson, at the California Institute of Technology, using cloud chamber experiments found that a portion of these charged particles had the same mass as that of an electron. This new particle also has the charge of an electron but is positive and are now called positrons. Also in cosmic rays particles have been found with electronic charge but masses from 200-500 times that of the electron which are called meson (Table I).

1932 also brought forth another discovery, by H. G. Urey, F. G. Brickwedde, and G. M. Murphy found that hydrogen had an isotope of mass number 2, present in natural hydrogen to one part in 5000. Because of its special importance this heavy species of hydrogen is given a name of its own, deuterium, and the corresponding nucleus is called the deuteron. The deuteron is not a fundamental particle being made of one proton and one neutron.

Curie and Joliot in 1934 while bombarding various light elements with alpha particles with the emission of neutrons found that the product nucleus continued to emit radiations even after the source of alpha particles had been removed. Further study showed this radiation to be positrons and the intensity of the radiation was shown to decrease exponentially with time, the same as natural radioactive substances. Using this decrease in radiation Curie and Joliot were able to calculate the half-lives of these artificially produced radioactive substances. They found that the alpha particle bombardment of aluminum, boron and magnesium performed this phenomena with half-lives of 3.25 minutes, 14 minutes and 2.5 minutes respectively. Shown in equation form



Where ${}_+e^0$ is the symbol used for the positron showing the positive charge and the zero mass number, the reactions from the boron and magnesium being of the same type as shown for the aluminum. Several other unstable isotopes that emit positrons have since been found (${}_{13}\text{Al}^{26}$, ${}_{11}\text{Na}^{22}$, ${}_{9}\text{F}^{17}$,

$^{34}_{17}\text{Cl}$). At this time nuclear physics was well on its way, and at the present time radioactive isotopes have been produced of practically all the known elements. Typical examples are shown in Table V. Note that in the neutron induced reaction with $^{12}_6\text{C}$ (Table V) the product nucleus is $^{11}_6\text{C}$ which emits a positron plus two neutrons. These two neutrons may in turn bombard another $^{12}_6\text{C}$ starting the reaction again with two neutrons as its result, thus causing a continuous action or chain reaction. This chain reaction is necessary in order to produce a continuous supply of power as we will see later.

With the production of radioactive isotopes great advances are being made in the fields of medicine, agriculture and engineering. For instance radioactive calcium may be fed to animals and then later the radiation from the various bones of the animal may be measured showing the distribution of the original calcium. Similarly fertilizer made with radioactive phosphorus will show the distribution in plant life. As Mechanical Engineers we will be interested in wear caused from friction in internal combustion engines. Work has been performed on piston rings which were made radioactive and then inserted in an engine. After several hundred hours of operation the oil is drained from the engine and examined for radioactive radiation. From this, calculations can show the amount of wear the piston rings have undergone. This is one of the many Mechanical Engineering uses of radioactive isotopes. Table VI shows a list of commercially used radioactive isotopes.

The forming of these radioactive isotopes stimulated similar experiments all over the world. In particular, E. Fermi reasoned that neutrons, because of their lack of charge, should be effective in penetrating nuclei; especially those nuclei of high atomic number which strongly repel protons and alpha particles. He was able to verify his prediction almost immediately. Finding that the nucleus of the bombarded atom captured the neutron and that there was thus produced an unstable nucleus which then achieved stability by emitting an electron. The several differences that exist between natural and artificial radioactivity are that positrons are never emitted from natural sources while alpha particles are very rare from artificial radioactivity. Also artificial radioactivity under certain conditions undergoes K-electron capture. Instead of the nucleus emitting a positron, it may capture an electron from the extra nuclear part of the atom, generally from the K shell of electrons. With this there are several changes the electron now in the nucleus combines with a proton to form a neutron, thereby increasing the atomic number by one, also an X-ray is emitted by this process. But careful calculations show that the law of momentum is not satisfied, therefore the physicist contends there is another very small particle emitted called the neutrino (Table I). The neutrino is still a theoretical prediction. As yet this particle has not been experimentally verified, though there is experimental evidence for belief in its existence.

TABLE V

TYPE	TYPICAL REACTION	PARTICLE EMITTED
PROTON INDUCED		
p.	${}^6_6\text{C}^{12} + {}^1_1\text{H}^1 \rightarrow ({}^7_7\text{N}^{13}) \rightarrow {}^7_7\text{N}^{13} + \gamma$	+ e ⁰
p.	${}^4_4\text{Be}^9 + {}^1_1\text{H}^1 \rightarrow ({}^5_5\text{B}^{10}) \rightarrow {}^5_5\text{B}^9 + {}^1_0\text{n}^1$	+ e ⁰
p.	${}^9_9\text{F}^{19} + {}^1_1\text{H}^1 \rightarrow ({}^{10}_{10}\text{Ne}^{20}) \rightarrow {}^8_8\text{O}^{16} + {}^2_2\text{He}^4$	None
p, d	${}^4_4\text{Be}^9 + {}^1_1\text{H}^1 \rightarrow ({}^5_5\text{B}^{10}) \rightarrow {}^4_4\text{Be}^8 + {}^1_1\text{H}^2$	+ e ⁰
NEUTRON INDUCED		
n.	${}^{48}_{48}\text{Cd}^{113} + {}^1_0\text{n}^1 \rightarrow ({}^{48}_{48}\text{Cd}^{114}) \rightarrow {}^{48}_{48}\text{Cd}^{114} + \gamma$	None
n, p	${}^7_7\text{N}^{14} + {}^1_0\text{n}^1 \rightarrow ({}^7_7\text{N}^{15}) \rightarrow {}^6_6\text{C}^{14} + {}^1_1\text{H}^1$	+ e ⁰
n.	${}^8_8\text{O}^{16} + {}^1_0\text{n}^1 \rightarrow ({}^8_8\text{O}^{17}) \rightarrow {}^6_6\text{C}^{13} + {}^2_2\text{He}^4$	+ e ⁰
n, 2n	${}^6_6\text{C}^{12} + {}^1_0\text{n}^1 \rightarrow ({}^6_6\text{C}^{13}) \rightarrow {}^6_6\text{C}^{11} + 2 {}^1_0\text{n}^1$	+ e ⁰
ALPHA PARTICLE INDUCED		
p	${}^7_7\text{N}^{14} + {}^2_2\text{He}^4 \rightarrow ({}^9_9\text{F}^{18}) \rightarrow {}^8_8\text{O}^{17} + {}^1_1\text{H}^1$	None
n	${}^5_5\text{B}^{10} + {}^2_2\text{He}^4 \rightarrow ({}^7_7\text{N}^{14}) \rightarrow {}^7_7\text{N}^{13} + {}^1_0\text{n}^1$	+ e ⁰
DEUTERON INDUCED		
d, p	${}^{11}_{11}\text{Na}^{23} + {}^1_1\text{H}^2 \rightarrow ({}^{12}_{12}\text{Mg}^{25}) \rightarrow {}^{11}_{11}\text{Na}^{24} + {}^1_1\text{H}^1$	+ e ⁰
d, n	${}^6_6\text{C}^{12} + {}^1_1\text{H}^2 \rightarrow ({}^7_7\text{N}^{14}) \rightarrow {}^7_7\text{N}^{13} + {}^1_0\text{n}^1$	+ e ⁰
d.	${}^8_8\text{O}^{16} + {}^1_1\text{H}^2 \rightarrow ({}^9_9\text{F}^{18}) \rightarrow {}^7_7\text{N}^{14} + {}^2_2\text{He}^4$	None

TABLE VI
USEFUL RADIOACTIVE ISOTOPES

Element	Isotope	Half-Life	Radiation	Typical Uses
Calcium	$^{45}_{20}\text{Ca}$	180 days	β^- , γ	Research on fertilizers, bone formation.
Carbon	$^{14}_6\text{C}$	4700 years	β^-	Study of photosynthesis, plant physiology, carbohydrate utilization in animals.
Chlorine	$^{36}_{17}\text{Cl}$	10^5 years	β^- , β^+ , K	Research on the physiology of plants and animals.
Gold	$^{198}_{79}\text{Au}$	2.7 days	β^- , γ	Treatment of leukemia.
Iodine	$^{130}_{53}\text{I}$	12.6 hours	β^- , γ	Treatment of thyroid cancer and hyperthyroidism.
Iodine	$^{131}_{53}\text{I}$	8.0 days		
Iron	$^{55}_{26}\text{Fe}$	4 years	K	Study of anemia, disease of plants, blood circulation.
Phosphorus	$^{32}_{15}\text{P}$	14.30 days	β^-	Treatment of leukemia (including lymphocarcinoma and Hodgkin's disease), polycythemia vera, skin cancer. Study of blood circulation and metabolism.
Potassium	$^{42}_{19}\text{K}$	12.4 hours	β^- , γ	Research on diseases of the heart and nervous system.
Sodium	$^{24}_{11}\text{Na}$	14.8 hours	β^- , γ	Study of blood circulation, cell function, congestive heart failures.
Sulfur	$^{35}_{16}\text{S}$	87.1 days	β^-	Research on plant physiology, proteins.

NUCLEAR ENERGY

In the basic courses of chemistry and physics there are two basic principles which govern all the reactions. The first--that matter can be neither created nor destroyed but only altered in form which has lead to the principle known as the law of conservation of mass. The second--that energy can be neither created nor destroyed but only altered in form, which is known as the law of conservation of energy. These two principles have constantly guided and disciplined the development and application of science. For all practical purposes they were unaltered and separate until this past decade. For most practical purposes they are still so, but it is now known that they are, in fact, two phases of a single principle for we have discovered that energy may sometimes be converted into matter and matter into energy. Specifically, such a conversion is observed in the phenomenon of nuclear fission of uranium which is the basis for nuclear power.

RELATIVITY:

In the development of the theory of relativity it was shown that the inertial mass of a moving body increases as its velocity increases (Equation 6). This implies an equivalence between an increase in energy of motion of a body, i.e., its kinetic energy, and an increase in its mass. To most practical physicists and engineers this appeared a mathematical fiction of no practical importance. Even Einstein could hardly have foreseen the present applications, but as early as 1905 he did clearly state that mass and energy were equivalent and suggested that proof of this equivalence might be found by the study of radioactive substances. He

concluded that the amount of energy, E in ergs, equivalent to a mass, m in grams, was given by the equation

$$E = mc^2 \quad (15)$$

where c is the velocity of light in cm/sec. It is interesting to note that Einstein's work was accomplished and published in Germany (1905) but the physicists and militarists at that time could not foresee a use for energy formed from matter. Equation (15) shows that one kilogram (2.2 pounds) of matter, if converted entirely into energy, could give 25 billion kilowatt hours of energy. This is equal to the energy that would be generated by the total electric power industry in the United States (as of 1939) running for approximately two months. Compare this fantastic figure with the 8.5 kilowatt hours of heat energy which may be produced by burning an equal amount of coal.

The extreme size of this conversion figure was interesting in several respects. In the first place, it explained why the equivalence of mass and energy was never observed in ordinary chemical combustion. We now believe that the heat given off in such a combustion has mass associated with it, but this mass is so small that it cannot be detected by the most sensitive balances available (it is of the order of a few billionths of a gram per mole). In the second place, it was made clear that no appreciable quantities of matter were being converted into energy in any familiar terrestrial processes, since no such large sources of energy were known. Therefore we may say that the conversion of matter to energy has been taking place in numerous Mechanical Engineering phenomenon but until recently we were unaware of its existence.

BINDING ENERGY:

In the discussion previously, the energy of the particles was purposely eliminated until this time when mass and energy conversion can be discussed in detail. Also the discussion has been of stable and unstable nuclei made up of assemblages of protons and neutrons held together by nuclear forces. It is a general principle of physics that work must be done on a stable system to break it up. Thus, if an assemblage of neutrons and protons is stable, energy must be supplied to separate its constituent particles. If energy and mass are really equivalent, then the total mass of a stable nucleus should be less than the total mass of the separate protons and neutrons that go to make it up. This mass difference, then, should be equivalent to the energy required to disrupt the nucleus completely, which is called the binding energy. It has been previously mentioned that the masses of all nuclei were approximately whole numbers. It is the small differences from whole numbers that are significant.

From the introduction we found that the nucleus of the helium atom (alpha particle) is composed of two protons and two neutrons having a mass number of four. If this nucleus were pulled apart and the weight of its parts carefully taken the following would be found--

$${}^4_2\text{He} \text{ (the nucleus before taken apart) } = 4.00276 \text{ amu}$$

if one neutron is taken from the nucleus leaving ${}^3_2\text{He}$.

$${}^3_2\text{He} \text{ (3.01589) } + {}^1_0\text{n} \text{ (1.00893) } = 4.02482 \text{ amu}$$

if the nucleus is split in two, leaving two nuclei of one proton and one neutron each (deuteron).

$${}^2_1\text{H} \text{ (2.01418) } + {}^2_1\text{H} \text{ (2.01418) } = 4.02836$$

If the nucleus were divided into its basic particles.

$$2\text{}^1_1\text{H} + 2\text{}^1_0\text{n} = 4.03302 \text{ amu}$$

Examining the total masses of the original nucleus and also after being pulled apart in various segments. When the alpha particle exists the mass is the least and should be the most stable of the four categories shown above because there is a tendency in nature for the nucleons to find the category of least mass and least energy. From this it would appear that any of the other three groups would have a tendency to transform into this one of lowest mass but as we know there are millions of $\text{}^3_2\text{He}$ and deuterons in nature which seem very stable and contented. The answer to this question is that deuterons and $\text{}^3_2\text{He}$ are the nuclei of atoms and are surrounded by a free atom or one chemically combined. The electrons forming a strong electrostatic field of repulsion to one another and even if ionized the nucleus itself also has an electrostatic force of repulsion except when two nuclei come to within 10^{-12} cm. apart then the short-range forces react.

Again examining the mass we find the mass of the alpha particle 4.00276 amu while dividing into the basic particles the total mass is 4.03302 amu; expressed by means of an equation

$$\text{}^4_2\text{He} = \text{}^1_1\text{H} + \text{}^1_1\text{H} + \text{}^1_0\text{n} + \text{}^1_0\text{n}$$
$$4.00276 = 4.03302$$

The law of conservation of mass does not hold true but previously it has been shown that mass and energy are interchangeable, therefore the mass difference must have been in the form of energy. 4.03302 minus 4.00276 equals 0.03026 amu

$$0.03026 \text{ amu} \times 931 \text{ Mev/amu} = 27.95 \text{ Mev}$$

This mass difference being converted into energy now shows the amount of energy required to pull apart the helium nucleus into protons and neutrons or may be stated as its Binding Energy. This energy of 27.95 Mev is the energy per nucleus or 2.7×10^{19} ergs per gram molecule of helium. In units more familiar to the engineer, this means that to break up the nuclei of all the helium atoms in a gram of helium would require 1.62×10^{11} gram calories or 190,000 kilowatt hours. Conversely, if free protons and neutrons could be assembled into helium nuclei, this energy would be released. Evidently it is worth explaining the possibility of getting energy by combining protons and neutrons or by transmuting one kind of nucleus into another.

By means of the mass spectrograph, F. W. Aston and others were able to determine the masses of the isotopes of many elements. From this and later work the binding energies of these isotopes has been accurately calculated. This binding energy, B is the difference between the true nuclear mass, M and the sum of the masses of all the protons and neutrons in the nucleus. That is,

$$B = (ZM_p + NM_n) - M$$

where M_p and M_n are the masses of the proton and neutron respectively, Z is the number of protons, $N = A - Z$ is the number of neutrons, and M is the true mass of the nucleus. Quite often this energy is in terms of B/A the binding energy per particle. Figure 17 shows this binding energy per particle (B/A) plotted against the mass number (A). The graph shows that, apart from fluctuations in light nuclei, the general trend of the binding

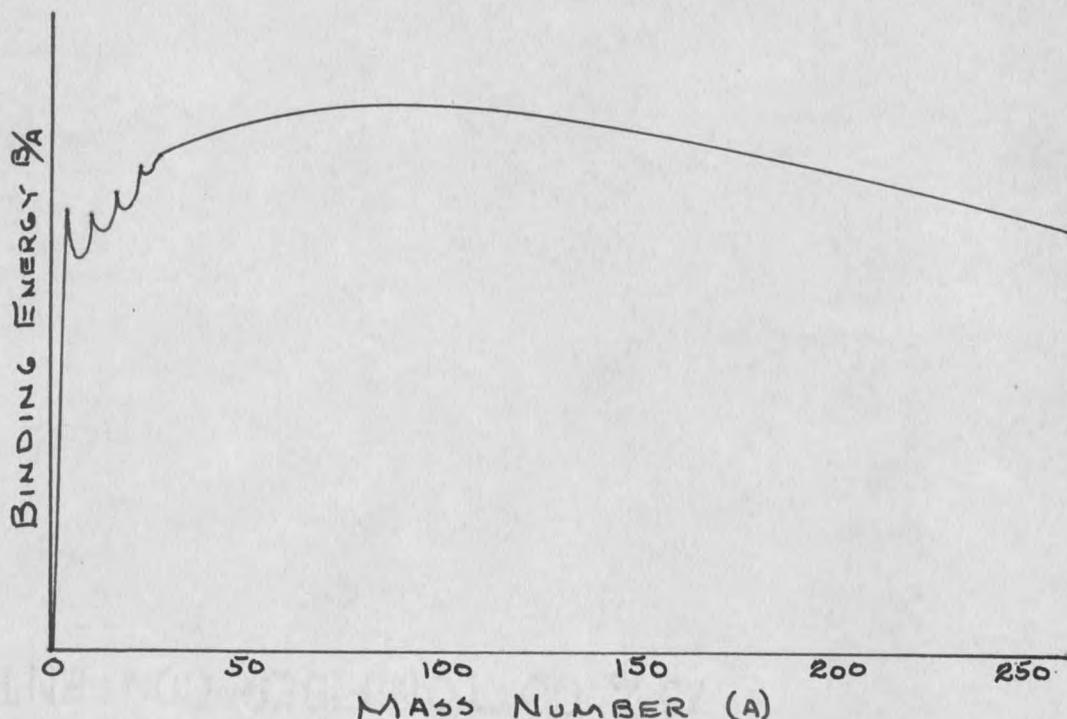


Figure 17 The Binding Energy per particle (B/A) plotted against the Mass Number (A)

energy per particle is to increase rapidly to a flat maximum around $A = 60$ (nickel) and then decrease again gradually. Evidently the nuclei in the middle of the periodic table, nuclei of mass numbers 40 to 100, are the most strongly bound. Any nuclear reaction where the particles in the resultant nuclei are more strongly bound than the particles in the initial nuclei will release energy. Thus, in general, energy may be gained by combining light nuclei to form heavier ones (i.e., nuclei in the medium range) or by breaking very heavy ones into two or three smaller fragments. However, not all of the lighter elements may be used to the best advantage as is sometimes shown in connection with their packing

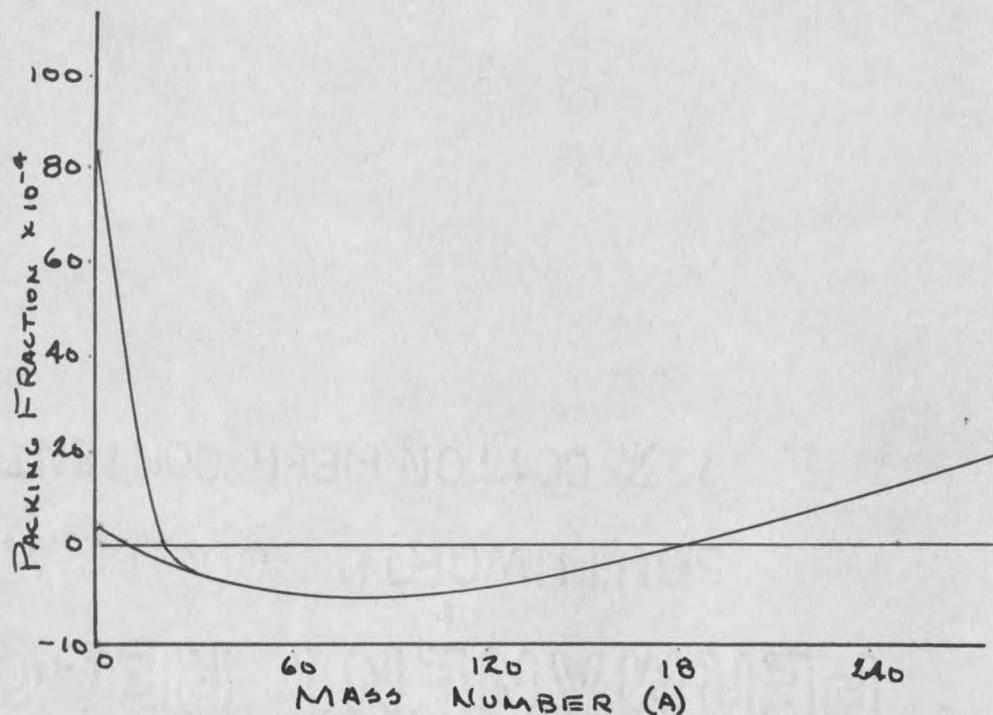


Figure 18 Packing Fraction plotted against mass number showing positive and negative values

fraction.

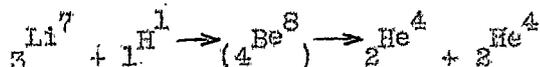
Packing Fraction

It has been previously mentioned that the actual masses (amu) of all the isotopes varies slightly from whole numbers, their mass number (A). The isotopes with mass numbers from 1 to 20 (or 21) have atomic masses (M) that are slightly greater than their mass number. From mass number of 20 to 168 the atomic mass is slightly less than the mass number and above 168 the atomic mass again becomes greater. Various sources of atomic masses will sometimes use packing fraction or the mass defect per elementary particle in the nucleus. That is

$$P = \frac{M - A}{A}$$

where P is the packing fraction and M - A is the mass defect or the mass difference from a whole number which will cause the packing fraction to be negative when using mass numbers of 20 to 168. Figure 18 also shows that for the lighter nuclei two curves must be used to satisfy all the isotopes.

Rutherford's work in 1919 on artificial nuclear disintegration, has previously been mentioned, and was followed by many similar and more advanced experiments. High voltage apparatus used to accelerate particles was replacing natural sources of alpha particles from radioactive substances. The energy at which an alpha particle is emitted from radioactive sources vary with the various atoms, for instance, the alpha particle from radon has a velocity of 1.63×10^9 cm/sec. while an alpha particle from thorium C has a velocity of 1.71×10^9 cm/sec. This difference does not seem to be very great but we must remember that this is the velocity and from equation (5) $E = \frac{1}{2}mv^2$ shows that the energy varies directly as the square of the velocity which will cause a greater difference in the energy. In 1932, J. D. Cockcroft and E. T. S. Walton bombarded a target of lithium with protons of 700 kilovolts energy and found that alpha particles were ejected. In equation form



Taking the masses of the nuclei and particles in the above equation we find

$$7.01816 + 1.00815 = 4.00386 + 4.00386$$

Adding $8.02629 = 8.00772$ amu

As can be seen the left hand side (initial) of the reaction is heavier than the right hand side, therefore something must be added to balance this equation. 8.02629 minus 8.00772 equals $.01857$ amu; this mass has disappeared in the reaction and if converted to energy units equals

$$.01858 \text{ amu} \times 931 = 17,298 \text{ Mev.}$$

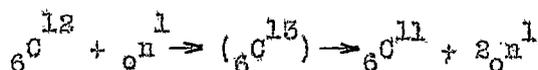
Experiments have shown that the two alpha particles emitted each have an energy of approximately 8.62 Mev or a total of 17.24 Mev which compares favorably with our calculated value $17,298$ Mev. However this is taking the initial energy of the proton (${}_1\text{H}^1$) as being negligible. It should also be noted that the masses used in the above calculations were those of the atoms, not just the nuclei. This is satisfactory because there is an equal number of electrons on each side of the reaction therefore actually cancelling out their masses.

The energy released during this reaction ($17,298$ Mev) may be converted into more frequently used engineering units.

$$17,298 \times 4.45 \times 10^{-20} = 76.98 \times 10^{-20} \text{ Kw-hr/atom}$$
$$\frac{76.98 \times 10^{-20}}{7.01816 \times 1.66 \times 10^{-24}} = 66,200 \text{ Kw-hr/gram}$$

from this can be seen the energy released per atom and also the energy per gram showing a source of nuclear power. But examining the source of this power (energy) we find that for each reaction to take place a proton is required that will bombard the nucleus of a lithium atom. Not all protons will cause such a reaction, the remainder just passing by all the lithium nuclei. The number of protons required per lithium atom will be

discussed under cross-section in the following paragraph. This probability could well be in the neighborhood of 1 to 1,000,000 which shows the enormous supply of protons required to keep a steady supply of energy. However at this time it can be foreseen that the most practical method for continuous energy would be to have a reaction where the initial particle is the same as one (or more) of the ejected particles. For instance in Table V,



where one neutron bombards a ${}_6\text{C}^{12}$ nucleus and there are two neutrons ejected which may bombard more ${}_6\text{C}^{12}$ nuclei causing a continuous reaction (chain reaction). However, this reaction cannot be used because energy is absorbed not released, but it does show the type of reaction needed.

CROSS-SECTION

As mentioned in the above paragraph, not all particles that move in the direction of a nucleus cause a reaction. This probability varies widely with the various particles, nuclei, and their kinetic energy. But instead of complex probability relationships, the interactions between projectile particles and nuclei are expressed very simply in terms of nuclear cross-section. The centers of the atoms in a very thin foil can be considered as points evenly distributed over a plane. The center of an atomic projectile striking this plane has geometrically a definite probability of passing within a certain distance (r) of one of these points. If there are n atomic centers in an area A of the plane, this probability is $n r^2/A$, which is simply the ratio of the aggregate area of circles of

radius r drawn around the points of the whole area. Let us consider these atoms (of area A) to be thin steel targets with a small impenetrable centers and for the projectiles let us use several calibers of guns. A 50 caliber shell would indicate that the cross-section of the target was just the diameter of the small impenetrable center while a bee bee gun would show the cross-section to be the full area of the target. However, in the case of particles and nuclei, sometimes (in the case of neutrons) the slower particles may have a larger cross-section to certain nuclei. Actually we would say that we were measuring the equivalent stopping cross-section of the nuclei. For example, the probability that an alpha particle striking a beryllium target will produce a neutron can be expressed as the equivalent cross-section of beryllium for this type of reaction. From the previous discussions we saw the long and short range forces and how they reacted with charged and uncharged particles. The cross-section of a nuclei also varies depending on the charge of the projected particle, i.e., the alpha particle has twice the positive charge of the proton while the neutron is neutral.

For all practical purposes in computing cross-section the impinging particles are taken as having a negligible diameter. The technical definition of cross-section for any nuclear reaction is therefore:

$$\frac{\text{number of processes occurring}}{\text{number of incident particles}} = (\text{number of target nuclei per cm}^2)(\text{nuclear cross-section in cm}^2)$$

this equation is for cross-section per nucleus. In many cases, the number of particles emitted or scattered in nuclear processes is not measured directly; one merely measures the attenuation produced in a parallel beam

of incident particles by the interposition of a known thickness of a particular material. The cross-section obtained in this way is called the total cross-section and is usually denoted by σ .

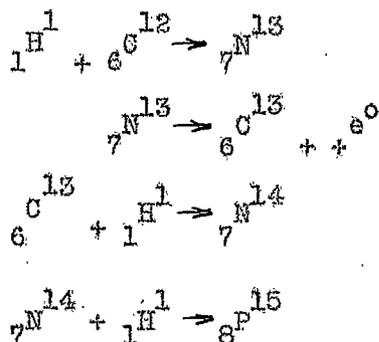
Previously the diameter of a nucleus was said to be in the neighborhood of 10^{-12} cm. We might therefore expect the cross-sections for nuclear reactions to be approximately 10^{-24} cm². For this reason the nuclear physicist has taken the area of 10^{-24} cm² equal to one barn (1 barn = 10^{-24} cm²/nucleus). For example, slow neutrons absorbed by the (n,) reaction the cross-section in some cases is as much as 1000×10^{-24} cm², while the cross-sections for transmutations by gamma-ray () absorption are in the neighborhood of $.001 \times 10^{-24}$ cm² (.001 barns).

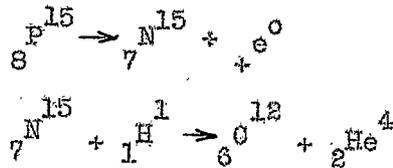
On the previous pages it was shown that a great amount of energy was released when lithium (${}^7_3\text{Li}$) is bombarded with protons. But the difficulties are in producing the highspeed protons and in controlling the energy produced. As the experiments we have been talking about have been done with very small quantities of materials, large enough in numbers of atoms, to be sure, but in terms of ordinary masses infinitesimal--not tons or pounds or grams, but fractions of micrograms. The amount of energy used up in the experiment was always far greater than the amount generated by the nuclear reaction. Compare this energy with common sources of power, chemical reactions (combustion of coal or oil), sunlight and waterpower. Combustion releases energy as the result of rearrangements of the outer electronic structures of the atoms. Combustion is always self-propagating; thus lighting a fire with a match releases enough heat to ignite the neighboring fuel, which releases more heat which ignites more

fuel, and so on; In the nuclear reactions that we have described this is not generally true; neither the energy released nor the new particles formed are sufficient to maintain the reaction. However nuclear energy for industrial and military purposes was publicized as early as 1930 by Prof. Arthur H. Compton, Nobel prize winner, in the Hearst newspapers. Soon after Compton's article the University of Chicago installed a huge atom smasher with all steel discs weighing over 164,000 pounds each, and containing more than four miles of copper wire placed between the discs to form a giant magnet. At Chicago, the gold nucleus was split, thus forming two other nuclei.

SOLAR ENERGY:

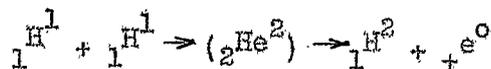
In 1940 Hans Bethe at Cornell University worked out a theory of the nuclear process that gives energy to the sun. Using the fact that astrophysical evidence shows the most abundant type of nucleus present in the stars (and sun) is the proton. There are two types of reactions that occur depending solely on the temperature. When the temperature is above about 15 million degrees, as it is in the sun, the following reaction takes place--four hydrogen atoms change into one helium with carbon as a catalyst.



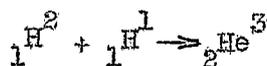


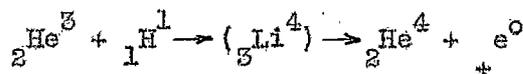
The ${}_6\text{C}^{12}$ atom, which acts as the catalyst reappears in the final products to be used again. Any ${}_6\text{C}^{12}$ atom that enters the reaction will emerge again as pure carbon only after about 5 million years. The two positrons (e^0) emitted will combine almost immediately with neighboring beta particles, and the masses of the particles completely disappears to form two gamma rays per positron reactions. The sun is converting its mass into energy at a rate of about 4 million tons per second. But the sun is so huge that it will require a billion and a half years for it to lose only 0.01% of its mass. In this process (solar) of changing protons to helium there is released only about one part in 125 of the mass of the proton. This mass reappears in the form of radiant heat. The earth being 95,000,000 miles away from the sun, intercepts only two parts in one billion of the sun's energy.

In the cooler stars, below 15 million degrees, a direct conversion of protons into helium appears to give the stars its energy. This is the reaction that occurs on the greater majority of stars. This reaction being the source of a star's light but very little energy beyond this reaches the earth and occurs as the following equation shows:



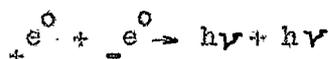
and is followed by two additional proton reactions to form a helium nuclei (alpha particle)





and again the positrons will be annihilated after coming into contact with two electrons forming two gamma rays.

This may be a good time to calculate the amount of energy released when a positron combines with an electron to form two gamma rays, written in equation form,



h being the energy in a gamma ray. The mass of the positron and electron is .00055 amu each and the gamma rays having zero mass their energy must be

$$M = 2 \times .00055 \text{ amu} = .0011 \text{ amu}$$

$$E = .0011 \times 931$$

$$= 1.0241 \text{ Mev (total energy in gamma rays)}$$

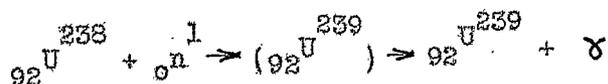
Going back to the equations of the reactions of the energy released by the sun we find an ideal situation for a continuous reaction. However, if this same train of reactions were performed in a laboratory here on earth we would find that the energy required to produce protons that would carry on such a reaction would be greater than the energy released. On the sun temperatures of up to 40 million degrees are reached being the reason for the reaction occurring. Therefore we are back where we started, without a reaction that is self-sustaining and will release large amounts of energy.

Thus far we have discussed several sources of nuclear energy none of which were suitable for a continuous source of nuclear power.

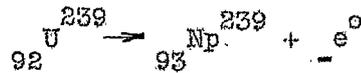
Figure 18 shows a graph of the packing fractions against mass numbers of all the isotopes. Noting on this curve that mass numbers from 1 - 20 and from 190 - 240 have packing fractions greater than zero and the mass numbers of from 20 - 190 have packing fractions of less than zero. This should indicate that if one of the heavier elements, above a mass number of 190, were split in half a great amount of energy would be released due to the maximum loss in mass. The problem now being the process used to split this atom. If protons, electrons or any charged particles were used for bombardment they must have a very great amount of energy to overcome the electrostatic forces of repulsion in such a large atom. The larger the atom the greater the number of protons and electrons which are the charged particles causing the electrostatic forces. Therefore the neutron seemed to be the answer because it is not affected by the electrostatic forces and may have very little energy (thermal neutrons) with a great amount of penetrating power. The neutron also seemed to be the answer because of the possibility of a chain reaction. This possibility was formulated because the heavier atoms have greater percentage of neutrons per proton than the atoms in the middle range. Therefore if one of the heavier nuclei (atoms) are split in half by means of neutron bombardment there should be an excess of neutrons in the product nuclei which may be emitted thus allowing a chain reaction. Suppose the ${}_{92}^{238}\text{U}$ nucleus is broken exactly in half; then, neglecting the mass of the incident neutron, we have two nuclei of atomic number 46 and mass number 119 (${}_{46}^{119}\text{Pd}$). But the heaviest stable isotope of palladium ($Z = 46$) has a mass number of only 110. Therefore to reach stability

each of these imaginary new nuclei must eject nine neutrons, becoming ${}_{46}^{100}\text{Pd}$ nuclei, or four neutrons in each nucleus must convert themselves to protons by emitting electrons thereby forming stable tin nuclei of mass number 119 and atomic number 50 (${}_{50}^{119}\text{Sn}$) or a combination of such ejections and conversions must occur to give some other pair of stable nuclei.

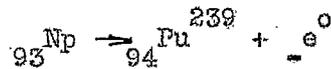
Fermi and his colleagues, in 1934, bombarded uranium with neutrons but their results were misinterpreted and proved puzzling. The puzzling part being the product nuclei formed emitted four beta rays of different half-life periods, while it is known that uranium is radioactive but emits an alpha particle. Careful chemical examination showed that one of the product nuclei has similar properties (chemical homologue) of manganese. Referring to the Periodic Chart of the atoms an element of atomic number 93 would be in the same column as manganese. Other chemical examinations showed that none of the nuclei in the range of atomic numbers from 86 - 92 could possibly be present. Chemical examinations of this nature are extremely difficult because of the micro study nature, i.e., only a minute amount available. However, it was not until 1940 after the works of Bohr, Frisch, Meitner, Hahn, Stassmann, Joliot and Fermi were known and discussed that the existence of transuranic elements were definitely established. The transuranic elements now known are of atomic numbers 93 - 96. ${}_{92}^{238}\text{U}$ was then bombarded by thermal neutrons and the following reactions are suggested:



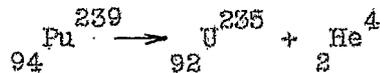
the product nuclei being an unstable isotope of uranium with a half-life of 23 minutes, with the following reaction occurring:



Np being one of the newly found transuranic elements of atomic number 93, which was named neptunium. This neptunium isotope is also unstable with a half-life of 2.2 days, with the following reaction occurring:

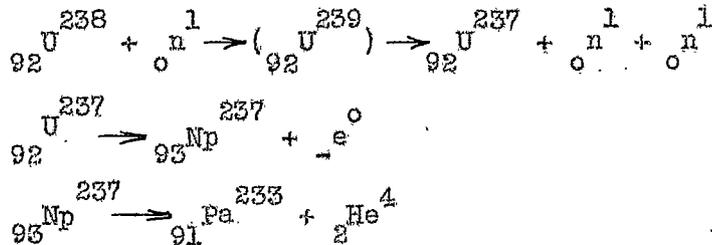


Pu is the transuranic element plutonium atomic number 94. This isotope is an alpha particle emitted with a half-life of 24,000 years

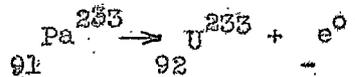


This series of reactions are not a source of nuclear power but plutonium will warrant mentioning later. The original thermal neutron has a resonance energy of 38 ev. Resonance energy being the energy of the bombarding particle for which a nucleus (${}_{92}^{238}\text{U}$) is exceptionally reactive.

Changing the energy of the incident neutron another isotope of neptunium was found, with the following reactions occurring:



the half-lives of the Np and Pa being 6.8 days and 2.25×10^6 years respectively. Then another beta emission occurs



With a half-life of 27.4 days:

In the above reactions it has been shown that two different reactions occur, depending entirely upon the energy of the incident neutron. A tabulation of the reaction that may occur when bombarding U²³⁸ with neutrons of any energy. The reactions will fall into several groups as shown in Table VI.

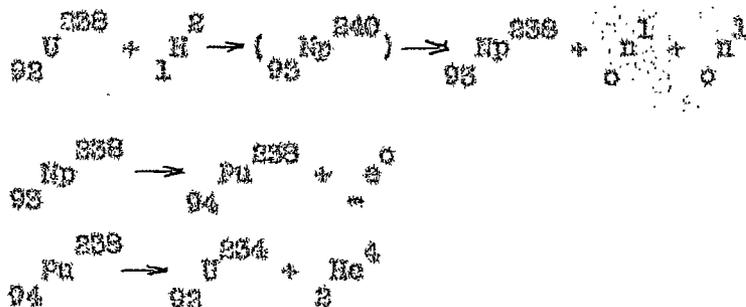
TABLE VI

Neutron Energy in ev	
Below .5	Low degree of absorption for Pu ²³⁹
0.5 - 50	High degree of absorption for Pu ²³⁹
50 - 100	Moderate absorption for Pu ²³⁹
100 - 1,000,000	Low absorption to yield Pu ²³⁹ or U ²³³
Over 1,000,000	Fissions

The fact that U²³⁸ fissions when bombarded by high energy neutrons is shown in Table VI, (Fission is the reaction where one nucleus is broken down into two lighter nuclei, sometimes referred to as atom smashing. This differs from previous discussed reactions where the result was a nucleus and a particle). The reason that this fission is not considered as a source of nuclear power is that the neutrons must be of very high energy.

In 1940 uranium was bombarded by deuterons in the laboratory of Seaborg, McMillan, Wahl and Kennedy which formed another isotope of

plutonium



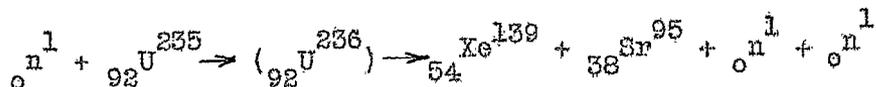
The ${}_{93}^{239}\text{Np}$ and ${}_{94}^{239}\text{Pu}$ having half-lives of 2.3 days and 50 years respectively. Note that the two plutonium isotopes formed have extremely long half-lives, Pu^{239} 24,000 years and Pu^{240} 60 years, which aided in their detection. The question may now occur why all this just to produce some plutonium, the answer is Pu^{239} fissions when bombarded by neutrons of any energy, being the ideal isotope as a source of nuclear energy. The next question being isn't there any natural supply of plutonium instead of forming these micro amounts. For our use of nuclear power or a nuclear bomb, greater amounts of plutonium will be needed. A natural source of uranium, pitchblende ore was examined as to a possible source of plutonium. But the amount of plutonium present was very minute and not a practical source. Therefore the only alternative was to produce plutonium on a production basis by means of nuclear reactions, which will be discussed in full later.

Observing the uranium atom we find three isotopes present U^{234} , U^{235} , U^{238} the relative abundance percent being 0.0051%, 0.719% and 99.274% respectively. We have already seen the reaction of U^{238} with neutrons but further study showed that U^{235} is fissionable when bombarded by neutrons of any energy similarly as Pu^{239} . The U^{234} isotope may be

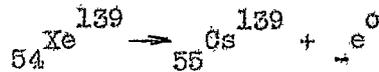
eliminated from this discussion because of its scarcity. Therefore we can consider the uranium atoms, as produced or found in nature, being 1 part ^{235}U isotope to 139 parts ^{238}U isotope. The remaining problem being to separate the two isotopes. In the case of chemical compounds (NaCl) there are several methods of separating the difference in their chemical behavior. But separating two isotopes of the same element, chemical means cannot be used because the isotopes are chemically identical. There is only one property that exists which is different, this being their masses. However, even their masses only differ slightly, a ratio of 235 to 238. This separation now being a problem for the physicists and engineers to solve. Prior to 1940 isotopes had been separated in laboratories by means of spectrographs but only several atoms of each isotope being produced. The discussion of isotope separation will be discussed in full later.

NUCLEAR FISSION OF ^{235}U :

In the previous paragraph it was mentioned that ^{235}U was fissionable with neutrons of any energy. But it was shown that ^{238}U reacted differently when bombarded by neutrons of different energies so does ^{235}U except that the only difference being the fission products (that is, fission always occurs but the nuclei formed and the number of neutrons, electrons, etc., emitted vary). Examining one of the possible fission reactions from ^{235}U using thermal neutrons of approximately .03 ev we found:



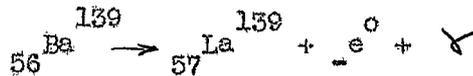
the xenon and strontium isotopes are unstable beta emitters with half-lives of 41 seconds and 2 minutes respectively. This above reaction splits into two branches, let us follow the xenon branch first.



this isotope of caesium is also unstable and emits a beta particle with a half-life of 7 minutes to produce a barium isotope.



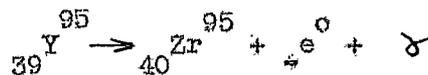
the half-life of the barium being 86 minutes



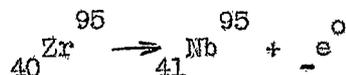
the lanthanum isotope being stable ending this branch. It may be noted that there is a series of isobars ${}_{54}^{139}\text{Xe}$, ${}_{55}^{139}\text{Cs}$, ${}_{56}^{139}\text{Ba}$ and ${}_{57}^{139}\text{La}$, that is, isotopes with the same mass number (139) but having different atomic numbers. Now second, let us follow the strontium branch



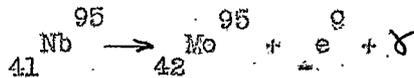
the half-life of yttrium being 11.5 hours to form



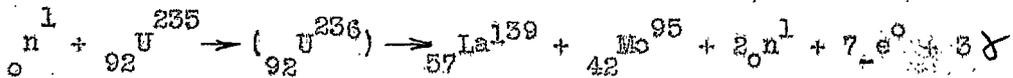
the half-life of the zirconium being 65 days



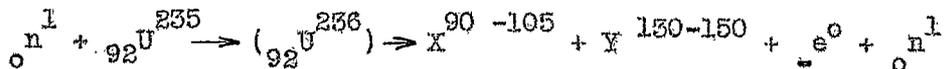
the columbium having isomers with two half-lives of 35 days and 90 hours the longer emitting a gamma ray



The complete reaction may be written



However, it must be remembered that this is only one of many of the fission reactions occurring when ${}_{92}^{235}\text{U}$ fissions from neutrons. A general equation may be written for all the possible reactions as follows:



This equation shows the two final product nuclei of fission as X and Y with mass numbers in the ranges of 90-115 and 130-150. (The average number of neutrons emitted during the fission of ${}_{92}^{235}\text{U}$ is 2.3 high energy neutrons). Which means then that the product nuclei will generally (always) be in these two ranges as shown in the graph on Figure 19. The graph of Figure 19 being fission yield (%) plotted against mass numbers (A). The most important characteristics of the yield-mass are, the definition of the fission nuclei into these two pronounced groups (heavy and light). Over 19% of the fissions fall in the mass range of 85-105 and 129-151. The most probable masses are 95 and 139 being the situation used in the proceeding example. No satisfactory theoretical explanations for this asymmetric nature of the fission process has yet to be offered.

Example No. 4

U^{235} has a packing fraction of 5.4×10^{-4} amu. Upon fission, one set of the products is thought to consist of Ba^{138} and ^{36}Kr with an emission of 13 neutrons.

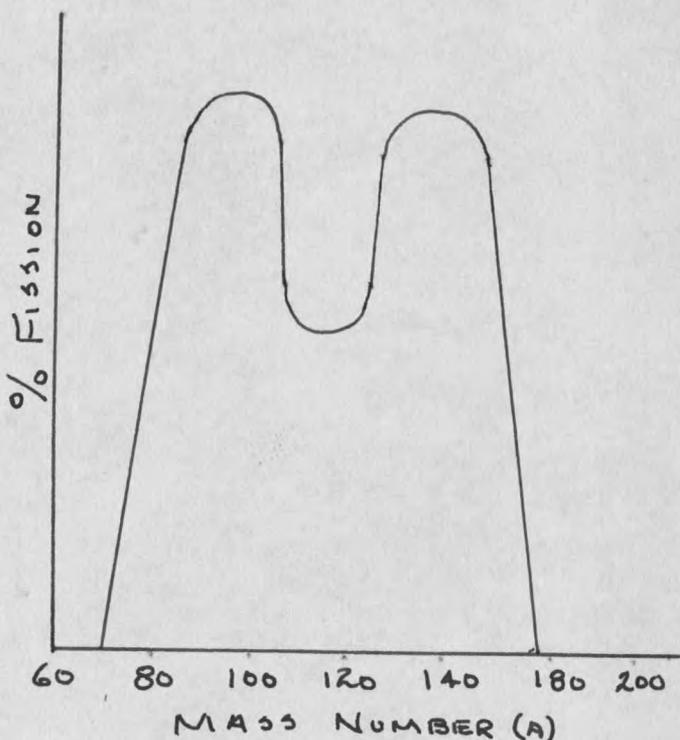
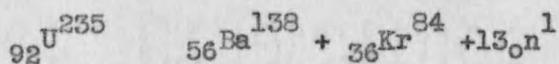


Figure 19 Percent Fission Products from U^{235}

a) Write the equation for this reaction neglecting the incident neutron.



b) Find the atomic weight of U^{235}

$$P = \frac{M - A}{A} = \frac{M - 235}{235} = 5.4 \times 10^{-4}$$

$$M - 235 = 0.1269$$

$$M = 235.1269$$

c) The Ba has an atomic weight of 137.9162 amu while Kr has packing fraction of -8.56×10^{-4} amu. Find the amount of mass that disappears in each fission process.

$$\frac{M - 84}{84} = 8.56 \times 10^{-4}$$

$$M = 83.9281 \text{ amu (for Kr)}$$

$$235.1269 = 137.9162 + 83.9281 + 13(1.00895) + Q$$

$$Q = .166534 \text{ amu}$$

- d) Find the energy in Kw-hr for one pound of U^{235} to completely fission in the above process.

$$\text{Kw-hr} = \frac{453.6 \times .1665 \times 4.15 \times 10^{-17}}{235.1269 \times 1.66 \times 10^{-24}} = 8.04 \times 10^6 \text{ Kw-hr}$$

To clarify the last equation it may be best to use dimensional analysis.

$$\text{Kw-hr} = \frac{\text{gms/lb} \times \text{amu/atom} \times \text{Kw-hr/amu}}{\text{amu/atom} \times \text{gms/amu}}$$

The above example showed a mass deficit of .166534 amu which may be converted to Mev per atom

$$.166534 \times .931 = 157 \text{ Mev/atom}$$

this value of 157 Mev is rather low; the average energy released per atom during fission of U^{235} is approximately 200 Mev.

By 1940 the following information on fission was known internationally (most of the following has been previously mentioned):

- a) Uranium, thorium and protactinium when bombarded by neutrons sometimes split into approximately equal fragments, and that these fragments were isotopes of elements in the middle of the periodic table, ranging from selenium to lanthanum.
- b) Most of these fissions fragments were unstable, decaying radioactively by successive emission of beta particles through a series of elements to various stable forms.
- c) These fission fragments have very great kinetic energy.
- d) That fission of thorium and protactinium was caused by high energy

neutrons.

- e) Fission in uranium could be produced by fast or slow (the energy of a particle varies as the square of the velocity) neutrons: specifically, that thermal neutrons caused fission in one isotope, U^{235} , and that fast neutrons had a lower probability of causing fission in U^{235} than thermal neutrons.
- f) At certain neutron speeds there was a large capture cross-section in U^{238} producing U^{239} but not fission.
- g) The energy released per fission of a U^{235} nucleus was approximately 200 Kev.
- h) High speed neutrons were emitted in the process of fission.
- i) The average number of neutrons released per fission was somewhere between one and three.
- j) That high-speed neutrons could lose energy by inelastic collision with uranium nuclei without any nuclear reaction taking place.

During the years 1939-40 the above-mentioned studies were made in the field of nuclear physics and published in numerous technical journals and then all of the investigations became secret for security reasons until after the first atomic bomb was dropped on Japan. Soon after this the United States published the Smyth Report officially called "A General Account of the Development of Method of Using Atomic Energy for Military Purposes Under the Auspices of the United States Government", August 1945. This document was written by Professor H. D. Smyth at the request of Major General L. R. Groves, United States Army.

We have now found a nuclear process where the ejected particles are the same as the incident particles. By bombarding U^{235} with thermal neutrons fission occurs forming two new nuclei and an average of 2.3 high energy neutrons. Thus we have a process capable of causing a chain reaction and there is a vast amount of energy emitted per fission process. Now let us examine the process, if one neutron causes a fission that produces more than one new neutron, the number of fissions may increase tremendously with the release of enormous amounts of energy, however, this is a question of probabilities. But neutrons produced in the fission process may escape entirely from the uranium, may be captured by uranium in a process not resulting in fission, or may be captured by impurities. Thus the question of whether a chain reaction does or does not occur depends on the result of a competition among the following processes:

- a) Escape
- b) Non-fission capture by uranium
- c) Non-fission capture by impurities
- d) Fission capture

It was previously mentioned that all we needed in order to maintain a chain reaction was, if more neutrons were created by fission than were absorbed. Evidently this was an over-simplification because as listed above there are four possible processes that the created neutrons may cause. The fourth process being the one that will produce power and maintain a chain reaction. If the loss of the neutrons by the first three processes is less than the surplus produced by the fourth, the chain reaction occurs; otherwise it does not. Evidently any one of the first three processes may

have such a high probability in a given arrangement that the extra neutrons created by fission will be insufficient to keep the reaction going. For example, should it turn out that non-fission capture by uranium has a much higher probability than fission capture, there would presumably be no possibility of achieving a chain reaction. The problem now being the limitations imposed by the first three processes and how their effects can be minimized. This is generally referred to as having a factor-k greater than one, i.e., factor-k being the ratio of the number of reoccurring fission neutrons to the number of incident neutrons. It is quite apparent that factor-k must be equal to or greater than one in order to have a self-sustaining chain reaction.

NEUTRON ESCAPE:

First, let us study means of reducing the number of neutrons that escape. This may be achieved by changing the size and shape of the uranium (this discussion will be for fission using uranium). This change should be so as to get the greatest volume with the smallest surface area, therefore a sphere seems to be the likely choice. In a sphere any surface effect is proportional to the square of the radius, any volume effect is proportional to the cube of the radius. The escape of neutrons from a quantity of uranium is a surface effect depending on the area of the surface, but fission capture occurs throughout the material and is therefore a volume effect. Consequently the greater the amount of uranium, the less probable it is that neutron escape will predominate over fission capture and prevent a chain reaction. Fission capture and neutron production is a volume effect and will increase at a greater rate than neutron escape.

Therefore, there must be a sphere of uranium with a certain radius where factor-k is equal to one. A smaller radius will not sustain a chain reaction while the greater the radius the greater the factor-k value. A sphere of uranium of this radius is said to be of critical size.

Critical size is defined as the size for which the production of free neutrons by fission is just equal to their loss by escape and non-fission capture. In 1940 calculations of the critical mass were made but varied considerably because of several estimates needed to complete their calculations. The results actually varied from 1 to 100 kilograms. Because of this variation, it seemed not improbable that the critical size might be too large for practical purposes. The question may now arise that the atomic bomb must be greater than critical size but what keeps it stable and safe to handle. The answer is comparatively simple being that the bomb is made in two parts, both being less than the critical size, but when placed together we have the bomb with a greater than critical size.

NON-FISSION CAPTURE BY URANIUM

Uranium, as found in nature, is composed of three isotopes ^{234}U , ^{235}U and ^{238}U with an abundance of 0.00518%, 0.719% and 99.274% respectively. The ^{234}U isotope present is in such small amounts that it may be eliminated from this discussion. ^{235}U undergoes fission with neutrons of any energy but its cross-section for neutrons varies inversely as the energy of the incident neutron. Thermal neutrons being the most accepted by ^{235}U to produce fission. ^{238}U on the other hand fissions only with neutrons of high energy. But the probability (cross-section) of fission with ^{235}U and thermal neutrons is much greater than

fission with U^{238} and fast neutrons. Thus far in this paragraph every statement seemed to be irradiated by the following statement making a chain reaction approach an impossibility. One more complication exists because the neutrons produced by fission are of very high energies. Also the energy at which non-fission is most probable is intermediate between the average energy of neutrons produced during fission and the energy at which fission capture is most probable.

One method of decreasing non-fission reactions is to decrease the energy of the neutrons produced before they come into contact with uranium nucleus. For some years before the discovery of fission, the customary way of slowing down neutrons was to cause them to pass through material of low atomic weight, such as hydrogenous material (similarly to the experiment of Chadwick during the discovery of the neutron). The process of slowing down or moderation is simply one of elastic collisions between high-speed particles and particles at rest. The more nearly identical the masses of neutron and struck particle the greater the loss of kinetic energy by the neutron.

Mixing uranium with a moderator in such a way that the high-speed fission neutrons, after being ejected from uranium and before re-encountering uranium nuclei, would have their speeds reduced below the speeds for which non-fission capture, is highly probable. The characteristics of a good moderator are that it should be of low atomic weight and that it should have little or no tendency to absorb neutrons. This would exclude lithium and boron because they have a large cross-section for neutrons. Helium is difficult to use because it is a gas and forms no

compounds. The choice of moderator therefore was between hydrogen, deuterium and beryllium until Fermi and Szilard proposed the use of graphite (carbon). All of these possibilities were carefully studied by the government in their atomic research laboratories and will be mentioned again under, Reactor Design. A specific manner of using a moderator was to use lumps of uranium of considerable size imbedded in a matrix of moderator material. Such a lattice (arrangement) can be shown to have real advantages over a homogeneous mixture. As the constants were more accurately determined, it became possible to calculate theoretically the type of lattice that would be most effective.

It has been previously stated that neutrons of certain intermediate speeds, U^{238} have a large capture cross-section for the production of U^{239} (and then Np and Pu) but not for fission. There is also a considerable probability of inelastic (non-capture producing) collisions between high-speed neutrons and U^{238} nuclei. Thus the presence of the U^{238} tends both to reduce the speed of the fast neutrons and to effect the capture of those of moderate speed. Although there may be some non-fission capture by U^{235} , it is evident that if we can separate the U^{235} from the U^{238} and discard the U^{238} , we can reduce non-fission capture and can thus promote the chain reaction. This separation brings about two problems both of which have been previously mentioned: first, that U^{235} and U^{238} are chemically identical which means that they cannot be separated by chemical reactions, their only difference being their masses which are in ratio of 235 to 238; and second, that U^{235} is only present in uranium of 1 part of U^{235} to 140 parts of U^{238} . Isotopes had been

separated in the past but only in micro amounts with laboratory equipment.

But mass production techniques must be used to satisfy the demand for

²³⁵U to be used in atomic bomb and nuclear power research (to be discussed later).

NON-FISSION CAPTURE BY IMPURITIES:

A typical analysis of commercial low carbon iron (ingot iron) made by the open-hearth process is about as follows:

Silicon	0.005%
Manganese	0.02
Carbon	0.02
Phosphorus	0.005
Sulfur	0.025

In our case we want to refine uranium and more difficulties will arise than in the process of refining iron. In the case of iron (steel) refinement small amounts of impurities have negligible effect on the physical properties of the final product. But the use of uranium as an agent of fission the metal must be chemically pure. If any atoms of foreign elements do exist they may have a cross-section for neutrons much greater than compared to the maximum fission cross-section of uranium. Calculations show that the maximum permissible concentrations of many impurity elements are a few parts per million--in either the uranium or the moderator. When it is recalled that up to 1940 the total amount of uranium metal produced in the country was not more than a few grams (and even this was of doubtful purity), that the total amount of metallic beryllium produced in this country was not more than a few pounds, that the total

amount of concentrated deuterium produced was not more than a few pounds, and that carbon had never been produced in quantity with anything like the purity required of a moderator. It must be kept in mind that when a moderator is used it must be of the purity as the uranium because any impurities may absorb the neutrons instead of a slowing down action by means of elastic collision.

A brief summary of the above would be that uranium (U^{235}) spheres placed in a definite lattice arrangement surrounded by a moderating material, the uranium would consist of only atoms of the U^{235} isotope and the moderator to be chemically pure. The use of small amounts of separated U^{235} in a lattice composed primarily of ordinary uranium or uranium oxide and of a moderator or two different moderators is usually referred to as "enriched piles". A uranium pile may be defined as a device using uranium to promote a controlled chain reaction (the name reactor has replaced the name pile).

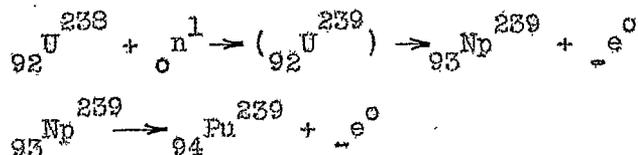
Thus far our discussion has been trying to develop a chain reaction but now the problem of control arises. The problem of control is different depending on whether we are interested in the steady production of power or in an explosion. To control a uranium pile for nuclear power use is just the opposite as the creation of a chain reaction, i.e., the factor-k is to be decreased in order to keep the fission reaction from getting out of hand. Probably the easiest method of control is to use a material with a very high cross-section for neutrons. This material could be entered or withdrawn from the reactor thus controlling the value of factor-k. Boron or cadmium rods are generally used for control and will

be discussed in more detail in Reactor Design.

Another limiting factor in controlling a chain reaction in a reactor is that fission-producing capture varies indirectly as the temperature of the reactor. This will tend toward self limitations because some of the nuclear energy liberated will be in the form of heat that will reduce the probability of further reactions. However, this limitation will not be enough to keep the reaction under control.

PLUTONIUM:

Another isotope that may replace the U^{235} in fission is the plutonium isotope found when U^{238} absorbs a neutron to form U^{239} .



Pu^{239} will fission with neutrons of any energy similarly to U^{235} . Plutonium cannot be found in nature to any amount and must be manufactured. The manufacture of Pu^{239} may be produced by the reactions shown in the above equations. If pure uranium, consisting of both isotopes U^{235} and U^{238} , is used in a reactor, neutrons will fission with the U^{235} nuclei and some of the U^{238} nuclei but the remains of the U^{238} will form Pu^{239} . Pu^{239} may be separated from the U^{235} , U^{238} and Np^{239} by chemical means. This separation may be easier than the separation of U^{235} from U^{238} , however during the progress of the atomic bomb project during the war, methods were devised to separate U^{235} on a mass production scale thus providing its use.

DETECTORS AND ISOTOPE SEPARATION

In the preceding pages the discussion of bombarding nuclei with high energy particles was mentioned, but the source or the production of these particles was eliminated. Also the separation of isotopes was mentioned but never a method of separation was discussed. Now we will discuss more fully all of this material, but before mentioning how a cyclotron operates or any such equipment it may be best to review some of the basic physics involved. In our discussion we will not derive basic physics equations but will discuss their use and work out examples. Some of the symbols used are as follows:

V - Potential difference (volts, abvolts)

F - force (dynes)

E - energy (ergs)

m - mass

e - charge (generally charge on an electron)

a - acceleration

t - time (sec)

v - velocity cm/sec.

H - magnetic field strength (in oersteds)

A previous discussion included the use of equations

$$E = Ve \quad (2)$$

$$E = h\nu \quad (3)$$

$$E = \frac{1}{2} mv^2 \quad (5)$$

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (6)$$

The force in dynes on an electron in an electrostatic field may be calculated by -

$$F = \frac{V}{d} e \quad (16)$$

where V is the potential difference in statvolts, d the distance between the charged plates in cm, and e the charge on an electron in statcoulombs.

The behavior of an electron in an electromagnetic field will be governed by the following two equations:

$$R = Hev \quad (17)$$

H being the magnetic field strength in oersteds, e the electronic charge in abcoulombs, and v the velocity of the electron in cm/sec.

$$F = \frac{mv^2}{R} \quad (18)$$

where m is the mass of the electron in grams, v its velocity and R the radius of the path followed by the particle in the magnetic field.

Example 1, illustrated the use of equations 2, 3 and 5 by means of an X-ray tube. For this next example we will use a cathode ray tube (Figure 20) which will cause the use of practically all of the above equations. Using an electrostatic field for accelerating the electrons and both electrostatic and electromagnetic field for deflection. Before starting there are three basic mechanics equations that must be reviewed first, that force is equal to mass times acceleration

$$F = ma \quad (19)$$

second that displacement during linear acceleration is equal to one half the product of acceleration and time squared.

$$s = \frac{1}{2}at^2 \quad (20)$$

and third that linear (or average) velocity is equal to displacement divided by time

$$v = \frac{s}{t} \quad (21)$$

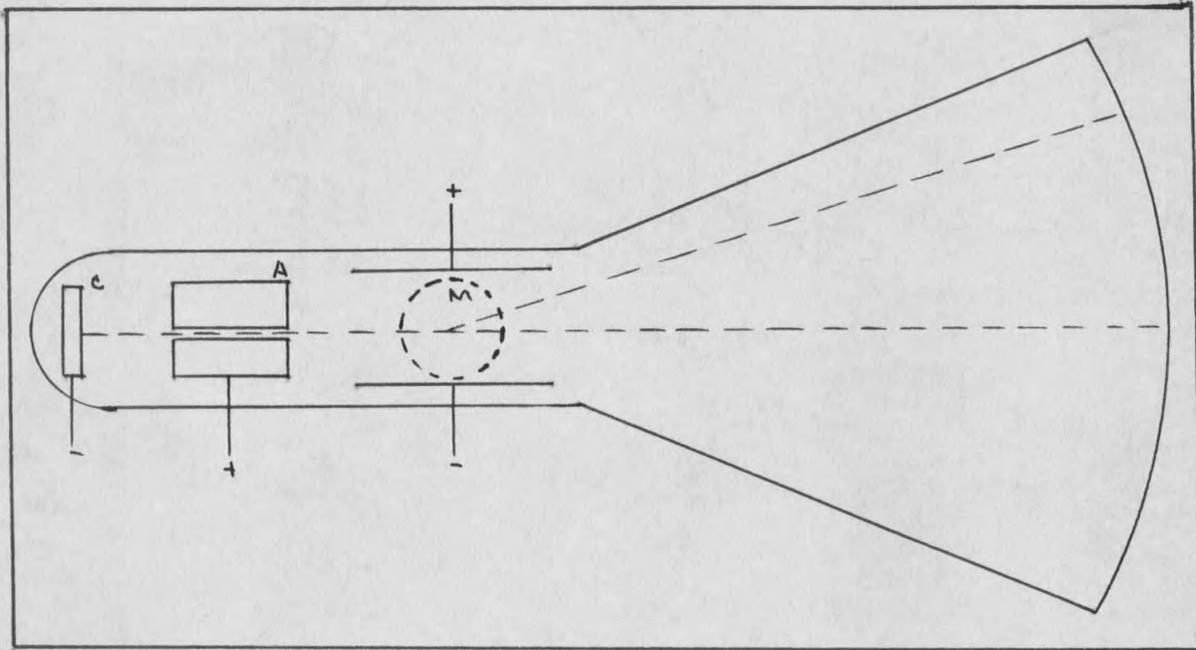


Figure 20 Cathode ray tube with electrostatic and electromagnetic deflection

taking equations (16) and (19)

$$F = \frac{Ve}{d} \quad (16)$$

$$F = ma \quad (19)$$

or
$$ma = \frac{Ve}{d}$$

the V being the difference in potential between the two deflection plates. The amount of deflection of the electron beam between the plates will be represented by equation (20).

$$s = \frac{1}{2}at^2 \quad (20)$$

the velocity parallel to the deflection plates

$$v = \frac{L}{t} \text{ or } t = \frac{L}{v}$$

where L is the length of the plates and v the velocity of the electrons in cm/sec. Then substituting this value of t into equation (20)

$$s = \frac{1}{2}a \frac{L^2}{v^2} \quad (20a)$$

solving for a in the above equation and equating it to the value of a, from the equation formed by (16) and (19)

$$a = \frac{Ve}{dm} = \frac{2sv^2}{L^2}$$

by applying an electromagnetic field around the deflection plates with a strength of H oersteds reacting against the deflection caused by the potential on the plates so that the electron beam will be centered or

$$F = \frac{V}{d} e \quad (16) \quad (\text{electrostatic})$$

$$F = Hev \quad (17) \quad (\text{electromagnetic})$$

or

$$\frac{Ve}{d} = Hev$$

$$v = \frac{V}{dH} \quad (22)$$

taking equations (17), (19) and (20a) and solving for a

$$a = \frac{2sv^2}{L^2} = \frac{Hev}{m} \quad (23)$$

substituting the value of v from equation (22)

$$\frac{e}{m} = \frac{2sV}{dH^2 L^2} \quad (23a)$$

Equation (23a) shows the value of the ratio of the charge on an electron to its mass, this was a method used in determining the mass of an electron.

In the case of a cathode ray tube (Figure 20) using only electromagnetic means of deflection, the calculation of e/m under these conditions would be with the use of equation (23)

$$\frac{e}{m} = \frac{2sv}{HL^2} \quad (23)$$

All the terms in the right hand side of this equation may be measured with the exception of the velocity (v) which must be calculated. In calculating this velocity the use of equations (2) and (5) is required -

$$E = Ve \quad (2)$$

$$E = \frac{1}{2}mv^2 \quad (5)$$

or
$$Ve = \frac{1}{2}mv^2$$

where V is the difference in potential between the cathode and the anode.

$$v^2 = \frac{2Ve}{m}$$

substituting this into equation (23)

$$\frac{e}{m} = \frac{2s \sqrt{\frac{2Ve}{m}}}{HL^2}$$

$$\frac{e}{m} = \frac{8s^2 V}{H^2 L^4}$$

when using this equation a conversion must be made because equation (23) has the units of emu/gm while equations (2) and (5) are in esu units. For this conversion refer to the tables in The Introduction.

The value of s in the preceding equations has been the displacement of the electron beam at the end of the electrostatic or electromagnetic fields. After leaving these forces the electron path will follow a straight line and by means of similar triangles the value of s may be calculated from the position of the electrons as they strike the fluorescent screen.

$$\frac{S}{x} = \frac{s}{L/2}$$

or
$$s = \frac{SL}{2x}$$

where x is the distance from the center of the deflection plates to the fluorescent screen and S the distance between the position of electrons on the screen and their position

when there is no deflection force applied as shown in Figure 21.

When studying the path of a charged particle in an electromagnetic it is found that equation (18) shows the value of the force acting with respect to its mass, velocity and radius of curvature.

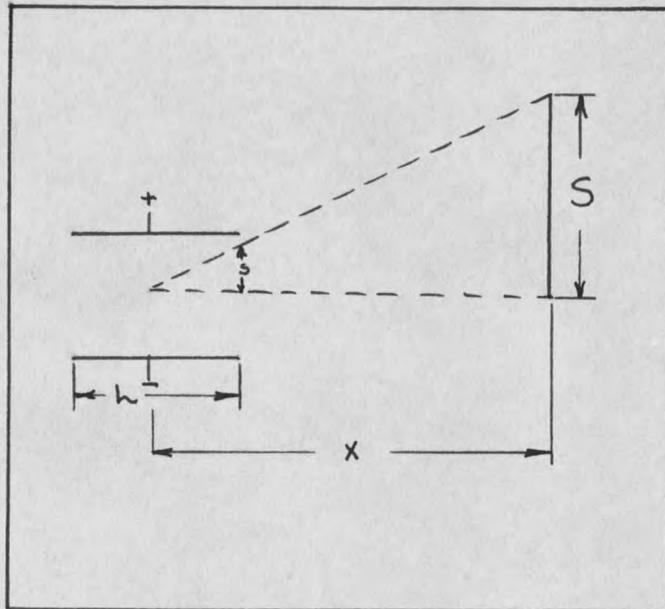


Figure 21 Use of similar triangles to determine the deflection in a Cathode Ray Tube

$$F = \frac{mv^2}{R} \quad (18)$$

this force may also be calculated by means of equation (17).

$$F = Hev \quad (17)$$

Example No. 5. An alpha particle with a velocity of 1.5×10^9 cm/sec. enters an electromagnetic field of 35,000 oersteds. Find the radius of curvature of the alpha particle if its charge to mass ratio is 4820 emu/gm. Taking equations (17) and (18) and equating

$$\begin{aligned} Hev &= \frac{mv^2}{R} \\ R &= \frac{v}{H(e/m)} \\ &= \frac{1.5 \times 10^9}{35,000 \times 4820} \\ R &= 8.9 \text{ cm} \end{aligned}$$

Figure 22 illustrates Example No. 5, and it should be noted in this example that the radius of curvature varies directly as the mass of the particle. This is the basis for the electromagnetic separation of isotopes.

With the background previously

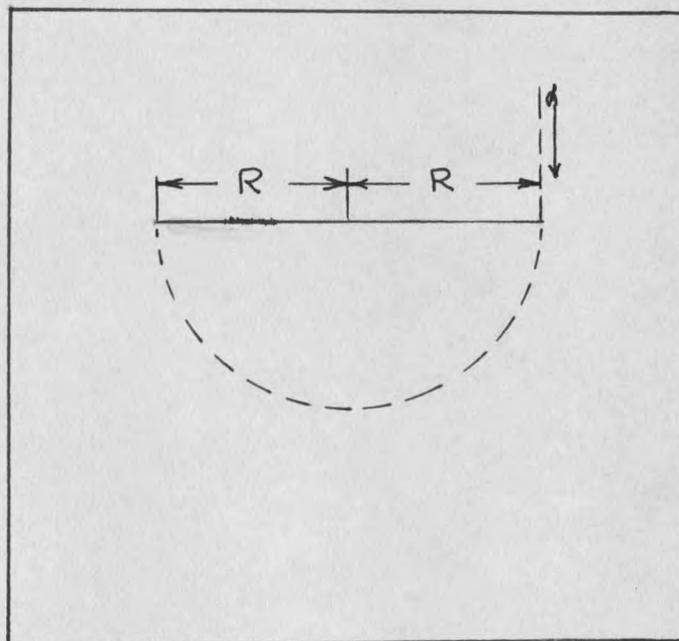


Figure 22 Path of a charged particle in a magnetic field

presented, we may now better understand the principle of operation of the "Tools of the Nuclear Physicist." Our next discussion will include various types of mass spectrographs and their relationship to the separation of isotopes.

MASS SPECTROGRAPHS:

The types of mass spectrographs most commonly used are named after their founders being Aston's, Dempster's, Bainbridge's and the Bainbridge and Jordan's mass spectrograph. The basic principle of operation is with the use of an electromagnetic field, electrostatic field or a combination of both fields. Using equations (17) and (18) and equating

$$Hev = \frac{mv^2}{R}$$

$$R = \frac{mv}{He}$$

showing that the radius of curvature of a charged particle, in an electromagnetic field, varies directly with the mass of the particle. Therefore, if a metallic gas was ionized and the positive ion (nuclei) were accelerated to a velocity (v) and then through an electromagnetic field the different isotopes will focus at different positions because of their mass difference.

In the case of the Aston mass spectrograph, positively charged ions of any substance pass through electric and magnetic fields to deflect them similarly as in the cathode ray tube previously discussed. As shown in Figure 23, positive ions enter from a discharge tube through the slits S_1 and S_2 . The ions after passing through S_2 will not all have the

same velocity and those with higher velocity will be deflected less than the slower ions as they pass between the two charged plates P_1 and P_2 .

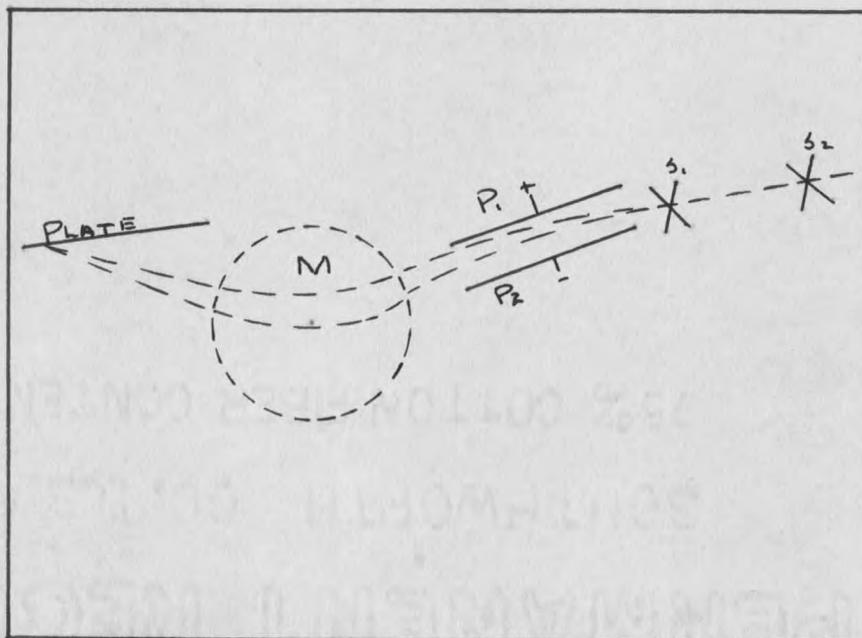


Figure 23 Schematic of the Aston Mass Spectrograph showing the path of the electrons

The ions next pass through a magnetic field which deflects them in the opposite direction of the electric field. The field intensities are adjusted so that no matter what velocity the ions had, they will converge on a common focus on the photographic plate. All of the ions of the same mass and charge (e/m) will converge at one point while ions of another mass will converge at another point. Therefore, if only atoms of one element are ionized in the discharge tube, uranium for instance, and then pass through the mass spectrograph, we find, upon observation, the photographic plate with three lines caused by the three isotopes in natural uranium U^{234} , U^{235} and U^{238} . One of these lines would be more

intense than the others, this line being formed by the more abundant isotope U^{238} . The exact mass of the isotope may be calculated by means of the previously discussed equations. The voltages and magnetic field intensities must be known and the distances measured very accurately.

The Dempster mass spectrograph uses magnetic deflection only, but to have all of the same isotopes converge at one point they must have the same velocity upon entering the magnetic field. By means of a difference in potential between S_1 and S_2 (Figure 24) all the particles of identical mass and

charge will have the same velocity as they enter S_2 from equations (2) and (5).

$$E = Ve \quad (2)$$

$$E = \frac{1}{2}mv^2 \quad (5)$$

$$v^2 = \frac{2Ve}{m}$$

After passing through S_2 the particles will enter a magnetic field and be deflected

with a radius of R and through 180° to S_3 . The distance between S_2 and S_3 will depend upon the energy at S_2 , the mass of the particle, and the strength of the magnetic field. If at S_1 only nuclei of one element enter and the magnetic field strength held constant, then the point where

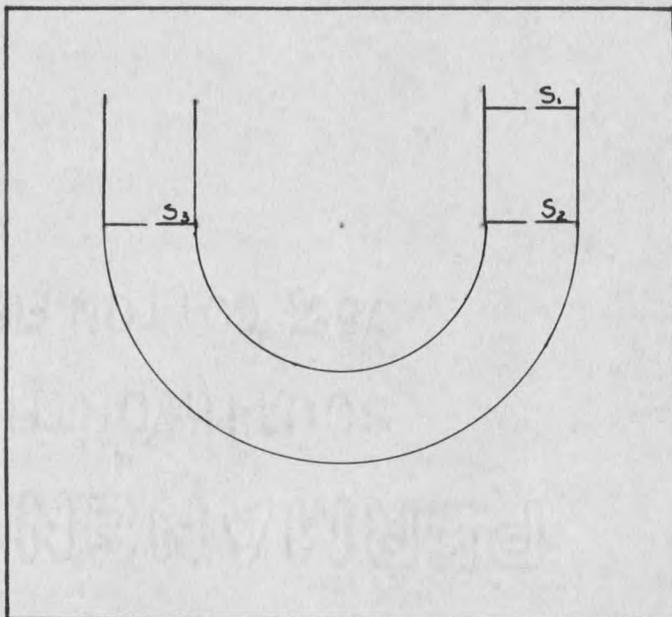


Figure 24 The Dempster Mass Spectrograph with energy selector

the nuclei converge (at S_2) will be at several points due to the difference in mass of the isotopes of an element. Also any slight divergent at S_2 will be compensated for as the particles travel through the 180° .

Bainbridge designed a mass spectrograph where he uses a velocity selector before the particles enter a magnetic field. This velocity selector consists of two plates, with a difference in potential of V volts, parallel to the path of the particles, and a magnetic field. The velocity of particles leaving the selector are governed by equations (16) and (17).

$$F = \frac{Ve}{d} \quad (16)$$

$$F = Hev \quad (17)$$

$$\frac{Ve}{d} = Hev$$

$$v = \frac{V}{dH}$$

The particles are then deflected by a magnetic field in the same manner as in the Dempster mass spectrograph.

There are several other types of mass spectrographs but their basic principles are similar to those previously discussed. Our main purpose in studying mass spectrographs is as a source of separating isotopes. The use of spectrographs has been used in laboratories, to separate isotopes but the amount separated was minute and if pure U^{235} was to be used as a nuclear fuel greater amounts would be needed. On a commercial scale this electromagnetic method of separation requires large amounts of electric power and complex electrical and mechanical control equipment. The electromagnetic plant at Oak Ridge, Tennessee, consists

of 175 buildings which cost 317 million dollars. The electromagnets were wound with more than 14,000 tons of pure silver, worth about 400 million dollars. One advantage of the electromagnetic process is that it can be carried out in individual units independent of one another and widely scattered throughout the country.

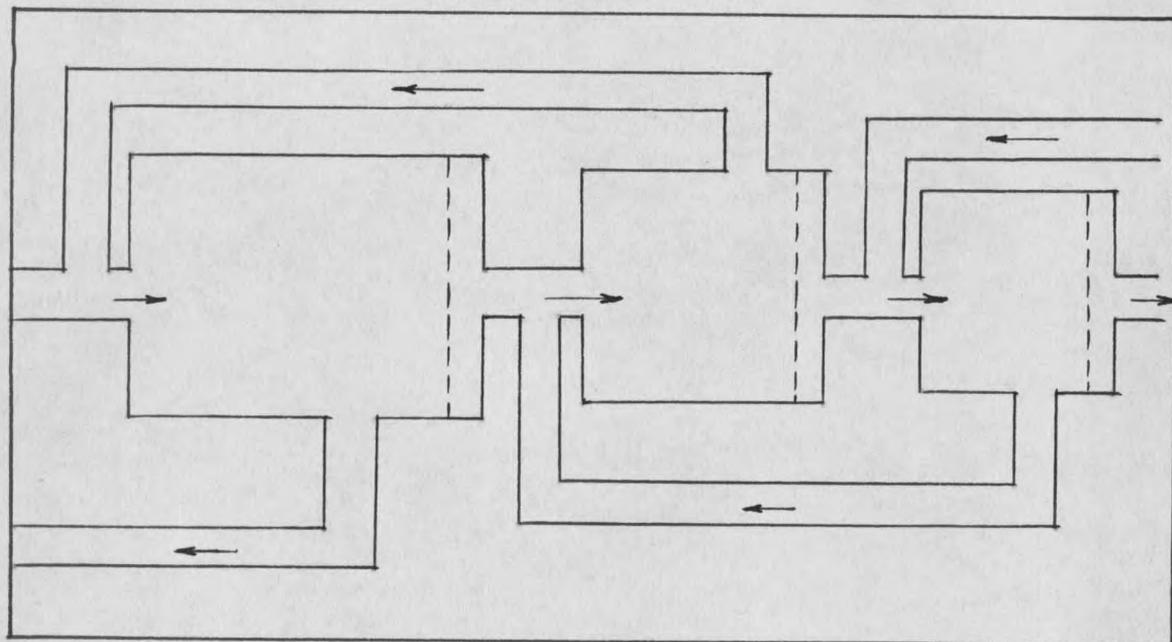


Figure 25 Schematic of Gaseous Diffusion plant showing three of the possible 5000 stages.

GASEOUS DIFFUSION:

In any method of isotope separation the only factor available is the mass difference. A process that takes advantage of the fact that a gas composed of lighter weight molecules diffuses through a porous barrier faster than one composed of heavier molecules is known as the Gaseous Diffusion Method. The gas used is uranium hexafluoride, UF_6 , which is fed into a long cascade made up of individual barrier stages (Figure 25).

After each stage the gas is slightly richer in U^{235} and the remainder is circulated back and fed into a previous stage where further refinement takes place. The gas from the final stage is then changed to uranium or a uranium compound by chemical means.

By 1941 the gaseous diffusion method had been demonstrated in principle, that is, a single stage separator had effected the enrichment of the U^{235} on a laboratory scale, to about the degree predicted theoretically. From this it was possible to estimate that about 5000 stages would be necessary for a diffusion system and that a total area of many acres would be required in a plant separating a kilogram of U^{235} each day. A gaseous diffusion plant was constructed at Oak Ridge and is equivalent to a building $\frac{1}{8}$ mile long, $\frac{1}{4}$ mile wide and 4 stories high (Figure 26). It requires a power plant supplying nearly a quarter million kilowatts of power and steam. The whole installation cost about 500 million dollars. The main engineering problems from a construction standpoint are: that uranium hexafluoride is one of the most corrosive of chemicals; the plant is of necessity a huge sprawling affair and cannot be broken up into smaller independent units; the construction of a barrier with no holes which are appreciably larger than 0.01 micron (4×10^{-7} inch) and must have billions of holes this size or smaller; the use of pumps that will not leak or cause any chemical or radioactive reactions.

THERMAL DIFFUSION:

The thermal diffusion method is sometimes used to enrich the U^{235} content of compounds and then fed into other separation plants.

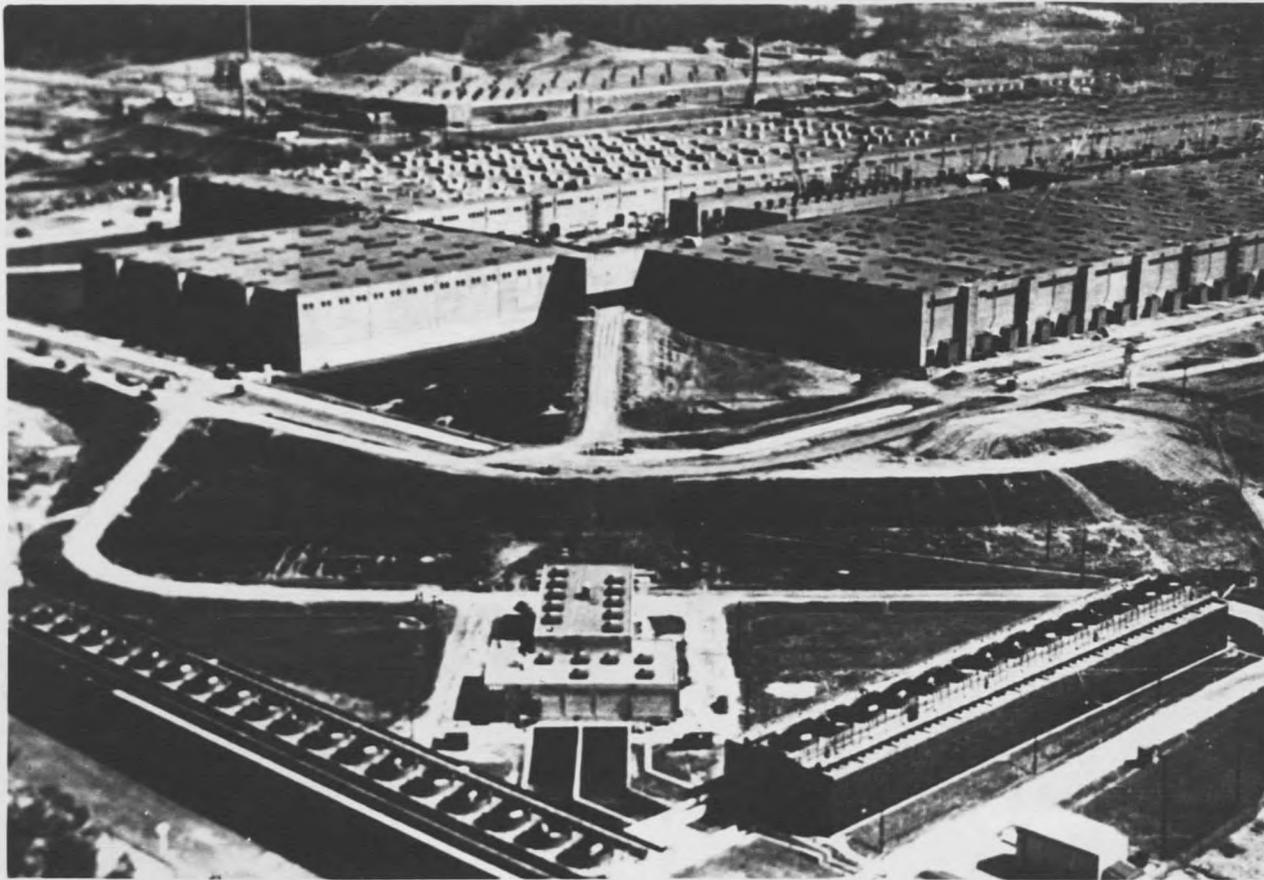


Figure 26 Aerial view of the isotope separation plant at the Clinton Engineer Works at Oak Ridge, Tenn. 1945

The possibility of accomplishing practical separation of isotopes by thermal diffusion was first suggested by theoretical studies of the details of molecular collisions and of the forces between molecules. Such studies made by Enskog and by Chapman before 1920 suggested that if there were a temperature gradient in a mixed gas there would be a tendency for one type of molecule to concentrate in the cold region and the other in the hot region. This tendency depends not only on the molecular weights but also on the forces between the molecules. If the gas is a mixture of two isotopes, the heavier isotope may accumulate at the hot region, or the cold region, or not at all, depending on the nature of the intermolecular forces. In fact, the direction of separation may reverse as the temperature or relative concentration is changed.

The separation of isotopes by this thermal diffusion was first used by H. Clusius and G. Dickel in Germany in 1938. They built a vertical tube containing a heated wire stretched along the axis of the tube and producing a temperature difference, of about 600°C , between the axis and the periphery. The heavy isotopes (in the substances they studied) became concentrated near the cool outer wall and then this cool gas on the outside tended to sink while the hot gas at the axis tended to rise.

Adapting this principle for the separation of U^{235} the fluid, uranium hexafluoride (UF_6) is introduced into the tube. The U^{235} component tends to collect at the top of the tube. A thermal diffusion plant was built during the war and its output, enriched in U^{235} , was fed

to other separation plants for final separation.

CENTRIFUGE METHOD:

When subjected to gravitational forces isotopes may be separated because the gravitational forces tending to move the molecules downward are proportional to the molecular weights ($F = mg$), and the intermolecular forces tending to resist the downward motion depend on the electronic configuration, not on molecular weights. In the centrifuge method of isotope separation, a gaseous mixture of the isotopes is placed in a tall, cylindrical, high-speed centrifuge. This type of centrifuge was first developed by J. W. Besms and then H. G. Vrey and proved successful where previous types had failed. The difference in mass of the isotopes causes a difference in the effect of the centrifuge on them (much as with milk and cream in a cream separator). The concentration of the lighter U²³⁵ atoms tends to rise in the central or axial region and the heavier atoms tend to flow downward in the outer part of the centrifuge. Across the interface region between the two currents there is a constant diffusion of both types of atoms from one current to the other until their mass difference puts them in one current or the other. The centrifuge method reached the pilot plant stage during the war, but a large production plant was never constructed. The reason being that advancements were made with other processes, gaseous diffusion, at a much faster rate. However, the centrifuge in the separation of heavy isotopes like uranium has the advantage that the separation factor depends on the difference between the masses of the two isotopes, not on the square root of the ratio of the masses as in diffusion methods. The mathematics involved can get

complicated and beyond the scope of the text. Therefore, all mathematics has been eliminated except in the case of the electromagnetic process because its calculations are similar to those of the cyclotron and linear accelerators to be discussed later.

There are several other methods of isotope separation that have proved successful in producing deuterium from hydrogen. These methods being ordinary chemical reactions and electrolysis. For example, in the catalytic exchange of hydrogen atoms between hydrogen gas and water, the water contains between three and four times as great a concentration of deuterium as the hydrogen gas in equilibrium with it. It is possible to adapt this method to a continuous countercurrent flow arrangement like that used in distillation, and such arrangements are actually in use for production of heavy water. The general method is well understood and the separation effects are known to decrease in general with increasing molecular weight, so that there is but a small chance of applying it successfully to heavy isotopes like uranium. The electrolysis method of separating isotopes resulted from the discovery that the water contained in electrolytic cells used in the regular commercial production of hydrogen and oxygen has an increased concentration of heavy water molecules. A full explanation of the effect has not yet been worked out. Before the war practically the entire production of heavy hydrogen was by the electrolysis method. However, it must be remembered that the mass ratio between a hydrogen nuclei and deuterium is one to two while the mass ratio of the isotopes of uranium are 235 to 238. This being the reason that the heavy water processes cannot always be used for all

isotope separation.

METHODS OF DETECTION:

Previously the use of counting devices has been discussed such as the Geiger Counter and the Wilson Cloud Chamber. Actually there are several methods of detecting the presence of charged and uncharged particles. These methods may be broken down into the following categories: ionization process, scintillation, photographic, cloud chamber and the electroscope. In the discussion of the use and operation of detection devices only a relative survey will be mentioned. A more detailed discussion is beyond the scope of this text but may be obtained from other sources.

IONIZATION PROCESS:

A high-speed alpha particle, or any charged particle loses energy, as it passes through matter by the process of ionization. What actually occurs is that the particle disrupts the molecules that it strikes by reason of the electrical forces between the charged particle and the electrons in the molecule. If the material is gaseous, the resultant fragments or ions may move apart and if there is an electric field present, the electrons knocked out of the molecules move in one direction and the residual positive ions in another direction depending on the polarity of the electric field. An initial beta particle with one Mev energy will produce 18,000 ionized atoms before it is stopped completely, since on the average it uses up about 60 ev energy in each ionization collision. Since each ionization process gives both a positive and a negative ion, there is a total of 36,000 charges set free by one

high-speed electron, but since each charge is only 1.6×10^{-19} coulomb, the total is only about 6×10^{-15} coulombs and is still very minute. The best galvanometer can be made to measure a charge of about 10^{-10} coulombs. However, it is possible to push the sensitivity of an electrometer to about 10^{-16} coulombs, but the electrometer is a very inconvenient instrument to use.

The rate at which the energy is lost depends on the charge, mass and velocity of the particle. The total energy lost is, of course, the initial energy of the particle. The distance the particle moves before losing all of its energy (the range of the particle in a particular substance) is thus determined by the type particle its charge, mass and initial velocity. For instance an alpha particle with the same energy as a beta particle will have different ranges. The alpha particle being stopped more rapidly, but it produces more ions per unit of path. However, the amounts of ionization are comparable. As for gamma rays and neutrons the ionization is produced by secondary particles. A gamma ray occasionally will set free an electron from a molecule by Compton scattering or the photoelectric effect and this secondary electron has enough energy to produce ionization. A neutron produces ionization only indirectly by giving high velocity to a nucleus by elastic collision and the ionization occurring as a result of these nuclei. When measuring the ionization effect of gamma rays or neutrons a great number of incident particles are required to cause any effect that can be measured.

SCINTILLATION:

It has been previously mentioned that when charged particles

strike a fluorescent screen a bright flash of light occurs. This fluorescent screen is generally a piece of glass covered with zinc sulfide; this is also the type of screen used on the oscilloscope, the substance used for covering the glass is the factor governing the length of time that light will be emitted (television screens are of the above-mentioned type). In order to count activity, by the scintillation method a low-power microscope, a dark room, and a well rested eye are needed. Each scintillation must be counted and then recorded by human means and for this reason the scintillation method for counting has been superseded by other means.

PHOTOGRAPHIC METHOD:

The use of the fact that when a charged particle moves through a photographic emulsion, the ionization in its wake sensitizes some of the grains. The track of the particle will appear when developing the emulsion. The use of this photographic method will show more than just the presence of a particle, it will also show the range of the particle. From the type of emulsion used (refinement and sensitivity) and the length of the track (range) the energy of the particle may be calculated. Taking an example, the tracks of fission products are to be developed on photographic plates. The natural radioactivity of U^{235} emitting alpha particles plus the number of beta ray emissions plus the fission products track, the combination of all of these would cause the photograph plates to become black. But photographic emulsions have been developed which will not sufficiently react with the ionization caused by the electrons and

alpha particles to show on the developed photographic plates. Therefore, only the tracks of the fission products will show on the developed plates. This photographic method is used quite extensively in health physics to tell the amount of radiation a person has been subjected to.

WILSON CLOUD CHAMBER

In 1912, Mr. C. T. R. Wilson of Cambridge, England, introduced a method for detecting charged particles and finding their mass and charge (or identifying the particle). His method depends directly on ionization but is not an electrical method. The Wilson Cloud Chamber (Figure 27)

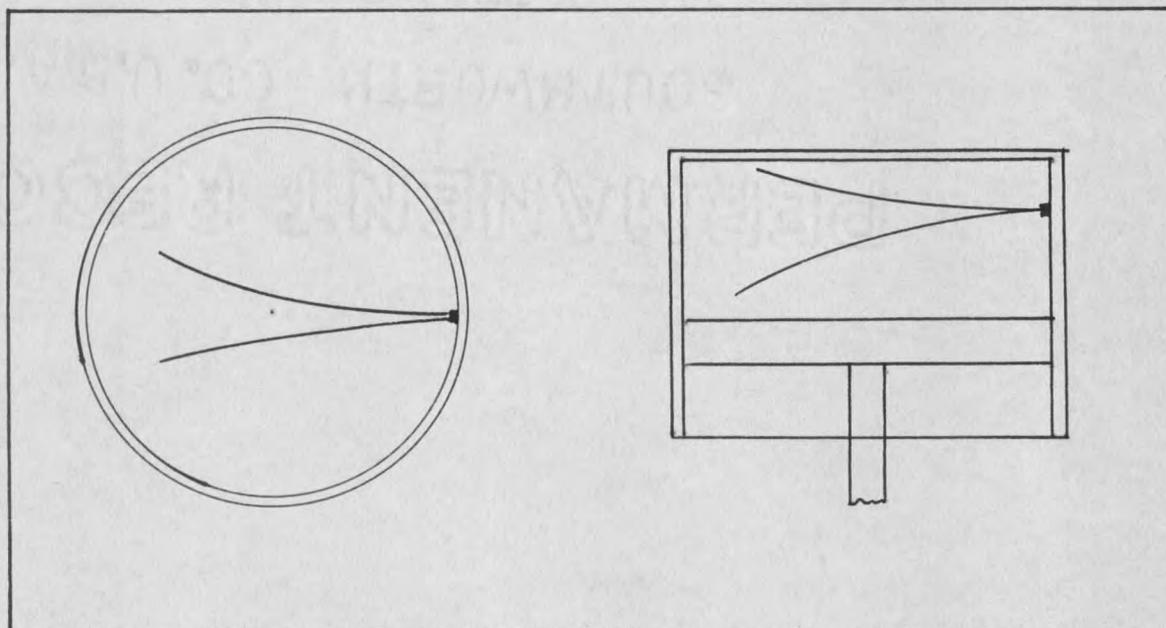


Figure 27 Wilson Cloud Chamber showing particle tracks in an electromagnetic field

uses the fact that supersaturated vapor will condense more readily on ions than on neutral molecules. If air is saturated with water vapor then cooled by expansion just after an alpha particle has passed through it,

tiny droplets of water (fog) condense on the ions formed by the alpha particle and will reflect a bright light strongly enough to be seen or photographed. Figure 27 shows the constructing of a cloud chamber, if the air in the chamber is saturated (or near saturated) with water vapor and then the piston (P) is instantly lowered causing an expansion of this saturated air and thus producing a cooling effect and supersaturation. If a charged particle is emitted from (R) the radioactive source it will form a track of water droplets or fog. A light source from the side of the chamber will illuminate the fog track. This track will now definitely prove the presence of a charged particle but it cannot be definitely identified from this. If an electromagnetic field is present in the chamber the path (track) of the charged particle will have a radius of curvature that may be measured and the e/m value of the particle calculated by means of equations (17) and (18). The plane of the track may not be perpendicular to the photograph taken; therefore, two photographs are taken 90° to one another and the true radius of curvature, of the track calculated.

ELECTROSCOPE:

The electroscope is a piece of basic equipment that is found in energetic and up-to-date high school and college physics laboratories. It is basically a device for measuring voltage but can be used to indicate the strength of radiations, of electromagnetic and charged particles. The simplest form of electroscope (Figure 28) is a strip of gold leaf a centimeter long, suspended by a hinge from a vertical insulated rod. If the rod is charged, the gold leaf also takes the same charge and stands out

at an angle as a result of the repulsion of like charges. As the charge leaks away, the leaf gradually moves back to its original position. The separation is a measure of difference in potential and the rate at which the leaves move back is a measure of the rate at which the gas in the chamber is being ionized and thus, the intensity of the ionizing of radiation.

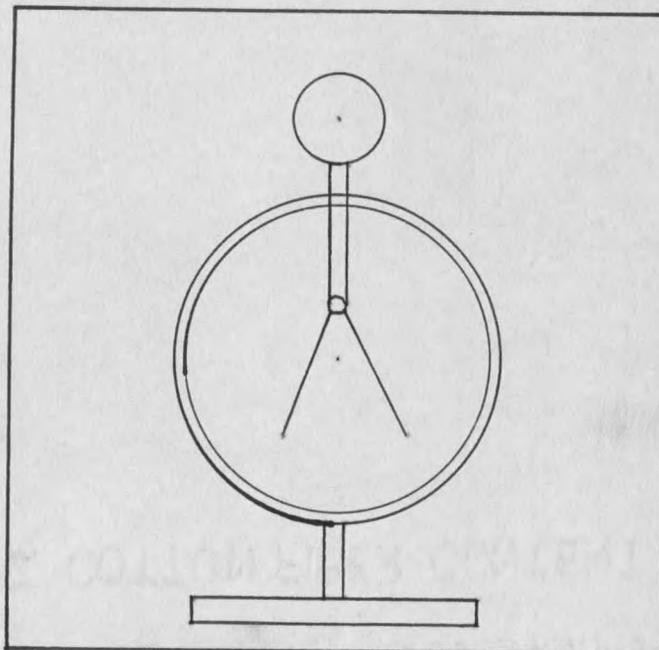


Figure 28 Electroscope

C. C. Lauritsen substituted a very light quartz fiber for the gold leaf and uses the elasticity of the

fiber as the restoring force instead of gravity. The fiber is coated with a thin layer of metal. This type of electroscope is more rugged than the gold leaf type and may be carried around in ones pocket and used for health physics to determine the intensity of radiation.

GEIGER COUNTER:

Probably the most publicized detector is the Geiger Counter. It was originally devised by the German physicists, H. Geiger and A. Muller. It consists of (Figure 29) a cylinder with a wire mounted parallel to the walls of the cylinder and insulated at one end, the wire then being connected to an amplifying circuit and counter. There is a difference in

potential between the wire and the cylinder walls, so great is this difference that it is on the verge of discharging.

Following the operation of the counter an electron may enter the cylinder through aperture (A), the electron then ionizes the gas along its path, the electric field then accelerates these ions and more ions

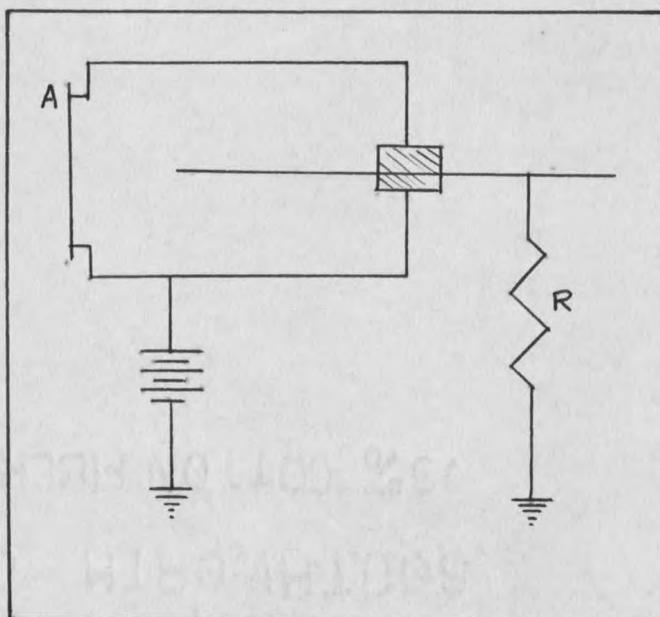


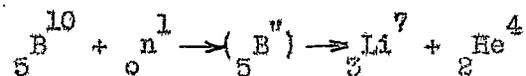
Figure 29 Geiger Counter

are formed which causes a momentary discharge through the large resistance (R). The momentary current is then amplified and may be recorded by a mechanical or electronic counter or shown on an oscilloscope. Geiger Counters have been constructed that are able to count up to over 4×10^{10} discharges per second.

Geiger Counters have been used for finding ore deposits containing uranium or other radioactive elements. It has been very helpful in tracing amounts of uranium and plutonium in various separation and chemical processes. It has also been used in tracer experiments and for health physics. By changing the design of the aperture (A) and shielding the cylinder with lead a Geiger Counter will only function when charged

particles enter through the aperture. By this it can be used as a directional finder for sources of radiation.

The detectors thus far discussed are not directly applicable for neutrons, but can only be detected by secondary (indirectly) means. Neutrons cannot produce ionization when passing through a substance but may cause ionization by one of two methods, by elastic collision or by nuclear reaction. A fast neutron in passing through matter occasionally approaches an atomic nucleus so closely as to impart to it a large amount of momentum and energy according to the laws of elastic collision. The nucleus thereby becomes a high-speed charged particle which will produce ionization. But in the case of thermal neutrons such an elastic collision would not produce enough energy to the collided nuclei to cause any ionization. Therefore, in order to measure the existence of thermal neutrons a nuclear reaction must first take place and then the product nuclei and charged particles will cause the ionization. Thus, for the detection of high-speed neutrons one has a choice between elastic collisions and nuclear reaction, but for thermal neutrons only nuclear reactions will produce ionization. The most commonly used nuclear reaction is with boron which has a very high cross-section for neutrons, the reaction being-



this reaction releases about 2.5 Mev energy shared between the resultant alpha particle and the ${}_{3}^{7}\text{Li}$ nucleus which is sufficient to produce ionization. This reaction is used by filling an ionization chamber with boron trifluoride gas so that the reaction occurs in the region where ioni-

zation is desired; as an alternative the interior of the chamber is lined with boron. The use of the fission of uranium as the nuclear reaction is also used for neutron detection. Using the fact that neutrons of different energies will cause different reactions with U^{238} .

Another method of neutron detection is with a foil known to be made radioactive by neutron bombardment is inserted at a point where the neutron intensity is wanted. After a given time it is removed and its activity measured by an electroscope or counter. The degree of activity that has been built up is then a measure of the number of neutrons that have been absorbed per unit time. This method gives an overall intensity of neutrons while the ionization chambers give instantaneous responses as neutrons are contacted.

Figure 30 shows photographs of the "Chang and Eng" instrument for neutron detection. Figure 31 shows a basic schematic diagram of the unit. "Chang and Eng" is a portable instrument for the detection of fast neutrons in the presence of gamma radiation. The model shown here is a modernization of the previous experimental designs built at the Clinton Laboratories. The original idea of a differential ionization chamber of this type is attributed to L. M. Gray, and the various designs have been used by others for neutron detection.

As shown in Figures 30 and 31 the "Chang and Eng" is a portable instrument for health physics surveying. It was designed to be compact, rugged and simple to operate. It consists of two ionization chambers of two ionization chambers, with their center electrodes connected in parallel and to the needle of an electrometer to measure the difference in

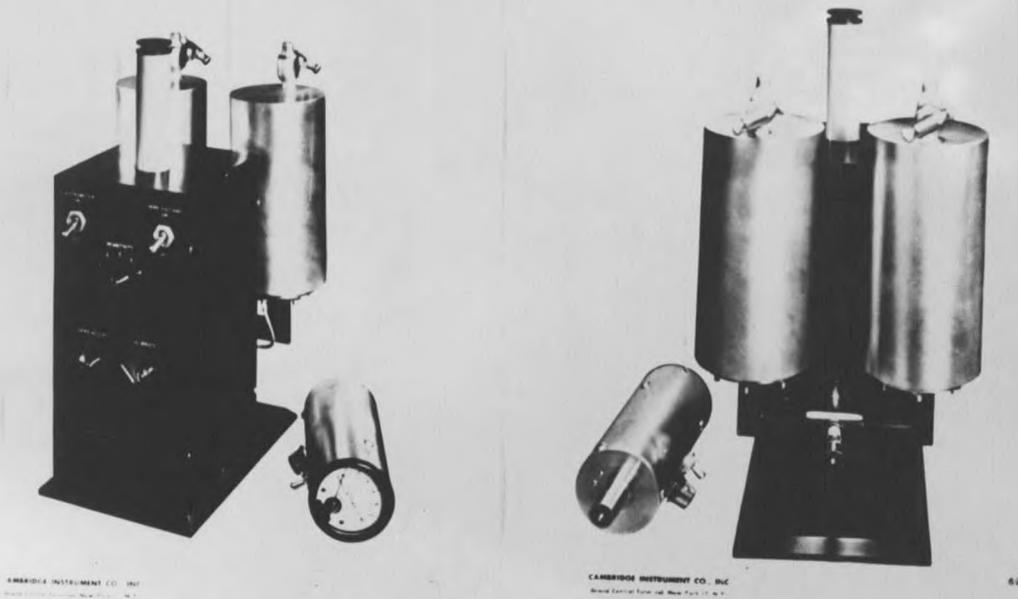


Figure 30 "Chang and Eng" Neutron Detector

the ionization currents in the two chambers. This principle of operation may be discussed with the help of Figure 31. Chamber A is filled with argon at about 30 psi pressure and chamber B is lined with paraffin and is filled with butane at 20 psi pressure. The relative pressures in the two chambers are adjusted so that the ionization currents are equal when both chambers are irradiated with gamma rays only. When placed in a fast neutron beam, recoil protons from the paraffin and butane produce a greater ionization in Chamber B. The difference in the ionization currents, as measured by the electrometer, is an indication of the neutron flux.

Figures 32

and 33 show photographs and schematics of the Cambridge Precision Ionization Meter (Failla Design).

The instrument is designed primarily for high accuracy measurements of C^{14} activity,

but is not limited to

use with this gas.

It may be used for

radon measurements and for almost any radioactive gas that may be enclosed safely in the copper ionization chambers. It also may be used for solid and liquid measurement with ionization chambers of proper design.

The method used is the "restitution" system where calibration of the electrometer is unimportant, it being necessary only to assure enough sensitivity to obtain the accuracy required. The accuracy required. The complete instrument consists of (a) the electrometer, projection lamp, microscope, and base assembly, (b) the dual ionization chambers, (c) a set of four standard condensers, (d) the adjustable voltage supply for the standard condensers and electrometer quadrants, (e) the fixed voltage supply for the ionization chambers. Figure 33 shows a simplified schematic of the circuit.

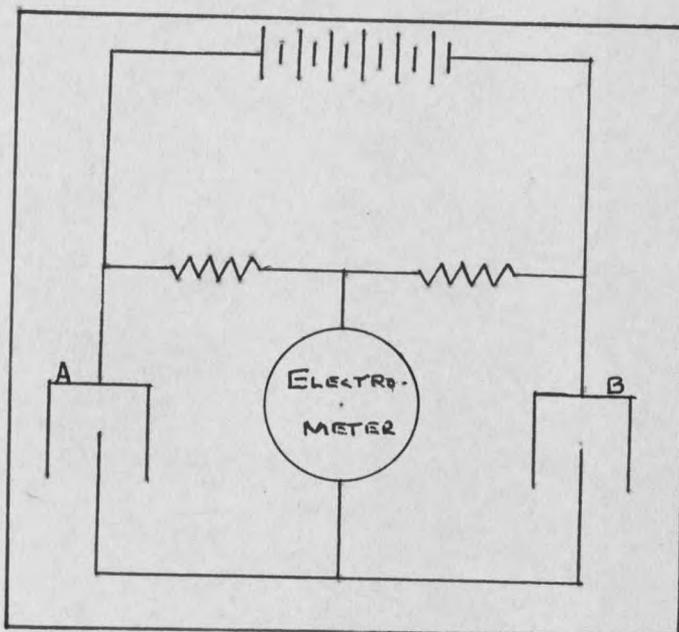


Figure 31 Schematic of the "Chang and Eng" instrument for the detection of fast neutrons in the presence of gamma radiation

The method employed may be summarized briefly as follows: The gas to be measured, after dilution by suitable means, is introduced to the evacuated sampling chamber through the self-scaling rubber stopper by means of a hypodermic needle.

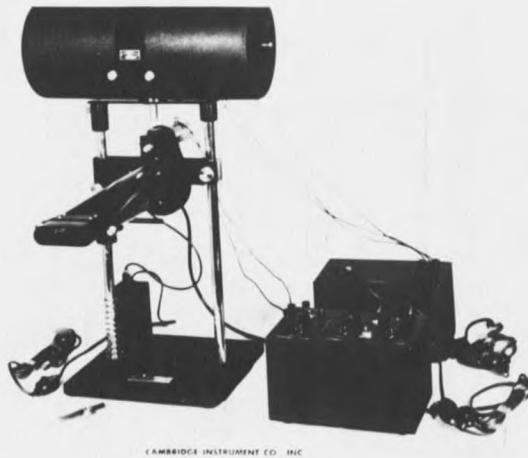


Figure 32 Cambridge Precision Ionization Meter

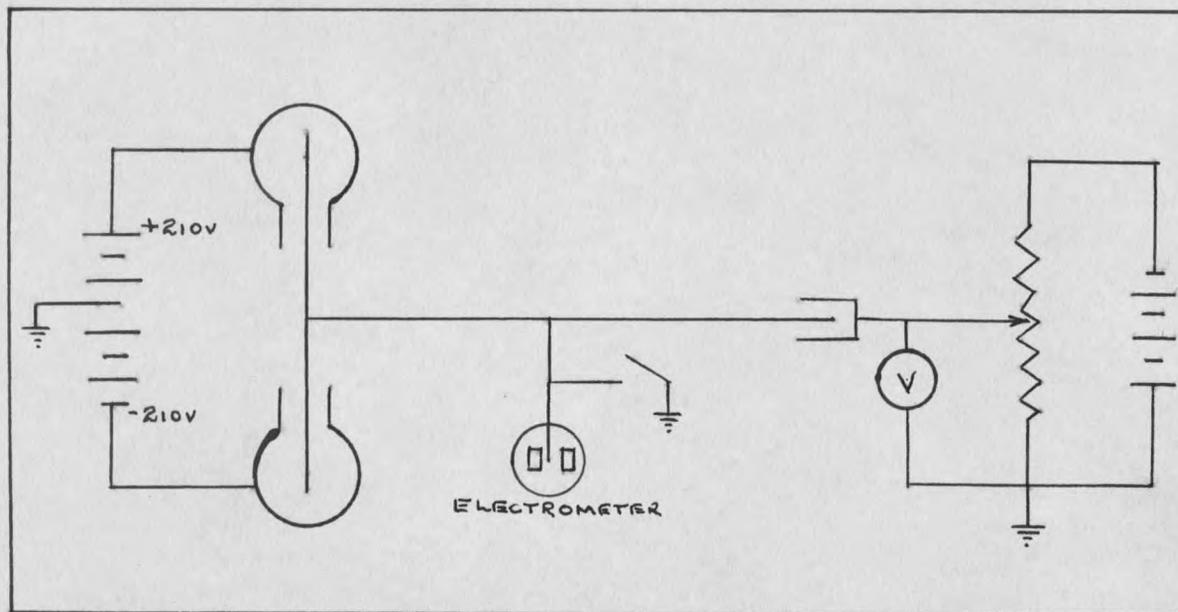


Figure 33 Schematic of Cambridge Precision Ionization Meter

Pressure is brought to atmospheric, the needle removed, and the cap replaced over the stopper. The evacuated compensating chamber is then filled to atmospheric pressure with a dry inert gas such as CO_2 . The electrometer, after being set to zero and stabilized, is connected to the ionization chambers and the system grounded. To start the test, the electrometer is lowered from the chambers. This automatically breaks the ground to the chambers. At this time a stop-watch is started. When sufficient time has elapsed (length of time depending upon activity and accuracy required), the electrometer, after being checked for zero and ungrounded, is reconnected to the chambers. A deflection is now noted. Voltage built up due to the ionizing effect of the active gas is in opposition to the voltage applied through the standard condenser. When this voltage equals the built-up voltage, as indicated by the electrometer's

reading at zero, the stop-watch is stopped and the condenser voltage read. Knowing the capacity of the condenser, it is a simple matter to compute the ionization current, which is, of course, proportional to the activity of the gas.

ATOM SMASHERS:

The name atom smashers is a misleading but a common name for equipment used to accelerate charged particles to a sufficient energy to cause nuclear reactions. In previous pages it has been mentioned that alpha particles, protons, etc, must have at least a definite energy in order to produce certain reactions. However, we did not mention the method used to produce these energies. The following discussion will cover the various types of atom smashers. Probably the cyclotron has been the most publicized of this type of equipment but there also are: the linear accelerator, the betatron, the synchrotron, the Van de Graaff generator, the Synchro-cyclotron, the bevatron and others.

THE LINEAR ACCELERATOR:

The linear accelerator is the simplest of energy producing equipment. It uses the fact that a charged particle is attracted to points of opposite charge and also that it is linearly accelerated along its path of attraction.

Figure 34 shows the basic parts of a linear accelerator. If an electron is to be accelerated and it is followed step by step, through a linear acceleration, we would find the following: using a heated filament (cathode) as a source of electrons, these electrons are then attracted by a positively charged electrode. This electrode will be a hollow cylinder

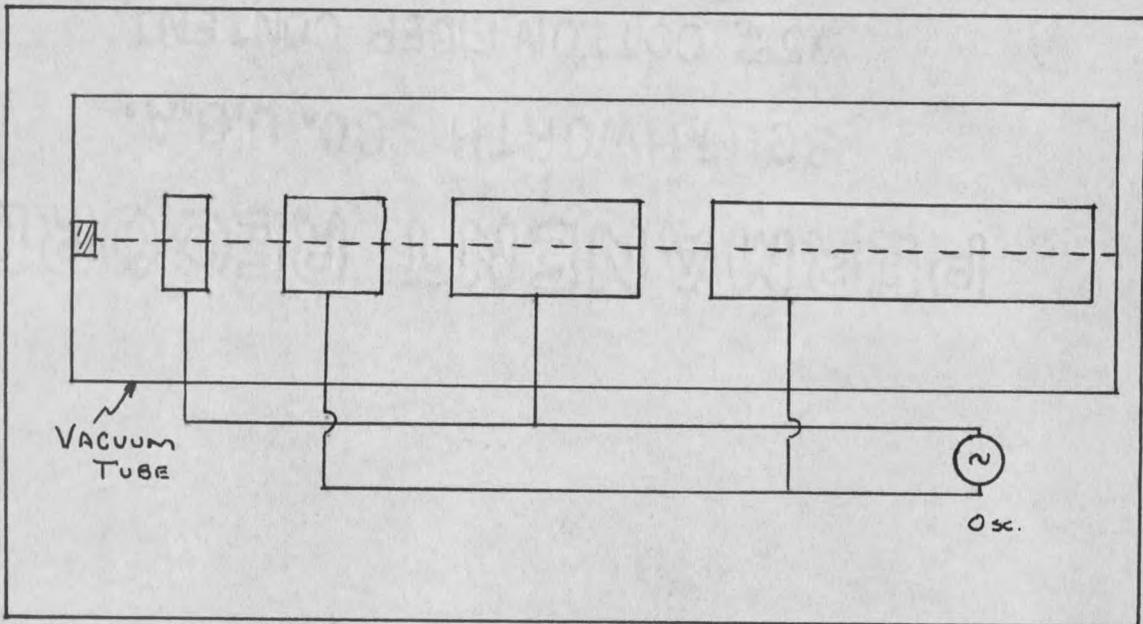


Figure 34 The Linear Accelerator

permitting electrons to pass through the cylinder. As the electrons pass from the cathode to the positive electrode it will be accelerated following the equations (2) and (5).

$$E = Ve \tag{2}$$

$$E = \frac{1}{2}mv^2 \tag{5}$$

or v

$$Ve = \frac{1}{2}mv^2$$

$$v^2 = 2Ve/m$$

this value of v (velocity) is the final velocity of the electron as it approaches the electrode. The acceleration can also be calculated by equations (16) and (19)

$$F = \frac{Ve}{d} \tag{16}$$

$$F = ma \tag{19}$$

$$a = \frac{Ve/m}{d}$$

The electrons will then pass through the cylinder (electrode) with no increase in velocity and as it passes the other end of the cylinder the voltage changes to become negative and the next electrode becomes positive again accelerating the electron thus giving it a "kick" in velocity. This process then continues down the length of the tube. Since the electrons gain velocity with each "kick", the accelerating electrodes are progressively greater in length (Figure 34):

THE BETATRON:

The betatron is used for accelerating electrons. It uses the principle that an electron in an electromagnetic field will increase in velocity (and energy) directly as the magnetic field is increased. The betatron consists of a doughnut-shaped glass tube, evacuated. A heated filament may be used as a source of electrons and a potential difference to acquire an initial velocity. This is accompanied by a changing magnetic field. The magnetic field gives the electrons additional energy as well as causing the electron path to be circular within the doughnut-shaped tube. The electrons make several hundred thousand revolutions while the magnetic field increases from zero to a maximum. The magnetic field alternates 180 times per second, but acceleration only occurs during a quarter of the cycle. The velocities of the electrons will approach the speed of light in the betatron.

SYNCHROTRON:

The synchrotron is similar to the betatron. It has a doughnut-shaped vacuum tube located within a "C" shaped magnet. The magnet is powered by an alternating current. The electrons are accelerated by

means of the increasing magnetic field which also keeps the electron path focused within the circular tube. Then the electrons are accelerated by means of an accelerating electrode within the vacuum tube and connected to a high frequency oscillator. The electrons in the synchrotron will approach the velocity of light. When a particle approaches the velocity of light its mass increases and approaches infinity. Einstein's theory of relativity produced an equation for this.

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (6)$$

VAN DE GRAAFF GENERATOR:

The Van De Graaff Generator is a form of electrostatic machine. It is used to generate high voltages that in turn may be used to accelerate charged particles. The principle of operation is comparatively simple and may be best explained by means of Figure 35. It consists of G a hollow metal terminal (generally a portion of a sphere) mounted on an insulating column and entirely enclosed in a pressure shell; a rubber belt B driven on pulleys H and I by means of a motor; and a power supply, supplying a small amount of negative electricity to several corona points, C. The air in the near vicinity of the points becomes ionized and electrostatic forces cause electrons to be attracted and deposited on the belt. The belt, by its movement, carries these negative charges (electrons) until attracted by the corona points D. The points D distribute the electrons to the upper pulley, H then becomes more negative than points F, therefore causing the air to become ionized and positive charges to be attracted to

and deposited on the belt as it passes over pulley H. As this process continues the terminal G gains more negative charge.

Figure 35 shows only basically the operation of the Van De Graaff Generator and none of the controlling circuits.

THE CYCLOTRON:

The cyclotron is probably the most interesting in

design of the atom smashers. It uses both electromagnetic and electrostatic fields, the electromagnetic used only for focusing the path of the charged particles and the electrostatic field used as the only accelerating force. Figure 36 shows basically the operation of the cyclotron. The main portion being the large electromagnet and the two accelerating electrodes which are the shape of the letter D (dee) and hollow. The electrodes are placed between the poles of the electromagnet and are connected to a high frequency oscillator. To start there must be an ion

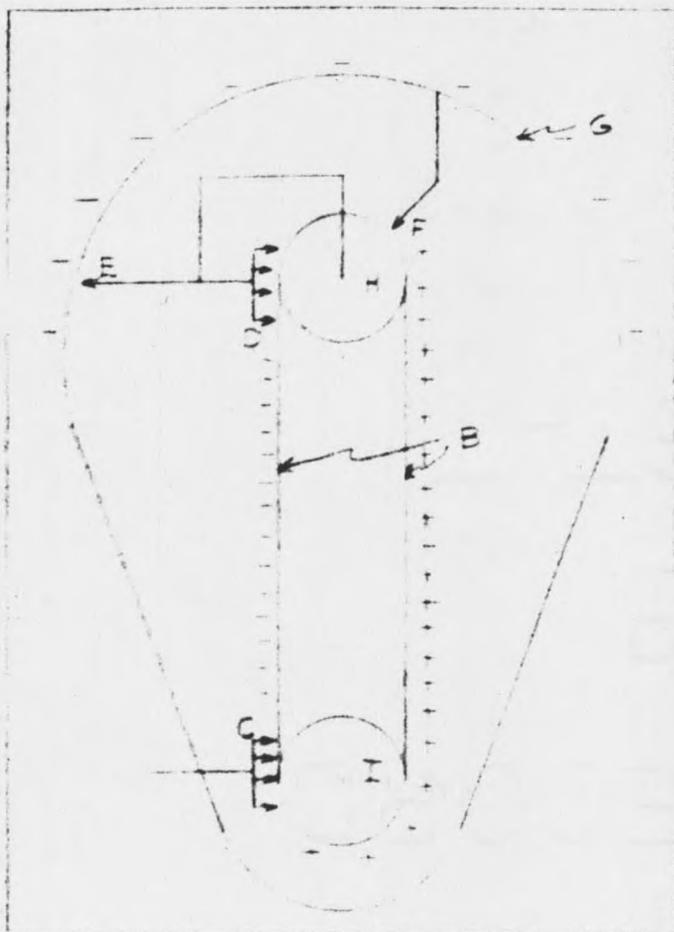


Figure 35 Van De Graaff Generator

source in the center of the cyclotron. The positive ion will be attracted to the negative electrode and be accelerated in doing so. After entering the hollow electrode the magnetic field will cause the ion to follow a circular path of radius R.

$$Hev = \frac{mv^2}{R}$$

causing the ion to again return to the gap between the electrode but the oscillator has changed the polarity on the electrodes thus causing the ion to be attracted to and accelerated towards the other electrode.

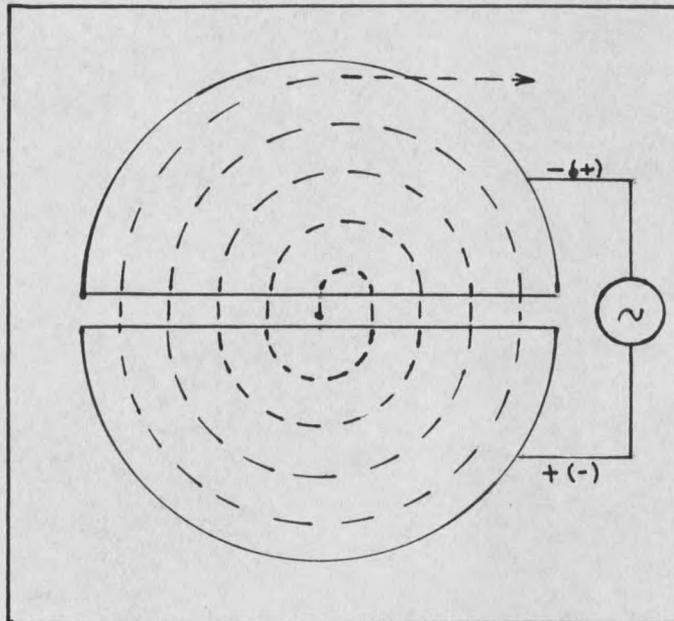


Figure 36 The Cyclotron

The magnetic field again focusing the ion in a circular arc but this time with a greater radius (r) because of the increased velocity. The greater the velocities, the greater their mass becomes. If enough mass is gained the ions will not be synchronized with the oscillator and will fail to reach the electrode at the time its polarity changes. To prevent this the larger cyclotrons use a gradual lowering of the frequency as the particles gain velocity and mass. Equipment using this have been named.

synchro-cyclotrons.

The frequency of the oscillator may be calculated in the following way. The distance traveled by the ion during one half a revolution is R with a velocity of v the time must be

$$t = \frac{\pi R}{v}$$

as shown above from equations (17) and (18)

$$Hev = \frac{mv^2}{R}$$

$$v = \frac{HeR}{m}$$

or

$$t = \frac{\pi R m}{HeR} = \frac{\pi m}{He}$$

the time for one complete revolution is

$$t = \frac{2\pi m}{He}$$

the frequency is

TABLE VII
COMPARISON OF ATOM SMASHERS

Name	Highest Energy Obtained (mev)	Highest Energy Proposed (mev)	Particles Accelerated	Characteristics
Linear Accelerator	30	200	Electrons, protons, deuterons, alpha particles	Pulses of charged particles, medium current
Van de Graaff Generator	5	15	Electrons, protons, deuterons, alpha particles	Very steady voltage, continuous high or low current
Cyclotron	20	20	Protons, deuterons, alpha particles	High voltage, high average current
Synchro-Cyclotron	400	400	Protons, deuterons, alpha particles	Very high voltage, low current, pulses
Betatron	100	300	Electrons	Pulses of electrons, very low current
Synchrotron	70	1000	Electrons	Pulses of electrons, very low current

(Courtesy of Westinghouse Electric Corporation)

$$f = \frac{1}{T}$$

$$f = \frac{He}{2\pi} = \frac{H e/m}{2\pi}$$

this of course must be altered in the case of the synchro-cyclotron.

As a comparison of the above types of Atom Smashers, Table VII shows their output and particles used.

Several other types of atom smashers are the voltage multiplier, the surge generator, the cascade transformer and the proton synchrotron. The first

three use electron tubes, capacitors and transformers but have limitations as to their use in producing high energy particles. A limitation in using transformers is that at voltages higher than about 200,000 volts it is difficult to insulate the transformer windings. The cascade transformer utilizes a group of transformers adding up the energies. However they get heavy, bulky and an accelerating voltage which is not steady.

The proton synchrotron is similar to the synchrotron but is designed to accelerate protons instead of electrons. Equipment of this nature is being built to produce protons of several billion electron volts. It also uses a Van De Graeff generator for initial acceleration.

REACTOR (PILE) DESIGN

Before discussing types of reactors in detail it may be advantageous to discuss the first reactor (pile) constructed. The information accumulated by the end of 1941, as to the possibility of producing an atomic bomb and nuclear power, was such as to warrant expansion of the work. It must be remembered that all the work done from 1941 until 1945 was under the supervision of the United States Government and was specifically aimed for military use. However much of the preliminary bomb work leads directly to industrial uses of nuclear power, such as, isotope separation, purification and reactor design.

PROCUREMENT:

One of the first problems to occur was the procurement of materials of sufficient purity. As far as uranium was concerned, it seemed

likely that it would be needed in highly purified metallic form or at least as highly purified uranium oxide. The other materials which were going to be needed (as moderators) were either graphite, heavy water, or possibly beryllium. It was clear at this time that, however advantageous heavy water might be as a moderator, no large quantities of it would be available for months or possibly years. Beryllium seemed less advantageous and almost as difficult to get. The choice of a material used as a moderator must be such that they have a low cross-section to neutrons and also low in atomic mass. Procurement efforts were then centered on graphite (carbon).

The sources of uranium metal and uranium oxide were surveyed. At the end of 1941 the only uranium metal in existence was a few grams of good material made on an experimental basis by the Westinghouse Electric and Manufacturing Company and others. A few pounds of highly impure pyrophoric powder was found at the Metal Hydrides Company. The only considerable amount of raw material then available in this country was in the form of a commercial grade of black uranium oxide, which could be obtained in limited quantities from the Canadian Radium and Uranium Company. It contained 2 to 5 per cent of impurities and was the material which gave a factor-K on only about 0.87 when used in an exponential pile. By May 1942, deliveries averaging 15 tons a month of black oxide of higher purity and more uniform grade started coming in. Total impurities were less than 1 per cent, boron comprised a few parts per million, and the factor-K was about 0.98. Boron has a very high cross-section for neutrons. (It is to be remembered that the factor-K also depends on the

purity of the graphite). Deliveries of this material reached a ton a day in September 1942.

Experiments at the National Bureau of Standards by J. I. Hoffman demonstrated that, by the use of an ether extraction method, all the impurities are removed by a single extraction of uranyl nitrate. The rise of this method removed the great bulk of the difficulties in securing pure oxide and pure materials for the production of metal. Early in May 1942, arrangements were completed with the Mallinckrodt Chemical Works in St. Louis to put the new grade of oxide through an ether extraction process on a production basis for a further reduction in impurity content and to deliver the final product as brown dioxide. Deliveries started in July 1942 at a rate of 50 tons a month. This oxide is now used as a starting point for all metal production, and no higher degree of purity can be expected on a commercial scale. In fact, it was a remarkable achievement to have developed and put into production on a scale of the order of one ton per day a process for transforming grossly impure commercial oxide to oxide of a degree of purity seldom achieved even on a laboratory scale.

The process which Westinghouse had been using to produce the metal was the electrolysis of KUF_5 at a cost of about \$1000 a pound. Since the KUF_5 was produced photochemically under the action of sunlight this method constituted a potential bottleneck in production. It was found that uranium tetrafluoride could be used instead of KUF_5 , and steps were taken to have this salt produced at the Harshaw Chemical Company in Cleveland and at the duPont plant in Penns Grove, New Jersey.

Production started in August 1942 and by October 1942 was up to 700 pounds per day at Harshaw and 500 pounds per day at duPont. As the result of this supply of raw materials to Westinghouse, and as a result of plant expansion, deliveries from Westinghouse had accumulated to a total of more than 6000 pounds by November 1942 and were expected to be at the rate of 500 pounds per day by January 1943. The purity of the metal was good, and the cost had dropped to \$22 per pound.

Intensive activity designed to accelerate metal production was also carried out independently by F. H. Spedding and his associates at Iowa State College and by C. J. Rodden at the National Bureau of Standards, resulting in a satisfactory method. Production facilities were set up at Ames, Iowa in the fall of 1942 and had already produced more than one ton by the end of November. The process was extremely simple, rapid and low cost. Further research indicated additional changes that could be made to advantage, and by the middle of 1943 Spedding at Iowa and other producers who entered the picture were using the final production method adopted.

As previously mentioned graphite seemed to be the best material for a moderator. The graphite produced prior to the war was not acceptable from a purity standpoint. But it was, of course, in quite a different condition from the metal production since the industrial production of graphite had already been very large. The problem was merely one of purity and priority. Largely through the efforts of W. Hilberry, the National Carbon Company and the Spear Carbon Company were both drawn into the picture. Following suggestions made by the experts of the National

Bureau of Standards, these companies were able to produce highly purified graphite with a neutron absorption some 20 per cent less than the standard commercial materials previously used. Although further efforts to reduce the impurities have had some success, the purity problem was essentially solved by the middle of 1942 and large orders were placed with the cooperation of the War Production Board.

Another problem that arose was the type of lattice formation of the uranium within the graphite moderator. One lattice formation would be lumps of uranium imbedded in the graphite moderator. There are two objections to such a type of lattice for production purposes: first, it is difficult to remove the uranium without disassembling the pile; second, it is difficult to concentrate the coolant at the uranium lumps, which are the points of maximum production of heat. However, a pile was built of a lattice of lumps of uranium and oxide within the graphite moderator because of design and calculation convenience. The following description of the first self-sustaining chain-reacting pile, at the University of Chicago, is taken directly from the Smyth report.

DESCRIPTION OF THE PILE:

The original plan called for an approximately spherical pile with the best materials near the center. Actually control measurements showed that the critical size had been reached before the sphere was complete, and the construction was modified accordingly. The final structure may be roughly described as an oblate spheroid flattened at the top, i.e., like a door knob. It was desired to have the uranium or uranium oxide lumps spaced in a cubic lattice imbedded in graphite. Consequently, the

graphite was cut in bricks and built up in layers, alternate ones on which contained lumps of uranium at the corners of squares. The critical size was reached when the pile had been built to a height only three-quarters of that needed according to the most cautious estimates. Consequently only one more layer was added. The graphite used was chiefly from the National Carbon Company and the Speer Graphite Company. The pile contained 12,400 pounds of metal, part of which was supplied by Westinghouse, part by Metal Hydrides, and part of Ames. Since there were many more lattice points than lumps of metal, the remaining ones were filled with pressed oxide lumps.

For purposes of control and experiment there were ten slots passing completely through the pile. Three of those near the center used for control and safety rods. Further to facilitate experiment, particularly the removal of samples, one row of bricks carrying uranium and passing near the center of the pile was arranged so that it could be pushed completely out of the pile.

This whole graphite sphere was supported by a timber framework resting on the floor of a squash court under the West Stands of Stag Field.

PREDICTED PERFORMANCE OF THE PILE:

The metal lattice at the center of the pile and the two other major lattices making up the bulk of the rest of the pile had each been studied separately in exponential experiments. These had given a factor-K of 1.07 for the metal lattice and 1.04 and 1.03 for the oxide lattices, the difference in the last two resulting from difference in the grade of

graphite used. It is to be remembered that these figures are factor-K for lattices of infinite size. Therefore a prediction of the actual effective factor- K_{eff} for the pile as constructed depended on the validity of the deduction of K from the exponential experiments, on a proper averaging for the different lattice, and on a proper deduction of K_{eff} from the average K for infinite size. Although the original design of the pile had been deliberately generous, its success when only partly completed indicated that the values of the multiplication factors as calculated from exponential experiments had been too low. The observed effective multiplication factor of the part of the planned structure actually built was about 1.0006 when all neutron absorbers were removed.

MEASUREMENTS PERFORMED DURING CONSTRUCTION:

A series of measurements was made while the pile was being assembled in order to be sure that the critical dimensions were not reached inadvertently. These measurements served also to check the neutron multiplication properties of the structure during assembly, making possible a prediction of where the critical point would be reached.

In general, any detector of neutrons or gamma radiation can be used for measuring the intensity of the reaction. Neutron detectors are somewhat preferable since they give response more quickly and are not affected by fission-product radiations after shut down. Actually both neutron detectors (boron trifluoride counters) and gamma ray ionization chambers were distributed in and around the pile. Certain of the ionization chambers were used to operate recording instruments and automatic safety controls.

In the pile itself measurements were made with two types of detectors. A boron trifluoride counter was inserted in a slot about 43" from the ground and its readings taken at frequent intervals. In addition, an indium foil was irradiated every night in a position as close as possible to the effective center of the pile, and its induced activity was measured the following morning and compared with the readings of the boron trifluoride counter.

The results of such measurements can be expressed in two ways. Since the number of secondary neutrons produced by fission will increase steadily as the pile is constructed, the activity "A" induced in a standard indium foil at the center will increase steadily as the number of layers of the pile is increased. Once the effective multiplication factor is above one, "A" would theoretically increase to infinity. Such an approach to infinity is hard to observe, so a second way of expressing the results was used. Suppose the lattice spacing and purity of materials of a graphite-uranium structure are such that the multiplication factor would be exactly one if the structure were a sphere of infinite radius. Then, for an actual sphere of similar construction but infinite radius, the activation of a detector placed at the center would be proportional to the square of the radius. It was possible to determine a corresponding effective radius R_{eff} for the real pile in each of its various stages. It followed, therefore, that, if the factor-K were precisely one on the average for the lattice in the pile, the activity "A" of the detector at the center should increase with increasing R_{eff} in such a way that R_{eff}^2/A remained constant,

but, if K for the lattice were greater than one, than as the pile size approached the critical value, that is, as K_{eff} approached one, A should approach infinity and therefore R_{eff}^2/A approach zero. Therefore by extrapolating a curve of R_{eff}^2/A vs. size of the pile, i.e., number of layers, to where it cut the axis, it was possible to predict at what layer K_{eff} would become one. Such a curve, shown in Figure 37, indicated at what layer the critical size would be reached.

During the construction, appreciably before reaching this critical layer, some cadmium strips were inserted in suitable slots. They were removed once a day with the proper precautions in order to check the approach to the critical conditions. The construction was carried in this way to the critical layer.

CONTROL:

The reaction was controlled by inserting in the pile some strips of neutron absorbing material---cadmium or boron steel. When the pile was not in operation, several such cadmium strips were inserted in a number of slots, bringing the effective multiplication factor considerable below one. In fact, any one of the cadmium strips alone was sufficient to bring the pile below the critical condition. Besides cadmium strips that could be used for manual operation of the pile, two safety rods and one automatic control rod were provided. The automatic control rod was operated by two electric motors responding to an ionization chamber and amplifying system so that, if the intensity of the reaction increased above the desired level, the rod was pushed in, and vice versa.

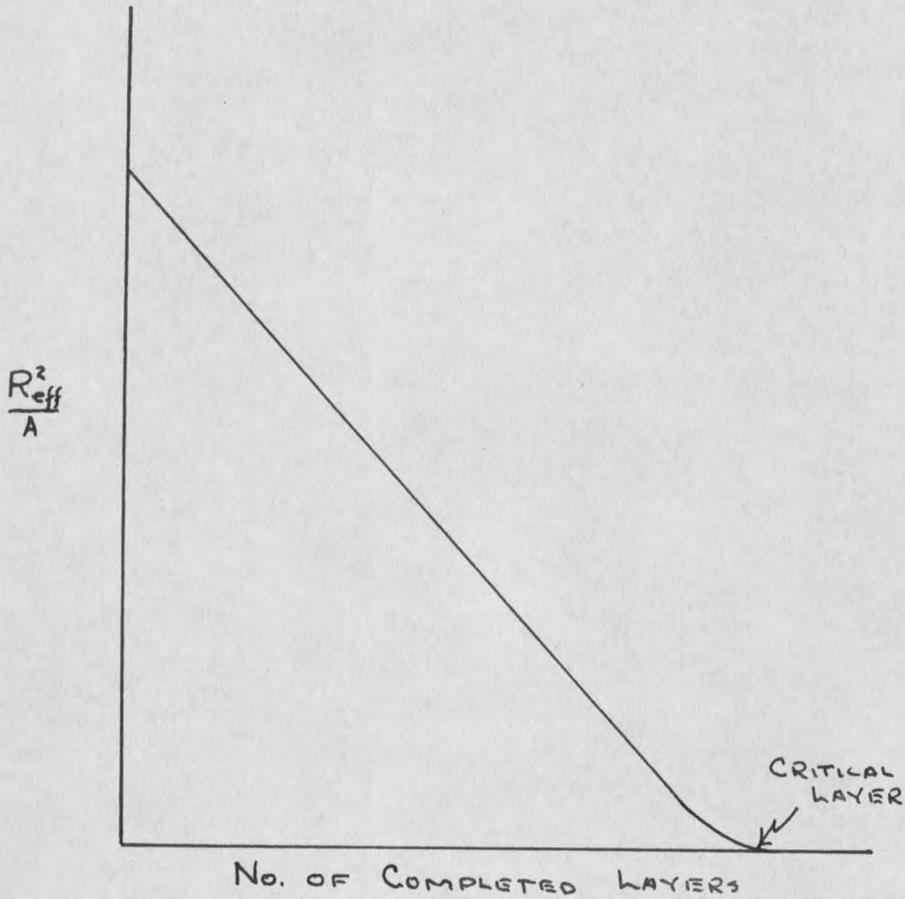


Figure 37 Graphically showing when critical size was reached with respect to the number of completed layers

OPERATION OF THE PILE:

To operate the pile all but one of the cadmium strips were taken out. The remaining one was then slowly pulled out. As the critical conditions were approached, the intensity of the neutrons emitted by the pile began to increase rapidly. It should be noticed, however, that, when this last strip of cadmium was so far inside the pile that the effective multiplication factor was just below one, it took a rather long time for the intensity to reach the saturation value. Similarly, if the cadmium strip was just far enough out to make K_{eff} greater than one, the intensity rose at a rather slow rate. For example, if one rod is only 1 cm. out from the critical position, the "relaxation time," i.e., the time for the intensity to double, is about four hours. These long "relaxation times" were the result of the small percentage of delayed neutrons and make it relatively easy to keep the pile operating at a constant level of intensity.

The pile was first operated on December 2, 1942 to a maximum energy production of about $\frac{1}{2}$ watt. On December 12, the intensity was run up to about 200 watts, but it was not felt safe to go higher because of the danger of the radiation to personnel in and around the building. During this high intensity run, measurements were made of radiation beside the pile, in the building, and on the sidewalk outside.

The purpose of this first pile was not only to produce nuclear power but also as a source of plutonium. The uranium and uranium oxide used was not modified in any respect as to its isotope concentration. Therefore the U^{238} formed the plutonium while the U^{235} caused the self-

sustaining chain-reaction by means of nuclear fission. This also caused the critical size to be very large and the factor-K to be low (approaching one). There are several other problems and they are not discussed above, such as, loading and unloading, corrosion, protection of the uranium from corrosion, controls, shielding, maintenance, waste disposal, recovery of uranium, and health of personnel.

As previously mentioned an increase in temperature will cause the factor-K to decrease and possibly below one. Therefore there is a need for some type of coolant. The advantages of one type of coolant over another will be discussed later, while for our immediate discussion let us consider water as the coolant. But we must now design some type of channels to carry the water where the heat is generated. From a neutron cross-section standpoint graphite pipes would be best to carry the water, but cannot be considered from a practical standpoint; some other type of pipe must be used. The pipes (channels) must be made of some material whose cross-section for neutrons was not large enough to bring the value of factor-K below one. Furthermore, the pipes must be made of some material which would not disintegrate under the heavy density of neutron and gamma radiation present in the pile. Finally, the pipes must meet all ordinary requirements of cooling system pipes: they must not leak; be able to withstand some stress; they must not corrode; they must not warp; and also they must exhibit these properties at elevated temperatures, possibly up to 1000^oF. From the nuclear physics point of view there were seven possible materials (Be, Al, Bi, Mg, Zn, Pb, Sn), none of which had high neutron absorption (cross-sections). Of the above mentioned materials

aluminum is best qualified from a standpoint of abundance, strength, formability, purity, and corrosion resistance. However, when first used it was debatable as to the corrosion resistance of aluminum pipes under dense radiation. But aluminum proved successful as pipes to carry the coolant.

Temperature measuring devices, radiation meters, and other instruments must also be inserted into the pile for accurate results. The insertion of these probes into the pile causes their design to be of such material that they will withstand intense radiation and still give accurate readings. Another interesting change takes place in the physical properties of graphite under neutron radiation; for instance, the electric resistance, the elasticity, and the heat conductivity all change.

COOLANTS:

As Mechanical Engineers we are most interested in the energy available, its form and how it can be converted into useful power. As previously stated water was used as a coolant, for convenience, to regulate the operating temperature of the pile. In fact several pilot plant reactors used water. The heated water was of a nuisance because in a closed system it had to be cooled and then used over again; and if used in an open system its radioactive properties may prove a hazard. This is one of the reasons why water may not be the best coolant (or heating median for our purposes) to use. Another reason being if the pile is to operate at a temperature range of between 600-1000^oF water will form high pressure steam and will cause the use of high pressure fittings. High pressure fittings are ruled out in a reactor because steel cannot be used and we

have previously decided on aluminum ducts (pipes) to pass the coolant. Water may also decompose at these high temperatures. From this it would seem that the water coolant should be replaced by possibly a gas or some liquid that will not volatilize. Several of the possible coolants are air, helium, hydrogen, mixture of helium and carbon dioxide, heavy water, sodium or a eutectic mixture of sodium and potassium. Of the mentioned gaseous coolants hydrogen is the best from a heat transmission standpoint but probably never will be used because of its hazardous properties.

Comparing air with helium or helium mixtures, the use of one coolant over the other would depend primarily on the type of cycle used. If a open cycle is used air or water would be the only practical coolants because of their vast supply and low cost. For instance to cool a reactor with helium using an open cycle would require a large supply of helium at a great cost, because the helium would only pass through the reactor once and then exhausted into the atmosphere. While in a closed cycle the coolant is used over and over again, and the cost being the initial amount plus small additions caused by minute leakage. However helium has approximately twice the heat transfer of air at pressures of from 100-800 PSia which makes it a better coolant than air, and elements under any conditions. It may be of interest at this time to review several reactors, that have been built, as to their coolant.

From Table VIII it is interesting to note that none of the named reactors use helium or any liquid metal for the coolant. The reason being that these reactors were built during the war (World War II) as part

TABLE VIII

<u>LOCATION</u>	<u>DATE</u>	<u>COOLANT</u>	<u>POWER DEVELOPED</u>
University of Chicago	Dec. 12, 1942	None	200 watts
Oak Ridge (Clinton)	Nov. 4, 1943	Air	2000 Kw
Argonne	1943	None	
Hanford	1944 -5	Water	1000 Kw
Argonne	May 15, 1944	Heavy Water	300 Kw
Los Alamos	1944	Water	10 Kw

Information taken from Smyth Report

of the atomic bomb program and no (or little) thought was made of using these reactors as a source of practical power. Practically all suggested post war reactors will use helium, helium mixtures or liquid metals as coolants. Thus far the use of liquid metals has not been discussed as to their adoption as coolants. Liquid metals as coolants have been suggested because they may prove to be the best coolant in the high temperature breeder type reactors. Sodium has very good thermal properties, not much neutron absorption, and its melting point may be considerably lowered by means of forming a eutectic mixture with potassium. However sodium will become radioactive but the radioactivity has a short life. Other advantages of metal coolants is their high boiling point and the fact that it can be pumped electrically. The electric pumping is that by running the molten metal through a spiral pipe the metal itself can be used as the rotor of an electric motor, thus eliminating possible leakage during pumping. A pump of this nature was used in one of the Oak Ridge

installations. One disadvantage of the metal coolant (the exception is the use of mercury) is that the heated liquid metal cannot be used directly for Mechanical Engineering purposes (prime movers) but must first convert the heat by means of a heat exchanger which in turn may produce steam for practical uses. Also the temperature of the metal coolant must be kept above its melting point.

At the present time (February 1950) there are several reactors in the process of design or construction, of which the following four are considered the Commission's reactor-development program.

- 1.) An Experimental breeder reactor to be constructed at Arco, Idaho.
- 2.) Materials-testing reactor at Oak Ridge.
- 3.) Ship propulsion reactor, Idaho.
- 4.) Intermediate Power - breeder type at Knolls Atomic Power Laboratory at Schenectady.

The experimental breeder reactor to be constructed in Arco, Idaho was designed (nuclear) by the Argonne National Laboratory, the other by Austin Company of Cleveland, and the Bechtel Corporation of San Francisco will complete all of the construction at a total cost of approximately \$3,500,000. This reactor will use fast neutrons because of their breeding characteristics and also to test the use of liquid metal coolant (as a possible coolant) at high temperatures. The use of a liquid metal coolant is one of the differences between this experimental-breeder reactor and the already operating fast neutron reactor at Los Alamos, the main other difference being the much higher power level and operating tem-

perature. This experimental reactor was to be originally constructed at Du Page County, Illinois (Argonne) but because of the high power level a more sparsely populated area was searched for and Arco, Idaho chosen. This reactor is primarily an experimental reactor and any useful power obtained may be considered as more or less a by-product. Also along these same lines it must be remembered that our reactor program is at the present time (March 1950) in a reconversion process, i.e., all of the reactors constructed during the war were solely for bomb production and bomb research, and any power produced (heating of the coolants) was a hazard, while now we are building our reactors with the outlook toward industrial power and various propulsion uses.

The future trend for reactors seems to be of high neutron density type which is the basic purpose for constructing a materials-testing reactor at Oak Ridge, at an expected cost of \$25,000,000. Materials that may be used in future reactors will be tested as to their properties under intense neutron bombardment. A reactor of this type will be of particular advantage in the field of aircraft propulsion because of the neutron density per unit volume or the possible compactness of such a reactor. The scientific design is being completed by the Argonne and Oak Ridge National Laboratories and the Engineering work by the Blaw-Knox Construction Company of Pittsburgh. Construction should start by this summer (1950).

The Westinghouse Electric Corporation and the Argonne National Laboratory are developing a reactor to produce large amounts of heat. This reactor will be built at the Nuclear Reactor Testing Station in Idaho at a cost of, at least, \$25,000,000. The engineering work will be performed by the Westinghouse Atomic Power Division at the old Bettis

Airport near Pittsburgh. The final construction of this reactor will probably not be completed until 1952. The purpose of this reactor is to produce large amounts of heat that may be converted into power for the use of marine propulsion, primarily submarine use. One of the main advantages of nuclear power for marine use is the elimination of refueling, a pound of U²³⁵ would last many months as will be shown in later examples.

The fourth and last reactor proposed in the Commissioner's reactor-development program is the Knoll's reactor being developed by the Knoll's Atomic Power Laboratory near Schenectady. This reactor will be the first to use neutrons of the intermediate energy range and will be a breeder type. It will also use liquid metal as a coolant and the heat liberated will be converted to generate power. Breeding by use of intermediate energy neutrons will be on an experimental basis and if successful will add to the already existing sources of fissionable materials. The cost should not exceed \$40,000,000 and construction should be completed by 1951.

In the above I have estimated final construction dates of the various reactors. These dates may vary as much as two years as shown in the problems that have occurred in the construction of the Brookhaven National Laboratory Reactor. The Brookhaven reactor (at Camp Upton Long Island, New York) was originally scheduled to start operation in the fall of 1949 but it now appears that its completion will not occur until late this summer (1950). The coolant to be used is air and the complications encountered were in a new type air duct system. The coolant system would not stand up under operating conditions and had to be redesigned. The output of this reactor is to be 30,000 Kw. Testing of any reactor must be

completed before actual operation starts because once the reactor starts repairs or modifications are sometimes impossible.

In conjunction with the choice of a coolant the type of contact between the coolant and the fissionable material must be chosen. The choice must take into consideration that uranium is very corrosive under practically any condition. But from a heat transfer standpoint the most satisfactory arrangement would be to have the coolant in direct contact with the uranium (this is considering that uranium is used as the fissionable material). This direct contact would have the disadvantages that the coolant (let us use water as the coolant for simplicity) would react chemically with the uranium to a sufficient extent to put a dangerous amount of radioactive material into solution and probably to the point of disintegrating the uranium slugs. Therefore it is necessary to find some method of protecting the uranium from direct contact with the water (coolant). During the war two possibilities were considered: one was some sort of coating, either by electroplating or dipping; the other was to seal the uranium slug in a protective jacket or "can". The Oak Ridge (1943) and Hanford (1944-5) reactors used the first method, the coating of the uranium rods with pure aluminum. This coating was an ALCLAD treatment similar to the coating put on duraluminum sheets and rods. However with the present trend to use molten metals as the coolant several new obstacles must be overcome. The molten metals must be run at a higher temperature and will probably cause the reactors to be designed on the principle of standard heat exchangers.

SHIELDING:

The problem of shielding with regards to health physics is very important because of its dangerous nature to operating personnel. This problem occurs not only near reactors but also near the separation processes and near any other source of radioactive materials. However radiation is most dangerous near reactors because of the vast number of neutrons in existence as well as alpha, beta and gamma radiation. The neutrons also have the property of being able to leak out through small holes or cracks in barriers. As for a comparison of the shielding needed for these various particles it has been estimated that a sheet of paper will somehow stop alpha particles, 500 sheets of paper to total a stop for beta particles (electrons), two inches of lead for gamma rays, and the equivalent of six feet of water to shield against neutrons.

The two inches of lead required to stop gamma rays is misleading because gamma rays do not have a maximum range in an absorber, but are merely absorbed exponentially in passing through the absorber. This absorption follows the equation

$$I = I_1 e^{-ut} \quad (24)$$

where I_1 is the initial intensity, I the final intensity, u is the linear absorption coefficient, and t the thickness of the absorber.

This amount of shielding needed does not take into account any sources of leakage which would require a greater amount of shielding. Another source of radiation leaks are in the coolant, the amount of leakage depending upon the coolant used and its rate of flow. Caution must be taken

that the instrumentation will not carry radioactive fluids vapors, or air from danger areas (radive) to the instrument panels or rooms. The use of pneumatic controls and instruments may cause a source of radioactive materials to escape from the reactor. (The name "radive" has recently been adopted for radiation above the tolerance level). As a general rule concrete walls are used for the shielding of reactors with slots in the sides for loading and unloading fissionable materials and the radioactive by-products. Figures 39, 40 and 41 show the handling of radioactive material from the Clinton Pile at Oak Ridge National Laboratory; note the use of health physics metering device used to measure the amount of radiation present. Further handling of radioactive materials is done by remote control, General Electric has developed an apparatus used for remote handling. Badges worn by personnel will contain film that will change color under radive conditions. The army may use a similar method by means of treating the men's "dog tags", they will be able to determine the amount of radiation encountered and thereby know what medical treatment is needed. This is a precaution in case of a future atomic war.

It is interesting to note that the raw material (uranium) is not dangerously radioactive. Even the product plutonium does not give off penetrating radiation, but the combination of its alpha-ray activity and chemical properties make it one of the most dangerous substances known if it once gets into the body. However, the really troublesome materials are the fission products, i.e., the major fragments into which uranium is split by fission. The fission products are extremely active and include some thirty elements. Among them are radioactive xenon and radioactive

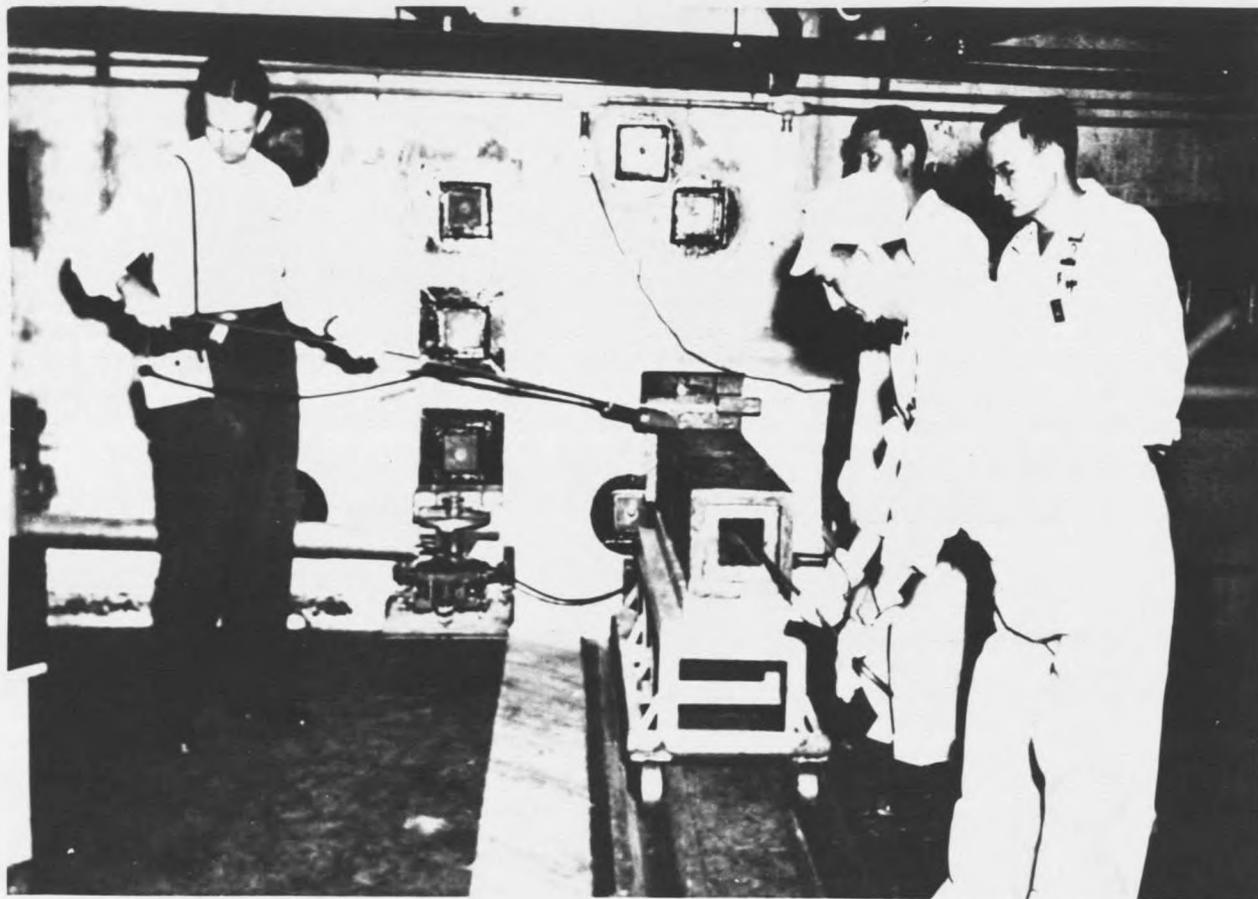


Figure 39 Radioisotopes applied to peacetime development at Oak Ridge, Tennessee. Operators are pulling an isotope stringer from the pile. Health physicist is monitoring the job.

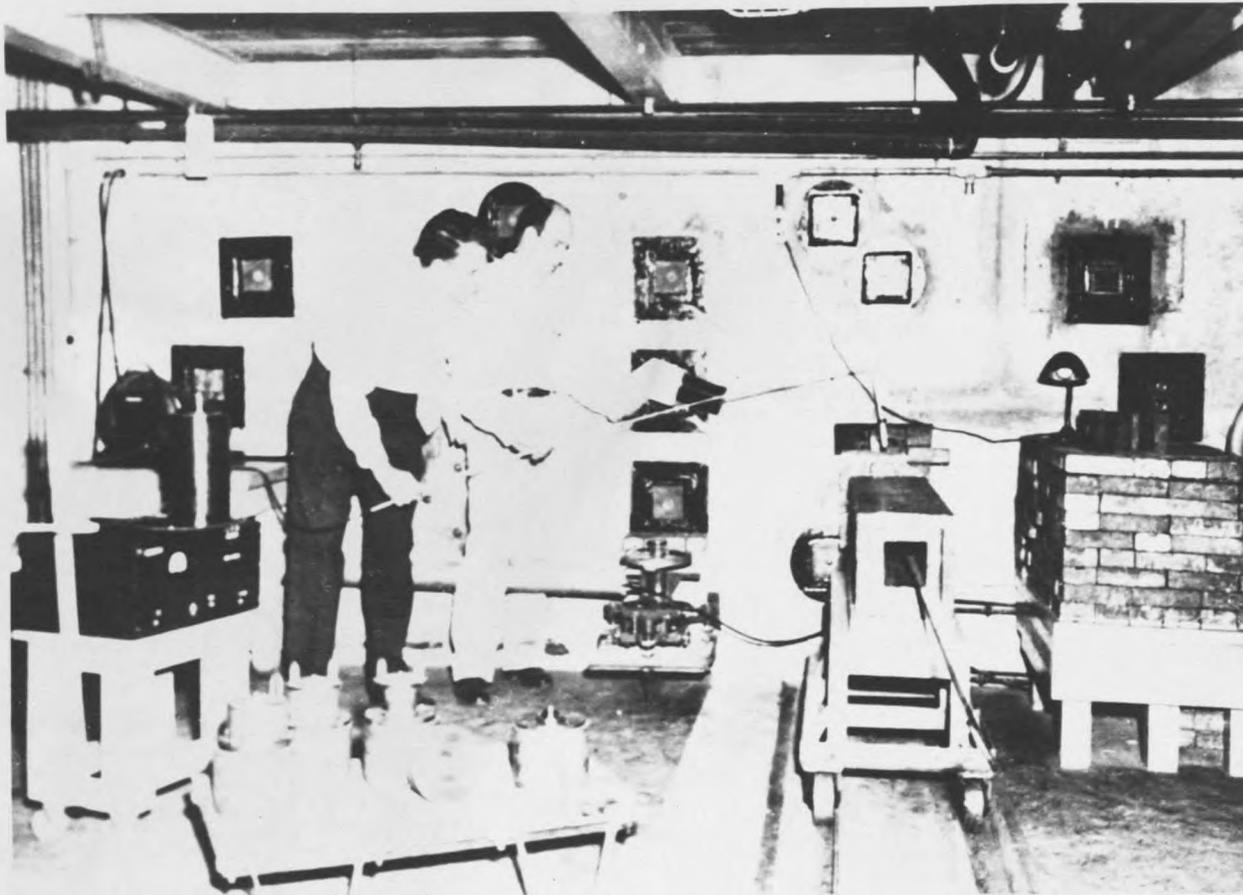


Figure 40 Operator removes the can radioisotopes from pile. Health physicist is monitoring sample at Oak Ridge.

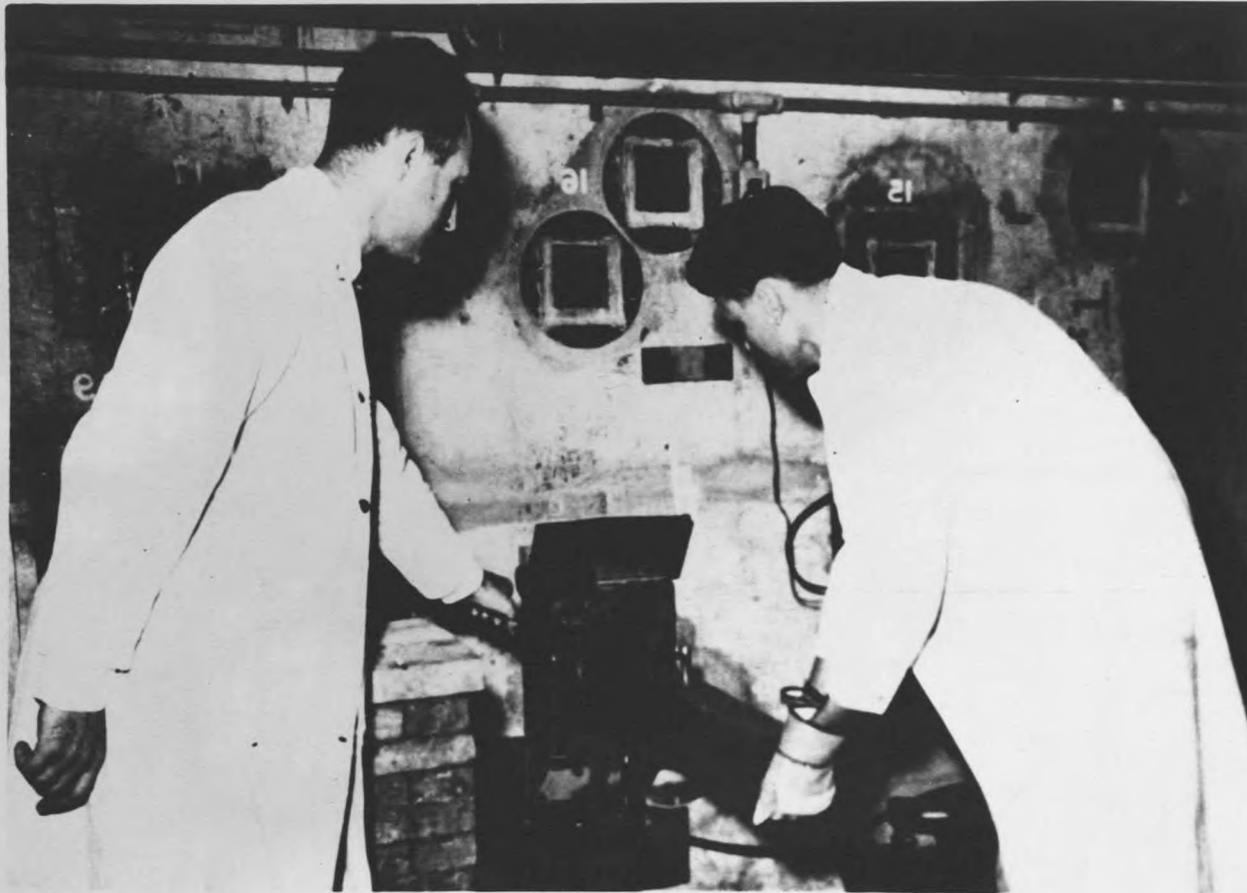


Figure 41 Start of a neutron bombardment for producing radioisotopes in Clinton chain-reacting uranium "pile". Dr. Waldo Cohn and Mr. Barker demonstrating at Oak Ridge.

iodine. These are released in considerable quantity when the slugs (the fission products) are dissolved and must be disposed of with special care. This problem of disposal has caused considerable work because in the process of reclaiming the unused uranium and the produced plutonium from the products of fission several of the radioactive fission products are in the form of gases. High stacks must be built which will carry off these along with the acid fumes (from the separation process) from the first dissolving unit and it must be established that the mixing of radioactive gases with the atmosphere will not endanger the surrounding territory. As in all other matters of health, the tolerance standards that are set and met are so rigid as to leave not the slightest probability of danger to the health of the community or operating personnel. Most of the other fission products can be retained in solution but must eventually be disposed of. Of course, possible pollution of any adjacent water supply must be considered. In fact, the standards of safety set and met with regard to river pollution are so strict that neither people nor fish down the river can possibly be affected. This problem of water pollution has occurred in the dissipation of the water coolant at the Hanford plant. A very good paper on health physics and the handling of radioisotopes was presented by G. G. Manoy and D. O. Lintz called "Safe Handling of Radioisotopes" and was published in the December 1949 issue of Mechanical Engineering.

The maintenance of reactors brings about a difficult problem which sometimes proves impossible. There can not be any maintenance inside the shield or reactor once the reactor had operated. This also holds true, to a somewhat lesser extent, to the separation unit. It is



Figure 42 Aerial view of pilot plant, Oak Ridge, Tennessee.

probable that a shut down for servicing could be effected, provided, of course, that adequate remotely controlled decontamination processes are carried out in order to reduce the radiation intensity below the level dangerous to personnel. The maintenance problem for the other auxiliary parts of the plant is normal except for the extreme importance of having standby pumping and power equipment to prevent a sudden accidental breakdown of the cooling system. If the coolant pumping system should fail no controls could react fast enough to keep the temperature of the reactor within a safe range and an explosion would probably result. Therefore the only solution would be as stated above to have a standby auxiliary system.

There are several more situations which should be discussed briefly before we start on the actual physical design of a reactor. If we study a reactor using natural uranium as the fissionable material, water as the coolant and carbon as the moderator, several things will be confronted. As we know the U^{235} will fission into a number of radioactive atoms and the U^{238} will absorb a neutron and be converted into Pu^{239} atoms. These newly formed plutonium atoms undergo fission (with neutrons of any energy) and will tend to maintain a chain reaction. But the fission products from U^{235} with large cross-sections from neutrons tend to stop the chain reaction. The determination of when a operating reactor should be shut down and the plutonium extracted involves a balancing of these factors against time schedules, materials cost, separation process efficiency, size of the unit, if plutonium is to be a by product, cost of loading and unloading. This problem of scheduling the unloading time is not directly connected.

with reactor design but indirectly governs the arrangement and form of the fissionable material. Even if the uranium were left in the reactor until all the U^{235} had undergone fission, there would still be a large amount of U^{238} which had not been converted to plutonium. Uranium is an expensive material and the total available supply is seriously limited. Therefore the possibility of recovering it after the plutonium is separated must be considered. However this problem may be partially or completely eliminated by one of several methods. It may be partially eliminated by the use of enriched piles, i.e., increase the ratio of U^{235} to U^{238} to a point where all of the U^{238} will be converted to plutonium before the supply of U^{235} is used or the factor-K becomes less than one. (However it must be remembered that the natural and enriched piles during the war were used primarily for plutonium production). If pure plutonium or 100% U^{235} are used as the fissionable material the problem of recovery is somewhat lessened because the only products, in either case, are the products of fission. The reactor may operate until the factor-K decreases below one and then the U^{235} (or plutonium) separated from the products of fission and reinserted with a sufficient amount of new fuel (fissionable material).

In 1942 a separation plant was designed in connection with the Clinton Pile to be constructed at Oak Ridge. The design included the building of a canyon which would consist of a series of compartments with heavy concrete walls arranged in a line and almost completely buried in the ground. Each compartment would contain the necessary dissolving or precipitating tanks or centrifuges to perform their function. A slug of U^{235} , U^{238} , plutonium and the products of fission would come into the compartment

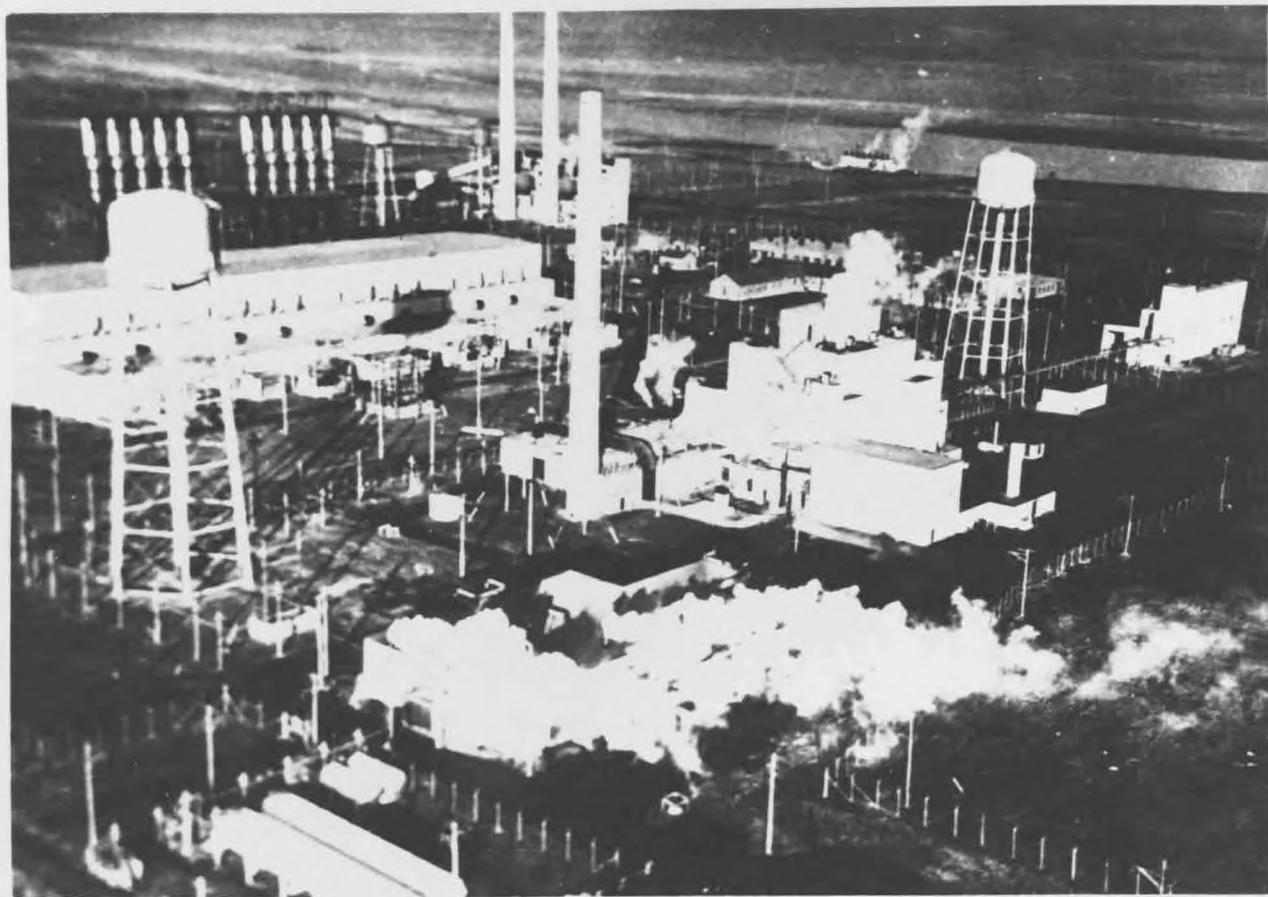


Figure 43 One of the three main plutonium areas in the Hanford area at Richland, Washington.

at one end of the canyon; they would then be dissolved and go through the various stages of solution, precipitation, oxidation, or reduction, being pumped from one compartment to the next until a solution of free plutonium from uranium and fission products comes out the last compartment. As the case of reactors, everything would be operated by remote control from above ground, but the operations would be far more complicated than in a reactor. The chemistry behind such an operation is essentially the same as any normal fields of chemical separation. However a problem of severe corrosion did occur in this separation process due to the high density of radiation. This corrosion created a serious problem because of the un-accessible locations of its occurrence. This situation has now been partially remedied with new processes and materials.

Very little has been said for the choice of a moderator. The moderator material must be such that it will have a very low cross-section for neutrons, withstand medium high temperatures (600-1000° F), not react chemically with the fissionable material, have a low atomic weight, and available in the chemically pure state. The moderator must have a low atomic weight so as to reduce the speed (energy) of the neutron with each elastic collision, the lower the weight the greater the amount of energy absorbed by the moderator and thereby lost by the neutron. However with the use of fast and intermediate neutron reactors moderators of higher atomic weight are desired so as not to slow down the neutrons below the required rate. For instance let us take an example to calculate the number of elastic collisions required to reduce the energy of a neutron a specified amount.

Example No. 6: What is the minimum number of collisions which a neutron having an energy of 1 Mev (1,000,000 ev) could make with C^{12} nuclei to have its energy reduced to 1 ev.

$$C^{12} = 12.00388 \text{ amu}$$

$$n^1 = 1.00893 \text{ amu}$$

assuming the C^{12} nuclei to be at rest and letting

V_1 - velocity of neutron before collision

v - velocity of neutron after collision (final)

V_c - velocity of C^{12} after collision

M - mass of C^{12} in amu

m - mass of n^1 in amu

Using the law of the conservation of energy and momentum the following equation is derived:

$$\frac{1}{2} mV_1^2 + 0 = \frac{1}{2} mv^2 + \frac{1}{2} MV_c^2 \quad (\text{Energy})$$

$$V_c^2 = \frac{m(V_1^2 - v^2)}{M}$$

$$mV_1 + 0 = mv + MV_c \quad (\text{Momentum})$$

$$V_c = \frac{m(V_1 - v)}{M}$$

$$V_c^2 = \frac{m^2(V_1 - v)^2}{M^2}$$

or

$$\frac{m(V_1^2 - v^2)}{M} = \frac{m^2(V_1 - v)^2}{M^2}$$

$$m(V_1 - v) = M(V_1 + v)$$

$$v = \frac{M - m}{M + m} V_1 \quad (25)$$

$$\frac{v}{V_1} = \frac{M - m}{M + m} = \frac{(12.00388 - 1.00893)}{(12.00388 + 1.00893)}$$

$$\frac{v}{V_1} = \frac{10.99495}{13.01281}$$

the original energy of the neutron is

$$E = \frac{1}{2} m V_1^2$$

and the final energy after one collision is

$$E_f = \frac{1}{2} m v^2$$

$$\text{or } \frac{E}{E_f} = \frac{\frac{1}{2} m V_1^2}{\frac{1}{2} m v^2} = \frac{V_1^2}{v^2}$$

this is just for one collision, the ratio of the energies for n collisions would be

$$\frac{E}{E_f} = \left(\frac{V_1}{v} \right)^{2n}$$

for this example the ratio of the energies is to be 1,000,000 to 1 and we have already calculated the ratio of the velocities and only leave n the number of collisions, to be calculated

$$\frac{1}{10^6} = \frac{10.99495^{2n}}{13.01281^{2n}}$$

$$10^{-6} = (.846)^{2n}$$

$$2n = 82.7$$

$$n = 41.35$$

From the above calculations it can be seen that as the mass of the moderator nuclei decreases it will take less elastic collisions to decrease the energy of a neutron by the same amount.

As shown in Table VIII heavy water and water have been used as coolants. In cases of this nature the coolant material was also used as a moderator. However with the new trend of liquid metals as coolants, graphite is still being used as the moderator. Graphite is also used as a reflector surrounding the reactor (inside of the shielding) to reduce the number of neutrons lost by escape.

REACTOR TYPES:

Thus far in this discussion we have been concerned with the major problems involved in the designing of nuclear reactors. Now let us discuss the types of reactors and their actual physical construction. As to the arrangement of the fissionable material reactors are classified as homogeneous or heterogeneous reactors. These two basic types of reactors are further classified into four other groups as to their neutron energy. These four groups are fast, intermediate, resonance and thermal. However the resonance energy will undoubtedly fall into one of the other three groups but may not always be used.

Previously we discussed the use of boron or cadmium rods to control reactors. The use of boron and cadmium is very successful in reactors using thermal neutrons but their cross-section for neutrons decreases as the energy of the neutrons increases. Therefore in reactors of the fast neutron type the control may prove to be more complicated or at least cause the use of new control rods (some of this material on

cross-section of fast neutrons is still classified).

Of reactors constructed during the war, and mentioned in Table VIII, only the Los Alamos is of the homogeneous type and all use thermal neutrons. This does not include the five atomic (nuclear) bombs which have been exploded, all of the bombs are of the homogeneous type with fast neutrons. If a homogeneous type reactor is to be used with the use of natural uranium there is a major problem to be overcome. This problem is that the factor-K will not reach one with the use of most moderators. The only exception to this is by using heavy water as the moderator. However heavy water is very expensive which is another disadvantage. With the use of graphite as the moderator the factor-K will only reach approximately .85 and most other moderators will have a maximum factor-K of less. There are several methods of solving this problem. One is to use an enriched pile as was done in the Los Alamos reactor. Another solution is to use plutonium or possibly some other nuclear fuel. A third method would be to use the fissionable material in lumps or rods, but this of course would change our basic type from a homogeneous to a heterogeneous reactor.

HOMOGENEOUS TYPE REACTORS:

In the design of a homogeneous type reactor one of the first considerations confronted is how is the fissionable material to be mixed (homogeneous) with the moderator, i.e., what form should this homogeneous mixture be solid, liquid or gaseous.

If a solid mixture is used it must consist of the fissionable material (U^{235} or Pu^{239}) and a diluent. The choice of a diluent (which will also act as a moderator) will depend on the energy of the neutrons

desired. The heavier the elements (or compounds) used as the diluent the less energy they will absorb from the neutrons thereby causing a fast neutron reactor. The diluents used for a thermal neutron reactor may be graphite, beryllium, magnesium, aluminum or possibly oxides of these elements. For a fast neutron reactor the diluent may be copper, tungsten, vanadium, or again possibly oxides of these elements. Also the uranium or plutonium may be in a compound oxygen, carbon or sulfur, the forming of these compounds sometimes aids in the processing of uranium ores to a chemically pure product.

This solid mixture will be stationary within the reactor, i.e., there will be no flow or movement of this mixture within the reactor. This non-flow process will have several disadvantages. The heat (energy) liberated by the nuclear reactions will be uniform throughout this homogeneous mixture, therefore the cooling effect produced by the coolant (which is piped through the reactor) will cause a great temperature gradient. This temperature gradient is caused by the conduction of heat through the mixture to the coolant tubes, thereby causing the choice of the diluent to have a high thermal conductivity. In conjunction with the thermal properties the diluent must have a low thermal expansion or excessive stresses may be created by operating the reactor at fairly high temperatures. Another disadvantage of the solid homogeneous reactor is the difficulty in loading and unloading small amounts of the mixture to refuel without causing "hot spots". The reactor will have to be completely shut down and all of the depleted mixture removed and new mixture loaded. Figure 44 shows a schematic drawing of a homogeneous reactor.

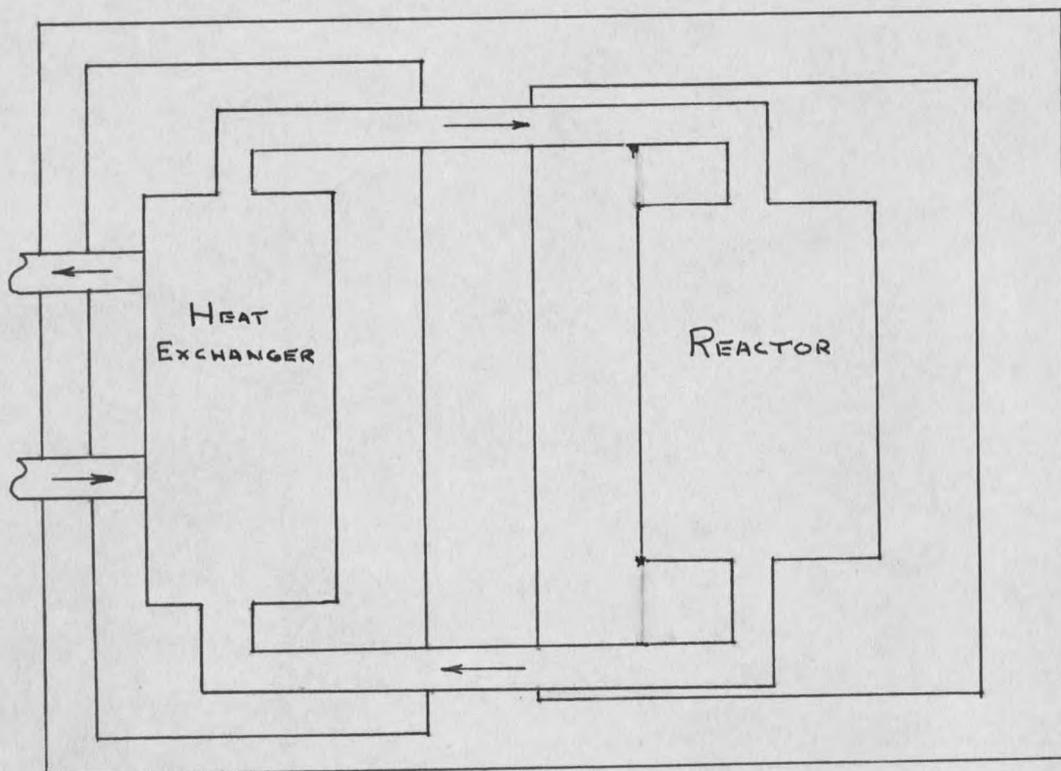


Figure 44 Homogeneous Reactor using a liquid coolant and solid fuel

The use of a liquid mixture in a homogeneous reactor is probably the most feasible of the homogeneous type reactors, however it too has limitations. The choice of the diluent is one of two types; first the use of low melting point alloys of uranium (or plutonium) such as lead, bismuth, sodium, antimony, (the uranium or plutonium alloy would probably have to form a binary or ternary eutectic in order to get the melting temperature low enough) or even possibly mercury; second the use of uranium or plutonium salts in solution, i.e., in solution with water or heavy water. The second type has the disadvantage that the waters will form steam and possibly decompose at high temperatures, therefore their use

should be restricted to low temperature reactors which will not be very useful as a power source.

This liquid type reactor does have the advantage that the fission material may be pumped (see Figure 45) so that all of the mixture,

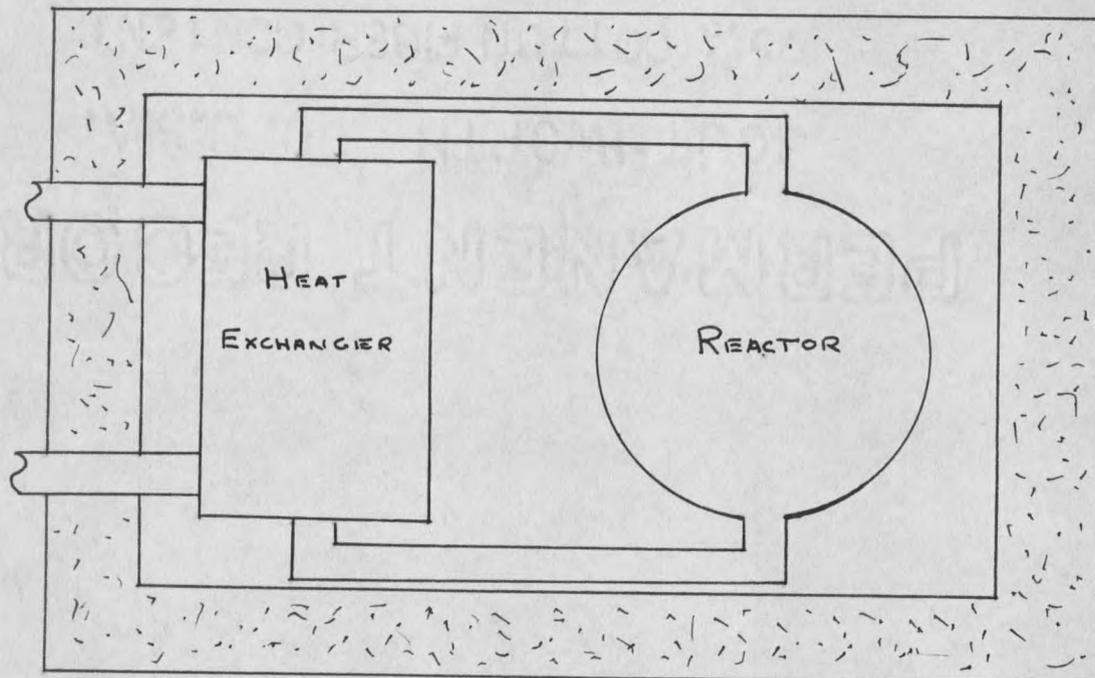


Figure 45 Homogeneous Reactor using liquid fuel and the diluent as the moderator

at one time or another, will come into direct contact with the cooling coils or pipes. This will aid greatly to the amount of heat transferred. Also an expansion tank will eliminate any thermal stresses that may form due to thermal expansion. The problem of loading and unloading will be eliminated because the used mixture may be pumped out at one end while a new mixture enters at another point, eliminating a shut down period.

The use of a homogeneous gaseous mixture has the same advantages as the liquid type but has several more strong disadvantages. The

diluent for this type of reactor could be uranium hexa-fluoride as used in the gaseous diffusion separation process. The strong disadvantages are: The reactor itself must be appreciably larger to be of critical size, or greater; leakage will occur more easily and more shielding is required.

The amount of shielding (See Figures 44 and 45) depends on the type of homogeneous reactor used. For the solid type as shown in Figure 44 a greater amount of shielding is required around the reactor than around the heat exchanger, while in the fluid type, as shown in Figure 45, the same amount of shielding is needed around the reactor and heat exchanger.

HETEROGENEOUS TYPE REACTORS:

The heterogeneous type of reactor has the great advantage over the homogeneous type, in that natural uranium may be used with any practical moderator and sustain a chain reaction. The basic difference between the two types is that in the heterogeneous type the fissionable material is in the form of lumps. These lumps will generally take the shape of a sphere, cylinder or rod. In the January 10, 1947 issue of the "Science" magazine, Enrico Fermi had an article on the size of these lumps with respect to the value of factor-K. Of course there is one other consideration that must be taken into account; that is, the choice of a moderator will change the factor-K with the same size lumps because of the different cross-section of the various moderators. The factor-K has been calculated theoretically as well as experimentally for heterogeneous reactors with various lump sizes. Because this type of reactor will sustain a chain reaction with natural uranium (U^{235} and U^{238}) it may be operated in one of

two ways; one, primarily for power output and secondary for plutonium production, which has been previously discussed.

Many problems are overcome with the use of the heterogeneous piles, the main one being that the uranium rods (assuming uranium rods are used as the source of fissionable material) may be located in a definite lattice arrangement within the reactor and facilities can be made to withdraw these rods and new ones inserted, see Figures 39, 40 and 41. The actual construction of such a reactor would be similar to the reactor in Figure 44; However the cooling could be accomplished more efficiently because the cooling tubes may be placed near the main concentrations of heat thus eliminating any great heat gradient. The heat will be concentrated where fission occurs or around (or within) the uranium rods.

The heterogeneous reactors are also classified as to whether the fuel coolant and moderator are in the solid, liquid or gaseous state. The first type could use solid fuel and a liquid moderator. This was illustrated in the Argonne and Chalk River reactors where natural uranium rods were used and heavy water performed the functions of the coolant as well as the moderator. This dual function is not always recommended because it is difficult to find a material that will meet the nuclear and thermal requirements as well as its chemical properties at high temperatures. As previously discussed heavy water cannot withstand the high temperatures of power reactors and may therefore be substituted by molten metals provided they can have the proper nuclear properties for a moderator.

A second type could use a solid fuel and moderator, and a liquid coolant. This is the type used in the Hanford reactor where uranium

ALCLAD rods were set in graphite and water passed through the coolant pipes.

A third type could use a liquid fuel and a solid moderator. The fuel could be similar to that used in the homogeneous reactor and would also be used as the coolant. The moderator could be the structural material used in the reactor and heat exchanger, or a portion of the solution in the liquid fuel. A large amount of shielding would be needed because of the larger volume and area in contact with the fissionable material and highly radioactive fission products.

INDUSTRIAL AND LOCOMOTIVE USES

The coming of nuclear (atomic) power will probably not be as eventful as many people estimate. Nuclear power will only be a new fuel as in the changes of wood to coal to gas or oil. The source of heat energy will not change the basic design in turbo-generator units because the turbine is independent of the steam generating unit. The only possible change would be in the shielding of the reactor and heat exchanger from the power producing units. At the present time the amount of shielding that must be used causes the reactor to be very bulky but in the near future it is assumed that a shielding material will be developed that is of light weight and only small amounts needed. The use of light weight shielding is practically essential for aircraft use. The use of nuclear power, of course, has a great advantage for various naval and aircraft use in the fact that only very small amounts of fuel (fissionable material) are needed. A submarine or ship could stay at sea for very great lengths of time. As for the disposal of the fission products,

I'm sure that the ocean would not become contaminated if they were dumped as the ship progressed.

AIRCRAFT USES:

At the present time the size, range and speed of all aircraft are limited by the amount of fuel to keep the aircraft in flight for a definite duration of time. The design of aircraft must specify its maximum range and from this determine the weight of fuel needed and then the operating speed to accomplish this range. The total weight of the aircraft must include the structure, engine and required fuel. Using this weight an aircraft will have a maximum range at a given speed. This maximum range cannot be extended under any conditions, unless a lighter weight fuel is used that will still give the same performance. The solution to the aircraft problem seems to be in finding a new fuel. Nuclear power may be the source of fuel (power) that the aviation industry has been looking for. At the present time supersonic planes run out of fuel in a matter of minutes, but with nuclear power the fuel supply is practically stable. Also high speeds may be obtained by the use of nuclear power.

There are several things that must be solved in the designing of a nuclear reactor for aircraft use. The size and weight is of greatest importance; therefore, a reactor that is small in size, light in weight and operating at very high temperatures should be of the type required. If high temperatures and high power output are required from a reactor, it must be of a very high neutron flux type. The high neutron flux (or radiation) will require the use of a very good shield. Another problem will be in the choice of materials to withstand these very high temperatures.

High neutron flux is just a simple matter of control and the temperature range of a reactor must be practically unlimited, as shown in the temperatures obtained in the atomic bomb (billions of degrees Fahrenheit).

The type of aircraft which may use nuclear power will probably be rocket, turbo-jet and ram-jet. The use of rockets has been speculated to a great extent and several presented types are not feasible or practical. One type that is not practical is shown in Figure 46A. This rocket must get its thrust from the recoil momentum of particles emitted. It must be granted that there will be some force present but it will not be sufficient to even move such a rocket.

Figure 46B shows a type of rocket that may operate. In this type of rocket, air is emitted through the nose of the rocket and is then heated as it passes through the reactor. Actually the air is compressed by the forward speed and is then heated by the reactor and expands giving a forward thrust. A problem will occur in getting the proper amount of heat transfer from the reactor to the air as it passes through the reactor. Limitations for this type would be that its efficiency would decrease as its altitude increased and it could not exceed the atmosphere of the earth. This rocket would probably not be self-starting and would need some mechanical device to put it into motion.

In the design of a rocket that is more efficient and may pass beyond the earth's atmosphere the heating of air may be replaced by some other fluid. The choice of this fluid should take into consideration the atomic (molecular) weight of the fluid for most efficient operation. Of the lightest elements hydrogen or helium seems to be the most practical.

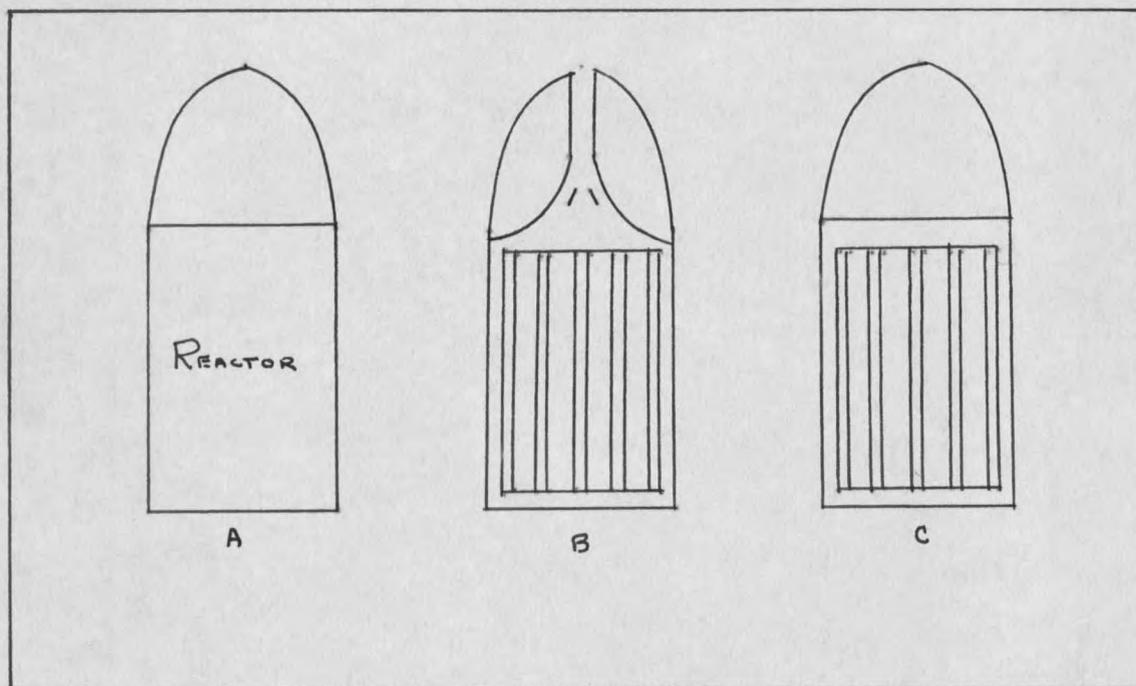


Figure 46 Practical and impractical uses of nuclear power for rocket propulsion

The boiling point of hydrogen is -252.7°C and helium is -268.9°C . The fluid could be stored in the nose of the rocket allowing a small stream to come into the reactor making this type self-starting and able to exceed the earth's atmosphere. Its limitation is the amount of fuel that may be stored which will directly effect the maximum range (Figure 46C).

The turbo-jet may be more practical than the rocket for commercial and military aircraft use. Figure 47 shows an idealized sketch of a turbo-jet engine for aircraft use. In this figure the letters A, B, C, D, and E locate the following parts respectively: air intake, axial flow compressor, combustion chamber, turbine, and exhaust cone (or tail nozzle). Figure 48 shows an actual cutaway model of the Westinghouse J-34 Turbo-

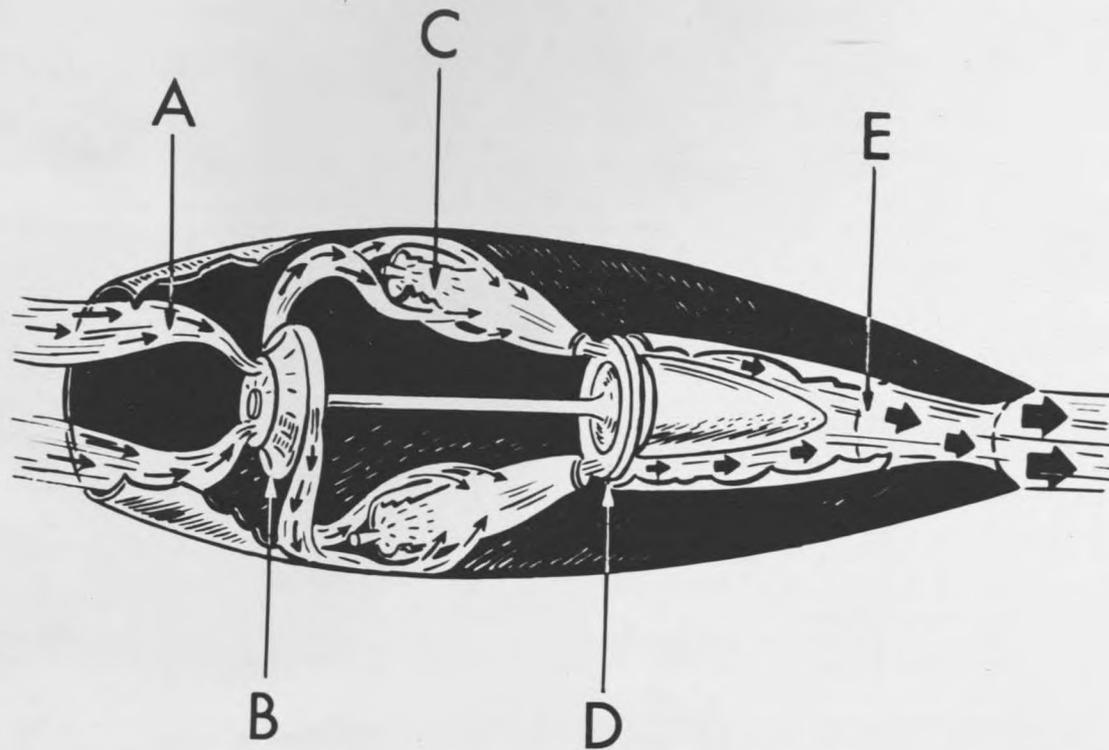
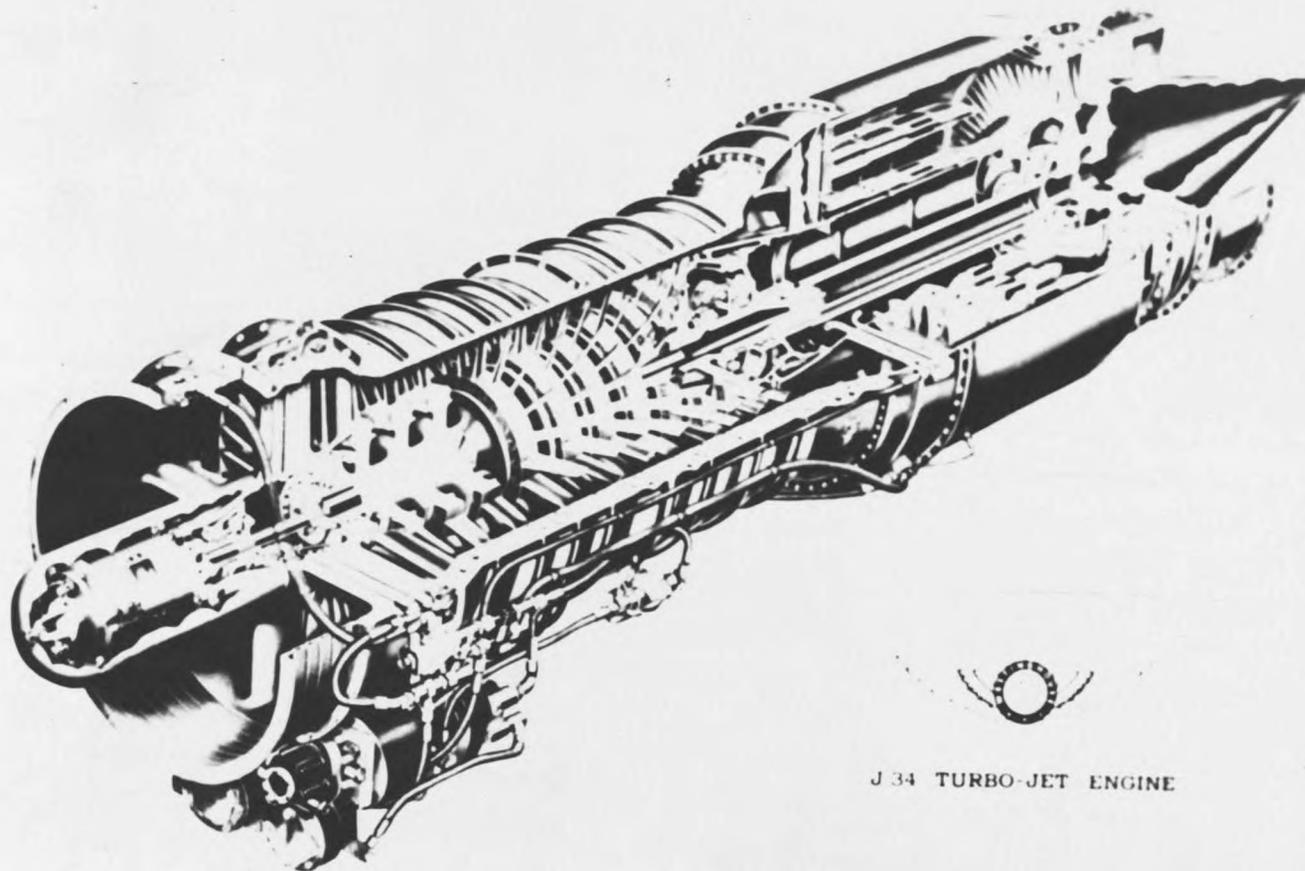


Figure 47 Idealized sketch of a turbo-jet (Courtesy General Electric Company).



J 34 TURBO-JET ENGINE

Figure 48 Westinghouse J-34 turbo-jet engine, cutaway model.

jet Engine used for military aircraft. Figure 49-54 show the various parts of the engine and several test installation views. The designing and calculating of efficiencies of turbo-jets is not thoroughly within the scope of this text. Our problem is to convert the combustion chamber from the use of the combustion of a chemical fuel to a reactor for its heat source. The reaction in the combustion chamber or reactor is just a means of heating and expanding the air. For efficient operation, very high temperatures are required, making the design of a reactor similar to those used in types B and C discussed under rockets. Again the main difficulty is in obtaining the required amount of heat transfer from the reactor to the passing air. This difficulty arises because of the high velocity of the air and the temperature to which it must be heated. The turbo-jet here discussed is used, in aircraft, without the use of a propeller. However, there is another type called propjet (or turboprop) that uses a propeller. The propjet has the advantages over the standard reciprocating engines with a propeller, that is, they are light weight, small diameter, good performance at higher altitudes and faster speeds. It also has the advantage over the turbo-jet in that higher temperatures in the turbine will improve its performance while the turbo-jet will benefit only by flying faster. This is quite obvious because the propellers action will directly govern the aircraft's performance. The Consolidated Vultee P-51 long range jet escort fighter is a good example of jet uses as it has a propjet in the nose and a turbo-jet in the tail, thereby combining speed with performance.

The ram-jet uses the principles similar to the rockets as shown

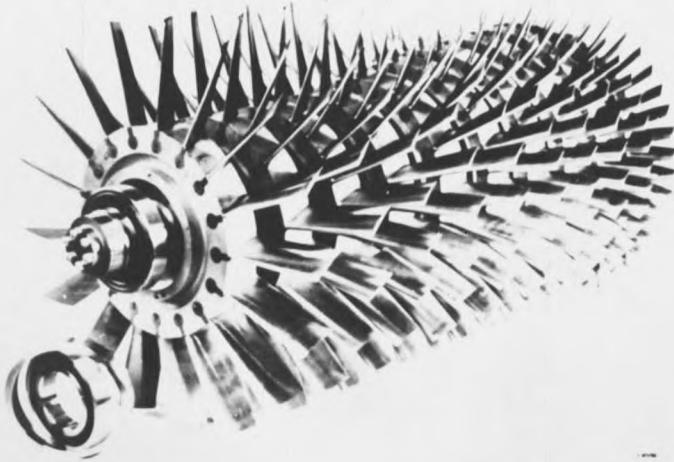


Figure 49 Axial flow compressor blades.

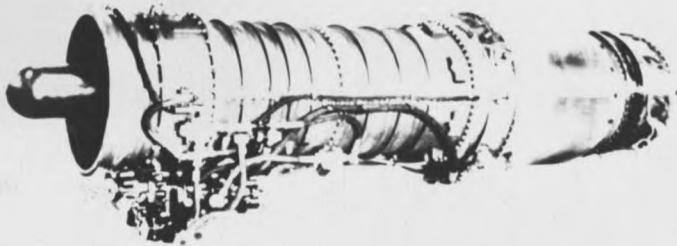


Figure 50 Assembled J-34 unit.

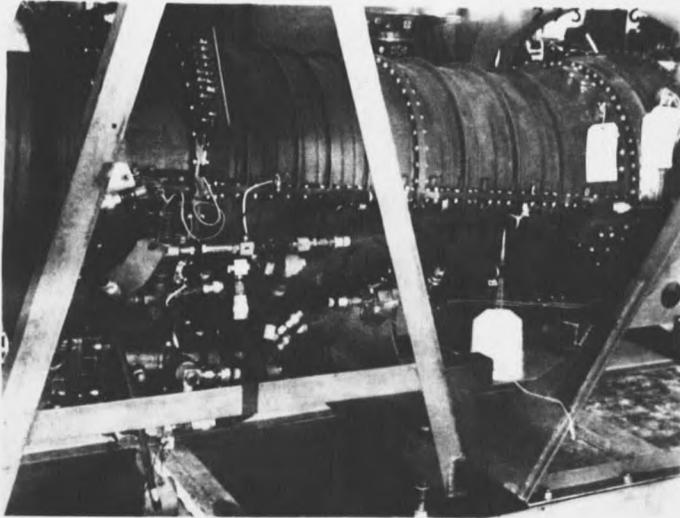


Figure 51 J-34 test installation, side view.

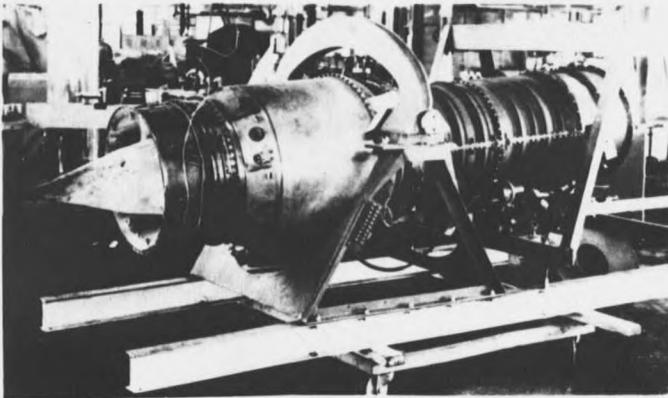
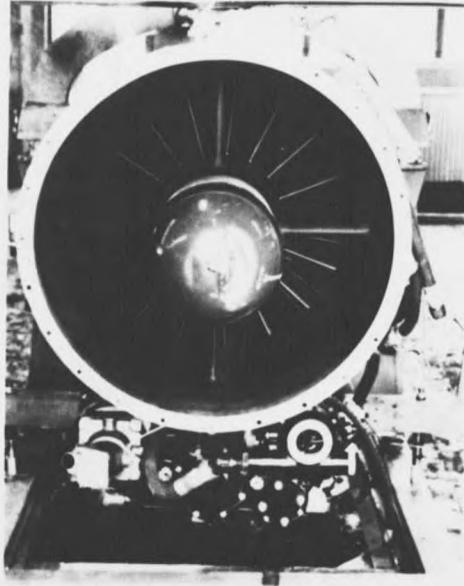


Figure 52 J-34 test installation.



J-34 test installation, end view showing second stage turbine blades and exhaust nozzle.

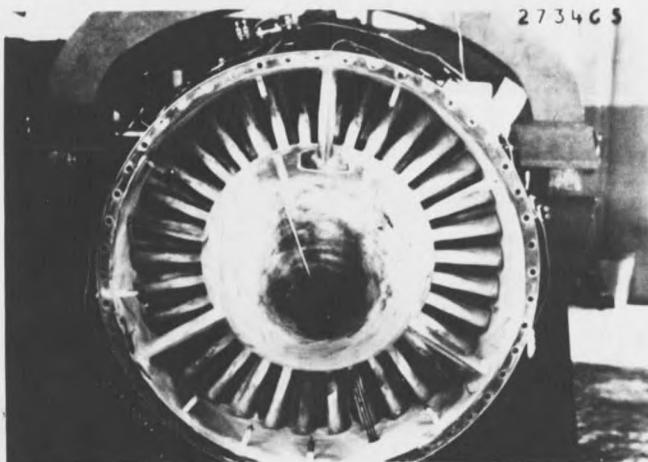


Figure 54 J-34 test installation front view.

in Figure 46B. Also unlike the turbo-jet it has no compressor but depends on the ramming effect of the entering air (pressure head) through a venturi type arrangement. It is then heated and goes into the exhaust nozzle where it expands and increases in velocity, thus creating a forward thrust. Again the heating may be done by a reactor in place of the combustion of chemical fuels. Another similar type is known as the pulse-jet but is still in the preliminary design stage.

POWER STATIONS:

The use of nuclear fission in reactors for the production of useful electrical energy may be accomplished in various manners. The simplest conversion of fission to electricity would be to use water as the coolant (or coolant and moderator) and have the water to steam conversion occur in the reactor. The steam may then be used in a turbo-generator unit for the final conversion. The pressure and temperature of the steam could be regulated by controls within the reactor. The exhaust steam from the turbine would be condensed and then pumped back into the reactor as feedwater. During World War II, the Hanford Works operated a nuclear reactor using water as the coolant. However, this reactor was specifically designed for plutonium production and not useful power. The water coolant was not heated to the extent of forming steam and the hot water was just dumped into the Columbia River. This reactor did not incorporate high temperature and pressure steam and therefore made the design of its coolant system comparatively simple. But for our use, we must design a reactor for these high temperature and pressures. The limitations of this type of reactor have been previously discussed and warrant no further

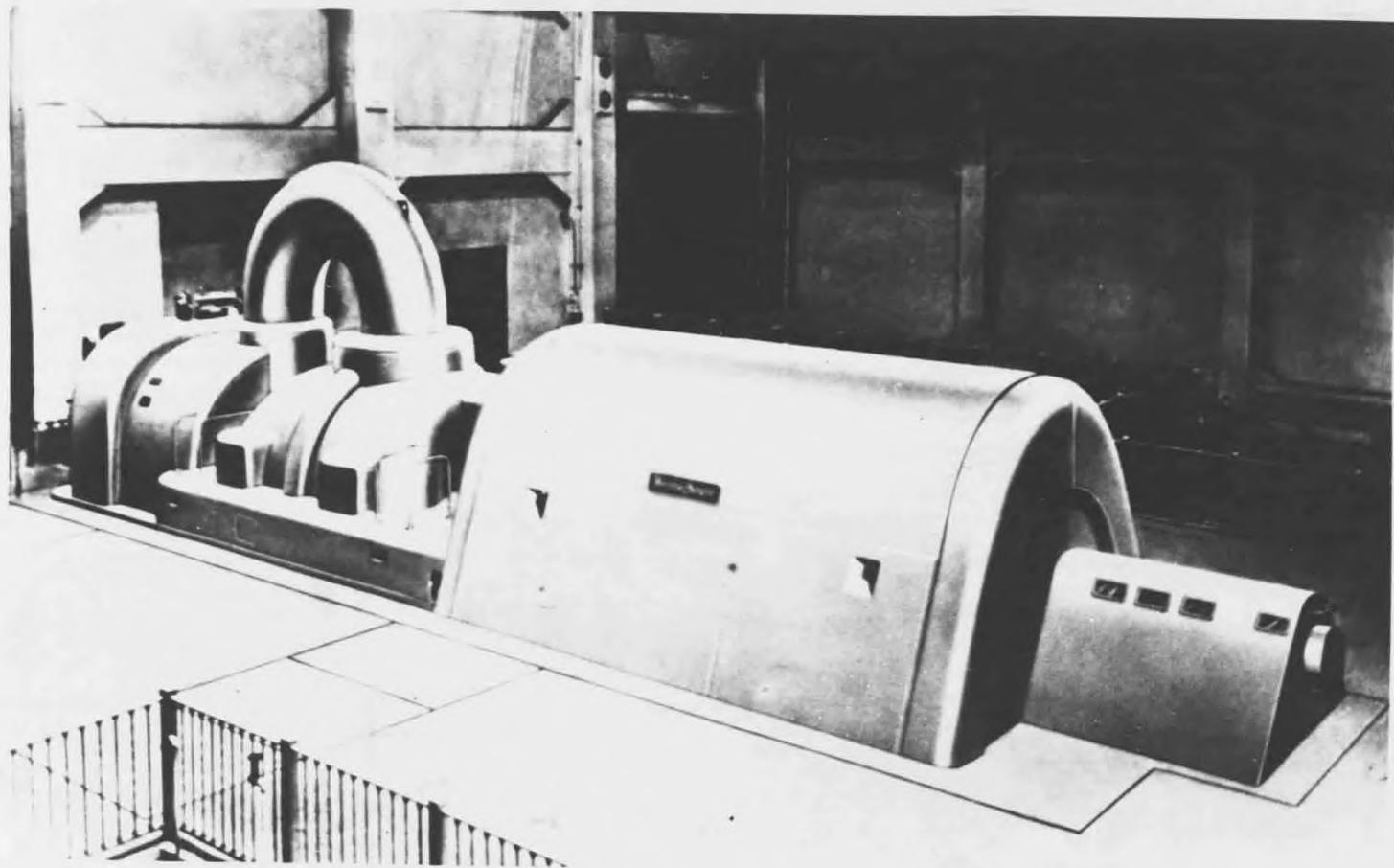


Figure 55 Westinghouse steam turbo-generator power station.

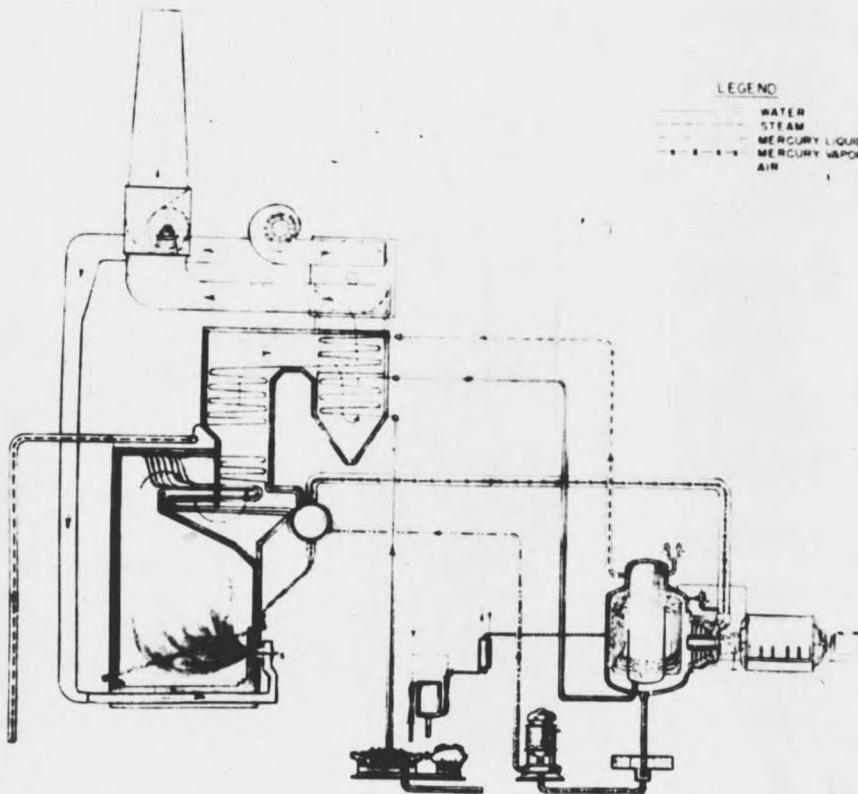
mention. Also previously discussed was the use of molten metal as the coolant. This type of reactor would heat the metal to a high temperature and pump it through a heat exchanger where it could transfer its heat to water thus forming steam. In either case, the greatest loss of heat is in the condensing of the exhaust steam before it is used for feedwater and reconverted to steam. For this reason, the "topping" process is quite often used to utilize more of the available heat thereby increasing the efficiency of the unit. Where the steam produced in the boiler (or reactor) will be of greater pressure and temperature than actually needed, it will be used for a useful output in some prime mover before going to its actual designed use, the basis of the "topping" process. For instance, let us consider an industrial plant that uses steam for heating. The useful output from the boiler (or reactor) may be increased greatly per pound of fuel used if the boiler would produce steam at a higher temperature and pressure. The steam may then be used to turn a turbine that may generate electrical energy or possibly coupled to a compressor. The exhaust steam from the turbine is then used for heating purposes. A good example of this is here at Montana State College campus where the exhaust steam from the exhaust pumps and feedwater pumps is used to heat the engineering laboratory and building. The reason for the increased efficiency is the steam that is utilized more than once before being condensed and used for feedwater. This may be more readily understood if we assume the steam from the boiler to have an enthalpy of 1300 BTU's/lb. of which 970.4 BTU's/lb. were used in converting the feedwater to steam, showing that approximately 75% of the steam's enthalpy was consumed to latent heat.

Therefore, if the steam is used more than once before condensing, the efficiency of the entire unit may double.

MERCURY VAPOR PROCESS:

The "topping" process is not new, in fact, a binary type system was used as early as 1923 by the Hartford Electric Light Company at their South Meadow Station with a capacity of 10,000 Kw. Several other installations have since been made with capacity up to 20,000 Kw. These binary systems all used a mercury turbine superposed on a steam turbine. The saturation pressures of mercury vapor are considerably lower than those of water vapor so that mercury vapor may be employed at relatively high temperatures without encountering the high pressures that occur with steam. The General Electric Company have lead in the development of the mercury vapor process and mercury turbine. Figures 56 and 57 show a schematic flow diagram and isometric section respectively of a mercury vapor power plant.

As shown in Figures 56 and 57 heat from the burning fuel is absorbed by liquid mercury within the tubes of the mercury boiler to form mercury vapor, which passes from the boiler to the mercury-turbine, where it releases a portion of its energy to produce electric power. The vapor from the turbine is exhausted to the vacuum shell of the mercury condenser boiler. There it condenses and releases its heat of vaporization to water within the tubes. The liquid mercury is returned from the sump, or hot well, to the boiler by a mercury feed pump, or by gravity as the case may be. It is interesting to note that if the liquid mercury is 50 feet above the lowest boiler tubes, approximately 300 PSI is available to



601900 5000-KW UNIT MERCURY POWER PLANT. SCHEMATIC FLOW DIAGRAM.
FILING NO. 480 E323 2-10-44

Figure 56 5000-Kw unit mercury power plant.
Schematic flow diagram.

cause circulation at an operating pressure of 150 PSI, without the use of a pump. Going back to the feedwater which absorbs heat from the condensing mercury vapor is boiled into steam at any desired pressure. This steam is then superheated in tubes located in gas passages of the mercury boiler (Figures 56 and 57). This superheated steam is then available to drive the steam turbine. If the mercury boiler is replaced by a nuclear reactor the superheating may have to be done in the mercury condenser boiler for reasons explained under Reactor Design.

It is interesting to note that the steam thus produced by the binary cycle is only slightly less in amount than it would be if the equivalent fuel were burned directly in a steam boiler, thus greatly increasing the efficiency of the total unit. In fact a steam turbine plant capacity may be increased some 60 percent for the same quantity of condensing water by mercury topping. For example, the new Schiller Station at Portsmouth includes a 25,000 Kw steam turbine which in effect is topped with 15000 Kw of mercury capacity. For the 40,000 Kw total capacity, only 25,000 Kw are effected by the usual condenser losses.

The question may arise as to the heat transfer of mercury in the tubes because of its non-contact characteristic. This is overcome by using titanium-magnesium treated mercury in the boiler which produces an intimate and perfect contact between the metal of the tubes and the flowing mercury forming a "wetted" surface.

The original South Meadow Plant was rebuilt in 1931 and not dismantled until 1947 after operating more than 116,000 hours. The turbine is of the single flow type, five stage and operating at 720 RPM. No appreci-

able wear was shown even though no maintenance or internal repairs were done during its 16 year operation. It has now been replaced by a 15000 Kw mercury turbine but the majority of the original parts were used for the new installation. The following table was made during a test run in February 1949.

TABLE IX

15000 Kw South Meadow Mercury Unit

Twenty-eight consecutive days operation at full load

Pounds oil burned	12,281,169
Pounds steam generated at 250PSig & 700TF	126,118,000
Kw-hr gross output from vapor driven generator	10,048,000
Kw-hr gross generated from steam	11,387,000
Kw-hr total auxiliary usage	565,000
Kw-hr net total unit output	20,870,000
Fuel rate - lb. oil/net Kw-hr	0.588
Heat rate, BTU/net Kw-hr	10,200

Table IX shows that to produce 20,870,000 Kw-hr of available energy 12,281,169 pounds of fuel oil were used. It should be of interest to calculate the amount of oil used in comparison to the amount of U²³⁵ required in a reactor to produce the same amount of heat. Assume the oil to have a density of 40 lbs. per cubic foot and a cost of \$0.15 per gallon.



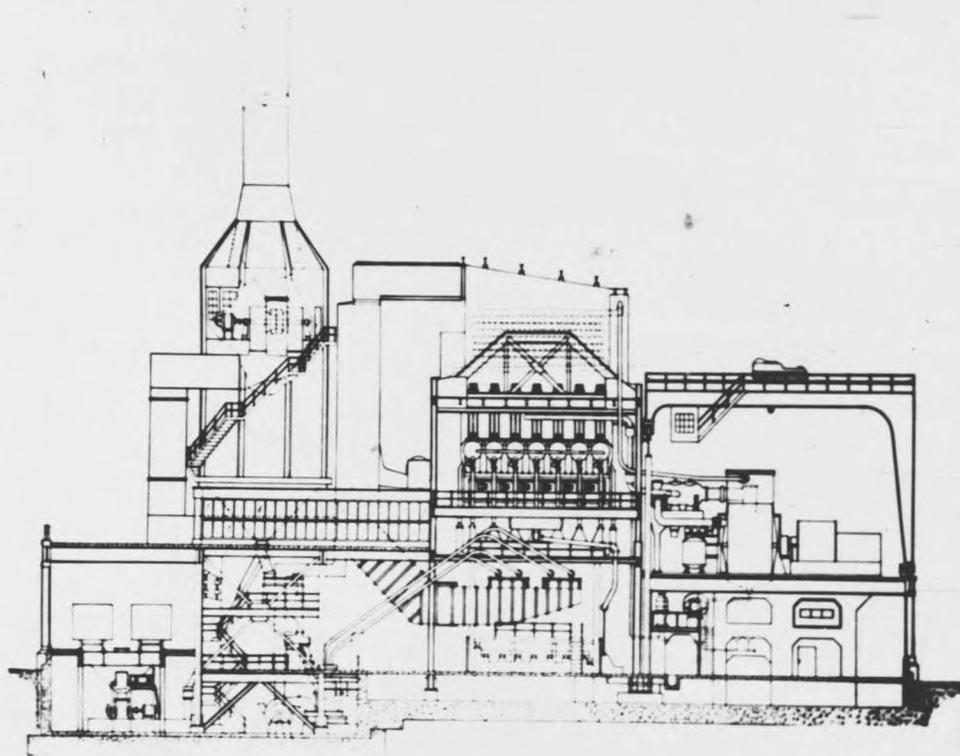
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G-E OUTDOOR MERCURY-STEAM-ELECTRIC POWER STATION
NORTHEAST-CORNER VIEW FROM ABOVE.
BUILDING 255, G-E SCHENECTADY WORKS.

FILING NO. 170E E328 E329 10-9-35

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Figure 58 G. E. outdoor mercury -steam-electric power station.



489914 G-E OUTDOOR MERCURY-STEAM-ELECTRIC POWER STATION.
VERTICAL SEMI-SECTION.
BUILDING 265, G-E SCHENECTADY WORKS.
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Figure 59 G. E. outdoor mercury-steam-electric power station vertical semi-section.

$$\frac{40\#/cu. ft.}{7.48 gal./cu.ft.} = 5.37\#/gal.$$

$$\frac{12,281,169\#}{5.37\#/gal.} = 2.29 \times 10^6 \text{ gals.}$$

$$\$0.15 \times 2.29 \times 10^6 = \$349,000$$

assume each fission of U^{235} releases 200 Mev.

$$(20,870,000 \text{ Kw-hr})(10,200 \text{ BTU/Kw-hr}) = 2.13 \times 10^{11} \text{ BTU}$$

this is the amount of heat released by the oil

$$\frac{(2.13 \times 10^{11} \text{ BTU})(6.62 \times 10^{15} \text{ Mev/BTU})}{200 \text{ Mev}} = 7.01 \times 10^{24} \text{ Fissions}$$

each fission requires one atom of U^{235} with a mass of 235.1269 amu,

$$\frac{(7.01 \times 10^{24})(235.1269 \text{ amu})(1.65 \times 10^{-24} \text{ gms/amu})}{(453.6 \text{ gms/lb})} = 6.06 \text{ lbs.}$$

the reactor would use only 6.06 pounds of U^{235} . Assuming the price of U^{235} to be \$100 a pound, the ratio of the costs between chemical (oil) fuel and nuclear fuel would be 580:1, this may not be a good comparison because the nuclear reactor will probably cost more initially than the mercury boiler. Assuming the initial costs of construction to be 10:1 the ratio of the total costs would still be 58:1 in favor of nuclear fuel. This ratio could be further increased by using natural uranium (at \$7.00 per pound) rather than U^{235} .

GAS TURBINES:

Even though the gas turbine has been in existence for more than

150 years there are only a few in actual use. The reason for this is probably due to the fact that few engineers understand the gas turbine and the high temperatures that it must operate at to develop more power than is consumed by its own compressor. The simple gas turbine cycle comprises three devices; an air compressor, a combustor and a turbine. As shown in Figure 60 air enters the axial flow compressor at atmospheric pressure where it is compressed to the required pressure and is then heated in the combustion chamber, the hot air under pressure then strikes the blades of the turbine thus causing it to rotate. The compressor, turbine and generator are all mounted on one shaft, causing the gas turbine cycle to require an external source of starting until the compressor is functioning. There are two general types; the open cycle where the gas (air) passes through the cycle once and is then exhausted to the atmosphere; and the closed cycle where the same gas is circulated through the cycle over again. The open cycle is the same as used in the turbo-jet, Figure 47. The gas turbine may be summed up with the following:

1. As compared to steam, the gas turbine cycle uses very large volumes and small temperature and pressure drops. The gas turbine cycle uses from four to six times more air than is required for perfect fuel combustion, instead of 20 to 25 per cent more as in the steam cycle.
2. The gas turbine is not self-starting.
3. The simple gas turbine cycle requires no water, either for use in the cycle or for cooling.
4. The gas turbine is not reversible.

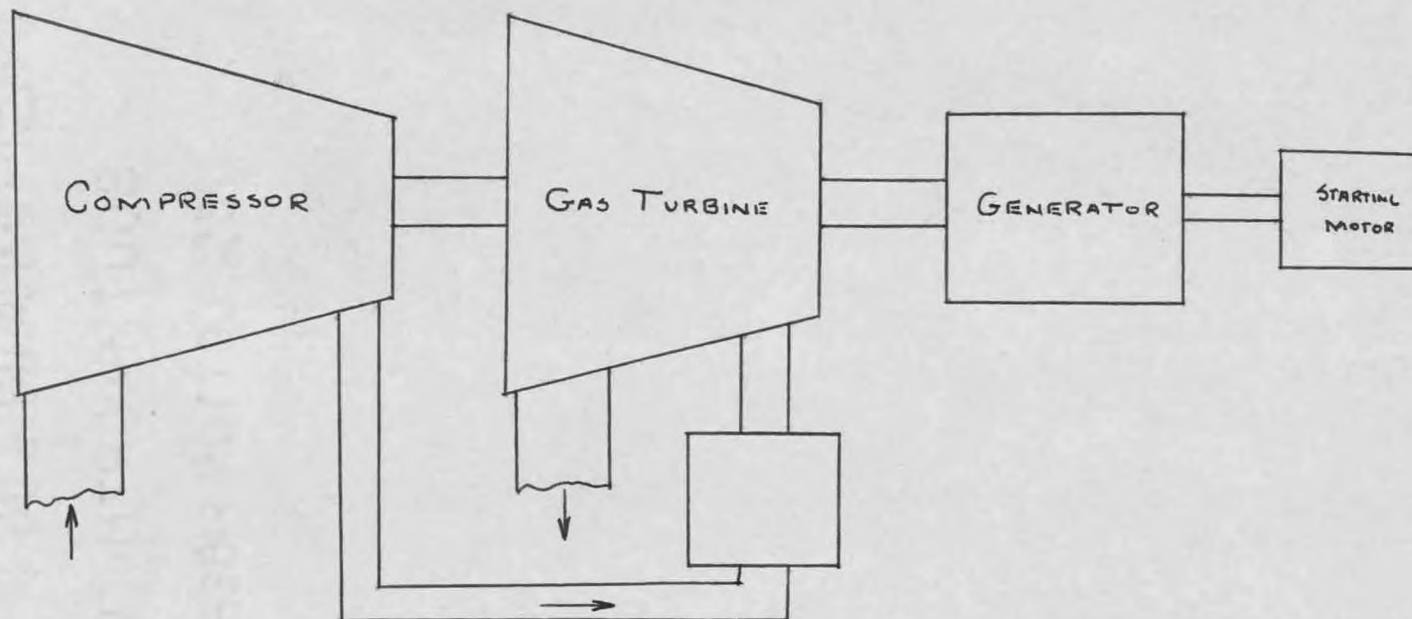
5. The efficiency of a gas turbine at full load is satisfactory and the control is simple. However, at partial load the efficiency of the open cycle gas turbine falls off sharply unless complicated features are added.
6. The high temperatures required has caused deterioration of structural materials used. This is being overcome with the advancements more in metallurgy during the war.

The simple open cycle has a maximum output of approximately 7500 Kw and may be increased with the addition of one or more features. The efficiency may also be increased by using one or more of the following:

- (a) Regenerator, use the exhaust gas from the turbine to pre-heat the gas before going into the combustion chamber.
- (b) Use two stage compression with an intercooler between, this may reduce the power consumed by the compressors as much as 15%.
- (c) Fuel reheater, use a two stage turbine with combustion chamber between.
- (d) Use of a closed cycle.

With the use of a, b and c in an open cycle, operating at 1200° F, the thermal efficiency may be raised from 20% to 32% with respect to the simple open cycle. This efficiency may still be increased with the use of a closed cycle or increased temperatures.

From a purely theoretical standpoint the combustion gas turbine cycle holds forth greater promise of efficiency than the steam cycle. Of more value as a basis of judgement are the thermal efficiencies obtainable



-191-

Figure 60 The Simple Open-cycle Gas-turbine Power Plant

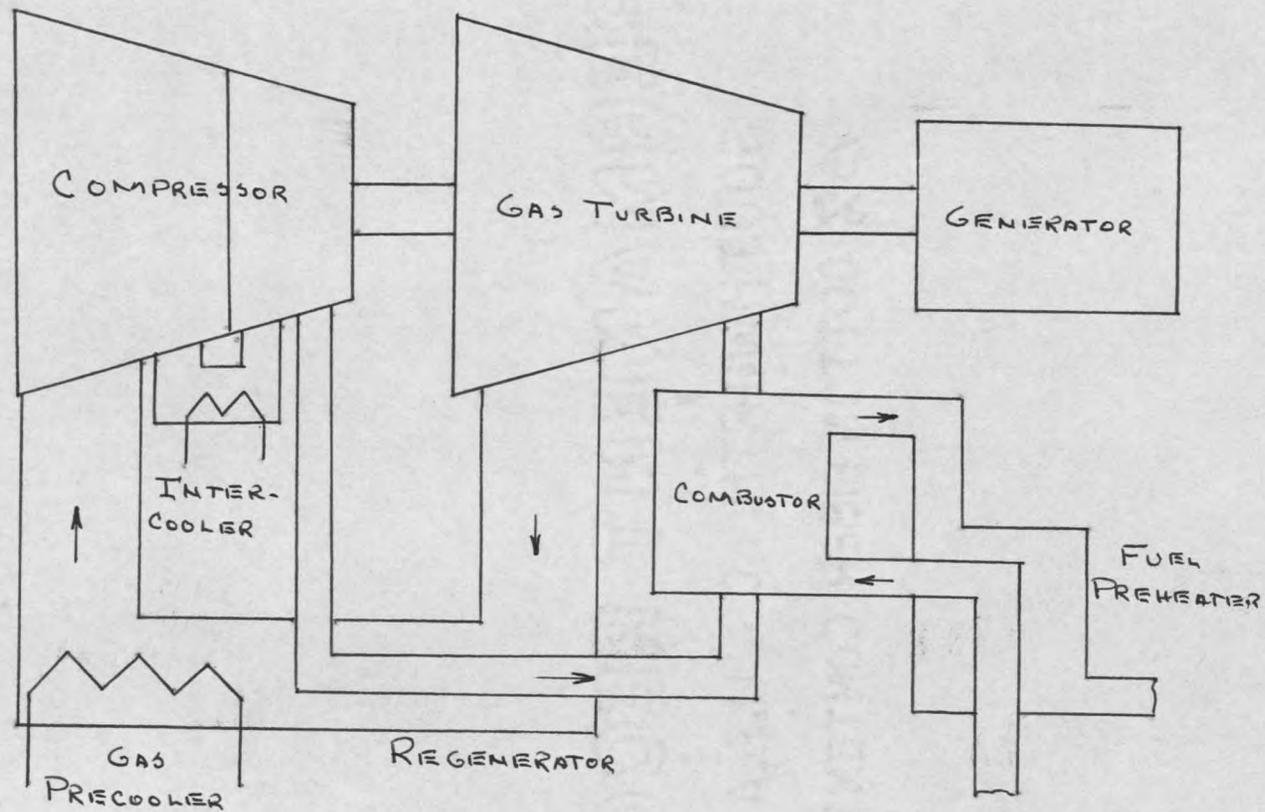


Figure 61 Complex Gas-turbine Cycle using Regeneration, Intercooling and Air Preheating

in practical applications. Above 1000 degrees the gas cycle efficiency increases approximately three times as fast as the steam cycle efficiency.

The possible applications of the gas turbine are numerous and important. In the simple open cycle for small capacity and the closed cycle units for larger, the device offers possibilities of competing with most types of engines and prime movers.

For an example, use an open cycle with a regenerator and inter-cooling between compression stages (Figure 62). If the power from the generator is 1000 Kw find the U^{235} used in 24 hour a day operation for one year. Assuming a gas temperature of 1200° F the overall thermal efficiency would be 29%.

$$\begin{array}{l} \text{output} \qquad 1000 \text{ Kw} \times 24 \text{ hr} \times 365 = 8.76 \times 10^6 \text{ Kw-hrs.} \\ \text{input} \qquad \frac{8.76 \times 10^6}{.29} = 30.2 \times 10^6 \text{ Kw-hrs.} \end{array}$$

assuming the efficiency of the reactor to be 30%.

$$\frac{30.2 \times 10^6}{.30} = 100.7 \times 10^6 \text{ Kw-hrs.}$$

the reactor must release an amount of energy equal to 100.7×10^6 Kw-hrs.

Each fission of U^{235} will release 200 Mev

$$200 \text{ Mev} \times 4.45 \times 10^{-20} \text{ Kw-hr/Mev} = 8.9 \times 10^{-18} \text{ Kw-hr}$$

$$\frac{100.7 \times 10^6}{8.9 \times 10^{-18}} = 1.13 \times 10^{24} \text{ Fission}$$

Each fission will require 235.1269 amu of U^{235}

$$(1.13 \times 10^{24})(235.1269)(1.66 \times 10^{-24}) = 443.6 \text{ lbs/yr.}$$

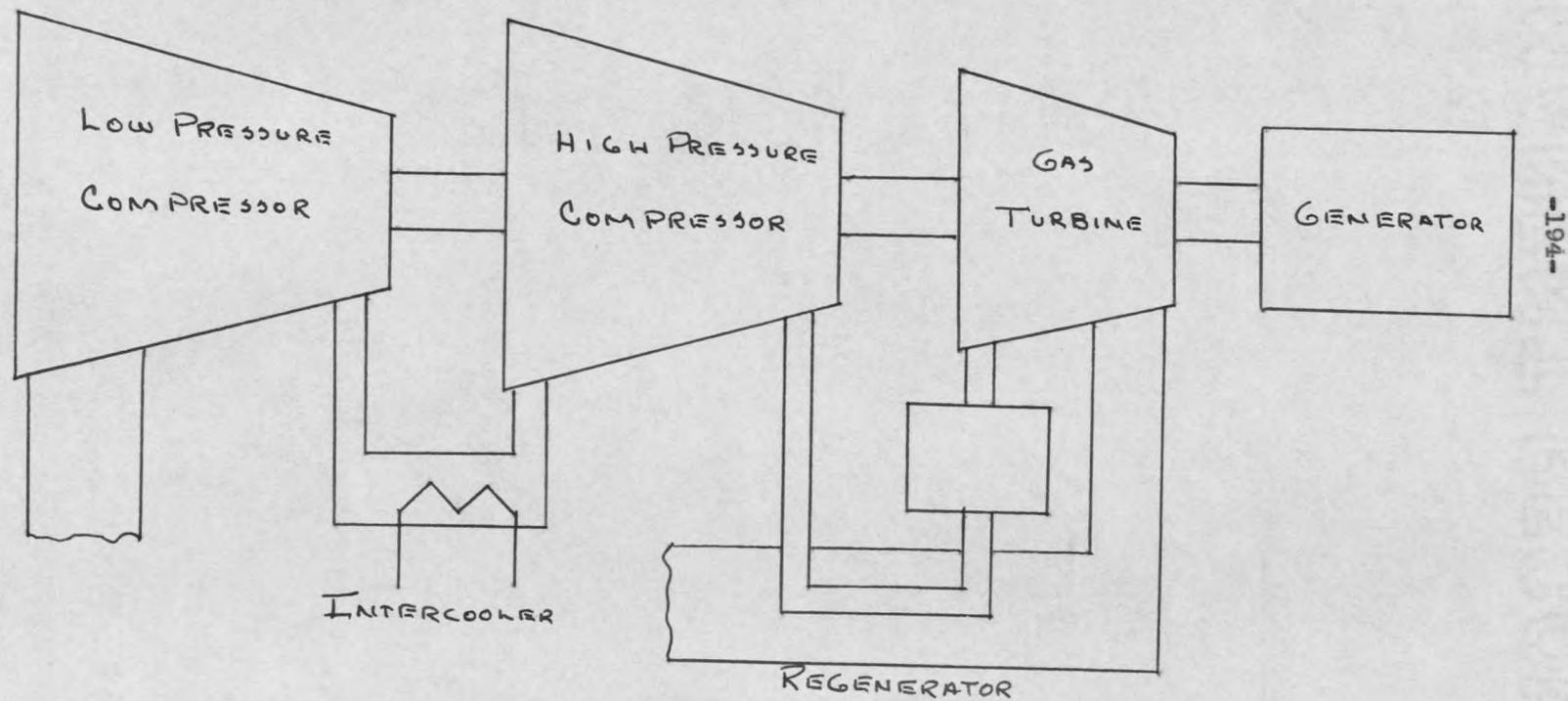
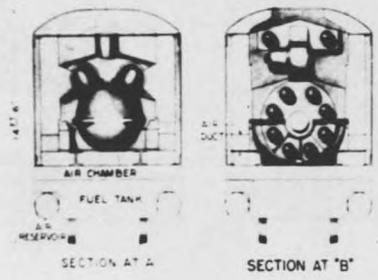
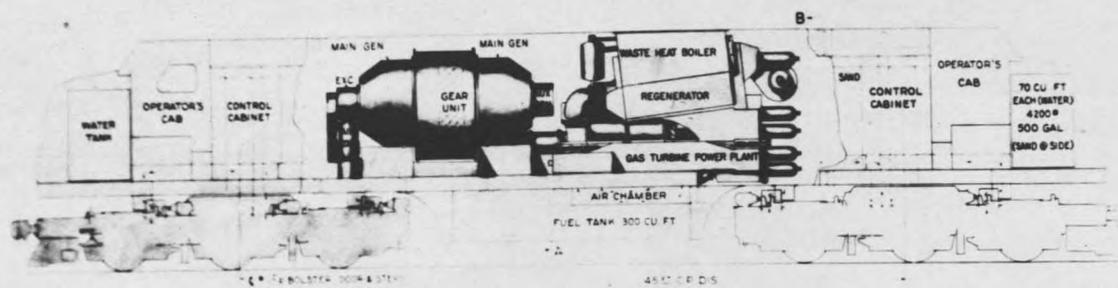


Figure 62 An Open-cycle Gas-turbine with Regeneration, and Intercooling between a two stage compressor

For an output of 10,000 Kw for one year would require only 36.7 pounds of U^{235} , an amount that could be carried around by hand, as compared to the equivalent amount of coal required in a steam unit (approximately 110 billion pounds of coal). However it is interesting to note that coal, in the pulverized form, will be used as fuel for gas turbines in the very near future. A great deal of development work has been performed by the Locomotive Development Committee of the Bituminous Coal Research Institute under the able direction of Dr. J. I. Yellott. The main obstacle is the coal ash which eats away the turbine blades. For our problem, using a nuclear reactor in place of the standard combustion chamber, will be in getting the required heat transfer to the gas flowing through the reactor. As previously mentioned the gas turbine cycle requires great amounts of gas (air) that must be heated to a very high temperature. The best transfer from the reactor will be, in the most part, by means of conduction. Therefore, the air will have to pass through many parallel connected tubes in the reactor to insure maximum conduction.

LOCOMOTIVE:

The simple open gas cycle requires no water. It is low in weight and it combines simplicity of design with small space requirements. With an efficiency approximately of 20 per cent at $1200^{\circ}F$, and the expected low maintenance of turbine apparatus it should prove a good locomotive drive. It possibly will offer strong competition to Diesel powered locomotives. The General Electric Company has constructed a gas turbine for 4800 HP locomotive drive, shown in Figures 65-68.



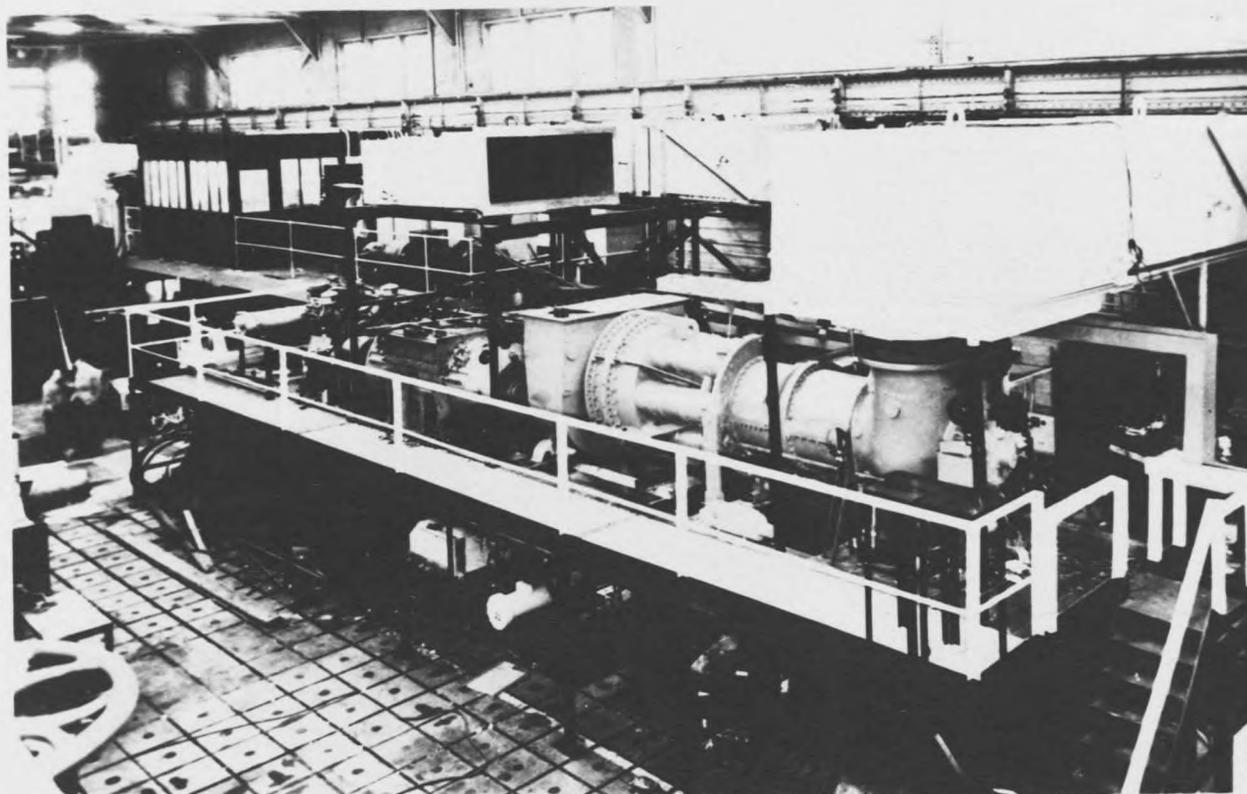
COMBUSTION GAS TURBINE
LOCOMOTIVE

GENERAL ELECTRIC COMPANY



604109 G-E GAS-TURBINE LOCOMOTIVE IN SHADED CUT-AWAY SECTION.
2 CROSS-SECTIONS ALSO SHOWN.

Figure 63 G. E. gas-turbine locomotive cut-away section.



1071 01 G-E GAS TURBINE FOR 4800-HP LOCOMOTIVE DRIVE. GENERAL VIEW OF TEST INSTALLATION UNDER CONSTRUCTION IN BUILDING 49 OF G-E SCHENECTADY WORKS.

Figure 64 G. E. turbine for 4800 HP locomotive drive. General view of test installation.

This General Electric 4800 HP unit is of the straight through type, in line arrangement of compressor, combustion chambers and turbine which results in a maximum of simplicity and a minimum of pressure losses. This simple design was decided upon both on the basis of the study of the economics of the railway application and because simplicity is inherently desirable. Simplicity was particularly desirable in the first power plant designed for relatively long life and for heavy fuels compared with aircraft practice. On the economic side, when space, weight, and cost of apparatus, as well as cost of fuel were considered, it seemed quite conclusive that neither a regenerator or other elaborations of the cycle were justified.

The plant is rated 4800 shaft horsepower for the locomotive application when running 6700 RPM with 1400°F turbine inlet temperature. The design altitude is 1500 feet with 80°F ambient air temperature.

The 15 stage axial flow compressor pumps approximately 70,000 cfm through a pressure ratio of about 6 to 1. The wheels of the first six stages are of aluminum alloy to reduce weight and rotating inertia. There are small gaps between the wheels at the rim to eliminate as far as possible any rotor bending effects caused by local heating as possible rubbing. The blades were made from 13 per cent chrome steel. Lubrication for the compressor creates a problem because experience with similar compressors for aircraft service has shown that if lubrication oil is permitted to enter the compressor with the air over any extended period of time a dirty varnish-like coating is formed on the blades and the efficiency

decreases appreciably. This plant was designed so that no lubricating oil from the unit can enter the air path of the compressor and the favorable results of the test runs show this precaution to be fruitful.

There are six all metal combustion chambers (Figure 68), in which the Bunker "C" fuel is burned, generally similar to that developed for the aircraft units. The outer casing is carbon steel, while the inner is stainless material. Each liner is approximately 35 inches long and 10 inches in diameter. Air enters the inner liner through the annular slits between the various sections, through radial holes and through louvers holes, excellent combustion is obtained over a wide range with good stability and ignition characteristics, and with good cooling of the liner. Ignition is by means of spark plugs located in two of the six combustors. When these two chambers fire, the others are ignited through the cross-ignition tubes interconnecting the chambers at the forward end. The unit uses diesel fuel when starting and after attaining idling speed is changed over to Bunker "C" fuel. The Bunker "C" fuel is preheated to between 200 and 300^oF before atomization.

The unit is started by means of one of the main locomotive generators used as a motor, the power for which is supplied by a diesel engine driven generator. The motor brings it to firing speed, about 55 RPM, in about 45 seconds, when the ignition is turned on and diesel fuel is admitted to the nozzles. Within a few seconds ignition takes place. During the next 155 seconds the unit accelerates to idle speed, 4700 RPM, where it runs under control of the governor, ready for load but with diesel fuel. The unit is then ready for load operation and conversion to

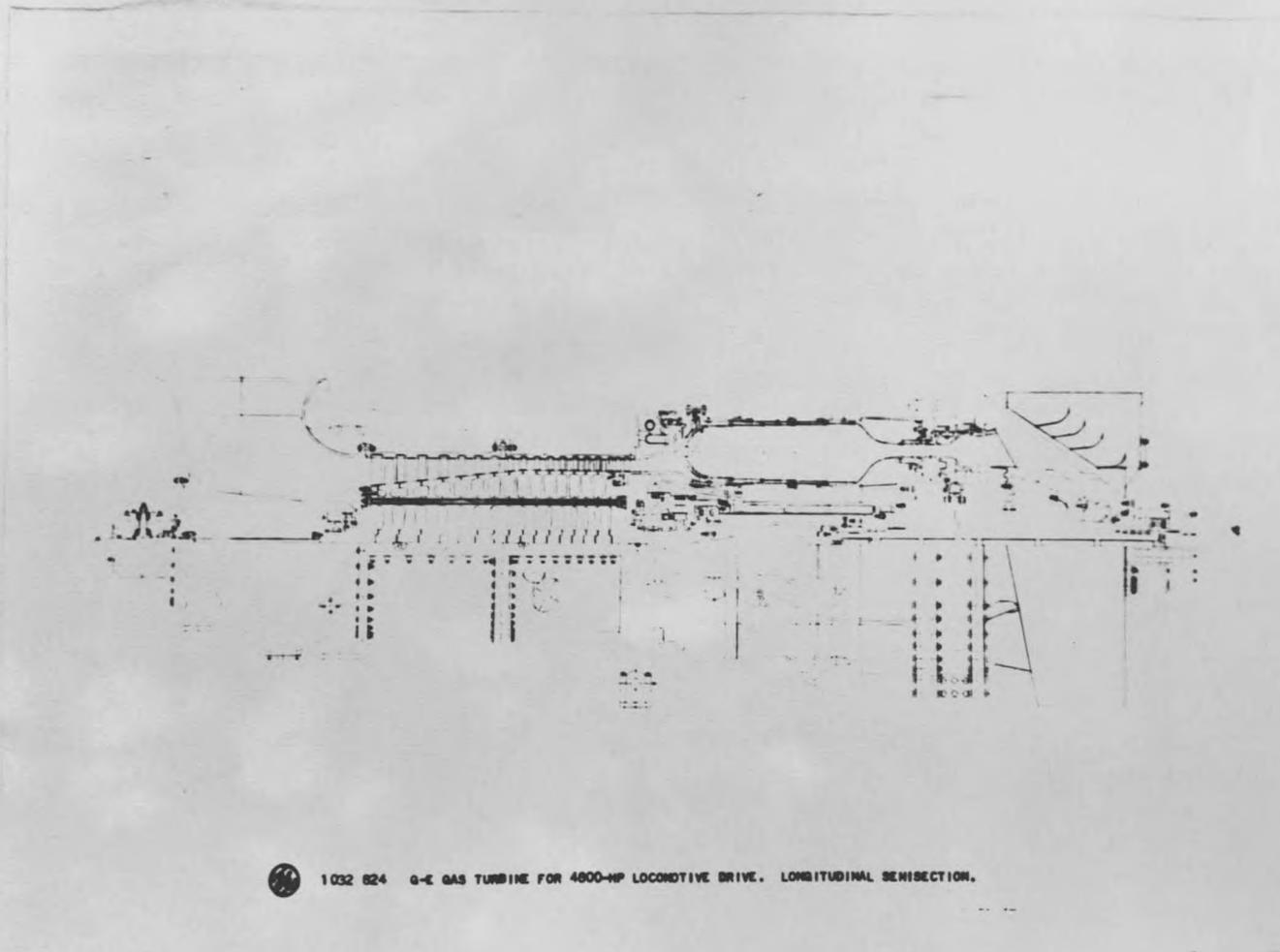
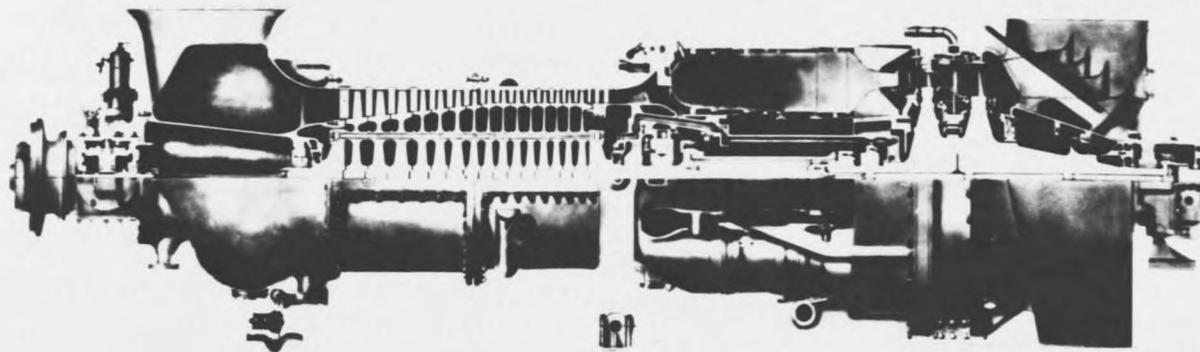


Figure 65
G. E. gas turbine for 4800 HP locomotive drive, longitudinal semisection.



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GE TURBINE FOR 4800 HP LOCOMOTIVE DRIVE. SHADED LONGITUDINAL SEMISECTION
SEE FIGURE 66 FOR DETAILS

Figure 66 G. E. gas turbine for 4800 HP locomotive drive. Shaded longitudinal semisection.

Bunker "C" fuel.

As installed in a locomotive it would drive d-c generators through a reduction gear. The general arrangement can be seen in Figure 64 showing the test set up. The base of girder construction resembles part of a main frame of a locomotive.

The conversion of the combustion chamber to a nuclear reactor will require much engineering to overcome the present day problems. Most of these problems are the same as those confronted in the turbo-jet used for aircraft. Proper heat transfer may prove to be the greatest problem second to size and weight. For locomotive use the size limitation is very exact while in the aircraft field weight is generally most important. The size of a locomotive (for railway service) must not exceed 10 feet in width in order to be used on standard existing rails. In this General Electric unit six combustion chambers are used, while for nuclear reactor use the reactor may have to be doughnut shape with the drive shaft from the turbine to the compressor running through the hole. Through the reactor must pass many tubes to allow the flow of air to pass from the compressor to the turbine and be heated in doing so. The air must be heated to at least 1200° F for efficient operation which may require the use of more than one reactor; the first for preheating to approximately 800° F and the second for the final heating. With the use of two reactors the first may be of moderate neutron flux and the second of high neutron flux which may keep the reactors within the 10 feet limit. However, operation of a reactor, at least at these high temperatures, may not be practical and only used to preheat the fuel and air. The reactors being

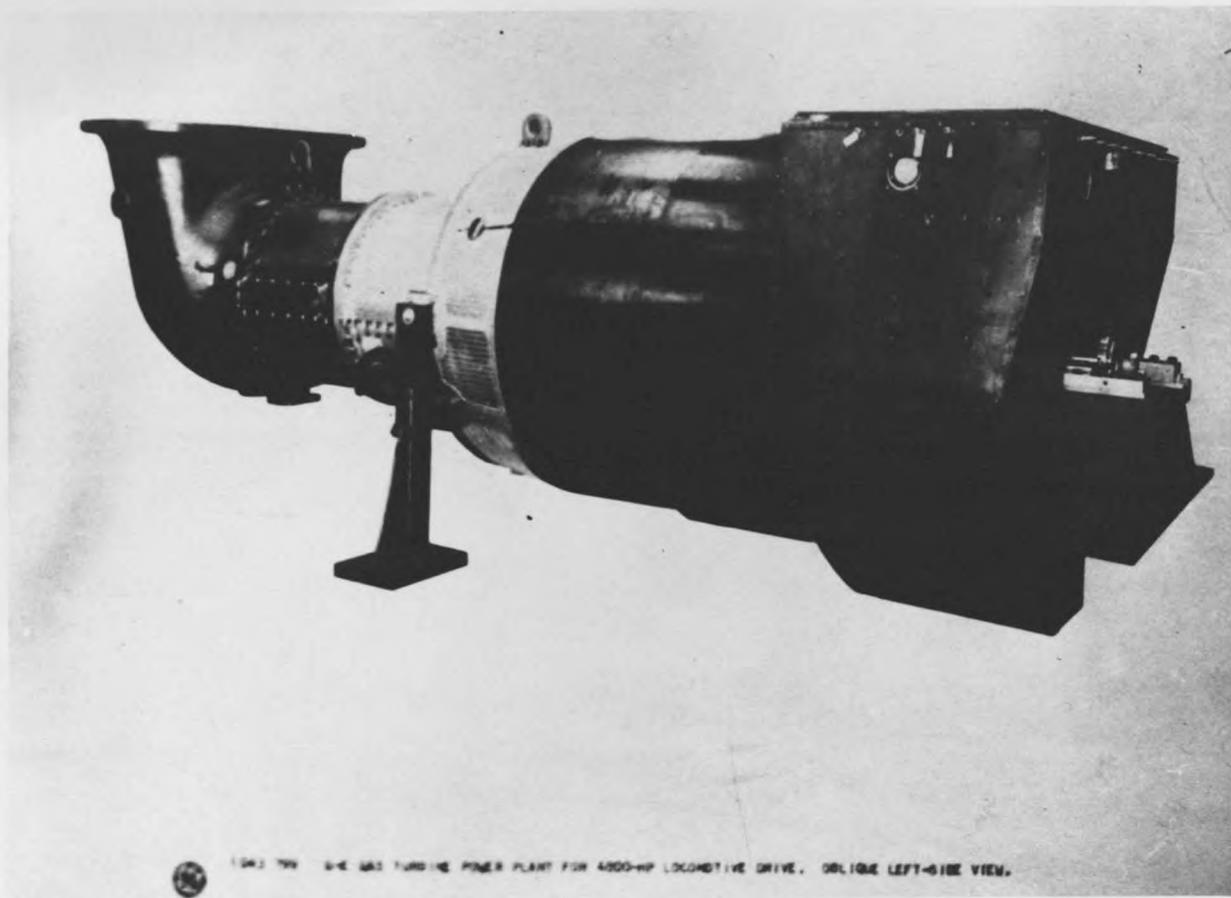
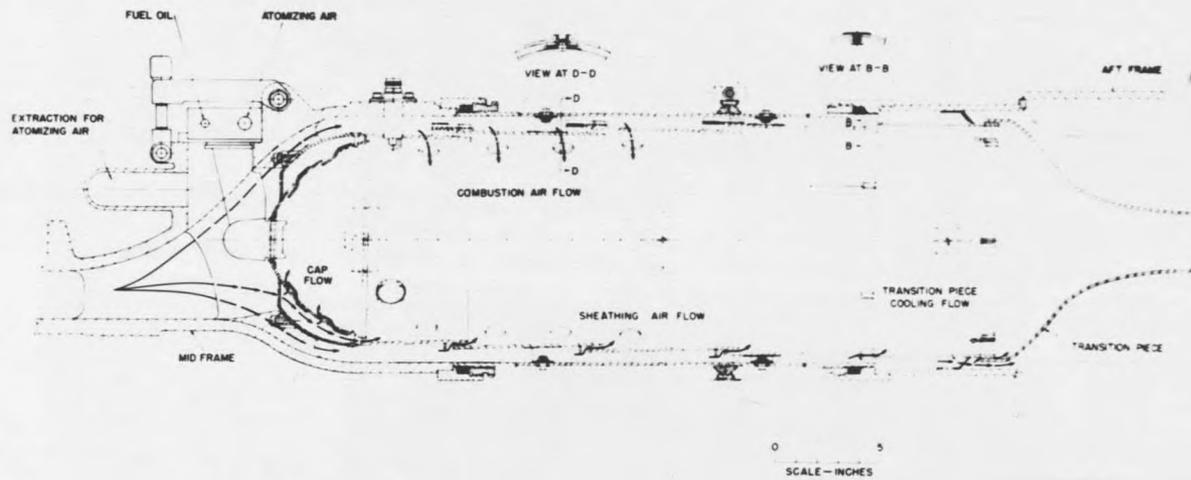


Figure 67 G. E. gas turbine power plant for 4800 HP locomotive drive. Oblique left-side view.



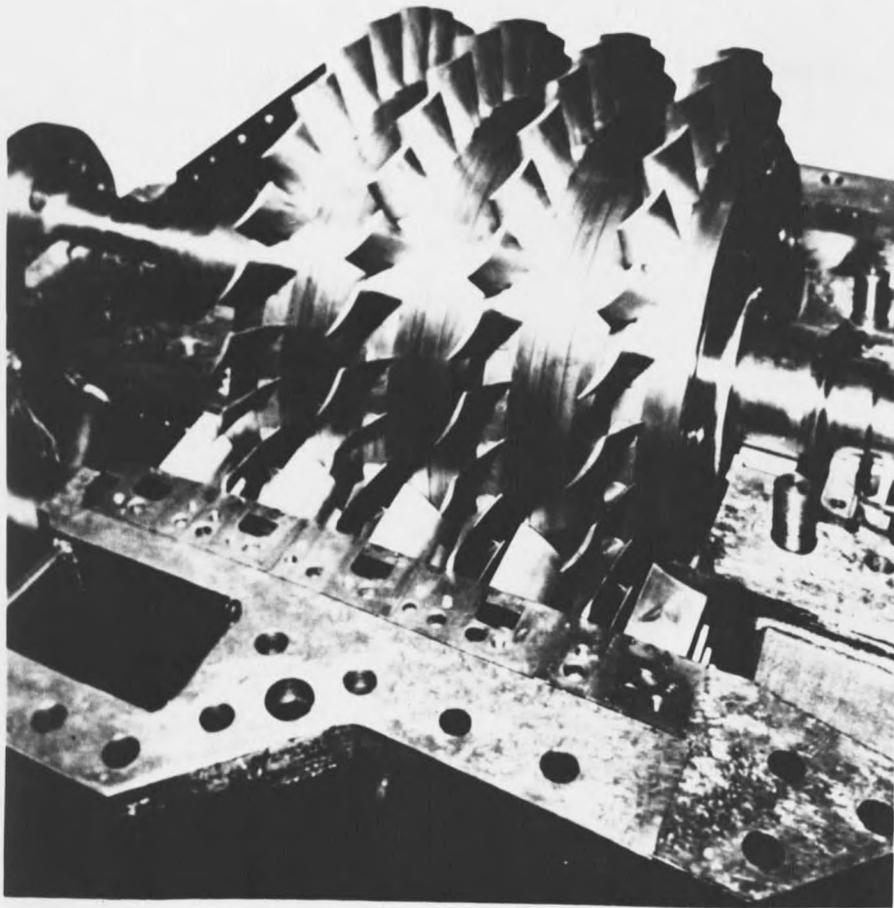
LOCOMOTIVE-GAS-TURBINE COMBUSTION CHAMBER, LONGITUDINAL SECTION

Figure 68 G. E. locomotive-gas-turbine combustion chamber, longitudinal view.

designed and constructed will tell of this feasibility. However, (assuming that nuclear fuel is solely used) a locomotive would have an infinite range and no fuel tender would be needed as for coal and oil. The coal tenders for long run trains contain as much as 50 tons of coal which will be eliminated in the advent of nuclear power.

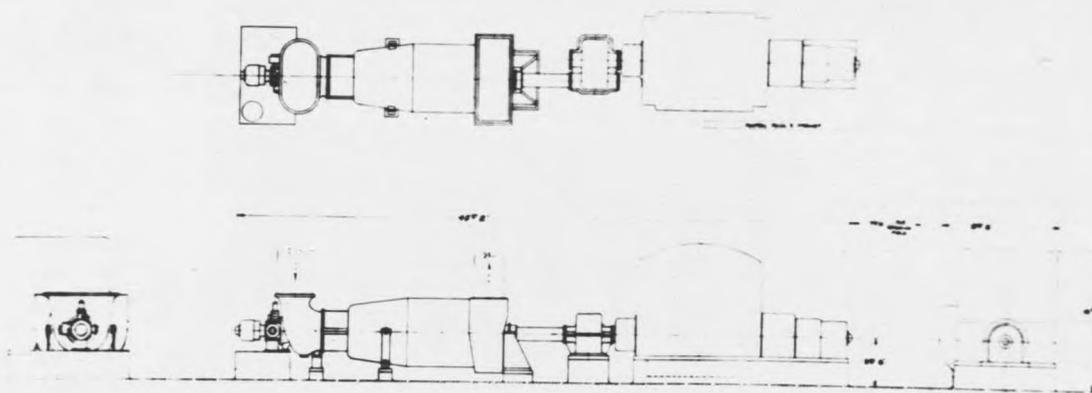
The above discussion dealt only with the gas turbine in conjunction with locomotive use which may be the least practical of nuclear powered locomotives. The simplest and possibly the most practical may be the conversion of the common steam engine. Where the production of the steam will be the only change. That is, producing steam in the reactor (or its heat-exchanger) instead of a coal fired boiler. Again the coal tender will be eliminated. Along these lines a reactor may be used for generating steam for a steam turbine.

The General Electric 4800 HP unit may have more than just locomotive application, it is expected this unit will prove attractive for other applications such as for industrial power, automatic peak load plants for power systems, oil field, or pipe line applications, and so on. For some applications, steam might be produced from the exhaust gases. An outline of this plant used as an a-c generator drive is shown in Figure 70. To reduce costs to a reasonable low level, manufacture of identical units in fairly large numbers is essential, so it is expected gas turbine plants, and particularly the power units, will be standardized. Thus, the power unit as shown in Figure 70 is essentially identical with the unit applied to locomotives.



4-STAGE AXIAL-FLOW COMPRESSOR (PROJECT TG-1) WITHOUT STATOR TOP HALF,
FOR G. E. GAS TURBINE. AFTER CONDITION "A" RUNS.

Figure 69' 4-stage axial flow compressor without stator half,
for G. E. gas turbine.



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1032 826 G-E 3500-KW GAS TURBINE-GENERATOR SET. TOP, FRONT-END, RIGHT-SIDE, AND BACK-END ELEVATIONS WITH DIMENSIONS (PRELIMINARY).

Figure 70 G. E. 3500 Kw gas turbines-generator set.

TABLE X

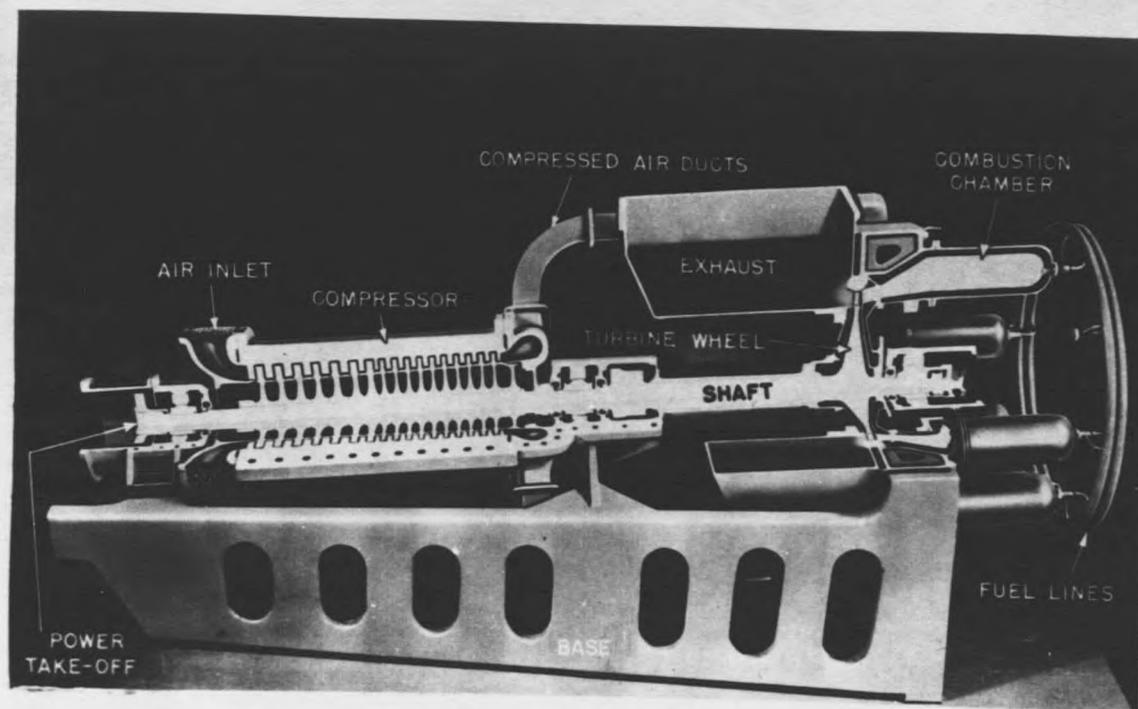
Comparison of diesel and gas turbine locomotives

TYPE	POWER OUTPUT	WEIGHT
Diesel - electric	4000 HP (two 2000 HP engines)	506,000 lbs.
Diesel - electric	4200 HP (six 700 HP engines)	404,350 lbs.
Diesel - electric	6000 HP (eight 750 HP engines)	650,000 lbs.
Gas turbine - electric	2200 HP (one unit)	202,000 lbs.
Gas turbine - electric	4500 HP (one unit)	364,000 lbs.

MARINE USES:

At the present time, and in the foreseeable future, all nuclear reactor use and development is under the direct supervision of the government, therefore the first nuclear powered ship will probably be for military use. Whether the vessel be a submarine, battleship or aircraft carrier, it will have unlimited range and may stay in enemy waters for many months.

In the future an aircraft carrier may be an unique device; try to visualize the power unit to be a nuclear reactor using natural uranium. The energy from the U²³⁵ fission could be used to generate steam turbo-electric units, or in place of combustion chambers in gas turbine-electric units. If the reactor is of the breeder type the U²³⁸ isotope in the



608 530 MODEL IN CUT-AWAY SECTION, OF G-E 3000-HP MARINE GAS TURBINE. SHADED LEFT-SIDE VIEW SHOWING TURBINE-TYPE COMPRESSOR (LEFT) MOUNTED ON CENTRAL SHAFT DRIVEN BY POWER TURBINE (RIGHT). AIR IS DRAWN THROUGH AIR INLET INTO COMPRESSION CHAMBER, THEN FORCED THROUGH COMPRESSOR CONDUITS INTO MULTIPLE "COMBUSTION CHAMBERS". OIL IS INJECTED FROM FUEL LINES INTO THE CHAMBERS, AND THE MIXTURE, BURNING, ISSUES FROM TURBINE NOZZLES AND STRIKES AGAINST BUCKETS OF THE TURBINE WHEEL WITH GREAT FORCE CAUSED BY EXPANSION OF THE BURNING GAS. LEAVING THE WHEEL, THE GAS ISSUES FROM THE EXHAUST. POWER IS TAKEN FROM SHAFT AT THE LEFT.

Figure 71 Model in cut-away section, of G. E. 3000 HP marine gas turbine.

natural uranium will form plutonium (Pu^{239}). The plutonium then may be separated and used for the production of atomic bombs. This would probably be a militarists dream come true, the production of an offensive weapon from the by-product of the power unit. The size of the reactor for large ships is of little importance and as for shielding it can also be used for armor plating thereby serving two purposes. An advantage for using the gas turbine unit is that of the vast supply of water that may be used for intercoolers, thereby allowing the use of a closed cycle to operate effectively.

For smaller marine vessels (and submarines) provisions must be made for maneuvering and astern operation. For d-c electric drive, the high torque requirements at the time of reversing can be met by maintaining nearly full speed on the set. Reversing can, of course, be accomplished electrically. Another very promising arrangement for marine applications is offered by the variable pitch propeller - or preferably the reversible pitch propeller. Use of this device permits independent control of the gas turbine speed, thus allowing the operator to obtain best thermal performance from the gas turbine at all times, and greatly facilitating the maneuvering problem. Figure 71 shows a cross-section of a marine unit for a gas turbine plant.

REFRIGERATION:

As previously mentioned a nuclear is just another source of heat. There are two types of standard refrigeration units that require a heat source, these being, the Electrolux-servel and the Silica Gel. The Electrolux-servel cycle is common in household and commercial units. For an example let us calculate the amount of uranium required to operate a Electrolux-

servel refrigerator unit.

Example 7: Calculate the amount of U^{235} required to operate 100 lockers of 1000 cubic feet each at $30^{\circ}F$ for one year.

Assume 10 foot cube and all surfaces to have a heat transmission of 3 BTU per Ft^2 per $^{\circ}F$ per day.

$$Q = (3)(6)(100)(70-30) = 72,000 \text{ BTU/day}$$

assuming three air changes per day

$$Q = 2170 \text{ BTU/day}$$

Total heat loss

$$Q = 72,000 + 2170 = 74,170 \text{ BTU/day}$$

The ratio of refrigerating effect to heat supply is 38%

$$\frac{74,170}{.38} = 195,000 \text{ BTU/day}$$

$$\frac{195,000 \times 365}{3413} = 20,800 \text{ Kw-hr/yr.}$$

assuming the reactor to be 85% efficient

$$\frac{20,800}{.85} = 24,400 \text{ Kw-hr/yr.}$$

assuming 200 Mev per fission

$$24,400 \times 2.25 \times 10^{19} = 5.49 \times 10^{23} \text{ Mev/yr.}$$

$$\frac{5.49 \times 10^{23}}{200} = 2.745 \times 10^{21} \text{ fissions/yr.}$$

$$(2.745 \times 10^{21})(235.1269)(1.659 \times 10^{-24}) = 1.056 \frac{\text{gms}}{\text{yr.}}$$

$$\frac{1.056}{453.6} = .00233 \text{ lbs. per yr. per locker.}$$

Total U²³⁵ required for all 100 lockers.

$$(.0233)(100) = 0.233 \text{ lbs./yr.}$$

Using a Celica Sol unit the amount of U²³⁵ required would be

0.0249 lbs. per yr. per locker

or 2.49 lbs/yr. for 100 lockers

ATOMIC HOME:

Attempting to look into the distant future we may see a resident home using nuclear energy to very good advantage. A nuclear reactor may be used to heat the home, heat the domestic hot water, used in a refrigeration cycle and used for cooking. All of these uses would have to be operated by means of closed cycles. The heating could use the principle of radiant heating and the common controls used in conjunction with a hot water boiler. The domestic hot water could also be thermostatically controlled. Refrigeration use has been previously discussed. As for cooking the Institute of Gas Technology, Chicago has developed a natural gas burner where the flue gas does not go directly into the atmosphere but is exhausted at a more convenient location. The walls of the oven would come into contact with the hot fluid from the reactor, or the fluid would flow through the walls thus heating the oven radiantly as in an electric stove.

Example 8: Taking an average home and using nuclear fuel (U²³⁵) to operate the above mentioned units calculate the amount of U²³⁵ required for one years operation.

Assume heat loss of home to be

60,000 BTU/hr. (30,000 BTU/yr. average loss)

$$(60,000)(24)(365)\left(\frac{1}{2}\right) = 2.625 \times 10^8 \text{ BTU/yr.}$$

heat required for domestic hot water assume

$$100,000 \text{ BTU/day}$$

$$(100,000)(365) = 3.65 \times 10^7 \text{ BTU/yr.}$$

heat required for refrigeration assume

$$1500 \text{ BTU/day}$$

$$(1500)(365) = 5.475 \times 10^5 \text{ BTU/yr.}$$

heat required for cooking assume 2000 BTU/day

$$2000 \text{ BTU/day}$$

$$(2000)(365) = 7.30 \times 10^5 \text{ BTU/yr.}$$

Total heat required

$$3.002 \times 10^8 \text{ BTU/yr.}$$

$$(3.002 \times 10^8)(6.59 \times 10^{15}) = 1.977 \times 10^{24} \text{ Mev/yr.}$$

each fission of U^{235} releases 200 Mev

$$\frac{1.977 \times 10^{24}}{2} = 9.89 \times 10^{23} \text{ fissions/yr.}$$

$$(9.89 \times 10^{23})(235.1269)(1.659 \times 10^{-24}) = 386 \text{ gms/yr.}$$

$$\frac{386}{453.6} = 0.851 \text{ lbs/yr.}$$

This is assuming the reactor to be 100% efficient its actual efficiency would increase the amount of uranium needed. At this rate a consumer could afford to pay approximately \$250 a pound for U^{235} taking the initial cost of the reactor to be comparable to that of a boiler and hot water heater. A greater amount of insulation would be required in conjunction with the piping leading from the reactor to the stove because it

would carry fluid of a temperature of from 500-600° F.

For industrial plants the nuclear reactor may be a source of heat used to generate power by means of a gas turbine cycle and the exhaust from the turbine used for heating or industrial drying. This may be of great advantage for chemical processing plants where great sources of heat are required.

The aforementioned uses of nuclear power are only a sample of its uses. Any process that requires heat may be converted to use nuclear fuel.

A DIRECT SOURCE OF ELECTRICITY:

Upon the fission of U²³⁵ unstable nuclei are the fission products which are beta emitters. During this process approximately seven electrons are emitted before stable nuclei are formed. If these electrons can be controlled and gathered they may form a direct source of electrical power or at least a difference in potential.

Example 9: Calculate the electrostatic charge created by the electrons omitted during the fission of one gram of U²³⁵. Assuming seven electrons per fission.

$$\frac{235.1269}{1.66 \times 10^{-24}} = 1.415 \times 10^{26} \text{ atoms/gram.}$$

$$(1.415 \times 10^{26})(7) = 9.905 \times 10^{26} \text{ electrons/gm}$$

$$(9.905 \times 10^{26})(1.602 \times 10^{-19}) = 1.585 \times 10^8 \text{ coulombs}$$

or

$$(1.585 \times 10^8)(0.00278) = 4.39 \times 10^4 \text{ ampere-hrs.}$$

The probability of using these electrons is not very great because of the difficulty in controlling them. It may very easily require more power for their control than is created.

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