UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
INDUSTRY PROGRAM

A PEACETIME SURVEY OF NUCLEAR ENERGY FROM AN INDUSTRIAL VIEWPOINT

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The University of Michigan College of Engineering takes pleasure in publishing this first report for distribution on the Industrial Program. It is significant that this survey should describe industry's participation in atomic energy research. As such, it is appropriate to mention the name of George W. Mason, the late Chairman of the Board and President of American Motors Corporation. Mr. Mason, a University alumnus, was a pioneer industrialist whose vision and foresight constantly served to inspire his many friends and associates. He had a unique understanding of the implications of atomic energy and was a driving force behind the University's Michigan Memorial-Phoenix Project designed to study means of harnassing the atom for peace. To the memory of George W. Mason this manual is faithfully dedicated.

Geo. G. Brown

George Granger Brown

ACKNOWLEDGEMENT

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I. INTRODUCTION

The possibilities of nuclear energy have captured the imagination of everyone. The publicity afforded the nuclear energy field has concentrated on depicting the wonderful benefits to be derived in the future. However, less glamorous aspects of the field, which are of great importance for the whole program to proceed on an industrial basis, have been neglected. The many queries from members of industry indicate that many of the phases of nuclear power-producing reactor operation have not received proper emphasis. It is the purpose of this report to briefly survey the field of nuclear energy, from the mining of fissionable material through its use as reactor fuel and subsequent reprocessing in what might be considered a typical industrial nuclear reactor. This survey should point up the unpublicized phases of nuclear energy and indicate where major problems still exist.

In order to outline the many steps necessary to put a nuclear power reactor into operation, it appears advisable to briefly discuss some of the theoretical aspects of the use of fissionable materials. This discussion will make the reasons for the steps more understandable, and serve as an aid in becoming familiar with the nomenclature and units that are commonly used in nuclear technology.

It is hoped that by discussing the steps and processes involved, it will become apparent to interested parties where a specific product or specialty would have application in this field. The question, "Where can my company or product fit into the nuclear energy field?", must be answered if American industry is to meet the challenging problems of this field, as it has done in the development of new technological fields many times in the past.

A. Definition of Nuclear Energy

Nuclear energy in its strictest definition could be taken to be those realms of activities that lie within the narrow band of producing power from nuclear fission. For the purposes of this discussion, the term nuclear energy is broadened to include not only power production, but many of the activities that are necessary to make a nuclear reactor operation possible, and the by-products that come about as a result of operating a nuclear reactor.

B. Scope of Industrial Participation

The scope of industry participation could then include a manufacturer that makes a valve installed in a plant processing spent reactor fuels to a chemical company or hospital that uses radioactive tracers in following phases of a chemical reaction.

On this basis the vast majority of United States manufacturers have participated in atomic energy by manufacturing a product used in some phase of the program, or using a product that resulted from nuclear energy activities. Industry participation in atomic energy, already on a large scale, will increase manyfold since revision of the Atomic Energy Act on August 30, 1954. Table I lists most of the companies that are actively participating in the nuclear energy field at the present time. The number of study team participants has grown rapidly, and this list may be out of date by the time this report is printed.

II. RAW MATERIAL

A. Fissionable Materials

Uranium ores contain several isotopes, only two of which are present in concentrations high enough to be of practical importance. These isotopes are uranium-238 and-235. Uranium-235 is the only material existing in nature in important quantities, that will undergo a self-sustaining fission process. It occurs in uranium ores to the extent of 0.7 per cent of the total uranium content.

There are other fissionable materials, occurring only to a very minor extent in natural materials, that can be man-made. These are plutonium, Pu-239, and another isotope of uranium, U-233. These manufactured fissionable materials are important, as will be discussed later, but initially, all nuclear reactors have to start with U-235, or secure a fuel from some reactor that did start with U-235.

B. Sources and Extent

1. Uranium. Carnotite ores are the chief source of uranium in the United States. This ore usually contains uranium and vanadium as a potassium-uranium vanadate. The extent of these deposits is apparently much greater than expected. Ore bodies are located principally in the

TABLE I

CORPORATIONS PARTICIPATING IN ATOMIC ENERGY

OPERATING OR HAVE OPERATED A.E.C. FACILITIES ON CONTRACT

- AMERICAN CYANAMID
- BENDIX AVIATION CORP.
- Du PONT de NEMOURS
- GENERAL ELECTRIC CO.
- MALLINCKRODT CHEMICAL WORKS
- NORTH AMERICAN AVIATION CORP.
- PHILLIPS PETROLEUM CO.
- STANDARD OIL OF NEW JERSEY
- UNION CARBIDE & CARBON CORP.
- UNITED AIRCRAFT CORP.
- WESTERN ELECTRIC CO.
- WESTINGHOUSE ELECTRIC CORP.

MINING & ORES REFINING

- ANACONDA COPPER MINING CO.
- CLIMAX URANIUM CO
- KERR - McGEE OIL INDUSTRIES, INC.
- U. S. VANADIUM CORP. OF AMERICA
- VITRO CORP. OF AMERICA

INDUSTRIAL POWER TEAMS STUDYING POWER PRODUCTION FROM NUCLEAR REACTORS

- NUCLEAR POWER GROUP
  - AMERICAN GAS & ELECTRIC CO
  - BECHTEL CORP.
  - COMMONWEALTH EDISON
  - PACIFIC GAS & ELECTRIC CO.
  - UNION ELECTRIC CO.
- THE DOW CHEMICAL CO.
- DUQUESNE LIGHT CO.-WALTER KIDDE NUCLEAR LAB.
- GENERAL ELECTRIC CO.
- NEWPORT NEWS SHIPBUILDING & DRY DOCK CO.
- MONSANTO CHEMICAL CO.
- FOSTER WHEELER-PIONEER SERVICE & ENGINEERING CO. - DIAMOND ALKALI CO.
  - CALIFORNIA-OREGON POWER CO.
  - LOUISVILLE GAS & ELECTRIC CO.
  - NORTHERN STATES POWER CO.
  - OKLAHOMA GAS & ELECTRIC CO.
  - SAN DIEGO GAS & ELECTRIC
  - WISCONSIN PUBLIC SERVICE CORP.
- PACIFIC NORTHWEST POWER CO.
  - MONTANA POWER CO.
  - MOUNTAIN STATES POWER CO.
  - PACIFIC POWER & LIGHT CO.
  - PORTLAND GENERAL ELECTRIC CO.
  - WASHINGTON WATER POWER CO.
- ATOMIC POWER DEVELOPMENT ASSOCIATES
  - ALLIS-CHALMERS MFG. CO.
  - ATLANTIC CITY ELECTRIC CO.
  - BABCOCK & WILCOX CO.
  - BENDIX AVIATION CORP.
  - CINCINNATI GAS & ELECTRIC CO.
  - CLEVELAND ELECTRIC ILLUMINATING CO.
  - CONSOLIDATED EDISON CO. OF N.Y.
  - CONSOLIDATED GAS ELECTRIC LIGHT & POWER CO.
  - CONSUMERS POWER CO.
  - THE DETROIT EDISON CO.
  - THE FORD MOTOR CO.
  - GENERAL PUBLIC UTILITIES CORP.
  - GIBBS & COX, INC.
  - HARTFORD ELECTRIC LIGHT CO.
  - NEW ENGLAND ELECTRIC SYSTEM
  - NIAGARA MOHAWK POWER CORP.
  - PHILADELPHIA ELECTRIC CO.
  - POTOMAC ELECTRIC POWER CO.
  - PUBLIC SERVICE ELECTRIC & GAS CO.
  - ROCHESTER GAS & ELECTRIC CORP.
  - SOUTHERN SERVICES, INC.
  - TOLEDO EDISON CO.
  - UNITED ENGINEERS & CONSTRUCTORS, INC.
  - VITRO CORP. OF AMERICA
  - WISCONSIN ELECTRIC POWER CO.

four-corners area of Colorado, Utah, New Mexico, and Arizona. While production figures are not available, exploration and mining have received such impetus that domestic uranium production is probably close to that of the Belgian Congo at the present time. Deposits of other types of uranium ore have been found in Wyoming, Idaho, South Dakota, Pennsylvania, Montana, Nevada, and California. As far as is known, only the deposits in Wyoming and South Dakota are being mined at the present time.

Other important sources in the United States are from phosphate rock occurring largely in Florida, Idaho, and Utah. The quantity of uranium in phosphate rock is approximately .01 per cent as U_3O_8. However, the phosphate deposits are so extensive that this is still an important source of uranium. Two plants for the production of uranium from phosphate rock are being negotiated. These are the International Minerals and Chemical Corporation at Bartow, Florida, and the Virginia-Caroline Chemical Corporation at Nichols, Florida. The Atomic Energy Commission is negotiating with several other phosphate chemical firms for the construction of additional facilities for this purpose. The process used for extraction of uranium from phosphate is a liquid-to-liquid extraction of an aqueous phosphoric acid-uranium-containing solution with an organic solvent. The solvent preferentially removes the uranium from the undesired phosphates.

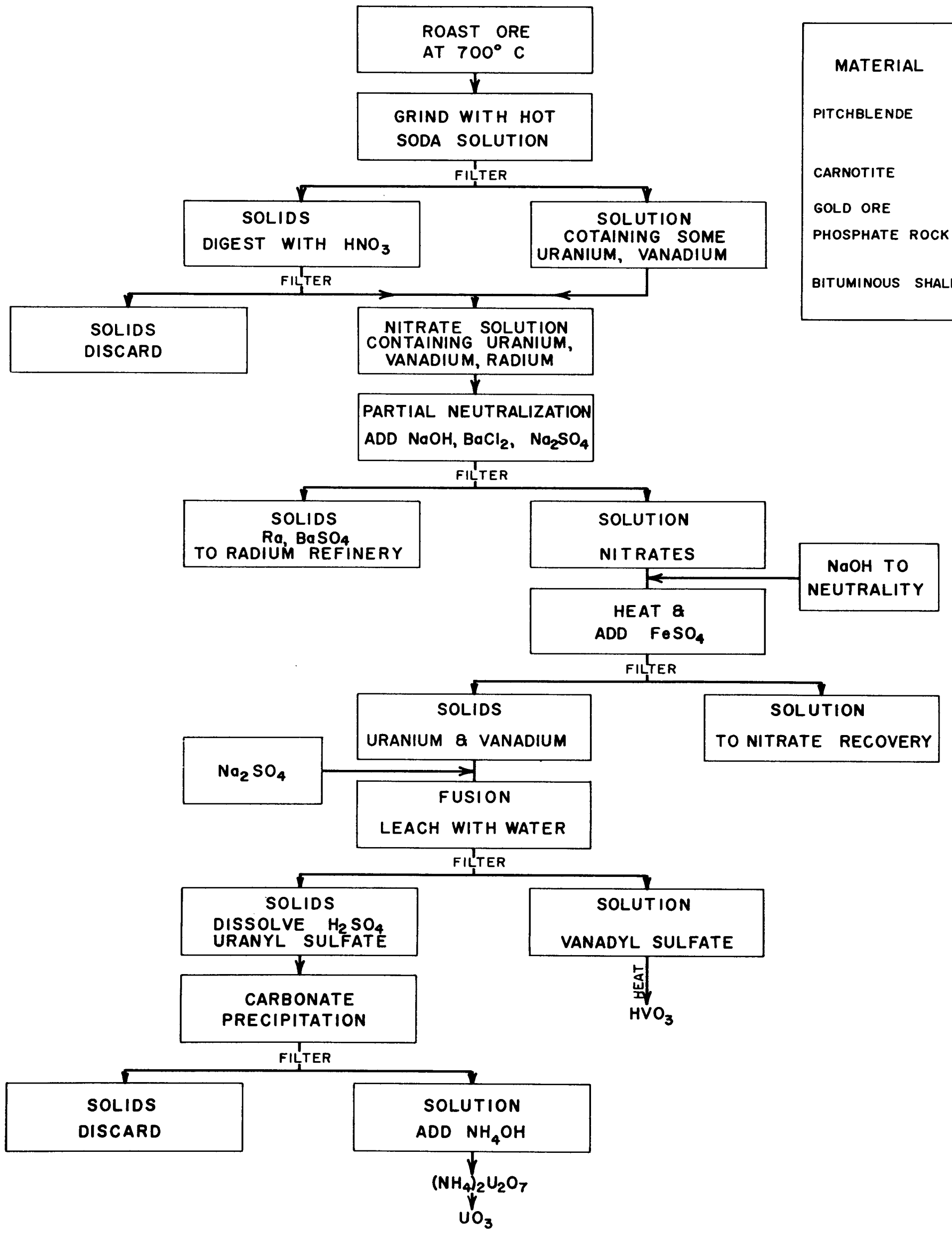
Another important domestic source of uranium is from bituminous shales. Reserves from this source are probably larger than all the other sources combined. Uranium content of these shales is low, and as yet no commercially feasible process has been devised for uranium extraction.

Some uranium is associated with thorium in monazite sands. These sands will be discussed with thorium production. Uranium from this source will become more important as production of thorium is increased.

Foreign sources of uranium are the Great Bear Lake area in Canada and at Katanga in the Belgian Congo. These ores are the pitchblende type (principally a complex, variable uranate containing thorium, zirconium, lanthanum, yttrium, and lead). These ores average much higher in uranium content than the domestic ores. As an example, Canadian ore runs from 30 to 62 per cent U_3O_8, while domestic carnotite ores average less than 1 per cent. Thus, foreign ores are much cheaper to process, and will probably continue to be a major source of fissionable materials for this country.

The data on uranium sources, extent, and processing of the ore are summarized in Figure 1.

(U.S. BUREAU OF MINES NITRIC ACID PROCESS FOR CARNOTITE ORES)



SOURCES OF URANIUM

MATERIAL	SOURCES	(%) U	APPROX. RESERVES TONS URANIUM
PITCHBLENDE	BELGIAN CONGO	5. - 50.	20,000
	CANADA	~ 1.	
	CZECHOSLOVAKIA	0.2 - 2.	
CARNOTITE	SIBERIA	0.2 - 1.	35,000
	COLORADO	0.2 - 1.	
GOLD ORE	SOUTH AFRICA	> 0.01	
PHOSPHATE ROCK	FLORIDA	~ 0.01	
BITUMINOUS SHALE	SWEDEN	0.025	2,000,000
	RUSSIA	0.01 - 0.025	
	EASTERN U.S.A.	0.003 - 0.01	

Figure 1. Uranium—Mining and Concentration.

2. Thorium. Thorium is actually more plentiful, by a factor of three, than uranium in the earth's crust. It is nearly always associated with uranium and the rare earths. Uranium is a by-product of thorium processing.

The major source of thorium is in monazite sands. Monazites are heavy, dark-colored phosphates of the cerium earths. They are found as sands along stream beds or beaches. Principal domestic sources are in Idaho and the Carolinas. Other deposits are found in India, Brazil, Australia, Ceylon, Africa, and Canada. The most important source of monazite is at Travancore, India. Concentrates from these sands average about 9 per cent thorium oxide.

Production of thorium for nuclear energy has lagged behind that of uranium. However, the thorium-U-233 cycle, which is discussed in later sections, does have some advantages. One of the new reactors proposed by the Atomic Energy Commission will utilize a thorium blanket for production of U-233.

In Figure 2, information on sources, purification, and uses of thorium for nuclear power purposes is outlined.

C. Mining, Ore Processing, and Metal Reduction

1. Uranium. Domestic mining is carried out using conventional small-scale mining techniques. Ore deposits are usually of a secondary sedimentary nature, lying between beds of sandstone. The bodies are normally spotty, and in most cases not adaptable to large-scale mining techniques that are used for primary vein type deposits. As a rule, the mining is carried out as a family affair or with two or three miners. There are, however, some large ore bodies, some 15 of which have 100,000 tons or more of ore blocked out. Large-scale mining techniques can be adapted to these deposits. The larger mines are becoming mechanized, with power equipment being standard. In at least two mines, the drifts are large enough to permit trucks with dump bodies to enter the mines directly.

Most small mines at this time have inadequate ventilating facilities. This could be a health hazard in breathing the dust, if such conditions persist over long periods. Ore concentrations are so low that no radiation hazards are present.

By law, the only legal buyer of fissionable materials is the Atomic Energy Commission or its designated contractor. The general practice is to buy the ore, and stockpile it at some location convenient to the source until mill schedules can be arranged for processing the ore. At present, mining is running ahead of processing, so most ore is going into the stockpile.

A representative flowsheet for the treatment of domestic carnotite ores is shown in Figure 1. This flowsheet was prepared by the U. S. Bureau of Mines in 1938. New processing techniques are being studied, but as yet no processes are in commercial use that differ materially from the flowsheet shown.

2. Thorium. Thorium mining is being done by dredging the monazite sands from the stream beds and beaches. The monazites are somewhat magnetic, and can be separated from the silica sands by a magnetic separator. The concentrated monazites are processed chemically to separate uranium and thorium from the cerium rare earths.

A possible flowsheet for processing monazite sands is given in Figure 2.

3. Metals Reduction. The chemical processing of uranium and thorium ores result in an oxide of these two elements that must still be transformed into the metallic state to be usable in many reactor applications. Due to the high value of the materials, reduction of the oxides to metals must be done by an efficient process to insure that metal losses during treatment are held to a minimum.

The reduction processes used in this country are classified, but the methods used by other countries have been published, and these processes will be used as an example of how reduction to the metals could be carried out. The information discussed is taken from two sources, "Critical Study of Methods of Preparation of Metallic Uranium" by C. Decroly and J. Van Impe, Bull. Tech. de l'Assoc. Ing., University Bruxelles III (5)(1950), and from a French Atomic Energy Commission release by C. Eichner, B. Goldschmidt, and P. Vertes, Bull. Soc. Chim. France (5) 18, 140 (1951).

The uranium product from ore treatment and purification processes is usually an orange oxide powder with the formula UO_3. This material is reduced to a brown oxide powder, UO_2, using mixtures of hydrogen and nitrogen at temperatures of 1200°F. The UO_2 oxide is converted to a uranium fluoride, UF_4, by digestion with a solution of hydrofluoric acid. The UF_4 produced is insoluble and is filtered from the solution and dried as a fine powder. The fine UF_4 powder is mixed with finely granulated calcium metal in a stainless-steel reactor lined with a crucible of CaF_2. All air is displaced from the mixture with inert argon. The reaction between calcium metal and UF_4 requires a high starting temperature, but maintains

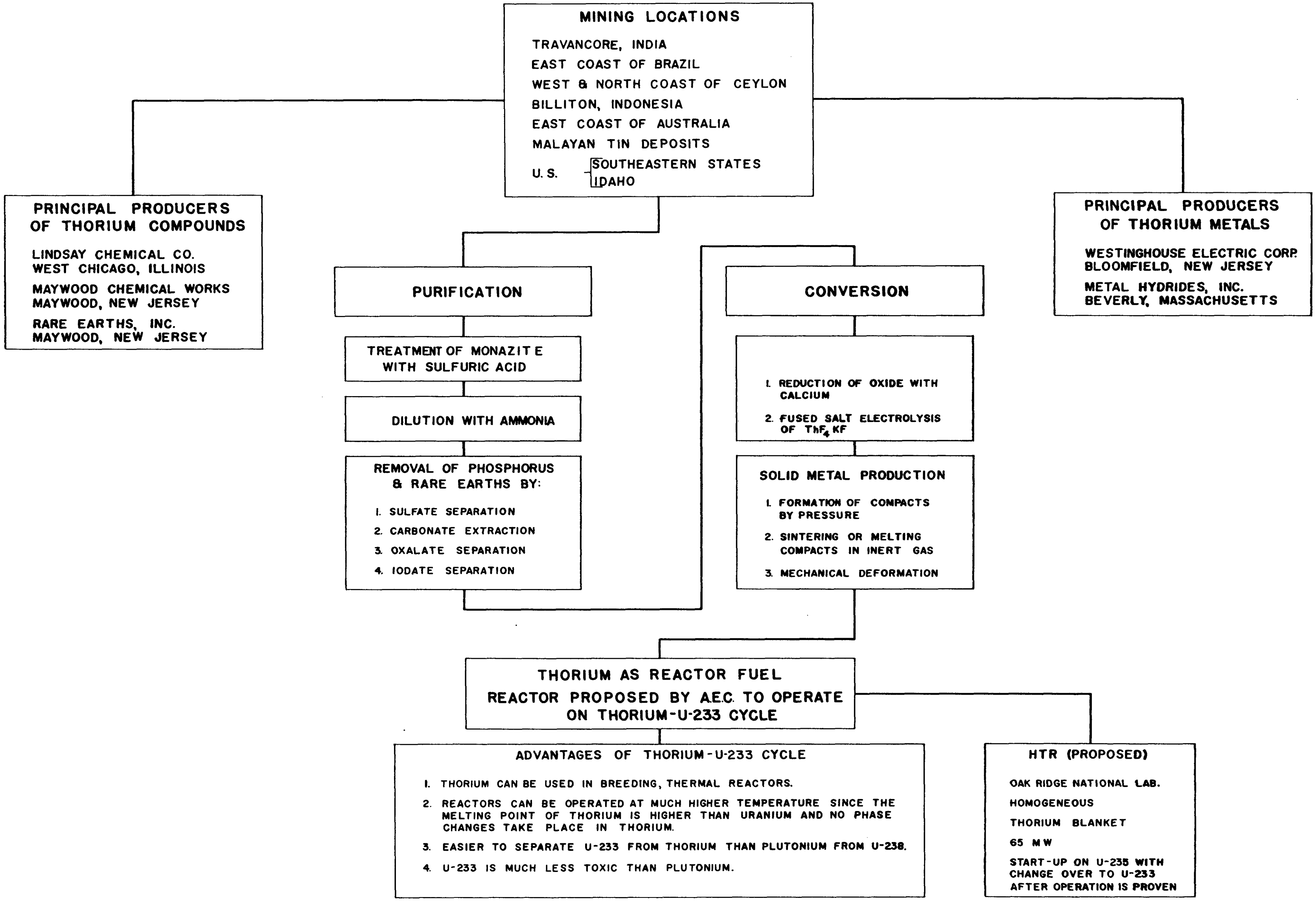


Figure 2. Thorium—Mining and Metal Preparation.

itself thereafter by its own heat of reaction. The initial starting temperature is achieved by igniting, with the cover removed, a magnesium ribbon that is threaded into the Ca-UF_4 mixture. The uranium metal produced is in the form of a massive chunk, has high purity, and recovery is reported to be better than 98 per cent. CaF_2 slag produced by the reduction is discarded.

The production of uranium metal from UO_3 is summarized in the following reactions:

$$UO_3 + H_2 \rightarrow UO_2 + H_2O$$
$$UO_2 + 4HF \rightarrow UF_4 + 2H_2O$$
$$UF_4 + 2Ca \rightarrow U\ \text{metal} + 2CaF_2$$

The similarity between the processes worked out by the French and Belgians for reducing UO_3 to metal indicates that there are few processes that are free of technical difficulties during one or more of the steps involved. It can also be noted that these processes are very similar to the Kroll process used in this country for the preparation of titanium and zirconium metals.

The reduction of thorium oxides to a metallic state is done by a process similar to that for uranium, except that thorium tetrachloride, $ThCl_4$, is usually reduced, instead of ThF_4. Thorium has less affinity for oxygen than uranium, so the oxide, ThO_2, can also be reduced by a more reactive metal, such as calcium, magnesium, sodium, or potassium. Preparation of thorium metal is not done on a scale equal to that of uranium at the present time.

D. Separation of Isotopes

Where compact reactors for high-power production per unit volume are required, it is necessary to use a core of highly concentrated fissionable material. At the present time, this means a choice between plutonium and uranium isotope U-235. Since plutonium is higher priced than U-235 and cannot be used as fuel where thermal breeding is desirable, U-235 is usually used. This means a separation of the isotopes of uranium, U-238 and U-235, is necessary. Separation of these isotopes has been done at Oak Ridge since 1944.

Two methods of separating U-235 and U-238 have been successful on the large scale required. These methods are based on the slightly different behavior of the two atoms, due to slight weight differences, when the two atoms are subject to kinetic diffusion or rapid motion in a magnetic field. In the first, or gaseous diffusion process, the uranium is converted into a volatile uranium-hexafluoride compound. This compound is vaporized and allowed to diffuse through permeable barriers. Since U-235 is lighter and tends to diffuse faster than U-238, this isotope is enriched somewhat after diffusing through each barrier. The desired enrichment is attained by using an appropriate number of diffusion barriers. Product streams from the diffusion battery are highly enriched in U-235 on one end and in U-238 on the other. The U-238 accounts for 99.3 per cent of the uranium fed to the diffusion battery, with U-235 accounting for the other 0.7 per cent. The second method of separating uranium isotopes is based on the differences in paths of electrically charged particles having different masses, while traveling at high velocity under the influence of a magnetic field. Under these conditions, a charged particle follows a curved parabolic path, and since U-235 has a different weight from U-235, the point at which it leaves the apparatus is different from that for U-238. Apparently, the gaseous diffusion process has been the most successful, or perhaps the most economical, since the electromagnetic separation is no longer used. At this time, the Atomic Energy Commission is increasing the country's isotope separation capacity by building a new gaseous diffusion facility at Paducah, Kentucky.

In the interim period, before breeder reactors making Pu-239 and U-233 can furnish appreciable quantities of fissionable material, the use of U-235 will probably increase sharply. Whether artificially produced fissionable material ultimately replaces the natural U-235, can be answered only by future economics. However, some U-235 will probably always have a place as a fuel where its specific characteristics are important.

Industry fits into the uranium isotope separations picture from the vast amount of varied industrial products that go into a gaseous diffusion plant. These products would include a wide array of materials, such as special alloys, fabrication of special vessels, chemicals, pipes and valves, control instruments, vacuum pumps, and many other products.

E. Value of Fissionable Materials

Ultimately, fissionable materials will have to be assessed at their fuel value. This would not include special military uses, to which a value based on standard economics cannot be applied.

Average energy from a uranium fission is about 192 million electron volts. On this basis, with coal at $7 per ton and with a heating value of 12,000 BTU per lb, a gram of uranium is worth about $22. This value assumes that all of the gram of uranium, U-235, fissions; this is not strictly true, as some of the uranium undergoes neutron capture and is not subsequently fissioned. A more realistic figure of about $18.50 should be used to account for the capture process in a thermal reactor. Actual costs for uranium, U-235, at this time is reputed to be about $20 per gram. This figure, however, could undergo considerable adjustment as new processes are developed and additional operating economies are achieved.

Costs of Pu-239 are reported to be anywhere from $40 to $100 per gram at this time. This cost figure probably arises by assessing Pu-239 at its military value, and will probably be revised downward when commercial power breeder reactors begin operations.

U-233 has never been produced in quantities to make production costs available. It is safe to say at this time that its cost will be as high, and probably higher than that of Pu-239. Quantity production of U-233 should bring about substantially lower costs for this material.

The energy of fission of Pu-239 and U-233 is approximately the same as for U-235 (192 mev per fission, or 75×10^6 BTU/gram fissioned), so on this basis, the value of these artificially produced fuels for industrial purposes can be no higher than that of U-235.

III. UTILIZATION OF FISSION ENERGY

A. The Fission Process

A discussion of reactors and reactor fuels without a definition of fission and some basic understanding of why fission occurs and the subsequent energy release would be out of place. As a brief orientation, some basic discussions of fission appear necessary. For brevity, only the self-sustaining nuclear fissions are considered here.

The process of self-sustaining fission is started by a neutron hitting the nucleus of a fissionable atom. The target atom splits into two particles with the release of considerable energy in the form of heat, and the emission of more than one neutron. These neutrons are available to cause additional atoms to fission, so the process is self-sustaining. Thus, one possible fission reaction of U-235 can be written as:

$$ {}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{57}La^{147} + {}_{35}Br^{87} + 2\,{}_{0}n^{1} $$

A neutron, ${}_{0}n^{1}$, has no protons in its nucleus and has an atomic weight of one. ${}_{57}La^{147}$ is an isotope of the element lanthanum, having 57 protons in its nucleus and a molecular weight of 147. ${}_{35}Br^{87}$ is an isotope of the element bromine and has 35 protons in its nucleus, with an atomic weight of 87. Lanthanum and bromine are the fission products of the process and will be highly radioactive. As can be seen, two neutrons are released from this particular fission. It must be emphasized that this is only one of the many mechanisms that can and do take place during fission. The combinations of fission products that could result in fission vary from an isotope of zinc with a molecular weight of 72 to an isotope of samarium with a molecular weight of 158. If all of the possible fission reactions are averaged, it is found that the average energy of fission from one atom of U-235 is about 192 mev (2.9×10^{-13} BTU per fission). It has also been found that 2.5 neutrons on the average are ejected per atom of U-235 fissioned with thermal neutrons.

The reason a nucleus will undergo fission with low-energy neutrons is that the structure of the nucleus is unstable. A neutron entering the fissionable nucleus may be regarded as the activation energy that causes the nucleus to split up into fragments having a more stable structure. Some of the bond energies formerly present in the original nucleus then go into the structure of the fission fragments, with the remainder being liberated as heat of fission.

The proportion of isotopes and the number of the neutrons that result from fission are to some extent dependent upon the neutron energy that starts the fission process. Precise differences caused by fission between thermal neutrons and fast neutrons are still classified material; however, some qualitative effects can be discussed. As an example, the average neutron yield after capture per fission of Pu-239 from a thermal neutron is approximately 1.9; however, at higher neutron energies, the neutron yield is over 2.0 neutrons per fission, after allowing for capture. The yield and distribution of fission products also differ somewhat between thermal and fast fission.

Fission of U-233 with thermal neutrons yields about 2.1 neutrons per fission after capture, which is approximately the same as for U-235.

There remains the question as to why so little activation energy is required for U-235 fission to occur, whereas fission of U-238 requires a good deal more energy. The answer appears to be that an even number of protons and an odd number of neutrons in the nucleus results in a nucleus with low stability. Isotopes of uranium or plutonium having an odd-numbered atomic weight may be fissioned with neutrons of essentially zero energy (i. e., thermal neutrons). Isotopes of these elements with even atomic weights require neutron energies of approximately 1 mev to instigate a fission. Only those isotopes requiring small activation energies for fission are of practical importance in a self-sustaining reactor.

At the present time, there exists no economical method to extract the energy inherent in fissionable materials in a form directly usable to industry. The most efficient process we have now is to permit the fission process to generate heat, use this heat to form steam, and then expand the steam in a turbine to generate electricity. This chain of energy transformation allows about 20 per cent efficiency at present reactor temperatures. This means that only one-fifth of the energy formed in the reactor reaches the transmission line as electrical energy.

An industrial reactor is a device that converts the energy locked up in the nucleus of a fissionable material into usable thermal energy at a controlled rate. Since the fission process must be self-sustaining, the reactor must assume the dimensions necessary for a critical configuration of the particular fuel being used. A wide variety of materials may be used as coolants to remove the heat of fission from the reactor.

B. Reactor Classification and Functions

1. Methods of Classifying. Reactors are classified by several means. One method is by the average energy of the neutrons in their cores. In this method the neutron energies are divided into three levels--thermal, intermediate, and fast. A second method of classification is by the nature of the fuel elements used. In this method a reactor having a continuous fuel system, such as a solution of uranium in water would be called a homogeneous reactor. A reactor having lumps of metal spaced in a fluid coolant or graphite moderator would be termed a heterogeneous reactor. Obviously, many other classifications could be used, but the two systems just discussed are the ones most commonly encountered; so these will be used in this discussion.

a. Classification by Neutron Energies. Neutrons always have the same mass, so the neutron energy becomes just a matter of the velocity with which the neutron travels. A convenient energy term commonly used when referring to neutron energies is the electron volt. Just after fission occurs in a uranium nucleus, neutrons are expelled with a most probable energy of about one million electron volts (1 mev). This energy is the maximum neutron energy at which a reactor can function.

The table below gives the energy regions in which reactors are classified. Given also are the neutron velocities corresponding to the given energy ranges.

TABLE II

NEUTRON ENERGY REGIONS

Energy Region	Average Electron Volts	Average Velocity, ft/sec
Thermal	.025	7,200
Intermediate	1,000	1,400,000
Fast	1,000,000	45,000,000

Obviously, the energy regions will overlap, so the classification must be based on an average or a most probable value of the neutron energies.

In Figure 3 are summarized the data on reactors that have been built in the United States. Also included are available data on proposed reactors that are being or will be built. Figure 4 gives similar data on reactors in countries other than the United States.

Each of these reactor types have certain advantages and disadvantages, as will be pointed out.

(1) Thermal Reactors. Reactors operating on neutrons with energies in the thermal region have the following advantages: Critical mass is small, so inventory costs on the fuel alone are small. Most of the reactors that have been built have been thermal reactors, so more data is available on reactors of this type. With small core size, bulk shielding costs can be kept low. High unit power per unit weight or unit volume is a considerable advantage where such a reactor is used for propulsion power. Thermal reactors can theoretically be breeders on the thorium-uranium-233 cycle.

Disadvantages are: A moderator is required to slow down the neutrons from fission energies. One of the best moderators, heavy water, is very expensive. Many materials have large neutron-capture cross sections in the thermal neutron ranges. This severely restricts the choice of construction materials for thermal reactors. Usually, aluminum (which is limited to fairly low operating temperatures) or zirconium (which is very expensive) is used as core or fuel element containers for these reactors. This factor also limits the coolant pumped through the reactor to water or a gas. It cannot breed on the uranium-238-plutonium-239 cycle. Such a reactor can be operated as a converter, however, if an efficient moderator is used.

(2) Intermediate Reactors. The advantages and disadvantages of an intermediate reactor, as the name suggests, fall between those of the

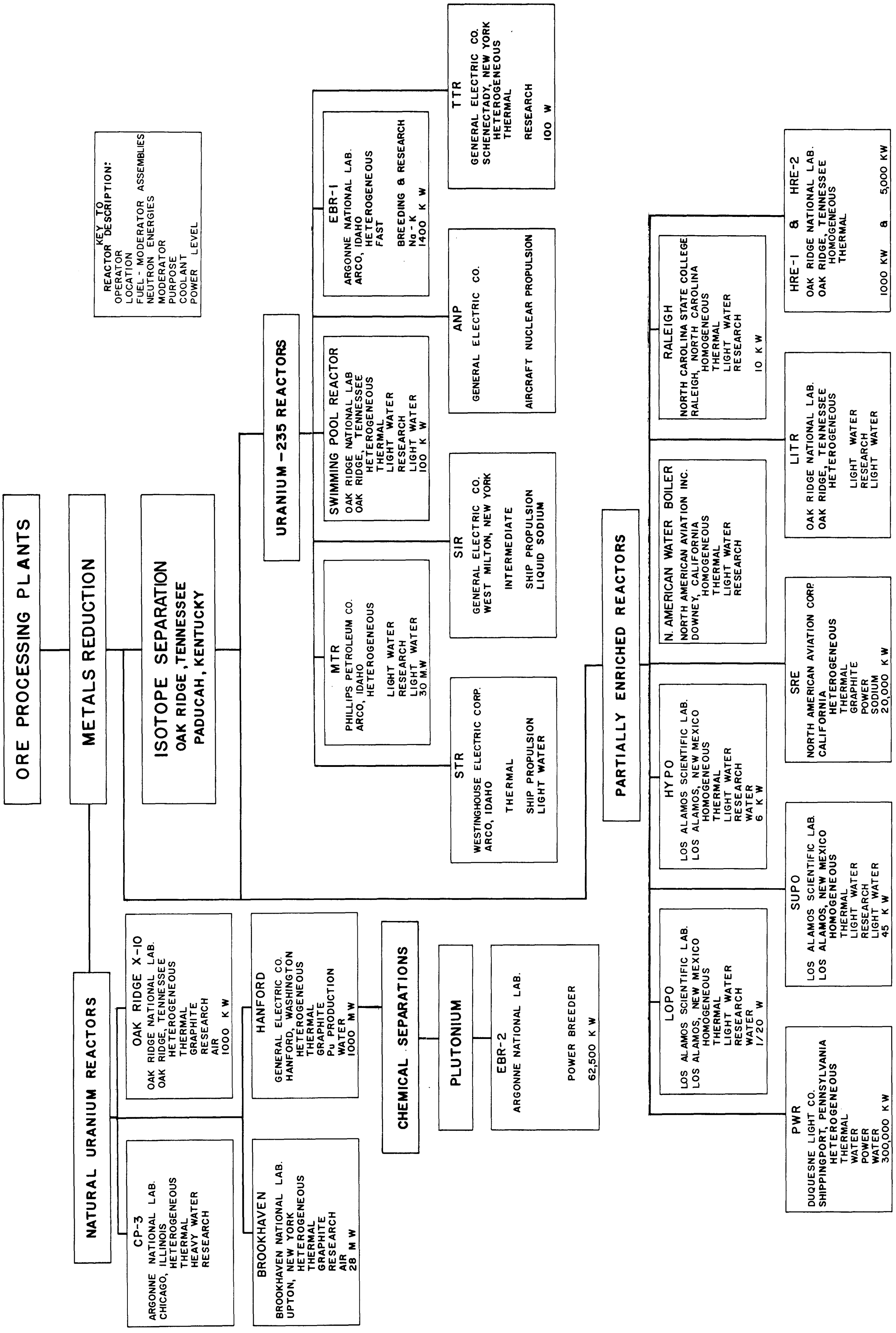


Figure 3. Reactors in the United States.

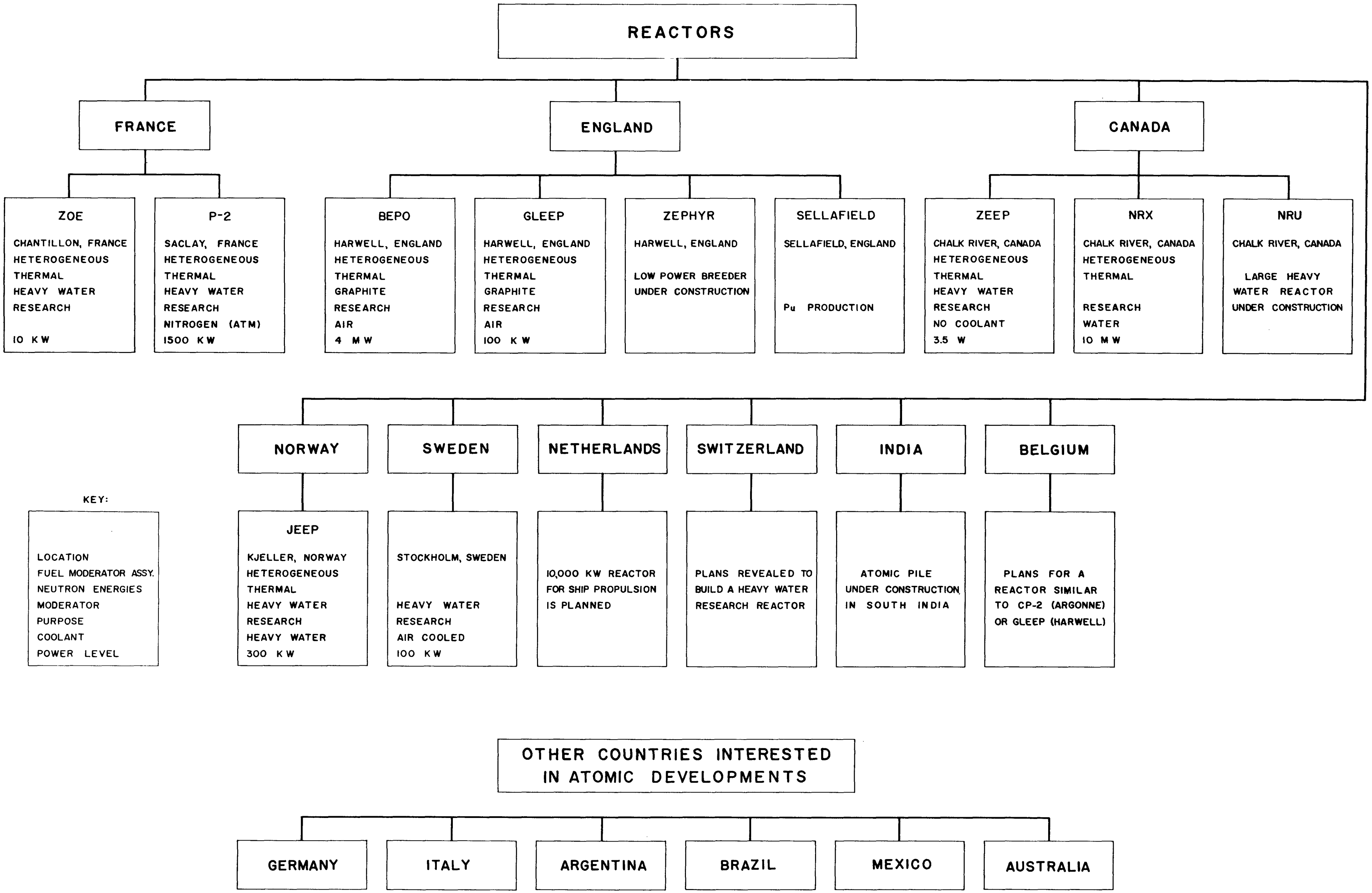


Figure 4. What the Rest of the World is Doing in Atomic Energy.

thermal and fast reactors. Its core size must be larger than the thermal reactor, but a much wider selection of materials of construction and of coolants is available. Liquid metal coolants can readily be used in intermediate reactors. Neutron energies are still not high enough to permit high breeding gain on the U-238, Pu-239 cycle, but breeding can still be accomplished in the Th-232, U-233 cycle.

(3) Fast Reactors. In reactors of this type, the neutron-capture cross sections are usually small for a good many materials. This offers many advantages, in that a wide range of materials of construction and coolants can be used. Thus, this reactor type can use liquid metal coolants and utilize core materials that will stand higher temperatures. Higher temperatures mean higher thermal efficiencies in the subsequent steam generation and turbine cycles. This type reactor can function as a breeder on the U-238, Pu-239 cycle.

Disadvantages of this type are that fairly large quantities of fissionable material are required to reach the critical size. Inventory costs on fuel are then higher than for the other types of reactors. Bulk shielding requirements are greater because of larger size. Consequently, shielding costs are higher.

b. Classification by Fuel Type. (1) Examples of a homogeneous reactor is the HR-1, which has been operated at Oak Ridge, and the HR-2, which is being built. In these reactors, the fissionable material is dissolved as a salt in heavy water, which serves as a moderator and coolant. There have also been several such reactors in operation at Los Alamos. Another type of homogeneous reactor would be one with a metallic fissionable material dissolved in a molten metal. Homogeneous reactors could be built with average neutron energies in either the thermal, intermediate, or fast ranges.

(2) Heterogeneous reactors use fissionable material in a solid state, usually fabricated into a fuel element. The fuel elements may be spaced in a lattice network to accomodate moderators or coolants. The reactors at Hanford, Washington, Materials Testing Reactor at Arco, Idaho, and the STR Reactor in the Nautilus are examples of heterogeneous reactors. These reactors can be built to operate in any of the neutron energy regions previously discussed.

2. Breeders and Converters. Breeders and converters are not types of reactors under the classification previously discussed. They are more of a reactor function or method of operation than a reactor type. However, these two functions are very important in reactor technology, so are included here.

A breeder is a reactor that produces more fuel than it burns up. In an earlier section, it was pointed out that thermal fission of U-235 or U-233 resulted in the emission of 2.5 neutrons per fission. One of these neutrons will be used to sustain the fission process. Of the total neutrons produced, about .38 of them will be captured by the uranium to become a higher isotope of uranium--U-236 or U-234, depending on whether U-235 or U-233 is the fuel, which leaves about 1.12 neutrons available for some other purpose. If U-238 is mixed with the U-235 in the proper configuration, and the reactor surrounded with a blanket of U-238, so that very few neutrons can escape, then the U-238 can capture neutrons and become, eventually, Pu-239. Theoretically, it is seen to be possible to produce about 1.1 parts of Pu-239 for every part of U-235 fissioned.

A Pu-239 atom, when fissioned by a thermal neutron, produces approximately 1.9 neutrons, after allowing for capture. Thus, it would be impossible to breed in a thermal reactor when using Pu-239 as fuel. This is not the case when Pu-239 is used as fuel in a fast reactor.

It is also possible to use U-235 or U-233 as fuel in a breeder for thermal, intermediate, or fast reactors.

A converter reactor is one that produces approximately the same quantity of fuel that it burns. In this type of reactor, neutron economy or leakage from the reactor is not as important a factor as in a breeder reactor. The same principles apply here as in breeders, as far as utilization of neutrons is concerned. A converter can operate without a blanket, or can be operated with U-238 in the core and a reflector. Construction and chemical processing of converter reactor fuels is simpler; and where economies in these operations are important, a converter can be chosen in preference to a breeder reactor.

The flow pattern of a reactor fuel and blanket material for both uranium and thorium is shown in Figure 5. This figure illustrates the many steps and processes that are necessary to operate an industrial power-producing breeder reactor.

C. Reactor Fuels

The only important reactor fuels, as first discussed, are U-235, U-233, and Pu-239. Of these three, only U-235 occurs in nature in usable amounts. U-233 and Pu-239 must be produced artificially.

There is another important reaction involving a neutron and a nucleus, and that is the capture of neutrons by a nucleus to ultimately

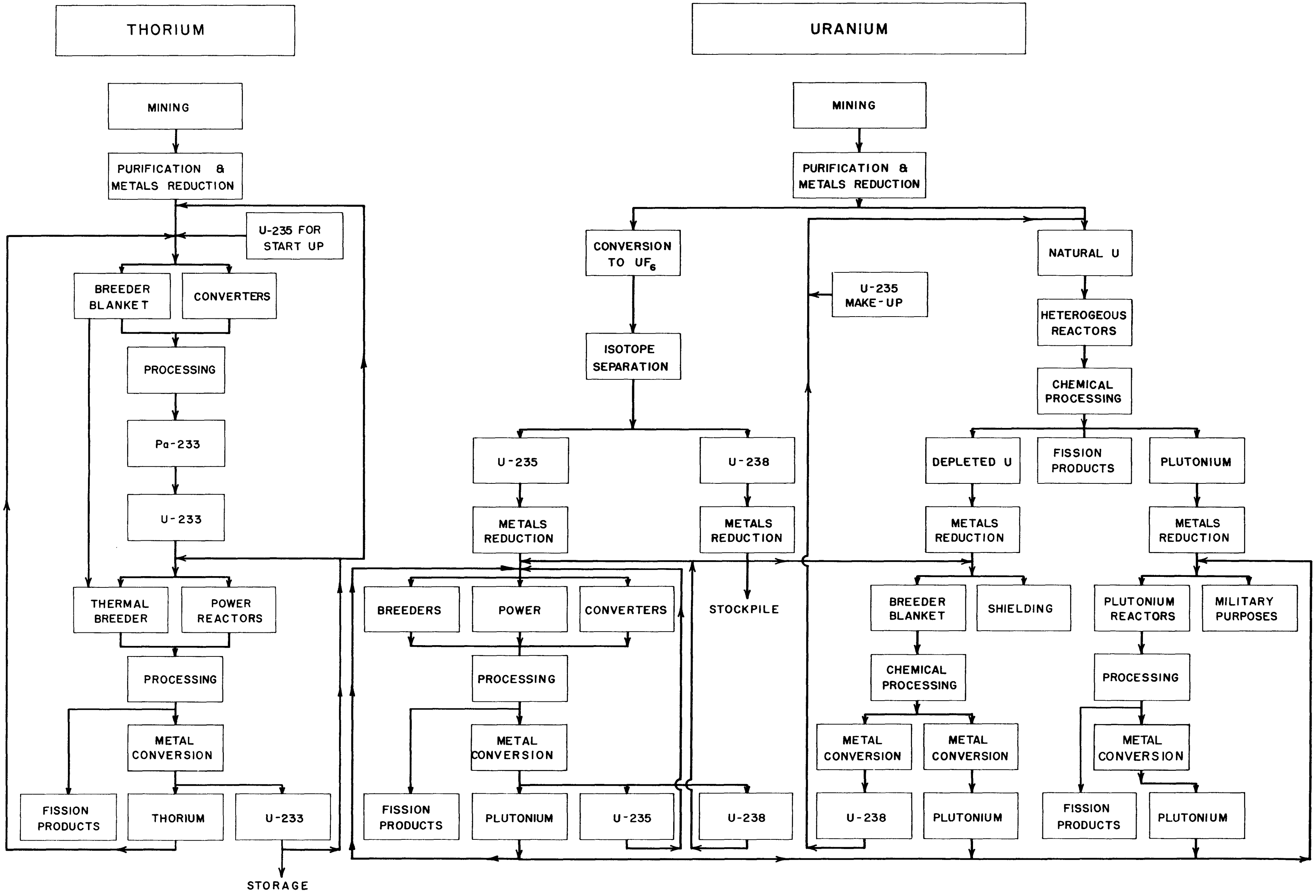


Figure 5. Overall Use of Fissionable Material.

become a new element. This phenomenon is utilized to maufacture the fissionable materials Pu-239 and U-233.

1. Uranium-Plutonium. The uranium isotope U-238, when exposed to bombardment by neutrons in a reactor, captures a neutron and becomes another isotope of uranium, U-239. This decays to an isotope of neptunium, Np-239, which subsequently decays to Pu-239. Since for all practical purposes Pu-239 is stable, the decay scheme stops with this element.

The plutonium is separated chemically from the uranium and fission products, and processed into the reactor fuel, or utilized in the weapons program.

2. Thorium-Uranium-233. U-233 is made in a very similar manner, except that the starting material is thorium, Th-232. The thorium nucleus captures a neutron and becomes another isotope of thorium, Th-233. This isotope decays to protactinium, Pa-233, which subsequently decays to uranium, U-233. U-233 is stable for all practical purposes, so the decay stops there.

U-233 is separated from the remaining thorium and fission products chemically and processed into reactor fuels.

Preparation of either Pu-239 or U-233 requires extensive chemical treatment to separate the final product from the parent substance. In both cases, the products, Pu-239 and U-233, have different chemical properties from U-238 and Th-232, so a chemical separation can be achieved. There are two major plants in the United States making these separations--one at Hanford, Washington, and the other at Savannah River, Georgia. Each plant represents an investment of many millions of dollars, and for which equipment was purchased from practically every manufacturer in the country.

These plants are designed to make a separation between U-238 and Pu-239. At the present time, there are no large-scale units in operation to make the U-233-Th-232 separation. Since U-233 has many advantages as a fuel and reactors utilizing this fuel are in the design stage, it appears quite certain that chemical processing plants making this separation on a large scale will be built.

D. Moderators and Poisons

Where thermal reactors are desired, it is necessary to slow the neutrons produced from fission at about 1 to 2 mev down to the thermal range, or about .025 electron volts. This is accomplished by a substance, having very special properties, called a moderator. The actual slowing down is done by a series of collisions between the neutron and the moderator atoms. A collision between a neutron and an atom much larger than the neutron, for example U-238, causes the neutron to rebound from the large atom with about the same energy it had before the impact took place. This is much like hitting a very large marble with a very small marble. The small marble rebounds, and the large marble barely moves. Thus, the energy or speed lost per collision is very small. If a neutron hits an atom of about the same size, it is possible for the neutron to lose considerable energy per collision. This action is identical to that of two billiard balls colliding. It is evident, then, that an atom must be light-weight in order to be efficient as a moderator.

The light-weight atoms are: hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen, and oxygen, in order as to their efficiency as moderators. Hydrogen, helium, nitrogen, and oxygen are gases under ordinary conditions, so are not dense enough to be good moderators. Lithium and boron unfortunately have the ability to capture neutrons, which is very undesirable in a moderator. This leaves only carbon and beryllium which can be used as moderators in the elemental state. Both these substances are used, but the expense and somewhat undesirable physical properties of beryllium prevent its extensive use as a moderator.

The fact that hydrogen and oxygen are gaseous under normal conditions doesn't eliminate their use as moderators in the form of compounds. Water, being the cheapest and most common compound of these two elements, is used extensively as a moderator. Unfortunately, normal hydrogen will capture neutrons and become heavy hydrogen or deuterium. This is undesirable where high neutron economy is desirable. From this standpoint, it would be desirable to use deuterium, to begin with, in the form of heavy water. Heavy water at the present time is very expensive--about $80 per pound, so the cost is a deterrent in a much greater use of homogeneous reactors. In this type of reactor, a uranium salt is dissolved in the heavy water moderator.

Due to the great promise of homogeneous reactors, industry can play a large part in working out economical processes for the preparation of heavy water. If this material could be produced for approximately $20 per pound, it would find wide acceptance in the homogeneous reactor field.

Industry has played a large part in the manufacture of moderators. Methods have been worked out by industry to prepare carbon in a very pure state, free of neutron absorbers like boron, so that this element in the form of graphite is used extensively as a moderator.

As far as a reactor is concerned, everything that absorbs neutrons decreases the reactivity and lessens the power it is capable of producing. Everything capturing a neutron in the reactor core can then be called a reactor poison. This would include the fission products that are built up as a result of fuel fissioning. In the case of control rods, reactor poisons are deliberately placed in the reactor core.

Reactors have to be designed so that they are still "critical", or capable of power production after some degree of burn-up. Obviously, this means that at initial start-up, there is an excess of critical material or reactivity in the core. Some means has to be provided to absorb this initial excess reactivity and prevent the reactor from getting out of control. This is done by inserting a poison in the form of a control rod into the reactor core. When the fission products build up, the control rod is gradually withdrawn from the core to maintain the power level of the reactor at a constant value.

The two best poisons appear to be the elements boron and cadmium. Boron may be fabricated into an alloy, used as an oxide, or in chemical solution. Elemental boron has been too expensive in the past to be used extensively as a control rod element

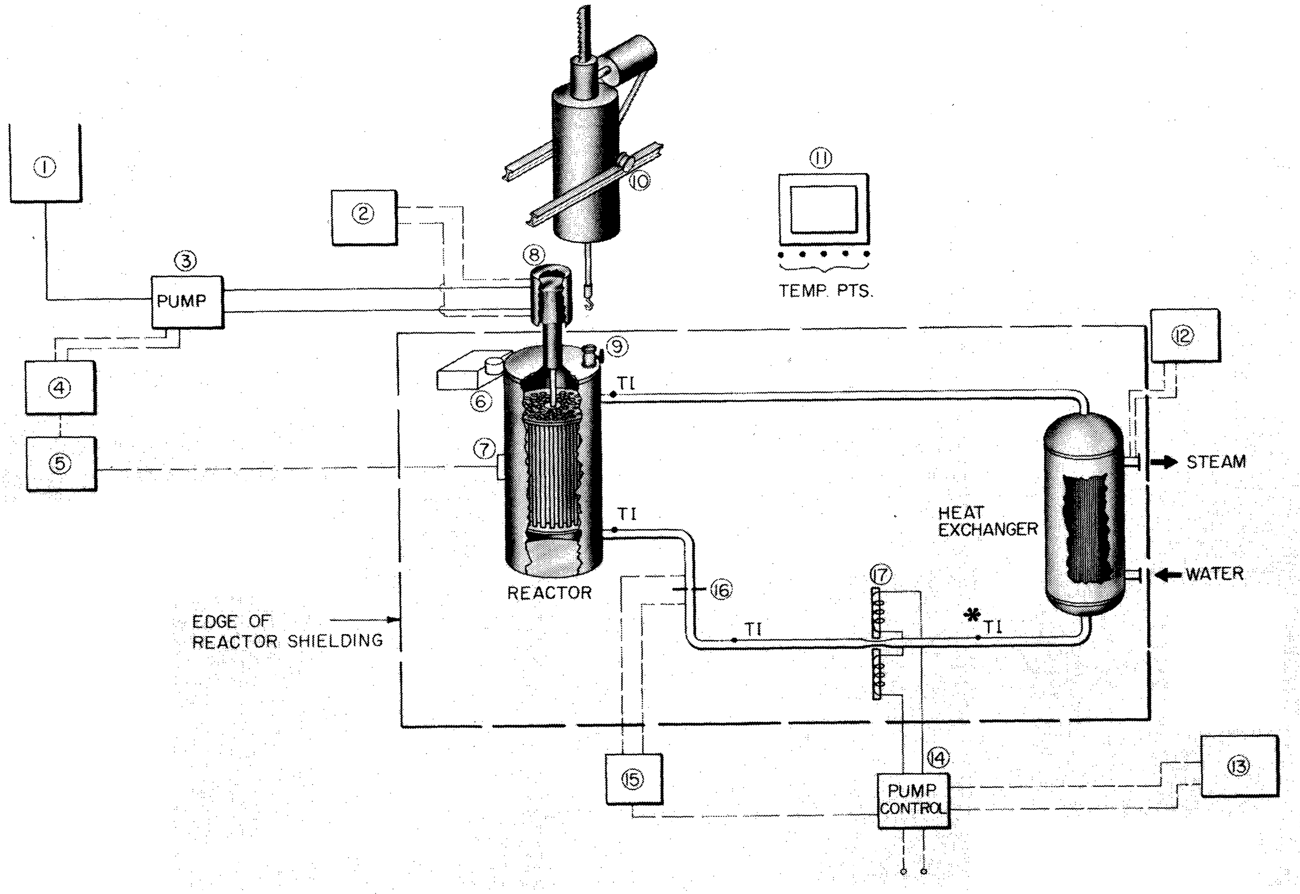
Cadmium may be plated on a base metal, or used in the form of rods or sheets. Since cadmium has been commonly used for many years, there are few problems in its use or fabrication that cannot be answered with present technology.

E. Reactor Controls and Accessories

A reactor, although simple in concept and operation, may not be simple in control nor in the methods used to extract the heat it generates. These two operations associated with reactors give in themselves wide use of industrial products. Figure 6 illustrates a typical power reactor with most of the associated control equipment.

Control of a reactor is possible only because some of the neutrons from fission are not emitted immediately. Some one per cent of the neutrons are not released for periods up to 10 seconds after fission has taken place. This allows the control mechanisms to act in time to prevent the reactor from going out of control.

Control is accomplished by sliding a rod containing some neutron-absorbing material, such as cadmium or boron, into the reactor core. The position of the control rod and its subsequent adsorption of neutrons determines whether the reactor continues to run at the same power level, increases its power level, or decreases its power level and ultimately shuts down. Control mechanisms consist of a sensing element, that usually measures neutron flux, which is tied through an electrical servo-mechanism that



1. OIL RESERVOIR FOR HYDRAULIC CONTROL ROD MECHANISM
2. CONTROL ROD POSITION INDICATOR
3. PUMP TO PUMP OIL TO CONTROL ROD PISTON
4. SERVO-MECHANISM TO CONTROL PUMP DIRECTION AND SPEED
5. NEUTRON FLUX RECORDER AND CONTROLLER FOR THE SERVO-MECHANISM
6. MECHANISM TO ROTATE TOP PLATE OF REACTOR
7. NEUTRON FLUX COUNTER
8. HYDRAULIC PISTON TO SET CONTROL ROD
9. EXIT PORT FOR SPENT FUEL ELEMENTS
10. COFFIN AND MECHANISM TO EXTRACT AND CONTAIN REMOVED FUEL ELEMENTS FROM REACTOR
11. MULTI-TEMPERATURE POINT RECORDER
12. RADIOACTIVE MONITOR TO INDICATE LEAKS IN HEAT EXCHANGER
13. STAND-BY POWER GENERATOR
14. PUMP CONTROL
15. FLOW RECORDER CONTROLLER FOR MOLTEN METAL
16. FLOW SENSING DEVICE
17. ELECTRO-MAGNETIC PUMP FOR MOLTEN METAL COOLANT

* TEMPERATURE INDICATOR POINT

Figure 6. Reactor and Control Components.

activates the control rod or rods. Rod movement is accomplished by hydraulic, mechanical, or electrical linkages. Usually connected with the rod are indicators to give the exact position of the rod in the reactor. Control mechanisms must be as foolproof in operation as possible. Careful design and thorough testing is a "must" before the adopted unit is installed in the reactor. Most control rods use electrical power somewhere in their operation, so it is important that the electrical power must not be interrupted. For this reason, most installations have standby electrical power generators that switch on automatically in the event of a power failure.

It should be mentioned at this time that not all types of reactors require control rods. Reactors in which the fuel is dissolved in a solvent, such as water, (i. e., homogeneous reactors) are self-regulating in their operation and apparently require no external controls. This type will be discussed in later paragraphs.

Cooling or removing the heat generated in a nuclear reactor is a difficult engineering problem in itself. Critical masses are usually small, so the heat generated per unit reactor volume is very large. This means that heat transfer areas are small, and if the reactor temperatures are to be maintained at reasonable levels, very high heat transfer coefficients are required. Most of the large power-producing reactors being proposed at this time use liquid metals as coolants. These coolants are pumped at high velocity through the reactor core, through a heat exchanger where part of its heat is removed, and back to the pump at a lower temperature. This cycle is also illustrated in Figure 6.

Where liquid metals are used as coolants, special pumps have been devised as coolant movers. In this pump design, electromagnets are placed so as to generate magnetic fields with the molten metal. These fields induce electrical current flow in the liquid metal. This current flow generates a magnetic field of its own that opposes the induced field from the outer magnets. This opposed force pushes the molten metal through the pump. Since there is no impeller or shaft, no seal is required, and leakage cannot occur. The pumps of this type in use today have rather low efficiencies, and electrical requirements for operation are high. However, the prime requisite of non-leakage and rugged simplicity are met.

IV. PROCESSING OF REACTOR FUELS

A reactor operating at a power level of 100,000,000 watts (100 megawatt-days) will fission about 100 grams of fuel per day. This means that 100 grams of fission products are going to accumulate in the reactor core every operating day. These fission products act as poisons, and will eventually stop the self-sustaining fission reaction and shut the reactor down. When this occurs, the reactor will still contain appreciable quantities of fissionable material, which at $20 per gram represents too high an investment to discard. Methods of separating the fission products from the fuel, so that the fuel can be returned to the reactor, is then necessary, if reactors are to produce power on an economical basis.

Some processes for separating fission products from nuclear fuels are classified, so any discussion at this time must be limited and very unspecific. However, the magnitude of the problems and the fields in which problems exist can be pointed out.

Separation of fission products from spent fuel is a very difficult problem for several reasons: (1) fission products are extremely radioactive, which makes it necessary to conduct all operations behind thick concrete shields, using techniques that were entirely new to the chemical industry; (2) the basic problem of separating uranium from some 30-odd other elements is not easy to begin with; (3) for most reactor fuel uses, the purity specifications set for the product are such that about one part fission product per million parts uranium is all that is permissible.

At the present time separations are made using solvent-extraction techniques. These processes are capable of fulfilling the above requirements technically, and at the same time furnish a means of separating artificially-produced materials, such as Pu-239 from U-238 and U-233 from Th-232. However, initial and operating expenses for such processes are high, and will require considerable reduction before fuels from power reactors can be economically processed by such means.

An example of a solvent-extraction processing plant for the separation of uranium, plutonium, and fission products is shown in Figure 7. In this process, it is assumed that a metallic fuel element is used in which the uranium, a mixture of U-235 and U-238, is perhaps alloyed with aluminum, and the alloy itself jacketed with an aluminum layer. This fuel element has been in the reactor sufficient time, so that the optimum burn-up and plutonium build-up have occurred. It is also assumed that the fuel element

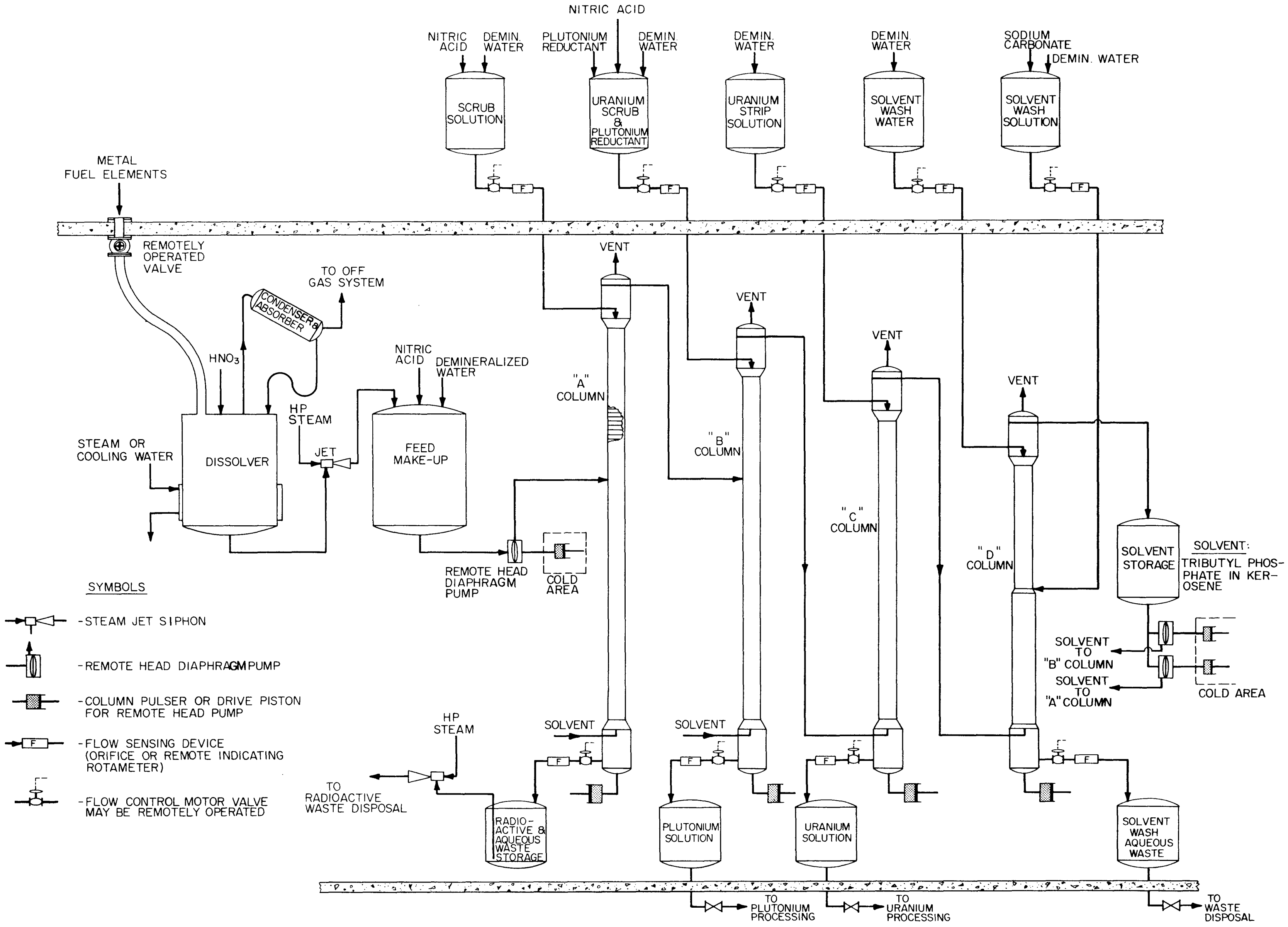


Figure 7. Typical Processing Flowsheet for Separating Plutonium, Uranium, and Fission Products by Solvent Extraction.

has been stored long enough for all the neptunium formed in the element to decay to plutonium.

This element is dropped through the slug chute into the dissolver, where the metal is dissolved in nitric acid. The dissolver solution is jetted to a feed make-up tank, where the nitric acid and uranium concentrations are adjusted to suitable extraction concentrations. This feed is then pumped to the extraction, or "A" column.

The columns shown in this flowsheet are typical pulse columns. The column contents are pulsed by the reciprocating piston shown at the base of the column. This pulsing action pushes and pulls the liquid contents through a series of pierced plates that are spaced approximately two inches apart in the small section of the columns. The pulsing action disperses the heavy and light phases very thoroughly into one another, and results in very good contact. Enlarged sections are provided at the ends of each column to allow the heavy and light phases to disengage from one to another.

In "A" column, an organic phase, tri-butyl phosphate, dissolved in kerosene, is introduced into the base of the column. This organic phase is lighter than and immiscible in water and water solutions, so it rises up through the column. In its passage through the lower section of the column, the organic phase extracts uranium and plutonium from the aqueous solution coming down from the feed point. Fission products are not extractable by this phase, and thus remain in the aqueous solution and pass out the bottom of the column into large storage tanks. After passing the column midpoint, the organic phase in its passage through the upper section of the column is scrubbed free of the last traces of fission products by the scrub solution introduced at the top of the column. It is then collected in the upper disengaging section, and overflows into "B" column.

"B" column's function is to separate the plutonium from uranium. This is done by adding a reductant solution to the top of the column. This reductant changes the valence state of plutonium, so that plutonium is no longer extractable by the organic phase. Uranium is unchanged by this treatment, so remains in the organic phase. Plutonium, free of uranium, then comes out in a water solution from the base of "B" column, while uranium, free of plutonium, remains in the organic phase, which cascades over into "C" column.

The function of "C" column is to strip uranium from the organic phase into an aqueous solution. Stripping is done by using water or very dilute acid solution in place of the concentrated nitric acid solution used for extractions in "A" column. The uranium in a very pure form leaves the bottom of "C" column in a water solution. The organic phase cascades from the top of "C" column to the bottom of "D" column.

"D" column is designed to scrub the organic phase free of any residual traces of uranium or fission products, and at the same time remove any decomposition products from the organic phase, that may have formed in the process. Scrubbed and essentially pure solvent from "D" column is then recirculated by means of pumps back to "A" and "B" columns.

The uranium and plutonium solutions from this process are free of radioactive fission products and can be handled without danger. These elements in solution are routed to metal-reduction processes and may be ultimately used again in the reactor.

One factor that contributes markedly to chemical processing costs is the disposal of the radioactive fission products. At the present time, these wastes are stored in large tanks, which means more tanks must be built as the ones in use fill up. Obviously, this is a stopgap measure that will be abandoned when more suitable disposal methods are worked out.

Another major problem of operating nuclear power reactors in populated areas is the gases that are liberated during reactor operation and during chemical processing of the reactor fuels. These gases are formed during fission, as fission products, or are present as a result of decay of a fission product through a gaseous phase. They are intensely radioactive, and as such cannot be released indiscriminately into the atmosphere. At present, these gases are handled by shooting them up a tall smokestack and depending upon the dilution by the atmosphere to reduce the concentration of radioactivity to a tolerable level. Obviously, the safety of this method is dependent upon atmospheric conditions, such as wind velocity, wind direction, temperature conditions, and to a large extent, the existence of a large uninhabited area to give the radioactive gases time to be diluted. Where a nuclear power reactor is to serve a highly populated area, other methods of handling these gases would have to be used. Processes have been worked out for removing radioactive gases from inert gas streams, but cost data on such processes are not firm at this time.

V. BY-PRODUCTS OF NUCLEAR ENERGY

A. Industrial Utilization of Fission Products

1. Introduction. Economical nuclear power may be contingent on the successful development of large-scale industrial uses for the extensive quantities of fission products produced in nuclear chain reactors. Thus far, the fission products have constituted a high-cost liability. Their presence in reactor fuel elements requires expensive chemical separations plants to

provide purified nuclear fuel suitable for re-use in reactors. Present as wastes after chemical separation, the fission products incur an even greater expense in handling and storage. Economic studies indicate that handling and storage costs may approach 60 per cent of the total costs of chemical separations. The consumers of reactor power will bear the expense of these operations, unless methods are devised to defray the cost by industrial utilization of the fission products. Research groups from industry and the universities are presently striving to resolve the fission-product problem by investigating potential uses for the fission products. Many of their findings have previously been put to profitable use, and some show definite promise for future applications; others are highly speculative. The final solution to this challenging problem will determine the degree to which power from nuclear reactors will compete in a free market.

The radioactivity of the fission products is due to the unstable form in which they are produced. It is characterized by the spontaneous emission by the fission products of nuclear particles or rays, in their attempt to attain a more stable state. The particles emitted are negatively charged electrons, called beta particles, with short ranges and capable of only superficial penetration of matter. The rays given off are electromagnetic rays similar in nature to x-rays. These "gamma" rays exert their effects over a much longer range and are extremely penetrating.

The primary effect of both types of radiation is the ionization of the material through which they pass. This ionizing effect makes possible the detection of radioactivity, permits sterilization of food and drugs, promotes chemical reactions, and is responsible for many other effects discussed in subsequent sections. The use of radiation in these and similar processes is not new to industry. Many manufacturers are presently making machines capable of producing ionizing radiations similar to those emitted by the fission products. However, the fission products have the advantages of greater versatility in source design, absence of mechanical or electrical breakdowns, and may be supplied at less cost for a given amount of radiation, once a market is established.

2. Classification of the Fission Products. After a fuel element is removed from a nuclear reactor, it goes through a series of chemical processes to separate the fuel from the fission products produced during operation of the reactor. The resultant mixture of fission products and chemical wastes present in water solution or as slurries form the usual plant waste stream. Gross fission products exist presently in storage at various sites in a variety of different chemical states and in a wide range of concentrations.

A potential use of fission products may require a specific type and energy of radiation different from that of gross fission products. Important to such users would be the specific activity (amount of radioactivity per pound) and the half-life of the material. Maximum utility of the fission products lies in the ability to manufacture them in such a manner that they possess specifications applicable to a wide range of uses. Certain uses may demand a product which consists of a relatively large proportion of an inert material, through which the fission products are dispersed. Other uses may demand high specific activities of fission products, or fractions thereof, in which, essentially, the total mass may be the fission products in a particular chemical form. For these reasons, there are general classifications of the fission products by their state of chemical separation and refinement.

Waste streams containing fission products must be handled in a variety of ways, depending upon the requirements of the fission-product user. To increase the specific activity of the gross fission products, some of the inert components must be removed. In this stage of chemical treatment, the fission products are classed as semi-refined. If a need exists for a particular type of radiation, additional separations could be performed to reduce the semi-refined fission products to a number of specific radioisotopes. After the required chemical processing, the fission products are redefined as mixed fission products. Such a degree of processing may be economical, if beta-emitters were all that are required for a particular application. The absence of the highly penetrating gamma rays would lessen the shielding requirements, resulting in lower structural cost, which could offset somewhat the costs of chemical treatment. Individual or separated fission products, with applications as tracers or long-lived, high-level radiation sources, are produced with additional chemical processing. Higher prices for the fission products reduced to individual radioisotopes would be offset by their ability to more adequately meet the needs of potential users.

3. Development. Investigations are being conducted, whereby the gross fission products can be converted to products possessing specifications which have marketable use. Some of these investigations are discussed below.

a. Adsorption. It appears that uses can be developed for fission products dispersed through selective inert adsorptive materials. In general, the products produced from such treatment may have lower specific activities than materials produced by other means. As an example, it appears possible to develop usable products by adsorbing fission products contained in an aqueous chemical solution in activated clay. It may be possible to cast such a clay, containing known quantities of fission products, into geometrical forms that permit ready handling, shipment, and use of the resultant product. Dependent upon developed end use, investigations may reveal a number of selective adsorbents which might be used, depending on the properties required of the end product.

b. Concentration by Evaporation. By employment of novel designs, it appears feasible to effect concentration of the fission products as they exist in conjunction with present metallic salts possessing high melting points. These molten solutions or slurries could be cast into suitable shapes. Under certain conditions, it may be possible to achieve products which contain very high specific activities. Extensive use of this method will necessarily depend on the development of containers into which the material can be solidified, packaged, and shipped.

c. Concentration by Chemical Conversion. Another feasible method would be to convert present fission product compounds to different states, which could permit safe storage over long periods of time. As an example, conversion of nitrates to oxides can accomplish a forty-fold reduction in volume. This field of investigation offers intriguing potentialities in effecting considerable savings in processing costs, as well as production of fission products in useful form.

d. Selective Separations of Short-Lived Fission Products from Long-Lived Groups. It appears feasible to consider investigations of methods of separation of fission products possessing long half-lives, in concentrated form from the mass of chemical salts and those fission products which decay rapidly to inert materials. An employment of such investigations appears realistic when employing ion-exchange techniques. It may be possible by such methods to reduce the volume of the long-lived fission products to about five per cent of the volume of the original solution.

4. Uses of the Fission Products. Potential uses of fission products are many, provided the price of the products can be held down. Development of economical processes to separate fission products into usable forms are needed before full use of these products can be realized.

The radioactive fission products are finding increasing applications in industry, both in research and process control. Another apparent and widely discussed area of investigation lies in the potential use of gross fission products as sources of energy, from which heat can be obtained. The development of such heat-energy sources is contingent upon processing of gross fission products which yield a product that has concentrated activity, and can be maintained for long periods of time at high temperatures. Since transportation of high-energy source products poses a major problem, one of the more obvious areas of utility lies in auxiliary preheat systems for nuclear power plants. Use of the fission products in this manner would also have the advantage of maximum utility of energy from short-lived fission products. Subsequent to the development of preheat systems for nuclear power plants, one use of fission products could be their application in similar duty in conventional power plants. Obviously, this would entail the solution of the additional problems of handling, storage, and transportation.

Dependent upon the energy level and temperature conditions, it appears that generation of steam from packaged fission-product boilers can be developed. Development of such utilities for concentrating energy sources is a challenge to the magination, and requires resolution of a great many technological problems. Successful resolution of these problems may lead to utilization of concentrated gross fission products in industrial applications in heating, ventilating, and air conditioning. With highly concentrated energy sources available, possibilities arise for reversibility, so that such energy could be utilized for refrigeration. Such a facility would be similar to the gas-burning refrigeration units available on the market. However, the generation unit for the refrigeration cycle requires remote location and heavy shielding, so this utility appears to be confined to large installations.

Another very broad and diversified field of application for the gross fission products as sources of energy lies in areas of use in the manufacture of chemicals and petroleum products. The effects of radiation on chemical reactions are not new. However, the industrial application has not been feasible until this time, because of the lack of cheap sources of radiation. With the vase quantities of fission products available from nuclear chain reactors, some of the reactions have great industrial promise.

A number of possible applications in radiation chemistry have been suggested in the Stanford Research Institute Report, Industrial Uses of Radioactive Fission Products, and are indicated in Figure 8. In general, it can be stated that any chemical combination or dissociation that requires promotion or acceleration is worthy of investigation under some influence of gamma irradiation. One of the fields of interest which offers vast opportunities for improvements in processes and products is polymerization. Such improvements can be accelerated by employing gross fission products. Polymerization is the process used in the production of long chain molecules, examples of which are the plastics—polyethylene and polystyrene. Preliminary feasibility studies have indicated that gamma-radiation-promoted chemical polymerizations will not be able to compete economically with conventional methods of production. However, possibilities lie in the production of new polymers which cannot be produced by present means, and in improving the properties of presently polymerized materials. Halogenation reactions, conventionally catalyzed either with a metallic catalyst or light, show

FIG. 8

POSSIBLE USES FOR FISSION PRODUCTS

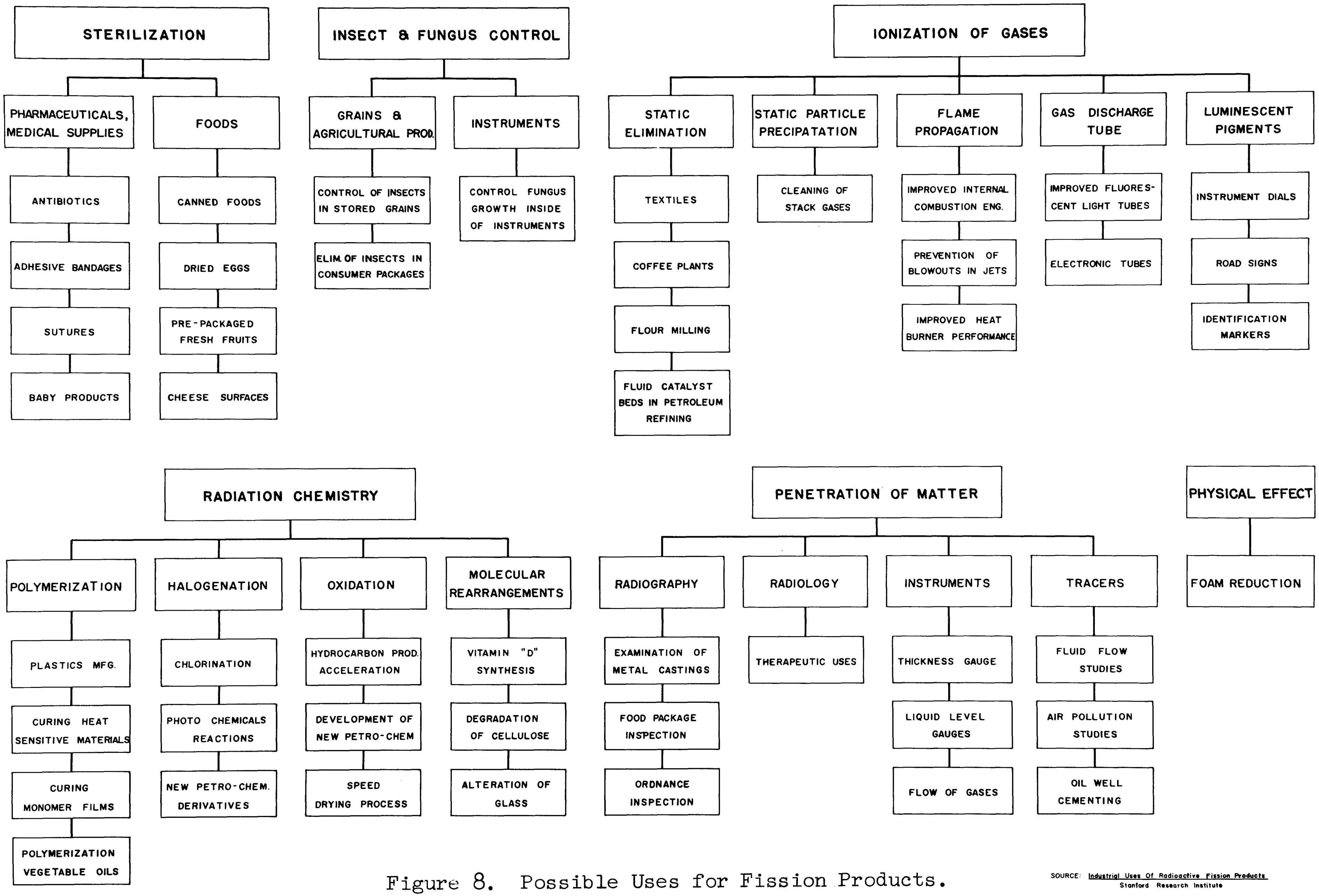


Figure 8. Possible Uses for Fission Products.

SOURCE: Industrial Uses Of Radioactive Fission Products
Stanford Research Institute

definite promise for utilizing the fission products. The University of Michigan has been investigating the chlorination of aromatic compounds and the polymerization of olefins, using a high-level source of gamma radiation. This source has been used in numerous instances of cooperative research with industry.

In addition to experiments on chemical reactions, investigations have been conducted at the University of Michigan on the pasteurization and sterilization of foods. Canned raw frozen foods, canned fresh foods, fresh meats, vegetables, and grains have been studied to determine the effects of gamma radiation on the storage, taste, and wholesome properties of foods. Another experiment, involving a long-term animal-feeding program, was designed to investigate the effects of an irradiated diet on the normal growth characteristics of a large number of albino rats.

The results of these studies have led to the design of radiation facilities to pasteurize meat and prevent sprouting in potatoes and onions, and another for the chlorination of aromatic compounds. Examples of the types of facilities considered for pasteurization of meat and prevention of potato sprouting are shown in Figures 9 and 10, respectively. In both of these designs, the materials to be irradiated are brought by means of a conveyor mechanism past a radiation source. In passing through the chamber, the material absorbs a certain amount of radiation, depending on the size of the source and the absorption characteristics of the material. The number of passes in the chamber made by the material depends on the dose or quantity of radiation required to produce the desired effect.

In the meat pasteurization facility, pre-packaged cut-up meats could be treated at meat packing plants and sent directly to retail outlets. Some advantages of this facility would the elimination of local butchering and extension of the shelf life of the meat. These and many other advantages are expected to produce economies, which would ultimately result in lower prices for the consumer.

The potato facility was designed to help eradicate the losses suffered by potato farmers and processors as a result of sprouting. Tests performed at the University of Michigan revealed that, with the proper dose of radiation, potato sprouting could be prevented for months, or indefinitely with a sufficiently high radiation dose. Potato processors who have to buy large quantities of potatoes at harvest time and then store them for long periods before processing would benefit considerably from such a facility.

The uses of the fission products mentioned thus far depend on the fission products as a source of energy and for their ability to kill microorganisms. Possibilities for other large-scale fission-product utilization lie in their use as radioactive tracers. The technique of using radioactive

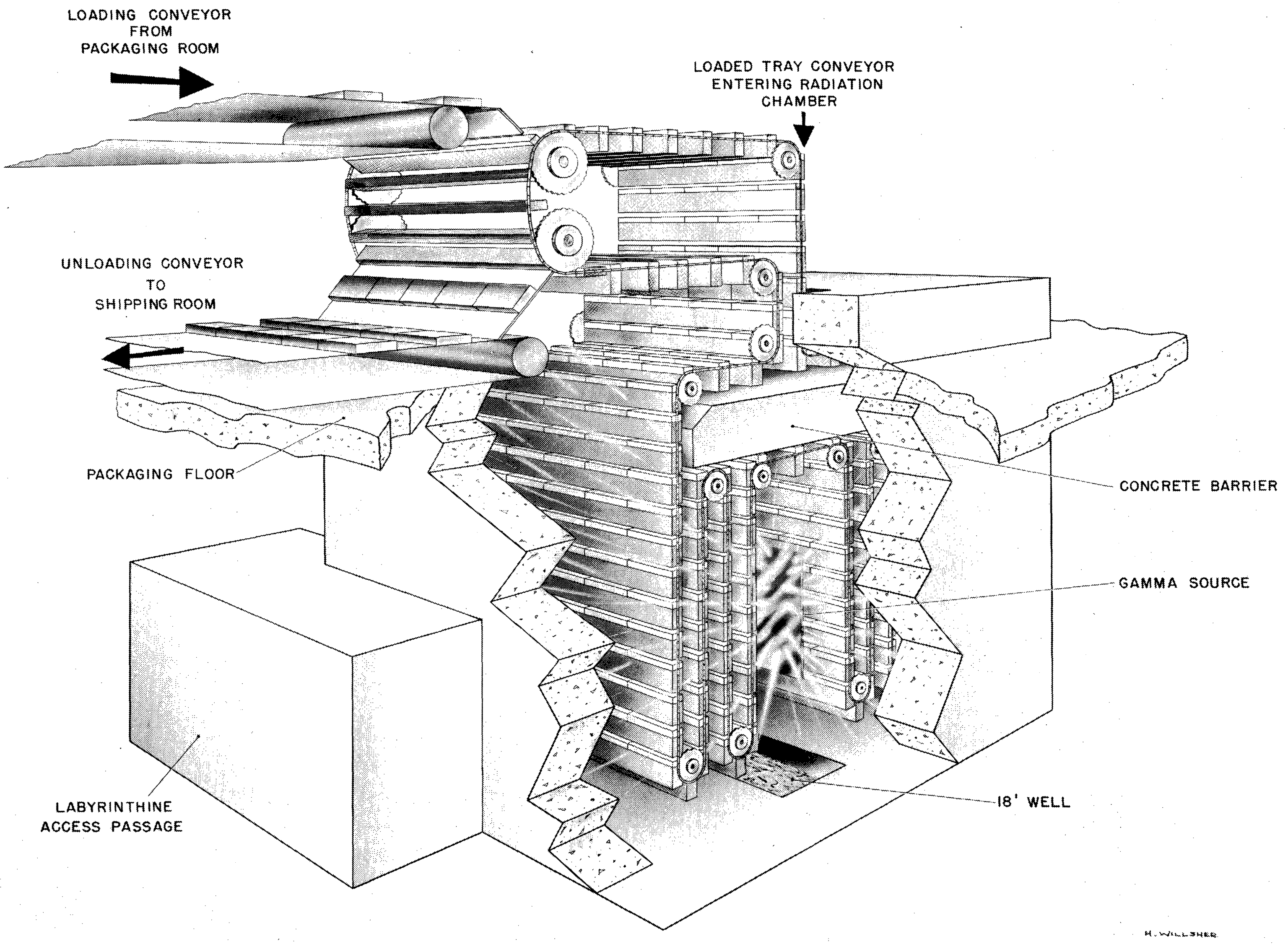


Figure 9. Radiation Facility for the Pasteurization of Fresh Meat.

Capacity, 13 tons/hour Radiation Dose, 80,000 rep Estimated Cost, Less than 1 mill/pound meat

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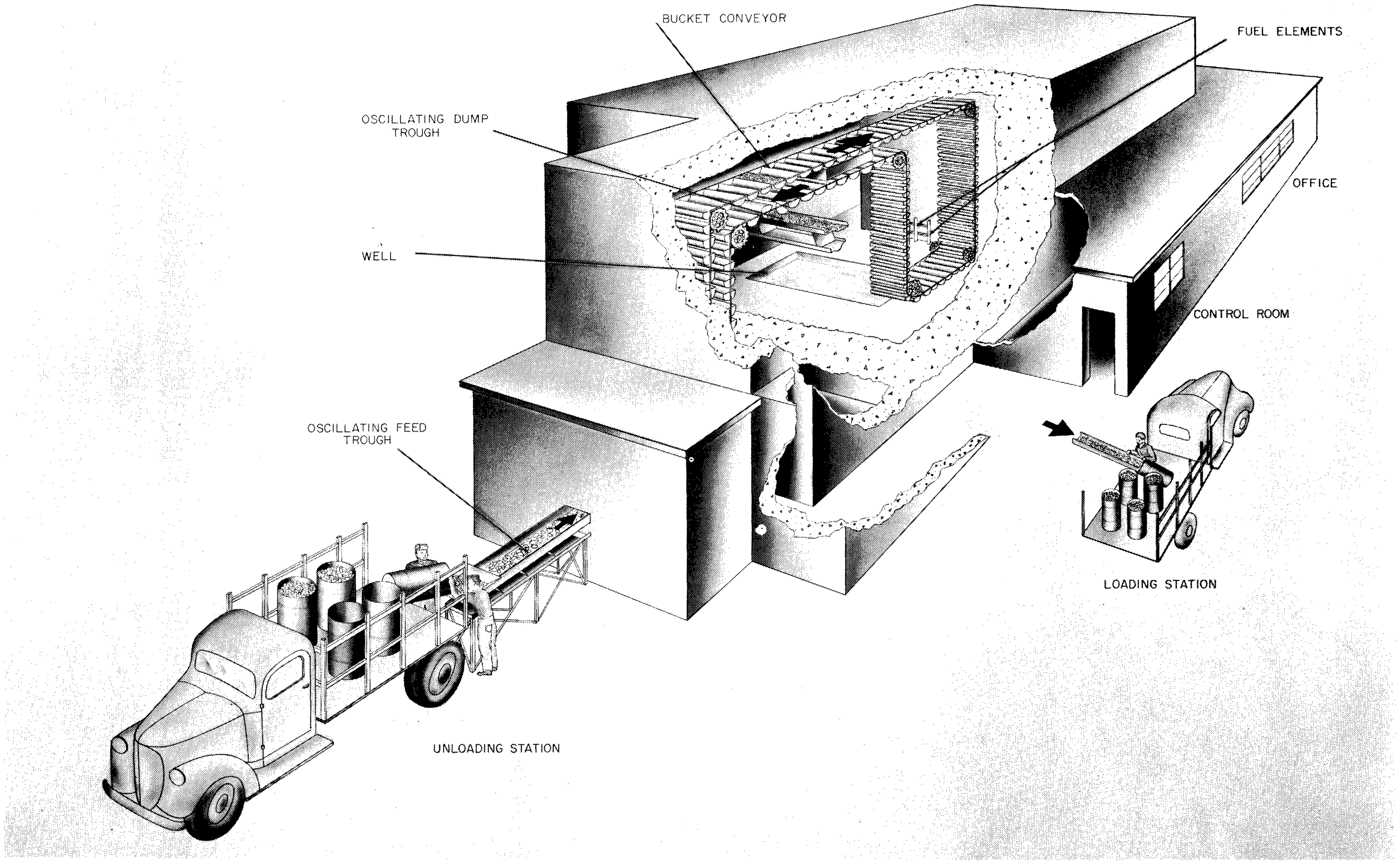

Figure 10. Radiation Facility for the Treatment of Potatoes.

Capacity, 6-1/2 tons/hour Radiation Dose, 10,000 rep Estimated Cost, $3.62/ton potatoes

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isotopes has been used to solve problems in all the physical sciences. Industry is finding numerous applications for small amounts of radioactive isotopes to be used as tracers. However, the phenomenon of radioactivity is not new to industrial research. As early as 1920, use was made of these techniques to investigate the solid state of lead. The widespread use of radioisotopes at the present time results from the numerous types and large quantities available from nuclear reactors.

The basic idea of the tracer technique is to mix some "tagged" (radioactive) isotopes among the stable isotopes of a test material. Since radioactive atoms can be detected by their radiations, they indicate the position and amount of test substance in the body of the material. Radioactive isotopes may be "manufactured" by two methods. One is to expose a material to neutron bombardment in a nuclear reactor to make it radioactive for use as tracer material. Fission products themselves, being highly radioactive, are the other source. This study is concerned only with fission products, as they are an unavoidable by-product of nuclear power.

Some of the uses to which tracer isotopes can be put are studies in flow components of process operations, metering of fluids, and as leak detectors in pipe lines. The determination of friction, wear, and corrosion rates in inaccessible places may prove easy, using this means. Certain elements of the fission products, such as strontium-90, are used in commercial thickness gauges in the paper and plastics industry. Large savings are effected by narrowing tolerance limits and achieving better process control.

Radioisotopes have been successful in eliminating static accumulation in flour mills, cement industries, and paper and textile plants. Mostly, naturally-occurring radioisotopes have been used up to the present. These may be supplanted in this use by fission products which have a greater range of the beta radiation. If successful, the fission-product radiation will help reduce the fire and explosion hazards present in these types of plants.

These are but a few of the many uses for fission products. Figure 8 shows many more possible applications. This list will continue to expand as sources become more readily available, and more people are trained.

B. Influence of Nuclear Energy on Technology

The advent of the nuclear energy era has altered the technology of all phases of scientific endeavor by providing researchers with new tools of investigation. Many of the complexities of chemical, metallurgical, and engineering processes, heretofore unassailable by conventional methods, have been resolved by using man's newly gained knowledge of nuclear energy. There have also been many advances made in the study of the fundamental processes of life by medical and biological researchers employing new techniques developed as a result of the atomic energy program.

1. Chemistry. Utilization of nuclear energy has brought with it some severe problems in the fields of analytical, physical, and organic chemistry. The major problems have been how to analyze or measure physical properties of substances that are highly radioactive. In many cases, analysis must be made on very small quantities of substance, and frequently the analysis must be completed in a very short time, as the substance may be changing to a different element by radioactive decay.

These problems have been met by several approaches, and where new approaches are worked out, new applications are rapidly found. For example, a process for the separation of plutonium from uranium and fission products was based on chemical properties worked out by Dr. G. T. Seaborg and co-workers at the University of California, using quantities of plutonium smaller than the head of a pin. The chemistry of neptunium, an isotope of which is the predecessor of plutonium-239, has been worked out. This element is highly radioactive and decays rapidly, resulting in radiation hazards; so the work was performed using very small quantities.

New elements americium, curium, berkelium, and californium have been discovered and their chemical properties worked out, using similar techniques.

Separation of elements in the rare-earth series has been achieved, largely due to the efforts of Dr. F. H. Spedding and co-workers at Iowa State College. These separations have been made by using ion-exchange techniques. Heretofore, these elements could be obtained only in the impure state.

Work on chemical separations of elements with closely related chemical properties by chelation-solvent extraction methods has been investigated extensively at all of the national laboratories. These methods are now used in preparing zirconium, and the separation of zirconium from hafnium, which is a difficult task by conventional chemical methods. These methods are also used extensively in purifying uranium and thorium for reactor purposes. Similar procedures could be used for other separations, such as nickel from cobalt or iron from manganese.

A major contribution to analytical chemistry has been the development of tracer techniques as analytical methods. As an illustration, assume it to be necessary to determine the part of impurities in a chemical process. Tracer isotopes of the impurity are added to the raw material, and after the ratio of impurity to tracer is established by a conventional analysis, all subsequent impurity concentrations can be determimed by placing a sample into an instrument that counts the radioactivity. From the counter results, the impurity is easily determined.

The chief advantages of this method of analysis are in the speed and accuracy with which determinations can be made. Major cost savings in analytical chemistry budgets have been achieved by these methods. If the beta or gamma emission from several tracers have different energies, counter instruments are available that will determine the activity on only one emission energy at a time, so several tracers can be carried through analytical procedures simultaneously.

Considerable study has been given to the subject of physical properties as process control indices. Properties, such as infra-red adsorption, gamma emission, as well as the more ordinary physical properties, are being extensively investigated as process control and automatic analyzers. Instruments utilizing many of these new developments should be available in the next few years.

All of these developments are presently or will become very useful tools to industry.

2. Metallurgy.

a. One of the major technical problems confronting the designers of nuclear reactors is the proper choice of the materials used in reactor construction or as coolants and moderators. The materials used in reactors must conform to operating conditions, which can vary over wide limits of temperature and pressure. The extreme quantities of heat produced in nuclear reactors must be dissipated, and as such, it functions as a type of heat exchanger. The materials chosen for reactor duty would have to meet requirements similar to those imposed on a heat exchanger operating under the same conditions. Not only must materials meet these general requirements, but they must also have the proper nuclear properties. Of primary concern to continuing reactor operation is the need for maintaining the supply of neutrons throughout the reactor. The nuclear properties of many materials are such that, by parasitic absorption of neutrons, the supply is decreased and the fission reaction inhibited. Also, the neutrons resulting from fission may alter the physical properties of a material so that it is no longer usable. Such phenomena are generally referred to as radiation damage.

Many construction materials normally used have poor nuclear properties. Research engineers, metallurgists, and physicists have been working hand in hand to develop new materials which have the necessary physical, mechanical, and nuclear properties suitable for use in nuclear reactors. The MTR (Material Testing Reactor) was designed and built for the express purpose of determining the behavior of materials exposed to high neutron irradiation.

Efficient removal of the heat generated in nuclear reactors at high temperatures has promoted the use of liquid metals as coolants. Water, heavy water, and air have been used, but do not have comparable heat transfer properties. Another advantage of liquid metals is that they can be used at atmospheric pressure, while water cooling would require pressurized systems to maintain the high working temperatures required. In addition to pure metals, the use of alloys has been mentioned. Prominent among these is the Na-K (sodium-potassium) alloy, which melts at room temperature and has fairly good nuclear properties in the intermediate and fast neutron ranges. Use of liquid metals results in corrosion problems for most materials of construction. An additional problem is pumping these metals at the high temperatures involved. The corrosion and pumping problems that arise from use of molten metals are still not completely solved.

In the realm of construction materials, the metal zirconium has received considerable attention, since it has the lowest absorption cross section for thermal neutrons, of all mechanically strong, corrosion-resistant materials. Zirconium is a preferred material of construction for power-producing reactors operating at temperatures below 800°F. The importance of zirconium resulted from the development of production processes which were economically feasible. Separation processes were developed at Oak Ridge National Laboratory to remove the contaminating element hafnium, which is always associated with zirconium. Hafnium has high neutron-absorbing characteristics, so its presence in the zirconium is very undesirable.

The two principal methods of producing zirconium and hafnium on a commercial scale are the hot-wire process and the Kroll process. The hot-wire process consists of the thermal decomposition of gaseous zirconium and hafnium iodides on a heated tungsten wire. The more expensive hot-wire process has been replaced by the Kroll process, which consists of the reduction of gaseous zirconium chloride with fused magnesium in an inert gas atmosphere. The Kroll process is being used to produce 270,000 pounds per year of zirconium sponge at the Albany, Oregon, Laboratory of the U. S. Bureau of Mines. The Atomic Power Division of the Westinghouse Electric Corporation produces a very pure zirconium metal in the form of crystal-bar. Some crystal-bar is also produced by the Foote Mineral Company.

Operation of nuclear reactors at high temperatures has stimulated interest in ceramics as materials of construction. The ceramics possess fine refractory properties, but have very poor mechanical properties. As a result, there have been developments made in the study of mixtures of ceramics and metals, known as cermets. In such materials, it is hoped to combine the mechanical properties of metals with the refractory properties of ceramics to produce a material well suited to reactor operation.

In addition to these new developments in reactor materials, there have been major advances in other phases of metallurgy, resulting from the influence of atomic energy. Nuclear reactor-produced radioisotopes have been used to determine the effect on the constituents of a material undergoing various treatments, such as hardening, quenching, and annealing. These studies were aided by the use of radioautographs to detect the distribution of radioisotopes throughout a material. Since radioactive and stable isotopes perform similarly, the distribution of the stable substance throughout a treated material is also indicated by the radioautograph.

Diffusion of atoms within metals, which plays an important role in many metallurgical processes, has been studied, using radioisotopes. Coatings of metallic radioactive isotopes have been applied to the surface of a metal, which is then heat-treated and subjected to various stresses. Subsequent detection of radioactivity in the sub-layers of the metal gives an indication of the amount of diffusion. This technique was used in 1920 to investigate the diffusion of the atoms in lead, using radioactive lead. Such studies were restricted to the use of only a limited number of radioisotopes, but now nuclear reactor-produced radioisotopes of many metals are available for further studies in this field.

Another new development in metallurgical techniques is the possible use of specific radioisotopes, which could be formed into special shapes to facilitate the investigation of metal castings. This new radiographic method may eventually supersede the older use of the expensive x-ray equipment required to perform the same tasks. As more personnel are trained in the proper handling of radioactive materials, their use as tools of research will expand considerably.

3. Medicine. Tracer techniques, using radioisotopes, have contributed valuable information to medical researchers investigating the fundamental life processes. In addition, radioisotopes have been used in diagnosis and treatment of diseases. Their use in such a manner is contingent on the preferential absorption of particular radioisotopes by certain portions of the body.

The blood system has been extensively studied, since samples are easily obtainable and the blood is the main medium for distributing chemicals to all parts of the body. Scientists at Boston University have been studying blood metabolism, using radioactive carbon. Other radioisotopes have been used in the treatment of the blood diseases, leukemia and polycthemia vera, at the University of Chicago and numerous other hospitals. Although not performing final cures in these cases, the diseases have been arrested. Blood volume and the amount of sodium contained in the body have been studied at the Radiation Laboratory, University of California, using radiosodium. Radioactive iron has also been used in dilution techniques of measuring blood volume. Anemia studies have been conducted, using radioisotopes, at Massachusetts Institute of Technology and Brookhaven National Laboratory. Other investigations have been concerned with studies of the blood plasma. Constrictions in the flow of blood have been diagnosed, using radiosodium.

Yale University scientists have been studying the thyroid gland, using radioiodine. Proper functioning of the thyroid depends on an ample supply of iodine in the body. Overactive thyroid glands have been detected, using radioiodine, and in some cases, it has been used to treat the condition. Being preferentially absorbed in the thyroid gland, the radioiodine becomes localized there, and the effects of its radiations are restricted to a definite area. The radiations emanating from radioiodine have successfully retarded the activity of overactive thyroids in many instances.

Cancer research has been underway at a number of institutions, including the University of Michigan, to develop radioactive cobalt-60 as a substitute for the expensive radium. Other experiments at AEC-operated National Laboratories have been performed, using radioisotopes to aid in the understanding of cancer formation. The successes met by using radioiodine for treating overactive and cancerous thyroids have prompted scientists to search for radioisotopes which could travel to other cancerous locations throughout the body.

University of Michigan scientists, as well as those from Harvard Medical School and numerous other institutions, have developed techniques for locating brain tumors, using radioisotopes of phosphorus and iodine, which are preferentially absorbed by tumorous tissue.

4. Engineering. The development of nuclear energy has produced new problems to be resolved by engineers. A difficulty arises, due to the lack of experience most engineers have concerning the phenomenon of radioactivity. The engineering colleges and universities of the country are rapidly revising and supplementing engineering programs to acquaint students with this phenomenon. The opinion of educators in such fields favors a continuation of the present engineering curriculum, giving the students a firm background in basic engineering principles, while acquainting them with the problems of nuclear engineering associated with their field of study. No new fields of engineering are expected to develop, since most of the problems confronted in this work may be resolved by extensions of well-known engineering principles.

One of the technical problems successfully solved has been the recovery of spent reactor fuels. The nuclear fuels which existed in solution with other substances had to be separated to a degree not attained previously. The combination of chemical engineers and production engineers with the aid of chemists resolved this difficult problem. The high recovery of the valuable element plutonium will aid the competitive position of nuclear power.

Due to the high levels of radiation emitted from nuclear processes, engineers have been faced with two severe problems. One problem was how to reduce the radiation levels down to tolerable levels--which was done with massive shielding; and second, after the massive shielding was in place, a problem of operating equipment through six-foot-thick concrete walls arose. The inaccessibility of equipment made it necessary to develop equipment that would operate remotely and for long periods of time without breakdown. With equipment in such service, problems that would be minor in a more normal service are major ones in this application. Such a problem would be one of lubrication of moving parts. Another example would be the determination of wear, so that a replacement schedule could be arranged. With the cooperation of mechanical, chemical, and electrical engineers, solutions have been found to many of these problems.

The heat generation possible in a reactor has produced other problems, with which engineers have not been acquainted until this time. The thermodynamically efficient transfer of heat at high temperatures is well-known to engineers, but the problem is to remove tremendous amounts of heat from small volumes. Engineers must be concerned with structural, mechanical, and other physical properties of materials of construction and coolants, and in addition must be aware of the nuclear properties of these materials. The final choice of a specific material would be a compromise of all these properties.

Not all the effects of atomic energy developments have led to new problems for engineers to tackle. The use of radioisotopes in engineering studies has made significant contributions to the understanding of the mechanisms of many processes. With the use of tracers, the components of a reaction can be followed through all stages of a particular process, demonstrating the effects they have on a reaction.

Engineers have found radioisotopes to be most useful in product and quality control. In the production of materials in which impurities cannot be tolerated, the use of radioisotopes has helped to produce an essentially pure product. Radioactive thickness gauges have supplanted older, inferior methods of quality control for the production of such materials as abrasive papers, plastic sheets, adhesive products, and metal foils. The use of thickness gauges depends on the absorption of the radiations emitted from a source located on one side of a moving material. Irregular absorption would cause variations in the machine controls in such a way as to offset the cause of the irregularity. Advantages of this method lie in the ability of the gauge to function without contacting the surface of the material. This permits continual, instead of intermittent, operation, and prevents damage to materials which could suffer from excessive surface pressures.

Tracers have also been used in the analysis of experimental data, and determining the efficiencies of reactants in certain processes. Petroleum engineers and other engineers associated with the petroleum industry have frequently used radioactive tracers in the study of hydrocarbon reactions. There have been many other techniques developed, using radioactive tracers, to aid engineers in the solution of their problems. The final effort of all such work is to produce better products more economically, so that everyone may share in the benefits to be attained by developments in the expanding nuclear energy program.

5. Special Products. The increased use of radioactive materials in industry, and rapid expansion of the nuclear reactor program has seen the development of many products of a specialized nature, manufactured mainly for service in this field. These materials were designed to cope with the problems arising out of the handling and transportation of radioactive materials. There should be applications for these special products in many industrial processes.

Chemical analyses using small quantities of radioactive materials are generally performed in hoods or dry boxes. The hoods used are quite similar to conventional hoods employed in working with toxic compounds. Dry boxes are gas-tight containers with glass windows and hand-holes with attached rubber gloves for performing operations inside the box. The use of these devices helps to concentrate any activity in one location. For medium- and high-level activities, cells constructed of concrete, lead, or steel are used in conjunction with remotely controlled manipulators viewed through glass or liquid windows to conduct experiments. Manipulators are available on the market for this type of work. Special types of glass have been developed for use in shielding which will not darken during irradiation. Designs for periscopes have been advanced, as well as mirror systems; and even television has found service in the viewing of operations within radioactive cells.

To prevent bodily contamination with radioisotopes, new types of tongs for handling dangerous materials have been designed for special uses. For experiments using high-level amounts of radioactivity within cells, remotely controlled manipulators have been designed. There are several types of such instruments in use today.

The problem of transporting radioactive materials has produced many novel designs of carriers and containers. These carriers are usually built with thick lead linings to reduce radiation levels to tolerable levels. Incorporated in the design may be cooling systems that dissipate the heat evolved from radioactive decay. These carriers are regularly used for transcontinental shipments of radioactive materials.

Other new developments have centered around remotely controlled valves of alloy construction. Valves with no packing glands have been developed, that have been used for long periods without leakage or operational failure. The problem of preventing leakage of radioactive materials from pumps has produced a number of different designs of pumps and seals. Special feed pumps have been designed to handle high-temperature radioactive solutions to approximately 1000 psi. There are pumps on the market today with the rotor of the driving electric motor submerged in the process fluid. These canned rotor pumps have no packing glands and have a wide adaptability in pumping solutions where leakage cannot be tolerated. A diaphragm pump is on the market, that has been successful in pumping radioactive solutions without leakage or mechanical difficulties.

Stability at elevated temperatures and good heat transfer properties have promoted much interest in liquid metals as coolants in reactors. To handle the liquid metals, several different types of pumps have been developed. Mechanical pumps have been developed, which do a satisfactory job, but have to contend with stringent sealing requirements to prevent contact of the liquid metals with the outside air. A large amount of study has gone into the development of bearings to be operated in liquid metal mediums.

The high electrical conductivity of some of the liquid metals has permitted the development of electromagnetic pumps. All such pumps operate on the same principle as a D.C. motor, in which a current-carrying conductor at right angles to a magnetic field has a force exerted on it which is perpendicular to both the field and the current. The liquid metal acts as the conductor, and the force exerted on it develops a pressure which is used to transport the metal. The variations in electromagnetic pump designs involve different methods of producing the magnetic field and the current.

A new plastic called Teflon was developed exclusively for use in the nuclear energy field. This plastic is a polymer of a fluorinated ethylene, and has shown superior properties at high temperatures and under severe service, such as chevron seal rings, gaskets, and in uses where other plastics are unsuitable. This plastic is now on the market. The success of this plastic has resulted in the development of similar plastics, which are marketed under the name of Kel-F and Fluorothene.

In the field of solvent extraction, where good liquid-to-liquid contactors are necessary, pulse columns and mixer settlers have been developed, that are superior to other equipment in certain applications. These contactors should find considerable use in industry in the future.

VI. SPECIAL HAZARDS

Hazards in nuclear energy include radiation and systemic poisons, as well as the normal industrial hazards, such as fire and explosions. That additional hazards existed in this field was recognized at a very early stage. Consequently, all practices and procedures were reviewed to establish where special precautions were necessary. The result of these efforts has been a safety record on the part of the AEC and its contractors, that is considerably better than that of normal industry. With the current safety procedures, a worker is safer working in nuclear energy plants than in most industrial plants.

Hazards from radiation have been reduced practically to the vanishing point by adequate shielding of all radioactive equipment, and by the development of special instruments that detect the presence of radiation. These instruments warn the workers before tolerance levels are reached, so they can leave the premises or start decontamination procedures that will reduce or remove the radioactivity.

Special monitors have been developed, that continually indicate and record activity in all streams leaving a process handling radioactive material. These instrument can give warnings when radiation exceeds a safe limit, or can operate automatically to stop or divert the stream containing the contaminants. Such equipment acts as a safeguard to prevent contamination of the atmosphere or water streams in the vicinity of a nuclear plant.

Light, portable survey instruments have been developed, that are very sensitive to radiation and can detect radioactivity on any equipment in or leaving a plant. These are used regularly in routine surveys throughout areas that might possibly be contaminated. In addition to this, each worker in a danger area wears a personal radiation indicator or badge. These are checked regularly to make sure the individual worker has not been irradiated inadvertently above the tolerance limit.

To insure the safety of people outside the plant area, health physics teams regularly tour the surrounding countryside, sampling the streams and inspecting the plants and animals to determine whether any radioactive isotope is accumulating in a given area, plant, or animal.

A systematic study of normal industrial operations has resulted in improved methods for doing many tasks. As an example, interlock systems have been developed to prevent a worker from performing a sequence of operations in any manner but by the prescribed safe procedure.

Special equipment has been devised for handling very poisonous materials in the laboratory, such as plutonium, so that the chemist performing the operations never comes into contact in any way with the material being analyzed. Procedures which are similar, but on a larger scale, apply to the actual plant operation.

In this field, the greatest industrial participation has been in the development and manufacture of radiation-monitoring instruments, which are used extensively in the program. Many new companies have been formed since 1943, that manufacture and develop instruments exclusively in this field or in the field of tracer analysis, with which such instrumentation is closely allied. With the entrance of nuclear power into the picture, it appears that there will be an increasing demand for such instruments in the future.

VII. IMPACT OF NUCLEAR ENERGY ON FUTURE UNITED STATES ECONOMY

Electrical power from nuclear energy has already been widely publicized. Considerable emphasis is being placed on studies of the economics of power from such a source. Most studies at the present time have come to the conclusion that a government subsidy, either as a payment for the plutonium produced, in processing the spent fuels, or direct support on installation costs, is necessary. It must be kept in mind that these conclusions are reached on the basis of present-day costs. Present-day costs mean equipment that is custom- or hand-built for each particular service, so no allowance is made for economies that could be achieved by multiple or mass production of the same items. In addition to this, many of the factors involved are unknown at this time; and where such conditions exist, the costs can easily be overestimated.

It is also significant that, of all the study teams in the field, no two teams have selected the same type of reactor and components. From this, it is evident that the optimum power-producing reactor has not yet been designed. When such a reactor is devised, a further reduction in costs, along with greater efficiencies, can be realized.

Another factor that cannot be overlooked is that fossil fuels in this country are being steadily depleted. As the higher-grade fuels are used up, more low-grade fuels must be utilized; and this can be done only at higher costs. What, then, are the possibilities that nuclear power will compete with fossil fuels in the near future?

In an address delivered to the twenty-seventh International Congress of Industrial Chemists on September 15, 1954, Walter Cisler and Arthur Griswold discussed some cost data on the St. Clair power plant of the Detroit Edison Company. In this address, entitled "Atomic Energy and the Electric Power Industry", coal costs were given as 35 cents per million BTU, delivered at the plant. Steam at the turbine throttle cost 57.7 cents per million BTU. If it is assumed that turbine and electrical generation efficiencies are such that electrical power can be generated for 0.7 cents per kilowatt hour, fuel costs are then approximately 60 per cent of the total costs. In Palmer Putnam's book, Energy in the Future,* data are given to indicate that coal costs have increased by 1.5 times between 1920 and 1947. Since more coal is being burned now, it appears that coal costs will be up by another factor of 1.5 in ten to fifteen years. By 1970, then, coal costs for the St. Clair power plant should be about 53 cents per million BTU, and power from the plant will cost 0.9 cents per kilowatt-hour, instead of 0.7.

Even if the technology of power from nuclear reactors stands still and more economical and efficient nuclear power plants are not designed, it appears likely that power from the nuclear reactors will be competitive with that from fossil fuels in ten to fifteen years. Advances in technology could well cut this time appreciably. A place for nuclear power in future United States economy then seems certain.

Another use of nuclear energy that could affect the country's economy is the heating of buildings. At present, only the largest-scale units, heating multiple-office buildings or industrial plants, would be economical. Since high temperatures are not required, the simplest reactor--such as the self-regulating water boiler--could be used in a building-heating application. Boiling solution or steam from the reactor could be circulated through an air heater. The heated air could then be carried through ducts to the buildings to be heated. Periodically, the "soup" solution in the reactor could be replaced and the spent fuel sent to a central plant for chemical processing. Such a heating unit could be very small and compact. Some of the high costs of the reactor and components could be offset by smaller charges on space and building requirements that house the reactor.

At Harwell, England, the waste heat from one of the experimental reactors is used in such a manner to heat the office buildings. This unit

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* Published by D. Van Nostrand Company, Inc., New York

is of an experimental nature, however, and probably is not competitive economically with conventional heating plants.

In very cold regions, such as Greenland or northern Canada, where fuel and transportation costs are high, such heating installations are entirely feasible at the present time.

Large propulsion units for ships utilizing nuclear power is, of course, feasible. Two military units have been developed for the submarines Nautilus and Sea Wolf. These units are not necessarily usable for commercial vessels, due to the high cost and special military features. Such units can, however, be the basis for developing economical commercial units. Nuclear power does not appear to be economically feasible for any but the largest vessels at this time.

For about eight years now, studies have been conducted on the feasibility of nuclear-powered aircraft. Design of reactors suitable for propelling aircraft is an extremely difficult problem. Light weight is a necessary criterion; but at the same time, the crew must be shielded in some way by massive shielding, or be placed a considerable distance from the nuclear engine. Once such an airplane becomes technically feasible, there are still some safety problems. Such an airplane obviously could not be landed at a congested commercial airport. It is also distinctly possible that such an airplane would be too large to utilize many of the runways in existence today.

While nuclear-powered aircraft may be feasible for special military uses where long range may be of paramount importance, it is doubtful that such an airplane will see common commercial use for many years.

Nuclear-powered locomotives have been proposed. Since locomotives are not required to travel extremely long distances without refueling and nuclear power is not competitive on this small scale with oil at the present time, such applications of nuclear power appear to be a development that will not see commercial application for some years.

One development that is certain to come, parallel with electrical generating plants powered by nuclear energy, is the construction of processing plants that will process multiple-type spent fuels. These plants could be designed to process a number of different types of nuclear fuels, and would be centrally located to several nuclear power plants. Spent fuel would be sent to the processing plant, which would separate the fission products from the spent fuel and return a usable fuel back to the power plant. Fission by-products could be utilized in any of the ways outlined in the previous section. By handling large quantities of spent fuel and marketing all possible by-products, processing costs per unit fuel could be held to a minimum.

The impact of new developments in the fields discussed earlier is difficult to estimate. It is certain, however, that the effects will be significant. As an example, the savings in time and expense, by using tracer techniques in chemical analysis and thickness gauging, amounts to $100,000,000 annually. A discussion of these savings is given in Chemical Engineering, October, 1954, published by the McGraw-Hill Publishing Company. The use of carbon-14 tracers in medicine and biology has resulted in developments that were heretofore impossible. Uses of radioactive fission products have barely been touched. It is possible that these materials, now a waste product, will have considerable value in the future, and be a commodity much in demand.

VIII. GLOSSARY OF TERMS

ATOM - The smallest part of an element that can exist and still retain the physical and chemical properties of that element. A classical picture of an atom is a core, or nucleus, containing neutrons and protons, surrounded by electrons in outer orbits.

BETA PARTICLE - A type of radiation emitted from some radioactive elements. It is emitted from the nucleus and has practically no mass and a negative charge. A beta particle has a charge and mass identical with that of an electron.

BURN-UP - This indicates the rate of utilization of fissionable fuel in a nuclear reactor. It includes that portion of the fuel fissioned, as well as that undergoing neutron capture without fission to become another isotope.

CRITICAL SIZE (CRITICAL MASS) - The mass of fissionable material that is just sufficient to maintain a self-sustaining fission process.

CROSS SECTION - The effective area presented by a nucleus for a particular type of reaction. It is a measure of the probability of the occurrence of a reaction. The cross section varies with the neutron energies. Its measuring unit is the barn (10^{-24} sq cm, or approximately .154 x 10^{-24} sq in.) or the millibarn (one-thousandth of a barn, or 10^{-27} sq cm).

ELECTRON - A very small particle having practically zero mass and a negative charge of unity. Beta particles and electrons are identical in physical properties.

ELECTRON VOLT - Amount of energy gained by an electron traveling through a potential difference of one volt.

GAMMA RAY - A type of radiation emitted from some radioactive elements. It is similar to, but far more penetrating than, x-rays. This radiation makes necessary the heavy shielding of nuclear reactor components.

GRAM - A unit of mass or weight. There are 453.6 grams in one pound.

HALF-LIFE - This term applies to radioactive materials, and represents the time required for half the original material present to decompose.

IONIZATION - A process by which an atom or molecule acquires an electric charge.

ISOTOPE - A form of an element which has all the chemical properties of that element, differing only in weight. For example, U-233, U-235, and U-238 are all isotopes of uranium.

MASS UNIT - Unit based upon one-sixteenth of the weight of an oxygen atom taken as 16.00000.

MEGAWATT - One million watts, or 10^6 watts.

MOLECULE - Smallest quantity of a compound that can exist by itself and have all the chemical and physical properties of the compound.

NEUTRON - One of the components of the nucleus. A neutron has a mass of one (the same as a hydrogen atom) and a zero charge.

NEUTRON CAPTURE - The nucleus of an element can absorb a neutron to become another isotope of the element with a unit higher atomic weight. This isotope then usually decays to another element. A typical neutron capture can be written as:

$$ {}_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236} \ , $$

where U-236 is the new uranium isotope, formed from U-235 by neutron capture.

NUCLEUS - The central part of an atom, around which the electrons move in their orbits. A nucleus is composed of protons with a positive charge and neutrons with zero charge.

PROTON - One of the components of the nucleus of an atom. A proton has a positive charge that is equal, but opposite in sign, to the charge on the electron. The proton and neutron both have a mass of unity.

RADIOACTIVITY - A process by which an atom having an unstable nuclear configuration releases energy in the form of alpha (a type of radiation which is essentially a helium nucleus having four mass units and a positive charge of two), beta, or gamma emissions, as the atom achieves a more stable state. Usually, an atom of a new element is formed in the process.