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PILES OF THE FUTURE REVIEW

Dr. Tolman's Committee
October 9, 10, 11, 1944

I. Purposes for which future piles may be built, as we see them now.

1. Primarily for the production of 49 or 23, and wasting the energy evolved.

   a) Using a chain depending on thermal neutrons, and uranium of natural isotopic composition; approximately replacing the 25 consumed by 49. (Wigner, Weinberg, Leverett)

   b) Using a "fast" chain and slightly enriched uranium for the production of more 49 than 25 or 49 consumed, or "total utilization of the uranium." (Fermi, Szilard)

   c) Converting 49 into 23, or 25 into 23. (Weinberg, Wigner)

2. Producing power to be used as heat or mechanical energy. (Leverett, economics and types)

   a) By the thermal chain in uranium of normal isotopic composition, possibly recovering the products. (Wigner, Weinberg, Allison)

   b) By the fast chain in slightly enriched uranium. (Fermi, Szilard)

   c) By the consumption of highly concentrated or pure 49, 23 or 25. (Fermi)

   d) By the consumption of enriched thorium.

3. Producing radioactive materials for medical research and therapy, and technological research and development in general. (Allison, MUC-SKA-509, Cohn, Friedman, Nordheim, Coryell, Turkevich, Brown, Borst)

4. Using the pile itself as an intense source of neutrons and other radiation to be used in re- [redacted]

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Piles of type 1 in the preceding summary, in which the evolved energy is wasted, will presumably be built for military purposes only. The future of such piles depends largely on the success or failure of the proposed demonstration of our product as a military weapon.

Piles of type 3, in which radioactive tracers and other products of scientific and therapeutic interest are produced, seem certain to be built. The need and importance are so obvious that if such enterprises are not supported by the government, they surely will be undertaken by private foundations.

Small piles of type 4 will certainly be constructed, providing the government will release the requisite amounts of 25, 49 or 23. Likely builders are institutes for research in physics and chemistry.

The situation regarding the use of nucleonic power seems somewhat more obscure. The scale at which the science and technology of nucleonics is developed in the near future probably will depend on whether or not nucleonic power is put into use. The remainder of this document is devoted to the discussion of possibilities of such power development.

II. How much energy and fuel is available?

Table II-1 gives some information on the amount of energy available from the chain reaction. The table does

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not distinguish between the amounts of energy liberated from the fission of 49, 25 or 23.

Table II-1

Energy Available from the Chain Reaction

Process	Energy Release (as heat)
Combustion of 1 kg. coal	7.4 kwh
Fission of 1 kg. 23, 49 or 25	21,200,000 kwh
Fission of all 25 in 1 kg. U	151,000 kwh
Fission in 1 kg. U enriched to p % 49 until fast chain stops at 4.9% 49, with reproduction factor γ less than unity	$\frac{0.01p - 0.049}{1 - \gamma} \times 2.1 \times 10^7$ kwh

Dr. P. Morrison has collected for us the available information concerning the amount of fissionable material in sight.

URANIUM

(a) In ores of considerable concentration. The estimates are very conservative and are supposed to represent amounts actually located as being available in the mines.

Location	% U Content	Tons U
U.S.A. (Colorado)	1	5000
Czechoslovakia	1	1000
One of five sites in Belgian Congo	20	5000
Canada	20 - 50	5000
Russia	1 - 2	3000
Conservative total, about		20,000

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(b) General abundance in earth's crust. The granitic rocks of the earth's crust contain an average of 4 ± 2 ppm uranium. This means that there are at least 10^{14} tons U in the earth's crust, including 10^{8} tons in sea water at a concentration of 0.001 ppm.

THORIUM

(a) In ores of considerable concentration. The ore is almost exalusively monazite sand with from 5 to 11% thorium content.

Location	Tons Th
U.S.A. (North Carolina, Florida, Idaho)	1000
Brazil (sea coast)	8000
British India	150,000
Netherland East Indies	5000
Total	160,000

(b) General abundance in the earth's crust. Thorium is found mostly in sedimentary rocks to the extent of 12 ± 4 ppm.

Mr. Zay Jeffries has often called to our attention the fact that the estimates given above have little meaning, in that the full value of uranium and thorium have never previously been recognized. As the price offered per ton increases, it is almost certain that new and large deposits will be located.

The total production of energy in the United States was 7.32×10^{12} kwh in 1941. Using only the 25 present in the 10,000 tons of uranium actually in sight on the North American continent, the present power level of the United States could only be supported for a few months.

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III. How should the energy be removed and used?

The power at which the energy can be removed from a nucleonic reactor is primarily a technological problem with certain rather drastic limitations on the structural materials and heat transfer media which can be used. In our conferences at the Metallurgical Laboratory we discussed various methods of removal of the power other than removal as heat. Some of the methods discussed were as follows:

(a) Direct removal as electrical energy derived from the motion of the charged particles emitted in fission and from the fission products.

(b) Electrical removal by the Peltier effect, i.e., using the energy generated in thermocouples.

(c) Using the radiations inside the reactor to drive some endothermic chemical reaction (such as $2H_2O \rightarrow 2H_2 + O_2$ or $2CO_2 \rightarrow 2CO + O_2$) and reversing the reaction outside the pile to recover the energy.

The conclusion was reached that the development work involved would be so extensive that none of these "radical" methods would supply nucleonic power in the near future. Rather it seemed that the most promising idea was to remove the energy as heat at high temperature, using a coolant which, if water, must be at high pressure, but could possibly be diphenyl oxide or a liquid fluorocarbon. The most promising coolant, as elaborated below, seemed to be a liquid metal.

Due to their high slowing down power for fast neutrons, or their low absorption of neutrons, or their ability to create more neutrons under neutron irradiation, certain

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materials seem destined to play key roles in promoting the chain reaction. Others, because of high neutron or gamma ray absorption, seem destined to be used to control the reaction, or to shield the reactor. These are indicated in Table III-1.

Table III-1

Key Materials in the Chain Reaction

A. Structural materials, moderators, and heat transfer media for reactor construction.

Metals	Uranium, beryllium, aluminum, bismuth, columbium(?)
Gases	Helium, carbon dioxide
Liquids	Water, deuterium oxide, liquid fluorocarbons(?), diphenyl, diphenyl oxide, liquid bismuth
Solids	Uranium oxides, fluoride, carbide. Beryllium oxide, graphite.

B. Shielding and controlling materials.

Metals	Iron, lead, cadmium, thorium
Liquid	Water
Solids	Boron compounds, lithium compounds, masonite or other dense, stable materials rich in hydrogen. Concrete; special concrete containing barytes.

IV. Characteristics of proposed nucleonic power plants

If we confine ourselves to the type of plant in which the energy is removed as heat and converted to mechanical energy in a thermal engine, any nucleonic power plant would consist of the following parts.

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(1) A reactor, or pile, in which the chain reaction proceeds under control.

(2) A shield, probably cooled, to protect personnel from pile radiations, and also to act as a reflector of neutrons back into the reactor.

(3) A heat exchanger in which the heat is transferred from the pile to the working substance in the thermal engine.

(4) A thermal engine (turbine?)

It should be noted that at present, no nucleonic reactor has as yet been constructed with utilization of the energy as the objective. Table IV-1 shows what has been accomplished to date in the way of removing this energy.

Table IV-1

Present Status of Heat Removal from Nucleonic Reactors
(October 9, 1944)

Type of Pile	Heat removal equivalent to	How long operated
Air-cooled graphite moderated (Clinton)	3000 kw	11 months
D_2O moderated cooled by heat exchanger	300 kw	3 months
Water cooled graphite moderated (Hanford)	38,000 kw	5 days

As regards piles constructed for the conversion of the energy to mechanical energy, it is hoped that conventional designs, with relatively slight modifications, would suffice for the heat exchanger and the thermal engine. Some general

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comments on the nucleonic reactor and its shield, which are the novel features of such a plant, follow.

The size of the reactor is determined in some cases by the critical dimensions for the inception of the chain reaction, in others by the limitations of heat removal per unit volume.

A. Piles for consuming normal uranium as in I-2a.

   Here the size is determined primarily by the critical dimensions for the chain reaction, and secondarily by the piping and other structural material in the pile for the removal of heat.

B. Piles for consuming pure or highly enriched 25, 49 or 23.

   Here the size is determined primarily by the apparatus for removing the energy, and the critical dimensions for the chain reaction constitute a relatively unimportant lower limit.

Some information about sizes of reactors is given in Table IV-2, although in many cases important considerations concerning the size do not appear.

At the present time it seems that coolants and structural materials must be selected from Table III-1. For power piles, it has been stated previously that removal of the heat at high temperature is strongly indicated by the increased efficiency of conversion to mechanical energy. If water or deuterium oxide were to be used, the corrosion difficulties, and the high pressures necessary at high temperatures seem to us to be very formidable difficulties. The only common metal with low neutron absorption which can be used for pipes

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Table IV-2

Approximate Sizes for Various Types of Pile

Type	Factors Influencing Size	Amount of Fuel	Amount of Moderator	Approximate Reactor Dimensions
Hanford 101	Reflector, power removal 250,000 kw., water cooled	200 tons U	1000 tons C	30' x 30' x 23'
Clinton	Reflector, 3000 kw power removal, air cooled	40 tons U	460 tons C	21' x 21' x 21'
Hanford 305	Reflector, no power removal (approx. critical size)	26 tons U	300 tons C	18' x 18' x 18'
Be moderated	No reflector, no cooling	50 tons U	50 tons Be	Cylinder 10 ft. diameter 10 ft. long
Fast chain in enriched U	No reflector, no cooling	49, 2 tons; U , 28 tons	No moderator	Sphere 46 ft. diameter
Homogeneous slurry or solution	No reflector, no cooling	8 tons U	40 tons P-9	Cylinder 11 ft. diameter 11 ft. long
Montreal	Power removal to 10,000 kw, water cooling	12 tons U	16 tons P-9	Cylinder 8.2 ft. diameter 8.2 ft. long
Argonne CP-3	Power removal to 300 kw	3.5 tons U	6 tons P-9	Cylinder 6 ft. diameter 6 ft. long
Site Y Pilito	BeO reflector no cooling	575 grams 25	15 kg H_2O	Sphere 1 ft. diameter
49 solution	H_2O reflector no cooling	350 grams 49	10 kilos H_2O	Sphere 10 inch diameter

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in the reactor is aluminum, and thus corrosion and strength difficulties are evident. If materials such as stainless steel, steel, copper, etc., are used in conducting coolants through the reactor, a relatively high neutron absorption loss must be accepted, which probably can only be overcome by the use of enriched fuel. The corrosive effects of the fluorocarbons and their stabilitiss under irradiation are not known to us. We anticipate that diphenyl or diphenyl oxide will break down under neutron bombardment, although it is true that these materials appear extraordinarily resistant in this respect, compared to other organic compounds (Burton).

A considerable amount of attention has been given to the homogeneous heavy water pile, consisting of a solution or slurry of some uranium compound in heavy water. The Montreal group has also considered such a reactor. Certain features, such as the simplicity of design of the reactor, which would be a large pressure vessel with the solution or slurry boiling in it, are attractive. When further details are investigated, such as circulatory pumps, slurry corrosion, stability of the slurry or solution, and gas evolution and recombination, great difficulties are foreseen. Further development of this type of pile has been abandoned. (Ohlinger, Wigner, Vernon)

Our committee was of the opinion that liquid metal coolants, namely bismuth or bismuth lead eutectic, look very promising. (Szilard, Foote) Beryllium for piping and

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structural material (including moderation) is a unique metal with respect to the chain reaction. It is a better moderator than graphite, has a very low absorption of neutrons, and itself acts as a further source of neutrons. A small fraction of the program of the Metallurgical Laboratory has been devoted to the following studies, stimulated by these ideas.

(1) Preparation of beryllium metal from beryllium compounds. (Spedding)

(2) Metallurgy of beryllium--extrusion, machining, powder metallurgy, etc. (Creutz)

(3) Diffusion of neutrons in beryllium and neutron multiplication by beryllium. (Morrison, Szilard, Allison, Zinn)

(4) Compounds between beryllium and uranium, and uranium beryllium phase diagram. (Creutz)

(5) Absorption of neutrons in bismuth, and danger coefficient of bismuth. (Levinger, Anderson)

(6) Properties of liquid bismuth and bismuth-lead eutectic with respect of corrosion of beryllium, etc. (Foote, Battelle Foundation)

The liquid metal coolant would flow through channels in a beryllium moderated pile, or through beryllium pipes in a graphite moderated pile. The heat, taken out at temperatures close to 500°C (as has been shown practicable in mercury turbines (Seitz)) would presumably be transferred to some conventional working fluid (water, mercury, diphenyl oxide) in a heat exchanger outside the pile. Polonium would be formed in the bismuth and could be recovered if, as seems likely, commercial or other uses for it are found. (C. A. Thomas, Monsanto Chemical Company)

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The circulation of the liquid metal would probably involve a pump development program, although two schemes which involve no contact between the pump and the hot metal have been proposed. One is the electrical induction pump (Szilard). Another is the "pulsating" reactor (Wigner) in which the liquid coolant is oscillated back and forth through the reactor and heat exchanger by means of gas pressure applied alternately at two end points of the system.

A nucleonic reactor operating even on the level of watts cannot be approached without physiological hazard unless a heavy shield is provided. This necessity seems to limit severely the types of power plants replaceable by such reactors. Application of nucleonic power directly to airplanes and automobiles seems out of the question until new discoveries in this matter are made. At the present time even a small nucleonic reactor delivering interesting amounts of power requires on the order of 100 tons of shield. No novel ideas concerning shields have arisen. Concrete has proven to be the cheapest but bulkiest shield. Combination iron and masonite shields are expensive and somewhat less bulky. From a scientific but not from a practical standpoint, gold would be one of the best shields, due to its high density, and high neutron and gamma-ray absorption.

V. Concluding remarks

The chief obstacle to the development and construction of

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a nucleonic power plant is lack of a directive or order to make one. It is difficult for engineers or physicists to work out the details of design for a plant which may never be constructed. In order to develop nucleonic power the government should sponsor the building of a plant to furnish power for a specific purpose. One striking difference from conventional plants is, of course, the minute amount of fuel consumed and thus the absence of a transportation problem for fuel. The absence of smoke is a consideration in the application to the heating of large buildings or cities.

The following are suggestions for government sponsored experiments in the use of nucleonic power.

(1) To propel naval vessels (submarines) and ships in general.

(2) To furnish light and power to army, navy, or government projects or stations in locations remote from fuel supplies. (Pearl Harbor, Guadalcanal, Dutch Harbor)

(3) Heating, light, and power for experimental towns or settlements. (Matanuska Valley, Alaska)

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