GENERAL RECOMMENDATIONS CONCERNING RESEARCH ON URANIUM.

There are at present three different lines of research which might lead to a chain reaction in uranium.

1) One line of research concerns the interaction of uranium with slow neutrons. It might lead to a chain reaction taking place in a large mass of uranium oxide, or uranium metal, mixed with another element, the latter serving the purpose of slowing down the neutrons.

The interaction of uranium with slow neutrons has been fairly extensively studied (at Columbia and in Paris) since February of this year, and the conditions in which a chain reaction could be maintained by means of slow neutrons are fairly well known. unpublished It might be that these conditions can be realized in the near future, If uranium oxide, which is a commercial product, can be used a large-scale experiment could be arranged at short notice. If, however, uranium metal, which is not a commercial product, has to be used a large-scale experiment might require a longer preparation since it would be necessary to arrange for reducing a large quantity of oxide to metal. If a chain reaction is maintained in uranium by means of slow neutrons large quantities of new radioactive elements could be generated and large quantities of energy would be liberated in the process. A mass of uranium in which a chain reaction is maintained may act as ~~an enormously~~ a powerful source of gamma-rays and neutrons. This radiation might be made strong enough to make it dangerous for human beings to approach it within a distance of perhaps 500 yards, and might by virtue of this aspect be of value for defense purposes. A chain reaction maintained in a large mass of uranium by slow neutrons might also lead to explosions, but it appears doubtful whether such explosions would be sufficiently violent to be of military importance.

Of the three lines of research which are subject of this memorandum this first line has at present the best chance to lead to far-reaching results in the immediate future.

Recommendation.

It appears desirable that a number of experiments be carried out now along this line on a moderately small ~~xxtxxxx@x~~ scale. One of these experiments concerns the absorption cross-section of carbon for thermal neutrons and requires about 3 to 4 metric tons of graphite. Other (desirable) experiments concern the capture cross-section of uranium for thermal neutrons and the neutron emission or other nuclear properties of uranium.

It would be desirable to have a special fund available for facilitating experiments on a moderately small scale along this line, which ought to be carried out in the near future. These experiments could be [carried out at Columbia & fitted into this work

2.) <u>The second line of research</u> concerns the interaction of uranium with neutrons which are not being slowed down by a second element. This line might lead to a chain reaction taking place in a large mass of uranium metal. It is likely that uranium oxide ~~could~~ could be used.

The neutrons emitted by uranium have energies of several million volts. It appears likely, though perhaps not absolutely certain, that these neutrons will be slowed down by inelastic collisions in uranium to perhaps 50 to 100.000 volts, and from then on are further slowed down by elastic collisions with uranium nuclei. Neutrons of about 50 to 100.000 volts energy have a much smaller splitting cross-section in uranium than neutrons of a few million volts of energy, but ~~preliminary~~ unpublished experiments ~~carried out by~~ of Dr. Zinn and myself seem to show that this splitting cross-section is not negligible and might ~~very well~~ perhaps be sufficient to make a chain reaction possible. In order to determine whether or not a chain reaction can be maintained without slowing down the neutrons to the thermal region it will be necessary to perform ~~a number of~~ further small-scale experiments. Only in this way can it be decided whether a large-scale experiment with uranium metal ought to be attempted with a view of setting up a chain reaction above the thermal region.

From what we know at present it appears likely that a mass of uranium metal weighing more than metric tons would be required for maintaining a chain reaction with non-thermal neutrons. If this can be done then we have to face the potential possibility of ~~bringing about~~ explosions which are far more dangerous than anything that has been hitherto ~~envisaged.~~ known.

Recommendations:

In order to see whether neutrons which are not being slowed down to the thermal region can maintain a chain reaction in uranium a number of small-scale experiments ought to be performed. Some of these experiments have been started or prepared at Columbia, other experiments, which appear to be necessary, would go beyond the framework of the present work at Columbia and ought to be carried out preferably at some other laboratory. In view of the difficult nature of experiments of this type some over-lapping and repitition of experiments carried out in different laboratories appears to be desirable. Funds, which might be required for this type of research would be mainly required for salaries, since expenses for material would be negligible.

3.) A third line of research concerns the separated isotopes of uranium.

It appears likely that of the two isotopes of uranium one is mainly responsible for the splitting effect which leads to a neutron emission, and the other is mainly responsible for the simple neutron absorption of uranium. If the two isotopes could be separated only a few kg of uranium of the right kind would be needed to maintain a chain reaction. Arguments have been put forward by Bohr that the rarer of the two isotopes of uranium, which has a relative abundance of only about 1% in commercial uranium, is the one which could be made useful.

To separate the two uranium isotopes on a small scale should not be too difficult, but the separation on an industrial scale, in order to obtain several kg within reasonable time will be probably a very difficult problem to solve. Two different methods have so far been advocated for this purpose:

a) separation by thermal diffusion, and

b) separation by centrifuging.

A small-scale separation by centrifuging is being attempted by Professor Beams at the University of Virginia. A small-scale separation by the method of the mass spectograph is ~~pher~~ perhaps also being attempted at present at the University of Minnesota.

Recommendations:

Experiments on small-scale separation of the two uranium isotopes should be regarded as urgent and supported by funds if necessary. Both, the mass spectograph method and the centrifuging method ought to be tried and perhaps also the diffusion method and other methods which might be invented for the purpose. The centrifuging method can undoubtedly be pursued at the University of Virginia. It might perhaps be ~~achieved~~ possible to achieve a mass spectograph separation at the University of Minesota.

It would further be advisable to study the theoretical limitations of the various methods with a view of determining the limitations of a separation on an industrial scale.

Further work has to be carried out along two different lines which have very little in common with each other, i.e. the slow neutron reaction and the fast neutron reaction.

1. The slow neutron reaction. This problem has been studied in small scale laboratory experiments with the result that it appears likely though perhaps not absolutely certain that a nuclear chain reaction can be maintained with slow neutrons in a large mass of uranium mixed with large quantities of certain other elements. It appears necessary to prepare a large scale experiment using 10 to 20 tons of uranium oxide. It is proposed however to carry out a large scale experiment on about   tons of material not containing uranium and having a value of about $ before actually embarking on the large scale uranium experiment.

There is reason to believe that such a chain reaction with slow neutrons can be controlled so as to avoid overheating of the mass. Large quantities of radioactive elements would be continuously produced in such a chain reaction, some of which might be used for a large scale production of luminous paint. Apart from this no military use is at present envisaged. It can be shown that bombs based on such a slow neutron chain reaction in uranium oxide are not sufficiently superior to bombs working with ordinary explosives to justify their high cost and other inconveniences.

2. The fast neutron reaction. has not been studied at all, and it is therefore not known whether it will go or whether it will not.

~~Apart from this no military use is at present envisaged. It can~~

2. <u>The fast neutron reaction.</u> This problem is of great military importance. It has so far not been properly investigated, and it is therefore impossible to say whether a fast neutron reaction can or cannot be set up. Small scale ~~xxxxxx~~ laboratory experiments have been devised to clear up this point which would require facilities for salaries, but practically no expenses for material.

There is reason to believe that if the fast neutron reaction will go extremely dangerous bombs could be constructed which could be properly controlled. It is very likely that the fast neutron reaction cannot be made to work with uranium oxide, and therefore a processing of ~~x~~ the uranium oxide would almost certainly be necessary, which might easily involve a cost of the order of $ 5.- per kg. Therefore, should the laboratory experiments make it ~~at all~~ likely that a fast neutron reaction is possible, the processing of some 20 to 50 tons of uranium oxide will be rather costly and [therefore] ~~will~~ [can] ~~not~~ [hardly] be attempted until all possibilities of small scale laboratory experiments have been exhausted.

Industrial Applications.

It appears very likely that a chain reaction can be maintained in a large mass of uranium oxide if mixed with certain other ingredients. There is reason to believe that this chain reaction can be controlled and that over-heating of the mass leading to an explosion can be avoided. Very large quantities of radioactive elements and heat would be produced in a continuous process if such a chain reaction is maintained.

Memorandum

July 6, 1940

Remarks to the memorandum of July 6, 1940

The question whether a chain reaction based on fission by thermal neutrons can be made to work which would consume the more abandoned uranium isotope appears to be also equivalent to the question whether the element which has a mass number 239 and an atomic number 94, which is produced from uranium 238 when the latter captures a neutron has an appreciable fission cross section for thermal neutrons. We assume hereby that more than two fast neutrons are emitted in the fission of element 239.

If a chain reaction is maintained in a system composed of uranium and carbon the uranium isotope 235 is gradually used up. At the same time a certain amount of element 239 has been produced. If necessary this element can be chemically separated and mixed with uranium 238 in such a concentration that if a mixture is used in a system for maintaining a chain reaction, for every atom of element 239 which undergoes fission by thermal neutrons, more than 1 atom of uranium 238 will be transformed into 239 by capturing a neutron. In this way the concentrations of element 239 would increase rather than decrease in the course of the chain reaction 1 ton of uranium could be made to yield as much energy as would correspond to the burning of 1 million tons of oil.

The situation would be even simpler if 1 fission cross section of element 239 for thermal neutrons were about as large or larger than the fission cross section of uranium 235. In that case conditions for a chain reaction might get more and more favorable if ordinary uranium is used in a system composed of uranium and carbon as the chain reaction must work in spite of the fact that the concentration of uranium 235 decreases. The chemical separation of element 239 previously mentioned may then be considered avoidable.

July 6, 1940

Memorandum

In the memoranda which I have previously submitted it was stated that we may expect 1 ton of uranium to produce as much energy as about 3000 tons of oil. The enclosed communication which I received from Professor Louis A. Turner in May of this year draws attention to the potential possibility of having a chain reaction in which 1 ton of uranium might produce as much energy as would correspond to about 1 million tons of oil. The question raised by Dr. Turner can be decided by a compatatively simple experiment which must be regarded at present at the most important single experiment. There is perhaps a 1 to 1 chance that the result will be positive and in that case we may expect 1 ton of uranium to be equivalent to 1 million tons of oil.

While in previous memoranda it was pointed out that a chain reaction maintained in uranium may be used for the purpose of a power production and the significance of this fact for the Navy was discussed. This question assumes an entirely different aspect if 1 ton of uranium represents 1 million tons of oil istead of 3000 tons of oil as previously assumed.

then we have to consider th possibility that the larger units as porjected by the present Naval problem may have to be cansidered obsolete by the time when they are launched. Of course all this presupposes that it will be possible to maintain a chain reaction in ordinary unseparated uranium but I am confident that this is a problem which can be solved in the near future if adequate facilities are available for ur work.

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INTRODUCTION.

There are at present three different lines of research which might lead ~~us~~ to achieve a chain reaction in uranium:

(1) One line of research concerns the interaction of uranium. ~~It might lead to research as to whether~~ a chain reaction ~~could be obtained~~ in a large mass of uranium oxide, mixed ~~with a large quantity~~ of another element, ~~which~~ serves the purpose of slowing down the neutrons.

Since uranium oxide is a commercial product, a large-scale experiment could ~~be set up at~~ any time along these lines at a moderate cost. ~~It would be~~ preferable to use uranium metal ~~in experiments of this type, but~~ this ~~would~~ require ~~some technological~~ preparation, and would certainly greatly ~~increase the cost of the experiment.~~

(2) Another line of research concerns the interaction ~~of neutrons~~ ~~with~~ uranium, which have not been slowed down to thermal energies, and might lead to ~~the setting-up of~~ a chain reaction in ~~the~~ large mass of uranium metal. ~~This line of research~~ has ~~so far~~ ~~been lagging~~ behind ~~for lack of funds, though only small funds would be required for preliminary experiments.~~

A large-scale experiment, ~~which alone can provide full certainty,~~ would require large quantities of uranium metal, which are at present not available. ~~and therefore~~ the final success of this ~~type~~ of research ~~cannot be secured at moderate cost~~. ~~Nevertheless, it must be emphasized that from the~~ point of view of national defense, the possibility of a chain reaction maintained in uranium metal would probably be more important than the possibility of a chain reaction in a mixture of uranium and an element which slows down the neutrons to thermal velocities.

(3) The third line of research concerns the possibility of separating the isotops of uranium by centerfuging a uranium compound, or by diffusion methods applied to uranium compounds. Separation of the isotops on an industrial scale would be required to produce a sufficient quantity of one of the two uranium isotops to make a chain reaction possible ~~in the amount of uranium obtained by the separation.~~

Though this [would involve] ~~is undoubtedly a~~ very costly and difficult problem of engineering, it might ultimately yield results which, from the point of view of national defense, might [even] be more important than the other two lines of research before mentioned. [Though there will be] ~~From the~~ great technical difficulty in achieving [on an industrial scale] the separation of the isotops, there ~~is hardly an~~ [are few] elements of doubt attached to the possibility of maintaining a chain reaction in a few kilogrammes of the separated uranium isotops. [Such doubt as still remains could be] ~~In view of this fact,~~ small-scale experiments for the purpose of separating minute quantities of the uranium isotops ought to be facilitated, and [also] the possibility of a separation on an industrial scale ought to be theoretically explored.

There is perhaps still an element of doubt left

~~THE POSSIBILITY OF A LARGE-SCALE EXPERIMENT~~
~~IN THE IMMEDIATE FUTURE.~~

concerning the possibility of maintaining a chain reaction in comparatively small quantities (a few kilogrammes) of the separated isotope. ~~But~~ Such doubt ~~could~~ as remains be ~~probably~~ removed by separating minute quantities of the isotope (by a mass spectrograph and