L. Szilard
January 8, 1943

MEMORANDUM ON THE PRODUCTION OF 94 AND THE PRODUCTION OF POWER BY MEANS OF THE FAST NEUTRON REACTION.

Turner suggested early in 1940 that a chain reaction can be maintained in a system composed of uranium and a slowing down element in which uranium 238 would be burned rather than U235. He pointed out that element 94 can be expected to show fission with thermal neutrons, and if more than two neutrons are emitted in this fission process one of these neutrons can carry on the chain while another neutron is absorbed by 238 at resonance and generates an atom of element 94. If the number of neutrons emitted in the fission process of the 94 is large enough and the absorption of the slowing down element low enough, then if we start with a system which contains only U238, a slowing down element, and a certain quantity of 94, we may in the course of the reaction increase the amount of element 94 present while the amount of U238 decreases. We may thus not only produce power from 238 in a chain reaction in which 94 is undergoing fission, but also increase the amount of 94 available. It is difficult to carry out this idea if the number of neutrons emitted for fission of 94 is about 2.5 or smaller, since there is absorption in the element used for slowing down neutrons and in addition leakage of neutrons across the boundary of the chain reacting mass. Perhaps if one used heavy water as a slowing medium and if there should be a large contribution to the chain reaction from the n-2n reaction caused by fission neutrons in deuterium, some such scheme could be made to work.

We can be confident however that power could be produced from U238 and 94 could be produced in large quantities under favorable conditions, If we set up a chain reaction in a mass of U metal, for instance, in a pile of 2 x 2 x 2 meters, weighing about 160 tons (a considerably smaller

quantity will most probably be sufficient) and have in the center of this pile in place of ordinary U a mixture of U and U235, or element 94. 60 kg. of94 could for instance be dispersed in the U within a sphere of about 60 cm.diameter, in the center of the pile. We may expect that such a unit will be chain reacting. The neutrons emitted from the fission of 94 will cause fission in the 238 which forms the bulk of ordinary U, and these fast neutrons originating from 238 will cause again fission in 238 so that we have a second and third, etd. generations. These neutrons which originate from 238 increase the number of neutrons which are liberated per fission of 49 and we may expect the total number of neutrons liberated per fission of 94 to be larger than 3. One of these neutrons will be used to carry on the chain reaction ~~where~~ while the residue of more than 2 neutrons will be absorbed by U238 and ~~from~~ from element 94. In the absence of a slowing down element there is no loss due to absorption and in the arrangement just described there is no leakage. Leakage can be ~~avoided~~ because the whole chain reacting unit is sufficiently small to absorbe all neutrons with a tolerably small quantity of ordinary U on the boundary of the pile. It may be pointed out that the amount of 94 originally needed may be less than 60 kg. and the possibility that the chain reaction can be maintained in ordinary U without any addition of 94 must by no means be neglected. Instead of using 94 in the center of the pile one might prefer to start the reaction by using ordinary U enriched by U 235. For instance, about 100 kg. of 235 could be dispersed in a sphere of 60 cm diameter in the center of the pile. Naturally as the reaction proceeds the U 235 would gradually disappear and its place would be taken by 94.

Considerably smaller quantities of 94 or 235 would be sufficient to maintain the chain reaction if dispersed within a smaller volume than proposed above. Such arrangements would however not be useful for our purpose.

In order to produce power and 94 considerations of heat transfer have to be kept in mind.

The chain reacting unit of this design can be efficiently cooled by a liquid metal, by bismuth or lead, or a bismuth-lead alloy which flows through thin steel pipes, for instance, in a vertical direction through the pile. A pile of this size can dissipate 1,000,000 kw and produce 1 kg of 94/day in excess of the amount of 94 which is used up.

Though the chain reaction which takes place in such a pile is carried on by fast neutrons, the control of the pile offers no difficulty. From the very beginning of this work, March, 1939, it has been realized that the delayed neutron emission, though rather small, will be the determining factor with respect to the time within which the controls have to respond.

L. Szilard

W. Zinn

S. Flügge - January 10, 1943

L. Szilard
January 8, 1943

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(36.5-10)

L. Szilard
January 8, 1943

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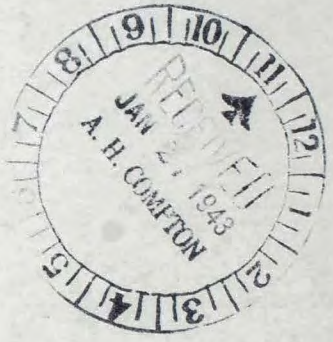
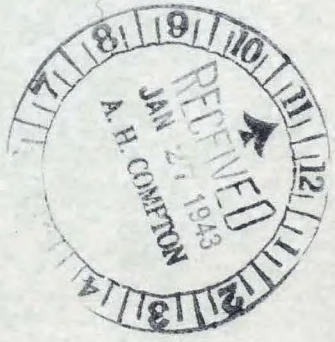
Witness:
Gertrude Weisenbaum - January 10, 1943

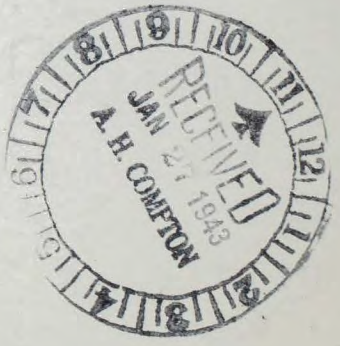
REMARKS TO MEMORANDUM OF JANUARY 8, 1943

L. Szilard
January 24, 1943

A somewhat smaller amount of 94 or 235 may be sufficient to have a chain reaction in enriched uranium if a small amount of hydrogen is used for slowing down the neutrons. About one-half atom of hydrogen per atom of uranium may be a suitable quantity. The addition of such an amount of hydrogen would not interfere too much with the fast neutron fission in 238, and yet, would be sufficient to slow down a considerable fraction of the neutrons to the thermal region, where they would be absorbed predominantly by 235 or 94 contained in the enriched uranium. In this respect, hydrogen is unique among the slowing down elements, since its cross section changes by about a factor of 6 when the energy of the neutrons goes below 100,000 volt, so that a given concentration of hydrogen slows down comparatively little above the fission threshold of U238, and slows down a lot in the region below 100,000 volt, ~~when~~ above radiative capture in U238 becomes particularly large. Hydrogen could be used in the form of water or diphenyl, and could be flown through pipes serving the double purpose of cooling and slowing down.







(bbs-38

L. Szilard
January 18, 1943

We can write the critical condition for a fast neutron chain reaction in ordinary uranium as follows:

(1) $$\frac{\sigma_f^*}{\sigma_f^* + \sigma_n^*}\,\nu^* q^* + \left(1 - \frac{\sigma_f^*}{\sigma_f^* + \sigma_n^*}\right) y\,\nu^{>35} = 1$$

a.4.

Or neglecting fission in 235 (y = 0) we can write

(2) $$\frac{\sigma_f^*}{\sigma_f^* + \sigma_n^*}\,\nu^* q^* \cong 1$$

In this equation, y tells us what fraction of those fission neutrons which have been slowed down below the threshold of U238, will cause fission in 235; q^*, is the fraction of the fission neutrons which have at the time of their emission, energies above the threshold of 238. σ_f^* and σ_n^* signify the average fission cross section of U238 for those of the fission neutrons which have an energy above the threshold of 238. Thus, $\sigma_f^* \cdot q^*$ means the average fission cross section in 238 for all fission neutrons. ν^* is the number of neutrons emitted by 238 fission caused by fission neutrons. The same letters without the stars will be used for the corresponding values for neutrons from Ra-Be sources.

An experiment performed with Ra-Be neutrons on a uranium sphere of 10 cm diameter, showed that a Ra-Be source in the center of the sphere increased the total number of neutrons by a factor of about 1.15. The same sphere caused a reduction of the fast fission count in a fission chamber by a factor of .675. Assuming $\nu = 2.5$, we may say that 0.25 fission neutrons have been created while 0.9 of the original Ra-Be neutrons survive, but a certain fraction of these has been slowed down below the threshold of 238.

If we neglect the fact that we have $q^* \sigma_f^* \neq q\,\sigma_f$, and also disregard that a fraction of the 0.15 excess neutrons created by the uranium sphere is also slowed down by the uranium sphere, we may write for the fraction of the surviving Ra-Be neutrons which have been slowed

$\sigma_2 = 2$

$\sigma_f = 0.7$

$\nu = 2.2$

$$\frac{\frac{2}{2.7}}{1 - 2.2\,\frac{0.7}{2.7}} = \frac{0.74}{0.425} = 1.75$$

$$\frac{1}{2} + \frac{2}{3} \times 1.75 = 0.575 + 1.16 + \frac{1}{3} = 1.49\overline{3} \approx 1.5$$

$2.2 \times 1.493 = 3.3$ neutrons per thermal fission

Total flux Ordinary

$$\frac{\sigma_{in}}{\sigma_{in} + \sigma_R}$$

$$1 - \nu \frac{\sigma_R}{\sigma_{in} + \sigma_f}$$

down below the threshold of 238:

$$1 - .675 + 0.15 = .475$$

We may conclude that if all the Ra-Be neutrons which survived and were originally capable of causing fission in 238 had been slowed down in a larger mass of uranium, we would have obtained in the first generation

$$0.25 \times \frac{0.9}{.475} \sim 0.470$$

fission neutrons.

We may therefore write

(3) $$0.47 = \frac{\sigma_f}{\sigma_f + \sigma_n} g \nu$$

~~or dividing No. 2 with No. 3, and putting $\nu = \nu^*$~~ or

$$\sigma_n = \frac{\sigma_f q \nu}{0.47} - \sigma_f$$

for $q = 2/3$

$$\frac{0.7 \quad \frac{2}{3} \quad 2.5}{0.47} - 0.7$$

$$2.48 - 0.7$$

$$1.8$$

we obtain

(4) $$\frac{1}{.47} \cong 2.1 = \frac{\sigma_f^* g^*}{\sigma_f g} \cdot \frac{\sigma_f + \sigma_n}{\sigma_f^* + \sigma_n^*}$$

$$\frac{0.93 \cdot 1/2 \; 2.5}{0.47} \qquad q = 1/2$$

$$-0.93$$

$$= 1.25$$

If we now assume that $\sigma_f^* = \sigma_f$. ; and further assume that 4/5 of the fission neutrons are at birth above the threshold of 238, and 2/3 of the Ra-Be neutrons are at birth above the threshold of 238, i.e.: $q^* = \frac{4}{5}$, $q = \frac{2}{3}$ then we obtain from (4)

(5) $$\frac{\sigma_f + \sigma_n}{\sigma_f^* + \sigma_n^*} = 1.75$$

$\sigma_f = 0.93$

$\sigma_f = 1.53$

This means that the chain reaction would go with fast neutrons in 238, for instance, for the following set of values:

$$\sigma_n = 2.7, \quad \sigma_n^* = 1.25; \quad \sigma_f = \sigma_f^* = 0.7 \quad .$$

If on the other hand, we assume $g = 1/2$ then, we obtain:

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and $f = \frac{2}{3}$ $\qquad \dfrac{\sigma_f + \sigma_n}{\sigma_f^* + \sigma_n^*} = 1.57$

which is consistent with the following set of values:

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L. Szilard
January 18, 1943

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In this equation, y tells us what fraction of those fission neutrons which have been slowed down below the threshold of U238, will cause fission in 235; q^*, is the fraction of the fission neutrons which have at the time of their emission, energies above the threshold of 238. σ_f^* and σ_n^* signify the average fission cross section of U238 for those of the fission neutrons which have an energy above the threshold of 238. Thus, $\sigma_f^* q^*$ means the average fission cross section in 238 for all fission neutrons. ν^* is the number of neutrons emitted by 238 fission caused by fission neutrons. The same letters without the stars will be used for the corresponding values for neutrons from Ra-Be sources.

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down below the threshold of 238:

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or dividing No. 2 with No. 3, and putting $\nu = \nu^*$

we obtain

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Szilard Memos
Korr.

MEMORANDUM

February 4, 1943
L. Szilard

Introduction: Is This a Physicist's War?

Although it may sound surprising, it is nevertheless a fact that the government has so far not enlisted the collaboration of the vast majority of scientists in this country. This could be a physicist's war, but it is not. It is quite true that practically every good physicist is employed on some government sponsored project; he is spending full time on the particular problem which has been assigned to him, and one may ask, if this is so, what more could be done?

Let us examine this in relation to the anti-submarine warfare, where it is common knowledge that only a few percent of the U boats detected are actually sunk. No doubt a number of good physicists are employed on projects and have been given the task of finding a remedy against this evil along some specific line. Manifestly, in the two years during which the physicists were almost fully mobilized, no solution was found and put into practice.

We know of a large number of physicists whose past records show imagination, foresight and balanced judgment, who could be exceedingly valuable in this connection, and whose collaboration could be enlisted, if they were properly approached. Practically all of these men are engaged in some defense work, but no men of imagination, particularly not those who possess an inventive mind, can work for years, 24 hours a day, on the same problem. They need spiritual recreation; whether it is a game of chess in the evening or week-ends, or whether it is playing around with problems other than those with which their attention is occupied 8 hours a day. I have often heard some of them discuss, in a dilettantish

sort of way, what could be done about the submarine menace. Occasionally one or the other developed ideas which sounded interesting, but all these discussions were based on profound ignorance of the elementary facts which are involved.

How To Deal With The Situation

In order to use these men it would be first of all necessary to transmit to them in the form of a booklet or otherwise, all the basic information which is not secret; such as, the speed of German submarines, the depths to which they can dive, the methods of detection which have been used in the last war, etc. This information should be placed into the hands of every physicist who is working on a government project not connected with anti-submarine warfare. A smaller number of men, those who are particularly inclined to think about these problems, should be given further restricted information, particularly, full information about what is known about the German submarines and also a complete description of all the proposed solutions which have been rejected as impractical by the government or which are at present not pushed with high priority.

Balanced Judgment Rather than New Inventions Needed

It can by no means be ruled out that a basically new idea may be the answer to the submarine warfare problem. It is much more likely, however, that some of the old proposals which had been judged impractical can be made to work. For this reason the collaboration with the physicists cannot take the form of giving them the basic information and inviting them to submit new ideas to the government. What is rather needed is that the physicists should be fully acquainted with the facts and should constantly discuss old and new ideas. We may hope that some of these men

will gradually come to feel that they could make this or that method work, and will express the desire of being given the responsibility of trying to work out the solution along one line or another. It is the faith that one can make a specific idea work and the determination to make it work which is the prerequisite of success, and if the physicists were approached in this spirit, appealing to their good judgment as much as to their inventiveness, results could, in my opinion, be expected.

Few of our outstanding inventive minds were engaged in thinking about war applications before October 1940. Few of them are thinking about the submarine warfare at present. All of them would be glad to think about it and some of them might be willing and eager to drop their present work as soon as they see a solution in which they have faith. Playing about with these ideas would not divert any one of them from their main work to which they are at present assigned. In the beginning, it would be rather a refreshing side-line activity, later one or the other may get deeply involved in some particular type of solution, in which case, he may decide to work on the submarine problem and ask to be relieved from his present assignment.

A certain number of people should be given the task of maintaining contact with men in the various "projects" in order to keep their interest in this problem alive, and in order to arrange for group discussions. Nothing can be expected of such measures however, unless the problem is approached in the right spirit, both by the scientists and on the part of the administration. The primary aim of such a loose organization would not be to obtain from the scientists suggestions based on basically new principles. Though there is a finite possibility that some fundamental

new approach might bring the solution, it is much more likely that the type of the contribution of the scientists will be of a very different nature. If the old ideas which have been put forward and the solutions which have been tried and rejected were put before the scientists, it may happen that after a careful study, one of the other of these men would see his way of making one or the other of these "solutions" work. If a man whose past record shows success has faith in a particular way of approaching this problem, and is willing to take the responsibility of tackling the problem, he ought to be given such facilities as he needs and be allowed to try his luck. More important than a new idea is the ability of selecting from the many ideas which are put forward the one which can be made to work. This task of selection cannot be the work of a few officials in a professional sort of way. Only a man who studies one idea carefully for a long time, and who makes a number of accessory inventions, can arrive at a balanced judgment as to the feasibility of a given method. To have a division of labor of the sort that one man says "this is feasible", and another man is asked to make a success of it, and to live up to the promise which was made by somebody else, is hardly the way to solve a problem in a field where so many things have been tried and so many things have failed.

Nothing suggested here would take any physicist away from his assigned task until such time as he himself feels that he would be more useful in a new assignment.

Men of inventive minds need some ~~spiritual~~ mental recreation. To think about anti-submarine warfare on the basis of factual information is as good a recreation as chess, and certainly a much better recreation than to think about submarine warfare in the absence of sufficient information.

MEMORANDUM ON THE PRODUCTION OF ELEMENT 94^{239} FROM U^{238}

L. Szilard

March 25, 1943

The possibility of burning U^{238} in the chain reaction by way of its conversion into element 94^{239} was first mentioned by Turner in the spring of 1940. Turner thought that if uranium enriched in U^{235} were used in a chain reacting system in which the neutrons are slowed down by water the transformation of U^{238} into element 94^{239} might compensate for the loss of U^{235} through fission and the chain reaction might be kept going in the long run essentially burning U^{238}.

It appears doubtful whether the number of neutrons emitted in the fission of element 94 will be sufficient to permit the use of Turner's idea in its original form for the production of element 94 from U^{238} after the initial quantity of U^{235} is exhausted. The purpose of the present memorandum is to propose a method for producing 94 from U^{238} which is based on a fast neutron chain reaction in uranium that is either enriched in U^{235} or enriched by the addition of a certain quantity of 94^{239} to the point at which we have a composition that is capable of maintaining a chain reaction without the use of slowing down agents.

Such a fast neutron chain reaction can be stabilized almost as conveniently as a chain reaction in a graphite-uranium system. One way of stabilizing the chain reaction is to make use of the fact that liquid alloy of bismuth and lead for instance if introduced in sufficient amounts into the chain reacting units will slow down by inelastic collisions a fraction of the

neutrons below the fission threshhold of U^{238}. The attached figures 4A and 4B illustrate such a control system which consists of a number of communicating tubes going vertically through the chain reacting unit which are connected by means of one or more electro-dynamic pumps to tanks outside the chain reacting unit. By raising or lowering the level of the bismuth-lead alloy within the chain reacting unit the multiplication factor of the unit can be changed. A similar system of control in case of the uranium carbon system has been previously described in connection with a bismuth cooled power unit.

The time of response of the control is fortunately independent of the life time between two successive generations of instantaneously emitted neutrons and is determined solely by the delayed neutron emission as long as we remain close to the critical conditions of the chain reacting unit. This dominant role of the delayed neutron emission with respect to the time within which the controls have to respond had been recognized since the very first beginnings of our work and was responsible for the continued interest in the fast neutron reaction for purposes of power production.

The chain reacting unit can be build in the form of a lattice of uranium rods of about 1 cm. diameter. One such rod is shown in Fig. 1 and the lattice structure is indicated in Fig. 2. 12, 13, and 14 in Fig. 3A show how these uranium rods are mounted in the chain reacting unit. Figs. 3A and 3B show the chain reacting unit. Helium at a high pressure or a bismuth-lead alloy can be used as a cooling agent and the flow of the cooling agent is indicated by arrows in Fig. 3A.

If uranium enriched in U235 or enriched by the addition of element 94^{239} is used and if the composition is so chosen to have a multiplication factor in infinite system of about 1.1 the conditions are about as follows:

Slightly above two neutrons are emitted in the fission process of U^{235} or 94. For every atom of 94 which undergoes fission about $\frac{1}{2}$ atom of U^{238} undergoes fission but fast neutron fission process which contributes on the average about one neutron. In these circumstances about three neutrons are liberated for one atom of U^{235} or 94 which disappears. Of these three neutrons one neutron is required to carry on the chain and the two remaining neutrons are utilized to form two atoms of 94 from U^{238}. One of these two atoms just compensates for the loss of the original atom of U^{235} or 94 which underwent fission and the remaining atom of 94 can be considered as net gain. If the outer layers of the chain reacting unit are composed of natural uranium there is practically no loss of neutrons through leakage and 94 may be produced at the rate of about 1 kg. of 94 per day if the chain reaction is maintained at a rate of 1.5 million KW.

Memorandum - May 12, 1943

A Radium-Beryllium source and a Radium-Boron source were compared by means of a fission chamber. The Radium-Beryillium source gave a larger number of fissions by a factor of 2.34. The same two sources compared in paraffin gave a ratio of the total number of neutrons of 2.21. This indicates that an average fission cross section of Radium-Beryllium neutrons is perhaps 6% higher than for Radium-Boron neutrons.

The Radium-Beryllium source gave about 13% increase whereas the Radium-Boron source gave about 7% increase in the total number of neutrons when placed in the center of a Uranium Sphere. The same Uranium Sphere reduced the fission count to 66% for Radium-Beryllium neutrons and to 62.5% for Radium Boron-neutrons. Taking into account the generation of neutrons amounting to 13 and 7% respectively, the inelastic cross section for the two sources is approximately the same.

(There was 2% less meat in the case of the boron source)

The difference between 13 and 7% must be mostly due to an n-2n reaction, since the average fission cross section is the same.

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MUC-LS. #1
This document consists of 2 pages and 0 figures
No. 4 of 7 copies, Series A

L. Szilard
June 12, 1943

Memorandum on Metallurgical Problems Connected with the Power Unit which is Cooled by Liquid Metal

The possibility of using a liquid bismuth, liquid lead and bismuth-lead alloys for cooling both graphite and heavy water power units is at present under investigation. Of particular interest is the eutectic alloy of bismuth and lead which has a melting point of about 130°C; and at the first step, it might be advisable to use this alloy between 150°C up to 300°C.

1. No particular metallurgical problems arise in connection with graphite power unit if uranium is used in the form of uranium carbide.

It will, however, be desirable to determine at what velocities does true erosion occur, if at all, in graphite and uranium carbide under the conditions of flow which may be expected to exist in the power unit.

2. If uranium is used in the form of uranium metal, we obtain wetting of the uranium by the eutectic Bi-Pb alloy. An experiment is being prepared for seeing if uranium is soluble in the liquid eutectic. It is known that uranium is soluble in liquid bismuth and an experiment is being prepared to determine whether uranium is soluble in liquid lead in order to determine whether there is any hope that bismuth-lead alloys, sufficiently rich in lead, can be used in direct contact with uranium.

3. If it should prove impossible to use uranium metal in direct contact with bismuth-lead alloys, the uranium metal will have to be protected by some other material. It is also of interest to see what materials other than uranium can be used to form tubes through which the bismuth-lead alloys can be led through the power unit. The following materials are under discussion: graphite, beryllium, aluminum, iron.

CLASSIFICATION CANCELLED
Date 10/3/56
For The Atomic Energy Commission
C. R. Murchison/mc L
Director, Division of Classification

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Graphite appears to be safe from the point of view of chemical action or carbide formation at low temperatures. Carbon is insoluble in bismuth and no bismuth carbide is known to exist.

Beryllium does not appear to be wetted by eutectic lead-bismuth alloys at 400°C. It would be desirable to see if beryllium is soluble in liquid bismuth, liquid lead and bismuth-lead alloys. No such experiments have been prepared so far.

Aluminum does not appear to be wetted at 400°C by the eutectic bismuth-lead alloy. Aluminum is not soluble in liquid lead but is slightly soluble in liquid bismuth. An experiment has been planned to determine whether or not aluminum is soluble in the eutectic bismuth-lead alloy. It appears likely that aluminum will prove to be insoluble in bismuth-lead alloys which are sufficiently rich in lead.

Iron is not soluble in either liquid bismuth or lead and it is expected that it is insoluble in lead-bismuth eutectic. Iron could be used in the form of a thin coating to protect the uranium and iron tubes have been successfully ground down by Creutz to .01 inch. It is expected it would be possible to grind down iron tubes from .022 inch which is a commercial size to .005 inch.

The behavior of 18-8 stainless steel and of duraluminum has a certain degree of interest and an experiment has been prepared to see whether the lead-bismuth eutectic wets either of these substances.

CC: Reading File
J. Chipman
F. Foote
E. Wigner
E. Creutz
H. Smyth
S. Allison

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E. Wigner

Szilard

MEMORANDUM CONCERNING LIQUID METAL COOLING

L. Szilard
July 30, 1943

The cooling of chain reacting power unit with liquid bismuth lead alloys is of some interest and in this connection it is proposed to explore the following possibility.

Uranium is, at present, mined in Canada at the rate of about 300 - 400 tons a year. This particular ore contains about 20% of lead in which Pb^{206} has a very high relative abundance. One should thus be able to obtain from the Canadian mines perhaps 70 tons of Pb^{206} per year, which would be sufficient to make up about 100 tons of bismuth lead eutectic. At present, it is not known whether lead 206 has a higher or lower thermal neutron absorption than ordinary lead. Ordinary lead contains about 1½% of 204, and 23.5% of 206, about 22.6% of 207, and about 52.4% of 208, and one might expect that most of the absorption of ordinary lead comes from the lead isotope 207. Accordingly, there is an appreciable hope that 206 has a smaller absorption than ordinary lead. It would be rather easy to verify whether this hope is justified by actually comparing the thermal neutron absorption of a sample of ordinary lead with a sample of lead from Canadian pitch blend. The lead from the pitch blend must, of course, be purified in the same way as pure commercial lead in order to be able to make this comparison.

I am trying to obtain a sample of lead from Canadian pitch blend and have it purified for the purpose of such a comparison.

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MEMORANDUM

L. Szilard
July 21, 1943

1. The approximation used in A-55 leads to formulae which make it possible to determine the size of the uranium sphere and the ratio of uranium to carbon in the lattice for which the multiplication factors comes close to its maximum value. The nuclear constants which have been put in this formula in order to carry out the calculations are all explicitly given in A-55. However, no other constants given in A-55 enter into this calculations particularly the value of the constant μ does not in any way enter into these calculations.

The formulae given in A-55 determine as the most favorable size at room temperature a radius of slightly above 5 cm at a density of 15 gms/cm^2. From 900°C the most favorable size comes out to be a radius of 8 cm. Spheres of 8 cm radius are not mentioned in A-55 except in conjunction with 900°C.

The corresponding most favorable ratio of uranium to carbon can be calculated from formulae 33 (or 35) or formula 33a. Both formulae give the same results provided that the values put into formulae a relation to each other which is defined by other formulae given in the paper.

The paper recommends explicitly for 5 cm radius, a weight ratio of uranium to ~~carbon~~ graphite of 3 to 10. It does not make any recommendation for 8 cm radius but the weight ratio for 8 cm radius at 900°C can be calculated by putting any of the two constant values given on page 20 into formulae 33, 35, or 33a.

2. The paper states explicitly that if the sizes and uranium to carbon ratios for which the multiplication factor becomes a maximum are used, then the multiplication factor will, in fact, be larger than 1. The multiplication factor is estimated at room temperature on page 21 to be about 1.2 and this comes out as a product $q\mu$ where the most probable value for q is taken as .6 and the most probable value for μ is taken as 2. The limits of error given for μ are about 10% which arises from the limits of error given for p, and for n = 30 in Halban, Joliot and Kowarski's paper, quoted on Page 17. Taking the most pessimistic value within these limits of error one would obtain for μ q, .6 x 1.8 = 108, for the multiplication factor.

3. Both the value of μ and the value of q were affected by the uncertainty of our knowledge of the amount of resonance absorption. However, they were affected in opposite ways. If the resonance absorption were larger as was assumed in the paper, q would be smaller and μ would be larger and vice versa. It is my contention that the reason why it was possible to state with some degree of assurance that the chain reacting would go with pure uranium in graphite if experimental conditions are used in the uranium-graphite system is the following:

Experiments carried out on homogenous and heterogenous uranium-water systems showed that the multiplication factor can be brought rather close to 1 in such systems. If I remember it correctly, one can extrapolate from the experiments of Joliot quoted under 13 in A-55 that the multiplication factor comes very close to 1 for the ratio of 6 hydrogen to 1 uranium atom. Without making any assumptions about μ and using only constants which were

established, it was then possible to argue in the following way: It takes in carbon, according to A-55, 6.5 collisions to slow the neutrons down as much as 1 collision hydrogen would slow them down. For the scattering cross section of graphite the paper assumes 4.8 and admits a possibility that the scattering cross section may be somewhat lower by a factor of 1.18 or about 4. In order to be on the safe side, we shall use in the following this more pessimistic value. The scattering cross section of hydrogen for resonance neutrons times known to be 18. From these values it follows that if we replace 1 hydrogen atom by 29 carbon atoms we have a system in which the resonance absorption is about the same as in the hydrogenous system. 6 hydrogen atoms thus correspond to 170 carbon atoms. The thermal absorption of 170 carbon atoms, however, is for σ_c = .005 about .86; whereas 6 hydrogen atoms have an absorption of about 1.8 which is considerably larger. It follows that we can expect the chain reaction to go in a uranium-graphite system provided that we can demonstrate that for the most favorable mixture the thermal neutron density in the graphite and/the in uranium spheres is fairly uniform.

The University of Chicago
Metallurgical Laboratory

MIDWAY 0800
EXT. 1290

27 December 1943

A memorandum of a conference held at the Chicago Area Office, U. S. Engineers, on 3 December 1943:

Present: General Groves, Dr. Szilard, Captain Lavender and Lt. Colonel Metcalf.

Szilard stated he desired to bring to the attention of the General personally the fact that he was willing to sign the contract covering the assingment of patent rights for a sum of $15,416.60 which covered a salary to him of $333.30 a month for twenty months while he was working on the Project at Columbia University without receiving any salary, expenses in carrying on such work, lawyers' fees and an item of $6,000.00 purporting to be an expense to him for settling a dispute between a Mr. Adam and himself, which dispute stood in the way of concluding the negotiations between Dr. Szilard and the Government. The copy of a proposed letter from Dr. Szilard to Captain Lavender, setting forth the above recited details, and a copy of a proposed letter in reply thereto from Captain Lavender to Dr. Szilard were shown to the General.

Dr. Szilard then stated that he felt that he should be placed back on the payroll of The University of Chicago and be paid his salary from the first of January 1943 without regard to whether or not he did sign the proposed contract of assignment of his patent rights. Dr. Szilard referred to his signing the contract under duress and asked that the General answer the question as to whether he would have Dr. Szilard put back on the payroll if Dr. Szilard refused to sign the contract. General Groves denied that any undue pressure has been or was being brought upon Dr. Szilard to sign the contract and referred to the fact that whether Dr. Szilard was employed by the University was a matter of free choice and free decisions by both Dr. Szilard and the University. The General stated that in any negotiations of employment there was always some "duress" and cited as an example that if Sears, Roebuck and Company offered him a million dollars a year as salary as its general manager it certainly would be duress on him. After further general discussion of the situation, Dr. Szilard then stated that he withdrew the question and did not desire an answer to his question.

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27 December 1943

A memorandum of a conference held at the Chicago Area Office, U. S. Engineers, on 3 December 1943 (continued):

Upon the return to the Metallurgical Laboratories, Dr. Szilard signed the contract in the presence of Captain Lavender and Lt. Colonel Metcalf. Dr. Szilard was particularly asked by Captain Lavender to read the notarial statement, which Dr. Szilard did and signified his understanding of and agreement to the provisions of the notarial statement by words and the gesture of nodding his head.

H. E. Metcalf
Advisor on Patent Matters
O.S.R.D., Chicago Group

Approved
Robert A. Lavender

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PERSONAL AND ~~CONFIDENTIAL~~

noted by JBC March 16, 1944

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

1530 P. Street, N. W.

INTER-OFFICE MEMORANDUM

March 9, 1944.

TO: Dr. J. B. Conant

FROM: V. Bush

SUBJECT: Conference with Dr. Szilard, March 6, 1944.

As a result of my correspondence, I had a long conference with Dr. Szilard on Monday, March 6, which lasted practically all day. He had prepared for the discussion by some written memoranda in order to bring up matters explicitly, but did not leave these with me, as he stated at the outset that he had prepared them simply as a basis for conversation, and he wished the conversation to be quite informal and frank.

He first mentioned the matter of the patents, and I told him that I was very glad to have this matter all cleared up, and in fact cleared up in such a form that I understood he had received from the Army a payment which approximately covered his expenses in the past, so that he was in the category with the rest of the scientists who had freely contributed their full ideas to the government. He replied that he felt that he had been under coercion to sign the agreement. I feel sure, however, that such is not the case, as we have a very complete record, including letters of mine in which I made it very clear indeed that he was entirely free to use his best judgment as to his procedure. He brought up the point that he had not been paid a back salary with Chicago until after the matter had been settled, and that this had been held out on him. I do not need to go into detail as to the way in which this was handled, as it was contained in correspondence, but the fact is there were two questions up at the same time: first, his proper salary and status at Chicago, and the other his invention, and both matters were settled at once, apparently quite amicably and certainly on a basis where he signed an agreement simply because after full consideration of all the factors involved he wished to sign it. Most of the day was taken up with the broad question of whether the present organization handling this subject is adequate and works well. Dr. Szilard raised a great many instances out of the past history where he felt that mistakes had been made in handling the affairs. I pointed