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LIQUID METAL COOLED FAST NEUTRON BREEDERS

MUC-LS-60

L. Szilard
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This is the first of a series of memoranda outlining a research and development program and the part which, given favorable conditions, I might be able to play in it. The aim of this program would be to have 10 tons of plutonium in production within three years at a total cost of less than $500 million and this memo relates to what will presumably be the later stages of the production process.

NRD

First type

Two different types of plutonium breeders which fall in this category are at present under discussion. To the first type belong breeders that are based on fission neutrons which are not appreciably slowed down. I am fairly confident that breeders of this type could be built which might double the investment of plutonium within about a year and which would produce about one atom of plutonium in excess for one atom of plutonium that is burned in the breeder. I suspect, however, it might prove impossible to have units of this type on a small scale, i.e. containing less than about 200 kg of plutonium which double the investment in one year. In spite of this limitation I would wish to give considerable attention to this first type of breeder and I believe that most of the nuclear information needed for work on such a breeder is available or what is not available could easily and reliably be obtained in the near future. I would like to work out a design and hold it in readiness for use in the later stages of the proposed production process.

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MAR 9 1945

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Second type

I feel that it is also urgent to decide between the relative merits of this type of breeder and a second type of breeder in which the neutrons are slowed down into an energy region between 1, 100, and 1000 volts. Mr. Wigner and his division show at present considerable interest in this second type of breeder.

Such breeders of the second type would indeed have the advantage of requiring a smaller quantity of plutonium per individual breeder which might double the investment within one year. But whether such breeders would in fact rapidly increase the plutonium investment cannot be determined without reliably knowing the ratio of radiative capture to fission in plutonium for energies between 1 and 1000 volts.

Various experiments can be devised for determining this ratio but it is not possible to foresee which of them will actually give a trustworthy value. I myself would therefore wish to attack this problem (if the required facilities can be put at my disposal) by observing the capture γ rays emitted from plutonium per fission in the thermal region, at the .3 volt resonance and between 1 and 1000 volts. In the thermal region and at resonance the ratio of radiative capture to fission can be measured by other comparatively simple methods and this can be used for calibrating the proposed setup so that by observing at various neutron energies simultaneously fission and the response of a counter (or a set of coincidence counters!) which are sensitive to the γ rays it will be possible to obtain the pertinent ratios of radiative capture to fission.

First type:

Pending the outcome of some such experiment I personally would rather prefer to think about breeders of the first type. Experiments carried out at Site Y with fission neutrons appear to confirm the expectation that the ratio of radiative capture to fission (α) becomes quite low for fission neutrons so that we may indeed expect that one excess atom of plutonium can be produced for one plutonium atom burned in the breeder. It may be recalled that it appeared a priori likely that from this point of view fast neutrons are far superior to thermal neutrons and it was on this basis that I urged the development of fast neutron breeders cooled by Bi-Pb eutectic or liquid Na in the meetings held on April 26 and April 28, 1944. The estimate which I gave for α was criticized at that time as being too optimistic; in the light of recent experimental evidence it appears however to have been rather in error on the conservative side. In the following I am recapitulating the views which I put forward in those meetings as reported by Ohlinger in MUC-LAO-17 and MUC-LAO-18. Fermi's views on the same subject are also recorded in the same reports but are not recapitulated here. The text is as follows:

MUC-LAO-17, April 26, 1944

"Mr. Szilard was the second speaker and proposed approaching the problem from a different viewpoint--that of assuming more optimistic values of the constants so as to indicate other potentialities. He pointed out that the fast reaction is preferable to the slow chain reaction for producing 49 from tubealloy and that this is probably more true if we assume more pessimistic values for ν or μ. Before discussing these values of the constants, sketches of a possible design were distributed and described briefly. These sketches are attached hereto.

"The sketches show two different arrangements. In sketch A, the enriched tubealloy (enriched to where the chain reaction will go) and natural tubealloy would be distributed in the form of rods in a cylindrical pile, in which the enriched material would be in the center portion of the rods lying within a circular area in the center of the pile. Part of the rods, located within three circular areas around the center (as indicated in Fig. 1) would be arranged so the cylindrical bundles could each be rotated about its axis. In each of the rotating bundles, part of the rods would be natural tubealloy and the balance of natural tubealloy with the center section enriched.

"In the beginning, the enriched material in the three bundles would all face the center of the pile and lie within a cylinder whose axis would coincide with the axis of the pile and whose cylindrical surface would pass through the three axes of the revolving bundles. By means of this arrangement, as the multiplication factor increased with the continued operation of the pile, the enriched material could be rotated away from the center of the pile and the natural tubealloy brought towards the center where it in turn would be enriched. In the center of the pile would be a single tube for introducing mercury, liquid bismuth, or some other absorbing or slowing material for controlling the pile. The coolant for this type pile would be a bismuth-lead alloy and would flow downward through the pile between the static and rotating rods. The possibility of using liquid sodium in place of bismuth-lead should also be looked into. The volumetric heat capacity of the liquid sodium is about the same as that of the bismuth-lead alloy but its density would be 10 times less, so that the pressure drop would be about 1/10 that for the bismuth-lead alloy or the velocity about 3 times larger for equal pressure drop. In the scheme just described, the following approximate conditions would obtain: (1) the bismuth-lead alloy would occupy about 1/3 of the enriched core and would pass through the pile at a velocity of about 15 meters per sec; (2) with 1/2 cm diameter rods raised to 700° C metal temperature at the center of the central rod and with 150° C temperature increase in the coolant, about 250,000 kw will be removed. The pumping power for the coolant will consume about 5% of the power produced.

"In the alternative scheme B, control of the pile would be obtained by means of a nest of tubes for the mercury or other controlling medium arranged as in Figs. 3A and 3B and 4A and 4B. The metal rods would all be stationary and vertical (nos. 12, 13 and 14 in Fig. 3A) and would be about 1/2 to 1 cm in diameter by about 2 meters long.

"In both designs the enriched core would be about 1/2 to 1 meter in diameter by about the same height. The balance of the material around the core would be ordinary tubealloy of the same rod size. The total diameter and the height of the pile would be about 2 meters.

"The objective of such a pile must be to produce as much extra 49 as invested. It is assumed that the production will be double the original investment. For every atom of 49 disintegrated, two atoms of 49 could be produced. Part of these will be produced in the enriched core and part in the surrounding natural tubealloy. Some of the production in the core will tend to leak out into the natural tubealloy and this leakage must be kept within certain limits. Then k will increase over a period of time. As the chain reaction goes on, the multiplication factor k will then increase so that the controls must provide for this as well as the normal operating control of the pile.

"In the slow chain reaction, 49 captures neutrons in radiative not fission capture to produce a new element which we will call super plutonium or 40-10. It is assumed there is a 50% chance that this new element will be fissionable. If it is not fissionable, it is assumed there is 50% chance that it will be formed only in negligible quantity in the capture of fast neutrons. Thus, there is a 75% chance in a fast chain reaction that we may use ν and not μ in getting the production balance (μ = 2.2 neutrons per neutron absorbed, $\nu_{25} = 2.2 \times 1.175 = 2.6$ neutrons produced per neutron absorbed). As the energy of the neutrons increases from thermal to fission energies, it is assumed there is no increase in ν. The main argument in favor of the fast chain reaction is that if a fission neutron is released in tubealloy, it causes fission in the 28 to produce 12 neutrons (fast effect). If all the neutrons are captured, the overall balance would be that for every atom of 49 destroyed, two atoms of 49 would be produced. One goes back into the chain reaction, the other replaces the 49 destroyed, providing a net gain in 49.

"In experiments in which a Ra-B neutron source was surrounded by 28, measurements indicated a 5.3% increase in the number of neutrons and that 63% of the neutrons remained above the fission threshold. This means that the increase in the number of neutrons for an infinite sphere would be $\frac{5.3}{1 - 0.63}$ or 19½%. If the fission cross section is taken at 0.35 and the inelastic cross section at 2.7 for a ν_{28} of 2.2 to 2.6 ε will vary from 1.18 to 1.245.

"Referring to the value above of ν_{25} of 2.6, if we were to use the more optimistic results reported by Y (that ν_{49} is 20% larger than ν_{25}) then ν_{49} equals 3.1 neutrons produced per neutron absorbed. If we are less optimistic and assume ν_{49} effective = 2.5 but use the 19½% increase indicated by the experiment mentioned above, we have three neutrons produced in a mixture of 28 and 49 for one atom of 49 destroyed."

MUC-LAO-18, April 28, 1944

"The second speaker was Mr. Szilard who continued his discussion from the previous meeting. He recapped first the three possibilities as he saw them:

(1) Unseparated tubealloy → 49 production

(2) Enriched tubealloy → 49 production

  (a) slow chain reaction

  (b) fast chain reaction

(3) Enriched tubealloy → no 49 production

"On the basis of Morrison's report, Mr. Szilard felt that the tubealloy should be utilized more efficiently, i.e., using the 28 and not just the 25. However, since the power production indicated in item (3) above is a long term proposition, he did not intend to discuss this phase at great length at this time.

"In item (1) above, heat is only a byproduct and not the primary object. Concerning item (2), Szilard proposed answering the question-- if an amount A of 49 were invested, how long would it be until 2A of 49 were obtained. In a fast chain reaction, if two tons of enriched ore containing 10% of 49 were used in the core surrounded by 28 at the rate of 125,000 kw, then 2A of 49 would be produced in 4½ years. In order to have any practical significance, this time should not be very much larger and the readjustment of the material should be easy during the time of operation.

"Considering first the slow chain reaction: assume a μ_{49} (neutrons emitted in fission/neutrons absorbed) equal to 2.0 - 2.2. Szilard struck out the latter figure when Fermi stated that the μ_{49} is probably lower than μ_{25}. With $\mu = 2$, just as much 49 is being produced as is being destroyed. In a slow chain reaction this might be improved by using the fission of 28 mixed with 49 but this is not very effective in a slow chain reaction because even from large lumps embedded for instance, in graphite, many neutrons escape, are slowed down, and do not produce fission. Since the super-plutonium (40-10) formed might be fissionable, there is, say, a fifty-fifty chance that we can improve μ to a $\mu_{\text{eff}} = 2.5$.

"Considering the fast chain reaction, the situation is more favorable. With a low concentration of 49 in the mixture with 28, experiments have shown that ε might be raised to 1.2. In addition, there is a high energy tail producing an (n, 2n) reaction which may give a $2\frac{1}{2}$% increase in μ (based on observations of Turkevich).

"(The value μ has been defined as the number of neutrons produced/number absorbed in 49. Szilard uses ν_0 defined as the number of neutrons produced/number of fissionable atoms used up.)

"In a fast chain reaction, even if 40-10 is not fissionable, Szilard felt that it is probably true that the branching ratio for 40-10 moves in a favorable direction, or that ν_0 may be taken as $\nu_0 = 2.5$. He felt strongly that there is a very good chance that Pu^{240} is either fissionable in the thermal region or at least that the branching ratio can be counted upon to decrease by a factor of 3 as one goes from thermal energies to, say, 1 Mev. (Fermi pointed out that the branching ratio of 49 is greater than that for 25.)

"The arguments for this belief is in part based on the rule of thumb $(\triangle M/M) - (2\triangle Z/Z)$ (see also Morrison in Project Handbook, Chapter IV Bl.1) which gives a rough indication of the fission threshold and is partly based on the belief that, with increasing neutron energy, the time required for fission decreases whereas the time required for radiative capture remains constant. Szilard therefore assumes that, in a mixture of 238 and Plutonium, $\varepsilon \nu_0 = 1.2 \times 2.5 = 3.0$ neutrons emitted per thermally fissionable atom destroyed and this would mean that there is a net gain of one thermally fissionable atom per similar atom destroyed.

"Referring to item (3), Szilard emphasized one possibility, i.e., the burning of Plutonium in a slow reaction and absorbing the neutrons by bismuth to give Polonium. Of the heat dissipated when Plutonium is destroyed to give Polonium, only about 3% would be stored in the Polonium. However, this energy will be available for use free of γ radiation and could be used for driving airplanes, etc.

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"In the discussion following, Fermi questioned the estimated value of $\nu_0 = 2.5$ on the ground that it might be too optimistic and pointed out that there is a long range future in developing the full utilization of 28 and thorium.

"Wigner questioned the feasibility of the rotating disc arrangement described at the previous meeting on the ground of poisoning and questioned the $4\frac{1}{2}$ year investment return. He felt this would probably be more nearly 10 to 20 years by which time, as Mr. Morrison suggested, we may be burning water."

This ends the text taken out of the report on the meeting of April 28, 1944.

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