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REPORT TO THE PRESIDENT
OF THE NATIONAL ACADEMY OF SCIENCES
by the Academy Committee on Uranium

November 6, 1941

UNITED STATES ATOMIC ENERGY COMMISSION
20

Dear Dr. Jewett:

Your committee, appointed to advise with regard to uranium fission, begs to submit the following supplement to its reports of May 17 and July 11, 1941. The special objective of the present report is to consider the possibilities of an explosive fission reaction with U235. The importance of this investigation lies in the possibility that within a few years the use of explosive fission may become the predominant factor in military action.

Since our last report, the progress toward separation of the isotopes of uranium has been such as to make urgent a consideration of (1) the probability of success in the attempt to produce a fission bomb, (2) the destructive effect to be expected from such a bomb, (3) the anticipated time before its development can be completed and production under way, and (4) a preliminary estimate of the costs involved.

1. Conditions for a fission bomb.

A fission bomb of superlatively destructive power will result from bringing quickly together a sufficient mass of element U235. This seems to be as sure as any untried prediction based upon theory and experiment can be.

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Our calculations (Appendix A) indicate further that the required masses can be brought together quickly enough for the reaction to become efficient. The destructive effect of the resulting fission explosion should be equivalent to that of vastly larger masses of chemical explosives (Appendix B).

2. Destructive effect of fission bombs.

a. Mass of the bomb (Appendix A)

The mass of U235 required to produce explosive fission under appropriate conditions can hardly be less than 2 kg nor greater than 100 kg. These wide limits reflect chiefly the experimental uncertainty in the capture cross-section of U235 for fast neutrons. It is difficult to improve these data until considerable quantities of the separated or enriched isotope are available. Because of the greater destructiveness of the larger bomb, however, the question of size between these limits is not one of major importance.

b. Energy released by explosive fission (Appendix A)

Calculations for the case of masses properly located at the initial instant indicate that between 1 and 5 per cent of the fission energy of the uranium should be released at a fission explosion. This means from 2 to 10 x 10^8 kilocalories per kg of uranium. The available explosive energy per kg of uranium is thus equivalent to about 300 tons of TNT.

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c. Destructiveness of a fission explosion (Appendix B)

The destruction caused by a bomb will depend upon the magnitude of the pressure wave produced in the outer part of the devastated region. For an explosion of so short duration as a fission reaction, a considerable part of the energy will be dissipated as heat. Taking this into account, we estimate roughly that the destructiveness of a fission explosion in air liberating the energy estimated above should be equivalent to about 30 tons of TNT per kg of U235.

We would note that this conclusion differs from a reported conclusion drawn by G. I. Taylor in England, which gave the destructiveness of the uranium as equal to that of the TNT delivering the same energy. Not having seen his calculation, we are unable to judge its reliability, and experimental data on such super-energy explosions are entirely lacking. It is known from experiment, however, that very fast explosions involving small masses are less effective than slower explosions of the same energy involving larger masses. Certain calculations (footnote 2, Appendix B) would suggest a much smaller effectivness for the fission explosion. We thus favor the more conservative estimate made above.

It is possible that the destructive effects on life caused by the intense radioactivity of the products of the explosion may be as important as those of the explosion itself.

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3. Time required for development and production of the necessary U235.

a. Amount of uranium needed (Appendix B)

Since the destructiveness of present bombs is already an important factor in warfare, it is evident that if the destructiveness of the bombs is thus increased 10,000-fold, they should become of decisive importance.

The amount of uranium required will, nevertheless, be large. If the estimate is correct that 500,000 tons of TNT bombs would be required to devastate Germany's military and industrial objectives, from 1 to 10 tons of U235 will be required to do the same job.

b. Separation of U235 (Appendix C)

The separation of the isotopes of uranium can be done in the necessary amounts. Several methods are under development, at least two of which seem definitely adequate, and are approaching the stage of practical test. These are the methods of the centrifuge and of diffusion through porous barriers. Other methods are being investigated or need study which may ultimately prove superior, but are now farther from the engineering stage.

c. Time required for production of fission bombs

An estimate of time required for development, engineering, and production of fission bombs can be made only very roughly at this time.

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If all possible effort is spent on the program, one might however expect fission bombs to be available in significant quantity within three or four years.

4. Rough estimate of costs (Appendix C)

The separation process will probably be the most expensive and time consuming part of the work required to produce fission bombs. The estimates in Appendix C indicate that unless some new method should appear, a cost of the order of $50,000,000 to $100,000,000 for building the separation plant should be envisaged. For its operation, large quantities of electric power will also be required.

The other costs in connection with producing the bombs will probably be smaller, of the order of $30,000,000.

It will be understood that these figures represent only the roughest estimates, since the scientific and engineering data needed to make them more precise are not available.

Immediate Requirements

Though eventually the funds needed for carrying through this program to its military use are thus large, the immediate requirements are relatively moderate. Before any large sums can be spent, at least the following work must be done:

1. Building and testing of trial units of the centrifugal separator and the diffusion separator.

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2. Securing by the most immediate method of samples of separated U235 for physical tests on spontaneous fission in U235, and on the capture cross-section of U235 for neutrons.

3. Certain direct physical tests, including (a) experiments on inelastic collision of neutrons in U238, and (b) measurement of the energy range of fast neutrons for fission of U238.

4. In the meantime, groundwork on the engineering of the isotope separation plants should be started, so that the plans can be ready when the requirements are more exactly known.

This program, part of which is already in hand, should have available now some millions of dollars, the exact amount of which can be estimated better by the working committee on uranium under Dr. Briggs.

Looking toward maximum speed and efficiency in carrying through such a program, we would note that the isotope separation has reached the development stage, and should be placed under the direction of a competent development engineer. This development program must be coordinated with an intensified research program.

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For best research progress, we would strongly recommend the selection of certain key research men of proven ability and integrity, to whom would be assigned certain major research tasks and adequate funds to be used for these tasks according to their best judgment.

For satisfactory coordination of the research and development, a reorganization of the entire uranium program may be called for. Such reorganization should be given prompt and careful attention by the appropriate administration officers.

Conclusion

The possibility must be seriously considered that within a few years the use of bombs such as described here, or something similar using uranium fission, may determine military superiority. Adequate care for our national defense seems to demand urgent development of this program.

Respectfully submitted, with the unanimous approval of the members of the committee,

(signed) ARTHUR H. COMPTON

C. E. Buckley
I. W. Chubb
W. D. Coolidge
G. B. Kistiakowsky
E. O. Lawrence
W. K. Lewis
R. S. Mulliken
J. C. Slater
J. H. Van Vleck

Arthur H. Compton, Chairman
National Academy of Sciences
Committee on Uranium

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APPENDIX A

Conditions and Efficiency of Fission Explosion
(Van Vleck and Compton)

1. Critical Size

a. The condition for a chain fission reaction is that the number of neutrons emitted by fissions resulting from capture of the initial neutrons shall exceed the number captured and lost. If the captured neutrons all produce fission and the loss is due wholly to escape from the mass of uranium, as is presumably the case for U235, there is a critical size of the mass above which the probable gain of neutrons exceeds the probable loss. If the uranium forms a sphere, its critical radius is of the order of magnitude of the average distance from the point of origin of a neutron to the point of its capture. Independent approximate calculations by various physicists give results in good agreement (cf. Footnote 1), and which are of substantially the form,

$$R = k\sqrt{l_t\, l_f}. \qquad (1)$$

Here R is the critical radius, k is a quantity of the order unity, involving the average number n of neutrons emitted per neutron captured, l_t and l_f are the mean free paths between collisions and before capture respectively. Typical of these calculations is that of Fermi, who obtains

$$k = 1.82\,/\sqrt{\ln n} \qquad (2)$$

$$= 1.73 \text{ for } n = 3 \text{ (case of U235)}$$

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[1] See end of appendix for footnotes.

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If the uranium sphere is surrounded by a shield of material which scatters the neutrons that escape so that there is good chance of their return, the critical radius is thus reduced by approximately a factor of 2, and by a greater ratio if a surrounding medium of higher scattering power can be used (cf. Footnote 2).

b. The greatest uncertainty in the value of $\underline{R}$ arises from the uncertainty of the mean free paths. These paths are usually described in terms of the cross-sectional areas of the nuclei of the uranium atoms, with the following relation between the cross-section and the mean free path:

$$\sigma_t = 1/Nl_t \quad \text{and} \quad \sigma_f = 1/Nl_f. \tag{3}$$

Here $\underline{\sigma_t}$ is the <u>total</u> cross-section for collision with a neutron, $\underline{\sigma_f}$ is that for <u>capture</u> of the neutron resulting in fission, and $\underline{N}$ is the number of uranium atoms per cm.^{3} Similarly we use the <u>scattering</u> cross-section $\underline{\sigma_s}$, which refers to the deflections of a neutron without capture. Thus

$$\sigma_t = \sigma_s + \sigma_f. \tag{4}$$

<u>Determination of Fission Cross-Section σ_f</u>

As pure U235 is not available at present, fission cross-sections can only be measured in commercial uranium (containing 238 and 235 about in the ration 140:1). Since 238 decomposes only for fast neutrons, the fission observed for

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thermal neutrons (i.e. neutrons of energies of the order kT) must be attributed entirely to 235. The corresponding fission cross-section is 4×10^{-22} om^2. This is, however, not the relevant quantity for a superbomb of pure 235, as the neutrons coming from the fission of 235 have energies of the order 10^6 volts, and usually will escape before being slowed to the thermal region, so what is needed is the cross-section for neutrons of the order 10^5 to 10^6 volts. Experimental data are available on the cross-sections of ordinary uranium for fast neutrons of approximately known energy (produced by gamma rays from disintegrating beryllium). The fission cross-sections of ordinary uranium for neutrons of energy .2, .6, .8, and 5 million volts are respectively about .017, .011, .014, and $.4 \times 10^{-24}$ cm^2. It is reasonably certain, theoretically, that the fission cross-section of 235 is at least as high as that of 238, and tends to decrease with increasing velocity. Thus $.4 \times 10^{-24}$ can be regarded as a lower limit to the cross-section for the fast neutrons in U235, with an estimate of $.5 \times 10^{-24}$ as a rough average over the range of energies of the fission neutrons.

A higher estimate of σ_f is obtained by assuming that the observed fission in the range .2 to .8 million volts is due mainly to 235, i.e. that the effect of 238 has practically disappeared when the neutron energy has sunk much below 10^6

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volts. If all the capture is due to 235, values of σ_f (235) are thus obtained between 2.4 and 4 x 10^{-24} cm^2 for the range of energies tested, leading to an average value of about 3 x 10^{-24} for fission neutrons. In favor of this higher value of σ_f is a reasonable but not well verified theory that there is a sharp threshold of neutron energies, below which impacts on U238 will not cause fission and above which the probability of fission increases linearly with the neutron energy. Tests have been made (Westinghouse, reported by Breit) which seem to show such a linear increase for neutron energies greater than some 2 x 10^6 volts. This would indicate a threshold for U238 at about this energy. Since the tests have not, however, been made with neutrons of definite energies, the significance of the results is open to question.

It will be noted that on the former interpretation U238 is subject to fission from capture of the fast neutrons, with a cross-section for 10^6 volt neutrons of between .01 and .02 x 10^{-24} cm^2. On the latter interpretation the capture cross-section of 238 for these neutrons is negligible.

Determination of the Scattering Cross-Section, σ_s

The uncertainties in σ_s are much less serious than those in σ_f. For the normal mixture of uranium isotopes σ_t has been

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measured as about 12 x 10^{-24} cm^2. A very small part of this corresponds to σ_f, but perhaps half is due to small angle scattering that has little effect upon the range of the neutrons. Thus the effective value of the scattering cross-section for normal uranium is about 6 x 10^{-24} cm^2. All evidence indicates that σ_s should be nearly the same for U235 and U238. This value may, therefore, be used for the scattering cross-section of either isotope.

It should be noted that an error of a factor of as much as 2 in the value of σ_s (235) would not be important, since a smaller value of σ_s could be compensated by using a surrounding shield of larger σ_s, as indicated in paragraph 1a.

c. Until further experiments are performed, we must, therefore, consider two possibilities, which may be summarized thus:

TABLE AI

CROSS SECTIONS FOR URANIUM (Units, 10^{-24} cm^2)

	σ_s	σ_f	σ_t
Case a.	Definite high threshold for U238		
U235	6	3	9
U238	6	0	6
Case b.	No definite high threshold for U238		
U235	6	0.5	6
U238	6	0.015	6

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From present information it seems that alternative a is the more probable. A choice between the two cases can be made experimentally by present technique if a sufficient quantity (perhaps .01 g) of U235 can be isolated. Using improved technique in more nearly homogeneous high energy neutrons a more definite indication should also be possible without separating the isotopes.

Substituting the values of σ_f and σ_t given above, assuming a sphere of metallic U235 (density 18.6, which gives $N = 4.8 \times 10^{22}$ cm^{-3}), and using Fermi's value of k the critical sizes are

TABLE AII

CRITICAL BOMB SIZES FOR U235

	l_f	l_t	R(bare)	R(shielded)	Mass(bare)	Mass(shield)
a	7 cm	2.3 cm	7 cm	3.5 cm	26 kg	3.4 kg
b	42 cm	3.5 cm	21 cm	10.5 cm	720 kg	87 kg

The critical sizes for the shielded bombs are calculated for large thicknesses of material with the same scattering cross-section as the U235, a condition which should be attainable. Thus the final column represents a reasonable expectation for the two cases. The experimental errors might make the critical masses uncertain by a factor of perhaps 2 for each case in question. As mentioned above, however, we cannot now say whether case a or b will prove correct.

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2. Possible Explosive Fission with U238.

Unless the energy of the fission neutrons is rapidly reduced by inelastic collisions in the uranium, explosive fission should occur with U238 as well as with U235. The critical radius calculated as above for the shielded sphere of U238 is 70 cm, or a mass of 27,000 kg. There is some evidence that inelastic collisions occur which will slow down the neutrons until a non-fission type of capture occurs, preventing the chain reaction; but this is not certain.

At first sight it might appear to be of advantage to dilute the U235 with U238 in order to obtain additional energy from the latter isotope. Calculation does not, however, support this suggestion. Thus if equal quantities of U235 and U238 are mixed, because of the much higher capture cross-section of the lighter isotope, at any instant after the chain reaction has started the ration of U235 fissions to U238 fissions will be σ_f (235) : σ_f (238), which is of the order of 30:1. That is, the U238 will add but little to the energy of the reaction, while it will considerably increase the size of the bomb required.

In case a, the presence of U238, as far as can be seen at present, would act merely as a dilutant, enlarging the critical value of the radius, and not affecting the fission reaction.

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3. Percentage of Available Energy Released at Explosion.

If the bomb has a larger mass than that corresponding to the critical radius, it will initially be highly explosive. However, because of the heat produced it will start to expand. This expansion lengthens the mean free paths, which increase inversely as the density. The critical radius R increases at the same rate, i.e., it is proportional to r^3, where r is the actual radius of the sphere. The chain reaction will develop in intensity until $R = r$, beyond which value the number of neutrons produced will be less than those that are absorbed and escape, so that the reaction will decline in intensity. The question arises as to what fraction of the total available energy of fission is released when the expansion is complete.

The appropriate mathematical problem has been studied by Pryce (Secret British ms P1), and in this country independently but with rougher approximations by Fermi, Oppenheimer and Compton (see Footnore 3). The results of Fermi and Compton are in good agreement with Pryce's calculations. Oppenheimer (probably through neglect of some factor considered by the others—details of his calculation have not been submitted) finds efficiencies about 10 times larger.

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The results of Pryce, for a sphere of U235 enclosed in a container of about half the mass of the uranium, and of 2 times the critical mass, give an efficiency of 3.5 per cent. Compton, for a bare sphere, finds 1.4 per cent, and a somewhat higher value for the shielded sphere. Fermi estimates roughly (within a factor of 10) 1 per cent. A value of 2 per cent can hardly be in error by more than a factor of 4.

If the mass is n times the critical value, the efficiency is proportional to n^2. If the explosion occurs before the parts are placed together the efficiency will be reduced by a factor lying between $\left[(a-1)/(a_o-1)\right]^0$ and $\left[(a-1)/(a_o-1)\right]^2$, where a is the actual effective multiplication factor and a_o is the value of thefactor when the parts are brought together. In the case of partial approach the efficiency will thus be reduced by a factor estimated roughly as $(a-1)/(a_o-1)$.

In the cases considered below, where the reaction is triggered by a neutron at the instant of critical approach, this ratio is about 25 per cent. This would reduce the efficiency of the explosion to about .5 per cent.

4. Avoidance of Predetonation.

In order to have a superbomb one puts two or more parts together such that combined they exceed the critical volume, but separately they do not. The possibility must be examined that stray neutrons may trigger off a reaction before the

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parts are thoroughly put together, so that the bomb "fizzles" instead of explodes. Uranium has some spontaneous fission, which will tend to introduce this effect. Measurements can be made at present only on commercial uranium, which has about 5 spontaneous fissions per kg per second. The question is how much of this is to be apportioned to U235. The theoretically favored viewpoint is that all the observed spontaneous fission is to be attributed to U235. On this basis, for a 7 kg bomb, about 2×10^{-4} seconds, and for a 150 kg bomb, about 1×10^{-5} seconds, would be available to bring the parts of the bomb together.

In the opinion of some competent theoretical physicists, however, there is no conclusive theoretical reason why the observed spontaneous fission of uranium should come entirely from 235, or even why the spontaneous fission of 235 should be pronouncedly larger than that of 238. If the probability of spontaneous fission is the same for 235 and 238, the available times are increased by a factor of 140, and the detonation difficulties to a large extent disappear.

The development interval of the chain fission reaction is also long enough to be significant. After the introduction of the first neutron, the time interval until the explosion is complete varies from about 3×10^{-6} to 10^{-4} second according to the initial conditions. For a sphere above the critical mass, the interval after the first fission until $\underline{N}$ fissions have occurred is

$$t = \tau_e \ln N \qquad (4)$$

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where τ_e is the time required for a multiplication by a factor e. This is in turn calculable from the relation

$$r_e = \tau / \ln a, \qquad (5)$$

where τ is the mean time spent by each neutron in the uranium, and a is the average number of neutrons produced per initial neutron. a is less than the multiplication factor n used in section 1 above, because of the probability of escape of neutrons without fission capture. For a sphere of twice the critical mass, a = ca. 1.4, and for a shielded U235 sphere of radius 4.4 cm, τ = ca. 2×10^{-8} sec. Thus $\tau_e = 6 \times 10^{-8}$ sec. Using in equation (4) the value $N = 3 \times 10^{25}$ (10 per cent of the total number of atoms), we obtain

$$t = \text{ca. } 3 \times 10^{-6} \text{ sec.}$$

Now consider the initial condition of two hemispheres, each having the critical mass, approaching each other with a velocity v. When the parts reach a certain critical distance from each other the value of a will rise to unity, and an explosion becomes possible. If at this instant a neutron is present, the rate of increase is given by the equation

$$\tau \frac{dN}{dt} = (a-1) N, \qquad (6)$$

where a is increasing according to roughly,

$$a = 1 + Avt. \qquad (7)$$

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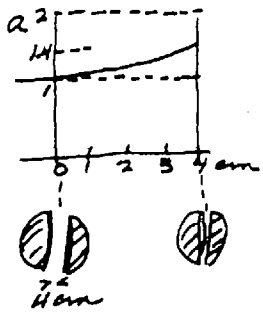

FIGURE

Substituting in eq. (6), and solving,

$$t^2 = \frac{2\tau}{Av} \ln N \qquad (8)$$

The value of A will depend upon the geometry, but for the smaller size bomb (case a) could probably be made as great as 0.1 per cm. Assuming $v = 10^5$ cm/sec, and τ and N as given above, this gives

(case a) $t = 1.5 \times 10^{-5}$ sec.

During this interval the hemispheres will have approached close enough to raise (a-1) to some 30 per cent of its maximum value, and the efficiency of the explosion may be expected to be roughly the same fraction of that from the bomb in its spherical form.

For the large sized bomb (case b) and base sphere the appropriate values of the constants are $\tau = 6 \times 10^{-6}$ sec., $N = 4 \times 10^{26}$, A = 0.02 and $v = .5 \times 10^5$ cm/sec. Using these values, the development interval for the sphere of twice the critical mass is by eq.4, $\tau = 1 \times 10^{-5}$ second. For the approaching hemispheres triggered at the instant of critical separation, equation (8) gives

(case b) $t = 1 \times 10^{-4}$ sec.

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This interval is long enough for (a-1) to grow to about 25 per cent of its value for the completed sphere, so that the explosion will be of high energy.

The total interval available to bring the parts of the bomb together is the sum of the probable interval between fissions and of the development interval. Considering all spontaneous fissions to occur in U235 (most unfavorable case), these total intervals are:

case a, 2×10^{-4} seconds

case b, 1×10^{-4} seconds.

These times should be reliable within a factor of 2. For the lighter bomb the interval is long enough to bring the parts to their optimum positions. For the heavier bomb, as noted above, though the interval is too short for optimum placing, it is nevertheless sufficient to ensure a high energy reaction.

Footnote A1. (A. H. Compton)

Mathematical calculations of the critical radius.

The only pertinent published paper is a preliminary calculation of Peierls (Camb.Phil.Soc.Proc.35, 610 1939). Van Vleck sets up a differential equation equivalent to

$$-D\nabla^2 \rho = N\sigma_f (n-1)\rho, \qquad (1)$$

where ρ is the neutron density, and D is the diffusion coefficient, given by

$$D = \tfrac{1}{3} \ell_t [1 + \sigma_t^{-1}(n-1)\sigma_f].$$

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N is the number of atoms per cm^3, σ_f and σ_t the fission and total cross sections, n the number of neutrons emitted per fission capture, and ℓ_t the neutron's mean free path between collisions. The left hand side of (1), when multiplied by dV, represents the loss due to diffusion from a small volume dV, while the right side, when similarly multiplied, gives the rate of neutron birth in dV. The spherically symmetric solutions of (1), finite at the origin, are

$$\rho = \frac{1}{r} \sin kr \cdot \left[k^2 = \frac{N\sigma_f(n-1)}{D}\right] \qquad (2)$$

The proper boundary condition is one which states that at the boundary of the sphere the neutrons diffuse into free space. The requisite analysis for this condition has been made by E. Hopf for an analogous astrophysical problem (Cambridge Tracts No.31, 1934, eq.174). The result is that at $r = R$ we must have

$$.71\,\ell_t \frac{\partial \rho}{\partial r} + \rho = 0. \qquad (3)$$

Combining this with eq. (2) gives the transcendental equation

$$kR \cot kR = 1 - R/.71\ell_t \qquad (4)$$

for determining R.

Following apparently a similar procedure (his calculations have not been available to us), Peierls is said to obtain the formula:

$$R_{\text{Peierls}} = \frac{3/2}{\sqrt{(n-1)\times\left[\frac{3}{2}+(n-1)\times\right]}}\,\ell_t \qquad \left[\times = \ell_t/\ell_f\right.$$

$$= 0.72\sqrt{\ell_t \ell_f} \qquad \text{for } n = 3.$$

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It is not clear to us whether this result is for a shielded or an unshielded sphere.

Fermi using a different procedure, obtains for an unshielded sphere,

$$R_{\text{Fermi}} = \frac{1.82}{\sqrt{n}} \sqrt{\ell_t \ell_f} = 1.73 \sqrt{\ell_t \ell_f}, \quad (n=3)$$

Oppenheimer, for unshielded sphere, gives approximately,

$$R_{\text{Oppenheimer}} = \frac{\pi}{\sqrt{3(n-1)}} \sqrt{\ell_t \ell_f} = 1.40 \sqrt{\ell_t \ell_f} \quad (n=3)$$

Approaching from two different limiting cases, Compton finds for the bare sphere the two approximations,

$$R_{\text{Compton 1}} = \frac{3}{2}\sqrt{2}\left[\frac{n}{n-1} - \frac{1}{n}\left(\frac{\ell_t \ell_f}{R^2}\right)^{3/2}\right] = 1.48 \sqrt{\ell_t \ell_f} \quad (n=3)$$

$$= 2.08 \left(\ln \frac{n}{n-1}\right)^{2/3} \left(\frac{\ell_f}{\ell_t}\right)^{2/3} \ell_t$$

$$R_{\text{Compton 2}} \approx 1.35 \sqrt{\ell_t \ell_f} \quad (n=3)$$

It is possible that Peierl's value of R refers to a shielded sphere, which would then be in line with the other calculations in light of footnote 2.

In the text we have used Fermi's value of k = 1.73, which is the largest of all. Very possibly a value of 1.4 would be nearer the truth. This would reduce the critical radii by the factor 0.8, and the critical masses by the factor 0.5. The sizes calculated in the text should thus be considered as upper limits.

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Footnote A2.

Effect of surrounding shield. Oppenheimer has calculated the effect of surrounding the uranium with a shield of material that will scatter the neutrons, thus increasing the chance of their absorption in the uranium. If l_f and l_t are the capture and total mean free paths respectively, and L is the scattering mean free path in the surrounding shield, Oppenheimer obtains,

$$R = \sqrt{\frac{L\, l_f}{n-1}}\left(1-\frac{1}{15}\frac{L}{l_t^2}+\cdots\right) \quad \text{if } l_t > L,$$

and

$$R = \frac{\pi}{2\sqrt{3}}\sqrt{\frac{L\, l_f}{n-1}} \quad \text{if } l_t \approx L.$$

For comparison, the equivalent (though less accurate) formula for the bare uranium is

$$R = \frac{\pi}{\sqrt{3}}\sqrt{\frac{l_t\, l_f}{n-1}}$$

Thus for $L = l_t$, the shield reduces the critical mass by a factor of 8. It is probable that a substance can be used for which $L < l_t$, in which case the reduction in size will be even greater.

It will be noted that the addition of the shield also increases the efficiency of the explosion (cf. footnote 3). A highly dense shield is to be preferred.

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Footnote A3. (A. H. Compton)

Calculation of Efficiency of Explosion.

A good approximation to the rate of expansion of the U235 results from assuming that as it becomes hot all portions of the sphere will expand at the same rate. If r is the radius of the sphere at any instant, ρ its density, and v the radial velocity of its outer surface, its kinetic energy can be shown to be

$$T = \frac{2\pi}{5} \rho r^3 v^2. \qquad (1)$$

The rate of increase of this kinetic energy can be equated to the rate at which work is done by the outward pressure of the high energy uranium. It is to be noted that no important part of the motion occurs until the temperature is over 10^5 deg. C., or 10 volts, and that after this temperature is reached the uranium may be treated as a perfect gas. Below 10^3 volts, where the pressure is due to molecular (and electronic) motions, the pressure is equal to .67 x the energy density. Above 10^4 volts the radiation pressure is predominant, and equals .33 x the energy density. Consider first only the molecular pressure. We have

$$P \times \frac{dv}{dt} = \frac{dT}{dt}$$

$$4\pi P r^2 \frac{dr}{dt} = \frac{4\pi}{5} \rho r^3 v \frac{dv}{dt},$$

or since dr/dt = v,

$$P = \frac{1}{5} \rho r \frac{dv}{dt}. \qquad (2)$$

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The rate of fission energy increase is however given by

$$\tau \frac{dE}{dt} = (a-1)E, \qquad (3)$$

where E is the energy per cm^3, τ is the mean life of a neutron and a is the multiplication factor, i.e., the ration of the number of neutrons in the second generation to the number in the first.

Writing $$\beta = (a-1)/\tau, \qquad (4)$$

eq. (3) becomes $$\frac{dE}{E} = \beta\, dt$$

and $$E = E_0 e^{\beta t} \qquad (5)$$

Also, since $P = \frac{2}{3}E$,

$$P = P_0 e^{\beta t} \qquad (6)$$

Substituting in eq(2) we have:

$$e^{\beta t} dt = \frac{\rho r}{5 P_0} dr. \qquad (7)$$

Note that if the mass is twice the critical value, the initial value r_0 of the radius is $2^{1/3} R_0$. Because of the lowered density, however, the critical radius at a later instant is

$$R = \frac{r^3}{r_0^3} R_0$$

The critical condition is reached when r has expanded to the value R, i.e.,

$$r = R = 2^{\frac{1}{2}} R_0.$$

The increase in r until the critical radius is reached is thus

$$\Delta r = R_0 (2^{\frac{1}{2}} - 2^{\frac{1}{3}}) = .15 R_0$$

$$= .12 r_0 .$$

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Thus in eq. (7) r, and hence also ρ, change only slightly during the critical part of the expansion, and a sufficient approximation is obtained by ascribing to them a constant average value of

$$\overline{\rho r} = .9 \rho_0 r_0 .$$

Eq. (7) may then be written,

$$e^{\beta t} dt = B dv, \quad \left[B = \frac{.9}{5} \frac{\rho_0 r_0}{P_0} = .18 \frac{\rho_0 r_0}{P_0} \right]$$

or integrating, $\frac{1}{\beta}(e^{\beta t} - 1) = B(v - v_0)$. (8)

Since $e^{\beta t} \gg 1$, and $v \gg v_0$, this becomes, to a good approximation,

$$v = \frac{1}{\beta B} e^{\beta t} \quad (9)$$

The critical radius is however reached when r has reached $r_0 + .12 r_0$, i.e. when

$$\int_0^t v \, dt = .12 r_0,$$

or by eq. (9)

$$\frac{1}{\beta B} \int_0^t e^{\beta t} dt = .12 r_0$$

$$\frac{1}{\beta^2 B}(e^{\beta t} - 1) = .12 r_0$$

or again since $e^{\beta t} \gg 1$,

$$e^{\beta t} = .12 r_0 \beta^2 B, \quad (10)$$

and $$t = \frac{1}{\beta} \ln (.12 r_0 \beta^2 B). \quad (11)$$

For the unshielded sphere of case a,

$$r_0 = 2^{1/3} R_0 = 8.8 \text{ cm}$$

$$\beta = (a-1)/\tau.$$

For the value of a, it can be shown that for n = 3, and $r_0 = 2^{1/3} R_0$, under the initial conditions a_0 = ca. 1.4. At the critical radius, a = 1. Since the efficiency is proportional to $(a-1)^2$, and since the value of t will be

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determined chiefly by the forces in the first part of the expansion, where (a - 1) is large, the larger values of (a - 1) should be heavily weighted in taking the average. We shall use $\overline{(a-1)} = .85(a_0 - 1) = .34$. $\tau = 10^8$ seconds. Thus $\beta = .34 \times 10^8 \text{ sec}^{-1}$

For evaluating E, we have at once $\rho_1 = 18.6$ g. cm^{-3}, $r_0 = 8.8$ cm. If we consider the zero instant to be when the pressure is $P_0 = 10^{12}$ dynes cm^{-2} (corresponding to a temperature of 10 or 20 volts, according to the degree of ionization), we obtain

$$B = 3 \times 10^{-11}$$

Thus by eq. (11),

$$t = 3.3 \times 10^{-7} \tag{12}$$

But corresponding to the initial pressure of 10^{12} dynes cm^{-2}, the energy per U235 atom is 20 ev. As in eq. (5), the energy at the time t is thus

$$E = 20 e^{\beta t} = 6 \times 10^5 \text{ ev.} \tag{13}$$

This is the energy developed by the time the reaction has reached its maximum rate of energy production. We may expect the energy developed after the maximum to be roughly the same as that before. Thus the total should be 2E. We note also that at the higher stages of temperature the pressure, being due to radiation, is ~~not~~ only half our estimated

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value. This leaves a longer time for the growth of energy. Pryce estimates this effect as introducing about an additional factor of 2, which appears to us (without however any good calculation) as reasonable. Thus finally for the bare sphere the efficiency will be about

$$\frac{4 \times 6 \times 10^5}{1.7 \times 10^8} = 1.4 \text{ per cent} \qquad (14)$$

It is not impossible that the higher value of 3.4 per cent calculated by Pryce may result from the shield which he assumes surrounding the sphere. The inertia of this shield should slow down the expansion, giving more time for energy development.

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APPENDIX B

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Report on
The Probable Destructive Action of Uranium Fission Bombs
G. B. Kistiakowsky.

The following is an attempt to evaluate the effects of the use of atomic fission for military purposes. The information given to the writer is that a bomb containing 20 kg of uranium may be expected to release some 20% of its nuclear fission energy within a time interval of one microsecond. Although these figures are admittedly uncertain, they will be taken as a basis for the following considerations in absence of more positive information. Taking the energy per atomic fission as 175 m.e.v., (Henderson, Phys.Rev.56, 703 1939) we obtain 3.4×10^9 kilocalories total available energy from the above-mentioned bomb. This is approximately the same energy as contained in 4000 tons of TNT[1]. The simplest assumption is to suppose that the destructive action of a bomb is proportional to the released energy and hence that the 20 kg uranium bomb will have the same destructive action as a bomb containing 4000 tons of TNT. This quantity of TNT is of course, very much greater than anything that has ever been used in a single bomb. However, some unintentional detonations of explosives magazines and some deliberate detonations of land mines in the last war approximate the conditions. Cf

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[1] On the basis of data available November 6, 1941. Total fission energy per kg U235 = 1.7×10^{10} kg cal/kg. Efficiency of bomb = 2 per cent. Explosion energy of TNT = 1.2×10^6 kg cal/ton. This gives energy released in fission explosion of 20 kg U235 bomb = energy released in explosion of 6000 tons TNT.
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the former, the case occasionally cited in the Halifax Explosion of a munitions ship during the last war. The damage there extended to a radius of much more than a mile but in the opinion of the writer this is not a fair case to consider because the conditions for large damage were unusually favorable in that the exploded ship was in the middle of the harbor and the city forms a sort of a natural amphitheatre with no barriers to reduce the effects of the blast. The land mines detonated in the last war, on the other hand, are very unfavorable cases because the detonations occurred at a great depth underground and their effect was mainly to produce large craters rather than to spread the damage over a large area. Consequently, for instance, the opinion found in many articles in Zeitschrift fur das allgemeine Schiess- and Sprengstoffwesen, on the effect of land mines of the last war is rather deprecatory and the radius of action from a charge of several hundred or even a thousand tons of explosives in a mine was found to be rather limited. In this war the British have gathered very extended information on the effect of German aerial bombs dropped over English cities. It is noteworthy that the destructive effects were found to vary from one bomb to another in a very striking manner, depending on the exact relation of the point of detonation to the

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location of nearby buildings, the type of construction of these buildings, the type of fuse used (instantaneous or delay), nature of the soil, etc.. It is possible, therefore, to draw only very rough estimates of the average effect of large German bombs. In that sense only, therefore, one can say that a destructive action from a one-ton bomb extends over a radius of about 100 meters, being naturally more intense near the origin and decreasing roughly linearly with the distance. Over this radius, however, the damage is quite serious in most instances, unless the structures are of reinforced concrete construction. The British have also established, on the basis of a large amount of experimental material, a dimensional law which says that if all distances are expressed in terms of charge diameters, the effects of all detonations are similar. Since the diameter of a 4000-ton NTN bomb is 15 times the diameter of a one-ton bomb, it may therefore be expected that the damage from a bomb of this size would extend to 1500 meters, varying of course very greatly from one bomb to another.

It is now necessary to consider whether there is any justification to the assumption made above that the section of the uranium bomb will be similar to that of a TNT bomb releasing the same amount of energy. Unfortunately there is no way of proving this contention theoretically and only some plausible arguments in its favor can be made.

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As mentioned above, a one-ton TNT bomb causes serious damage over an area of 100 meters' radius. Now the weight of air in a sphere of this radius is 5000 tons and we see that the weight of the explosive relative to the mass of air which is blown about within the effective volume is very insignificant. Hence it would seem to be reasonable to believe that the weight of the explosive itself is unessential for the effects produced and thus that nearly the same effect will be produced by a lighter but more powerful explosive. The British report that RDX bombs have about 10% greater radius of action than TNT bombs of the same weight, hence about 30% greater action volume. The energy content of RDX bombs is some 30% greater than that of TNT bombs which agrees well with the above figure for increased action. No quantitative data are available on the increased effectiveness in air of mixed explosives containing aluminum, but the British informed the writer that the effects of such bombs are greater than those of pure TNT bombs. This, qualitatively at least, is again in agreement with the increased energy content. Stronger experimental evidence has been obtained by the British to show that in underwater explosions the effectiveness is to a large extent determined by the energy content of the explosive. These conclusions, however, cannot be extended to cover the case of uranium which is so far beyond the range of available explosives, even with the aid of the now available mathematical theory of shock waves (for theory of shock waves see,

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for instance, reports of Division B, NDRC, by G. B. Kistiakowsky and E. B. Wilson, Jr., and also by John von Neumann). Only certain qualitative arguments can be here presented: the shock wave is an irreversible phenomenon and its passage through air (and through water, but to a very much lesser extent) is accompanied by an increase of entropy of the medium, that is, by an irreversible conversion of mechanical into heat energy. The fraction of energy thus dissipated cannot be calculated quantitatively because of the incompleteness of the theory, but qualitatively one knows that the greater the intensity of the wave, that is the greater the deviation from infinitesimal acoustic waves, the more, proportionately, is this dissipation. Therefore, in the immediate vicinity of the uranium bomb, where the shock wave will be thousands of times more intense than in the vicinity of a larger TNT bomb of the same total energy content, greater fraction of mechanical energy will be converted into heat and hence will be lost as potential source of damage. In water, because of its low compressibility, shock waves with a maximum pressure of as much as 2 tons/sq. inch behave as infinitesimal acoustic waves and it has been found that as much as 40% of the total explosive energy is transferred into the shock wave in water. In air, on the other hand, a very much smaller fraction of the total

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energy is transferred to the shock wave because of higher compressibility and shock waves with a maximum pressure of 2 tons per square inch are already very different from acoustical waves (i.e. much faster) and are accompanied by a considerable (not known wuantitatively) dissipation of energy. Because of the absence of a quantitative theory of shock waves even of such intensity as caused by ordinary explosives and because of additional difficulties of extrapolation into regions which correspond more closely to conditions in the interior of the stars than anything met with on Earth, nc calculations can be now made. The opinion of the writer is that uranium bombs detonated deep under water will have a destructive action which is very nearly the same as that of TNT of the same energy content. In regard to uranium bombs detonated in air or on the ground, the writer is not convinced of their equivalence with TNT bombs and rather believes that they destructive action will be proportionately less, perhaps by as much as a factor of ten.[2]

Some words now on a subject which is perhaps outside of the scope of this report but which is nonetheless of interest to the writer. This is the question of the economics of uranium bombs. If one takes, as the basis of comparison, the cost of TNT per pound, some fifteen cents, then evidently

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[2] See following page 6a.

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[2] Note added November 6, 1941.

The following calculation qualitatively supports this lower effectiveness of U235 for the same energy, but suggests a much greater reduction factor.

It we assume that it is the outward momentum of the explosion which produces the destructive air wave, we have

$$p_r = mv = 2mW, \qquad (1)$$

where m is the effective mass of the bomb, and W is the energy released. For equivalent explosion, therefore,

$$2\, m_f W_f = 2\, m_c W_c ,$$

where m_f and m_c are the effective masses of the exploding materials for the fission and chemical explosions respectively, and W_f and W_c are the corresponding energies. Thus

$$m_c = \frac{W_f}{W_c}\, m_f \qquad (2)$$

Under optimum conditions of surrounding shield we may roughly assume $m_c = 1.5\, m_{TNT}$, and $m_f = 10\, m_{235}$, $W_f/W_c = m_{235}\, J_{235}/m_{TNT}\, J_{TNT}$, where J is the energy released per unit mass. Eq. (2) then becomes

$$m_{TNT} = 2.6(J_{235}/J_{TNT})^{\frac{1}{2}}\, m_{235}. \qquad (3)$$

Using (footnote 1) $J_{235}/J_{TNT} = 3 \times 10^5$, we thus obtain

$$m_{TNT} = 1400\, m_{235}.$$

This would mean that 20 kg of U235 would be equivalent to about 30 tons of TNT, a reduction factor of 2000 as cqmpared with the estimate based on equivalent energies.

From the evidence presented by Kistiakowsky, it would appear that the reduction factor of 10 is much more probable. Yet in our present state of inexperience with such super-explosions more theoretical attention should be given to this point.

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a TNT bomb of 4000 tons costing $1,200,000 is incomparably cheaper than a uranium bomb, in terms, which, in the last analysis, represent man hours of work and hence the strain on the national economy. It seems, however, that this is not a fair basis of comparison. Rather, one should include in the cost estimates the auxiliary costs, such as those of aircraft, crews, flying fields, etc.. Although the writer is not in possession of exact figures on these matters, the following is probably not too far from the truth to be unworthy of consideration. The cost of a heavy bomber will be taken as $350,000 and the cost of training its crew as $150,000. 5% of all bombers will be assumed lost in each operational flight, which means that each flight costs $25,000. To this must be added the cost of maintaining ground crews, flying fields, service on the bombers, etc. which will probably double the figure, giving $50,000 per flight, in which 4 tons of explosives will be assumed to be dropped. Therefore the cost of dropping 4000 tons of TNT bombs, which were assumed to be the equivalent to one uranium bomb, is $50,000,000. This is then a sum which in all fairness should be compared with the cost of uranium bombs except that the actual figures must be treated as subject to revision in light of more exact information which is undoubtedly available to the proper authorities.

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There are further, tactical, considerations which the writer will not attempt to assess. They are the greater facility of getting to the objective one bomber with a uranium bomb as contrasted with 1,000 bombers carrying 4000 tons of TNT; but on the other hand there is the advantage of a greater area of moderate damage caused by, say, 4000 one-ton TNT bombs dropped at random as contrasted with the intense and concentrated damage by one uranium bomb.

In regard to the problem of starting the rapid fission reaction in the bomb, two methods appear possible at present, although others are decidedly worthy of further consideration. The two methods are:

1. The firing of two halves of the bomb towards each other, until, on close approach, the fission reaction sets in, initiated by an artificial source of neutrons or spontaneously. It seems entirely feasible to bring together the two pieces of uranium, weighing some ten (or even hundred) kg. each with a speed of several thousand feet per second. One alternative is to use a double gun with the uranium pieces acting as projectiles and facing each other, the other is to adopt the principle of the "fragment gun", developed by the British, for this purpose. The second alternative has the advantage that the weight of the auxiliary parts of the bomb will be greatly reduced, the length of the acceleration period also reduced and yet the terminal velocity maintained. Of course considerable development work must be done on both devices before they

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can be considered as practical.

2. The second method is to have a barrier between the two halves of the bomb, which is impenetrable to neutrons and which is shot out in the instant before fission is to occur. This is also entirely feasible, as one might use a mixture of metallic boron, for instance, and TNT, which may be made to give any degree of brisance (i.e. speed of explosion) depending on the composition, particle size, etc.. If this mixture is not too brisant, the damage to the uranium hemispheres between which the explosive is placed as a layer of proper thickness, will be minimized and yet the detonation will progress through the explosive layer at a speed of several thousand meters per second and the products of the detonation will be ejected at a speed of about 1000 meters per second. During this time interval the motion of the uranium hemispheres, because of their large mass, will be quite small and may be reduced still further by backing them up with larger masses of properly dimensioned inert metal. The details of the procedure must again be worked out by experimentation, but a priori the method appears to be feasible.

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APPENDIX C

Report on Feasibility of Separation Methods

R. S. Mulliken

Summary and Conclusions

There are several separation methods which show promise for large-scale production, using the hexafluoride. Three of these are in a more or less advanced stage of development. (1) We cannct adequately judge the promise of the English method for molecular diffusion of vapor at low pressures on the basis of information now available; in about two weeks we should have a first-hand report. For 1 kg/day production of metal, the estimated diffusion area is 70,000 sq. meters and plant cost $50,000,000. (2) The atmospheric-pressure vapor diffusion method looks feasible but may be slow in development. For 1 kg/day production the estimated diffusion area is 10,000 sq. meters, plant cost $27,000,000., and power consumption 72,000 kw. For 10 kg/day production, the estimated plant cost is $80,000,000. A study of this method from engineering viewpoints should be begun at once. (3) The vapor-centrifuging methods look feasible and their engineering and certain other aspects are farther advanced than for the vapor diffusion method. For 1 kg/day production, the present estimate is that 22,000 separately-drives 3-foot centrifuge units would be needed at a cost of $44,000,000. The centrifuge method also looks promising for relatively prompt, small-scale production of material for experimental work. The study of the centrifugal method on both experimental and engineering scales should be pushed. (4) Work

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now in progress on the possibility of separation by electrolysis and by other methods should be continued, and a study of certain recently proposed new methods should be undertaken: in particular, methods involving the use of positive rays. At the moment, the use of positive rays in the mass spectrograph furnishes the only means of obtaining large concentrations of the rare isotope, although only in extremely small quantities; the use of this method to obtain samples for experimental work should be pushed. (5) The feasibility of molecular evaporation at low pressures from a solvent, including engineering aspects, should be studied. If a suitable solvent can be found, this method appears to involve fewer new experimental and engineering problems than the diffusion methods. (6) Study of the possibility of separation by ordinary fractional distillation should be pushed in collaboration with chemical engineers. While at the moment the method looks relatively unpromising, it may, if feasible, offer the minimum of expense and of new problems to be solved.

The development of certain compounds which promise to be suitable as lubricants resistant to, and as solvents of, the fluoride should be strongly pushed. As lubricants, these compounds are important or possibly essential for the success of methods (1)-(3), or as solvents, essential for (5). Search for possible liquid uranium compounds of

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moderate volatility should be intensified, since if a suitable compound could be found, the relatively quick and inexpensive evaporation method could be used.

In general, to accelerate progress: (1) closer contact or unification should be effected between projects located at different institutions but closely related in their objectives; (2) increased support, including added personnel, should be brought to some of the work now going on, and provision should further be made for developing certain additional phases of the whole problem, particularly along engineering lines; (3) in view of the crucial importance of the time element, the principle of parallel development should be very extensively applied, (a) in the simultaneous study of all methods of separation which have any promise, at least until one or more methods have conclusively outdistanced the others, (b) in simultaneous study of successive stages of development of a given separation process (e.g. laboratory and engineering stages; and in each stage, simultaneous study of different phases when possible).

General Considerations

In general, any system of separation is based on the coordinated operation of a large number of individual separation units arranged in a number of stages. In the operation of each unit the ratio c_1/c_2 of the concentrations of the light and heavy isotopes is changed in the light fraction to

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a value $\alpha(c_1/c_2)$, α being the enrichment ration for a single unit. In our raw material, $c_1/c_2 = 1/139$; let us call this $(c_1/c_2)_i$. It is desired to secure a final product with a relatively large terminal value, say $(c_1/c_2)_t$, of c_1/c_2. At the other end of the apparatus, waste heavy fraction must be discharged in which c_1/c_2 has been decreased to a value $(c_1/c_2)_w$ perhaps half as large as $(c_1/c_2)_i$. Let $(c_1/c_2)_t = G\,(c_1/c_2)_w$. For $(c_1/c_2)_t = 100$ and $(c_1/c_2)_w = 1/278$, $G = 27{,}800$.

For a type of unit in which the separating process is molecular diffusion operating at theoretical maximum efficiency,

$$\alpha_{dif} = \sqrt{M_2/M_1}\ (\ln C)/(C-1), \qquad (1)$$

where $\sqrt{M_2/M_1} = 1.00426$ for our compound; the cut C is so defined that $1/C$ is that fraction of the material entering the unit which undergoes diffusion. A simple and convenient procedure is to divide the entering material into two equal fractions ($C = 2$); Eq. (1) then gives $\alpha_{dif} - 1 = 0.00295$. In practice, efficiency must be sacrificed more or less to speed, and α becomes

$$\alpha_{dif} - 1 = 0.00426\ E\ (\ln C)/(C-1), \qquad (2)$$

where E is the efficiency of the unit.

In order to operate the process with an over-all factor G, we must send the material through a number n of successive

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stages of enrichment such that $\alpha^{\underline{n}} = G$. Or,

$$n = \ln G/\ln\alpha \approx \ln G/(\alpha - 1). \qquad (3)$$

For the diffusion process just considered, assuming $\underline{\Xi} = 0.7$, which seems feasible for rapid operation, and $\underline{G} = 27{,}800$, we find $\underline{n} \approx 4950$.

In operation, the inflow into each stage divides into a light fraction which goes into the next stage forward and a heavy fraction which goes to the next stage backward (see Fig.1). In the rectifying stages $\underline{c}_1/\underline{c}_2 > (\underline{c}_1/\underline{c}_2)_1$), there is a net excess of forward flow (the transport $\underline{T}$), in the stripping stages ($\underline{c}_1/\underline{c}_2 < (\underline{c}_1/\underline{c}_2)_1$) a net excess of backward flow. The inflow into each stage has a maximum at the input or feed stage, and tapers off toward both outflow ends (see e.g.Fig.2, which corresponds approximately to the operating conditions of the previous paragraph). If there is one unit per stage, its flow capacity must be varied proportionally; or a proportional number of units of uniform capacity may be connected in paralle. The <u>total</u> required capacity $\underline{A}$ of the installation is proportional to the area under a curve such as that in Fig. 2. Since both the ordinate and the abscissa are proportional to $\underline{n}$ of Eq. (3), the area is proportional to $\underline{n}^2$. It is found that $\underline{A}$ is given by

$$\underline{A} \approx \underline{a}\underline{T}/\underline{F}(1-\alpha)^2(\underline{c}_1/\underline{c}_2)_{\underline{w}} \qquad (4)$$

where $\underline{T}$ is the output rate and $\underline{F}$ is the rate of flow per unit of operating capacity. For a diffusion system, $\underline{A}$ is the

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total diffusion area in square meters, and $a = 21$, if F is the rate of diffusion in kg/per square meter per day and T is in kg/day. If a centrifuging system is used, A may represent the number of units if F is the inflow per unit.

It is important to notice that the final stages of enrichment require relatively small flow capacity. In fact, just as much capacity is required to change c_1/c_2 from 1/139 to 1/25 as from 1/25 to 1.

An important feature of any installation is the hold-up H, equal to the total amount of light isotope present in the installation at any moment. The larger the holdup the longer it will take to build up the necessary steady state which must be produced before the installation will begin to deliver an output approximating the desired composition. H is evidently proportional to A, and to a depth factor (i.e. hold-up per unit of diffusion area or per centrifuge unit) depending on the design of the units and their pumping connections.

Vapor-Diffusion and Centrifugal Methods

In general, the following problems must be faced in connection with all the proposed separation methods which are being most actively pushed at present (vapor-diffusion and centrifugal methods): (1) design and testing of a rapid efficient single unit; (2) pumping system to transport material

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from one unit or stage to the next; (3) provision for automatic control of the flow and for cutting out and replacing defective units. Common to all of these is the question of obtaining resistant materials for walls, pipes, membranes, and so forth, and the question of a lubricant which is not attacked too rapidly. If the vapor is kept free from moisture (a suitable getter is available for removing the products produced by moisture), there are metals which seem not to be attacked, thus probably answering the first question. For a lubricant, an oil is known which is attacked only slowly and may prove usable; on the other hand, a program is under way toward the synthesis of lubricants which are not attached at all. In case this program should be unsuccessful, it may be necessary to turn to labyrinth glands; these are now being studied. The matter of a pumping system and that of automatic controls are engineering problems whose solution may be difficult and time-consuming.

There are at present the following four more or less promising types of single unit in various stages of development. (1) The low-pressure vapor diffusion unit (pressure 2 mm on the high-pressure side), with molecular diffusion through very thin membranes with fine holes; Eq. (2) applies. (2) The high-pressure vapor diffusion unit (upper pressure about 1 atmosphere), with diffusion through thin submicroscopically porous membranes; Eq. (2) may be used, although

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possibly the nature of the diffusion process is somewhat altered. (3) The flow-through centrifuge unit, in which vapor flows through a fairly large metallic cylinder rotating at perhaps 550 r.p.s. and is divided into a heavier fraction taken out near the periphery and a lighter one taken out nearer the center. (4) A unit in which fractional distillation or a related type of counter-current flow takes place in a centrifuge to give a multiplied separation.

The type (1) or English unit, of which preliminary sketches are available, includes a rotor which serves at the same time as pump, and according to theoretical calculations should give good efficiency at high speed. (E = 0.4 or perhaps 0.5, C = 2 in Eq.(2), A of Eq.(4) perhaps 70,000 square meters for 1 kg/day output). Preliminary practical tests are encouraging, but we do not yet have full details. This unit seems to have the following advantages: (1) a membrane which is highly permeable and probably sufficiently rugged seems to be available; (2) the preliminary testing and engineering design are probably fairly well advanced. It is not clear whether automatic control and easy repair can readily be arranged, nor how the lubrication problem is being solved. The pumping work and frictional losses should be large because of the low pressures used. The cost of a plant for 1 kg/day of metal output is estimated as $50,000,000 with a time-lag of only 5-12 days, after construction is complete, to build up the steady state.

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The type (2) unit might consist of flat diffusion screens on grills, or of say fifty diffusion tubes between two headers, with a very thin laminar feed box at the input header, into which the input vapor is forced in a thin sheet with turbulent flow at 1 atmosphere pressure by a centrifugal pump. Encouraging progress has been made (Columbia: experiment and theory) in the laboratory production of suitable membranes resistant to the gas and suitably porous; tests with other gases indicate that $\underline{E}$ = 70 per cent or better can be secured at F = 7000 kg per square meter per day, but direct tests for our vapor have not yet been finished. A 5-stage pilot plant is about to be set up to test the performance of these membranes in the separation of carbon isotopes in CO_2. The data now available indicate that a total diffusion area of 10,000 square meters should give an output of 1 kg/day. Determination of the best type of membrane, and its industrial fabrication, remain to be worked out. Assuming that this problem can be solved, it is estimated that a plant to produce 1 kg/day of metal can be built for $27,000,000. Of this estimate, more than half is for pumps. For operation, a power requirement of 72,000 kw is estimated, or $3,000,000 per year at 1/2 cent per kw hr. For a plant of 10 kg/day capacity, the estimated cost of construction is about $80,000,000 and the power consumption 700,000 kw. It should be noted that these cost estimates are preliminary; no detailed engineering

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lay-out has yet been made. The problems of automatic control and replacement of defective units remain to be worked out. The hold-up tends to be high, but it is hoped that it can be kept down to 4 tons of total UF_6 for 1 kg/day output. The time required to reach the steady operating state, barring accidents, is estimated as 100 days. Although prediction is uncertain, it seems very unlikely that such a plant could be set up ready to operate in less than two years.

The type (3) and (4) units appear promising for prompt results in that the mechanical problems of materials and operation appear to have been solved. Lubrication may present difficulties as already noted. An experimental type (3) unit in actual operation may be ready within two weeks. The general theory for this type of unit can be counted on, and has been tested for other gases and other related types of units; several tests just reported for our substance indicate that it separates in accordance with the theory. An enrichment ratio α of 1.04 in each unit, as compared with 1.003 in the diffusion units, appears practical (still larger values could be obtained if the peripheral speed could be increased), but theoretical calculations indicate that for large-scale operation this advantage must be partially sacrificed, α being cut to about 1.01, in order to obtain speed. According to these calculations, the best procedure would call for a large number of separate units, each a cylindrical tube of 6 or 8 inches

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diameter and 1 to 3 meters length. For a production of 1 kg/day of metal, it is estimated that 58,000 units of 3-foot length would be needed, and that 60 days would be required to reach the steady state needed for production.

The type (4) unit shows theoretical possibilities of using much greater enrichment in a single unit: α values as large as 4.0 may be feasible, although only for a low rate of flow per unit. This looks promising for the prompt production of relatively small amounts of material for experimental work, since a relatively small number of units arranged in relatively few stages would suffice. However, the calculations indicate that the use of large α values and slow flow would require units of excessive length, also a somewhat larger installation for a given rate of production than the use of α values near 1.2 with more rapid flow. Thus the latter appears to be preferable for large-scale production. Using an arrangement of the latter type, it is estimated that 22,000 3-foot units would separate 1 kg/day, and that 20 days or less would suffice to set up the operating steady state.

Engineering plans have already to a considerable extent been worked out for a system using either type (3) or (4) units. The cost of construction is estimated as about $2,000

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per unit, or about $44,000,000 for the type (4) system producing 1 kg/day. The cost per unit includes about $1,000 for building the unit, $250 for the electrical drive (a separate 7 H.P. motor for each unit), and the remainder for accessories. It may be possible to reduce the costs by increasing the length and altering the metal used in constructing the units. The problems of control and certain other items of equipment may also be simplified if the type (4) unit is successful. Two varieties of the type (4) unit have been proposed, one with liquid and recently one with vapor reflux; the latter appears to be the more promising for successful operation. A preliminary experimental unit using liquid reflux is already being tested, and one using vapor reflux should be ready within three months.

The diffusion and centrifugal methods both appear sufficiently promising that the experimental and engineering developments should be pushed as fast as possible. This would be a safeguard against unexpected difficulties with either method. Moreover, it has been suggested that one method, perhaps the diffusion method, might prove to be better adapted to the earlier or quantity stages of enrichment, and the centrifugal method to the later or quality stages.

Evaporation and Distillation Methods

If a liquid compound having moderate or small vapor pressure at room temperature were available, a very simple

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type of unit could be used in which the active process is irreversible evaporation at low pressure. The theory is similar to that for diffusion, and α is given by the same formula. Such units could easily be combined into a fractionating scheme requiring only heating and cooling and practically no mechanical power. The absence of moving parts and the probable ease of automatic control indicate that the method (which has been tested in the laboratory with mercury and works excellently), might be the simplest and most rapid to put into operation if a suitable liquid compound could be found. Although no satisfactory compound has yet been prepared, progress has been made, and efforts in this direction should be intensified.

If a suitable solvent can be found, our compound dissolved in this could be evaporated at low temperatures (perhaps 0° or -20°C) very much as if it were itself a liquid, although the complexities of the method would be greater. It is estimated that the evaporation area needed would be comparable to the diffusion area needed in the high-pressure diffusion methods. Pumping equipment would be needed, but the problem would be far easier than that of pumping gas as in the diffusion methods. It seems probable that a stable solvent of sufficiently low vapor pressure can be made, although considerable time might be required to produce this in adequate quantities. However, it would seem that efforts in this

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direction should be pushed, especially since the same or related compounds may be valuable as resistant lubricants. (This latter use is the basis of a research project just being organized on the preparation of such compounds.)

It is possible that the liquid metal itself might be subjected to separation by an evaporation process, although the high temperatures needed make it questionable that this would be feasible.

Instead of differential evaporation, differential condensation also offers possibilities.

Simplest and least expensive of all to put into operation would be fractional distillation, if it would work. It has been estimated from theoretical considerations that $\alpha - 1$ for distillation is only 5-7 per cent as large as for diffusion. Even with this handicap, the method probably would be successful if it were not for the relatively enormous hold-up, which it is estimated would entail a delay of years before the steady state necessary to begin production would be reached, even using a very efficient column packing. Nevertheless, in view of the remarkable achievements in the oil industry in cutting down hold-up in fractionating columns, the method seems worth examining as soon as possible in collaboration with chemical engineers. Experiments already made in our compound using a 30-foot, 100-plate column were negative, but the work is being continued with a 200-plate column and improved technique.

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Other Diffusion Methods

Thermal diffusion of the vapor of our compound has been tried with negative results in three different laboratories. In general, thermal diffusion in vapor is a rather effective method, but the theory is complicated and the results depend on molecular parameters of the particular compound. If different temperature conditions or a different volatile compound could be used, there might be a possibility of success.

Theremal diffusion of some compound in solution (liquid thermal diffusion) is another possibility. Some trials made recently with a solution using this method in an ingenious laboratory apparatus showed an astonishing rate and degree of separation of a dissolved salt from the water.

Diffusion of the vapor through a streaming gas, a method which offers considerable promise, is being tried. Unfortunately the obtaining of a high efficiency is dependent on diffusion through an inert gas of high molecular weight. Compounds of the same class as the hoped-for lubricants and solvents mentioned above may be of value here.

Electrolytic Methods

Experiments on certain salt solutions indicate it to be probable that isotopic ions differ in mobility. If this is confirmed, extremely great enrichment ratios may be secured by keeping the ions on a sort of electrolytic tread-mill for

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some days. Tests are now being made in suitable compounds. This method may, even if successful and valuable for obtaining small samples, prove to be too expensive (cost of electric power) for large-scale production; but calculations on this should be rechecked.

Partial separation in the process of electro-deposition or electro-solution is a remote possibility.

Other Methods

Methods of separation depending on differences in chemical equilibria (such as have proved successful for lighter lements) do not look promising.

Photochemical methods, although possible in principle, are unpromising.

A method using differential adsorption of uranyl ions from acid solution was proposed at the committee meeting on October 21. This deserves further examination. A method using dialysis was also proposed, and seems worthy of attention. Counter-current extraction of uranyl ions between water and ether has been tried with negative results.

The possibilities of the positive ray method, giving large separations but very small samples, are well known, but should be re-examined with respect to large-scale operation. The use of this method for obtaining small quantities

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of separated material, much needed for experimental purposes, should in any event be pushed. Two attractive positive-ray methods for completly separating the isotopes in considerable quantities in a single operation were proposed at the meeting of the committee. Although the difficulty of getting enough positive rays, and the electrical power cost, might be prohibitive for large-scale production, these methods deserve investigation.

The foregoing report is based on a series of interviews and consultations, during a period of about three weeks, with members of the uranium committee and others working on its projects, and with members of the present committee. It embodies information and ideas from all these sources. Although it cannot be expected that the report is entirely complete or accurate, the writer believes that it presents a roughly correct view of the situation.

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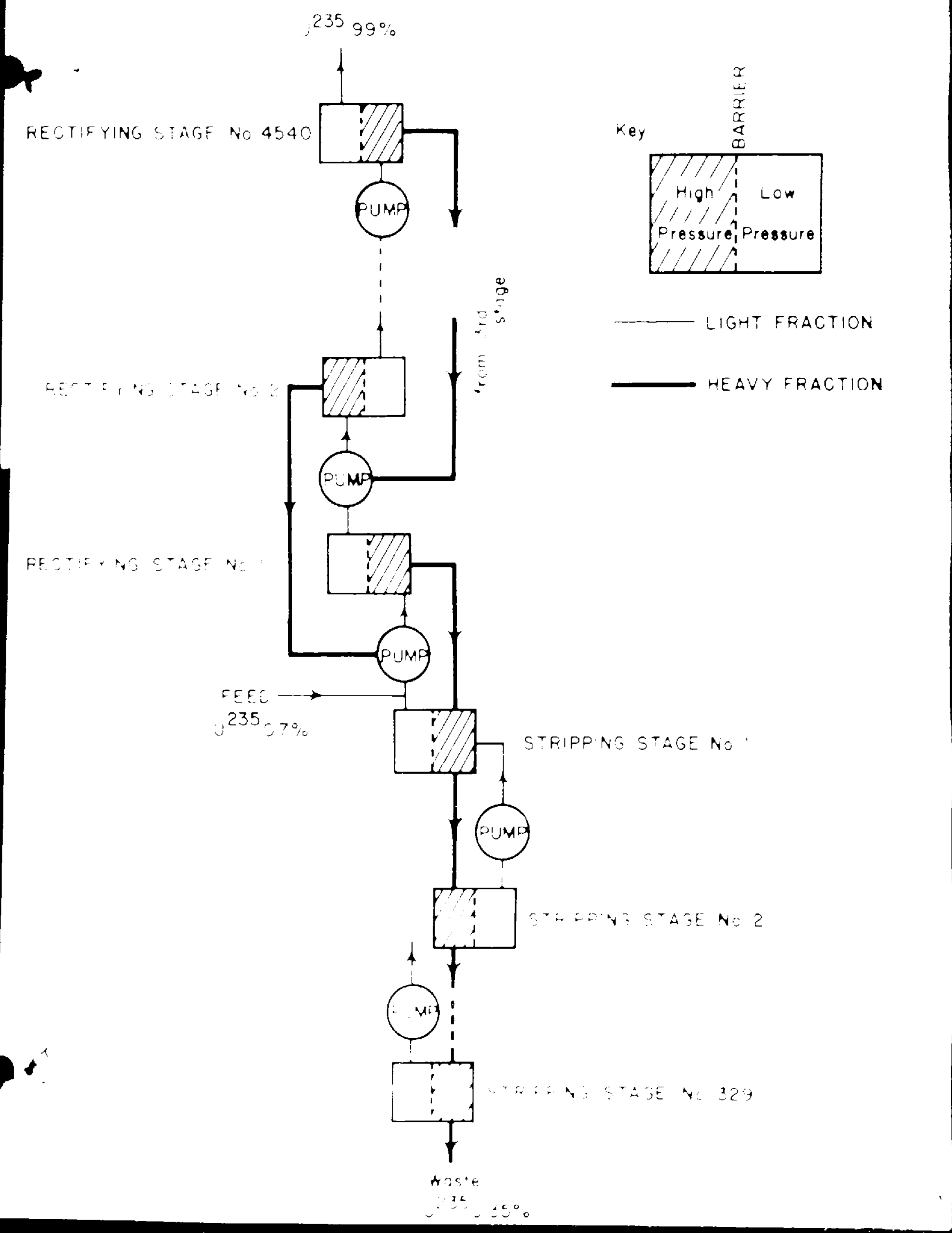
FIGURE I

U^{235} SEPARATION PLANT



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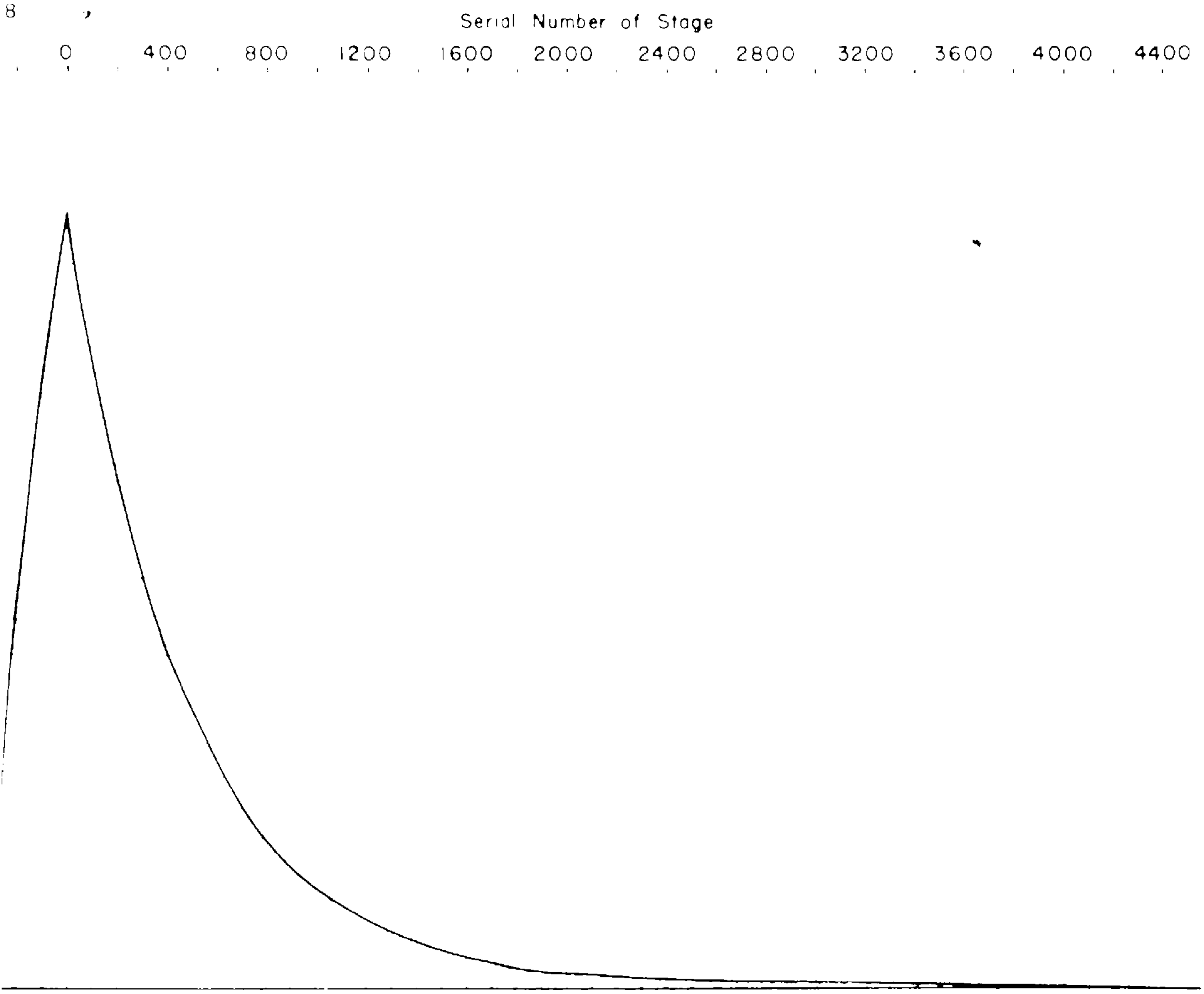
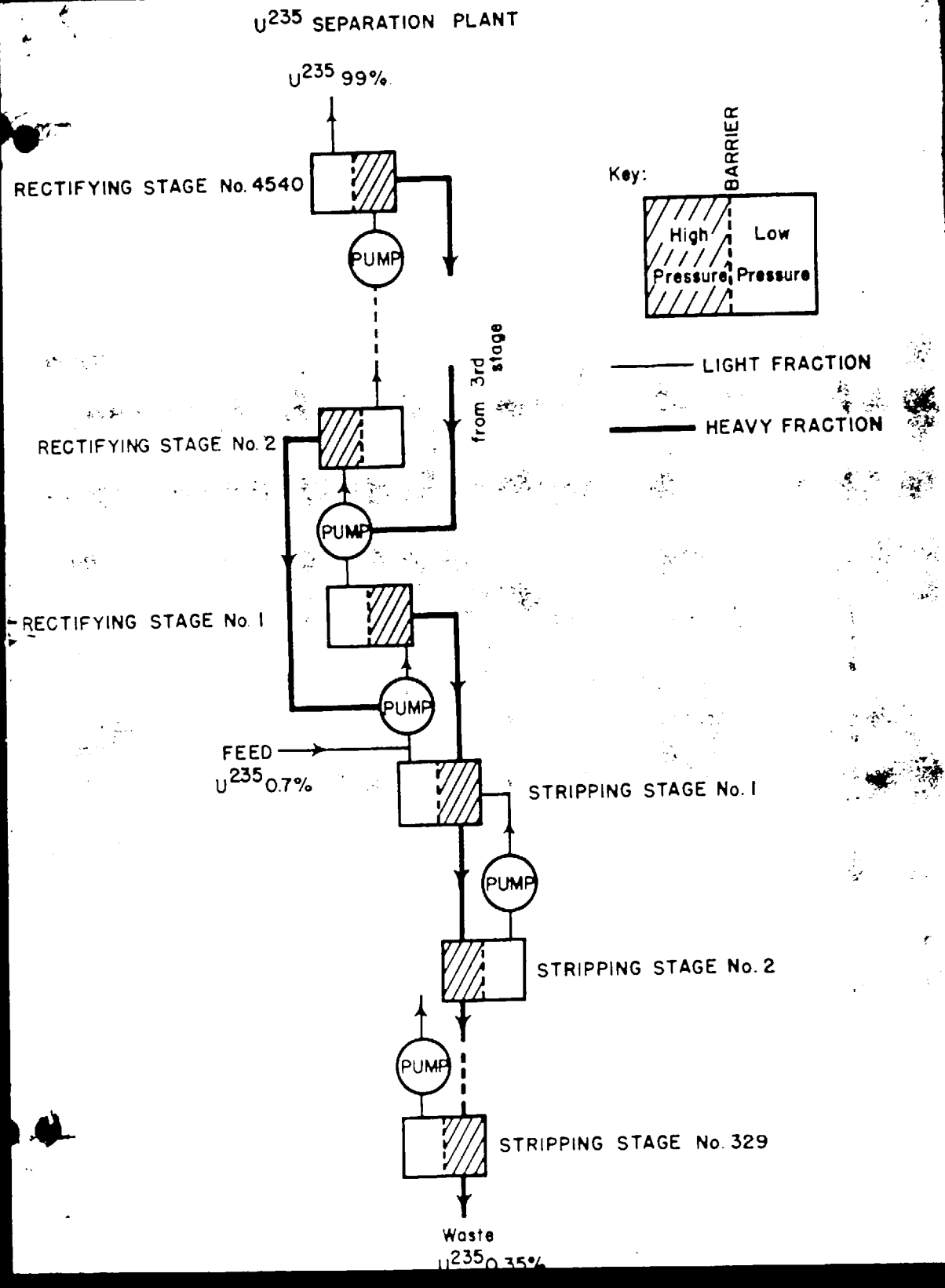
[redacted]



Scale Sketch of Apparatus

[redacted]


U235 SEPARATION PLANT
U235 99%
RECTIFYING STAGE No. 4540
PUMP
Key:
BARRIER
High Pressure
Low Pressure
LIGHT FRACTION
HEAVY FRACTION
from 3rd stage
RECTIFYING STAGE No. 2
PUMP
RECTIFYING STAGE No. 1
PUMP
FEED
U235 0.7%
STRIPPING STAGE No. 1
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