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Report by M.A.U.D. Committee
on the use of Uranium for a Bomb

PART I

1. General Statement

Work to investigate the possibilities of utilising the atomic energy of uranium for military purposes has been in progress since 1939, and a stage has now been reached when it seems desirable to report progress.

We should like to emphasize at the beginning of this report that we entered the project with more scepticism than belief, though we felt it was a matter which had to be investigated. As we proceeded we became more and more convinced that release of atomic energy on a large scale is possible and that conditions can be chosen which would make it a very powerful weapon of war. We have now reached the conclusion that it will be possible to make an effective uranium bomb which, containing some 25 lbs. of active material, would be equivalent as regards destructive effect to 1,000 tons of T.N.T. and would also release large quantities of radioactive substances, which would make places near to where the bomb exploded dangerous to human life for a long period. The bomb would be composed of an active constituent (referred to in what follows as U.235) present to the extent of about 1 part in 140 in ordinary Uranium. Owing to the very small difference in properties (other than explosive) between this substance and the rest of the Uranium, its extraction is a matter of great difficulty and a plant to produce 2¼ lbs (1 kilogram) per day (or 3 bombs per month) is estimated to cost approximately £5,000,000, of which sum a considerable proportion would be spent on engineering, requiring labour of the same highly skilled character as is needed for making turbines.

In spite of this very large expenditure we consider that the destructive effect both material and moral is so great that every effort should be made to produce bombs of this kind. As regards the time required, Imperial Chemical Industries(1) after consultation with Dr. Guy of Metropolitan Vickers, estimate that the material for the first bomb could be ready by the end of 1943. This of course assumes that no major difficulty of an entirely unforeseen character arises. Dr. Ferguson of Woolwich (2) estimates that the time required to work out the method of producing high velocities required for fusing (see para. 3) is 1 - 2 months. As this could be done concurrently with the production of the material no further delay is to be anticipated on this score. Even if the war should end before the bombs are ready the effort would not be wasted, except in the unlikely event of complete disarmament, since no nation would care to risk being caught without a weapon of such decisive possibilities.

We know that Germany has taken a great deal of trouble to secure supplies of the substance known as heavy water. In the earlier stages we thought that this substance might be of great importance for our work. It appears in fact that its usefulness in the release of atomic energy is limited to processes which are not likely to be of immediate war value (3), but the Germans may by now have realised this, and it may be mentioned that the lines on which we are now working are such as would be likely to suggest themselves to any capable physicist.

By far the largest supplies of Uranium are in Canada and the Belgian Congo, and since it has been actively looked for because of the radium which accompanies it, it is unlikely that any considerable quantities exist which are unknown except possibly in unexplored regions.

(1) Appendix I (2) Appendix II (3) Report of M.A.U.D. Committee on use of Uranium as a source of power.

2. Principle Involved.

This type of bomb is possible because of the enormous store of energy resident in atoms and because of the special properties of the active constituent of Uranium. The explosion is very different in its mechanism from the ordinary chemical explosion, for it can occur only if the quantity of U.235 is greater than a certain critical amount. Quantities of the material less than the critical amount are quite stable. Such quantities are therefore perfectly safe and this is a point which we wish to emphasize. On the other hand, if the amount of material exceeds the critical value it is unstable and a reaction will develop and multiply itself with enormous rapidity, resulting in an explosion of unprecedented violence. Thus all that is necessary to detonate the bomb is to bring together two pieces of the active material each less than the critical size but which when in contact form a mass exceeding it.

3. Method of Fusing

In order to achieve the greatest efficiency in an explosion of this type, it is necessary to bring the 2 halves together at high velocity and it is proposed to do this by firing them together with charges of ordinary explosive in a form of double gun.

The weight of this gun will of course greatly exceed the weight of the bomb itself, but should not be more than 1 ton, and it would certainly be within the carrying capacity of a modern bomber. It is suggested that the bomb (contained in the gun) should be dropped by parachute and that the gun should be fired by means of a percussion device when it hits the ground. The time of drop can be made long enough to allow the aeroplane to escape from the danger zone, and as this is very large, great accuracy of aim is not required.

4. Probable Effect

The best estimate of the kind of damage likely to be produced by the explosion of 1,800 tons of TNT is afforded by the great explosion at Halifax N.S. in 1917. The following account is from the "History of Explosives"*. "The ship contained 450,000 lb. of TNT, 122,960 lb. of guncotton, and 4,661,794 lb. of picric acid wet and dry, making a total of 5,234,754 lb. The zone of the explosion extended for about $\frac{3}{4}$ mile in every direction and in this zone the destruction was almost complete. Severe structural damage extended generally for a radius of $1\frac{1}{8}$ to $1\frac{1}{4}$ miles, and in one direction up to $1\frac{3}{4}$ miles from the origin. Missiles were projected to 3 - 4 miles, window glass broken up to 10 miles generally, and in one instance up to 61 miles."

In considering this description it is to be remembered that part of the explosives cargo was situated below water level and part above.

5. Preparation of Material and Cost

We have considered in great detail the possible methods of extracting the U.235 from ordinary Uranium and have made a number of experiments. The scheme which we recommend is described in Part II of this report and in greater detail in Appendix IV. It involves essentially the gaseous diffusion of a compound of Uranium through gauzes of very fine mesh.

In the estimates of size and cost which accompany this report, we have only assumed types of gauze which are at present in existence. It is probable that a comparatively small amount of development would enable gauzes of smaller mesh to be made and this would allow the construction of a somewhat smaller and consequently cheaper separation plant for the same output.

* Published under the direction of the Institute of Makers of Explosives by the Press of the Charles L. Story Co., Wilmington, Del., U.S.A.

Although the cost per lb. of this explosive is so great it compares very favourably (4) with ordinary explosives when reckoned in terms of energy released and damage done. It is, in fact, considerably cheaper, but the points which we regard as of overwhelming importance are the concentrated destruction which it would produce, the large moral effect, and the saving in air effort the use of this substance would allow, as compared with bombing with ordinary explosives.

6. Discussion

One outstanding difficulty of the scheme is that the main principle cannot be tested on a small scale. Even to produce a bomb of the minimum critical size would involve a great expenditure of time and money. We are however convinced that the principle is correct, and whilst there is still some uncertainty as to the critical size it is most unlikely that the best estimate we can make is so far in error as to invalidate the general conclusions. We feel that the present evidence is sufficient to justify the scheme being strongly pressed.

As regards the manufacture of the U.235 we have gone nearly as far as we can on a laboratory scale. The principle of the method is certain, and its application does not appear unduly difficult as a piece of chemical engineering. The need to work on a larger scale is now very apparent and we are beginning to have difficulty in finding the necessary scientific personnel. Further, if the weapon is to be available in say two years from now, it is necessary to start plans for the erection of a factory, though no really large expenditure will be needed till the 20 stage model (5) has been tested. It is also important to begin training men who can ultimately act as supervisors of the manufacture. There are a number of auxiliary pieces of apparatus to be developed, such as those for measuring the concentration of the U.235. In addition, work on a fairly large scale is needed to develop the chemical side for the production in bulk of uranium hexafluoride, the gaseous compound we propose to use.

It will be seen from the foregoing that a stage in the work has now been reached at which it is important that a decision should be made as to whether the work is to be continued on the increasing scale which would be necessary if we are to hope for it as an effective weapon for this war. Any considerable delay now would retard by an equivalent amount the date by which the weapon could come into effect.

7. Action in U.S.

We are informed that while the Americans are working on the uranium problem the bulk of their effort has been directed to the production of energy, as discussed in our report on Uranium as a source of power, rather than to the production of a bomb. We are in fact co-operating with the United States to the extent of exchanging information, and they have undertaken one or two pieces of laboratory work for us. We feel that it is important and desirable that development work should proceed on both sides of the Atlantic irrespective of where it may be finally decided to locate the plant for separating the U.235, and for this purpose it seems desirable that certain members of the committee should visit the United States. We are informed that such a visit would be welcomed by members of the United States committees which are dealing with this matter.

8. Conclusions and Recommendations

(i) The committee considers that the scheme for a Uranium bomb is practicable and likely to lead to decisive results in the war.

(ii) It recommends that this work be continued on the highest priority and on the increasing scale necessary to obtain the weapon in the shortest possible time, and

(iii) That the present collaboration with America should be continued and extended especially in the region of experimental work.

(4) Appendix I. (5) S 15. Part II

Report by M.A.U.D. Committee
on the Uranium Bomb

PART II

Technical Evidence supporting the Statements of Part I

1. Introduction

The first evidence of the great stores of energy latent in atomic nuclei was provided by the phenomena of radioactivity, and it has been confirmed by many observations of artificial transformations. Among these artificial disintegration processes the disintegration of certain heavy nuclei, in particular uranium, by neutrons shows a special feature, known as nuclear fission; the uranium nucleus splits up into two roughly equal halves. This fission process is exceptional in two ways. First, in the enormous amount of energy released, 180 million electron volts per fission, which is equivalent to over 10 million times the energy released by the explosion of an equal weight of dynamite, the second, in the possibility that the process may be made self perpetuating and self increasing, so that what starts as an action affecting only one or two atoms may in a short time affect a large proportion of the atoms in a block of material.

This possibility is due to the fact that the fission itself produces neutrons in addition to the two main fragments into which the atom splits; these neutrons in turn can produce fission in other uranium atoms. The number of neutrons produced per fission has been measured by various workers and is about 3. Thus, ideally, if no neutrons are wasted, a rapidly divergent chain reaction is possible, which owing to the great velocity of the neutrons would soon involve a considerable fraction of the uranium atoms present in the mass. Clearly this might give rise to an extremely powerful source of energy, and if the speed of multiplication was large enough, to a very violent explosion.

In order to produce a divergent reaction it is necessary and sufficient that, of the neutrons produced by each fission, rather over one, on an average, should be absorbed by a uranium atom in such a way as to cause a fission. Neutrons may be lost in two ways. They may escape from the mass into the outer air or they may be absorbed either by the uranium itself in such a way as not to lead to fission or by other atoms present in the material. As regards the first, the importance of this effect can, in principle, be reduced indefinitely by increasing the size, since the production, which is a volume effect, will increase more rapidly with size than the loss by escape, which is a surface effect. It follows that if the divergent chain is possible it will require at least a minimum mass of material which we shall call the critical size, but that the possibility of the chain is decided by the second type of loss.

We have therefore two questions to answer:-

(1) is a divergent chain process possible?

(2) if the divergent chain is possible, what is the critical amount of uranium required?

We shall assume that accidental impurities can be reduced to such a degree that the loss of neutrons by absorption due to this cause can be neglected. We have then only the properties of uranium to consider.

2. Relevant Properties of Uranium

Ordinary uranium is a mixture of three isotopes of masses 238, 235 and 234 in the proportions 1: 1/140 : 1/17,000. The isotope 234 is so rare that we need consider, for the possibility of a chain reaction, the properties of 238 and 235 only.

In uranium 238 alone, a nuclear chain reaction cannot develop for the following reasons:-

(a) Neutrons of less than a certain threshold energy (about 1 MeV according to measurements in Washington and Liverpool) do not cause fission of U.238.

(b) Even neutrons of more than the threshold energy cause fission in about one out of six to eight collisions only; in most collisions the neutrons are scattered "inelastically", their energy after collision being then less than the threshold value. The "elastically" scattered neutrons are deviated only through small angles by the collisions and to a first approximation may be treated as unscattered.

In U.235, however, conditions are favourable to a chain reaction since

(a) neutrons of all energies, however low, can cause fission of U.235;

(b) about one out of two or three collisions leads to fission in this case; most of the others are inelastic, as with U.238, but the energy loss increases their ability to cause fission in U.235;

(c) the probability of neutrons being captured by a U.235 nucleus without causing fission is very small.
Capture cross-sections for fast neutrons have been measured for some elements, including ordinary Uranium, and the values are all of the order of 10^{-26} cm^2. This is negligible in comparison with the fission cross section of U.235.

3. Possibility of a Chain Reaction

It appears, therefore, that the possibility of developing a divergent chain reaction depends on the properties of U.235. It is as yet undecided whether the normal percentage of U.235 in ordinary uranium is sufficient for this purpose, but on the whole the evidence is against this possibility. Even, however, if a chain reaction in ordinary uranium were possible, the critical amount of uranium required to realise it would be so enormous, of the order of 100 tons, as to prevent the development of the process into a military weapon. In addition, the proper fuzing of such a large mass (see §6) would be quite impossible.

It may be mentioned that conditions under which ordinary uranium can support a divergent chain reaction can be realised by adding suitable light elements in order to reduce the energy of the neutrons and thus increase their ability to cause fission. Systems of this kind, which may prove to be of great importance as sources of power, are discussed in a separate report. They are, however, not suitable as a basis for an explosive bomb, for the reason that a reaction propagated by slow neutrons does not develop rapidly enough (see §4).

The only possible way to produce an efficient explosion is to remove at least part of the 'inert' isotope 238 from ordinary uranium, thus increasing the proportion of 235. As the concentration of U.235 is increased, the critical mass falls rapidly. An investigation of the amount of material required and of the expenditure involved in obtaining a certain concentration of U.235 shows that by far the best procedure is to produce nearly pure U.235; this is so essentially because the later stages of concentration require an expenditure small compared with that for the initial stages.

If pure or nearly pure U.235 is available in sufficient bulk any neutron produced in it will cause a fission, since neutrons of any energy are effective, and since the only competing process, capture without causing fission, is unimportant. As each fission produces on the average three neutrons, the fission process will multiply itself exponentially with time and an explosion will occur.

4. Efficiency of the Reaction

If an appreciable fraction of the atoms in a mass of uranium undergo fission within a very short time the amount of energy liberated will be so great that the mass will attain a temperature of several million degrees and a pressure of many millions of atmospheres. It will then violently expand with very great rapidity. As the density of the mass decreases the neutrons can escape more easily from it, and the chain reaction will come to an end. In order to liberate an appreciable fraction of the energy available it is therefore necessary that the reaction should develop so rapidly that a considerable part of the material can react before the system has time to fly apart. This condition cannot be fulfilled if one relies upon the slowed-down neutrons to produce fissions as in the arrangement described in our former report. One must use the fast neutrons.

The neutrons produced by fission have an average energy of about 2 MeV, corresponding to a velocity of about [illegible] cm/sec. The main part of the reaction - the final avalanche of neutrons - will be completed in a time of the order of 10^{-8} sec. In this interval the mass will have expanded so much that the reaction breaks off owing to escape of neutrons. From these considerations one can calculate the speed of expansion and hence the kinetic energy given to the mass. It appears that the efficiency of the reaction increases with the velocity of the neutrons, the rapidity with which they multiply, and the mass of material. Calculations of the efficiency have been made by Professor Peierls and in more detail by Dr. F. Laurysen. The results show that efficiencies of from 1 to 10 per cent may be obtained, depending upon the ratio of the mass to that of the smallest amount of uranium in which a divergent chain reaction is possible and on certain other factors. It should be remembered that a uranium bomb with an efficiency of 1 per cent would release as much energy as 20,000 times the weight of T.N.T.

5. Critical Size

As we have pointed out in [illegible], a nuclear chain reaction can develop only if the amount of material exceeds a certain critical size, in sharp distinction to ordinary chemical explosions. This is due to the fact that the uranium nuclei have collision cross-sections for neutrons of the order of 10^{-24} cm^2 only. In consequence of which neutrons in solid uranium travel several centimetres, on the average, before hitting a uranium nucleus. If, for example, the dimensions of the uranium mass are smaller than 1 cm, most of the neutrons escape without causing fission. In a large mass, however, the number of escaping neutrons is more than compensated by those produced by fission [illegible] and one has a mass which can initiate the divergent chain reaction.

The critical size of a spherical mass of U.235 can be calculated from formulae derived by Professor Peierls. In the following lets are known:

(a) the number of neutrons produced in [illegible] fission. Evidence from various sources indicates that this number is about 3, and certainly greater than 2.5;

(b) The density of the material. For a bomb of small mass, the material must be as dense as possible. It is therefore necessary to use metallic U.235 in a compact form. The density of ordinary metallic uranium is 19.6.

(c) The collision cross-section. This cannot yet be measured for U.235 but it is legitimate to assume that it has the same value as in ordinary uranium, since collision cross-sections for fast neutrons vary little from one element to the next. The total cross-section, half of which is due to diffraction, has been measured for ordinary uranium, using fast neutrons. The results indicate that for neutrons of 1 Million electron-Volts it lies between 7 and 10 x 10^{-24} cm^2. The collision cross-section is therefore between 3.5 and 5 x 10^{-24} cm^2, and in the case of U.235 this will include the fission cross-section. The diffraction effect (elastic scattering) is confined mainly to small angles and has small importance for the calculation of critical size.

(d) The fission cross-section. This is the most important quantity which concerns the critical size and we must discuss the information available in some detail.

So far only very small quantities of separated U.235 and U.238 have been prepared. Experiments have shown that 235 undergoes fission with slow neutrons and that 238 does not, but the amounts were too small for measurement of fission cross-sections, especially at high energies. At the request of the Committee the American N.D.R.C. have asked Dr. Nier to prepare a small quantity of separated 235, sufficient to enable these measurements to be made, and we hope to receive this material shortly, together with the results of American workers.

In the meantime, nearly all the evidence required can be obtained from measurements made, on ordinary uranium, of the variation of fission cross-section with the energy of the bombarding neutrons.

Experiments both in Washington and Liverpool show that the fission cross-section increases very rapidly when the neutron energy exceeds 1 MeV and approaches a constant value for energies above 2 MeV. This effect is in accord with the predictions of the Bohr and Wheeler theory, that with increasing neutron energy fission should set in at a definite threshold energy and quickly reach a constant probability.

Both from the magnitude of the above effect and the fact that 238 does not give fission with slow neutrons, it is clear that the jump at 1 MeV represents the threshold of 238. The fission which takes place with neutrons of energy less than 1 MeV must therefore be ascribed to 235.

On this assumption the Liverpool measurements give values for the fission cross-section of U.235 varying from 2.1 x 10^{-24} cm^2 for neutrons of about 0.35 MeV to 1.5 x 10^{-24} cm^2 for neutrons of about 0.8 MeV.

Another measurement of this quantity has been obtained by Dr. Frisch using a mixed beam of neutrons, comprising energies from 0.2 MeV to nearly 1 MeV. The value obtained was 2.3 x 10^{-24} cm^2.

It should be pointed out that these values of the fission cross-section refer to neutron energies rather less than the average energy of the fission neutrons. On the other hand, one inelastic collision will reduce the neutron energy to about 0.2 MeV so that we shall not be far wrong in adopting the mean of the values given above, say 2.0 x 10^{-24} cm^2, with 1.5 x 10^{-24} cm^2 as a lower limit.

We shall take first the values which we believe to be most likely: number of fission neutrons = 3; collision cross-section 4.0 x 10^{-24} cm^2, to which we add 1 x 10^{-24} cm^2 to allow for elastic scattering; and 2.0 x 10^{-24} cm^2 for the fission cross-section. We find that the critical mass of the sphere is just over 9 Kg.

x Bohr and Wheeler, Phys. Rev. 56 p.426 1939.

If we now take the most pessimistic view, number of fission neutrons = 2.5; collision cross-section = 3.5×10^{-24} cm^2 with no allowance for elastic scattering; fission cross-section = 1.5×10^{-24} cm^2, we obtain 43 Kg for the critical mass. This is however definitely an overestimate as the elastic scattering has been completely neglected, and the fission cross-section selected, though a possible figure for the original neutrons, is certainly too small for neutrons which have made even one inelastic collision.

6. Best size of Bomb

We will now consider the best size for the bomb. As the efficiency of energy release increases with the excess of the mass over the critical, it is desirable from the point of view of explosive effect to use a large mass. On the other hand, cost of manufacture and difficulties of fuzing increase with the size of the bomb. The critical size calculated in §5 is for a sphere in free space, but it will pay us to surround the uranium by a tamping of steel or other massive material. This has two advantages. In the first place the mass resists the expansion of the bomb during the explosion and so improves the efficiency and in the second, the surrounding material scatters back some neutrons which would otherwise escape and so reduces the critical mass. In order to get a good efficiency it is best to make the mass about twice the critical as modified by the presence of the tamping. The attached table gives values for this modified critical size, as well as for the uranium tamper, for various assumptions as to the number of neutrons per fission and the cross-sections. It will be noticed that the tamping has more relative effect when the critical mass is large.

Critical Mass in Kilos

Assumptions		Cross-section assumed for fission		
		1.0×10^{-24}	2.0×10^{-24}	2.5×10^{-24}
2 Neutrons per fission:				
Cross-section for collision 4×10^{-24}; Allowance for diffraction 1×10^{-24}	Unreflected	17.4	3.6	2.3
	Fully tamped	5.56	1.0	1.87
2.5 Neutrons per fission:				
Cross section for collision 3.5×10^{-24}; diffraction ignored.	Untamped	12.7	2.8	1.63
	Fully tamped	4.2	0.9	0.7

* A shell of material of a thickness two or three times the radius of the bearing sphere would give a result approximating to the fully tamped condition.

Taking all considerations into account, we assume as a mass of 10 Kg for the bomb as a reasonable estimate, and we shall adopt this figure provisionally in the rest of this report. This is a sphere of about 10 cm diameter. If the truth is nearer the pessimistic estimate, fewer bombs would be made by a given plant in a given time but the destructive effect of each would be correspondingly larger.

7. Methods of fuzing

The problem of fuzing is not so much how to cause the explosion at the required instant, but how to prevent it from occurring prematurely, for trigger neutrons are always present. It is therefore necessary to manufacture the bomb in two or more parts, each of less than critical size, which are kept at a safe distance and which are only brought together by an explosive mechanism when explosion is wanted.

The assembly of the parts should be done as rapidly as possible for the following reasons. As the parts approach one another, critical conditions for a chain reaction will be reached at a certain point and any trigger neutron coming after that can cause an explosion. The violence of the explosion depends however (see §4) on the rate at which the neutrons multiply and will be diminished if it occurs before the parts of the bomb are completely assembled. A premature explosion though less efficient is still of very great violence.

The probability of such a 'premature' explosion depends on the frequency of trigger neutrons and on the time taken between reaching the critical distance and complete assembly of the parts.

There are a few neutrons always present due to the cosmic rays, but the most important source of trigger neutrons is the spontaneous fission of the uranium. This occurs to a measurable extent in ordinary uranium, and is probably mostly due to the isotope U.235 though the very rare U.234 may contribute appreciably. From measurements of Dr. Frisch in Liverpool it appears that 1 Kg of U.235 would give about 800 fissions per sec., provided the other isotopes do not contribute to the observed effect. This assumption gives the worst conditions for the problem of fuzing.

In addition there are a few 'delayed' neutrons arising from products of the fission process, which represent an additional source of trigger neutrons. The effect of 'delayed' neutrons can be kept small if the separate parts of the bomb are well below the critical size.

Assuming a mass of 10 Kg for the bomb, it would be possible to reduce the chance of a premature explosion to about 10% by bringing the two halves together with a relative speed of about 6000 ft./sec. We are informed by Dr. Ferguson* of Research Dept. Woolwich, that this can be done.

In use the whole bomb and guns would be dropped by parachute from an aeroplane and the guns fired by a percussion fuse on striking the ground. The time of fall would be long enough to enable the aeroplane to escape from the danger area, and owing to the large radius of damage of the bomb the resulting inaccuracy in aiming would be unimportant. The weight of the whole would be well within the capacity of a modern bomber.

Though the design of such a gun would involve considerable development work, this could proceed simultaneously with the construction of the factory and should not cause any extra delay.

If for any reason it were necessary to use a bomb much larger than the size assumed, difficulty might arise, as the larger bomb would have more spontaneous fissions in a given time.

The chance of a premature burst would thus increase, especially as the distance in which a partial explosion is possible is proportional to the diameter of the bomb, unless a corresponding increase in velocity is possible. This might be difficult as this larger mass would be hard to handle, and in any case it is difficult to get relative velocities much exceeding 6,000 ft./sec. On the other hand, one should remember that even the premature explosion will on the average release a considerable fraction of the possible energy.

8. Estimate of damage

The 10 kilogramme bomb we are supposing could readily be given an efficiency of 2% and the resulting release of energy will be equivalent to that of 3,600 tons T.N.T.

In considering such a proposal it is first necessary to be sure that the release of very large quantities of energy from a small mass will in fact do the damage that might be expected from experience with ordinary explosives. In the absence of such a bomb this can only be dealt with by calculation.

* Appendix II

Prof. G.I.Taylor has examined this point for us and reports "the wave at big distances is quite comparable in pressure and in duration with that produced by the amount of T.N.T. which releases the same energy as your U bomb". The exact ratio depends on detailed assumptions but it is not far from $\frac{1}{2}$ i.e. twice the energy release is needed from the U bomb to give the effect of T.N.T. Thus the damage done by a 10 Kg bomb will be equal to that of 1800 tons of T.N.T. Prof. Taylor * has calculated the pressures at various distances due to the U bomb but as they last for much longer than those for experimental quantities of T.N.T., and so will probably do more damage, it is probably best to use as a standard the known effect of large accidental explosions such as that at Halifax in 1917. (Part I of this report).

Besides the effects of the explosion, there will be very large amounts of radioactive material produced which will be scattered over the area affected by the explosion. It is in fact known that the products of the fissions are β active, passing through a number of transformations before becoming inert. It is very difficult to estimate the extent of their effect especially as the most important substances would be those of long life, which are the hardest to study under laboratory conditions. It does however seem certain that the area devastated by the explosion would be dangerous to life for a considerable time. The physiological effects of these radiations are delayed and cumulative so that great care would have to be taken in working anywhere near. If this were realised, the danger to life from this cause would probably be small compared with that due to the actual explosion.

9. Problems of Development

The main problem is the production of relatively very large quantities of separated isotopes. Secondary ones are the arrangements for producing the explosion when and where required.

10. Separation of Isotopes

Small quantities of pure isotopes have been produced by positive rays. It is by this method that the few micro-grammes for the measurement of fission cross section are being made by Nier. The production of even a few grammes by this method is however out of the question. The Committee have considered carefully a number of possible methods of producing quantities of nearly pure U_{235}. Among these are thermal diffusion, centrifuging and the diffusion of gases through small holes. We have come to the conclusion that the latter is by far the most promising for large scale production. It has the advantage of being based on physical principles which have long been fully understood and are easily amenable to calculation. As compared with centrifuging, of which this is also true, it scores because the machinery does not require the extreme precision of the high speed centrifuge which is so far only a laboratory instrument. Thermal diffusion, which at one time seemed the most promising, has had to be abandoned because no uranium compound is known with which it will work. We understand that the same conclusion has been reached in U.S. Another disadvantage is that the equilibrium time for this kind of apparatus is very large.

11. Simon apparatus

The method of separation by diffusing a gaseous compound through holes is one of the methods tried by Aston in the early days of isotopes, and has more recently been used successfully by Hertz and others. If a porous material such as pipeclay is used to provide the holes the method is a slow one, but Prof. Peierls has pointed out that if thin foil pierced with holes is used for the diaphragm the process is quickened and gives a reasonable yield. Dr. Simon has devised an apparatus to make use of this principle.

* Appendix V

12. Material

In order to use this method the uranium must be in gaseous form. The best and indeed almost the only possible, compound for the purpose is uranium hexafluoride, a white solid which has an appreciable vapour pressure at room temperature and sublimes at 60°C. The properties and methods of preparing this substance have been studied by Prof. Haworth and his collaborators in conjunction with Imperial Chemical Industries, who have made 3 kilos for us, and have also considered the methods of production on a large scale. They consider that the process is a feasible one, and though some large-scale, and therefore expensive, development work would have to be done, this could be done in the time required to construct a Simon plant of the size considered below.

13. Character of plant

Each process of diffusion results in a slight increase in the concentration of the lighter isotopes in the part that has passed through, and a corresponding decrease in the part left behind. This increase is only about 2 parts in a thousand, the exact value depending on the conditions of mixing. To double the concentration (i.e. make it 2/140), about 350 stages are required, and to reach 99% about 4500 stages are needed. As in all concentration processes, the reject from each stage is used again in the stage before, and the product in the stage after. It is a common feature of such plants that the early stages have to be very large compared with the final stage which only has to deliver the material actually used. For the concentrations with which we are concerned the total area of diffusing membrane in the whole plant bears to that in the last stage the ratio $1+\varepsilon/\varepsilon^2$ where $1+\varepsilon$ is the factor by which the concentration* is increased in a single stage. It will also be necessary to provide a recovery plant to use the reject from the first stage as otherwise the consumption of material will be prohibitive. The best compromise between size of recovery plant and economy of material is probably to make the bulk of the recovery plant about 10% that of the main plant. With this arrangement about 400 kilos of raw material are required for each kilo of finished product. Since the isotope 235 is initially present in the proportion of 1:140 this means that about one-third the 235 in the initial material would be produced in the concentrated product, the remainder being rejected.

14. Mechanical Arrangement

Three things are essential in the construction of the plant apart, of course, from a suitable diffusion membrane:

(1) the creation of pressure differences between each two consecutive stages.

(2) Provision for thorough mixing of the gas in the immediate neighbourhood of the diffusion membrane.

(3) Simple and short tubing connections.

(A) Dr. Simon originally proposed to use a centrifugal blower for the creation of the pressures and as the peripheral velocity can easily be made to surpass the molecular velocity of the gas (120 m/sec), to use them at the same time for the thorough mixing of the gas in the immediate neighbourhood of the membrane by mounting the membranes round the periphery of the rotor. Alternate sectors of the circumference are composed of diffusion membranes and ports for the escape of the rejected fraction. A number of such impellers with the membrane arrangements can easily be put on one shaft to form a unit of about 10 to 20 stages. The tubing connections become very simple and the whole unit lends itself to mass production as it can be built up from the repetition of few parts.

* Strictly speaking the quantity $\frac{1}{C^2}$, where C is the concentration.

(B) Professor Peierls has recently suggested another way of mixing the gas which dispenses with the mechanical stirring. The gas is forced through a narrow space of which two membranes form the walls. Some of the gas diffuses through these membranes and this leaves the gas near the walls poor in light isotope. If the distance of the two walls from each other is kept sufficiently small this loss of light component will, by diffusion, be spread uniformly over the whole width. The gas therefore travels along the membrane pair with uniform but steadily decreasing content of light isotope. At the end of the pair just half the amount put in remains and this residue forms the heavy portion. The gas which has diffused through the membrane into the space outside the membrane pair forms the light fraction.

The practical possibilities of this arrangement have also been considered by Dr. Simon. He came to the conclusion that the general layout would be much the same as in (A) thus retaining the advantages of the centrifugal blower and the simple pipework.

The chief advantage of arrangement (B) is the fact that one can place more membranes per rotor- if necessary by arranging more than one layer of membrane pairs. This is of importance if the permeability of the membrane at our disposal is small, as in this case the whole output of an impeller cannot be handled with arrangement (A). The disadvantage of arrangement (B) is the fact that the mounting of the membranes becomes more complicated and increasingly so the higher the permeability of the membranes as this necessitates a very small size of the membrane pair. Generally speaking it can be stated that great permeability of the membrane favours (A), low permeability, (B). The choice as to which is the better arrangement depends therefore chiefly on the fineness of the original gauze at our disposal, but also on the relative costs of the impeller arrangement and that of the mountings of the membrane.

15. Present position of Experiments.

The experiments carried out up to the present in the Clarendon Laboratory have shown that a very compact arrangement of the kind discussed will be possible as the frictional heat even at peripheral velocities of 170 m/sec is negligible. Preliminary experiments separating two gases of about the same average molecular weight as the fluoride but greater molecular difference have also shown a separation of the order to be expected. A great number of auxiliary experiments are being carried out on the question of heat transfer, corrosion, and particularly membranes. The whole evidence suggests that there are no insuperable difficulties to be overcome, although of course much attention has still to be given to detail.

At the same time the designs for a 20-stage model are being prepared. Metropolitan-Vickers has a contract for this and Dr. Guy and his assistant Mr. Rice are working on the design. A contract has also been placed with Messrs. Imperial Chemical Industries with a view to obtaining their advice on general matters including lubrication and gas tight seals, with which special care has to be taken because of the corrosive nature of the gas. They are being most helpful in co-operation with Dr. Simon and Professor Haworth in these and other matters. The 20-stage model is being designed in 2 units of 10 stages each, one working according to arrangement (A), the other to (B). It will give enough separation for tests to be made on UF_6.

For a full scale plant the membrane question is the one of over-riding importance. Very satisfactory specimens have been rolled by Mr. Arms in the Clarendon Laboratory from 430 mesh wire gauze, giving a hole size of 1/100 mm with a permeability of about 1/30. These gauzes, however, have been produced on the Continent and cannot be obtained in big amounts, or if their production can be undertaken it would mean a prohibitive delay. The finest gauze which can be at present obtained in sufficient amounts is 200 mesh.

16. Size of Plant.

Dr. Simon, has estimated size and price of the plant (see his report which is attached as Appendix IV), on the basis of material which can be obtained at present and has therefore considered only the 200 mesh gauze. While it cannot

/be

be decided without detailed investigation whether at 450 mesh arrangement (A) or (B) would be more advantageous, at 200 mesh it is certainly arrangement (B), at least for the stages which form the bulk of the plant. The prices were based on information from Metropolitan-Vickers for the probable cost in mass production of a unit comprising 10 stages with a rotor diameter of 72 cm and blades 9 cm wide, which they think for technical reasons to be the most advantageous size. The data for auxiliary apparatus, production of the material, erection of the factory, etc., were provided by Mr. Lipscombe of I.C.I. co-operating with Dr. Simon in the Clarendon Laboratory.

It turned out that 1900 units of the type described would be necessary which can be produced for about £1,750 each, so that a total price of £3,300,000 results for the separation machines while the total cost of the plant would be £4,500,000, or with contingencies £5,000,000.

For this amount the plant can be erected with materials obtainable at present. Improvements in the gauze would reduce this price. The most promising seems to be the product "Lectromesh" of an American firm who make a wire mesh not by weaving but electrolytically. We understand that these gauzes can be made up to 400 mesh and it is also under discussion whether they can produce slit type membranes which would be still more favourable. Other methods of producing membrane, including some proposed by Professor Lindermann, will be investigated.

July, 1941.

M.A.U.D. Committee,
Ministry of Aircraft Production,
London.

APPENDIX I.

NUCLEAR ENERGY AS AN EXPLOSIVE.

Note by Messrs. I.C.I.

(1) Work on the exploitation of nuclear energy to provide an explosive in the form of a bomb which can be dropped from the air has now reached the stage when the problems connected with large scale production can be defined. It is the opinion of Imperial Chemical Industries Ltd., that these problems can be overcome and that a manufacturing plant can be erected.

(NOTE: In the following, the symbol U is used for the ordinary isotope mixture of uranium and the symbol U(235) is used for the separated reactive isotope.)

(2) The use of nuclear energy to provide an explosive involves the following processes:-

(a) Production of UF_6.

(b) Separation of the reactive isotope.

(c) Production of massive uranium metal (235) from $U(235)F_6$.

The production of 1 kilogram per day of U(235) involves the manufacture of 650 - 650 kg/day of UF_6, and it is considered that this quantity of UF_6 can be made on a commercial scale. The process which is recommended is the one which has been used for the preparation of 3 kilos of UF_6 for M.A.P. and involves the direct reaction between fluorine and metallic uranium. A plant to manufacture 650 kg. per day of UF_6 would cost approximately £100,000. The whole plant could be completed in approximately 18 months if certain investigations are started at once.

The separation of the reactive isotope in a diffusion plant of the type suggested by Professor Simon appears to us to be practicable on the scale up to 1 kg. U(235) per day. The total capital expenditure for a plant of this size is estimated to be about £5 million.

If every possible effort is made we believe that a separation unit could be ready for testing by March 1st 1942 and the detailed design of the annual units for the plant should then be ready between June and September 1942. During this time plans could be prepared for the full scale plant and preliminary work could be started on the site.

After August 1st 1942 we consider that manufacture of separation units could start and in six months (i.e. by February 1st 1943) a steady output of these units would be going to the factory site. These would be installed and production of $U(235)F_6$ could be started in the autumn of 1943 and the first bomb would be produced by the end of 1943. Within a year the plant would be producing 30 kg. per month (1 kg (U235) per day), if this output were required.

This estimate is not based upon any firm figures for speed of production given by Messrs. Metropolitan-Vickers, but it is given after a thorough discussion with Dr. Guy on the assumption that the highest priority is given to the production of the units in the engineering shops where they would be made.

The $U(235)F_6$ separated in such a plant can be converted to metallic uranium (235).

(3) The essential raw material for the process is uranium, of which the known supplies are very limited geographically. The two most important sources of the ore are in the Belgian Congo and Canada. The ore is now mined for its radium content and the output of uranium before the war was approximately 300 tons/year

There is a stock in Canada of probably 500 tons of uranium. In this country there is sufficient for research and development of the process of making metallic uranium.

/For

For the manufacture of UF_6 we recommend that the metallic uranium should be made by reducing the oxide with calcium hydride. The fluorine could be recovered from treated UF_6 and used again to react with more uranium.

(4) The diffusion process for the separation of the reactive isotope has now reached a stage of development at which we recommend that a production committee should take charge of the problem. This committee would see that all the problems to be solved for the contruction of a full scale plant were investigated so that the results would be ready as they were required. It would also examine and report on the cost of smaller plants if for technical or other reasons it was considered desirable to produce less than 1 kilo per day. The committee would recommend a suitable site for the plant.

I.C.I. is prepared to take executive charge of this work on behalf of the M.A.P. The arrangement would be similar to that already made in other cases with this Ministry.

COST OF URANIUM BOMBS

Capital cost of the Isotope Separation Plant to make 360 kilos per year.	£5,000,000
Working cost for 1 year	1,500,000
Cost of uranium and other materials	2,000,000
Cost of case and charging 36 bombs @ £300	10,000
	£8,510,000

If the total cost is charged to the 36 bombs
cost per bomb is £236,000 each.
(One bomb is equivalent to 1800 tons $T.N.T._e$)

COST OF T.N.T. BOMB

Capital cost of $T.N.T._e$ plant to make 65,000 tons per year.	£5,050,000
Cost of manufacture @ £90 per ton	5,850,000
Cost of case and charging of 65,000 bombs each containing 1 ton $T.N.T._e$ @ £50 per bomb	3,250,000
	£14,150,000

If the total cost is charged to the 65,000 bombs
the cost per bomb is £218 each
and the total cost of 1,800 tons $T.N.T._e$ in bombs would be £392,000

APPENDIX II.

Extract from letter from Dr. R. Ferguson Research Dept. Woolwich.

If the weights of the two approaching bodies are of the order of 10 Kg. each, no especial difficulty is foreseen in imparting to each of these bodies a velocity of the order of 3000 f't./sec. The major difficulty which at-present I forsee would be to ensure that under the conditions of set-back and set-forward the condition of the material packed in the moving bodies remained satisfactory. This could, I think, be determined only by actual trial.

Provided that the weight of the two bodies to be projected is, as I have indicated above, to be of the order of 10 Kg., the time required to work out the method by means of which a velocity of 3000 f't./sec. could be imparted to each of them simultaneously would be approximately 1 - 2 months, if the work were put on high priority and if the necessary staff were available.

July, 1941.

APPENDIX III.

Extract from letter from Dr. H.L. Guy of Messrs. METROPOLITAN-VICKERS ELECTRICAL CO. LTD.

If we have correctly understood the requirements of the plant from a physical and chemical point of view, we believe that a suitable machine can be evolved. Some of the constructional features will require satisfactory solutions but we would anticipate that such solutions can be obtained. Along the lines that we at present visualise, the machine should be a practical apparatus but not a simple apparatus. If suitably manufactured it could be a satisfactory working machine but certain development difficulties must be anticipated.

(Sgd.) H.L. GUY,

CHIEF ENGINEER, MECH. ENGG. DEPT.

28th June, 1941.

APPENDIX IV

REMARKS ON THE SEPARATION PLANT

by

Dr. F. Simon, Clarendon Laboratory, Oxford

The aim of this report is to provide data for the size and costs of a plant which separates 1 kg per day of U_2^{235} from the natural product. The estimates are based on experiments in the Clarendon Laboratory* as well as on data provided from other laboratories and arrived at after discussion with Metropolitan-Vickers who have given careful consideration to the construction of a big model of the machine, and I.C.I. with whom the whole aspects of the plant have been discussed. In the theoretical questions we enjoyed the frequent co-operation of Professor Peierls.

The leading idea of this report was to find out the size and cost of a plant which can be realised with materials, and particularly membranes, which are at present available and can be produced in sufficient quantity without undue difficulty. As research will still go on before beginning the building of the actual plant one certainly can still expect improvements and simplifications which would result in a lower price or correspondingly quicker time in the erection of the factory. As nothing certain can, however, be predicted about these improvements, the policy in the immediate future should be based on the maximum figures given here.

THE PRINCIPLE OF THE APPARATUS

The apparatus uses diffusion through membranes as the fundamental process as had the one built by Hertz 10 years ago. While that apparatus, however, had to deal with minute amounts of substance only, we are here concerned with quite different orders of magnitude, and in addition the relative difference in the weight of the isotopes is very small. A simple multiplication of the Hertz plant would therefore have led to an absolutely impossible size, apart from the fact that the chemical activity of our gas would have excluded an arrangement of this type.

Three things are essential in the construction of the plant here, of course, from a suitable diffusion membrane:

(1) The creation of pressure differences between each 2 consecutive stages.

(2) Provision for a thorough mixing of the gas in the immediate neighbourhood of the diffusion membrane.

(3) Simple and short tubing connections. The shortness is essential as the equilibrium time of a plant possessing such a great number of stages is anyhow a serious question and the time is proportional to the total volume of the plant.

(A) The original proposal for solving this question is as follows:

The pressures necessary to drive the gas through the plant are created by centrifugal blowers inserted between each two consecutive stages. In order to produce appreciable pressure ratios in this way the peripheral velocity of the rotor must reach molecular velocity, and here the high molecular weight of our molecule is of advantage. The molecular velocity at room temperature is about 120 metres per second, a velocity which can easily be reached and surpassed without any appreciable technical difficulties.

The thorough mixing of the gas in the immediate neighbourhood of the membrane is done in the apparatus by utilising the high velocity of the blades of the rotor for this purpose in the manner indicated in Figure 1. The centre of the figure shows the rotor, while the diffusion membrane is fixed near its periphery.

* These experiments have been carried out by Dr. Arms and Dr. Kurti, who have more recently been joined by Dr. Fyfe and Mr. Llewellyn.

The gas enters somewhere near the axis and is pressed through the membrane, while at the same time the gas in the immediate neighbourhood of it is stirred thoroughly. The light isotope diffuses preferentially through the membrane while at the other side of the membrane a fraction richer in the heavy isotope gradually accumulates, progressing from R to S. This part, which is almost equal to that passing through the membrane, is ejected through the opening H after which the cycle begins anew. The length of the section of the membrane and, what is equivalent, the number of membranes at any one cross section, depends on the properties of the membrane and the velocity of the blades.

In Figure 2 a sketch of an assembly of a few stages is given as a cross section. The left hand side of the figure shows a cross section through the diffusing membrane while on the right hand side the plane of the drawing crosses one of the channels through which the heavy fraction is removed. The light fractions are passed on to the next stage in a way easily to be understood from the figure, while the heavy fractions are handed back to the previous stage. It can be seen that by repeating the parts between N and M the whole plant could be built up quite simply without complicated tube connections and so on.

(B) Peierls has proposed recently another solution for the question of mixing the gas which dispenses with the mechanical stirring. The idea is to force the gas through a narrow space (Figure 3) of which two membranes form the walls. Some of the gas diffuses through these membranes and this leaves the gas near the walls poor in light isotope. If the distance of the two walls from each other is kept sufficiently small this loss of light component will, by diffusion, be spread uniformly over the whole width. The gas therefore travels along the membrane pair with uniform but steadily decreasing content of light isotope. At the end of the pair just half the amount put in remains and this residue forms the heavy portion. The gas which has diffused through the membrane into the space outside the membrane pair forms the light fraction. The dimensions of the pair depend on the characteristics of the membrane (hole size and permeability) and it should be mentioned that with the membranes at present at our disposal the dimensions remain within reasonable limits; for instance, the distance between the two membranes is of the order of $\frac{1}{2}$ to 1 mm.

The gas can be supplied to such an arrangement by any means as the blades do not serve the double purpose as in (A) and therefore one can consider employing quite different types of compressors. One can show, however, that the centrifugal blower is far superior to any other arrangement. Also, the advantages of combining the different stages in the manner discussed under (A) are so great from the point of view of simplicity and shortness of connection that if membrane pairs are used one would still retain the other features of arrangement (A). A plant with membrane pairs would therefore look very much like the former except that the swept membranes are replaced by an assembly of membrane pairs of appropriate dimensions, and the light and heavy fractions are handed on to the other stages in the same way as in Figure 3.

In arrangement (A) the amount of membrane area which can be used is determined by the area of the cylindrical surface of the rotor, or at the best by about 3 times this amount if one uses in addition an equal area of membrane arranged horizontally above and below the blades of each section. This restriction does not exist in arrangement (B). First, a greater amount of membrane can be placed in a single stage if the membranes are arranged in a radial direction, and if this should not suffice, a second or even a third "layer" of membrane pairs can be arranged round the rotor. This is the chief advantage of the membrane pair apart from the somewhat higher separation efficiency of a single element. The chief disadvantage is the fact that the arrangement of these membrane pairs is technically more complicated than the arrangement of (A), particularly if we have to use more than one "layer" of pairs around the rotor. A second disadvantage will become noticeable when working with membranes of high permeability as then the membrane pairs will have to have uncomfortably small dimensions.

Generally speaking it can be stated that great permeability of the membrane favours (A), low permeability, (B). The choice as to which is the better arrangement depends therefore chiefly on the fineness of the original gauze at our disposal, but also on the relative costs of the impeller arrangement and that of the mountings of the membrane. This point will be discussed later.

/EXPERIMENTS

EXPERIMENTS

A number of experiments have been carried out which show that a plant of the kind described is a feasible proposition. Experiments in Professor Haworth's Laboratory as well as in those of I.C.I. in Widnes, have proved that most metals are not attacked when in a dry state so that there is no difficulty in finding suitable materials for the construction of the machine and the membranes. Also a few substances are available which can be used for sealing purposes. No entirely satisfactory liquid, however, has yet been found, either for lubricating purposes or for use in a centrifugal seal. It seems, therefore, certain that the bearings have to run in an atmosphere free from our gas and thus the provision of glands is essential. We have given much attention, together with Metropolitan-Vickers, to this point, and we are convinced that a labyrinth gland of conventional construction together with the use of a buffer gas which at intervals is removed from our gas, will give a satisfactory solution.

Experiments with models of different sizes have shown that peripheral speeds of the rotor even twice as high as the velocity of sound do not give rise to appreciable heat of friction in the gas at our working pressures, which are of the order of 1 to 2 millimetres. One therefore can create pressure ratios of 4 or 5 to 1 without encountering any difficulties in removing the heat of friction and a very compact machine is possible.

A great number of experiments have been carried out for the production of suitable membranes by rolling wire gauzes. The best results obtained so far have been achieved with 450 mesh gauze which allowed the production of holes of a diameter of 10^{-5}cm and a permeability of the membrane of [illegible]. Experiments in Professor Thomson's Laboratory have given a value of the viscosity and therefore of the mean free path, and one can deduce from those results that at a pressure of 2 cm mercury the mean free path will be equal to this hole size and thus result in satisfactory separation.

Experiments were carried out on the actual separation of two gases of about the same molecular weight as our gas but with a much bigger difference so that even a single stage can give separations which can be measured. Experiments with arrangement (A) have not yet given final results owing to difficulties of a secondary nature. Experiments with a membrane pair, however, have now been carried out successfully and the separations attained show an effect of the right order. More accurate data as well as data on (A) can be expected within a short time.

In conclusion we can state, and this is also the opinion of Metropolitan-Vickers, that there do not seem to exist any indications that a plant of this type cannot be built, although much attention has, of course, still to be given to details.

THE SIZE OF THE PLANT

In order to keep the size and consequently the price down one has to make the maximum use of the output of each impeller. Under our conditions the limiting factor for the output of an impeller is determined by the conditions at the place where the gas is introduced, which will be situated at about half way along the radius of the impeller. We are going to work with a pressure ratio of about 4 to 1 so that the velocity at the "eye" is about 3 times that of the gas leaving the impeller. As the former should not exceed the velocity of sound the maximum velocity at which we can draw off gas radially is about 70 M/sec.

The question whether this amount of gas can be taken up by the arrangement (A) depends on the permeability of the membrane. Even the membranes of highest permeability formed of 450 mesh would with the smallest hole which we could produce by rolling, not be able to cope with the whole output of the impeller. The margin, however, is not so big that without careful consideration of detail it could be decided whether the corresponding greater complication of a (B) arrangement would be compensated by the smaller size of the plant. But it seems proved that these membranes had been produced on the Continent and could not at present be obtained in sufficient quantities or only produced at very high cost. The finest mesh which we can get at present in sufficient quantities at a reasonable price is 200 mesh and we have therefore to base our calculations on this. The permeabilities of 200 mesh cannot be rolled down to obtain a reasonable hole size and for [illegible] arrangement

/(B)

(A) to take the whole output of an impeller. Therefore arrangement (B) has to be chosen which can always take up the output of the impeller, if necessary, by arranging the membrane pairs in more layers. As it also seems that cost of the plant is determined more by the impeller than by the membrane mounting, arrangement (B) is clearly the better in this case.

This is true only in the region where the amount of material handled is big compared with the amount handled by a single unit of practical size. This ceases to be true at the higher stages, about from the 2,000th and upwards. At these stages the total volume of the plant is no longer of over-riding importance, but to an ever growing extent the simplicity of the arrangement, which favours (A). As, however, this part does not constitute the bulk of the plant, which definitely lies between the 1st and 2,000th stage, we can base the calculation without any appreciable error on the assumption that the whole plant is made in the manner (B).

The total amount of gas circulating in the plant can be calculated from the formula derived by Peierls and it turns out to be 1.30×10^6 g/sec for an output of 1 kg per day of the metal. This determines the size of the plant between the input stage and the output of the light fraction. The size of the part between input and output of the heavy fraction depends on the concentration of the reject which we choose. The choice is determined by the relative costs of the separation plant and the plant for the production of the substance. As the former influence is by far the prevailing one it pays to reject at a relatively high concentration. We choose for this a concentration of 0.45% (the original product enters with 0.7%). This means that we have to feed to the plant, for an output of 1 kilo of metal, 0.63 tons of the compound and calculation shows that now the size of the second part of the plant is 10% of that of the first one. The total amount circulating will therefore be 1.43×10^6 g/sec.

A 10-stage rotor of 72 cm diameter and 9 cm blade width has been chosen by Metropolitan-Vickers as the most convenient size for technical and production reasons. Such a rotor has a total surface at the periphery of 2 M^2 and therefore a total output of 2M^2 x 10M/sec = 20M^3/sec. Our gas has a density of 37.5g/M^3 at a working pressure of 2mm and 25°C. Therefore 1900 of these units are necessary to handle the total amount.

The total area of a membrane manufactured from about 200 mesh gauze would under our conditions be about 100,000 M^2 or roughly 60 M^2 per machine. These could be accommodated in 5 concentric layers of membrane-pairs, thus adding 15 to 20 cm to the radius. The width of each pair would be 1 cm, the length 20 mm.

In the opinion of I.C.I. a convenient size of building for housing these machines would be 320 ft. x 80 ft. containing 500 machines so that five of these buildings would be required. These together with the auxiliary and preparation plants could easily be accommodated on a site of about 20 acres.

As regards the power consumption no exact figure can be given at present, of the power required for each machine but it seems very improbable that this will exceed 10 - 15 K.W. Allowing a margin on this and adding the power for auxiliary machinery we may assume that 20 K.W. per machine or 40 M.W. for the whole plant will cover the power requirements.

THE PRICE OF THE PLANT.

Metropolitan-Vickers have gone into the question of the cost of a unit of the size mentioned and they estimate that in mass production each machine would cost between £1,500 and £2,000 (say £1,750). The total number of machines would therefore cost 1900 x 1750 = £3,300,000. Mr. Lipscomb of I.C.I. believes that some economy is possible by choosing a different size for the unit but in his opinion the above estimate is on the upper limit; but to be on the safe side we will accept it.

Mr. Lipscomb, who has had particular experience in the construction of plants, has estimated the further capital outlay involved. His estimate is as follows:-

/Foundations

Foundations and buildings	160,000
Services, stores and workshops	600,000
Auxiliary machinery and instruments	150,000
Preparation and purification plant for incoming material	200,000
	£1,110,000

The total capital expenditure for the plant would therefore be £4,500,000 or say with a margin for contingencies £5,000,000.

This is an estimate of the price at which a plant with the materials available at present can be made. But at this stage no very accurate estimate is possible. More accurate estimates can only be given towards the end of 1941, when the 20-stage model will have been run and production methods will have been investigated more thoroughly.

Mr. Lipscomb's estimate for the running cost is about £1,000,000 a year, the two chief items being wages (£400,000 for a personnel of 1200) and electric power (£450,000). This estimate does not include the cost of the raw material which at a reject concentration of 0,45% may be about £200,000.

The production of better membranes would result in an economy. The factors of importance are, apart from the price which serves as a measure for the ease of production:

Diameter and length of the holes in the membrane,
the permeability,
the mechanical strength.

The mechanical strength will become a limiting factor, as small diameter of the hole must be accompanied by small length, which means a thin membrane. On the other hand the finer holes are aimed at because they permit a higher working pressure, which in its turn necessitates stronger membranes.

Research on the production of membranes is being accelerated as much as possible and the following possibilities are envisaged at present:

(1) The electro-deposited material "Lectromesh" might be produced at very fine mesh.

(2) The "Lectromesh" procedure might be utilised to produce slit type membranes which would increase the permeability (given the same working pressure). We have enquired of the makers of "Lectromesh" about these two possibilities.

(3) I.C.I. are conducting experiments for producing slit-type membranes by winding thin wire round a former.

(4) According to a suggestion of Professor Lindemann's an attempt can be made to produce very small holes in thin foils by bombarding them with colloidal particles in a vacuum. Various other suggestions for perforating thin foil are also under consideration.

If any of these suggested improvements should prove successful it will affect only the number of machines required and not the design of each machine, so the construction of the 20-stage model will be put in hand as soon as possible. It is proposed to build this 20-stage model in two units of 10 stages each, one working according to arrangement (A), the other with arrangement (B).

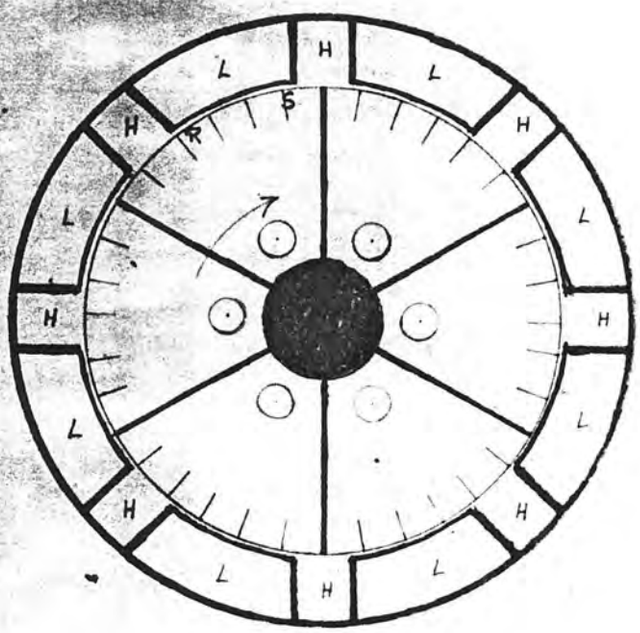
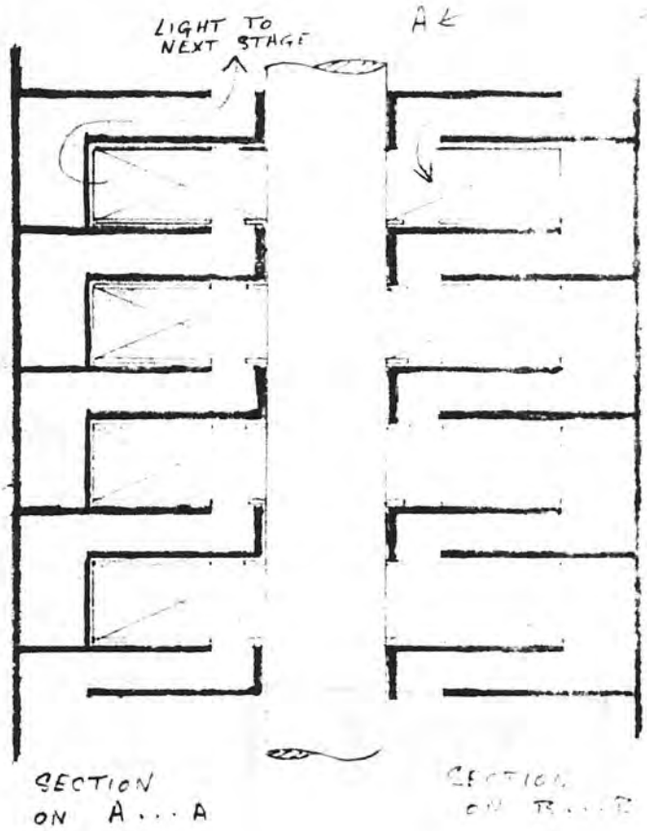
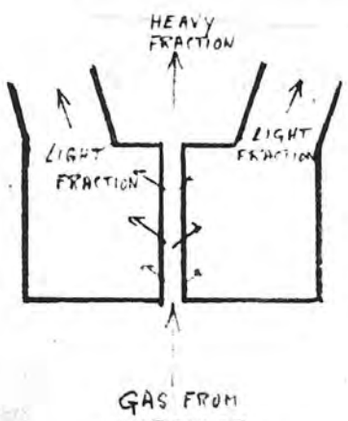


Fig 1



MEMBRANES SHOWN IN RED -



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