November 13, 1944

TO: Mr. E. P. Wigner

FROM: Mr. L. Szilard

You asked me how the tentative draft of a patent application came about which was repeatedly mentioned to you in the last few days by the O. S. R. D. Patent Division. The answer is as follows:

Captain Lavender asked me in 1943 to write down inventions made by me before November 1940 in the form of a draft of a patent application. The purpose of this draft was to enable Captain Lavender to investigate the value of my alleged inventions to the Government. Captain Lavender told me that he would have to investigate the validity of my claims and determine their value for the Government and that consequently I should write into that draft anything which I might consider as an invention made by me before November 1940. Practically the only written document which I had prior to November 1940 was the manuscript which I sent to the Physical Review, which is essentially identical with Report A-55. I therefore made a draft essentially based on A-55 and sent this to Captain Lavender.

After I signed the agreement transferring my inventions to the Government in December 1941 I suggested to Col. Metcalf that they prepare a joint patent application with Fermi or with yourself and Fermi as co-inventors. The draft of such a proposed patent application was submitted to me about three months ago and was dealt with by correspondence with Captain Lavender. I am inclosing the text of this correspondence for your information. Please return the inclosure to me after you have read it. If you wish I could let you have a copy of this correspondence.

LS:ls

Application as prepared by Dr. Szilard and forwarded to Washington on May 29, 1943.

Foster York ~~By~~ V. Kuiper

Foster York

L.Szilard
May 23, 1943

Claim 1.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, and the said lattice being embedded in a mass of a slowing agent.

Claim 3.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, and the said lattice being embedded in a mass of an efficient slowing agent.

Claim 4.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent.

Claim 5.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass having carbon as its main component.

Claim 6.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite.

Claim 6a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, the weight ratio of carbon to uranium in the graphite being between 3 to 1 and 10 to 1.

Claim 6b.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, the weight ratio of carbon to uranium in the lattice being between 5 to 1 and 10 to 1.

Claim 7.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium in the form of uranium metal, the said lattice being embedded in a mass of graphite.

Claim 7a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium in the form of uranium metal, and the said lattice being embedded in a mass of graphite, the weight ratio of carbon to uranium in the lattice being between 10 to 1 and 3 to 1.

Claim 7b.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium in the form of uranium metal, the said lattice being embedded in a mass of graphite, the weight ratio of carbon to uranium in the lattice being between 10 to 1 and 5 to 1.

Claim 8.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass containing a compound of deuterium.

Claim 9.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass containing heavy water.

Claim 10.

A potentially chain reacting system comprising a lattice of spheroid shaped aggregates which contain uranium, the said lattice being embedded in a mass which is an efficient slowing agent.

Claim 10a.

A potentially chain reacting system comprising a lattice of spheroid shaped aggregates which contain uranium, the said lattice being embedded in a mass of graphite.

Claim 10b.

A potentially chain reacting system comprising a lattice of spheroid shaped aggregates of uranium metal, the said lattice being embedded in a mass which is an efficient slowing agent.

Claim 10c.

A potentially chain reacting system comprising a lattice of spheroid shaped aggregates of uranium metal, the said lattice being embedded in a mass of graphite.

Claim 11.

A potentially chain reacting system comprising a lattice of rod-like shaped aggregates which contain uranium, the said lattice being embedded in a mass of an efficient slowing agent.

Claim 11a.

A potentially chain reacting system comprising a lattice of rod-like shaped aggregates which contain uranium, the said lattice being embedded in a mass of graphite.

Claim 11b.

A potentially chain reacting system comprising a lattice of rod-like shapes aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent.

Claim 11c.

A potentially chain reacting system comprising a lattice of rod-like shaped aggregates of uranium metal, the said lattice being embedded in a mass of graphite.

Claim 12.

A potentially chain reacting system comprising a lattice of aggregates which contain uranium and have the shape of cylindrical rods, the said lattice being embedded in a mass of an efficient slowing agent.

Claim 12a.

A potentially chain reacting system comprising a lattice of aggregates which contain uranium and have the shape of cylindrical rods, the said lattice being embedded in a mass of graphite.

Claim 12b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, and have the shape of cylindrical rods, the said lattice being embedded in a mass of an efficient slowing agent.

Claim 12c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal having the shape of cylindrical rods, the said lattice being embedded in a mass of graphite.

Claim 13.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 13a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, a cooling agent flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 13b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 13c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, a cooling agent flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 14.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent consisting in a liquid metal flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 14.5.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent consisting in a low melting liquid metal composed of atoms having atomic numbers above 81 flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 14.5a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, a cooling agent consisting in a low melting liquid metal composed of atoms having atomic numbers above 81 flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 14.5b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent consisting in a low melting liquid metal composed of atoms having an atomic number above 81 flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 14.5c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, a cooling agent consisting in a low melting liquid metal composed of atoms having atomic numbers above 81 flowing within the said system in thermal contact with the said uranium-containing aggregates.

Claim 15.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent consisting in a low melting liquid metal containing bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 15a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, a cooling agent consisting in a low melting liquid metal containing bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 15b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, a cooling agent consisting in a low melting liquid metal containing bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 15c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, a cooling agent consisting in a low melting liquid metal containing bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 16.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of an efficient slowing agent, liquid bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 16a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said lattice being embedded in a mass of graphite, liquid bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 16b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, liquid bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 16c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite liquid bismuth flowing within the said system in thermal contact with the said uranium-containing substance.

Claim 17.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of the slow neutron absorber within the system adapted to be moved from a point of high neutron density towards a point of low neutron density and vice versa.

Claim 17a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of the slow neutron absorber within the system adapted to be moved from a point of high neutron density towards a point of low neutron density and vice versa.

Claim 17b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of the slow neutron absorber within the system adapted to be moved from a point of high neutron density towards a point of low neutron density.

Claim 17c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of the slow neutron absorber within the system adapted to be moved from a point of high neutron density towards a point of low neutron density and vice versa.

Claim 18.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of a slow neutron absorber adapted to be moved into the interior and moved out from the interior of the said system.

Claim 18a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of a slow neutron absorber adapted to be moved into the interior and moved out from the interior of the said system.

Claim 18b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of a slow neutron absorber adapted to be moved into the interior and moved out from the interior of the said system.

Claim 18c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of a slow neutron absorber adapted to be moved into the interior and moved out from the interior of the said system.

Claim 19.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of rod-shaped slow neutron absorbers within the system, means for changing the position of the said slow neutron absorbers.

Claim 19a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of rod-shaped slow neutron absorbers within the system, means for changing the position of the said slow neutron absorbers.

Claim 19b.

A potentially chain reaction system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of rod-shaped slow neutron absorbers within the system, means for changing the position of the said slow neutron absorbers.

Claim 19c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of rod-shaped slow neutron absorbers within the system, means for changing the position of the said slow neutron absorbers.

Claim 20.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of a slow neutron absorber within the system the position of which is controlled by the radiation emanated from the chain reacting system.

Claim 20a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing an element that undergoes slow neutron fission, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of a slow neutron absorber within the system the position of which is controlled by the radiation emanated from the chain reacting system.

Claim 20b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of an efficient slowing agent, means for controlling the function of the said system consisting of a slow neutron absorber within the system the position of which is controlled by the radiation emanated from the chain reaction system.

Claim 20c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said lattice being embedded in a mass of graphite, means for controlling the function of the said system consisting of a slow neutron absorber within the system the position of which is controlled by the radiation emanated from the chain reacting system.

Claim 21.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said aggregates being surrounded by a layer of beryllium, and the said lattice being embedded in a mass of an efficient slowing agent.

Claim 21a.

A potentially chain reacting system comprising a lattice of aggregates of substance containing uranium, the said aggregates being surrounded by a layer of beryllium, and the said lattice being embedded in a mass of graphite.

Claim 21b.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said aggregates being surrounded by a layer of beryllium, and the said lattice being embedded in a mass of an efficient slowing agent.

Claim 21c.

A potentially chain reacting system comprising a lattice of aggregates of uranium metal, the said aggregates being surrounded by a layer of beryllium, and the said lattice being embedded in a mass of graphite.

II

According to this invention a nuclear chain reaction can be maintained in a system which contains a lattice of aggregates of a substance that contains an element which is capable of undergoing fission under the action of slow neutrons and which lattice is embedded in a mass containing a suitable slowing agent which slows down the fast neutrons emitted during the process of fission of the said heavy element.

Natural uranium is one example of a heavy element that undergoes fission by neutrons which have been slowed down to thermal energies. Fission induced by slow neutrons in natural uranium is attributed to the rare isotope U^{235} contained in natural uranium. Fast neutrons such as are emitted in the fission of U^{235} cause, however, fission also in the abundant isotope U^{238} which is contained in natural uranium. According to this invention a nuclear chain reaction can be maintained in a lattice of aggregates of substance which contains uranium and which is embedded in a mass of a slowing agent which fulfills certain requirements which will be defined further below. Slowing agents which fulfill these requirements will be called, for the purpose of these specifications, "efficient" slowing agents. Carbon in its pure form of low ash graphite belongs to this class of slowing agents and so does deuterium in the form of deuterium oxide, also called heavy water.

Introduction to Graphite Lattice.

For the purposes of this invention, graphite with a low ash content, less than 0.1% ash and preferably less

than .06% ash should be used. It is not only important to keep the ash content low, it is also important to keep the boron content of the ash low. If a low boron petroleum coke is used for making the graphite and if such petroleum coke is also used as the resistor material in the graphitizing process and if the charge in the graphitizing furnace is so located as to reach a very high temperature, one can produce a quality of graphite which is satisfactory.

The uranium compound or uranium metal which is used should also be of high purity. It may be obtained from carnotites or pitchblende which is comparatively high in rare earths. This additional process of purification must be so designed as to remove the rare earths from the uranium compound. This may be done by one of several methods, for instance: by recrystallization of uranyl nitrate or by extracting uranyl nitrate with ether or by precipitating the rare earths as fluorides, etc..

The uranium can be used in the form of U_3O_8, in the form of the dioxide, in the form of one of its several carbides and in the form of metal. Other uranium compounds might perhaps be also suitable. Uranium metal can be produced from uranium chloride by reduction with calcium and a pure product can be obtained by this method if distilled calcium is used. In a similar manner, pure uranium can be produced by using pure uranium tetrafluoride with chemically pure magnesium. In this latter process, the purest commercial brands of magnesium are satisfactory.

Let us now consider an infinitely extended lattice of uranium-containing aggregates embedded in graphite. On

the average of the neutrons emitted in a fission process, a fraction q is absorbed within the system as a slow neutron (thermal or quasi-thermal) by uranium, and on the average η fast neutrons are emitted for every such slow neutron absorbed by uranium. The system is potentially chain reacting if the product $q\eta$ is larger than 1.

In order to have an actually chain reacting mass, we must build a sufficiently extended system. If the system is not surrounded with much material which efficiently reflects neutrons, the neutrons can escape from the surface of the chain reacting mass, and in that case, the critical radius ℓ for which a spherically shaped mass becomes chain reacting, is given by the formula

$$(1) \qquad \ell = \pi \sqrt{\frac{\overline{r^2}}{3(\mu g - 1)}} \simeq \sqrt{\frac{3\,\overline{r^2}}{\mu g - 1}}$$

In this formula, r^2, is related to the average square of the distance to which a fast neutron emitted in a fission process diffuses within the system until it gets slowed down and is absorbed and has for graphite of 1.7 gm/cm^3 of density a value of about $(50\ cm)^2$ so that we have

$$\ell \simeq \sqrt{\frac{7500}{\mu g - 1}}$$

For a system the composition of which will be described below, and which contains a lattice of aggregates of uranium embedded in graphite of a density of about 1.6 gm/cm^3, a sphere containing about 500 tons of pure graphite is sufficiently large to maintain a chain reaction. If in place of a spherical shape, a cylindrical shape is used, and if the diameter of the cylinder is about equal to its height, the critical mass is about

10% higher.

For any given shape the critical mass is defined as the mass at which under the given condition, the intensity of the chain reaction just remains stationary. If the critical mass is exceeded, the intensity of the chain reaction (which manifests itself in the intensity of the neutron and gamma radiations emitted from the chain reacting pile), increases exponentially with time. If the mass is lower than the critical mass, but close to it, and if we have a source of neutrons (initial neutron radiation) within the mass, the number of neutrons produced in the chain reaction can be made larger than the number of the neutrons of the initial radiation by a factor which increases more and more steeply as the mass approaches to the critical mass. In order to maintain a chain reaction, it is not necessary, however, to make use of an artificial source of neutrons, since initial neutrons are always present; they are for instance emitted in the spontaneous fission of uranium contained in the chain reacting mass and present in the cosmic rays.

The critical mass can be varied by introducing a slow neutron absorber, such as cadmium, steel, a cobalt iron, or cobalt nickel alloy, into the interior of the mass, or by withdrawing the absorbers therefrom, by which means the critical mass is increased or decreased, respectively. This can be used for controlling the chain reacting, for instance, by moving the slow neutron absorber in and out in such a manner as to have the system part of the time below, and part of the time above, the critical condition.

In order to determine empirically the critical mass such slow neutron absorbers may be built into the system

while the system is being assembled, and after a sufficiently large mass is assembled, these absorbers may be one after the other withdrawn. While these absorbers are being withdrawn, the radiation emanating from the mass may be observed, and the position of the absorbers may be determined at which the neutron intensity begins to rise exponentially with time, which signifies that the critical condition has been reached.

Of the neutrons emitted in fission, a fraction η/ν which is close to 1 is emitted instantaneously and only a small fraction $1-\eta/\nu$ is emitted with a time delay of a few seconds. Though this delayed neutron emission is small, it has an important effect on the rate at which the neutron intensity rises exponentially with time if the mass of the chain reacting unit exceeds the critical mass, only slightly. In order to discuss this we may introduce the concept of the "critical mass for instantaneous neutron emission" which corresponds to the value of β' while the critical mass for the total neutron emission corresponds to β . The critical mass for instantaneous neutron emission is larger than the critical mass. We can avoid a rapid exponential rise of the chain reaction intensity by keeping conditions so that while we may exceed the critical mass, the system should remain in the interval between the critical mass tne the critical mass for instantaneous neutron emission. Preferably in order fully to profit from the effect of the delayed neutron emission, the system should remain within the interval between the two critical masses close to the critical mass for the total neutron emission.

According to the present invention, a chain reaction may be maintained in a system which contains embedded in graphite, a lattice, the lattice element being aggregates

of a substance which contains uranium, in place of graphite some other efficient slowing agent can be used, for instance, heavy water.

The aggregate which forms the lattice element can be a single body containing uranium or can be something like a cluster of a number of separate bodies, each of which contains uranium. This latter case is illustrated by an example shown in Fig. 1. This figure we see the lattice element in the form of a spherically shaped aggregate of uranium metal rods (pencils) of different lengths.

The simplest example for a potentially chain reaction system is probably one in which the aggregate that forms the lattice element is a single body having the shape of a sphere and being composed of uranium metal. Such uranium metal spheres may then be embedded in graphite in such a manner as to form one of the three existing close-packed lattices. Such a system is potentially chain reacting provided the radius of the uranium metal sphere is between a lower and upper limit which is determined by its density, and the ratio of the weight of carbon to uranium within the lattice is kept between certain lower and upper limits which are determined by the radius of the uranium sphere which forms the lattice element.

It is not necessary to use uranium in the form of uranium metal, but U_3O_8 or uranium dioxide or uranium carbide can be used in place of uranium metal. Some other uranium compounds might perhaps also be operative.

The aggregate composed of uranium or uranium compounds need not have the shape of a sphere but can have the shape of a short cylinder of about equal diameter and height, or can have the shape of a short square rod of about equal sides (a body close to a cube). All these and similar

shapes which shall be designated as spheroids are operative, but some other shapes which deviate considerably from the spherical shape are also operative under otherwise favorable conditions.

Lattices in which the aggregate either consists of one uranium-containing body or composed of several uranium-containing bodies, and in which the aggregate has the shape of a long cylindrical rod are also operative. Such cylindrical rods can be arranged into a lattice which, for instance, may have trigonal or tetragonal symmetry, but some other lattices which have no such symmetry are also operative.

A recipe will be given further below for an operative close-packed lattice of uranium metal spheres from which recipe an operative combination for the radius of the sphere and the spacing of such spheres in the lattice can be determined.

In the following, examples will be given for the following systems:

1. Lattices in which the lattice elements are cylindrically shaped uranium rods which may be arranged in trigonal and tetragonal lattice and which are cooled by a cooling agent flowing along the surface of the rod. Arrangements of this type fall into three classes:

A. A class in which the cooling agent flows inside a uranium tube (inside cooling).

B. A class in which the cooling agent is flowing along the surface of a uranium rod in a gap between the uranium rod and a thin tube which separates the cooling agent from the slowing agent.

C. Arrangements in which the cooling agent flows along the surface of a uranium rod in a gap between the uranium rod and graphite which acts as a slowing agent.

The class 1C is represented by various examples which again fall into two classes, alpha and beta. To the class alpha belong arrangements in which the cooling agent passes through the whole structure in continuous contact with the lattice element; whereas, to class beta belong arrangements in which various sections of the rod-shaped lattice element are connected in parallel from the point of view of the flow of the cooling agent.

2. Lattices of which the elements are spheres of uranium or short cylinders of uranium or uranium compounds of about equal height and diameter. These spheroid-shaped uranium bodies may be arranged in any one of the closed-packed lattices, or may be arranged in a cubic lattice. Groups of one or more lattice elements are connected in parallel from the point of view of the flow of the cooling agent.

General Remarks on Cooling

Suitable cooling agents for a chain reaction unit are for instance heavy low melting metals which have a low absorption for slow neutrons. Elements which are in the periodic table in the region of bismuth and having an atomic number above 81 have a low absorption for slow neutrons and do not slow down appreciably fission neutrons. For this reason they are suitable as a cooling agent and can be used for cooling along internal surfaces within the lattice element. Liquid bismuth, liquid alloys of bismuth, and lead, and liquid lead can be thus used as cooling agent. Bismuth is more favorable from the point of view of slow neutron absorption than lead, and the liquid bismuth alloys occupy a position in between according to their composition.

Liquid bismuth can be used in contact with uranium carbide or uranium oxide, but if uranium metal is used the bismuth must be separated from the metal by a sheet of a protecting substance, preferably steel, otherwise the bismuth would dissolve uranium metal and that is not desirable. Bismuth-lead alloys and lead can be used in a way similar to bismuth in contact with uranium carbide or uranium oxide or in thermal contact with uranium metal which is protected by an iron or steel coating. Among the bismuth-lead alloys, the bismuth-lead eutectic which has a melting point of about 130°C is of particular interest on account of its low melting point which makes it possible to circulate it through a heat exchanger in which heat is transferred to water.

If graphite is used as a slowing down medium, we can have two types of circulations: a closed circulation in

which the heavy liquid metal flows, for instance, inside a steel tube through the graphite under pressure which can be arbitrarily chosen within certain fairly wide limits, and an open circulation in which the heavy liquid metal flows through the graphite essentially under the action of gravity and the velocity of the flow is essentially determined by the friction in the vertical channels through which the heavy liquid metal flows through the graphite.

If heavy water is used as a slowing agent, the heavy liquid metal may be led through tubes vertically through the power unit and steel tubes can for instance be used for this purpose. The examples shown further below in which a closed circulation is used belong to the type of series flow. Examples for gravity flow include examples of parallel flow in the case of a graphite power unit.

In general, cooling agents may be led through pipes of a number of elements, for instance, aluminum, magnesium, lead, bismuth, graphite, beryllium, steel, tin, or uranium. If the cooling agent is a heavy liquid metal containing either lead or bismuth or both, only steel, graphite and beryllium appear to be suitable. Uranium tubes and tubes made of some of the abovementioned metals can, of course, be used for heavy liquid metals containing bismuth or lead if a direct contact between the cooling liquid and the uranium metal is prevented by an iron coating, for instance, a steel tube, which separates the cooling agent and the uranium metal. The choice of the cooling agent and the tubing system within the power unit has an influence on the size of the power unit inasmuch as the neutron absorption of the cooling agent and the tubing affects the value of μq.

For instance, if the amount of bismuth inside that lattice of the power unit is about equal by weight to the amount of uranium, we should count on an increase of μq of about .7%. If the amount is smaller, the increase is proportionally smaller. Similarly, if the amount of lead is equal to about one-fourth of the amount of uranium by weight, we should count on an increase of about .7% in μq. From these data, the expected increase in μq can be calculated for any bismuth-lead alloys if their quantity by weight in ratio to the uranium by weight is given. If iron pipes are used and if the amount of iron is about 1% by weight, we ought to count on an increase in μq of 2%. In this way, depending on the quantity of the cooling agent and according to the neutron absorption of the cooling agent and depending on the quantity of piping material and according to the neutron absorption of the piping material, the decrease in μq can be estimated. For a lattice using uranium metal which does not deviate too much from the optimum conditions we may count on μq being about 1.07. If a cooling agent and the piping reduced μq to about 1.035 then the linear dimensions of the lattice which contains both the cooling agent and piping have to be according to formula No. 1 about $\sqrt{2}$ times larger than the linear dimensions of the lattice which does not contain such neutron absorbers.

Figures 3, 4, 5 illustrate examples in which the lattice elements are rods of uranium either cylindrical rods, or tube-like rods. These lattice elements are all supposed to be vertical and form a lattice of trigonal

or tetragonal symmetry. They are designed for series flow in contrast to parallel flow which we will mention further below.

Figure 3 shows an example for the lattice element. In Figure 3, (1) is a cylindrical uranium rod covered by a thin steel tube (2). An anular gap (4) is left free for the flow of the cooling agent inside the steel tube (3) which is embedded in a mass of graphite (5). Liquid bismuth or a liquid bismuth lead alloy may be used as a cooling agent in this arrangement.

Figure 4 shows another example for the lattice element. In Figure 4, (1) is a cylindrical uranium tube; (2) is a thin walled tube inside of the said uranium tube. Liquid bismuth or a bismuth lead alloy flows through the tube (2); (4) is a thin protecting coating covering the uranium tube (1); (5) is a mass of graphite into which the uranium tube is embedded. There is a small gap between the uranium tube (1) and the mass of graphite (5).

Figure 5 shows another example for the lattice element. In Figure 5, (1) is a cylindrical uranium rod; (2) is a thin walled steel tube; a cooling agent is flowing through the steel tube (2) in the axis of the uranium rod (1). (4) is a tube on the outside of the uranium rod (1); (5) is a gap between the uranium rod and a tube (6); (7) is the slowing agent.

This arrangement can be used if a bismuth-lead eutectic alloy is used as a cooling agent and heavy water is used as a slowing agent. Tube (6) can be of aluminum and the gap (5) may be filled with helium which in this particular case serves as a heat insulator.

Figure 80 shows another example for the lattice element. In Figure 80 (1) is a uranium rod surrounded by a thick-

walled beryllium tube (2). The uranium rod is covered by a thin-steel tube (3). Liquid bismuth lead alloy flows through the gap (4) between the uranium rod (1) and the beryllium tube (2). The beryllium tube may be surrounded by a thin aluminum tube (5) leaving a gap (6) for purposes of heat insulation. (7) is a slowing down agent into which this lattice element is embedded.

Figure 81 shows another example for the lattice element. (1), (2), (3), (4), (5), (6), (7), and (8) are uranium rods inside thin steel tubes which form together a rod-like aggregate. This aggregate is within a thick-walled bismuth tube (9) which is covered with a thin aluminum tube (10), and the entire assembly is embedded in the slowing agent (11). The slowing agent may be graphite. If heavy water is used as the slowing agent, it is advisable to leave a gap free between the aluminum tube (10) and the beryllium tube (9) for purposes of heat insulation as mentioned in the description of Figure 80.

In Figure 82 (1) is a uranium rod or thick-walled uranium tube. (2) is a thin-walled steel tube in the axis of the uranium rod (1). (3) is a thin-walled steel tube covering the uranium rod (1). (4) is a thin-walled steel tube which contains the uranium rod (1) leaving an anular gap (5) free for the flow of a cooling agent. Bismuth-lead eutectic may be used as a cooling agent in this arrangement. (6) is a thin-walled aluminum tube which surrounds the steel tube (4) leaving an anular gap (7) which is filled with helium for purposes of heat insulation. (8) is a mass of heavy water which acts as a slowing agent in this arrangement. The uranium rod (1) is fastened by means of a screw (9) to the thick-walled steel tube (10).

Openings (11) and (12) in the thick-walled steel tube (10) admit the cooling agent as indicated by the arrows into the interior of the steel tube (2).

Figure 105 shows a lattice of cylindrical uranium rods in a system in which heavy water serves as a slowing agent and in which a eutectic bismuth-lead alloy containing about 60% bismuth may serve as a cooling agent. In Figure 105, (1), (2), and (3) are cylindrical uranium rods (thick walled tubes). The uranium rod (1) is covered by a thin layer (4) which separates it from the gas in the cylindrical gap between the uranium rod (1) and the aluminum tube (5). This gap serves to heat insulate the uranium rod from the heavy water (8) which is in contact with the aluminum tubes (5), (6), and (7). A thin-walled steel tube (9) runs in the axis of the uranium rod (1) and the bismuth-lead alloy flows through this tube as indicated by the arrow. (12) and (13) are the bottom and top of a tank which distributes the cooling agent into the lattice. (11) and (12) are the bottom and top of a space which distributes an inert gas into the annular gaps which heat insulate the uranium rods from the heavy water.

A heavy water plant of this type is shown diagrammatically in Figure 106. In this figure, (1) is a tank containing a lattice of uranium rods immersed in heavy water which forms the chain reacting unit. (2) is the electrodynamic control system which serves to stabilize the chain reaction which is described in detail in connection with Figure 41. Mercury may be used in place of the bismuth-lead-cadmium alloy in the case of heavy water power units in the stabilizer (2). The hot liquid bismuth-lead alloy leaves the chain reaction unit through tube (3) and this alloy is led through a boiler (4) in which steam is produced from water for purposes of power production. From the boiler the liquid bismuth-lead alloy goes through a pipe (5) into a heat exchanger (6) where it is cooled

down to a temperature slightly above its melting point of about 130°C. The cold liquid bismuth-lead alloy goes through the pipe (7) into the pump (8). From here through the pipe (9) it goes back to the top of the chain reaction power unit. (10) and (11) are pipes carrying water to and from the heat exchanger (6).

Figure 100 shows diagrammatically a lattice of cylindrical uranium rods embedded in graphite. This lattice is surrounded by a layer of graphite which serves as a neutron reflector. The lattice is cooled by liquid bismuth or a bismuth-lead alloy, the former being more favorable from the point of view of the efficiency of the chain reaction. The cooling agent is distributed by the pipe (1) to steel tubes (1), (2), (3), etc. (1) and (2) go through the peripheral of graphite layer whereas (3) goes through the cylindrical uranium rod (4), one of the lattice elements of the uranium rod lattice. The cooling agent is collected at the bottom of the pile in pipe (5).

Figure 100B shows the top view from which it is visible in what way the cooling agent is distributed on the top and collected on the bottom, carried by the pipes (6) and (7) respectively.

Figure 101 shows a diagram of a graphite power unit of this type. The chain reaction unit is contained in the steel tank (1). The system (2) which is described in detail in connection with Figure 41 serves the purpose of stabilizing the chain reaction unit. The cooling agent leaves the chain reacting unit at the bottom and goes through the heat exchanger (3) where it transfers its heat to a eutectic alloy of lead and bismuth. The bismuth-lead eutectic coming from the heat exchanger (3) transfers

heat to the boiler (4) in which steam for purposes of power production may be generated. After leaving the boiler (4) the bismuth-lead eutectic goes through the heat exchanger (5) in which heat is transferred to water and through the pump (6) back to the heat exchanger (3).

V

Arrangement Class 1C alpha.

Metal, Series Flow, (gravity flow)--Figure 40 shows an example in which the lattice is built of uranium metal rods. An element of the lattice is shown in the Figure. 401 is part of a graphite column which contains a cylindrical rod 402 of uranium metal which is surrounded by a thin steel tube 403, contained in a cylindrical bore in the graphite column 401, leaving an annular gap 404 between the graphite and the steel tube. This cylindrical uranium rod is hollow but no cooling agent is passed through the hollow space in the axis of the rod. The cooling agent flows in the downward direction through the whole length of the entire graphite structure in the annular gap 404. Figure 14 shows in what manner two adjacent sections of the graphite column are joined together. In Figure 14, 401 is the lower graphite brick and 405 is the adjacent brick, which are joined together to form part of the vertical graphite column which goes through the entire graphite structure.

Figure 41 shows an example where the lattice element is formed by an aggregate of 3 uranium metal rods. This aggregate forms an approximately triangularly-shaped rod which represents the lattice element. The 3 uranium rods 406, 407, and 408 are covered by thin steel tubes, one of which is designated by 409. The cooling agent passes downward in the space 410 inside the circular bore in the graphite brick 401. Figure 42 shows another example for an aggregate in which 7 uranium rods together form one lattice element. In Figure 42 we have 7 such rods

placed in a cylindrical bore of the graphite brick 401. The cooling liquid passes along this uranium aggregate in the space which is left free within the cylindrical bore in the vertical graphite column.

Figure 43 shows another example in which there are 4 uranium rods, (each within a thin steel tube) placed within a cylindrical bore in the graphite brick 401. 411 is a steel plate which serves to hold the 4 uranium rods shown in Figure 43 in position. That fraction of the cooling agent which flows within the uranium rod aggregate proper is deflected by the steel plate 411 and united with the main flow of the cooling agent which passes between the steel plate 411 and the surface of the cylindrical bore in the graphite column.

Figure 45 shows how one may assemble a lattice having lattice elements as those shown in Figure 40, in a manner which permits the removal of the uranium rod 402 of Figure 40 from the graphite structure. In Figure 45, (1), (2), (3), (4), and (5) are adjacent square graphite columns arranged in a vertical position. Uranium rods 402 form a lattice which has a tetragonal symmetry. A liquid Bi-Pb alloy flows from the pipe (10), (11), and (12) into the steel cylinders (13), (14) and (15) respectively. These steel cylinders communicate with the steel cylinders (16), (17) and (18) and the Bi-Pb alloy will have a certain level in the cylinders (13) to (18) and will flow under the action of gravity into the gaps 404 between the uranium rods 402 and the graphite. Bi-Pb alloy flows along the surface of the uranium rod through the whole structure and is collected in the

bottom, goes through a heat exchanger and is pumped back to the top of the structure. The steel rods (19) are attached to the uranium rods 402 and the uranium rods can be pulled out of the structure by means of the steel rods.

Uranium metal rod arrangement -- parallel flow. In Figure 33, 331 is a square shaped graphite brick with a cylindrical bore in the center. A uranium rod 333 covered by a thinwalled steel tube, 334 goes through the bore in the center of the graphite brick, leaving an annular space 335 free for the flow of the cooling agent. 332 is another square shaped graphite brick which forms together with 331 part of a vertical graphite column which goes through the entire pile structure. The cooling agent moves in the downward direction in the duct to 336. It enters the annular space 335 through the channel 337 from where about half flows upward and half flows downward in the annular gap surrounding the cylindrical uranium rod 333. The cooling agent which has been in thermal contact with the uranium rod 333 is collected in the duct 338 in which it passes through the pile in the downward direction.

Another similar arrangement in which the uranium rod is composed of a number of sections which are joined together in the same place in which the sections of the graphite column are joined together is shown in Figure 30. 301 and 302 are adjacent graphite bricks in the vertical graphite column. 305 is the annular gap surrounding the uranium rod 303. 304 is a thin steel tube

which covers the uranium rod 303. The cooling agent enters from the duct 306 into the annular space surrounding the two sections of the uranium rod which are shown in the figure through the channels 307 and 308. 309 and 310 are steel disks which center the uranium rods in the bore in the graphite column. Channels in these steel disks, like, for instance, the channel 311, permits a drainage of the cooling agent in case a liquid cooling agent is used. Otherwise, the same applies to the construction shown in Figure 30 as applies to the construction in Figure 33.

(Carbide Rods--Bi Cooling). Figure 17 shows a square shaped graphite rod 178 which forms part of the vertical graphite column that goes through the whole graphite power unit. A circular bore in the center of the square graphite rod contains cylindrical rods or uranium carbide 179, 180, 181, 182, and 183, etc.. These pieces of uranium carbide are piled up one on top of the other and aggregate into a long cylindrical rod of uranium carbide going through the whole length of the graphite structure. Each of the sections 179, 180, etc., has a shape similar to the cross section AA' in Figure 16c. The sections 179 and 180 are separated by a ring of uranium carbide 184 and similarly, sections 182 and 183 are separated by such a ring 185. The cooling agent flowing downward in duct 186 passes through the channel 187 into the interior of the ring 184 and about half of the amount entering into the ring 184 passes through the slits in 180, 181 and 182

into the interior of the ring 185. From here the cooling agent goes through the channel 188 and into the duct 189.

This arrangement represents again parallel flow. The length of the uranium carbide rod between 2 adjacent rings 187 and 188 will be smaller towards the center of the graphite structure and larger towards the periphery of the power unit as discussed above in conjunction with Figure 16.

A number of square-shaped graphite bricks 178 placed side by side in the manner shown in Figure 16a will form a tetragonal lattice of uranium carbide rods. If a graphite brick of a slightly different shape is used and placed side by side in the manner illustrated in Figure 16b, we obtain a trigonal lattice of cylindrical uranium carbide rods.

Figure 16 shows a graphite column 161, containing a string of short cylinders of uranium carbide, 162, 163, 164, 166. By placing a number of such graphite columns side by side, standing in a vertical position, one obtains a cubic lattice of short uranium carbide cylinders. The square shaped graphite rod 161 has a circular bore in its center and cylindrical graphite rods 167, 168, 169, 170, and 171 alternate with the above-mentioned short uranium carbide cylinders in this bore. A cooling agent, for instance, liquid bismuth, flows through the graphite column in the duct 172 and a certain fraction of this flow enters through the duct 173, the graphite rod 169. About half of this quantity flows through the uranium carbide cylinders 164 and 166 and the channel

174 to the duct 175 which passes downward through the graphite column 161. The rest flows through the uranium carbide cylinders 163 and 162 and enters through the channel 176 into the duct 175.

This type of flow we shall call parallel flow and in particular sections of the lattice which are shown in the drawing, two lattice elements are in series. The number of lattice elements which are in series may be different in different parts of the lattice. Near the center of the graphite where the neutron density is largest, we may have only few lattice elements in series or perhaps all lattice elements in parallel. Towards the periphery of the graphite structure, however, where the neutron density is lowest, a larger number of lattice elements may be connected in series. In this manner we may, if we wish, have approximately the same rise in temperature in the cooling agent which passes from one duct 172 to the other duct 175, in spite of the fact that the neutron density, and accordingly the heat production, differs greatly between the center of the graphite structure and the periphery.

Figure 15 shows how a vertical graphite column is built from several sections. In Figure 15, 161 is the square shaped graphite rod shown in Figure 17 and 177 is another square shaped graphite rod which is joined to the former in the manner shown in the figure. A ground surface of conical shape forms the seal for the cooling agent which flows through the ducts 172 and 175.

Figure 16a shows in what manner a cubic lattice is built from such square shaped rods, which, like 161,

have equal sides.

Figure 16b shows in what manner a close-packed lattice may be built up from graphite rods for which the ratio of the two sides is 3:2. These two figures, 16a and 16b, may be understood without further explanation if viewed in conjunction with Figure 16.

Figure 16c shows a cross-section and a side view of the uranium carbide plugs numbers 162, 163, 164, and 166 in Figure 16. Section AA' in Figure 16c shows the slits in which the liquid cooling agent can flow through the uranium carbide plug.

It is of advantage to surround the lattice which is embedded in a slowing agent with a layer which is composed of a scatterer that has a low absorption for thermal neutrons. Heavy elements which have a low absorption, such as lead or bismuth, can be used, and bismuth is preferable to lead from the point of view of low neutron absorption for equal scattering cross section. Graphite can be used as a scatterer and a layer of graphite about 50 cm thick has a considerable effect in reducing the critical thickness of the lattice. Layers containing one or more of such scattering elements may be used, and the combination of graphite and a heavy element if used as a scattering layer acts also partially as a neutron and gamma ray shield.

Such shields are necessary in order to protect personnel from the action of these penetrating radiations. In order to get perfect shielding, one has to use, outside the reflector, a shield which contains elements that absorb thermal neutrons. A shield built of layers of

graphite and iron is suitable; graphite and iron built up in alternate layers form a satisfactory shield against neutrons and gamma rays, if the weight ratio is about 2 to 3 in favor of iron and the thickness of the layer is adequate.

Use of Beryllium.

Uranium spheres surrounded with a layer of beryllium or cylindrical uranium rods surrounded with a cylindrical layer of beryllium, may be used as lattice elements in a lattice which is embedded in graphite or heavy water. Spheres of uranium metal, 5 cm in diameter, surrounded by a $2\frac{1}{2}$ cm layer of beryllium metal are, for instance, an example of the lattice element which can be used in graphite to be in the potentially chain reacting unit. An example for a lattice element in which a cylindrical rod of uranium is surrounded with a layer of beryllium is shown in Figure 80.

May 25, 1943

VI

CONTROLS

Various ways of controlling the chain reaction are illustrated in the following figures. Figures 50 and 50b show a cylindrical graphite structure (1) of about equal diameter and height. The core (2) of this pile, as defined by the dotted line, may weigh about 500 tons and contains the uranium lattice. The graphite layer (10) (between two dotted lines) serves as a reflector for the neutrons and a layer (11) on the periphery of the structure which is built of alternate layers of graphite and iron serves as a radiation shield. A number of thin-walled steel tubes, 4, 5, 6, of about 1 cm diameter and .2 mm wall thickness go through the core of the graphite pile and rods, 7, 8, 9, built of slow neutron absorbing material, for instance steel or cobalt or an iron-cobalt alloy of high cobalt content, or nickel or a nickel-cobalt alloy can be moved up and down within these steel tubes. The thin-walled steel tubes are satisfactory from the point of view of having a low absorption, provided that the diameter of the tube is small compared to the mean free path of the thermal neutrons in graphite. Since this is about 2.5 cm, tubes of 1 cm diameter fulfill this condition. These neutron absorbing rods may be hollow tubes, and may be cooled by having a flow of a suitable cooling gas, maintained through the tubes 4, 5 and 6, as indicated by the arrows in the figure. All these rods may be rigidly held together and moved jointly up and down, the movement be controlled by the radiation emanating from the chain reaction, by means of an ionization chamber. If the radiation increases the current through the ionization increases and by means of a suitable amplifier and relay a motor may be set into motion which moves the control rods

inward in the chain reacting pile. If the radiation decreases the current in the ionization chamber decreases and by means of a suitable gadget the motor may be reversed and the rods may be moved in the upward direction out of the interior of the pile. If the system is damped it is adapted to stabilize the chain reaction if above a certain radiation intensity the motor is set into motion moving the rods in the downward direction and below a certain radiation intensity the motor is set into motion pulling the control rod upward out of the interior of the pile.

Figure 41 shows another way of controlling the pile. In Figure 41 (1) is a thin-walled steel tube of about 1 cm diameter and .2 mm wall. It goes vertically through the pile and forms together with a tank (4) which is outside the chain reacting unit, a communicating system. This system contains a bismuth-lead-cadmium alloy which is a liquid down to low temperatures and an electrodynamic pump (3) is so connected as to pump this absorbing liquid out of the pile and into the tank (4) if a sufficient electric potential is applied to the stator of the pump. If the pump is switched off the cadmium alloy flows from the tank into the pile and stops the chain reaction. An ionization chamber which is exposed to the radiation of the pile controls the potential on the stator of the pump in the following manner: if the current through the ionization chamber is low the potential applied to the pump is high and accordingly the equilibrium position of the liquid cadmium alloy column in the pile towards which the liquid alloy meniscus moves is comparatively low. Accordingly, the cadmium alloy moves in the system towards the tank (4) and thereby increases the intensity of the chain reaction

and increases the current through the controlling ionization chamber. Thereby, the potential applied to the electromagnetic pump is decreased and the equilibrium position of the meniscus in the steel tube (1) is raised, so that the cadmium alloy may now be pumped out of the tank 4. In this manner the chain reaction can be controlled in a satisfactory manner if the controlling system is sufficiently strongly damped. If this type of control is used we may have several independent controlling units as indicated in the view shown in Figure 4lb.

The steel tube (1) is cooled by a cooling agent, for instance liquid bismuth or a liquid bismuth-lead alloy which flows in an annular gap between steel tube (1) and the surface of a circular bore in the graphite column which contains the steel tube (1). The electrodynamic pump (3) is cooled by a flow of the cadmium alloy through a cooler (5) which is connected to the entrance and exit tubes to the electrodynamic pump (3). A valve (6) controls the flow through the cooler (5) in such a manner that this flow should be small compared to the pumping capacity of the pump (3).

In place of a cadmium, alloy, mercury can be used inside a thin-walled steel tube of about 1 cm diameter provided that the temperature at which the power unit operates is sufficiently low, otherwise the mercury pressure would disrupt the thin-walled steel tubes. Two concentric steel tubes may be used leaving an annular gap in which a liquid Bi-Pb alloy (eutectic) flows for the purpose of cooling the mercury inside the inner steel tube. If it is desired to use water in place of the liquid Bi-Pb alloy as a cooling agent, both steel tubes ought to be preferably stainless steel tubes in order to avoid corrosion by the water.

Another way in which the chain reaction may be controlled is shown in Figure 142. In this figure (1) is a uranium sphere, (2) is a rod composed of a thermal neutron absorber moving in a vertical tube (3). Section (2) of the control rod (5), which is composed of an element that strongly absorbs thermal neutrons, is near the center sphere and is shielded by the uranium from thermal neutrons so that it is in a position where the thermal neutron density is comparatively low. This absorbing section of the control rod can move within a tube in the vertical direction and its position may be controlled by the intensity of the neutron radiation emitted by the chain reaction. If the intensity of this radiation increases the absorbing section of the rod may be automatically moved away from the center of the uranium sphere and ultimately, if required, may be moved entirely out of the uranium sphere. It will then absorb larger and larger numbers of thermal neutrons thereby reducing the fraction of the neutrons which are absorbed in the thermal region by uranium, thus stabilizing the chain reaction. In Fig. 142 (6) is liquid bismuth or bismuth alloy which may serve as a cooling agent.

Apart from the control rods or liquid containing control tubes we may have safety devices of a similar structure as the control devices which operate only in case of an emergency and have the purpose of stopping the chain reaction if the radiation emitted in the chain reaction becomes too intense. Since these devices stop the reaction in a very short time it is not necessary to have them cooled. We may have, for instance, a number of rods similar to those shown in Figure 50 which are entirely moved out of the pile and are suspended by an electromagnet. If the radiation becomes too intense the magnet is switched off and the rods fall under the action of gravity into the pile.

May 25, 1943

VII

SLOWING AGENTS

If we have a lattice of aggregates which contain in sufficient concentration uranium that is sufficiently enriched in U^{235} or element 94^{239} or U^{233} embedded in a slowing agent we may have a chain reacting system for a number of slowing agents. Water can, for instance, be used as a slowing agent in such systems. However, if we have a system in which natural uranium is used or at least if natural uranium is used to start with, the slowing agent has to be selected from a very narrow choice of slowing agents which we have called "efficient" slowing agents. In the following, we characterize this class of slowing agents by their various properties:

First, in order to have a practical system the efficient slowing agent must be of sufficient density and, therefore, must be either liquid or solid at operating temperature and pressure, and preferably also at room temperature and atmospheric pressure.

Secondly, it is necessary that the efficient slowing agent should show a favorable balance between neutron absorption and the slowing down ability of the slowing agent. In this respect it must be about as favorable as or more favorable than impure graphite which has an average capture cross section per carbon atom of $\overline{\sigma_c}$ (C) 0.01×10^{-24} cm^2. The absorption cross section of pure graphite is considerably smaller, about 0.005×10^{-24} cm^2; but if impurities are present in the graphite which raise the average absorption cross section into the neighborhood of 0.01, we can still have a chain reaction in a system of otherwise favorable composition and structure. This is no longer

possible if we allow the cross section of the slowing agent of the carbon atom to rise above approximately 0.01×10^{-24} cm^2.

Carbon and other light elements can be characterized from the point of view of their suitability as slowing down agents in a chain reaction by a dimensionless constant, N, which we may call the characteristic number of the slowing agent. This number, N, is defined by the following formula:

$$N = \frac{\sigma^*_{sc}}{\sigma_c} \qquad \ln\left(1 + \frac{2m}{1+m^2}\right)$$

where m is the mass number of the element, σ^*_{sc} is the scattering cross section of the element for neutrons which are above the thermal region and have energies between a few volts and a few hundred volts, and σ_c is the capture cross section of the element in the thermal region. For pure carbon [σ_c (C) $\sim 5 \times 10^{-27}$ cm^2 and m equal 12] the characteristic number N(C) is about N(C) $\sim$ 160.

As we have stated before, impure carbon for which the absorption cross section σ_c is about twice that of pure carbon is close to the limit at which a chain reaction is no longer possible in graphite. Such impure graphite would have a characteristic number of $N = \frac{1}{2} N(C) = 80$. Accordingly, we may define the class of slowing agents which are capable of sustaining a chain reaction in natural uranium by the requirement that the characteristic number, N, must necessarily be larger than 80 and should preferably be appreciably higher. A value of N = 120 would be already quite satisfactory. This requirement is fulfilled for carbon in the form of pure graphite and for heavy hydrogen in the form of deuterium oxide. In order to compute the approximate value for the characteristic number, N, of deuterium oxide, we have therefore,

$$m = 2; \sigma_c = \sigma_c(D) + \tfrac{1}{2}\sigma_c(O); \sigma^*_{sc} \sim \sigma^*_{sc}(D).$$

The criterion of the characteristic number must, however, not be applied to elements which apart from scattering fast neutrons undergo also other reactions with fast neutrons such as n-2n, n-p, or n-α reactings.

Apart from N, the characteristic number of the slowing agent, another property of the slowing agent has a bearing on the question whether the slowing agent is an efficient slowing agent and suitable for a system in which a lattice of uranium-containing aggregates is used. For a slowing agent, it is of advantage in this connection that the range, A, of the thermal neutrons should be large in comparison with range, B, of the low energy resonance neutrons.

A, the range of the thermal neutrons is defined by the value

$$A = \lambda \sqrt{\frac{\sigma_{sc}}{3\sigma_c}} \qquad (3)$$

where λ is the mean free-path of thermal neutrons in the slowing agent, and σ_{sc} and σ_c are the scattering cross section of the capture cross section for thermal neutrons of the molecule which acts as the slowing agent.

B, the range of the low energy resonance neutrons is defined by

$$B = \lambda * \sqrt{\frac{k}{3}} \qquad (4)$$

where $\lambda *$ is the mean free path for scattering of neutrons having the energy between few volts and a few hundred volts in the slowing agent, and k is defined as follows:

$$k = \frac{\ln 1/10}{\ln \left(1 - \frac{2m}{(1+m)^2}\right)} \qquad (5)$$

If, instead of an element like carbon, a compound of a light element and a much heavier element is used as

slowing agent, the value given for k has to be multiplied approximately by the fraction of the scattering cross section of the molecule of the compound which is due to the light element.

For D_2O, for instance, one has to multiply k by approximately

$$\frac{2\ \sigma_{sc}(D)}{2\ \sigma_{sc}(D) + \sigma_{sc}(O)}$$

Accordingly, the requirements that the range A should be large compared to the range B amounts to

$$(6) \qquad A/B = \frac{\lambda}{\lambda^*} \sqrt{\frac{\sigma_{sc}}{\sigma_c\ k}} >> 1$$

or writing $\frac{\lambda}{\lambda^*} = \left(\frac{m}{m+1}\right)^2$

$$(7) \qquad A/B = \left(\frac{m}{m+1}\right)^2 \sqrt{\frac{\sigma_{sc}}{\sigma_c\ k}} >> 1$$

This condition is fulfilled for graphite, heavy water, and beryllium.

For instance, for carbon we have about

$$k \sim 15$$

$$\frac{\sigma_{sc}}{\sigma_c} \sim 1000$$

$$\left(\frac{m}{m+1}\right)^2 = \frac{1}{1.18}$$

$$A/B \sim 7$$

which is a satisfactory ratio.

FUNCTIONAL DESCRIPTION

Of the thermal neutrons which are absorbed in the uranium contained in the lattice-element a fraction will cause fission and will give rise to the emission of fast fission neutrons. Some of these fast fission neutrons will cause fission (in the same lattice element from which they originate) before they are slowed down by collisions with uranium or carbon below the fission threshold of the abundant isotope U^{238}. In this manner, for every thermal neutron absorbed a certain number, η, of fast neutrons are generated which are slowed down partly by inelastic collisions in uranium, but mostly by elastic collisions in carbon and a fraction $(1 - p)$ of these eventually reaches thermal energies. Another fraction p is absorbed at resonance by uranium before reaching thermal energies.

The neutrons which are absorbed at resonance by uranium are removed from the chain reaction without leading to fission and the generation of neutrons. Some of these neutrons are absorbed at comparatively high energies, between a few hundred volts and some 10,000 volts, while others are absorbed at comparatively low energies, between a few volts and a few hundred volts. The lattice elements are moderately transparent for the high energy resonance neutrons but are practically black for at least part of the low energy resonance neutrons, i.e., a certain fraction of the resonance neutrons is absorbed in a thin surface layer of the lattice element whereas another fraction penetrates. Accordingly, the resonance absorption of the lattice element may be divided into two terms, one of which may be called surface absorption and one of which may be called mass absorption. If the dimensions of the lattice element are small, the fraction of the neutrons

which is removed from the chain reaction by mass absorption is essentially determined by the ratio of uranium to carbon and is independent of the shape and size of the lattice elements. If it were only for this type of resonance absorption it would be immaterial how small we make the lattice elements and we could make them very small indeed and still have a potentially chain reaction system.

In reality a graphite system in which the dimensions of the lattice element are made very small are not potentially chain reacting since too large a fraction of the neutrons would be removed from the chain reaction by the surface resonance absorption. Clearly if for a given ratio of uranium to carbon we decrease the dimensions of the lattice elements we increase the total surface and thereby the fraction of the neutrons which are removed by absorption at resonance.

In most practical cases a lattice element can be fairly well represented by replacing it with an ellipsoid and we may then express the above-mentioned point of view by saying that the smallest of the three axes of that ellipsoid must not be made too short compared with the range of thermal neutrons in the lattice element. This range "U" is proportionate to the density of the U in the lattice element and increases with the temperature of the neutrons somewhat faster than the fourth root of the temperature. For room temperature and uranium metal of density 18 the range is about 1.4 cm.

Approximate Theory

A very simple but only approximately correct theory of the most important quantities which enter into the construction of a potentially chain reacting system had been given for a lattice, for instance, a close-packed lattice, the elements of which are spheres of uranium metal, in an unpublished paper submitted to Phys. Rev. in February, 1940. The outlines of this theory are the following:

The picture is simplified by assuming that the fast neutron generated in a chain reacting lattice can be considered as produced uniformly throughout the graphite within the cell of the lattice (Q fast neutrons per cc and sec). The average thermal neutron density within the lattice is smaller by a factor $\mathcal{L}$ than it would be in graphite in the absence of uranium for equal fast neutron production per cc in graphite. The approximation used in the theory assumes that the flow of thermal neutrons j_{th} into a uranium sphere within the lattice is equal to $\mathcal{L} j_{th}$ where j_{th} is the flow of thermal neutrons into a single uranium sphere embedded in an infinite amount of graphite for equal production of fast neutrons per cc in graphite. The theory further assumes that the flow of resonance neutrons, j_{res}, into a sphere in the lattice is equal to j_{res} the flow of resonance neutrons into a single sphere embedded into an infinite amount of graphite for equal fast neutron production per cc in the graphite.

With these assumptions it is easy to determine the fraction q of the neutrons which are slowed down to the thermal region and are absorbed in the thermal region by the uranium spheres in the lattice. For a uranium sphere of given radius R, the most favorable ratio of uranium to carbon (the most favorable lattice spacing) is the ratio for which q becomes a maximum. For the corresponding value of $\mathcal{L} = \mathcal{L}_m$, the theory gives the equation

(8) $$\mathcal{L}_m = \frac{1 - \mathcal{J}_m}{2}$$

Since $\mathcal{L}$ is equal to the fraction of the neutrons which are slowed down to the thermal region and are absorbed in the thermal region by carbon, and since q is the fraction of the usefully absorbed neutrons, the above equation expresses the fact that for the most favorable ratio of uranium to carbon, half of the neutrons which are not usefully absorbed are absorbed as thermal neutrons by carbon. It follows that the other half of the 'not-usefully' absorbed neutrons must be absorbed at resonance by uranium. This fact can be expressed by writing:

(9) $$\frac{1 - \mathcal{J}_m}{2} = \frac{1}{V} \quad \frac{\mathcal{J}_{res}}{Q}$$

which we can write also in the form

(9a) $$\frac{1 - \mathcal{J}_m}{6} \quad \frac{4\pi R^3}{3} \quad \left(\frac{\mathcal{J}_{res}}{Q\ 4\ R^3}\right)$$

The expression $\mathcal{J}_{res}/Q$ signifies the number of resonance neutrons absorbed per sec by a single sphere of uranium which is embedded in an infinite mass of graphite if one fast neutron is produced in the graphite per

cc and sec; V stands for the volume of graphite per uranium sphere in the lattice. (9A) may be used to calculate $\frac{4\pi R^3}{3} \Big/ V$, the ratio of uranium volume to carbon volume in the lattice. From this, the ratio of weights is obtained by multiplying with the ratio of the densities.

q can be calculated within the validity of this simple theory for any given radius R of the uranium spheres which form the lattice element from ε, the ratio of the thermal neutron absorption to the resonance neutron absorption which holds for a single sphere of the radius R that is embedded into an infinite mass of graphite in which there is a uniform production of fast neutrons per cc of graphite.

According to the above definitions we may write for

(10) $$\varepsilon = \frac{J^{th}}{J^{res}}$$

According to the simple theory, we may calculate q from ε from the equation

(11) $$\varepsilon = \frac{4\, J m}{(1 - J m)^2}$$

In order to obtain an approximate value for $\frac{J^{res}}{Ce}$ the resonance absorption of a uranium sphere may be represented for a given size sphere by assuming that the uranium is black for resonance neutrons with a certain energy interval and does not absorb resonance neutrons outside that energy interval. The resonance absorption of the uranium sphere is then determined by a certain range B of the resonance neutrons in graphite, for which we may write

(12) $$B = \frac{\lambda^*}{\sqrt{3}} \sqrt{\frac{\ln E_1/E_2}{\ln \left(1 - \frac{2m}{(1+m)^2}\right)}}$$

where E_1 and E_2 are the limits of the energy interval within

which the uranium is considered as black for resonance neutrons. Or putting in general $E_1/E_2 = 1/10$ and for graphite in particular, m = 12. We obtain for graphite of density 1.7

(12b) $$B \sim \frac{\lambda^*}{\sqrt{3}} \sqrt{6.5 \ln 10}$$

If the resonance absorption of the uranium sphere is thus represented, we may write

(13) $$\frac{\text{Ques}}{Q} = 4\pi RB^2 \ (1 + R/B)$$

so that we have from 9a

(14) $$\frac{1 - \varrho m}{2} = \frac{4\pi RB^2 \ (1 + R/B)}{V}$$

or

(15) $$\frac{4\pi R^3/V}{3} = \frac{1 - qm}{6} \ \frac{R^2}{B^2} \ \frac{1}{1 + R/B}$$

Within the limits of the approximation for the resonance neutron absorption, we may write for

(16) $$\varepsilon = \frac{A^2}{B^2} \times \left\{ \frac{1}{1 + R/B} \times \frac{1}{\frac{\nu(C)}{RG\sqrt{\frac{3\,6a\,(U)}{\sigma sc\,(U)}}} + \frac{1}{1 + R/A}} \right\}$$

where

(17) $$G = \frac{e^{R/U} - e^{-R/U}}{e^{R/U} - e^{-R/U}}$$

and

$$R/U \quad \frac{R}{\nu(U)} \sqrt{\frac{3\,6a(U)}{\sigma sc(U)}}$$

According to the simplified theory, we obtain the highest value of q for a value of R for which ε becomes maximum. In choosing the most suitable size for the lattice element, there are, however, other points of view

which have to be considered and the value of R = 5 cm for a uranium density of 15 gm/cm^2 was recommended on the basis of this simplified theory. A ratio of about 30 tons of uranium per 100 tons of graphite was recommended for R = 5 cm.

It should be noted that while this simplified theory may be applied to small uranium spheres, and while the formulae give correctly the trend which characterized the variations of q, ε, and V, the formulae given are not strictly speaking correct and in order to improve them, one would have to consider η and B as functions of R. The variation of η with R may then take into account the fact that the neutron contribution of fission caused by fission neutrons in the uranium sphere increases with increasing R and by writing B as a function of R, we may account for the fact that the uranium sphere is not black for higher energy resonance neutrons so that we have a term in the resonance absorption which is proportionate to the mass of the sphere. The corrections which one would have to apply, cancel out, however, rather well for spheres of about 5cm radium. By neglecting the fission by fission neutrons, we have shifted the optimum towards smaller spheres than would correspond to reality, while by neglecting the absorption of higher energy resonance neutrons, we have shifted the optimum towards larger spheres than would correspond to reality. Finally, by writing

we have tended to favor smaller spheres than correspond to reality.

A 5 cm sphere of 15 gms/cc density weighs about 7.5 kg, and it may be that from the strict point of view of having the highest value for q, a somewhat smaller mass of the lattice element which has a spheroid shape would be preferable, if no gap is left free between the lattice element and the graphite mass which contains the lattice.

The formula 9A or 15 permits a quick survey of the most favorable ratio of uranium to carbon if various factors are varied, since the value of q does not change much, with the radius or the density of the uranium in the sphere as long as we do not go to extreme values. With q having a value between .7 and .8, one has only to insert into 9A or 15 the value for g^{res} or B respectively, to obtain the approximate ratio of the volume of uranium to carbon. By multiplying this with the ratio of the densities, one obtains the ratio of the weights of uranium to carbon.

As it has been stated before, a lattice of uranium spheres is capable of maintaining a chain reaction even in impure graphite which corresponds to a capture cross section of carbon of nearly 0.01×10^{-24} cm^2, particularly if the uranium is cooled while part of the graphite is allowed to heat up. If the uranium and enough of the surrounding graphite is kept cool, the thermal neutrons which diffuse to the uranium spheres will be cold even though the rest of the graphite has been allowed to heat up. In these conditions of the neutrons which are slowed down to thermal energies, a smaller fraction is absorbed by carbon and a larger fraction is absorbed by uranium, than would be the case for a uniform temperature throughout the lattice. In order to maintain a large temperature difference with the

heat flow that can be taken care of by the cooling system, the uranium and its surrounding graphite layer may be thermally insulated from the rest of the graphite by a gap (which may be filled with lamp black or some other fluffy material that does not appreciably absorb neutrons). Structurally, these conditions are easier to realize for a lattice of rods than for a lattice of spheres.

The approximate theory which treats all the resonance absorption as surface absorption and which leads to formula 15 gives a somewhat too rapid rise of the ratio of carbon weight to uranium weight with the increasing radius R, and one may, therefore, not extrapolate to very small values of R from formula 15.

For instance, for a density of 18 and a radius of 3 cm the most favorable ratio of carbon weight to uranium weight is close to 4.5, whereas formula 15 would give a larger value. If we have to deal with such small spheres we may replace the lattice of spheres by a lattice of cylindrical rods by choosing the radius of the cylindrical rod to about two-thirds of the radius of the sphere and by having in both cases about the same ratio of weights of carbon to uranium. Accordingly, for a lattice of cylindrical rods of a radius of 2 cm a ratio of carbon weight to uranium weight of about 4.5 is close to the most favorable ratio. A sphere of 2 cm radius and density 18 would require a carbon to uranium weight ratio of about 5.5 and about the same weight ratio would correspond to a lattice of cylindrical rods if the rods have a radius of 2 x 2/3, or about 1.3 cm.

If we have to deal with such spheres or cylindrical rods of such small radius and if we change the bulk density of the uranium, then we ought to increase the radius of the sphere or the radius of the cylindrical rod in the following manner: in the case of a sphere the radius should be changed so that the weight should lie somewhere between the product of the old weight multiplied with the ratio of the densities and the old weight multiplied with the square of the ratio of the densities. The corresponding size for the cylindrical rods is again obtained by multiplying the radius of the sphere with 2/3

in order to obtain the radius of the cylindrical rod. In practice the greatest change of density will be a reduction of the density by a factor 2. For a density of 9 and the radius of 3 cm the ratio of weight of carbon to the weight of uranium for a lattice of spheres would be about 6.2 and the same would hold for lattices of cylinders of density 9 and radius of 2 cm. Such low bulk densities may occur if either uranium carbide is used or if an aggregate of uranium metal is used in a helium cooled lattice.

While for a simple body like a sphere, the surface of the sphere determines the value of the surface absorption, for more complicated shapes it is not always the total surface of the uranium which counts. For instance, if we have a rod of uranium which has a cross section as illustrated in Figure 2, and if this rod is placed in a cylindrical hole in the graphite, it is the surface of the cylinder and not the surface of the rod which determines the surface absorption. Moreover, internal surfaces which are not exposed to neutrons coming from the graphite but are shielded from such neutrons by uranium do not contribute to the surface absorption. Such internal surfaces fall into two categories: we may have a lattice element consisting of a single body which has slits or holes going through it so that internal surfaces arise; or we may have an aggregate of a number of uranium bodies assembled together and have the aggregates play the role of one single lattice element. An example for this has been described in connection with Figure 1.

The absence of surface absorption on internal surfaces makes it possible to have heat transfer from the lattice element to the cooling agent across internal surfaces without appreciable loss of neutrons. This is

certainly true if we use as a cooling agent a gas like helium at a density which corresponds to about 10 times atmospheric pressure, since, at this density, the gas does not appreciably slow down neutrons in their passage from a point of internal surface to another point of internal surface. It is also true if we use as a cooling agent a heavy liquid metal like bismuth in thin layers since bismuth, on account of its great atomic weight, does not appreciably slow down low energy resonance neutrons.

Heavy Water

The considerations which were applied above lattices of uranium-containing aggregates in graphite can also be applied to such lattices contained in certain other slowing down media with the exception of media in which hydrogen is the slowing agent.

If heavy water is used as a slowing agent in place of graphite, it is of interest to know the ratio of the weights of heavy water to uranium which is equivalent to a given ratio of carbon to uranium in the sense that a lattice of a given uranium-containing aggregate has the same resonance absorption in both cases. We obtain equivalent systems if we replace eight carbon atoms by about one molecule of heavy water; i.e., four carbon atoms by one atom of deuterium and a half atom of oxygen. Expressed in terms of weights this means that for equivalent lattice systems, the weight ratio of heavy water to uranium has to be about 4.8 times smaller than the weight ratio of graphite to uranium.

This statement concerning the equivalent amounts of carbon and heavy water for equal resonance absorption is derived from a scattering cross section of deuterium for resonance neutrons having a value between 3 and 4 (about 3.3), and from a scattering cross section for carbon of 4.8/1.18 4. The slowing down per collision of carbon and deuterium is determined by the masses of the carbon and deuterium atoms. The number of collisions needed to slow down the neutron from E_2 to E_1 is for carbon

$$k(C) \quad 6.5 \ln E_2/E_1$$

The same number for collisions with deuterium is

$$k(D) \quad 1.4 \ln E_2/E_1$$

The ratio of the corresponding numbers of atoms of carbon and deuterium is accordingly

$$\frac{3.3}{1.4} \Big/ \frac{4.8}{1.18} \quad \frac{1}{6.5} \quad 3.8$$

However, if deuterium is used in the form of heavy water, a slight correction is to be applied to take into account the slowing down by oxygen so that 4 may be taken for the ratio of the equivalent number of atoms of carbon to deuterium.

Since carbon has a thermal absorption cross section of about 0.005 and the thermal absorption of heavy water per deuterium atom may be taken for the purpose of the present discussion to be about 0.003, it follows that of the two systems which have equal resonance absorption, the one in which the slowing down is due to deuterium is more favorable. It may, therefore, be stated that if a given lattice in graphite is capable of maintaining in a sufficiently large mass a chain reaction, the equivalent lattice in heavy water is also capable of maintaining a chain reaction in a sufficiently large mass. If we take a lattice element of uranium metal which is close to the most favorable case in graphite, then a heavy water system which is equivalent to the most favorable graphite system can be made potentially chain reacting with a quantity of about 20 tons of heavy water.