put?

General Statements about Cooling Agents

Most of the heat generated in the chain reaction is generated by the fission process in the lattice element and the cooling agent must, therefore, be in good thermal contact with the lattice element. Some heat, however, is generated in the graphite, where the neutrons and gamma radiations emitted in the fission process are scattered or absorbed. The uranium graphite lattice may be surrounded by a layer of graphite which does not contain uranium and a further layer of material which serves as a radiation shield. This radiation shield may be a heterogeneous system composed of iron and graphite. Heat is produced both in the scattering layer and the radiation shield while neutrons and gamma rays are scattered or absorbed. Provisions must be made for cooling of both the scattering layer and the radiation shield.

The chain reacting pile should be enclosed into a steel tank and an inert atmosphere be maintained within the tank. Helium gas is a suitable inert gas for this purpose both because it does not absorb neutrons and because it facilitates the heat transfer across gaps between solid bodies.

Helium gas can also be used as a cooling agent and may be circulated either in parallel flow or in series flow through the graphite pile. See examples given in figures . Another, and the most obvious cooling agent is, of course, water. If water is used, it is advisable to use series flow, have a closed circulation, and have the water flow through pipes which are inserted into the graphite pile. It is advisable to protect the uranium against chemical action by water and a possible arrangement is shown in Fig. 3. In Fig. 3, (1) is a uranium rod which forms the lattice element. This uranium rod is covered with a thin aluminum tube (2). This Al-covered uranium rod is placed inside an aluminum tube (3) which goes through the graphite pile. The gap between the Al tube and the graphite is kept as small as possible. Water is flown through for allowing for the passage of the cooling water the anular gap between the Al tubes (3) and the Al-covered uranium rod (1). In order to have a potentially chain reacting system, it is necessary to have the gap which is filled with water rather small, but if the uranium rod has a diameter of about 3 cm. and if the gap is about 1 mm. and if water is flowing through the gap, we still have a potentially chain reacting lattice.

Fig 4 If liquid bismuth is used as a cooling agent, we may have either parallel or series flow. The liquid bismuth may be in direct touch with the graphite and we may have either closed circulation or a gravity flow through the pile. Uranium carbide may be used in direct contact with bismuth, but uranium metal may be used coated with iron. If uranium rods are used, a thin steel coating consisting, for instance, in a thin steel tube covering the uranium rod will permit the construction of a potentially chain reacting unit if the wall thickness of the steel tube is about 1% of the diameter of the uranium rod or less. In the example given in figures   , such steel coated uranium rods are drawn. If the same arrangement is used for He cooling rather than bismuth cooling, the uranium may remain uncoated.

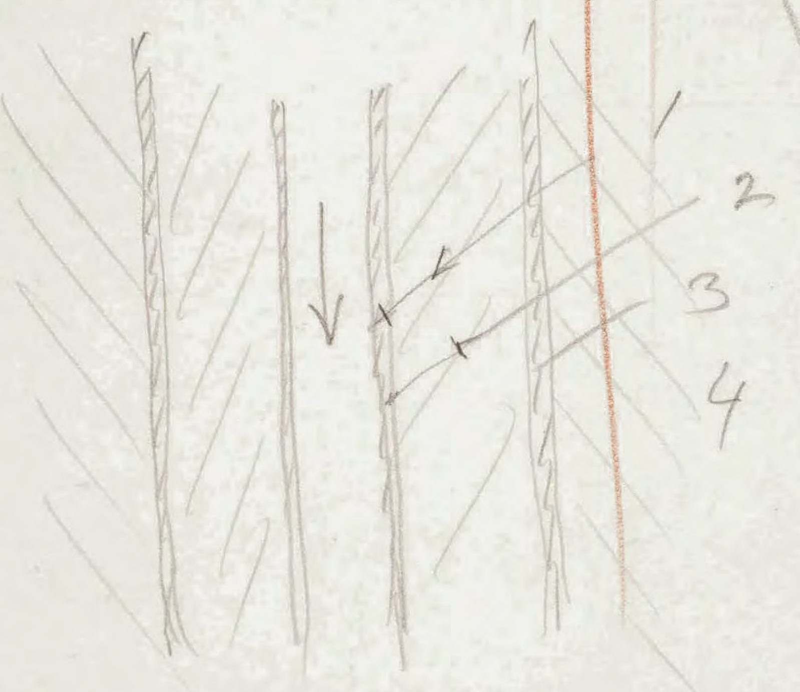

Fig 4

the annular gap between the Al tubes (3) and the Al-covered uranium rod (1). In order to have a potentially chain reacting system, it is necessary to have the gap which is filled with water rather small, but if the uranium rod has a diameter of about 3 cm and if the gap is about 1 mm and if water is flowing through the gap, we still have a potentially chain reacting lattice.

Figure 4 shows a somewhat different cooling system. In figure 4, (1) is a cylindrical uranium rod which forms the lattice element. An Al tube (2) is in thermal contact with the uranium, and water flows through this Al tube. (3), is an Al coating which covers the outside of the cylindrical uranium rod and (4) is the graphite into which a lattice of such uranium rods is embedded.

If liquid Bi is used as a cooling agent in a system described by figure 3 or figure 4, steel coatings or steel tubes have to be used in place of Al coatings or Al tubes. The steel coatings or steel tubes will not prevent the chain reaction, but in order to keep the losses sufficiently low, it is advisable to cover the wall thickness of the steel tubes or steel coatings down to about 1% of the diameter of the uranium rod. In the examples given in figures

such steel coated uranium rods are drawn.

If liquid Bi is used as a cooling agent it may be allowed to be in direct touch with the graphite and need not have a closed circulation but may have a gravity flow of liquid Bi through the chain reaction pile. Uranium metal must not be used in direct contact with Bi but uranium carbide may be used in that manner.

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 belongs 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).

General Remarks on Cooling

A suitable cooling agent for a chain reaction unit are heavy low melting metals which have a low absorption for slow neutrons. Examples for this are liquid bismuth, alloys of bismuth and lead, and liquid lead. 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. But those of the bismuth-lead alloys which do not melt uranium metal up to temperatures of 200°C can be used in direct contact with the metal. 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 cool it down in 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 channel 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 belongs to the type of series flow. Whereas, 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 and 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 may be used if a non-wetting Bi-Pb alloy is used as a cooling agent. Uranium tubes and tubes made of some of the above mentioned 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.

L. Szilard
May 13, 1943

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 but 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 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 ~~may~~ it ought to count on an increase of μq by 2%. In this way, depending on the quantity of the cooling agent and according to the neutrons 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 for example 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 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, ~~bundles of rod-like aggregates composed of a cluster of thin rods.~~ These lattice elements are all supposed to be vertical and form a lattice of ~~three-gonia~~ hexagonal or tetragonal symmetry. They are designed for series flow in contrast to parallel flow which we will mention further below. and are designed for closed circulation, not gravity flow.—

Cooling of lattice elements

In Figure 3, (1) is a cylindrical uranium rod covered by a ~~thin~~ layer (2). An annular gap (4) is left free for the flow of the cooling agent inside the tube (3) which is embedded in a mass of the slowing agent (5).

This arrangement can be used if a gas is used as a cooling agent.

If water is used as a cooling agent, the layers (2) and (3) can be made of aluminum and the slowing agent may be either graphite or heavy water.

If bismuth or a liquid bismuth-lead alloy is used as the cooling agent and graphite is used as the slowing down agent, the layer (2) may be a thin-walled layer of steel which is in good thermal contact with the cylindrical uranium rod, and the tube (3) may be left off and the liquid bismuth or bismuth-lead alloy may be allowed to be in contact with the graphite.

Figure 4 shows another example. In this figure, (1) is a cylindrical uranium rod; (2) is a thin-walled tube in the axis of thr uranium rod (1). A cooling agent (3) flows through the tube (2). (4) is a layer covering the uranium rod which is embedded in a mass (5) of the slowing agent. If a bismuth-lead eutectic allow is used as a cooling agent the tube (2) can be a thin-walled steel tube in good thermal contact with the uranium and this arrangement can be used with graphite used as a slowing agent (4).

Figure 5 shows another example. In Figure 5, (1) is a cylindrical uranium rod; (2) is a thin-walled steel tube; ~~(3) is~~ a cooling agent is flowing through the steel tube (2) in the axis of the uranium rod (1). (4) is a ~~coating~~ 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.

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In the case of the cooling system illustrated by Figure 3, the cylindrical uranium rod could be replaced by clusters such as shown in Figures 41, 42 or 43 (which deal with uranium lattices in which the cooling agent circulates by gravity flow in graphite and which are described further below.) In the case of the cooling system illustrated in Figure 3, it would be also possible to have the uranium rod or the uranium rod clusters in sections in the manner illustrated in Figures 32, 30 or 31. The use of such sections is indicated if it is intended to remove the uranium from a graphite pile, from the top of the pile.

(5) Lattices

Of the various lattices which can be used, there are two classes which are of particular interest. To the first class belong lattices, the elements of which are spheres of uranium or short cylinders of uranium of about equal height and diameter or other such forms which more or less resemble spheres. To the second class belong lattices which are composed of rods of uranium, for instance, cylinders or square shaped rods. Of the lattices belonging to the first class, there are two types of lattices which are particularly simple, namely the three possible close-packed lattices on the one hand, and the simple cubic lattice on the other. Of the lattices belonging to the second class, there are again two types which are particularly simple, one which has trigonal and one which has tetragonal ~~hexagonal geometry.~~ symmetry

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 the 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 $\sqrt{3}: 2$. 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 number in Figure 16. Section AA' in Figure 16c shows the slits in which the liquid cooling agent can flow through the uranium carbide plug.

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 of 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 downwards 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 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.

(gravity flow)
Metal, Series Flow.--Figure 40 shows an example in which the lattice is built of uranium metal rods. An element of thelattice 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.

Uranium metal rod arrangement--parallel flow.--In Fig. 33, 331 is a square shaped graphite brick with a cylindrical bore in the center. A uranium rod 333 covered by a thin-walled steel tube, 334 goes through the bore in the center of the graphite brick 331 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 Fig. 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 Fig. 30 as applies to the construction in Fig. 33.

The construction shown in Fig. 32 is very similar to the construction shown in Fig. 30, the only difference being that instead of a solid uranium rod, we have here a hollow uranium rod, the inner wall of which is covered by a thin-walled steel tube, and the cooling agent flows both through the annular gap outside and the steel tube inside the uranium rod.

Fig. 31 differs from the previous figures 32 and 33 only in as much as we have here an aggregate of uranium rod inside thin steel tubes and these aggregates which have the contour of a cylindrical rod form the lattice element in place of a single massive uranium rod shown in the previous figures.

III

Replacement Sect 5

General Remarks on Cooling

~~A~~ suitable cooling agent for a chain reaction unit are for inst. 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 withing the lattice element. Liquid bismuth, liquid alloys of bismuth, and lead, and liquid lead can thus be 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. ~~But those of the bismuth-lead alloys which do not uranium metal up to a certain temperature 200° C can safely be used~~

~~in direct contact with the metal below that temperature.~~ 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 cool it down in~~ 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 volocity 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 be used for this purpose. The examples shown further below in which a closed circulation is used belongs to the type of series flow. Whereas, 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 and 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 may be used if a non-wetting bi-Pb alloy is used as a cooling agent. Uranium tubes and tubes made of some of the above mentioned 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 ~~but~~ 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~~ on an increase of about .7% in μq. From these data, the expected increase in q 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 ~~of~~ in μq ~~by~~ 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 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 Ligonal or tetragonal symmetry. They are designed for series flow in contrast to parallel flow which we will mention further below and one designed for

Figure 3 shows an example for the lattice element. In Fig. 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.

Fig. 4 shows another example for the lattice element. In Fig. 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).

Fig. 5 shows another example for the lattice element. In Fig. 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.

Fig. 80 shows another example for the lattice element. In Fig. 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 with inset 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 whole thing 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 free gap 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 annular gap (5) free for the flowof 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 annular 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-waled 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).

Repl. Sect 5 (Copy)

General Remarks on Cooling

A suitable cooling agent for a chain reaction unit are 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 withing the lattice element. Liquid bismuth, liquid alloys of bismuth, and lead, and liquid lead can thus be 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. But those of the bismuth-lead alloys which do not uranium metal up to a certain temperature 200° C can safely be used in direct contact with the metal below that temperature. 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 cool it down in 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 be used for this purpose. The examples shown further below in which a closed circulation is used belongs to the type of series flow. Whereas, 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 and 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 may be used if a non-wetting bi-Pb alloy is used as a cooling agent. Uranium tubes and tubes made of some of the above mentioned 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 q,

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 q but 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 about .7% in q. From these data, the expected increase in q 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 of q by 2%. In this way, depending on the quantity of the cooling agent and according to the neutrons 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 q can be estimated. For a lattice using uranium metal which does not deviate too much from the optimum conditions we may count on q being about 1.07. If a cooling agent and the piping reduced q 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 about 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 Ligonal or tetragonal symmetry. They are designed for series flow in contrast to parallel flow which we will mention further below and one designed for

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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.

Fig. 80 shows another example for the lattice element. In Fig. 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 with inset thin steel tubes which form together a rod-like aggregate. This aggregate is within a thick-walled bismuth tube (8) which is covered with a thin aluminum tube (10), and the whole thing 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 free gap 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 83, (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 annular gap (5) free for the flowof 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 annular 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-waled 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).

C O P Y

ASSEMBLY (7)

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 prevents chemical action on the uranium by 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 touching the aluminum tubes (5) and (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 has been described in detail in connection with Figure 41. Mercury is 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 further layer of graphite. The lattice is cooled by liquid bismuth or a bismuth-lead alloy the former automatically being much more favorable from a 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) gothrough the periphery of graphite layers 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 the pipe (5).

Figure 100B showsthe 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 tank (1). The system (2) which is described in detail in connection with Figure 41 serves the purpose of stabilizing the chain reacting 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 ooming 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).