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# NOTES AND SUGGESTIONS ON PILE APPLICATIONS

By

John J. Grebe

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FOREWORD

This report has been put together from a set of rough draft notes written by the author during his year at the Clinton Training School while on leave of absence from Dow Chemical Company. Some general considerations are given, and several piles adapted to specific purposes are indicated in the outline.

We are indebted to Miss Sue Elam for preparing the material for publication.

Gale Young

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*Some of this material has been reported previously and is not repeated here; in such cases, references are given in the text.

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# NOTES AND SUGGESTIONS ON PILE APPLICATIONS

By

John J. Grebe

## I. SOME GENERAL CONSIDERATIONS

To get a broader view of the various possibilities in connection with nuclear energy applications by different combinations of materials and methods, a series of charts was started*. They show, first, the likely forms of fuel that might be used; second, the materials and forms of the various moderators to be considered; third, the heat transfer fluids that appear to be pertinent; and fourth, the fluids used to carry the energy to produce useful chemical or mechanical work. A good many of these have naturally been considered at great length in the past. Nevertheless, an expanded list of possibilities cannot help but keep the many alternatives in front of us so that one is free to consider alternate methods every time difficulties arise in connection with the design for any one method.

Out of these possible combinations (they run up to millions) a relatively small number have been selected and separately considered as likely ones for specific applications. These charts are by no means exhaustive, nor do they take into account much new data that should be available. They are merely presented as a way of looking at these projects and the possibilities of different combinations. Much more work is required to expand these into a practical guide for the analysis of problems dealing with the application of nuclear energy.

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* These charts are reproduced at the end of MonP-335, which report should be read in conjunction with the present one.

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No search has been made of the project literature to make it complete and locate references. The important fields that are not covered at all are possibilities along the line of nuclear reactions that may be used as a source of energy other than those based on uranium and plutonium fission.

The most important general factors seem to be the desirability of using a homogeneous pile, using almost any fluid other than water. There are plenty of elements from which one should be able to choose desirable pile fluids without using a compound that is readily dissociated and hard to recombine. Fluoro compounds should be permissible since fluorine does not require any activation energy for recombining.

It is also good to look for possibilities of combining all four, or at least three, functions in a single material. A number of possibilities have been indicated.

The third point is the necessity of overcoming the prejudice against vaporization within the pile proper. It is true that it is not necessary for the fluid of a homogeneous pile to vaporize within the pile. In fact, it is well known that, in general, more heat energy can be removed with a given amount of power for circulation by using specific heat than by heat of vaporization. Nevertheless, vaporization within a homogeneous pile, when the heat generation has increased beyond the transfer capacity of the circulating system, should be looked on with favor since it automatically reduces the content of fissionable material within the volume traversed by neutron flux and so reduces the pile activity. While this may cause a form of surging or bumping commonly observed in laboratory distillation flasks, it must be recognized that no commercial equipment is so crudely designed as to allow uncontrolled circulation and bumping.

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The list of cooling methods and agents has been expanded to include some methods that would normally be considered impractical but which may, nevertheless, have very good specific applications. They are listed as follows:

1. Particle Emission. This includes neutrons, Alpha particles, Beta rays, and fission products. Instead of restraining the emission of such particles, there are conditions under which one should look for the maximum emission over the longest distances possible in order to distribute the energy over a mass larger than that containing the active fuel.
2. Radiation. While Gamma and X-ray radiation is generally expected, much more might be done by the use of thermal radiation. This requires higher temperatures of operation in the pile itself, but it is not inconceivable in view of the high boiling point of uranium carbides and graphite. I did not have time to give an illustration of a pile cooled primarily by thermal radiation as applied to an industrial operation that might be commercially practical, but every effort should be made to find and analyze such an application.
3. Conduction. This is very generally understood and used, and should not require special discussion.
4. Mechanical Work by Expansion of Gases or Vibration of Liquids or Solids. This method applies particularly to homogeneous gaseous piles and possible liquid and solid piles generating high sonic frequencies.
5. Convection. This, also, is well understood and should not require special discussion.

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6. Changes of State. Many efforts have been directed in the line of finding materials that will remove heat, especially in the form of heat of fusion. A slurry of solid in a liquid having good lubricating properties permits the alternate freezing and melting of the solid, thus increasing the heat transfer capacity. The change of state from liquid to vapor, as mentioned above, is not likely to be part of a commercial operation, although the pile as listed under No. VIII for producing radioactive rain and poisons depends primarily on the boiling of water for its effectiveness and self regulation.

7. Heat of Dissociation and Cracking. This should be a particularly profitable way of removing heat from a pile. Hydrogen can be dissociated to atomic hydrogen, natural gases and other hydro-carbons into $CH^{+++}$ radicals and oils, and other liquids into lower boiling cracked products.

8. Heat of Transformation or Rearrangement of Atoms and Molecules in the Solid State. This method may well be used for short time pulses of atomic energy. By means of these, a considerable amount of pressure can be generated. In general, the cycle is not sufficiently reversible.

9. Heat of Reaction. This may also be used for removing energy, particularly in the form of heat of solution and dilution in a liquid state and as heat of rearrangement or combination in the gaseous state. In some instances, it is hard to differentiate from heat of dissociation and cracking, while in other

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cases it is quite potent in removing large quantities of heat due to endothermic reactions taking place at high temperatures, such as the formation of HCN and $C_2H_2$.

10. Electromagnetic Energy Transfer. This should not be excluded as a means of cooling the pile. Any liquid conductor passed through a magnetic field can serve to remove energy by causing induced currents in a coil outside.

11. Electrostatic Energy Absorption. As a by-product of particle emission, particularly Beta rays, variations in the charge on liquids and gases can be used to induce electrostatic energy transfer. This, of course, has very little, if any capacity or efficiency at low frequencies. However, at higher frequencies, the sky is the limit, and it would be foolish to overlook the possibility of high frequency generation directly from radioactive materials or fission reactions. An alternating magnetic field can direct Beta rays to alternate targets, thus transmitting the energy.

12. Producing Thermo-electric Currents Directly Between a Hot Junction and a Cold Junction. This possibility has often been investigated and, of course, demonstrated on some practical applications. In the case of pile cooling where heavy metals have to be used anyway for the sake of retaining walls, shielding, and breeding, there is no good reason for not incorporating the direct conversion to electrical currents by this method. This low voltage D. C. power can be alterated by a sodium jet conductor for transforming to high voltage

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A. C. Many details of construction have been worked out or suggested in the past, which should apply here. The combination of this method with the electromagnetic and electrostatic methods of energy absorption may well produce unique results that will have great value, both in the extremely high frequency signal range and in the 60 cycle power range.

An effort should be made, in all cases, to reduce the number of steps and transfers to a very minimum. Only by doing so can the overall equipment become compact and light so that it can call for the minimum of shielding. In general, there is too much concern about the reliability and life of the turbo generators and the like. There is no reason why boilers, turbines, generators, and condensers cannot be made a part of the shielding with the idea that they can be replaced every two or three years, if necessary. This is particularly true on board ship. It would be easy to replace whole units, dumping the old ones in the depths of the sea, while careful maintenance schedules of obsolete equipment would emesh the operation in endless details and manpower requirements.

The following illustrations of specific pile designs for definite purposes are not intended to be a basis for actual proposals for construction, but merely to illustrate the variety of conditions and methods that might be used to construct piles.

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## II. PUBLIC UTILITY PILE USING PHOSPHORUS AS COOLANT AND MOTIVE FLUID

This section was reported separately as MonP-344. Earlier mention is found in MonP-228, page 34; MonP-269, page 25; and MonP-335, page 15.

## III. PILES AS HIGH TEMPERATURE CHEMICAL REACTORS

See MonP-335, page 11-13, and MonP-314, page 123.

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## IV. HIGH FLUX PILE FOR ACTIVATING GAS HEATERS FOR RAM JETS, TURBO JETS AND ROCKETS

While a lot of work will have to be done on producing a pile suitable for rockets and bombers, it would seem most urgent to get away from any use of a pile for operating any unit that may not come back. The small percentage of the fuel that would be used up on any one trip justifies the trouble of salvaging the remainder. It is also very difficult to do away with such a pile so that fissile material cannot be recovered. Only the dispersion in a large body of water or vaporization into air would be good enough.

One way around this difficulty is often discussed but seldom taken seriously. It involves the use of radioactive materials whose half-life is of approximately the right value to serve for any one trip. The appended list (Table I) of materials selected from current charts gives a number of them with their most important characteristics.

It is desirable to have a material of high melting point, preferably a metal that has a high cross-section for conversion to the radioactive isotope by neutron absorption. It should be an Alpha or Beta emitter with very little, if any, Gamma emission. This makes the shielding simple and cheap. The half life should be approximately two times the time required for the power to be in use for any one "charge".

It has been calculated that a neutron flux density of $10^{16}$ with a cross-section of 20 barns will permit one tenth of one percent of a heater grid to be converted to radioactive material, thus producing approximately one kilowatt of heat for every 10 grams of mass. Even if it should take ten times the weight of heater grid, or if the flux of $10^{16}$ could not be reached, it would not matter too much since this sort of energy per unit weight is suffi-

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# TABLE I

| | Absorption Cross-Section | Half-Life | Beta Activity | Gamma Energies | Percent Occurrence | Notes |
|---|---|---|---|---|---|---|
| Mn$^{55}$ | 13 | 2.59 Hr | .75 → 2.88 | .7 → 2.14 | 100 | |
| Ta$^{181}$ | 21 | 117 Da | 1 | 1.6 → .15 | 100 | Submarine |
| Pd$^{108}$ | 12 | 13 Hr | 1.03 | No | 27 | No $\gamma$ in any Pd |
| Pd$^{110}$ | .39 | 26 Min | 3.5 | No | 13.5 | |
| Co$^{59}$ | 31 | 10% - 5.3 Yr<br>90% - 10.7 Min | .3<br>1.35 | Low (.056) | 100 | Rocket |
| Sc$^{45}$ | 22 | 85 Da | .26 — 1.5 | 1.4 | 100 | Submarine |
| Va$^{51}$ | 5 | 3.9 Min | 2.05 → 2.65 | 1.3 | 100 | |
| W$^{186}$ | 34 | 24 Hr | 1.4 | .9 | 28 | |
| W$^{184}$ | 2.1 | 74 Da | .6 | No | 31 | |
| Cu$^{63}$ | 2.8 | 12.8 Hr | .6 | No | 70 | |
| Cu$^{65}$ | 1.8 | 5 Min | 2.9 | No | 30 | |
| Ga$^{69}$ | 1.5 | 20 Min | 1.7 | No | 61 | |
| Ga$^{71}$ | 3.4 | 14 Hr | 1.7 | 2.65 | 38 | High $\gamma$ |
| As$^{75}$ | 4.6 | 27 Hr | .7 and 2.6 | 1.5 → 3.2 | 100 | |
| Se$^{80}$ | .52 | 57 Min<br>19 Min | No<br>1.5 | Low<br>No | 48.0 | |
| Br$^{79}$ | 2.8<br>8.1 | 4.4 Hr<br>18 Min | Low<br>.2 | Low<br>.5 | 51 | |
| Br$^{81}$ | 2.25 | 34 Hr | .7 | .65 | 49 | |
| Rh$^{103}$ | 13.7<br>11.6 | 44 Sec<br>4.4 Min | 2.3<br>No | No<br>Low | 100 | Rocket |
| Ag$^{107}$ | 44 | 2.3 Min | 2.8 | No | 52 | Rocket |
| Ag$^{109}$ | 97<br>2 | 22 Sec<br>225 Da | .38 → 1.3 | .6 → 1.5 | 48 | |
| In$^{113}$ | 56 | 48 Da | | Low | 5 | |

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| | Absorption Cross-Section | Half-Life | Beta Activity | Gamma Energies | Percent Occurrence | Notes |
|---|---|---|---|---|---|---|
| $In^{115}$ | 52<br>145 | 13 Sec<br>54 Min | 2.8<br>.85 | No<br>1.8 and 1.4 | 95 | High γ |
| $Sb^{121}$ | 6.8 | 2.8 Da | .81 — 1.64 | .57 | 56 | — |
| $Sb^{123}$ | 2.5 | 60 Da | 2.45 | 1.71 | 44 | High γ |
| $I^{127}$ | 6.25 | 25 Min | 2.0 | .4 | 100 | |
| $La^{139}$ | 8 | 40 Hr | 1.45 | 1.65 | 100 | |
| $Pr^{139}$ | 10 | 19.3 Hr | 2.14 | 1.9 | 100 | High γ |
| $Re^{185}$ | 101 | 90 Hr | 1.05 | No | 38 | |
| $Re^{187}$ | 75 | 18.9 | 2.5 | .8 | 62 | |
| $Ir^{191}$ | 260<br>1010 | 1.5 Min<br>60 Da | 5.9 | .3 — .6 | 38.5 | |
| $Ir^{193}$ | 128 | 19 Hr | 2.2 | 1.35 | 61.5 | |
| $Au^{197}$ | 96 | 2.7 Da | .8 | .2 → 2.5 | 100 | |
| $Pt^{196}$ | 1.1<br>4.5 | 18 Hr<br>3.3 Da | .7 | | 27 | |
| $Pt^{198}$ | 3.9 | 31 Min | 1.8 | No | 7.2 | |

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ciently large to allow for a lot of leeway. In any case, one could do a lot better this way than by using only one part in 2000 of the fissionable material in a rocket, or one part in 500 of the fissionable material carried by a bomber.

Calculations indicate that the maximum percent conversion of the material in the heater grid is independent of the half-life of the isotope being produced. Approximately one half of the total energy produced by the radioactive isotope is usable. The other half is given off during the time that it is being produced. In addition, one obtains only about one percent of the energy out of each neutron that would have been obtained if the neutron had been used to produce fission. Much depends upon the particular material used and the energy content of its Beta or Alpha rays. But even at this low estimated efficiency of one half of one percent, it is still better by a factor of ten than the use of a fissionable material in a hydrogen rocket powered by nuclear energy according to present concepts.

One material that is well known and has some of the characteristics desired is platinum. For simplicity and convenience we will use it as a general term in describing the design and operation of such a unit.

The exact arrangement for converting the platinum and making it radioactive will naturally be the object of much experimentation and development. Two general ways are available:

First, one can disperse or dissolve the platinum in a homogeneous pile fluid where it can pick up neutrons at the maximum concentration for high conversion. The material would then be plated, filtered, or adsorbed onto a grid suitable for heating air or the like in a rocket, ram-jet, or turbo jet unit. It may even be possible to keep the platinum in a fluid condition, depending

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on centrifugal force to retain it in a heater unit while it heats the air. During the time the platinum is transferred from the pile into the rocket, it has to be kept cool in as much cooling fluid as would be necessary for actual use. This makes the transfer quite a problem.

The second form in which the platinum could be used is as one or more grids, manufactured ahead of time in the exact shape and form desired, which are then put into the center of a high-high flux pile. The units would have to be introduced through tubes that continually conduct a stream of air over the grid. When the activity has come up to the maximum, the same stream of air can follow it as it is transferred into a jet unit that has been backed up to the pile. It is then locked in place and used as soon as possible with the air stream never being shut off. The main difficulty in this design, which is more easily visualized, is that the neutron flux in the center of each unit would be hard to keep at a maximum value. Sub-dividing does, however, reduce this effect considerably.

Some consideration has been given to the method of energizing, which involves putting the solid grid into the circulating stream of a homogeneous pile so that both the mechanical structure as well as the high flux density can be had at the same time. This, however, requires a transfer from the fluid in the pile to air that may become a major operation. It would be necessary to remove the grid from the center of the pile to a chamber in which the same cooling medium without fissionable material would be circulated through the grid to wash it free of entrained uranium. From this chamber, some distance away from the high flux and shield, the transfer to a stream of air would have to be made. Water or oil or some other cooling medium that can be blown away at a high velocity could be used as an intermediate coolant.

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Naturally there are a great many ways by which this sort of a device can be worked out. Any description of any one phase of it should be merely used as an illustration of what we now think might be possible. More fundamental data which may be forthcoming on all of our elements and isotopes will modify this considerably. Entirely different methods of approach may become possible. For example, last fall I hunted for quite a while for an isotope with two isomers, one of which is stable or of a long life, and the other with a short life. It should then be possible to energize the first into the second by Gamma radiation so that one could have controlled radioactive decay just as one has controlled fission. This would increase the efficiency considerably. So far, it seems as though the cross-section for energy absorption by radiation of any of the isomers is fairly low. It is hard to tell, though, when new information will change this picture and make it very practical to do something of this type.

The design of a pile that is able to furnish a neutron flux of $10^{16}$ would naturally be quite a problem. Nevertheless, one should not be scared away from it. Rough calculations indicate that a heat generation of one kilowatt per cubic centimeter would be required. The removal of this amount of heat would tax the best known methods to the limit.

It is also obvious that this heat should be generated within the heat transfer medium, at least to a very large extent. This would leave only a small portion of the heat that could be generated within a rigid structure and transferred from it to the fluid medium. A pile that could produce this high flux will also require a very large heat output, something on the order of one million kilowatts of heat - three Hanford piles in one cubic meter. Naturally all this heat should not be wasted, but should have some other practical util-

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ity. In general, only about one half of one percent of the power produced by such a central station could be furnished as power available from radioactive disintegration of the platinum.

The most important development for such a pile is to make lithium hydride or lithium deuteride available in sufficient quantities to serve as a moderator and heat transfer medium. It melts at 680°C. The $Li^7$ isotope having a low cross-section is required. This, combined with other hydrides or deuterides of metal such as uranium, beryllium, bismuth, sodium, and rubidium metal, should make it possible to have a molten metal, hydride, homogeneous pile with the very maximum of heat transfer possibilities.

It is well established that the maximum heat can be transferred from one given point to another, better in the form of a liquid than in the form of vapor or gas. Even steam heating facilities are being replaced by hot water circulation systems as a result of new knowledge and understanding of the engineering problems involved. On the other hand, there is no more compact and efficient cooling method than mixing a volatile liquid with the first, which then flashes off as a vapor. This means that in any really high flux pile design, it is essential to remove the heat from the pile space as specific heat in the liquid, after which the liquid is cooled by direct contact or admixture with a more volatile liquid.

If, then, one takes advantage of the vapor produced to give an air-lift effect in the system, one can get the benefit of a power cycle containing an engine and a pump of the most simple design possible. (See Figure I).

The vapor, on being separated from the liquid at a higher elevation, can then be condensed on a tubular boiler for any desired fluid. Mercury would be preferable in this case, as it does not require super-heating for

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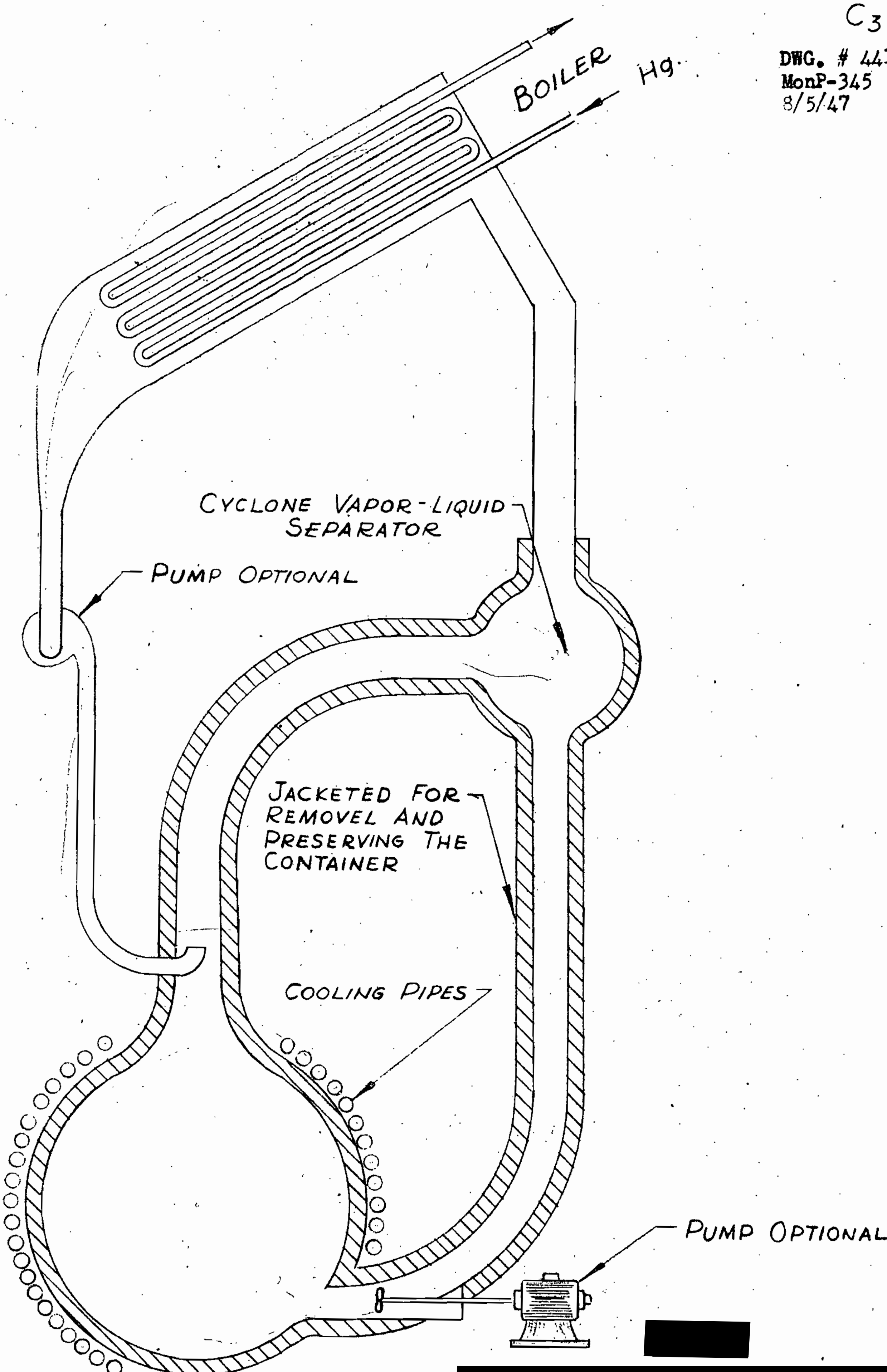


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FIGURE 1 [redacted]

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satisfactory operation of turbines, and permits cycle efficiencies in excess of 50 percent overall. The condensed vapor of the volatile liquid could be returned for recycling into the same process of mixing with the heat transfer fluid, vaporizing, lifting the fluid to a higher level, separating, and then condensing.

In the case of a boiler containing metals and their hydrides or deuterides, a logical material might well be rubidium metal which boils at 705°C, while the lithium has a boiling point of around 1400°C. Bismuth that may be present to reduce the melting point and to produce polonium has a boiling point of 1450°C.

One problem that is particularly pertinent in this case is the residual concentration of the volatile material such as the rubidium. By flashing it off under vacuum, only a very low concentration remains to be circulated down and into the pile. There its volatilization is repressed by the increase in pressure due to the hydrostatic head of the molten metals and hydrides. A fairly high condensing temperature of about 600°C is desirable in order to produce high temperature mercury vapor. This, however, limits the temperature rise permissible. Nevertheless, a cycle between, say, 900°C and 600°C should permit a low holdup of fluid and fissionable material outside of the pile itself.

In order to reduce the velocity head loss in entering and leaving the pile space itself, it is quite desirable to break the total stream of liquid into many smaller ones with approximately constant fluid velocity throughout the cycle. This means that the liquid metal leaving the bottom of the cyclone separator would go down through a tube which would pass through the pile space, making a 180 degree turn in a loop of the maximum possible radius. It would then spiral upwards to a point where it would separate from the spherical geometry of

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the pile and travel through the breeder section of the pile where the neutron flux would be absorbed rapidly and many of the delayed neutrons would be salvaged. At this point, the addition of the volatile liquid would take place, which would gradually mix in and vaporize as the hydrostatic head is reduced. The tubular duct would have to increase in diameter from here on up to prevent undue increase in velocity until it finally can be discharged tangentially into a cyclone separator. No sketch is shown for this multiple tube arrangement, but a rough geometrical model has been made.

This pile would also have inherently built in self regulation in excess of what is usually obtained by temperature coefficient alone. Fission product poisoning would be reduced to a minimum since the volatile products, such as iodine and xenon, would be removed continually in the form of HI and Xe gas. Those fission products that would be soluble in the mixture could be burned out by the neutrons, accounting for a one percent loss.

Whenever the heat generated would be in excess of the heat that can be removed by whatever may limit the heat removal at the time, the rubidium would not be completely separated and more rubidium would remain in the circulating mass, causing a higher neutron absorption as well as vaporization of the rubidium in the pile zone. This would reduce the concentration of the fissionable material as a result of both the increase in volume due to thermal expansion and the increase in volume due to the vapors being produced. There would be no danger of sudden collapse of the bubbles due to changes in the circulation within the pile.

No matter whether the limitation in heat removal is a result of the turbine being shut off, a tendency on the part of the pile to go beyond the capacity of the system, or any other change in rating, the pile could not exceed

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a moderate temperature rise above the normal operating temperature without reducing the heat generation in proportion. The excess volume displaced as a result of the expansion and formation of bubbles would be retained in the vapor separator at the top of the system. It would be out of the neutron flux entirely and would still further reduce the effectiveness of delayed neutrons by the increased retention period outside of the pile. In other words, even if by error some unusually large amounts of fuel were added to make up for depletion, we could still be safe-guarded against the pile going critical on a prompt neutron basis by a displacement of the liquid up through the riser tubes, and by preventing it from entering into the pile through the down-comer tube.

A pressure wave will travel through the fluid fast enough to prevent inflow of fluid when gas bubbles are being produced suddenly. To avoid surging and water-hammer effects that might collapse the bubbles, all that is necessary is a sufficient amount of friction in the circulating system so that the rate of inflow can not exceed the normal operating rates. This should be inherent with a system using a large pressure head for circulation, especially where that pressure head is so cheaply obtained by merely flashing a volatile liquid and condensing it, after expanding it in an air lift.

It is true that this method of circulation taxes the overall cycle by a high temperature differential which makes materials of construction for high temperature necessary, but this is not an impossible handicap, particularly when a high temperature rise is desired in order to get the maximum heat capacity per unit weight and volume from the circulating medium. It is unfortunate that all this does not reduce the total volume and content of fissionable material much below a factor of 2 to 4 times the volume of the pile itself.

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With such a high flux there is still a very high rate of consumption of the fissionable material and a very low content of fuel per kilowatt of heat produced.

The space between the tubular conductors carrying the homogeneous pile fluid would be filled with a moderator such as graphite, Be, BeC, lithium hydride, and possibly beryllium hydride.

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## V. SUBMARINE PILE

For producing power on board ship it is very desirable not to carry any materials that might produce toxic gases in the enclosed spaces. A homogeneous pile could be used for this purpose, consisting of enriched uranium and uranium carbides for fuel, dissolved or suspended in a mixture of metals and their hydrides and carbides such as Be, Bi, Rb, Na, $Li^7$, $BeH_2$ or $BeD_2$, $Na_2H_2$, $Na_2C_2$ and possibly NaH or NaD. Since $Na_2H_2$ melts at 800°C, sodium carbide boils at 700°C, bismuth melts at 271°C, and rubidium and sodium are of still lower melting point, such a mixture of hydrides and carbides should be quite fluid at a temperature of about 200°C even though some components may well be in suspension.

The rubidium and sodium carbide would be the lowest boiling constituents and would be used as a means of transferring heat from the molten liquid in the form of heat of vaporization to be transmitted to a mercury or steam boiler. The vapor would condense and return to produce air-lift action and supply the cooling required for recycling, as in the pile described in Section IV. Since there would be no need for tubes in which the grids could be energized, this pile could be more compact and more simple. Also, since the requirement for high flux does not exist, simpler methods of circulation of the fluid with a lower temperature differential and a low circulation rate may be employed. This reduces the head loss on change in velocity and makes it possible for the pile to be one solid mass with or without a porous filling of moderator such as beryllium metal, graphite, or jacketed metal hydrides.

This pile could be designed for much more breeding, using thorium hydride and the like for reflecting, slowing down, and absorbing the neutrons.

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The breeder material would be both on the outside of the pile as well as around the inductor tube through which the fluid would rise. A single discharge tube from the top of the pile leading to the surface of the fluid may serve the purpose instead of a number of tubes described for the High-High Flux pile in Section IV. This makes it possible to have the amount of circulation unaffected by variations in tilt of a pile such as it would get on board ship due to pitch and roll.

This pile, too, has the feature of providing more than the usual self regulation due to thermal expansion and the decrease of the fission cross-section with rise in temperature. Any bubbles formed due to the production of heat in excess of the capacity of the vaporizing and circulating system to remove, will reduce the amount of fissionable material within the pile volume by holding back the fluid trying to enter. Here again, in order to avoid water hammer effects, it is desirable to have a high head and a reasonably high velocity and friction loss in the down-comers delivering the fluid into the pile volume, so as to make the period for oscillations within the down-comer circuit much slower than the period of the system, including the riser. The high inlet velocity also can be used to provide effective agitation in the pile. This permits fluid to get out in a hurry but come back at a predetermined maximum rate. Such a pile does not necessarily have to operate on slow neutrons. If a large amount can be invested in fissionable material, it can operate on intermediate energy neutrons with a decrease in the size of the pile and amount of shielding required.

A sketch of this design is given in Figure 2.

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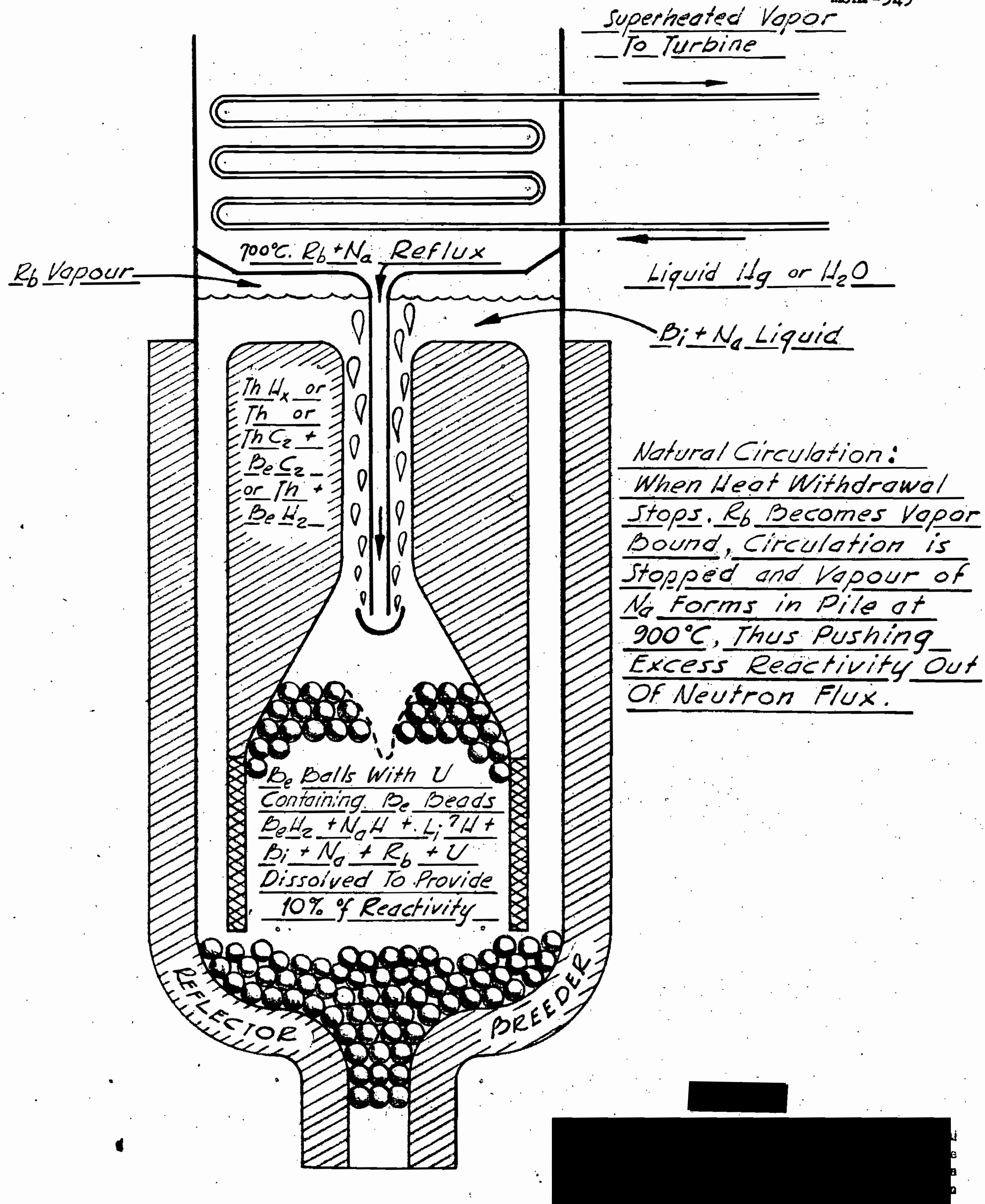


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FIGURE 2

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## VI. AIR POWER PILE

In an airplane an important requirement would seem to be avoidance of any materials that are highly inflammable so as to produce fire when there is a crash. For this reason, the materials described under Sections IV and V would not be so practical. Shielding is also a problem. Avoiding hydrogen, hydrides, carbides and alkali metals will not reduce the size of the pile, but increase it. Nevertheless, in this instance, it should be possible to use a pile that has a cylindrical shape and is several times longer than its diameter. The cross-section, therefore, in the direction of the passengers can be reduced, thus avoiding some of the heavy shielding requirements. In this particular instance, gravity is not a desirable source of head for producing circulation so that another circulating system, if possible not using rotating shafts and close fitting machinery, should be employed.

Here again, the scheme of using an added power cycle, superimposed on the system for producing circulating power, would seem to be desirable. The pile circulating fluid would consist of a mixture of metals and their oxides, fluorides and oxyfluorides. These would include, particularly, Bi, $Li^7$, Be, Sb and Sn. The fuel would be uranium oxyfluoride. The breeder, if any, could be thorium metal or carbide and $U^{238}$ oxyfluoride.

The literature shows that $BeF_2$ softens at 600°C and becomes a transparent, melting at 780°C. The addition of only one molecule of NaF to $2BeF_2$ reduces the melting point as low as 360°C. If $Li^7$ would act like sodium in this system, and is made available, a lower melting point for $Li^7F + 2BeF_2 + NaF$ should be obtained. Since this mixture would be an alkaline melt, it may well be that carbonates can also be added, still further reducing the melting point and lowering the molecular weight for improved action as a moderator.

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To avoid the need of gravity for circulating, the most volatile constituents of $SnF_4$ boiling at 705°C and $SbF_3$ would be the heat transfer medium. This could be carried on by means of a series of traps, or continually, by means of jets. In the case of traps, the circulating fluid would enter a tube which then would be sealed off roughly with the fluid diverted to the next tube by a simple rotating plug valve. $SnF_4$ and $SbF_3$ would then be injected into the column of hot fluid producing vapors which would discharge the liquid against the pressure head through the pile, followed by venting of the vaporized material into the heat transfer system.

In the case of the ram jet or turbo jet most of the heat would be delivered into the compressed air. The tubular heat interchange system required for heating this air would naturally have to be designed for a rather high pressure differential in order to keep its air resistance to a minimum. For this reason, the metal fluoride vapors would have to be generated at a sufficiently high pressure to permit high velocities. The temperatures required for this air jet, in order to get efficient operation, are probably higher than one could tolerate in the turbine of a turbo compressor so that a secondary medium such as mercury, boiled by contact with the circulating pile fluid after the metal fluorides are vaporized off, may well be the best choice. This mercury, after driving the turbo compressor, would be condensed in the air before it receives heat from the metal fluoride vapor.

It may even become possible to use a liquid metal oxide such as bismuth oxide mixed with tin and lead metal and oxide as a direct contact heat transfer medium between the portions of the pile that have to be liquid cooled outside of the fuel mixture, allowing the high centrifugal force in the compressor to separate the spray of metals and oxides from the air being heated.

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Under conditions where the extremes in compactness are not necessary, such as on locomotives, surface ships and stationary power plants, the metal oxyfluoride pile has many additional attractive features. The bismuth which is converted to polonium can easily be separated in a small unit serving as a continuous clean up by adding fluorine. The polonium fluoride, being more volatile, would be easily removed by distillation. Similarly, plutonium, which might have better uses other places, could be volatilized out as the fluoride or even the oxyfluoride. Iodine and xenon would be continually removed so that the only regeneration that should be necessary is the addition of new fuel to maintain the reactivity at the desired level.

Many of the fission products from fluorine compounds have a very high melting point and are, therefore, likely to be precipitated out in the clean up unit. Either the multiple tubular system described under Section IV or the single draft inductor unit described under Section V should serve for cooling and producing circulation, - the metal fluoride compounds taking the place of the rubidium as the heat transfer medium used for producing superheated steam or mercury vapor.

The materials of construction for the oxyfluoride pile will provide a particularly tough problem since nickel has a fairly high neutron absorption cross-section. Metal sulfides having very high melting points may well help out. Refractories made of fluorine compounds such as magnesium and calcium fluorides may well be used in the pile zone where temperature differences might make it very difficult to maintain metals. The important item is to do enough experimental work to establish the desirability of using a metal oxyfluoride pile for specific purposes. Once this is established, it is quite likely that the materials of construction could be developed.

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## VII. PILES FOR ROCKETS

For this section see MonP-335, page 13-18. Also the figure following page 21. The picture did not reproduce well in that report, and so is re-sketched here as Figure 3.

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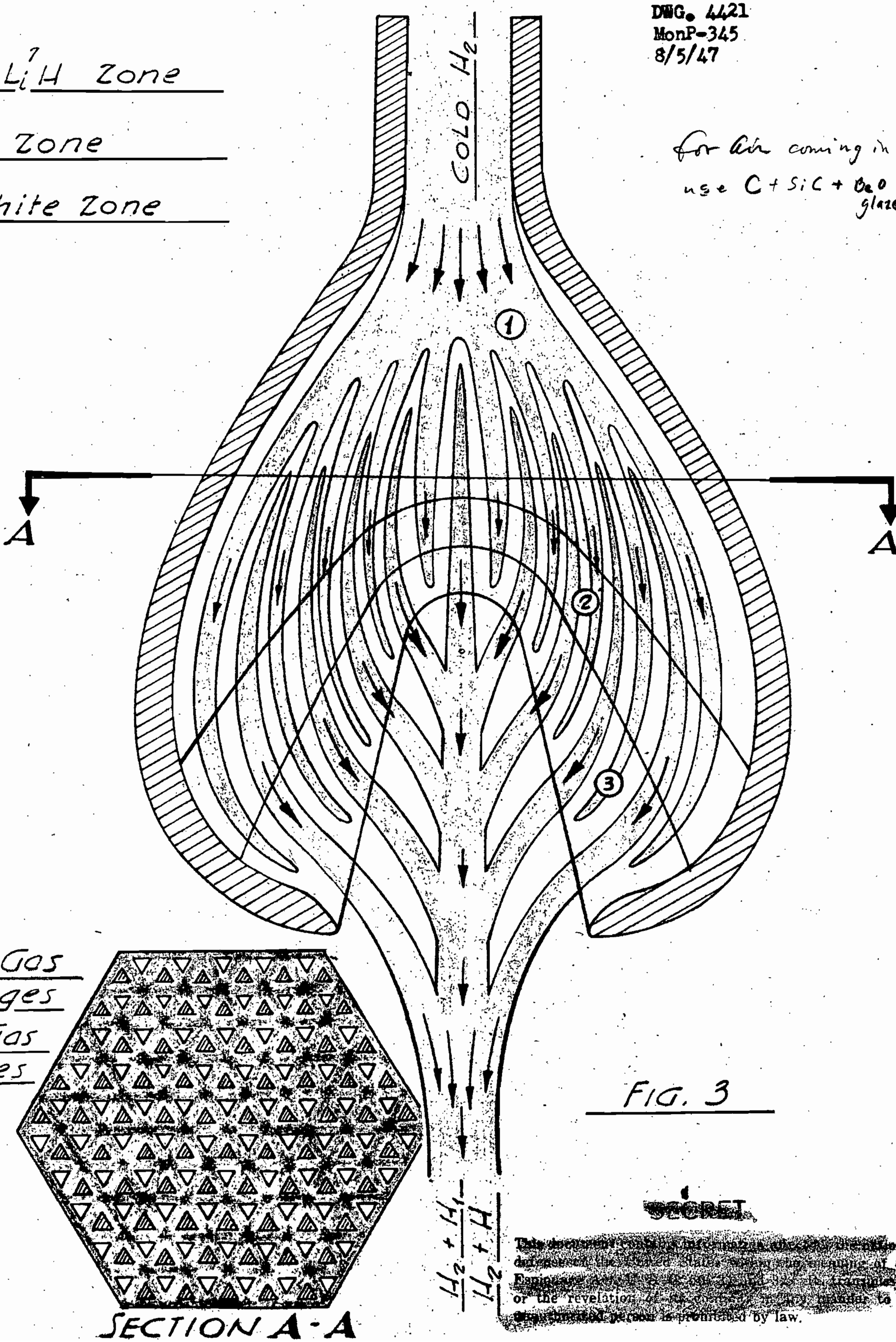
① Be or Li⁷H Zone

② $BeC_2$ Zone

③ Graphite Zone

for air coming in use C + SiC + BeO glaze.




▲ = Cold Gas Passages

△ = Hot Gas Passages

FIG. 3

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, 50 U.S.C. 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

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## VIII. PILE FOR PRODUCING RADIOACTIVE RAIN AND POISONS

Ever since I saw the second burst at Bikini, the potency of radioactive rain, air and water as a means of crippling industrial production without injuring many people directly has become increasingly apparent. Practically all industrial operations are centered around water transportation and ample fresh water supplies. Destroying the usefulness of each of these makes industrial operations impossible for a considerable period of time, while giving the population some time for dispersing.

The problem of designing a compact and very light, fool-proof pile that can be dropped into water and act completely automatically until most of the fissionable material has been consumed is very intriguing. Bodies of water, such as harbors, lakes and water reservoirs, should be fairly easy targets to hit. It is desirable to find a location that is close to shipping and transportation centers, as well as the drinking water supply. Our Great Lakes, especially Lake Huron and Lake Superior, are particularly potent targets. Similar communication and water supplies are likely to be found all over the world.

An important part of this pile would be a large strong metal draft tube that would permit a rather high head of water to act on the pile proper. It would be designed to float in an upright position with the pile at the bottom. A grid of fissionable material, alloyed with high melting metals that would withstand the temperature shocks, would be placed inside of this tube. Under ordinary conditions, it would not be active since it requires water as a moderator to slow down enough neutrons to make it critical. The amount of water required is so gaged as to permit almost complete vaporization of the water with the heat produced by a given immersion. Since the unit might be 15 feet long,

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there would be more than 10 feet of head available to force the water in and blow the steam out of the tube.

Whenever too much water enters, more steam is generated than the pressure head is able to discharge from the draft tube, so that further inflow of water is reduced. Only the bottom end of the pile material is, therefore, active at any one time. As this becomes depleted, more of the metal is immersed in a higher concentration of foam and water until finally the entire mass needs to be flooded in order to make the pile critical.

When the unit has spent itself, it is desirable, even though it is very radioactive, that it disintegrate in the water at a fairly rapid rate, distributing the remaining activity over as large an amount of water as possible. This can be done by means of galvanic action provided to cause heavy currents for corroding the uranium and fission product containing metal. For this purpose, the shell and possibly other surfaces should be coated with silver oxide or platinum black, which would have a very low hydrogen over-voltage, thus permitting heavy currents to flow. It may also be practical to clad the fuel with a thin layer of metal which peals off and deteriorates as a result of the action of fission products and temperature change. To prevent such a unit from being easily retrieved in case it should not fall into water or deep enough water to work well, water should be provided inside of the draft tube in such a way that retaining disks would burst on impact. This would provide the initial supply of water to make the unit highly active and disintegrable. In all, the action might well take several days, providing radioactive rain, air and water over a wide area.

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Another discussion of this topic was given by Mr. Grebe as an example in connection with the charts of Section I. It is as follows:

A pile is to be built which will be under critical while being stored and transported. When it is immersed in ordinary water, (say, in a river or lake which is to be contaminated) it should become very active and operate in a self-controlled manner so as to use up the maximum of the fissionable material.

Under these conditions, a combination of materials ordinarily not considered at all practical may be used. A chart giving the data in a much more complete form than the samples submitted herewith will then help solve the design problems from a much broader and more efficient point of view.

For example, in this case, Pu metal alloyed with Na and Mg clad in a very thin layer of Al might serve best. A sheet of this material corrugated at a slight diagonal, laid against a sheet that has been turned to make the diagonals cross those of the first sheet, the two wound up into a close spiral coil, would make a very simple and strong assembly that would be quite inert until immersed in water. The water would be able to penetrate between these sheets only to the extent of making the pile critical, when the steam produced would blow the water out. Surges of this type would continue to use up the fissionable material until the assembly would go below critical when totally immersed.

A stack attached to the upper end would increase the circulation of the water and make the action more steady and intense.

The alloy being corroded, after the Al jacket has lost its impervious properties due to fission recoils, would probably cause the remaining Pu to be dissolved in alkaline solution if it acts like other similar metals.

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To avoid the danger of capture intact if the pile should not drop into a lake or large river, the stack could be filled with water to flood the pile initially on impact with the ground. This would make it so hot that it would be difficult, if not impossible, to recover.

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## IX. A SIMPLE PILE

Going on the principle that eventually we will end up with an exceedingly simple, compact, and cheap pile design, I have speculated a lot on what it might look like in the end. No doubt others have often contemplated these same sorts of processes, but may not have had the courage of their convictions to advocate it.

Assuming that we are to use very cheap and simple materials such as graphite, and U, Pu and Th carbides for fuel and breeder material, moderator, reflector and heat transfer medium, one could think of drilling a number of small holes in a large diameter graphite electrode. This graphite cylinder would be placed into a space surrounded by a cold coil for producing steam or mercury vapor, or even heating metallic sodium by radiation and some convection from the quite hot graphite.

Into these holes drilled into the graphite from the top would be placed U, or Pu and Th, as needed. When sufficient fuel has been added, it would become hot and form carbides with the graphite of the chamber. Further heating would result in diffusion of the fuel out to a zone where the cooling of the graphite is sufficient to bring the temperature down to about $2300^{\circ}C$. If the fuel would get too hot, it would volatilize to a higher section of the tubes, thus decreasing the reactivity until it flows down again to the bottom. The upper portion, having a much larger area for conducting heat out and the surface from which it can be radiated and conducted to the cooling coil, would not permit the vapors of the fuel to boil out completely. Some of the fission products, particularly the poisons, would be volatilized out. In other words, there would be only a very slight excess reactivity required at any one time which can be held in check by volatilization and refluxing of the fuel. New

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fuel would have to be added to make up for depletion.

Such units could be used in multiple as needed to build up higher capacities. The heat from the outside of the containers might well be radiated to thermocouples which would then carry the energy partly as electrical current and partly by conduction to the cold junctions, which would serve to heat the motive fluid. The thermocouple material would then be serving, not only as a current generator, but also as a shield, and possibly a breeder. It may also be designed to furnish the retaining wall that might be required to increase the vapor pressure within the pile zone by the use of helium gas or the like.

If other moderators and containers can be found, such as beryllium oxide, or if the pile is made sufficiently fast so that the cross-section of high melting alloys is not troublesome, uranium metal, its oxyfluorides, and possibly its halogen compounds, may be used to produce a fuel that will volatilize when it becomes too hot in the container.

The important aspect is that the fuel is so disposed inside of the container that dispersion by vaporization and condensation some distance away will reduce the activity of the pile and regulate it to the boiling point of the materials involved under the pressure supplied.

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