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OUTLINE OF A LIQUID METAL PILE

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By G. Young

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Outline of a Liquid Metal Pile

G. Young

1. Introduction

The purpose of the present report is to elaborate a little on a remark made in Mon P-190 (footnote no. 50, p 25), and to consider more explicitly the possible use of fissionable material in a fluid form. The report cited gives (p 15) some discussion and references relating to such a possibility, and CL-GY-2 comments on the advantage of being able to continually replenish the fissionable material as it is destroyed.

We here consider a thermal 23-thorium pile with Be moderator and Bi coolant. The fissionable material is imagined to be in a liquid metal alloy resting within Be metal walls thru which the heat is conducted to the coolant flowing on the other side of the walls; thus, in effect, the Be separates the stationary fissioning liquid from the moving cooling liquid, and holds the former in place in the pile while the latter rushes thru to carry away the heat.

Evidently the resistance of Be to attack by the liquid metals will be important for such a proposal; there is some evidence (p 8 and 22, Summary of New Pile Studies*, Young 10/22/46) that Be may be resistant to Bi and Pb, but this is highly preliminary. Work on the resistance of Be metal to Na-K alloys has been carried somewhat farther (CT-3726; Summary, p 9 and 22), and Na cooled Be piles (MUC-GY-39; Mon P-190) are being considered by G. E. for the Navy.

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*Hereafter to be referred to simply as "Summary".

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2. Nuclear Constants

Table I gives some nuclear constants estimated in discussion with K. Way.

Table I

Material	Property*	Value	References and Remarks
23	$\overline{\sigma_a}$	500	CLM-KW-1
	λ	2.34	CLM-KW-1
Bi	$\overline{\sigma_a}$	.015	Taken a little larger than activation result.
	$\overline{\sigma_{tr}}$	9	liquid Bi; MUC-HHG-7
Be	$\overline{\sigma_a}$	.01	MUC-KW-60
	$\overline{\sigma_{tr}}$	4	MUC-KW-60 gives a value of 3.5; more recent results (CP-3647) suggest that with finer crystals the value might be as large as 5 to 7.
	λ	115±15	MUC-WC-MLG-10 (or CF-3403, p 43), CL-AMW-1, and Mon P-160, p 5 give a calculated value of 94-98 cm^2 for a metal density of 1.85. This is probably a lower limit to the true value, and a larger value has been guessed here.

*The bars denote Maxwell averages(taken in the appropriate way) at ordinary room temperature. In the thermal region the scattering cross-sections will be assumed independent of energy, and the absorption cross-sections to vary as 1/v.

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We imagine the pile to contain equal volumes of Be and Bi with, at operating temperatures, densities of 1.82 and 9.8 respectively. There are then 4.3 atoms of Be per atom of Bi, and at thermal energies we have

$$\frac{\text{absorption in Bi}}{\text{absorption in Be}} = 0.35$$

$$\frac{\text{scattering in Bi}}{\text{scattering in Be}} = 0.52$$

The values in Table II are taken from MUC-HHG-7. As a rough guess we take $\sigma_s(Bi) \div \sigma_s(Be)$ to have an effective value of 1.6 in the slowing down range; thus

Table II

Neutron Energy	$\sigma_s(Be)$	$\sigma_s(Bi)$	$\sigma_s(Bi) \div \sigma_s(Be)$
resonance	6	9	1.5
0.1 MEV	4.5	10.5	2.34
1 MEV	2.9	5.3	1.83
3 MEV	2	6.2	3.1

in this range

$$\frac{\text{scattering in Bi}}{\text{scattering in Be}} = 0.37$$

An age of 115 at $\rho = 1.85$ increases to 119 at $\rho = 1.82$, and upon admixing Bi as assumed above this is further multiplied by $\frac{4}{1.37}$ to reach a value of 347. In the absence of a better calculation we shall use this value for the age in the pile.

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Similarly the value of 557 cm^2 for L^2 in pure Be of $\rho = 1.82$ is multiplied by $\frac{4}{1.35 \times 1.52}$ to become 1085 cm^2 in the Be - Bi mixture. In passing from room temperature to an absolute temperature 3 times as great (about 600° C) the value of L^2 is further multiplied by $\sqrt{3}$ to become 1880 cm^2.

3. Pile Size

Consider, for example, a pile containing 3000 Be atoms for each atom of 23. Then $\frac{\text{wt } 23}{\text{wt Be}} = 0.86\%$, $\frac{\text{abs in Be}}{\text{abs in } 23} = 6\%$, $\frac{\text{abs in Bi}}{\text{abs in } 23} = 2.1\%$, and for L^2 in such a mixture we have $1880 \; \frac{.081}{1.081} = 141$ cm^2. The losses just described amount to 8.1%; we shall assume a value of 2.135 for k, which amounts to increasing the losses by 1.5% ($2.135 = \frac{2.34}{1.096}$). With these values the solution of $1 + BL^2 = ke^{-B\tau}$ is $B = 16 \times 10^{-4} = (.04)^2$, so that the radius of a bare spherical pile is $\frac{\pi}{.04} = 78.5$ cm. For a bare cylinder of minimum volume the height is 136 cm and the radius is 73.6 cm; this gives a pile volume of 2.31 m^3, a Be weight of 2.1 tons, and calls for 18 kg of 23.

4. Heat Output

The total cross-section area of the Bi ducts in such a uniform pile is 8500 cm^2, and at a velocity of 2 meters per second the total flow is $1.7 \times 10^6 \; \frac{cm^3}{sec}$. The heat capacity of Bi is $\rho c = 0.36$ (physicial data on Bi is taken largely from CP-3061) $\frac{cal}{deg \; cm^3}$, so that if the average temperature rise is 100° C (temperature rise along central stream = 232°) we find a heat output of $6.1 \times 10^7 \; \frac{cal}{sec}$ or 255,000 kw, which amounts to 14,200 kw per kg of 23.

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If the 23 is contained in Be plates of 4mm thickness the total surface of the plates is 5.8×10^6 cm^2, so that the average heat flux from the Be surface is 10.5 $\frac{cal}{cm^2\ sec}$. The maximum heat flux is 3.64 times this, or about 38 $\frac{cal}{cm^2\ sec}$ from a plate at the center of the pile.

We imagine each 4 mm plate to comprise two 2 mm plates with the fissioning liquid held in a thin layer between them, as indicated in Fig. 1. Then the distance

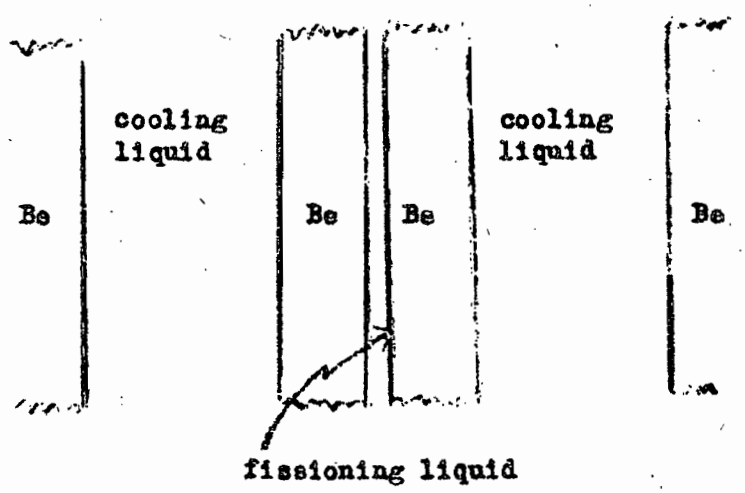

Fig. 1

the heat flows in Be is 2 mm. If the conductivity of the Be is (Mon P-190; p 4, 7, 10; reference No. 45 on p 24; Summary, p 22; P-762) 0.2 in cgs-calorie units, the maximum temperature drop in the plates is about 40° and the corresponding value of $\bar{\theta}$ (Mon P-190; p 6 - 8, 10) is 20°.

5. Heat Transfer

The temperature drop between the plate and the Bi stream is somewhat uncertain (Summary p 10, 97; Mon P-147, p 26-29, 72-74; CF-3582, p 42; CK-2737, p 26). If we apply the usual turbulent

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convection formula we get a heat transfer coefficient

$$h = H \frac{G^{.8}}{D^{.2}} , \qquad (1)$$

where G is mass velocity, D is diameter, and H is a constant which (CP-3061, p 6) for Bi at 500° has a value 5×10^{-3} in cgs-calorie units. With $G = 9.8 \times 200$ and $D = .8$ cm, this gives $h = 2.25$ so that the maximum "film drop" would be $\frac{38}{2.25} = 17°$.

This value of 17° is probably too low. A calculation made by Karush (CP-3289; Mon P-147, p72-74; CF-2796, p25) for Bi suggests doubling the value to get 34°. Factors smaller than 2 have also been suggested (CF-3582, p 42).

An overestimate for the temperature drop is gotten by imagining the heat coming into the stream to flow thru stationary Bi for a distance equal to ¼ the thickness of the stream. This gives $h = \frac{.04}{.1} = 0.4$, wherein 0.04 is the thermal conductivity of Bi; and the corresponding temperature drop is $\frac{38}{.4} = 95°$.

Another consideration which may be made is that an average value for the eddy diffusion coefficient in a flat stream of thickness 2a and velocity V is given (CP-3041; Mon P-147, p 70) by $E = 0.1\, a\, V \sqrt{f}$, where (eg. McAdams, Heat Transmission, p 119) f is the Fanning friction factor. Taking the viscosity μ of Bi to be 0.012 poise; we have for the Reynolds number in the present case a value $\frac{DV\rho}{\mu} = 1.3 \times 10^5$; the value of f is then (McAdams, p118) about $(.07)^2$ so that E comes out to be 0.28. This is equivalent to an eddy thermal conductivity $E\rho C = 0.1$; since this is 2.5 times the molecular thermal conductivity it

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appears that the above value of 95° may be two or three times too large.

Work is currently in progress on heat transfer to liquid metals at Argonne (cf. talk by Zinn at October, 1946, Information Meeting at Clinton; and lecture by M. Novick on Feb. 11, 1947, to the Pile Technology class), at Clinton (R. Lyon), and at Dow Chemical Co.

6. Pressure Drop.

The pressure drop along a stream is given in dynamic units by

$$\frac{dp}{dx} = 0.092 \frac{\mu^2}{\rho} \frac{G^{1.8}}{D^{1.2}} . \qquad (2)$$

With the numerical values used previously (2) comes out to be 4270 dynes/cm^3, and over a length of 136 cm the pressure difference is thus 5.8×10^5 dynes/cm^2 or 0.58 atmospheres. The power required to pump 1.7×10^6 cm^3/sec thru such a pressure difference is 100 Kw; if the flow is throttled over the pile cross-section so as to keep the temperature rise everywhere the same, the total flow rate and the power expenditure are both divided by 2.3. On the other hand, the additional pressure drop in the reflector, piping, heat exchangers, etc. outside the pile proper will somewhat increase the pumping power.

7. Fissioning Liquid

It is not known just what this liquid might be. Some search for low-melting alloys containing U or Th has been unsuccessful (Summary, p. 10; CT-3726), but is being continued by Brewer at California and similar work is getting under way at M.I.T. (CT-3573, p 10; CT-3602, p 11; CT-3619, p 7; CT-3650, p 12 and 12-a). A suggestion

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may perhaps be gained from the story that Brewer has obtained 5% solubility of U in liquid Pb with a small amount of Na.

Assuming 25 Pb atoms (with absorption $\bar{\sigma}$ = 0.15 b) for each 23 atom gives a neutron loss to the Pb of 0.75%. If Bi can be used with or in place of Pb the melting point and neutron loss would be lowered, and greater dilution of the 23 would be possible (see section 11).

To get an estimate for the thickness of the fissioning layer we assume that the 18 kg of 23 is present in 400 kg of liquid of density 10, giving a volume of 4×10^4 cm^3. This is spread over a surface of 2.9×10^6 cm^2, so that the thickness would be about 1.4×10^{-2} cm which is of capillary dimensions.

The range r of fission fragments in matter of density 10 is around 5×10^{-4}cm, and the number emerging from a surface of a uniform fissioning slab is (eg. MUC-GY-20) equal to the number produced in a layer of thickness r/4. Thus even with the fissioning liquid spread as thinly as estimated above, the fraction of the fission products recoiling into smooth walls in only $\frac{2.5 \times 10^{-4}}{1.4 \times 10^{-2}}$ or around 2%. This fraction will, of course, be greater if there is any adsorption or concentration of 23 at the solid-liquid interface, or if the walls are rough.

According to Seitz the solubility of heavy noble gases such as Xe may be expected to amount (at a partial pressure of 1 atmosphere) to an atomic fraction of 10^{-5} or less in metals. The absorption cross-section of Xe^{135} is some 5000 times that of 23, and hence this Xe causes a neutron loss of 1% if it is present to the extent of 2×10^{-6} atoms per atom of 23 or (if the 23 has an atomic dilution of 20 in the fissioning liquid) 10^{-7} atoms of

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Xe per atom of the fissioning mixture. Thus at a partial pressure of 10^{-2} atmosphere of Xe^{135} above the liquid metal we should expect the Xe to be soluble to the extent of causing 1% neutron loss. At 250,000 kw the amount of 23 fissioned per day is 250 g or about 1 mol., and the daily amount of Xe^{135} produced* is about 0.06 mol. Since the Xe^{135} radio-active lifetime is about 14 hours, there would be about 0.035 mol present if it were all decaying outside the pile; at one atmosphere this would occupy 0.8 liters, and to reduce the partial pressure to 0.01 atmosphere it suffices to provide an empty space** of .08 m^3. However, the Xe is produced inside the pile and (MUC-EPW-134, p 22-23) must get out in a minute or so if its neutron capture is to be avoided; it probably will not do this naturally in the narrow confines of the fissioning layers, and may need to be aided somehow. One has a considerably longer time during which the parent iodine may be removed, if some way of doing this is available.

A considerable fraction of the fission product chains include noble gas members, and if these could be swept out it would help in the elimination of fission products from the pile; see various discussions which were given in the Clinton study of homogeneous solution piles (eg. CL-P-406). Others of the products might

*There are, of course, Xe isotopes other than Xe^{135} which are produced in fission.

**It appears (MUC-EPW-101; Mon T-221) that activated charcoal may be hundreds of times as effective in absorbing Xe as a like volume of empty space.

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precipitate out of the liquid and tend to be separable because of density differences, though many might remain in the liquid or adhere to the walls. In processing the liquid some products might be evaporated out by heating, or frozen out by cooling. Evidently, purifying such a dangerously radio-active liquid and removing fission products which deposit on the pile walls constitute major problems; probably the liquid metal carrier (Pb etc) would be eventually discarded with the fission products, and only the 23 saved by solvent extraction etc. methods for re-use in the pile.

The effect of the fission products on the thermal conductivity, viscosity, U solubility, wall attack, etc. of the liquid mixture will, of course, need investigation.

We will return later (section 11) to the mechanical disadvantages of having the fissioning liquid in such thin layers.

8. Cooling Liquid.

There are about 11 tons of Bi in the pile proper; probably the total in the entire system would be nearer 100 tons. At a cost of one dollar for 1 lb. (figure quoted in Handbook of Chemistry and Physics) this amounts to $200,000, or an investment of $3.20 per mechanical kw (assuming an engine efficiency of 25%).

In the present plant about 280 g or 1.2 mol. of 23 are destroyed per day. With 2% as many neutrons being captured in Bi, the production of Po is about 2.4×10^{-2} mols or 5 g per day. Since the lifetime of Po is 200 days, we see that the plant maintains 1 kg of Po in existence. If this amount is present in 100 tons of Bi the concentration of Po is 1 part in 10^5. It may be remarked that 1 kg

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of Po generates about 140 kw of heat.

A kg of Po amounts to 1.7×10^{17} disintegrations per second. Morgan (Tolerance and Permissible Concentration of Polonium in the Water and Air, 10/6/45; Tolerance Values for Polonium, 12-20-45) estimates the tolerance level of Po in air which is continually breathed by people to be 17 dis per sec per cubic meter. Thus if all the Po produced were uniformly dispersed in air, the above plant would maintain 10^{16} m^3 of air at a near-dangerous level of activity; this amounts to all the air above the United States to a height of 0.8 mile. Of course, impressive amounts of radio-activity are produced in any major pile operation, and the problem is largely one of successfully confining the active material. In this respect (Lum 12/16/46; de Benedetti) the Po problem may not be so different from that encountered in other cases; eg. radio-activity in a Na coolant, or fission products in high pressure helium as in the Daniels' pile.

An inquiry (CL-GY-3) to the Dayton project regarding the tendency of Po to escape from molten Bi has recieved the following reply (1/23/47):

> "At one time, part of the routine operation consisted of melting bismuth containing approximately 2 mc of polonium per gram of bismuth and running the molten bismuth through small orifices into cold water. For this purpose an electrically heated stainless steel furnace was found suitable. The loss of polonium, while small, was believed to substantially contribute to the high

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level of contamination generally existent at that time. Since the operation was abandoned some time ago, no further consideration has been given to the problem.

At present, work is in progress on the vapor pressure of pure polonium. As yet no vapor pressure measurements have been made on alloys or mixtures. So far as we know, the polonium appears to be soluble in molten bismuth in the concentrations mentioned above."

The concentration quoted here is one (1) part of Po in 2.3×10^6 parts of Bi, or about 4% of the concentration estimated above for the coolant of the present pile. Evidently open air operations with such liquids are not recommended, and attention should be paid to keeping the system tight. Electro-magnetic leakless pumps (Summary, p 11; Dow Chemical Co; current work at Argonne) may be advantageous in this respect. If submerged solid parts are unloaded from the Bi bath it may be necessary to do this through vapor locks, scrubbing chambers, etc.

There seems to be a report (LA-604) on physical properties of Po, but we have not succeeded to get hold of this. Lum (12/16/46) remarks that the recovery and isolation of Po from Bi is done by a simple process.

9. Breeding Losses.

The losses due to neutron capture in Be, Bi, and Pb as estimated earlier are repeated in Table III.

While the above discussion of Xe solubility and related items does not suggest that it will be easy to get rid of the

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Xe, the fluidity of the system gives us at least a fighting chance to do something about it. Thus instead of the usual (eg Mon P-190, section 6) value of 7% for the Xe + Sm loss, we shall here assume that it will be possible to reduce this to say 3%.

As regards the rest of the fission products, we shall here merely assume them to represent an average (CL-LCN-1; Mon P-190, section 6; CL-GY-1) cross-section of 50 barns per fission, or 45 barns for atom of 23 destroyed, and proceed as in the references just cited. Presumably in the present system there will be a continuous feed of 23 to keep the amount in the pile constant, and we imagine the fissioning liquid to be periodically purified in a batch to remove the fission products. Let the amount of 23 destroyed in the pile between purifications be a fraction f of the constant amount present in the pile, C = fraction of the 23 lost in the purification process, and $p = \frac{45}{500} = 0.09$ the ratio of the cross-section of the fission products resulting from a capture to the cross-section of the 23 atom before the capture occurred. Then (Mon P-190, p 12; CL-GY-1, p 7) the breeding loss is

$$L = \frac{C}{f} + \frac{pf}{2} \quad , \tag{3}$$

with a minimum value given by

$$f = \frac{L}{p} = \sqrt{\frac{2c}{p}} \tag{4}$$

With C = 0.5% and the other values as above we find f = 1/3 and L = 3%, this latter value being equally divided between poisoning and purification losses.

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These various losses are shown in Table III. Besides the items mentioned here there remain for consideration the capture

Table III

Be	6 %
Bi	2.1
Pb	0.8
Xe + Sm	3.0
Other fission products	1.5
Purification	1.5
Total	14.9 %

products or heavy isotopes (CL-RWS-31), the losses in pile controls, and the losses in the thorium breeding blanket around the pile (Mon P-190, section 8; CL-RWS-31; current work by Goertzel and Householder). As seen from Table I, the sum of all the losses must be less than 34% if the breeding ratio $g = \eta - 1 -$ losses is to exceed unity. If g is less than 1 the plant would operate as a "daughter pile" giving power corresponding to $\frac{1}{1-g}$ times the amount of 23 fuel fed to it; it could similarly operate on 25 feed, but with a somewhat smaller value of g.

10. Miscellaneous.

Each atom of 23 in this pile is associated with 3000 atoms of Be and 700 atoms of Bi (not to mention some 25 atoms of Pb used in the particular fissioning liquid mentioned). For each gram of

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23 this amounts to a heat capacity of about 70 $\frac{cal}{deg}$ in the Be and 20 $\frac{cal}{deg}$ in the Bi. The heat output is $6.1 \times 10^7 \frac{cal}{sec}$, or 3400 cal per sec for each gram of 23. Thus if the cooling circulation should stop the rate of temperature rise would be $\frac{3400}{90} = 38$ o/sec on the average, or $3.64 \times 38 \simeq 140$ °/sec at the center of the pile. If the coolant should suddenly be lost from the pile the initial rates of rise would be larger by a factor of 9/7.

The above assumes that the fissioning liquid maintains its thermal contact with the Be walls; if it should get insulated from these by a gas film its temperature would rise more than a hundred times faster. Thus the fissioning liquid should reliably wet the walls. The total amount of fission product gases formed is considerably greater than will dissolve in the liquid metal and and it may be desirable to take steps to vent these; the yield of permanent noble gas atoms (mostly Xe) is around 0.15 per fission, and thus when 0.3 of the 23 has fissioned there are 0.05 such gas atoms per 23 atom or about 2×10^{-3} gas atoms per Pb atom. Thus it appears that there may be problems connected with gas phase formation, bubbles, etc. in the fissioning liquid; perhaps this liquid will need to be slowly circulated (say by natural convection) through the outer parts of the pile where it can be degassed, heated or cooled, precipitates separated, etc. If it has to be taken outside the active part of the pile for this purpose, there will be an additional holdup of 23.

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The "plate" arrangement pictured above should perhaps not be taken too literally, and various mechanical alternates can be considered. For example, Fig. 2 shows a hollow pipe arrangement

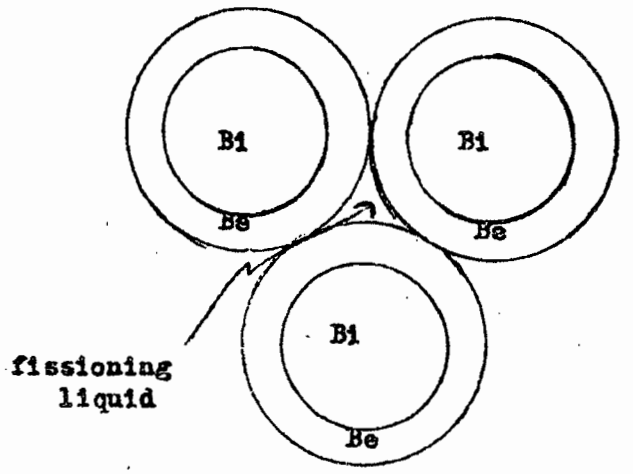

Fig. 2

with the cooling streams flowing inside the pipes and the fissioning liquid in the interstices between the pipes. In Fig. 2 the fissioning liquid occupies about 9% of the total volume, whereas with the previous numbers it should occupy only about 2%; thus the round pipe arrangement should perhaps be modified to hexagonal pipes as indicated in Fig. 3. A variety of such Be shapes have been fabricated (Summary, p 21,22), but the construction of such a tight Be heat exchanger structure is doubtless a difficult problem. Fig. 3 does not show the ribs which would be needed to space and support

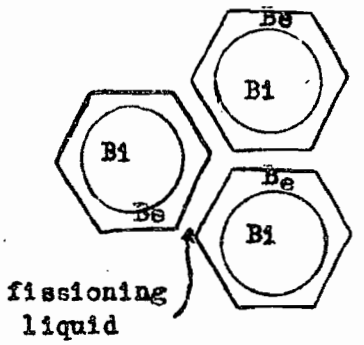

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Fig. 3

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the hexagons.

Besides reducing the neutron losses, elimination of Xe^{135} is desirable to avoid making the pile dead after shutdown, and other reactivity effects (Summary, p 59, 62, 63, 67).

Use of a reflector around the pile will reduce the amount of 23 needed and increase the average heat output per unit amount of 23. On the other hand, taking into account the neutron losses in fission products, pile controls, etc will decrease k and increase the amount of 23 needed.

It has been suggested (Friedman) that a horizontal arrangement might reduce the hazard of the fissionable material settling to the bottom of the pile if it came out of solution.

Be metal thermal piles cooled with Na-K alloy are being considered at Argonne (ANL-WHZ-55; ANL-RGS-12); in these calculations Sachs uses 5.9 b for the thermal transport cross- section of Be.

11. <u>Revised Sketch.</u>

The thickness of 1.4×10^{-2} cm for the fissioning liquid streams with which we came out in section 7 is so small as to seem quite unreasonable in practice because of inaccuracies in fabrication, possible growth (Johnson) of alloy layers or dissolving away of Be, or slight changes generally. It therefore seems preferable to give the 23 an appreciably greater dilution, and we shall consider the thickness of the fissioning layers to be increased to 1 mm while

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the thickness of the cooling streams is decreased to 3 mm. We imagine the 23 to be dissolved in essentially Bi, so that of the entire Bi in the pile $\frac{1}{4}$ is devoted to holding the 23 and 3/4 to cooling. Under these conditions the 23 is diluted about 175 atoms to 1 in its liquid matrix, instead of about 25 to 1 as before. Presumably some additional ingredients (Pb, Na, etc.) will be needed in the Bi to dissolve the 23, but effort would be made to keep the neutron absorption in these small while attaining the desired solubility (about 0.6 atomic %)

Reduction in dimension of the cooling streams would multiply the power output by 3/4 to give some 10,600 kw per kg of 23, for the same coolant speed and temperature rise. The heat transfer coefficient will be somewhat better for the thinner streams. The pressure drop will be multiplied by $(4/3)^{1.2} = 1.41$ to become 0.82 atmospheres, and pumping power for the pile proper by $1.41 \times 3/4 = 1.06$.

The gas dissolving power of the fissioning liquid is multiplied by about 7, and so also would the "free space" requirement as estimated in section 7. The heat capacity of the fissioning liquid is also multiplied by this same factor.

The fissioning liquid now occupies 12.5% of the total volume, which is attained in Fig. 2 with the cylinders slightly separated.

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12. Comparison with Fast Pile.

The same sort of two-liquid arrangement is also considered for fast piles or for mixed fast and slow piles (Mon P-250, pp 32-34), with perhaps Fe replacing Be as the material keeping the two liquids separated.

The dilution of the fissionable material is much lower in fast piles. Thus the thermal pile we have just been discussing, and the fast piles being studied by Menke (who goes to unusually high dilution as compared with other fast piles such as CF-3107), contrast somewhat as indicated in Table IV. The numbers quoted for the fast pile (or the fast core of a mixed pile) are

Table IV

Relative Atomic Numbers

Material	Thermal Pile	Fast Pile
23	1	1
Fissioning liquid	175	15
Be or Fe separating walls	3000	7
cooling liquid	525	15
total atomic dilution	3700	37

somewhat sketchy and are given mainly by way of illustration.

Thus an order of magnitude greater solubility is desired for the fissioning liquid in the fast pile; if the fast pile were less dilute as a whole, or if one attempts to increase the of cooling liquid at the expense of the fissonable liquid, still higher solubilities are called for. On the other hand, the

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the fissioning liquid in the thermal pile was assumed to be largely Bi, while a greater freedom of choice of materials exists in the fast case. If true liquid solutions with the desired compositions can not be found, it may be necessary to consider semi-liquid slurries, etc.

Roughly speaking, the heat capacity of the thermal pile per unit amount of 23 is 100 times that of the fast pile, for the heat capacity of the pile minus cooling liquid the ratio is 140, and for the fissioning liquid it is 12.

13. Postscript Section

Since the previous sections were written a few more references have become available. The navy pile being studied by G. E. is described in a memo by Rickover, "Report on Conferences With General Electric Company on Nuclear Power Developments" dated 1/30/47. The fast and mixed piles being studied by Menke are described in a Pile Technology lecture given by him on 3/4/47.

A more recent M.I.T. report CT-3718 gives the solubility of U in pure Bi and in pure Al as functions of temperature; the solubility of 0.6 atomic percent assumed above (p 18) is attained in pure Bi for temperatures greater than about 460° C. A note received from Brewer (MB-LB-165) tells that the liquid metal work is not being pursued at California at present because of lack of manpower, but may be revived to some extent in the near future.

CL-GY-4 mentions the importance of liquids with high atomic density for fast piles; eg. Al has more than twice the density of Na or Bi.

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