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SOME NOTES ON POWER PILES

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Report Written by: Gale Young

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TABLE OF CONTENTS

		Page
1.	Introduction	1
2.	Gas Cooling	1
3.	Liquid Metal Cooling	4
4.	Heat Flow in Pile Assemblies	6
5.	Comparison of Different Moderators	9
6.	Bombardment Effects and Breeding Losses	11
7.	Semi-Fluid Piles	15
8.	Losses in Blanket	15
9.	Heavy Isotopes	18
10.	Economic Considerations	18
	References	22-26

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SOME NOTES ON POWER PILES

By

Gale Young

1. Introduction. This report presents some considerations on power piles operating on thermal or near-thermal neutrons. Attention will here be limited to high temperature units, the coolants being gases or liquid metals; there is also current discussion of medium temperature power piles cooled by water under high pressure.[1] As moderator, we shall mainly consider Be metal, with some mention of other high temperature moderators such as graphite and Be oxide.[41] Further references on various pile types and materials have been given in a recent memo.[2]

It is hoped that a power pile operating on slow neutrons can about hold its own on fissionable material in a 23-Th cycle, and thus essentially burn thorium as fuel to obtain useful heat and power. As a necessary step in this direction, we shall require the neutron losses in the pile to be reasonably low[52]; some mention of losses in the thorium blanket and in the chemical processing plants is also made, but no real discussion of breeding losses is attempted.

Because of its availability and relative freedom from health hazards, it appears that the first test piles[42] will use 25 instead of 23, and the pile calculations have, for the most part, been made for 25; however, the nuclear properties of Be, BeO, and Na are unmeasured or uncertain to such an extent that the calculations are largely guess-work anyway.

2. Gas Cooling. Some calculations on the output of a Be metal pile cooled with helium have been reported previously.[3] The specific power obtained was quite high; however, the pile composition was such as to involve considerable neutron loss to the moderator, the assumed helium pressure was

[redacted]

high, and the pile plates were assumed quite thin. As there suggested, one would like to increase the concentration of fissionable material in the moderator in order to reduce the neutron loss to a value not inconsistent with the hope of breeding, and see how much this lowers the specific power output (power per unit amount of fissionable material). Also, one would like to see the effect of increasing the plate[44] thickness, and the effect of lowering the gas pressure.

Table I gives the results of some calculations made in this connection, based on pile computations by Goldberger.[4] The first column of results is repeated from before[3]; in the last two columns the breeding loss due to moderator absorption has been reduced to 4.5%, and in the last column the plate thickness has been increased to 0.5 cm. Reduction in gas pressure would further decrease the power output, approximately in proportion to the pressure; and so likewise would a reduction in the temperature rise allowed in the pile.

Introduction of eg. graphite powder has been considered[5] for the purpose of increasing the heat capacity of the gas. The specific heat of graphite is about one-third that of helium, and thus we would need a graphite flow of 100 g/cm^2 sec to match the heat capacity of the helium flow in Table I. If the graphite can be carried at a density of 0.5, this would require a speed of two meters per second, as compared to the 140 meter speed in Table I; also the high gas pressure can be avoided. Such a graphite "liquid" has attractive features, but has perhaps rather poor thermal conductivity and heat transfer properties, and is probably quite a nuisance to handle and to keep flowing in narrow ducts.

Hydrogen has better cooling properties than helium and has been given some consideration.[5]

Table I

	CP-3290	Present Cases	
Wt. of 25 ÷ wt. of Be	0.3%	1%	
Atoms of Be ÷ atoms of 25	8,700	2,600	
Absorption in Be ÷ abs. in 25	15%	4.5%	
25 in bare solid sphere	3.8 kg	6.3 kg	
Be in bare solid sphere	1,260 kg	630 kg	
Radius of bare cylindrical pile	103 cm	103	65
Height of bare cylindrical pile	190 cm	190	121
Gap volume ÷ total volume	0.5	0.6	0.375
Total volume ÷ solid volume	2	2.52	1.6
Amount of 25	17.3 kg	45.7	18.4
Amount of Be	5.8 m tons	4.6	1.8
Stream thickness[44]	3 mm	3	3
Plate thickness[44]	3 mm	1.97	5
Helium pressure	50 atmos.	50	50
Maximum helium flow rate	32 $\frac{g}{cm^2\ sec}$	32	32
Maximum helium velocity	145 m/sec	145	138
Pressure drop in pile proper	1.2 atmos.	1.2	0.74
Gas flow entering pile at ~300°	$5.5 \times 10^7\ \frac{cm^3}{sec}$	6.6×10^7	1.6×10^7
Pile friction pumping power	6,600 kw	8,000	1,200
Maximum wall temperature rise	581° C.	581	581
Wall rise ÷ stream rise	1.12	1.12	1.26
Stream rise	518°	518	461
Heat output	617,000 kw	743,000	164,000
Output per amount of 25	35,600 kw/kg	16,300	8,900
Factor by which output per 25 is reduced from preceding column	----	2.2	1.8
Output per amount of Be	106 kw/kg	162	91
Maximum heat flux from plate	25 $\frac{cal}{cm^2\ sec}$	25	36

3. Liquid Metal Cooling. Some previous estimates[6] on a Be metal pile cooled with Na are essentially repeated in the first column of results in Table II. The last column gives the results of some calculations on a different system in which the neutron losses have been somewhat reduced and the stream thickness increased. The pile size estimates are based on work by Goldberger.[4] In the present case, many of the neutrons are absorbed before they reach thermal energy, so that we have actually a "semi-resonance" or "semi-thermal" pile[15]; to take account of this would require refinements in the calculations, but in view of the uncertainties in the basic data such corrections have not been worried about. For "full-resonance" piles of this type see other estimates given by Goldberger.[7]

The neutron losses[8] are rather larger than in the gas cooling case above; however, the Na loss can be reduced (by perhaps a factor of 1.5) by decreasing the relative amount of Na in the outer parts of the pile where less cooling is needed. The capture cross-section of Na was taken as 0.6 barns in the present calculations, and the thermal conductivity of Be and of Na was assumed to be 0.2 in cgs-calorie units.

The absorption in Pb is about one-third that of Na, and that in pure Bi is about 0.1 that in Pb; thus the coolant losses may be reduced correspondingly[50] by the use of these liquid metals[9]; their thermal conductivity is, however, only 0.2 that of Na, and they are about ten times as heavy, which may make them somewhat more difficult to pump and handle. The production of Po by neutron capture invests Bi with a peculiar health hazard.

Piles of this sort are on the way toward 49 resonance breeders.[7, 10]

Table II

	Modified from Muc-GY-39	Present Case
Wt. 25 ÷ wt. of Be	1%	4%
Atoms of Be ÷ atoms of 25	2,600	650
Absorption in Be ÷ abs. in 25	4.5%	1.1%
25 in bare solid sphere	6.3 kg	18 kg
Be in bare solid sphere	630 kg	450 kg
Plate thickness[44]	1 cm	4 mm
Stream thickness[44]	1 mm	2 mm
Absorption in Na ÷ abs. in 25	4.7%	5.8%
Amount of 25	8.4 kg	40 kg
Amount of Be	840 kg	1,000 kg
Radius of bare cylindrical pile	44 cm	52 cm
Height of bare cylindrical pile	82 cm	96 cm
Total duct cross-section	560 cm^2	2,830 cm^2
Maximum coolant speed	10^3 cm/sec	10^3 cm/sec
Center stream ÷ average stream	2.32	2.32
Total flow	2.4×10^5 cm^3/sec	1.2×10^6 cm^3/sec
Temperature rise	333° C	333° C
Heat capacity per unit volume	$0.3 \frac{cal}{cm^3\ deg}$	$0.3 \frac{cal}{cm^3\ deg}$
Heat output	100,000 kw	500,000 kw
Output per 25	$12,000 \frac{kw}{kg}$	12,500 kw/kg
Output per Be	$120 \frac{kw}{kg}$	500 kw/kg
Maximum flux from plate	$96 \frac{cal}{cm^2\ sec}$	$160 \frac{cal}{cm^2\ sec}$
Maximum temp. drop in plate	120°	80°
Maximum film drop	10°	35°
Maximum local rise ÷ stream rise	1.14	1.1

4. Heat Flow in Pile Assemblies. Pile assemblies frequently approximate plate or rod shapes. Let a denote the radius or half-thickness, p = uniform rate of heat production per unit volume, θ = center temperature measured above the surface temperature, $\bar{\theta}$ = average temperature measured above that at the surface, and k = thermal conductivity of the material. Then we have the results given in Table III. For the

Table III

	θ	$\bar{\theta}$
Plate	$\frac{pa^2}{2k}$	$\frac{pa^2}{3k}$
Rod	$\frac{pa^2}{4k}$	$\frac{pa^2}{8k}$

same surface-to-volume ratio rods are worse[11] than plates by a factor of 2 on θ and a factor of 1.5 on $\bar{\theta}$.

Thermal stresses or strains at a cooled surface depend[12] on $\bar{\theta}$ and on properties of the material, and their allowable values depend upon the strength and ductility of the material. Thus we may consider[49] that there is a maximum allowable value of $\bar{\theta}$ for a given material; since the properties of the material may vary with temperature, the allowable value of $\bar{\theta}$ may depend upon the temperature of the assembly.

Let E = Young's modulus of elasticity, α = linear expansion coefficient, and γ = Poisson's ratio. At the cooled surface of a perfectly elastic (i.e., showing no plastic flow) material we have[12]

$$\text{stress} = \frac{E\alpha\bar{\theta}}{1-\gamma} \quad ;$$

and, more generally,

$$\text{strain} = \alpha \bar{\theta}. \qquad (2)$$

Table IV gives some rough numerical values by way of illustration. It appears[13] that BeO shows little plastic flow, even at elevated temperature, and hence that $\bar{\theta}$ must really be kept quite low. Graphite[43] and U appear quite good, even if they did not show plastic flow. The ductility of Be metal depends upon its method of preparation and upon its temperature.

With the pile described in the last column of Table I we find that the maximum value of $\bar{\theta}$ for homogeneous plates is $3/k$. Assuming $k = 0.2$ cal, etc., for Be metal gives $\bar{\theta} = 15^\circ$ which sounds safe, but using $k = 0.02$ for BeO gives $\bar{\theta} = 150^\circ$ which is unsafe. With Be metal the pile described in the last column of Table II gives $\bar{\theta} = 53^\circ$, which may or may not be safe depending on the ductility.

Table IV

	Be*	BeO	Graphite	U	Concrete
E in atmospheres[56]	2.6×10^6	3.1×10^6	17×10^4	1.5×10^6	2.5×10^5
Tensile breaking strength in atm	2.2×10^3	10^3	10^2	7×10^3	19
Breaking strain if perfectly elastic	0.08%	0.03%	0.17%	0.47%	0.008%
Typical observed strain	0 to 2%	----	----	Several %	----
α per degree C	15×10^{-6}	10×10^{-6}	4×10^{-6}	20×10^{-6}	11×10^{-6}
$\bar{\theta}$ to give strain (2) of 1/2%	333°	500°	1250°	250°	450°
$\bar{\theta}$ to make the stress (1) equal to the breaking stress, assuming $\gamma = 1/3$ (except for concrete, where 0.2 was used)	38°	22°	100°	156°	6°
References	Chicago Handbook IX E2	(13) and (14)	Handbook II E	Handbook IX A	(16)
	*Forged or extruded metal				

5. Comparison of Different Moderators. Some early[6, 61] and some more recent [13, 14, 17, 18, 19] discussion of the relative merits of various moderators has been given. Current work by Daniels[20, 13] contemplate the use of graphite with U installed in its pores in the form of oxide, rather than with U carbide as first considered.

Some comparison between solid moderators was made in the previous section above, and this is carried a little farther in Table V. Occasion is taken in this table to present a few estimates on relative pile sizes and amounts of fissionable material required, with piles of the type discussed in section 2 in mind. Table VI compares some further quantities for Be metal and graphite piles having the same neutron loss to the moderator, the same fractional volume in cooling voids, and the same plate thickness. It is seen that graphite shows up quite well, its lower absorption giving it three times as much cooled surface with consequent reduction in film drop. There have not yet been any tests of the effect of internal fissions[21] upon Be metal or graphite, and the values given in the third line of Table V may be quite misleading.[45]

Table V

	Be	BeO	Graphite
Density	1.85	3	1.6
Relative neutron absorption per unit volume	3	2	1
Thermal conductivity of bombarded material[45]	.2 cal.,etc.	.02	.02
Equally allowable $\bar{\theta}$ (guessed from Table IV)	40°	10	100
Relative specific power output for same plate thickness and same neutron losses	26	1	20
τ = age*	96 cm^2	110 cm^2	387 cm^2
L^2 cold†	622 cm^2	582 cm^2	2,500 cm^2
L^2 hot, estimated as 1.6 x L^2 cold	994 cm^2	930 cm^2	4,000 cm^2
L^2 in pile for about 5% neutron loss to moderator	50 cm^2	47 cm^2	200 cm^2
$\tau + L^2$ in pile	146 cm^2	157 cm^2	587 cm^2
Relative $\tau + L^2$	1	1.06	3.96
Relative pile volume $\sim(\tau + L^2)^{3/2}$	1	1.09	7.9
Relative absorption per unit volume	1	2/3	1/3
Relative critical mass of fissionable material for bare piles with same neutron loss	1	0.73	2.64
Relative heat capacity per unit amount of fissionable material	1	1.6	1.7
Cost per pound[57]	30 dollars	15 dollars	15 cents

*Graphite value from Handbook IV; Be and BeO values from (22)

† Be and BeO values from (23)

Table VI

	Be	Graphite
Linear dimension	1	1.99
Cross-section area	1	3.96
Amount of fissionable material	1	2.64
Total plate surface	1	7.9
Duct area for unit fissionable material	1	1.5
Heat transfer surface per unit fissionable material	1	3
Plate power output (line 5 of Table V)	1	0.77

6. Bombardment Effects and Breeding Losses in Pile. Hanford slugs successfully withstand, but perhaps show some effects from[24], an exposure in which one atom out of 2,000 is fissioned. A rod made of BeO with U oxide had its thermal resistance increased by a factor of five when one atom in 50,000 total was fissioned. A U foil was observed to be completely powdered after one atom in 30 had fissioned.[25] In the absence of any real information we shall guess that a pile alloy can be run until a fraction $\frac{1}{\alpha}$ of its atoms has fissioned, where α is a few thousand. This suggests that the piles of Table I and the first column of Table II might last until most of the active material had fissioned (provided not too much of the Be is present in the form of inert jackets, spacers, etc.), but that the pile in the last column of Table II might withstand the fissioning of only a fraction of its active material.

Another consideration involved in determining the length of time a pile plate should be run is the breeding loss arising from fission products. If not removed, these absorb neutrons, and if they are removed, a fraction c of the active material is lost in the chemical purification process; this conflict results in an optimum period of operation between purifications.[26]

For present purposes, we shall give only a rough approximate treatment of these matters. Assuming a fixed loss (of about 7%) to the Xe and Sm, we suppose[27] that the rest of the fission products can be represented as a permanent cross-section of 50 barns per fission or (in the case of 23) 45 barns per destruction. If the fraction f of the active material used up before the plate is reprocessed is small, we have (in addition to the Xe and Sm loss)

$$L = \frac{\text{Losses}}{\text{Absorption in U}} = \frac{N_P \sigma_P}{N_U \sigma_U} + \frac{c}{f} + \frac{\sigma_F}{2\,\sigma_U} f \qquad (3)$$

where N = number of atoms, σ = cross-section for absorption, and the subscripts P, U, F refer respectively to plate, uranium, and the above described (non Xe or Sm) fission product atoms.

A quantity of the form $\frac{c}{f} + A f$ has its minimum value $2\sqrt{Ac}$ for $f = \sqrt{c/A}$; the nature of the solution being such that the two terms contribute equally to the resulting minimum value. Thus, the sum of the last two terms on the right of (3) has its smallest value

$$\sqrt{2c\,\frac{\sigma_F}{\sigma_U}} \qquad (4)$$

for

$$f = \sqrt{2c\,\frac{\sigma_U}{\sigma_F}} \qquad (5)$$

With our present materials we have $\sigma_F = 45$, $\sigma_U = 620$ for 23; and assuming 1% for c gives a loss (4) of 3.8% for a value (5) of $f = 0.53$. For such a large value of f the above formulae are inaccurate, but at least we have here some indication that it may be desirable to deplete appreciably the plates before reprocessing them. Using these values we have for the losses in the piles described in the last two columns of Table I the values given in Table VII.

Table VII

Xe and Sm	7%
Other fission products	1.9
Chemical	1.9
Plate	4.5
Total	15.3%

When the above plate has been run to $f = 0.53$, we have one atom fissioned out of 4,900. If $\alpha = 2,000$, we could reduce the relative amount of Be in the pile and so decrease the plate loss from 4.5% to $\frac{20}{49} \times 4.5 = 1.8\%$, which is a saving of 2.7%.

However, we can go even further in the adjustment of the Be/U ratio to reduce losses. In the first term on the right side of (3) introduce $f\alpha = N_P/N_U$ to get

$$L = \frac{c}{f} + \left(\frac{\alpha \quad \sigma_P}{\sigma_U} + \frac{\sigma_F}{2 \quad \sigma_U} \right) f, \qquad (6)$$

which minimizes in the same way as before, but with an increased value for A. With $\alpha = 2,000$, $\sigma_P = 0.0107$ for Be (which makes the 4.5% plate

loss in Table I consistent with our other numbers), and the other values as before we obtain L min = 5.3% (as compared to 5.6% in the preceding paragraph and to 8.3% in Table VII), f = 0.38, and N_P/N_U = 760. This value of N_P/N_U is close to the composition in the last column of Table II, and thus for such a pile we have losses as given in Table VIII. With

Table VIII

Xe and Sm	7%
Other fission products	1.4
Chemical	2.6
Plate	1.3
Na	6.7
Total	19 %

possible reduction in the Na loss, as mentioned in section 3, the total loss decreases to about 17%; with Pb cooling the total loss might be reduced to around 14%; and[50] with Bi cooling, to about 13%.

In the foregoing estimates we have assumed an ideal unloading scheme whereby each piece was brought to a given value of f before reprocessing; in practice some compromise would likely be made for mechanical convenience, and this would increase the losses somewhat. Also, there will be losses due to pile controls[31] and to heavy isotope formation.[28]

In the above scheme of operation, the amount of active material that goes to the chemical plant for purification is $\frac{1-f}{f}$ times the amount destroyed in the pile.

7. Semi-Fluid Piles. Some of the piles mentioned above contain appreciable amounts of liquid metal and are perhaps suggestive of designs in which the fissionable material is located in a liquid metal bath resting against Be walls through which the heat passes to a moving coolant on the other side of the wall, the object being to have the solid parts free of internal fissions[29, 56].

Use of the fissionable material in a fluid form would not appear, from the results of the preceding section, to help much to reduce the losses in the above thermal piles except as it makes the fission products (especially Xe^{135}) more easily removable; this might be the case with some of the gases[30]. However, in resonance piles[7] the ratio of Be atoms to fissionable atoms may be more like 100 which, with $\alpha = 2{,}000$, would require f not to exceed 0.05; in this case[46] with c = 1% the chemical losses would be 20%, and it becomes important to either improve the chemical plant or to increase the residence time of fissionable material in the pile between reprocessings.

Use of the active material in a fluid or semi-fluid form may, in addition to increasing the allowable residence time, permit more of a continuous flow purification process with less refabrication of the moderator or other solid pile parts and consequent reduction in operating costs[60].

8. Losses in Blanket. Table IX gives a few estimates adapted from the reports named[33]. These are intended to illustrate some of the items involved in arranging thorium blankets around piles, but have not the status of real calculations or design choices. Water-thorium mixtures have been mentioned[32], but not really computed; the leakage per cent

quoted here is just a guess.* In the heavy water case the thorium (as a thorium oxide slurry) is considered as stirred about; in case of the solid arrangements the variation in neutron density through the reflector would have to be taken into account, as well as the unloading schedule, before the absorption in Pa and in 23 and the amount of 23 can be ascertained. The loss due to Pa is doubled because a capture destroys both the neutron and the potential parent of a 23 atom. The graphite blanket does not take into account any provision for cooling, and this would increase the losses and blanket thickness; similarly, no allowance for coatings has been made in the water case.

Considerable work is needed on the problem of high efficiency blankets, including engineering arrangement for cooling them and for getting the pile coolant in and out through them without introducing too great leakage and absorption losses.

There are advantages and disadvantages in locating part of the thorium within the pile proper[33].

*The leakages and thicknesses quoted are not really comparable since in some cases a plain reflector has been assumed outside the thorium and in other cases not.

Table IX

	MUC-EPW-134	CP-2222	
Moderator	Heavy water	Graphite	Water
Volume of Th ÷ volume of moderator	----	.1	3
Wt. of Th ÷ wt. of moderator	1	.7	35
Absorption loss in moderator	1/2 %	2 %	3 %
Reflector thickness	40 cm	80 cm	40 cm
Leakage loss	1/2 %	1 %	2 %
Assumed radius for spherical pile	60 cm	60 cm	60 cm
Wt. of moderator	3.3 m tons	1.8 tons	0.8 ton
Wt. of thorium	3.3 tons	13 tons	28 tons
Assumed power output	100,000 kw	100,000 kw	100,000 kw
Wt. of Pa	4.8 kg	4.8 kg	4.8 kg
$\sigma_{Pa} \div \sigma_{Th}$	13	13	13
Abs. in Pa ÷ abs. in thorium	2 %		
Total loss due to Pa	4 %		
Wt. of 23 in blanket	3.3 kg		
Abs. in 23 ÷ abs. in Th	8 %		
Loss due to 23 fission (guess)	2 %		
Chemical loss of 23 or Pa	1 %		
Total breeding loss	8 %		
Total Pa or 23 holdup in blanket	8 kg		
Reprocessing loss of Th	0.1 %		
Fraction of Th utilized	50 %		

9. Heavy Isotopes. Besides making fission products, plant operation also generates various heavy isotopes. These cause neutron losses[34, 51] and complicate the chemical processing. Isotopes of process materials (e.g., U and Th) cannot be removed by chemical methods, and the materials may be thus made hot to handle, requiring remote control operations, or may have their neutron properties changed (e.g., the 23 may be denatured against bomb use). In some cases enough dilution may occur (e.g., of 23 by 24) to appreciably affect the pile composition and give metallurgy or solubility changes[35, 51].

10. Economic Considerations. Assuming[36] that rock can be processed for 10 $/ton, and that an adequate amount of atomic raw material (U and Th) is available in 100 ppm concentration (a figure ten times the average for the earth's crust), the cost[59] of raw material is 100 $/kg. Pile use of fissionable material gives about 2,000 $\frac{\text{kw year}}{\text{kg}}$, so that if half of the raw material can be utilized the ore cost for heat comes out to be 10 cents/kw year. The cost of heat energy as coal is typically[53] about 8 $/kw year, and the cost of generating electrical energy in coal burning plants is about 50 $/kw year.

The cost of atomic power is essentially that of maintaining and operating the plant required to obtain it, the cost of the fuel used up being small. Some estimates by Thompson[37] on the use of a Hanford type pile to generate electrical energy indicate a plant investment of 200 to 300 $ per electrical kw, and an operating and maintenance cost of 60 to 80 $ per electrical kw year. No similar estimates are yet available for piles of the sort we are considering here.

Some attempt can be made to estimate the amounts of various materials needed in the plant. As an example, consider the pile in the last column of Table I. This contains 18 kg of 23 and, assuming operation at 100,000 kw, about 110 g of 23 are destroyed per day. Suppose that f = 0.2 and that it takes 10 days to reprocess a unit and return it to the pile; then we have a core processing holdup of about 4 kg. The holdup as Pa is 5 kg[54], and the holdup of 23 in the blanket is 3 kg in the heavy water case of Table IX (probably higher in the other cases). If it takes ten days to remove 23 from the blanket and install it in the pile, there is 1 kg holdup in this process. For definiteness we guess 14 kg for Pa and 23 holdup in the blanket and blanket processing; this gives a total of 36 kg or twice the amount in the core proper. The same plant also requires two tons of Be, and about[47] five tons of Th, and four of heavy water if this type of blanket is employed.

Table X gives some estimates on the cost of materials, with a guess as to how these may change with future developments. Although not based

Table X

	Now	Later
Fissionable material	30,000 $/kg	5,000
Thorium	10 $/kg	100
Be[38]	60,000 $/ton	20,000
Heavy Water[39]	70,000 $/ton	40,000

on any real knowledge, the figure quoted for the present cost of fissionable material is intended to represent the K-25 type process, and the figure quoted for later on is intended to indicate how the cost of producing fissionable material may be expected to be lower with a pile breeding process in which much or all of the operating costs can be met by the value of the power produced[40].

Table XI shows costs for the pile just described with a heavy water blanket, figured according to the prices given in Table X. The engine

Table XI

Material	Amount Needed	Present Cost	Later Cost
Fissionable material	36 kg	10.8×10^5 $	1.8×10^5 $
Be	2 tons	1.2×10^5	0.4×10^5
Th	5 tons	0.5×10^5	5×10^5
Heavy water	4 tons	2.8×10^5	1.6×10^5
Total of items shown		15.3×10^5	8.8×10^5
Total per mechanical kw		61 $/kw	35 $/kw

efficiency was assumed to be 25%, giving a mechanical or electrical output of 25,000 kw. With a graphite reflector using 12 tons of Th, the present cost drops from 61 to 52 $/kw, provided that the 23 holdup in the blanket is not increased.

At a fixed charge of 10% per year for investment, insurance, etc. costs, the items just discussed amount to about 5 $ per electrical kw

year, which does not seem an unduly large fraction of the current cost of 50 $/kw year. Of course, many other items[60] will have to be considered before the total cost of power from such a plant can be estimated.

It may be remarked that if fissionable material should become low cost and plentiful, one would likely build plants with a lower kw/kg output and not "strain" the pile so hard.

At present the significant source of fissionable material is the K-25 plant. If we assume that it can supply 5 kg/day and that this is used to start up[48] power plants operating at an average heat rate of 2,000 kw/kg and mechanical efficiency of 25%, we can from this source increase our electrical generating capacity at a rate of 0.7 million kw per year, which would double the electrical capacity of the United States in about 50 years. If the K-25 plant extracts one-third of the 25, it would in 10 years operation at this rate use 8,000 tons of natural uranium; this is an amount comparable[36] to the U. S. rich deposits, and so we would soon at this rate have to turn to lower grade ores or to foreign sources.

The same amount of uranium might be used to construct about 40 high temperature Hanford type plants[37] which would yield an amount of 49 comparable to the K-25 output of 25, and probably at a comparable cost[55].

If a plant such as described above (100,000 kw from 36 kg) can be made to show a breeding gain of 9%, it would each day create 10 g of new fissionable material[40], and could thus "double itself" in 10 years.

The author is indebted to Mr. W. I. Thompson and Mr. J. Menke, who have read the manuscript and made a number of suggestions for its improvement.

References

(1) MUC-LAO-22; Mon P-93; calculations by Babcock and Wilcox Co.; memo by Benedetti dated 6/12/46; some preliminary work done by Abelson for the Navy, as mentioned in CF-3403, p. 41; NEPA is considering steam engine and pile systems operating above the critical point for water.

(2) Summary of new Pile Studies, Young, October 1946.

(3) CF-3290.

(4) MUC-WC-MLG-7.

(5) See section 2.2 of reference (2).

(6) MUC-GY-39.

(7) CF-3490; Mon S-124.

(8) See section 6 for further discussion.

(9) See section 2.1 of reference (2).

(10) See section 6 of reference (2).

(11) Mon P-147, p. 78.

(12) CP-1698; Mon P-147, p. 89; for further references see section 9.5 of reference (2).

(13) Report of Meeting to Discuss Fuel Rod Problem, Etherington, 7/18/46.

(14) MUC-JEW-127; CT-3528.

(15) See section 6.3 of reference (2).

(16) Urquhart, Civil Engineering Handbook, pp. 552, 563, 567, 190.

(17) MUC-JEW-63.

(18) Current work in McCullough's division.

(19) See section 3.6 of reference (2).

(20) ANL-OCS-32.

(21) See section 6.

(22) MUC-WC-MLG-10, or CF-3403, p. 43; see also CP-3407 and Mon P-160, p. 5.

(23) MUC-KW-60; section 3.1 of reference (2); but see also CF-3562.

(24) See section 8.1 of reference (2).

(25) MUC-GTS-1882.

(26) MUC-KW-41; Mon P-147, p. 106-110; section 8.2 of reference (2).

(27) Estimate by Leona Marshall from Hanford observations, as quoted in Mon P-152.

(28) See section 9.

(29) CF-3352, p. 18; MUC-GY-40; section 6.6 of reference (2); some further descriptions of such systems exist in an unpublished memo by Young to Zinn.

(30) Cf. work at Clinton on the heavy water homogeneous pile.

(31) See section 8.3 of reference (2).

(32) Christy in CP-387.

(33) See section 8.4 of reference (2) for additional references.

(34) Section 8; MUC-EPW-134, pp. 2, 26, 27, 31.

(35) See section 8.6 of reference (2) MUC-WHZ-FF-169.

(36) MUC-LAO-18; MUC-LAO-19; M-1003; graph by Goodman reproduced in notes on recent meetings of new pile group, Young, 9/6/46; Nuclear Fission as an Economic Source of Industrial Power, J. R. Menke; Some Estimates on the Availability of U and Th and their Cost in the U. S., J. R. Menke, November 1946.

(37) Recent Baruch report; notes on meetings of new pile group, Young, 7/29/46; Thompson, 6/11/46; Leverett, 7/6/46; and other memos.

(38) These figures are quoted from a discussion with Kyger. Possible shortage in the Be ore supply has not been taken into account here; Menke is looking a little into this matter, and we understand that the Madison Square Area is starting an investigation. The weight of Be in the earth's crust is thought to be similar to the weight of Th + U.

(39) The value quoted is thought to be about right for the Trail plant; the corresponding cost with the DuPont plant is perhaps more like 100,000 $/ton. The lower value given for later on is an estimate by Karl Cohen.

(40) With an external blanket operated as in section 8, it is necessary to reprocess 1,000 kg of Th for each kg of 23 obtained. This ratio of 1,000 to 1 can be reduced somewhat by removing the Pa along with the 23. The cost of reprocessing to metal is several dollars per kg; the cost of reprocessing to oxide might be rather less. If a power pile which just holds its own on fissionable material is modified to use a greater fraction of the excess neutrons and so give a breeding gain, a greater investment is required. If, to take a crude example, it

requires an extra ton each of Th and heavy water to get an additional 9% production of 23 in a 100,000 kw pile, we have an added investment of $140,000 to gain 10 g/day of 23. Assuming a charge of 7% per year on the investment gives a cost of 2,700 $ per kg of 23 from this item alone.

The investment and operating costs for the Th may be appreciably reduced by putting some or all of it inside the pile proper[33]. Further work on this point is needed.

(41) BeO has featured in work on the Daniels' pile at Chicago and in McCullough's division at Clinton. A review of this development is being written by Daniels.

(42) Also, the start-up of later piles may be done on 25 or possibly 49; see reference (48) and section 10.

(43) Recent experimental work by Daniels tends to confirm the good resistance of unbombarded graphite to temperature differences.

(44) The piles discussed in the present report are cylindrical with the coolant flowing parallel to the axis between plates which constitute the solid parts of the structure. The notion of a "plate pile" is used in a fairly general way: Actually the "plates" may be bent into hollow cylinders or spirals, or may be flat or curved pieces held in frameworks in a variety of ways; see MUC-LAO-57, Mon N-108, and current work on the Clinton high flux pile for a number of examples. Similar remarks apply to the shape of the coolant streams.

(45) The values given are guesses as to the conductivity of bombarded material. The values for unbombarded material are more nearly equal; rough values at 500° C. being perhaps 0.2 for a Be alloy (CP-2332), 0.2 for graphite (Proc. Phys. Soc. of London 51, p. 168, year 1939), and 0.1 for BeO (MUC-JEW-127; CT-3437).

(46) Similar remarks may apply to thermal piles using graphite or BeO. For example, with about 5% neutron loss to these materials there would be about 5,000 moderator atoms for each atom of fissionable material. Then if α is 50,000 for these materials (cf. section 6) we have $f = 0.1$ and with $c = 1\%$ the chemical losses would be 10%.

(47) Account has not been taken of the fact that some of the Pa is in the blanket reprocessing plant outside the pile. If the reprocessing time is 10 days, there will be about one ton of thorium in this stage (flow of 23 = 110 g/day, and of Th is a thousand times greater or 110 kg/day; 10 days holdup thus amounts to 1.1 tons). Also, there is some external holdup in the slurry cooling system. These considerations would reduce the Pa loss to say 3%, increase the amounts of Th and heavy water required, and increase the 23 holdup in the blanket.

(48) In starting up a plant by means of fissionable material less efficient than 23, more of such material has to be supplied than the amount of 23

needed. If the plant just holds its own on 23, it will need about 1.3 times as much 25 or about 1.4 times as much 49.

(49) The present discussion is rather idealized and over-simplified. No attempt is made to consider the effect of cracks and stress concentration, radial tension on cooling, repeated temperature cycling, etc.

(50) It may be noted that pure Bi has only about 0.4 as much neutron absorption as an equal volume of Be. Thus relatively large volumes of coolant can be tolerated and its velocity need not be so high. A pile with say 3% loss to Be and an equal volume of Bi would do quite well with a coolant velocity of 2 meters/sec. and might compare favorably with the piles described in more detail in the text.

(51) Current calculations by Stoughton.

(52) For some purposes (e.g., in mobile units) the requirements on neutron economy may be relaxed; thus permitting the use of more absorbing materials in the pile, reduction or elimination of the blanket, etc. If piles showing a significant breeding gain (e.g., fast breeders) are developed, they will be able to sustain the operation of some units which do not hold their own on fissionable material, in a so-called system of "mother" and "daughter" piles.

(53) At 7 $/short ton: this value may be a little high.

(54) MUC-EPW-134, p. 27.

(55) The operating and maintenance costs would be of the order of 100,000 $ per kg of 49 produced, but the plants would give about 3 million kw of electrical energy which would meet much of the expenses. If the power covered 0.8 of the expenses, the "cost" of the 49 would be about 20,000 $/kg, etc.

(56) The value of E for unbombarded graphite is about 6×10^4 atmospheres. Both E and the breaking strength increase upon irradiation, but E increases more rapidly (see section 8.1 of reference (2)). To make some allowance for this, we have here multiplied the normal value of E by 2.8.

(57) Be cost from Kyger (see reference 38); BeO cost is given as 14 $/lb. in CL-FD-16. The graphite cost quoted is just a guess.

(58) Menke and Donelian have considered a mixture of active and inactive grains packed loosely, with the pores filled with liquid metal.

(59) Recovery of by-products from the rock might tend to reduce the cost of U and Th.

(60) One of these is the cost of reprocessing the Be and returning it to the pile. Chemical methods for decontaminating Be are not developed, and remaking into metal is at present quite expensive. For α = 2,000, the weight of Be reworked is 80 times the weight of U fissioned. The fission of one kg of U gives about 2,700 kw year, and if the cost of

reprocessing the Be is 30 $/lb. or 70 $/kg. this item amounts to about 2$ per kw year of heat. For the pile described in the last columns of Table I operated as discussed below Table VII, this item is about 2.5 times greater. Thus, as has been pointed out by Daniels, it is expensive to process the Be any oftener than demanded by bombardment damage; it might be preferable to take some loss in specific output, by concentrating the U into "fuel rods" or into smaller piles, in order to reduce the amount of Be reworked. The "semi-fluid" designs aim at a similar economy without necessarily sacrificing specific power.

Similarly, if α = 50,000 for BeO (which may be a misleading number since recent observations suggest that the bombardment effects in this material show some tendency to saturate), we should have to reprocess about 2,500 kg of BeO for each kg of U which is fissioned. At 14 $/lb. = 30 $/kg, this amounts to nearly 30 $ per kw year of heat, or about four times the cost of coal.

(61) A discussion somewhat similar to the present report was given in an unpublished memo "Oxide and Other Piles" from Young to Zinn in the fall of 1945.