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PHYSICAL DATA ON NEW HIGH FLUX PILE

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Addendum I: Some Engineering Details of Proposed Pile

In order to make this report on the physical data of the new pile more easily understood we give here a short general description of the machine. For more details we refer the reader to Mon-201 in which the general engineering features of the pile are described.

The pile proper will be a light water moderated and cooled pile with beryllium reflector. The active part will consist of closely packed vertically stacked plate assemblies. The individual plates are made of an alclad Al-enriched U alloy. They are spaced in the assemblies so that water can flow between the plates, thus serving both as moderator and coolant. The whole pile, active part, beryllium reflector and control rod arrangement will be set at the bottom of a tall ($\sim$30 feet high) tower which is always filled with flowing water. The water which flows at the rate of 10,000 g.p.m., enters the tower at the top and passes through the pile and reflector.

The details of the various parts will be as follows. The plates of the assemblies are about 1 mm thick, 8 cm wide, 60 cm long. They will contain about 14 mg. of U^{235}/cm^2. The separation of the plates for the cooling stream will be 2 mm. The plates will be fabricated into "multiplate assemblies"; each assembly will consist of about 20 parallel active plates held together by side walls of Al into which each plate is

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brazed. The overall dimensions of the active part of an assembly will be about 8 x 6 x 60 cm, and each assembly will contain about 100 grams of fissionable material.

About thirty of these assemblies, stacked vertically side-by-side into a prism about 40 cm x 40 cm x 60 cm will ordinarily constitute the active part of the pile. Around this active portion there will be the Be reflector extending outward about 40 cm from the edge of the active material. In order to achieve maximum flexibility it will probably be composed of two sections. The part next to the pile, whose cross-section fills out a rectangle of dimension 80cm x 60 cm, will be built out of long (approximate dimensions 6cm x 8 cm x 100 cm) Be columns stacked together much like the assemblies themselves. This part of the reflector is readily removable and is interchangeable, column by column, with active assemblies. Its purpose is to make it possible to change the pattern of active lattices rather drastically without major reconstruction of the pile. The remaining part of the Be reflector, which extends out until it completes a circle of 120 cm diameter, will consist of large Be blocks keyed together and provided with small through holes through which cooling water can flow.

Control rods will go vertically through the active lattice and will be actuated from below. As described in the main text, they will consist of a length of Be, above this a length of Th, (or possibly Li) and above this a

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length of Cd. During operation the Be or Th will be in the pile; the Cd tops of the rods supply an added control margin which will be used for safety. In addition to these rods, which will be used mostly for shimming or for safety, there will be one or two small rods in the reflector which can be used for control. We estimate that a control margin of 1% in these rods should be sufficient.

Outside the active lattice, and in the block part of the Be reflector, there will be a row of Th rods which will constitute a 23 factory. Beyond the Be reflector, in a fairly thick layer (~ 75 cm) of graphite, there will be additional holes for production of C^{14} and other isotopes.

The pile and reflector are to be surrounded by a thick concrete shield. The shield and reflector will be pierced by a large number of experimental holes distributed around the pile. Most of these holes will be used for beam experiments. For long irradiations it is planned to use mostly the removable Be reflector columns. In addition to the experimental holes there will be a horizontal graphite thermal column jutting out from one side of the machine.

Although the active pile is insignificant in size (~40 x 40 x 60 cm), the whole pile will not be small. It will probably look, from the outside, like a large concrete octagonal prism, about 30 feet tall and about 25 feet across.

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Physical Data on New High Flux Pile

General

Since the appearance of report Mon P-108 in which a heavy water moderated-experimental pile was described, the physics division, and the laboratory generally has turned its attention to a light water moderated machine. In this section we examine the reasons for this change, and in so doing we restate the general philosophy underlying the construction of a high flux thermal neutron pile.

The general aims of a high flux experimental pile were stated in Mon P-108 to be

1) Attainment of a very high flux, of the order of several x 10^{14}, for general experimental purposes. The figure $\sim 10^{14}$ was arrived at because this is about the flux level at which an economical thermal breeder would operate.

2) Production of sizeable quantities of U^{233} and other isotopes. In addition, three other requirements for a general purpose high flux pile can now be stated. These are

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3) The machine should be very flexible; that is, it should be possible easily to change the disposition of the fissionable material in a manner dictated by the needs of the particular experiment that is to be performed.

4) The machine should be so simple that it might serve as a prototype for other research centers desirous of building an experimental chain reactor. This point is considered desirable but not essential.

5) The spectrum of epi-thermal neutrons should be as energetic as possible.

We now inquire to what extent the present proposal achieves the added advantages, #3, 4 and 5.

3) Flexibility: The pile, as is described in the report on engineering, will consist of a number of "multiplate" Al assemblies, each plate containing about 14 mg/cm^2 of fissionable material. The assemblies are mounted together at the bottom of a deep well; cooling is afforded by water which enters at the top of the well and leaves at the bottom.

The essential flexibility of this arrangement arises from the fact that there are no individual water feed lines to the separate assemblies. It is therefore possible to rearrange the assemblies in many different ways without being restricted by the necessity for providing a new disposition of water feed lines for each arrangement.

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An additional feature of flexibility is achieved in the present design by making all pile elements easily removable. For example, a higher fast flux could be obtained by replacing part of the Be in the reflector by Al. This could be done without too much trouble in the new machine.

4) Simplicity: We believe that the elimination of the individual water feed systems and the substitution of a solid Be reflector for a liquid heavy water moderator makes this pile much simpler than the one considered previously. With an Al instead of Be reflector, the pile would use no rare materials aside from the 25. The reason we do not use an Al reflector in the current version is twofold: first an Al reflected pile would require higher critical mass and consequently would necessitate a higher power to achieve a given flux; and second, isotope production is less efficient with an Al reflector than with a Be reflector.

5) Spectrum of Epi-thermal Neutrons: Distribution of thermal neutron fluxes. This is one of the most important reasons for eliminating the heavy water moderator in the present version of the pile. The flux, $(n\,v)_0$, of neutrons which have suffered no collisions is related to q, the number of neutrons produced per sec per c.c. and to Σ_{in}, the macros-

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copic cross-section for reduction of the neutron energy, by the relation

$$(n v)_o = \frac{q}{\Sigma_{in}} .$$

This is a correct equation if the pile is large compared to a mean free path. The quantity q is proportional to the power per unit volume of pile. Hence the flux of virgin neutrons, which is the flux of most use in radiation experiments, is determined by how much power can be extracted from a given volume of pile. The old version of the pile had a volume about 8 times greater than the new one, while the power output is about the same, as is the average Σ_{in} for fission neutrons. The very high energy neutron flux in the new version is therefore approximately 8 times as high as the very high energy flux in the heavy water version.

This very fast neutron flux is now quite comparable with the flux of the proposed Argonne all metal "fast" pile. This follows from the fact that the "inelastic" cross-section of U for fission neutrons is not very different from the "inelastic" cross-section of our mixture of light water and aluminum since the hydrogen scattering, which is mainly responsible for degrading the energy of fission neutrons in our pile, is very small at fission neutron energy.

As far as thermal neutrons are concerned, a thermal pile of the type discussed here has evident advantages over a

fast neutron pile. We believe our thermal neutron flux can be as high as $4 \times 10^{14} cm^{-2} sec^{-1}$ in the region of an active assembly. This figure is determined by the maximum heat transfer which can be achieved and it corresponds to a power somewhat above 30×10^{3}kw, depending on the degree of flatness of the neutron density distribution across the pile.

The thermal neutron distribution in the present machine is lowest at the center and highest in the reflector just outside the active region. Just how large the rise is depends on the disposition of control rods. If all the rods are out, the distribution is nearly flat inside the active region, and rises to perhaps 1.3 times its interior value a few centimeters out. With all control rods in (at the center of the pile) the ratio of density at the edge to average may be as high as 3.

The circumstance that the region of maximum thermal neutron flux occurs at the outside of the pile is doubly advantageous. First, the maximum is at a place, the reflector, which is naturally convenient for experimentation. An early objection to a water moderated pile was that it is too small for experimental work to be done effectively on it. But with the best experimental region being in the reflector, of a size comparable to the overall size of the heavy water machine, this objection has very much less force. We estimate that the overall experimental facilities of the proposed

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machine will be less than those in the heavy water machine by perhaps 30%, whereas the volume of the active region is only 1/8 the volume of the old device.

The second advantage of the high neutron density in the reflector is that it makes it possible to achieve a flux which is higher than that which would be determined by the heat transfer bottleneck, if the highest flux occured near active material. The maximum slow flux anywhere in such a pile would be 4×10^{-14}. However, with the maximum flux occuring outside the pile where there is no active material, a flux larger than 4×10^{14} is attainable in the region of most value for experiments.

In the following we give comparisons of the fluxes in the heavy water, the light water, and the Argonne fast piles:

	Heavy Water	Light Water	Argonne Fast Pile
Power	30×10^3 kw	30×10^3 kw	10^3 kw
Active Volume	800 li	100 li	5 li
Power/Volume	~37.5 kw/li	300 kw/li	200 kw/li
Σ_{in}	~1/5 cm^{-1}	~1/5 cm^{-1}	~1/8 cm^{-1}
"Virgin" $n\nu$	~0.15×10^{14}	~1.2×10^{14}	~1.3×10^{14}
Epi-thermal $n\nu$	~3.5×10^{14}	~5×10^{14}	~2×10^{14}
Max. Slow $n\nu$	~4×10^{14}	~2×10^{14}	

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II. Critical Data

In this section we record the results of calculations on the critical mass of the proposed pile. The results cannot be considered particularly reliable for two reasons:

1) The age in the mixture of H_2O and Al which constitutes the pile was calculated on the assumption that the high energy scattering in Al is spherically symmetric. The experimental data show the Al scattering to be non-spherical, but give no indication whether it is predominantly forward or predominantly backward. In the absence of such knowledge, we have made the assumption of spherical symmetry.

A similar uncertainty exists in the calculated values of the age in Be. Thus the reflector saving may be over or underestimated, depending on whether the assymmetry of the Be scattering is predominantly backward or forward.

2) Besides these systematic uncertainties in the quoted critical masses there are uncertainties which arise from experimental holes in the reflector. The calculations apply to idealized cylinders or prisms with solid reflectors. In practice the experimental holes will cause an increase in the critical mass which we are not yet in a position to estimate reliably.

The uncertainties (1) and (2) will be largely eliminated when critical experiments which are now getting under way are completed.

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The critical mass calculations were performed by means of a two-group theory. The constants used were

Pile

Volume of Al to Volume of H_2O = 0.75

35.7 g/li of U^{235}

λ_{fast} = 3.73 cm, λ_{slow} = 0.793 cm, τ = 64 cm^2, L^2 = 3.64 cm^2

Side Reflector

Volume of H_2O to Volume of Be = 0.02

λ_{fast} = 1.8 cm, λ_{slow} = 1.92 cm, τ = 89 cm^2, L = 20cm

We list below calculated critical dimensions for three dispositions of fissionable material characterized by k values of 1.606, 1.432, and 1.373 respectively. When the pile is cold and unpoisoned, the k value is 1.606; the lower values correspond to various amounts of poison in the pile. In each case the top and bottom are supposed reflected with an infinitely large H_2O-Al mixture having the same Al to H_2O volume ratio as the pile, and the sides are reflected with an infinitely large mass of Be + 2% H_2O.

Critical Data for Cylinders

k	1.606	1.432	1.373
radius	12.78 cm	17.85 cm	21.12 cm
height	53.4 cm	52.6 cm	52.2 cm
Reflector saving radius	16.69 cm	19.17 cm	20.17 cm
Reflector saving height	16.6 cm	17.4 cm	17.8 cm
Mass of U^{235}	0.98 kg	1.88 kg	2.61 kg.

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The pile must be built considerably larger than is needed to be critical in the cold, clean state. Before summarizing in detail the reactivity losses which are entailed by Xe, depletion of 25, and temperature rise, we shall explain our conventions for expressing reactivity loss.

If a critical pile with reflector is perturbed so that it is no longer critical, it will rise or fall with a period T. This is related to the quantity $\frac{\delta k_{eff}}{k}$ by the inhour formula, which, in the usual notation is

$$\frac{\delta k_{eff}}{k} = \frac{\ell}{kT} + \sum \frac{\beta_i \tau_i}{\tau_i + T} \qquad (1)$$

On the other hand, $\frac{\delta k_{eff}}{k}$ can be related to $\frac{\delta k}{k}$, $\frac{\delta \sigma_s}{\sigma_s}$, $\frac{\delta D_s}{D_s}$, $\frac{\delta \sigma_f}{\sigma_f}$ and $\frac{\delta D_f}{D_f}$ in the core of the pile by the formula

$$\frac{\delta k_{eff}}{k} = \frac{\delta k}{k} + \omega_s \frac{\delta \sigma_s}{\sigma_s} + \omega_{D_s} \frac{\delta D_s}{D_s} + \omega_f \frac{\delta \sigma_f}{\sigma_f} + \omega_{D_f} \frac{\delta D_f}{D_f} \qquad (2)$$

where σ_s, D_s, σ_f, and D_f are absorption coefficients and diffusion constants for slow and fast neutrons, respectively, and the ω's are statistical weight factors which involve the neutron density and the adjoint density in a complicated manner.

If all other quantities except $\frac{\delta k}{k}$ are constant, then from (2) $\frac{\delta k_{eff}}{k}$ is just equal to $\frac{\delta k}{k}$. For a thermal absorber in the proposed pile, such as Xe or 25, this is practically the

case, since L^2 is so small. Another way of saying this is that ω_s in (2) is very small.

In the case of temperature variation, the major effect on $\frac{\delta k_{eff}}{k}$ comes through a change in age. The $\frac{\delta k_{eff}}{k}$ due to temperature change can always be regarded as equivalent to the same change in $\frac{\delta K}{K}$, all other quantities being held constant.

The identity of $\frac{\delta k_{eff}}{k}$ and $\frac{\delta K}{K}$ of the core enables us to relate a given reactivity change to an increase in critical mass in the following manner:

We have computed a sequence of critical masses for different k values, all other quantities being constant. Hence we know how much $\frac{\delta k}{k}$ (or $\frac{\delta k_{eff}}{K}$) means in terms of added critical mass. For example, if a temperature change caused a change in $\frac{\delta k_{eff}}{K}$ of 12.4% (this of course is very much greater than the actual change, but is used as an example), then according to the table the extra critical mass needed to override this change in $\frac{\delta k_{eff}}{K}$ would be, 1.8 kg - .98 kg = 0.92 kg.

1) <u>Xenon and Sm Poisoning</u>

At full power (2×10^{14} flux) the Xe^{135} causes a k loss of $\frac{\delta k}{K}$ = 3.9%. After shutdown the Xe builds up and goes through a maximum at 10 hours; at this maximum it absorbs 55% as many neutrons as the U^{235}. Evidently it would be impractical to build so much excess reactivity into the pile that it could

override the Xe at all times after shutdown. However, there should be sufficient extra reactivity so that every accidental scram does not keep the pile shut down for several days. It is felt that if the pile can override 1/2 hour of accumulated Xe it will have sufficient operational flexibility. After 1/2 hour the Xe absorption is about double its steady state value. Besides the Xe, the Sm^{149} also causes a reactivity loss. This amounts to about $\frac{\delta K}{K} = 0.9\%$ at equilibrium, and it rises, very much more slowly than the Xe, to a maximum $\frac{\delta K}{K} = 3.3\%$ at long times after shut down.

We summarize the Xe + Sm poisoning in the following table:

<u>Xe + Sm Poisoning τ hours after shutdown, Flux = 2×10^{14}</u>

τ (hours	$\frac{\delta K}{K}$ for Xe^{135} + Sm^{149}	$\frac{\delta K}{K}$ for Sm^{149}
0	4.8%	0.97%
½	9.6%	
1	13.6%	
10	43.5%	1.2%
20	35.8%	
48	9.2%	2.1%

If 9.6% extra $\frac{\delta K}{K}$ is available for the pile, the machine can be started up within ½ hour or after about 2 days, following a long period of operation at 2×10^{14} flux.

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It is clear from this discussion that the shutting down and starting up of this pile cannot be done on the informal basis which is satisfactory for the present graphite piles.

2) Depletion

We estimate that the loss in $\frac{\delta k}{k}$ per day due to depletion is 0.33%; this figure applies to the pile running at 10,000 kw/kg of 25, or a flux of 2×10^{14}. We contemplate a running cycle of about 10 days, which means that 3.3% in $\frac{\delta k}{k}$ must be available for this purpose.

3) Temperature

An accurate calculation of the temperature coefficient is not available yet. Some preliminary estimates, based on a homogeneous Al-H_2O mixture indicate that an increase of 10°C in the H_2O and Al temperature will decrease the reactivity by an amount which is the same as if $\frac{\delta k}{k}$ were reduced by about 0.3% and τ, L^2 were kept constant.

4) Other reactivity losses

Experimental set-ups around and in the pile will reduce the reactivity of the machine. It is hard to estimate how much this will amount to - we guess than an additional $\frac{\delta k}{k}$ of 5% should handle this.

Total Reactivity of Pile:

The total extra reactivity allowed in the pile is summarized as follows:

(see page 13)

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	$\frac{\delta k}{k}$
Xe + Sm	9.6%
Depletion	3.3%
Temperature	0.5%
Others	5%
Total $\frac{\delta k}{k}$	18.4%

According to our estimates, a 2.6 kg pile with no holes in the reflector has a k of 1.373; this gives, compared with the cold, clean k = 1.606, a $\frac{\delta k}{k} = \frac{1.606 - 1.373}{1.373} = 17\%$ which is fairly close to the extra amount required. However, because of the presence of the reflector holes, and the fact that Be displaces some U^{235} when the control rods are out, we consider 3 kg to be a better estimate for the mass required to ensure an excess $\frac{\delta k}{k}$ of about 18%. Under ordinary conditions the pile will be operated with a 3 kg loading.

It is recognized that the critical calculations are rather unreliable. Fortunately, because of the great flexibility of the machine, it is not particularly important that the critical amounts be known with great accuracy at this stage. The design is being carried forward on the basis that 3 kg is the standard loading, and that 4.5 kg. can be put into the pile without major change. In any event, critical experiments which are just getting underway will eliminate whatever uncertainties remain in our knowledge of the critical mass.

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Neutron Distributions

The slow neutron distributions display a characteristic rise in the reflector. The reason for this is that the neutron lifetime is very much longer in the reflector than in the pile, while their rate of production there is only slightly smaller. Consequently slow neutrons build up to a higher density just outside the pile than inside.

The magnitude of the rise in the reflector depends on both the size and shape of the pile. In a large (low k) pile the neutron density falls appreciably from the center of the pile to the edge, and the rise in the reflector hardly compensates. In a smaller pile the rise is more important. Again a pile shaped like a slab has a higher reflector rise than one shaped like a cylinder.

In general, it is best to have the highest flux in the reflector where experiments can be done. A high reflector to center neutron density ratio makes for maximum experimental usefulness with minimum expenditure of fuel. This situation will be achieved even in the low k pile if during operation control rods are in place at the center of the pile. The rods cause a depression in the central neutron density and thus improve the reflector to center density ratio.

The fast neutron, i.e. epi-thermal, density follows rather closely the Bessel function curve. The center to edge ratio is about 1.6 in a pile containing 2.6 kg of U^{235}.

Longitudinally the neutron density is well approximated by a cosine curve with an extrapolation distance of about 8.5 cm on top and bottom. Thus a pile which is 60 cm high has a center to top (or bottom) ratio of $\left[\cos\left(\frac{\pi \times 30}{77}\right)\right]^{-1} = 2.92$. The maximum to average ratio is about 1.3.

In the following table we give the maximum in reflector to edge and the maximum in reflector to center slow neutron density ratios for the piles computed previously.

Maximum in Reflector to Edge and to Center Slow Neutron Density Ratios

k	1.606	1.432	1.373
Crit. Mass	0.98 kg	1.88 kg	2.61 kg
Max. to Edge Density	1.27	1.07	1.00
Max. to Density Center	1.18	1.10	.63
Distance of Max. from Pile Edge	3.2 cm	3.2 cm	0 cm

It may be remarked that in an infinite slab pile, k = 1.606, the maximum to center ratio is 1.57, the maximum to edge ratio is 1.28. These values are higher than any found for cylindrical piles and serve to illustrate the point that the rise in the reflector is largest for a plane.

It should be reemphasized that the density distributions in the pile will be greatly modified by the presence of a control rod. In general, when the rods are in place near the center, the edge to center ratio is better than when they are out.

III. Control

1) Disposition of Control Elements

The control elements should be made of Th so that neutrons which would otherwise be wasted will produce 23. It is necessary to avoid empty holes in the pile when the controls are out; this can be done by constructing the rods out of two pieces, a top Th piece and a bottom Be piece. When the Th is removed, the Be takes its place in the pile. The control margin provided by a single rod is, in this way, increased considerably over what it would be if its removal left an empty hole in the pile.

Some preliminary results are available on the thickness of a Th sheet which, when stretched across the mid-plane of a rectangular pile of size 40x40x60 cm, will keep it just critical. We find that a vertical Th sheet, 1.5 cm in half thickness*, which divides the pile in half, will give a control margin $\frac{\delta k_{eff}}{k}$ of about 14%. The sheet can probably be replaced by a parallel line of slabs or rods of rather larger dimension provided the total amount of Th in the rods is the same as the amount in the sheet. The rods or slabs cannot be too large in diameter, because near the Be rod bottoms there is a local rise in neutron density; this causes hot spots in the neighboring assemblies. In the following table we give the value of n(Be), the neutron density next to the Be rod divided by n(co), the

* This figure has not yet been checked completely.

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Addendum II: Local Heating near Be Control Elements

Further calculations on the local heat rise near the Be control elements show that, if the dead layer of water between the Be and the active assemblies is taken into account, then the rise will be considerably more serious than indicated in the body of the report. Thus a 4 mm layer of water between Be and active lattice raises the maximum to minimum heat load in the assemblies from 1.15 to 1.36; a 8 mm layer raises it to 1.58. A roughly equal rise (from 1.065 to 1.25) was noted for a 4 mm H_2O layer around a 2 cm Be rod. The conclusion to be drawn from these computations is that the presence of a dead H_2O layer around the Be will cause serious local heating where, in the absence of such a layer, the heating is not serious.

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neutron density far from the rod, for rods of various diameters. This ratio is a measure of the local heating caused by the presence of the Be.

Radius of Be	$\frac{n(Be)}{n(\infty)}$
0.49 cm	1.009
0.95 cm	1.024
1.9 cm	1.061
2.85 cm	1.100
3.81 cm	1.141
4.76 cm	1.180

It is seen that even a rod of radius 4 cm does not cause very serious excess heating. If the radius of the rods is 4cm, the number of rods needed to put as much Th in the pile, and therefore give as much control as a Th sheet of thickness 3cm is about 5.

2) Pile Period, Generation Time

The pile generation time is considerably longer than the lifetime of a neutron in the core itself. This is because some neutrons have been reflected from the Be; the lifetime against capture in the Be being very long, these neutrons lengthen the average lifetime of all the neutrons in the pile.

The generation times depends on the amount of metal loaded into the pile. The larger the amount of metal, the less important is the reflector and the smaller is the degree to which the generation time is lengthened. We give in the following table the generation times for various sized piles:

kg. of U	k	Generation time
0.98	1.606	2.36×10^{-4} sec
1.88	1.432	1.52×10^{-4}
2.61	1.373	1.26×10^{-4}

The fact that the generation time depends so strongly on the size of the loading will make it necessary to check the transient behavior of the pile whenever a new loading pattern is adopted.

Xe Instability

In a thermal neutron machine operating at such high flux as we expect, the Xe^{135} causes an essential instability in the pile operation. The Xe is produced from the decay of 6.7 hour I; its rate of production is therefore insensitive to fluctuations in the power density, while its consumption follows these fluctuations instantaneously. A small reduction in power will therefore result in a build-up of Xe which in turn will tend further to reduce the power; this manifests itself as an instability.

The instability caused by the Xe is balanced, to some extent, by the inherent temperature stability of the pile. Whether the overall effect is stable or unstable depends upon the flux (since the Xe instability increases with the power level). At Clinton, the overall effect is a tendency toward stability; at Hanford the overall effect is a slight tendency toward instability; in the heavy water heterogeneous pile the overall effect was unstable with a period of about 8 minutes.

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In the present pile the Xe instability at 4×10^{14} flux will be rather more marked (shorter period) than in the heavy water pile because the temperature coefficient is lower.

The presence of a fairly short Xe instability makes it advisable to provide the pile with automatic controls.

Bubbles

One striking advantage of this pile over the old heavy water one is that there will be essentially no power fluctuations from bubbles. The reason for this is that the moderating water is in the pile too short a time to allow decomposition gases to reach their saturation pressure.

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IV. Heat Transfer and Heat Removal

Heat Transfer Data: A heat transfer of 30 cal/cm^2/sec is considered feasible in the present pile. If the plate separation is 2 mm, and the water flow velocity is 10M/sec, the heat transfer coefficient is 1 cal/cm^2/sec/^{o}C; this corresponds to a maximum film drop of 30°C, if 30 cal/cm^2/sec are transferred.

The assembly plates will contain about 14 mgm/cm^2 of U^{235}. Hence if 30 cal/cm^2/sec are taken from each side of the plate, the corresponding slow neutron flux is 4×10^{14}. This may be regarded as the maximum flux attainable; this value will be reached only occasionally because it corresponds to an overall power of about 60,000 kw.

Heating in Reflector:

Outside the active part of the pile heat is produced primarily from absorption of γ-rays. Most of these come from the pile itself, but some arise from neutron capture in Be and in graphite.

An additional source of heat is fission of the 23 which is built up in the Th surrounding the pile. This heat will be discussed more fully in the section on 23 production.

The heat load in the Be and graphite reflectors for a 30×10^3 kw output is summarized in the following table.

Holes in Be

(see page 21)

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A. Heating in Be and Graphite Neglecting Experimental Holes in Be

Source	Heat Flux into Be	How Distributed In Median Plane	Heat Flux into Graphite
Pile γ's	475 kW	$2.3F_1(.07x)$ cal/cm^3/sec	11 kW
Fast Neutrons	15 kW		
Be Captures	236 kW	uniform-.04 cal/cm^3/sec	30 kW
Th Captures	161 kW	$.033\ F_0(.04\bar{x})$ cal/cm^3/sec $\bar{x}$ = distance from Be-Th interface	16 kW
	887 kW		

B. Additional Heating in Graphite due to Holes

(A = cross sectional area of hole)
(x = distance of C surface from pile surface)

Source	Total Heat	Maximum Heat production in C looking directly at pile surface
Pile γ-rays	$.021\frac{A^2}{x^2}$ kW	$0.35\frac{A}{x^2}$ cal/cm^3/sec

The worst heat load outside the pile occurs in the mid-plane of the Be at the interface between Be and pile. We estimate this maximum to be about 2.3 cal/cm^3/sec. If the Be is in the shape of a slab, cooled on both front and back faces, the temperature rise in the center is

$$\Delta T = \frac{qx^2}{2k} = 2.9x^2$$

where q is the heat production, x is the half-thickness of the slab, k is the conductivity. We have assumed the Be retains its normal heat conductivity, 0.4 cal deg^{-1}cm^{-1}sec^{-1}. A temperature rise of 75°C is certainly safe - this allows the

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slabs to be 10 cm in total thickness. However, this figure applies to a 30,000 kw pile; if the pile is run at 60,000 kw (as it may be, for short times) the allowable thickness of uncooled Be is reduced by a factor $\sqrt{2}$.

Heating of Foreign Materials Inside Pile

Foreign materials, such as control rods or experiments which are placed in the center of the pile will be heated even more strongly than the Be at the pile-reflector interface. The γ-ray energy production at the center of the pile running at 30×10^3 kw is about 5.85 cal/cm^3/sec; this is also the γ-heat absorbed in the pile. Since the pile has an average density of about 1.7 gm/c.c. we estimate that the heat production in a foreign body placed at the center of the pile will be about 3.4 cal/gm/sec. Thus in Be, density 1.85, the heat load is 6.3 cal/c.c./sec, while in Th, density 11, the heat load is 38 cal/c.c./sec. At 60,000 kw, these heat loads would be 12.6 and 76 cal/c.c./sec, respectively. If the control rods are shaped like thin slabs, of half thickness x, then the temperature rise at 60,000 kw would be

$$\Delta T = 16x^2 \text{ in Be}$$

$$\Delta T = 380x^2 \text{ in Th.}$$

It is true that the Th rod reduces the flux in its vicinity and therefore these figures are probabily overestimates. However, at the point where the Th and Be parts of the control

rod meet, the neutron density is not reduced very much; here the Th will be heated at a rate close to the enormous value of 76 cal/c.c./sec. Also, the above figures include only γ-heating; the 23 fission increases them by perhaps 35% (see below).

In any case, the heat production in the Th is so high that it probably will be advisable to provide internal cooling of the rods.

In addition to the high temperature rise in the Th, the heat transfer from the surface will also require careful consideration. If the Th is in the shape of a rod of radius r, then at 60 MW the heat transfer required is

$$\frac{\pi r^2 \times 76}{2\pi r} = 38r \quad \text{cal/cm}^2\text{/sec.}$$

Evidently it will be necessary to provide internal, as well as external cooling for the rods on this account also.

The amount of water used to cool the control rods, and the size of the rod must be adjusted so that the cooling is adequate, yet the local neutron density rise caused by the presence of extra water is not excessive.

Shielding

To estimate the gross shielding requirements we have compared the neutron and γ-ray fluxes incident on the inner face of the graphite reflector in the high flux pile with the corresponding fluxes incident on the graphite reflector in the

Hanford and Clinton piles. From a knowledge of the performance of the X and W shields, we are able to estimate the additional shielding that we need.

Ratio of fluxes (30,000 kw) incident on graphite in proposed pile and Hanford and Clinton.

	Hanford	Clinton
Ratio of γ-fluxes	8.2	151
Extra shield needed for γ's	8.6 cm Fe	70 cm concrete
Ratio of neutron fluxes	2.85	34
Extra shield needed for neutrons	5.6 cm masonite	40 cm concrete

An additional Hanford sandwich added to the present Hanford shield would be adequate, or an additional 70 cm of concrete added to the present Clinton shield would be adequate. The 70 cm of concrete can be reduced to 40 cm, the length needed for neutrons, if a 10 cm thermal shield of iron is placed behind the graphite.

At the top of the pile there will be a tall column of water. If this alone is used as a shield, we estimate that a height of 21 feet above the pile would be adequate at 30,000 kw. This estimate is based on an absorption mean free path for γ's in H_2O of 33 cm, which is rather long; however, it does not include the effect of multiple scattering of γ's.

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VI. 23 Production; Heating in Th due to 23 Fission.

Significant quantities of 23 will be manufactured both in the Th control rods and in the Th rods surrounding the pile.

The production in the control rods was calculated for a control sheet of Th, 1.5 cm in half thickness. Such a sheet, which may be considered an idealization of an actual array of control rods, would control a $\frac{\delta k_{eff}}{k} = 14\%$. It was found that for every 25 atoms destroyed inside the pile, .081 atoms of 23 are made in the control sheet. At 30,000 kw, 35 gms of 25 are destroyed per day; hence we can expect 2.8 gms of 23 to be made each day in the control system.

There will be a row of Th rods about 20 cm out from the active pile surface. If these rods are 2 cm radius, 80 cm long, and if they are spaced 10 cm apart, then we estimate they will capture 33% of all the neutrons escaping sideways. When the pile is clean, .55 neutrons escape per neutron absorbed; of these 0.37 escape sideways, where the Th rods are located. Hence per neutron absorbed .33 x .37 = .123 neutrons are captured per neutron absorbed in the pile, or 0.16 atoms of 23 are made outside per 25 destroyed. At 30,000 kw, there will be 5.6 gm of 23 manufactured per day in the external row of Th - this is to be compared with the 2.8 gms/day manufactured inside. The total 23 production at 30,000 kw is 8.4 g /day, corresponding to an overall conversion ratio of 24%.

From the computed absorption of neutrons in the Th rods, and the assumed Th cross-section, we estimate the average $n\bar{v}$

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over the Th to be about 3×10^{13}.

Heating in Th due to 23 Fission

Inside the pile the heating of the Th due to fission of 23 which has been built up is appreciable even compared with the γ-ray heating. We have estimated that 8% as many neutrons are absorbed in the control system as are absorbed in the 25 of the pile. If all of these neutrons created fission, then, at 60,000 kw, the total heat production in the control sheet would be

$$.08 \times 60{,}000 = 4800 \text{ kw.}$$

However, the 23 concentration should never go higher than an amount which would absorb $\frac{1}{10}$ as many neutrons as are absorbed in the Th. The heat load in this case, due to 23 fission, is 480 kw. On the other hand, at 60 MW the γ-heat in the Th is 5.2 cal/gm/sec. The Th control sheet has dimensions 40 x 60 x 3; hence the total γ-heat produced therein is

$$40 \times 60 \times 3 \times 5.2 \times 11 \times 4.2 \times 10^{-3} = 1730 \text{ kw.}$$

At the center the γ-ray is 1.3 times the average; the fission heat however is more nearly 1.3^2 times higher (since the concentration of 23, as well as the neutron density, goes like the flux). Hence at the worst point the 23 fission contributes a heat load which is 35% of the γ-ray heating.

This heat load is probably what limits the 23 concentration in the Th controls. If we set the maximum additional heat load due to 23 fission at $\frac{1}{3}$ of the γ-ray load, then, as we have noted, this sets a limit of about $\frac{1}{10}$ to 23 absorption/Th

absorption. This corresponds to a maximum concentration of 23 in the Th of 0.1%. If the Th controls (in the pile) weigh 80 kg (40x60x3 cm sheet), then this allows a build-up of 80 gms of 23 before changing the control sheet. The number of grams built up in the Th controls and in the blanket, assuming a steady operation at 30,000 kw, is given in the following table:

Build-up of 23 in Th Controls and Blanket, 3×10^4 kw Power

Time in Days	Grams of 23 in Control	Grams in Blanket
0	0	0
20	10	20
40	36	72
60	80	160
100	109	218

The table shows that the control sheets will have to be changed about every 60 days, if heating due to 23 fission is the factor which determines the frequency of change.

The heat load from neutron capture in the Th rods outside the pile can be estimated easily from the fact that 5.6 gms of Th per day corresponds to a power production of 1.68 kw. Altogether, there are about 26 Th rods; hence the heat production in them is 6.5 kw per rod. The rods are 80 cm long, and their radius is 2 cm. The average heat flux through their surface is therefore 1.5 cal/cm^2/sec. If the 23 is allowed to

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build up to the point where $\frac{1}{10}$ of the captures produce fission, the heat produced by 23 fission alone gives an additional average heat flux of about 4.5 cal/cm^2/sec. The total average heat flux under these circumstances is about 6 cal/cm^2/sec. At the center of the rod it will be roughly about 1.3^2 higher or in the neighborhood of 10 cal/cm^2/sec.

ALW:dkw
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