MUC-JEW-33

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Table of Contents

	Page
I. Considerations Governing Design of Proposed Pilot Plant	
A. Demonstration of Power Production	1
B. Significance of a Pilot Plant	2
II. General Features of Design	
A. Temperature of Operation and Materials of Construction	2
B. Preliminary Design	3
C. Type of Fuel	4
III. Data Now Available and Problems to be Solved	
A. Neutron Physics of the Pile	
1. Preliminary Calculation of Critical Pile Size and Critical Mass of U^{235}	4
2. Experimental Data Needed	4
3. Calculations Needed	6
4. Neutron Absorption by the BeO moderator and Impurities	6
5. Neutron Absorption by Coolant	6
B. Method of Distributing UO_2 in Pile	7
C. Fabrication of BeO Moderator	9
D. Heat Conductivity of BeO and BeO-UO_2 Mixtures	10
E. Coefficient of Expansion, Resistance to Thermal Stress	13
F. Mechanical and Structural Features of the Pile	13
1. Pile Bed	13
2. Reflector and Breeder Blanket	14
3. Outer Container of the Pile	14
4. Changing and Discharging Mechanism	15
5. Coolant System	16
6. Power System	16
7. Shielding	17
8. Safety Features	17
G. Pressure Drop Through the Pile	17
H. Vapor Pressure of BeO and UO_2	19
I. Chemical Problems	19
J. Radiation Effects	20
K. Fission Product Problems	21
L. Subdivision of Problems	22
M. Major Items for Procurement and Construction	22

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September 14, 1945

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To: Farrington Daniels

From: John E. Willard

In Re: Summary of Work on a BeO Moderated, Steam Cooled Pile Designed to Operate at High Temperatures for Use in the Production of Electrical Energy from Atomic Power

In accordance with your request, I am summarizing below the results of the work which has been done to date on problems related to the construction of a BeO moderated pile for operation at high temperature and am outlining in addition information which must still be obtained before a pilot plant can be put into operation. The program which is now in effect and the planning of future efforts are being directed toward the construction at Argonne of a pilot plant with a pile operating at about 4000 kw.

I. Considerations Governing Design of Proposed Pilot Plant

A. Demonstration of Power Production

It has now been demonstrated that atomic energy can be successfully used for military purposes. In achieving this demonstration, the Manhattan Project has not had either the authorization or the time to investigate the military or peace time utilization of atomic energy as a power source. However, incidental to the development of the atomic bomb, the basic information necessary for the utilization of atomic energy for power has been obtained. With the end of the war, it is now important that immediate investigation be made of the application of this basic information to the problem of power production. Economic aspects of the utilization of atomic power are not yet and cannot be fully clarified until such time as scientific demonstration of methods for its use is made. For these reasons, it is proposed to construct an atomic power pilot plant at Argonne as soon as possible. In planning such a plant, it is proposed to choose the design which can be completed most rapidly even though this involves a sacrifice in efficiency of conversion of the heat energy of the pile to electricity and a sacrifice in breeding

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efficiency in the pile. It is felt that the coupling of efficient power production with efficient breeding will probably be attained more rapidly by placing emphasis on a preliminary demonstration of the unit designed primarily for power production than if the building of the test unit were delayed in the interests of obtaining a more perfect final design.

B. Significance of a Pilot Plant

A pilot plant for the production of atomic power can be of the same design and size as the higher power production unit which the pilot plant is designed to precede. The pilot plant will serve to test mechanical design features, resistance of construction materials to the temperature gradients which will occur in a high power unit, heat transfer characteristics, the coolant circulation mechanism, the discharge mechanism, and operating characteristics. Such a pilot plant will demonstrate the production of electric power from atomic power with a much smaller investment for turbine and generator and for shielding against radioactivity than will be necessary in the case of a full scale 100,000 kw plant. If properly designed, it is expected that the plant which is contemplated could later be converted to operation at much higher power than 4000 kw, possibly as high as 100,000 kw, simply by changing over to a larger boiler, evaporator, turbine and generator and by introducing some added shielding.

A 4000 kw pilot plant will give a neutron flux for experimental purposes equal to that available in the Hanford piles.

II. General Features of Design

A. Temperature of Operation and Materials of Construction

A pile designed to produce useful power must operate at a much higher temperature than the present Hanford piles or the heavy water pile now being designed at Clinton. The higher the temperature of operation, the greater will be the thermodynamic efficiency of power production from the heat energy produced in the pile. Materials of construction which have been satisfactory in the Hanford plutonium

producing piles or could be used in low temperature breeder piles are not satisfactory at the elevated temperatures required in a power producing unit. For the pilot plant under consideration, it is proposed to use BeO as a moderator, a matrix of BeO containing UO_2 as the fissionable fuel, and H_2O as the coolant. Thorium in the form of ThO_2 will be used to breed U^{233} by absorption of excess neutrons at the outer surfaces of the pile. These materials are all oxides and hence will not deteriorate by oxidation at the high temperatures proposed.

Since the high temperatures and the presence in the pile of high levels of radioactivity would make the maintenance of operating parts very difficult, it is planned to operate with no moving parts in the pile or coolant stream.

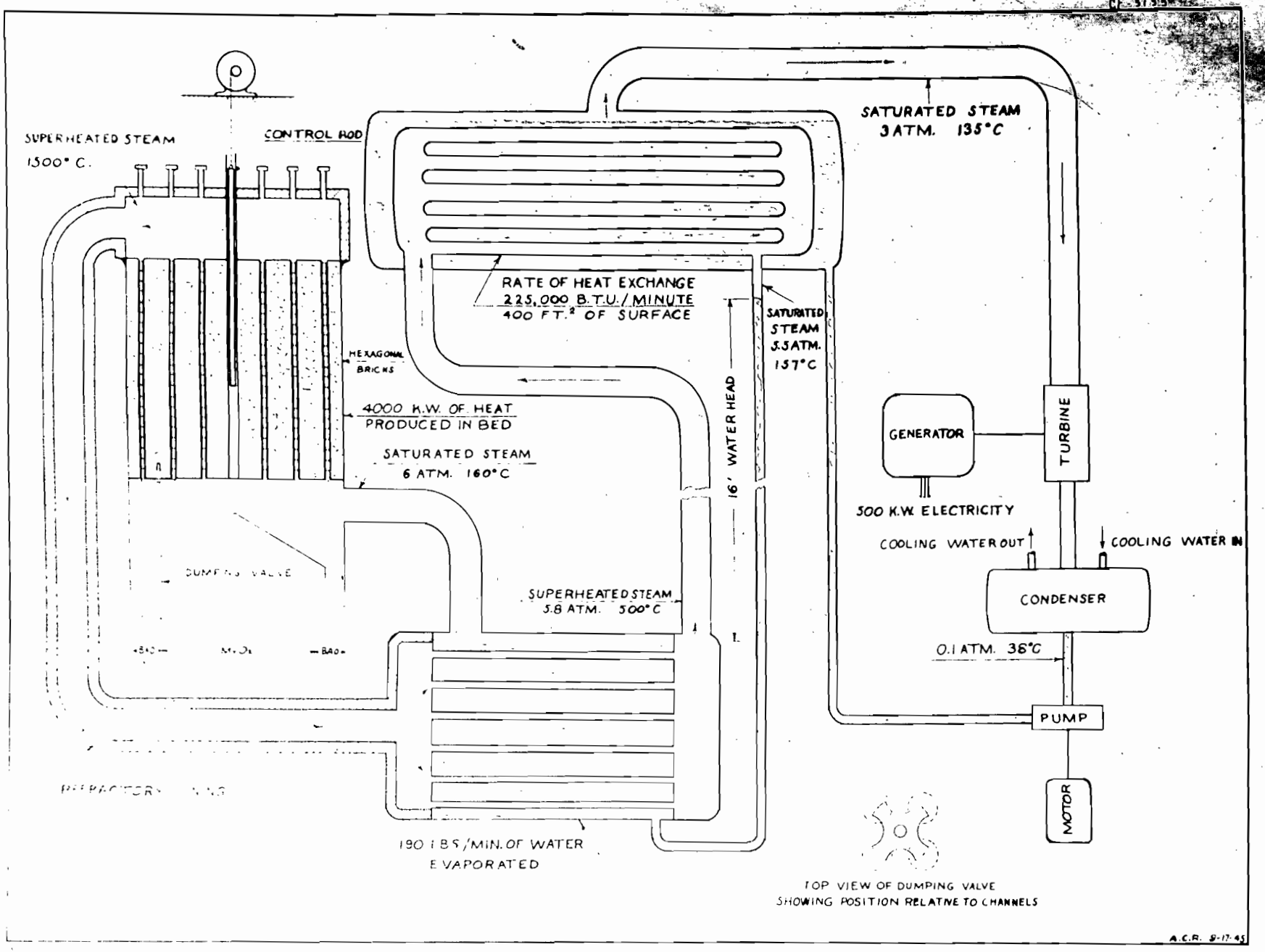
B. Preliminary Design

A pile unit (as shown schematically in Figure I) will consist of a bed of BeO moderator through which pass vertical channels containing BeO-UO_2 rods of such size as to leave an annular channel for the flow of the steam which serves as a coolant. Steam will enter at the bottom of these channels, be highly superheated in its passage through the pile, flow through an internally insulated conduit to a boiler where a portion of its heat ($\sim$80% of the superheat) will be used to produce steam which will be circulated to the bottom of the pile to continue the cooling cycle. From the initial boiler, the steam will go to an evaporator where the remaining superheat and the heat of condensation will be used to produce steam which will run an external turbine and generator system. The condensate of the steam from the pile circuit will then flow as liquid water to the initial boiler where it will be evaporated for recirculation through the pile. Since a pressure drop occurs in the passage of the steam through the pile, a hydrostatic head will be maintained (as shown in Figures I and II) in order to maintain the pressure necessary for circulation without the use of a pump in the radioactively contaminated system.

An alternative design which ~~at present~~ is considered less desirable is shown

MUC-JEW-33

Figure I



4 of 27

MUC-JEW-33

Figure III

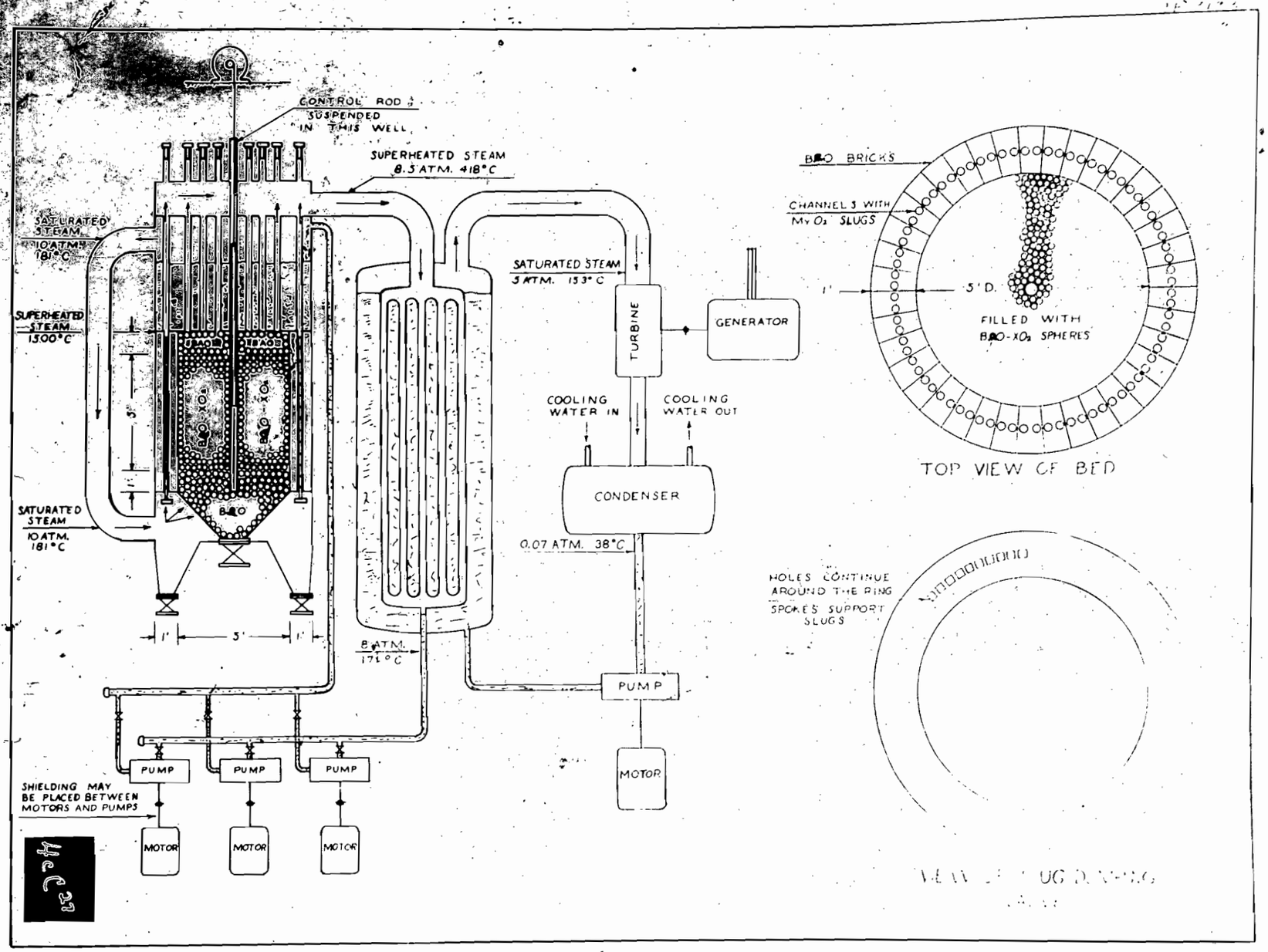


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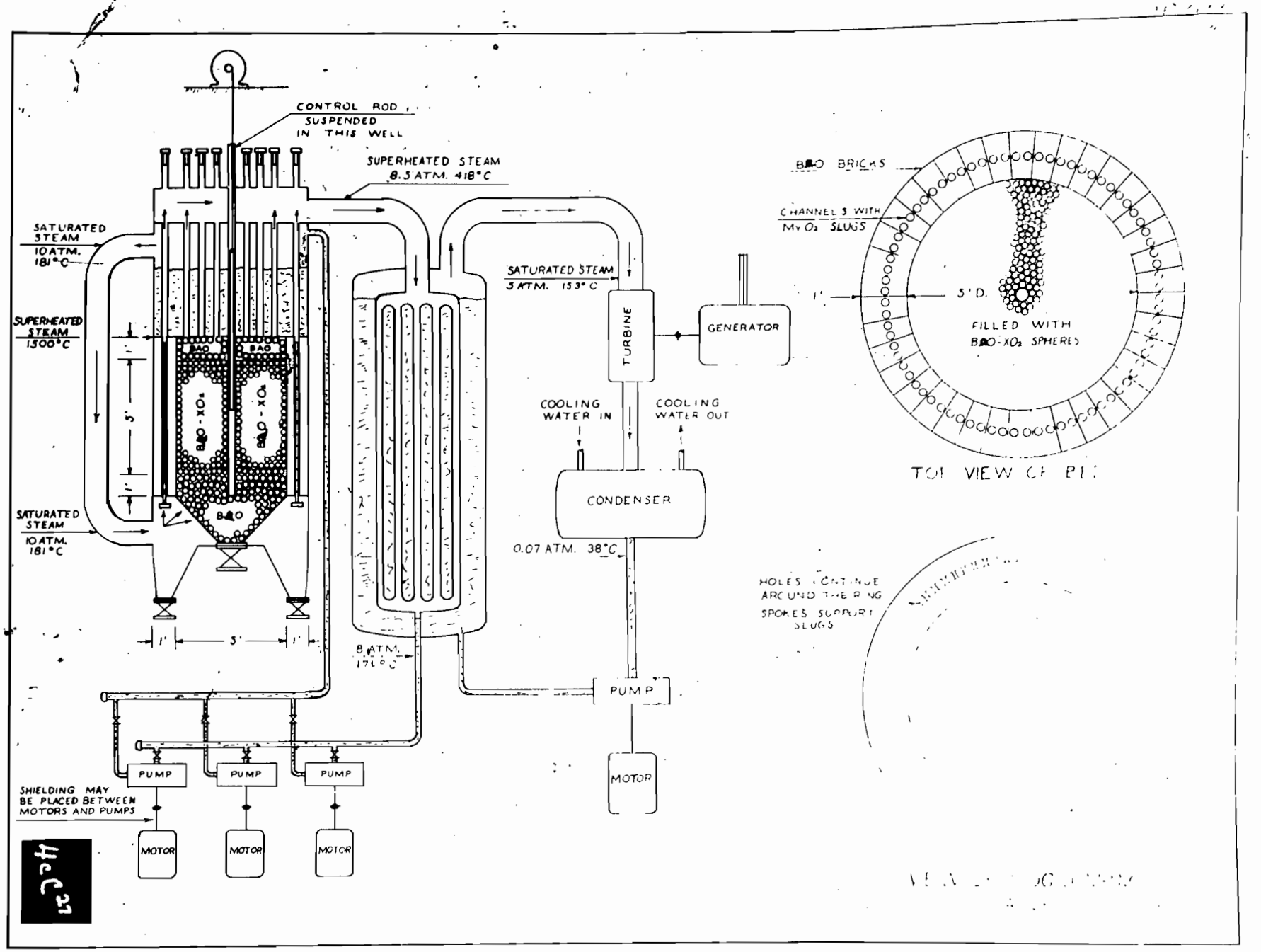
Figure III



in Figure III. This design indicates the possibility of having the whole pile consist of a bed of $BeO-UO_2$ pebbles and of using pumps to maintain the pressure necessary for steam circulation rather than using a hydrostatic head.

It is anticipated that the pile unit, shown in Figure I, will have a temperature of about 160°C at the bottom of the pile and 1500°C at the top, a temperature differential of about 1340°C.

C. Type of Fuel

In its eventual applications, a pile of the type under consideration probably would best utilize U^{233} oxide as fuel and breed U^{233} by the use of a blanket of ThO_2 absorber. Since U^{233} is not as yet available, the pilot plant demonstration unit must use either enriched U^{235} or Pu^{239}. Of these two materials, enriched U^{235} is probably more available, introduces less health hazard in construction and will poison less rapidly than the Pu^{239} which suffers from the production of Pu^{240}.

III. Data Now Available and Problems to be Solved

A. Neutron Physics of the Pile

1. Preliminary Calculation of Critical Pile Size and Critical Mass of U^{235}

Preliminary calculations (made by Goldberger) to determine the minimum amount of U^{235} necessary for the construction of the BeO moderated pile indicate that if a spherical pile could be constructed with no voids for cooling and using BeO with a density of 3 it would contain 3.8 T of BeO and 31.3 kg of 20% enriched UO_2, and would be 4.3 ft. in diameter. A cylindrical pile with 20% voids for cooling using BeO of apparent density 2.2 will require 11.6T of BeO and 104 kg of 20% enriched UO_2 and will be 6.5 ft. high and 7 ft. in diameter. The quantitative results of these calculations are subject to revision because of uncertainties in the "age" and absorption cross section for neutrons in Be. The fact that the pile operating temperature is assumed to be 1800°C with no temperature gradient and the fact that the calculations neglect the possibility of using a reflector tend to make the estimates high. On the other hand, the production of poisons during pile operation is not considered. From these estimates, it is to be seen that the amount of U^{235} required increases as the density of the Be moderator decreases, thus placing a premium on obtaining as high density as possible in the structural material and of maintaining the void spaces for coolant at as low a value as possible.

2. Experimental Data Needed

As a basis for quantitative calculation of the neutron physics of the high temperature pile, the discrepancies which now exist between different determinations of the "age" of neutrons in BeO and of the absorption cross section of Be must be resolved. In addition, the effect of neutron energy on the absorption cross sections of all the elements to be used in the pile construction and of the fission product isotopes produced in pile operation must be determined up to 0.2 Mev (ie up to thermal energy at the maximum operating temperature of the pile). Experiments to determine the age of neutrons in BeO and the absorption cross section of Be are under consideration by the groups working at Argonne while experiments on the effect of neutron energy on fission product cross sections are in progress at Clinton.

A conclusive answer as to the effect of elevated temperatures of operation on poisoning of the pile by fission products can only be obtained when the pile is put into operation since it is only under actual operating conditions that the effect of very short lived species can be tested. However, with the aid of a neutron spectrometer, it is possible to determine the gross absorption coefficient as a function of neutron energy for non-gaseous fission products with a half life of a few days or longer. The measurements of this type which are now being made at the Clinton Laboratories on a gross fission product sample extracted from dissolved pile uranium are expected to detect the presence of any isotope or isotopes with a cross sections sufficiently great to produce an average cross section for the mixture as high as 100 barns.

The chance that any fission products will show a much higher absorption cross section at 0.15-0.2 Mev than they do at 0.025 Mev is probably slight since resonance peaks for neutron capture as a rule have a slope which is broad compared to the energy range involved here and since the 1/v law is in favor of a decreasing cross section as the energy is increased.

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3. Calculations Needed

As steps in establishing the final design of the pile, it will be necessary to:

(a) Refine the present preliminary calculations of critical size on the basis of improved experimental data

(b) Determine the optimum amount of BeO reflector with which to surround the active portion of the pile

(c) Determine the optimum amount and distribution of ThO_2 for utilization of excess neutrons

(d) Determine the position and construction of control rods and calculate the problems of control as a function of temperature distribution in the pile

(e) Determine the effect of fission product poisons and of Pu^{239} and Pu^{240} on the pile operating characteristics

(f) Determine the optimum time and power of pile operation before discharge of the fuel for reprocessing.

4. Neutron Absorption by the BeO Moderator and Impurities

If a value of 0.01 barns for the absorption cross section of Be is assumed, it may be calculated that 9% as many neutrons will be absorbed by the BeO as by the U^{235} in a pile with 20% voids and BeO parts with an apparent density of 2.2. Available analyses on both Clifton Product Company BeO and Brush Beryllium Company BeO indicate that the commercial material is sufficiently pure so that the impurities will not increase the neutron absorption by a significant amount. Further investigation and standardization of methods for BeO analysis are being carried out to insure adequate control on the pile construction material.

5. Neutron Absorption by Coolant

In a BeO moderated pile constructed with 20% void space through which steam at 5 atm circulates as coolant, the steam will absorb about 0.05% as many neutrons as the U^{235} in the pile. If the whole of the void space (assumed to be 20 cu. ft.)

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should become filled with liquid water, the hydrogen in this water would absorb ~ 50% as many neutrons as the U^{235} in the pile.

B. Method of Distributing UO_2 in Pile

A decision as to how to disperse the UO_2 in the pile structure must be based upon a number of considerations including:

(a) The heat conductivity of $BeO-UO_2$ mixtures

(b) The probability that $BeO-UO_2$ will crumble as a result of fissioning if the uranium content is too high

(c) The tendency of UO_2 to convert to U_3O_8 with consequent crumbling, when heated in an oxidizing atmosphere

(d) The fact that chemical processing of the highly active $BeO-UO_2$ mixtures from the pile will be much simplified if the volume of active material is kept low by using a high concentration of uranium

(e) The fact that some geometries of fuel distribution will cause a lower pressure drop in the coolant stream than others

(f) The fact that certain shapes of fuel matrix will be much easier to fabricate and to charge and discharge than others.

Of the factors listed above, the heat conductivity and the possibility of crumbling as a result of fissioning or $UO_2-U_3O_8$ conversion favor the use of dilute mixtures of UO_2 in BeO while the requirements of chemical processing and of maintaining a minimum pressure drop through the pile favor the use of concentrated mixtures. A pile design employing 1.5" diameter fuel rods and 2" holes has been tentatively settled upon as affording a satisfactory compromise between the opposing requirements.

The simplest method for preparation of the fuel is to mix BeO and UO_2 powders, tamp the mixture in a graphite mold and fire at some temperature between

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1400 and 2200°C. Tests are currently being conducted to determine whether fuel rods can be prepared in this way which will be sufficiently resistant to the chemical and physical effects of high speed steam over the temperature range to be encountered in the pile and to deterioration by the radiations of the pile. It is known that if 2%, 10% or 50% mixtures of UO_2 in BeO are heated in air, the UO_2 is converted to U_3O_8 which, because of its lower density, causes crumbling. Above 800° or so, the U_3O_8 is unstable at low oxygen pressures and reverts to UO_2 so that repeated heating and cooling may accentuate the tendency to crumble. Preliminary tests which have recently been made at Chicago indicate that pieces of BeO-UO_2 heated slowly in steam to 1100°C and then cooled in steam do not crumble, whereas the same pieces heated in air break up badly. Further tests to cover the whole temperature range of proposed pile operation are in progress.

Work is being conducted at Battelle Institute on the properties of BeO and BeO-UO_2 mixtures, in cooperation with the high temperature pile program at Chicago. The tests at Battelle have indicated that under some conditions of heating, UO_2 is vaporized out of UO_2-BeO mixtures. This vaporization has not as yet been observed in the case of BeO-UO_2 pieces heated in steam but is being studied further. The investigations at the Battelle Institute have shown that no compound formation occurs between BeO and UO_2 when the oxides are fused together.

In case the method of sintering mixtures of powdered BeO-UO_2 does not prove capable of producing fuel rods which are resistant to crumbling caused by UO_2-U_3O_8 conversion, one of the following alternate methods of fabrication, which are now under investigation, may be used.

(a) A porous sintered BeO rod may be degassed in a vacuum and then submerged in a concentrated uranyl nitrate hexahydrate solution under atmospheric pressure. The rod which has thus been impregnated can then be dried and ignited in order to deposit U_3O_8 on the walls

of the BeO pores. If the vapor pressure of U_3O_8 is too high to allow its use at the operating temperatures of the pile, it may be reduced by heating the impregnated rod in hydrogen

(b) BeO powder may be mixed with concentrated uranyl nitrate hexahydrate as a binder, tamped in molds having the desired form for the fuel rods, and ignited

(c) BeO rods may be prepared with holes in the center which can be filled with UO_2 and closed by a BeO plug

(d) A protective glaze may be formed on the surface of any one of the types of fuel rods mentioned to prevent access of steam or air to the UO_2. The possibilities of producing such a glaze by flash heating of the surface of the BeO rod or by wetting the rod with a concentrated $Be(NO_3)_2$ solution and igniting are being investigated.

(e) BeO-U_3O_8 powders may be mixed for firing.

Provision has been made to test the effect of steam on fuel rods made by these methods.

A decision as to the relative desirability of retaining the fission products in the fuel rods as contrasted to allowing them to diffuse into the coolant stream may be a factor in determining the method of fabrication of the rods.

C. Fabrication of BeO Moderator

It is proposed to construct the high temperature pile of a series of bricks which are small enough so that they can be readily fabricated and will not be subject to undue thermal stress as a result of the temperature differences in the pile but at the same time will be large enough so that they will form a stable pile structure and the total number will not be impracticable. The present design calls for bricks in the form of hexagonal nuts which are 3" high, measure 3" between parallel sides and have a 2" diameter hole in the center.

The higher the density of the moderator bricks, the lower will be the volume of the pile and the weight of the fissionable isotope required to reach a chain reacting condition. The density of crystalline BeO is 3.025, which is the maximum theoretical obtainable density in the fabrication of moderator bricks. Rather extensive experience in the production of fired BeO pieces from BeO powder, both at Chicago and other sites, has indicated that the maximum reproducibly obtainable density is about 2.7 and that such a value can only be obtained by a lengthy procedure which involves pressing, followed by firing at about 1250°C, followed by machining, followed by pressing while firing at high temperatures. In the course of exploratory work being carried out as part of the high temperature pile program, various methods have been tested in the hope of finding a simple way of producing high density. These include the use of pressures up to 50,000 lb/sq.in., the use of mixed particle sizes of the BeO powder, firing at temperatures of 2000 to 2200°C, and the use of different binders including water, nitric acid, dextrin and Be $(NO_3)_2$. As yet, no rapid method has been found for obtaining a density of final product greater than about 2.2. An attempt will be made to obtain increased densities by soaking porous BeO bricks in concentrated $Be(NO_3)_2$ solution under low pressure and then applying pressure to force the solution into the pores prior to drying and igniting the bricks. If rapid methods of producing bricks of densities greater than 2.2 are not discovered, it probably will be desirable to compromise on the use of this density and employ larger amounts of fissionable isotope rather than to undertake the fabrication of a large number of bricks by the lengthy high temperature pressing technique. Considerable work is still necessary before finally standardizing upon a procedure by which to obtain bricks of reproducible size and density for the pile construction.

D. Heat Conductivity of BeO and BeO-UO_2 Mixtures

In a pile in which the fissionable isotope is homogeneously dispersed through

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fuel rods of $BeO-UO_2$ in channels passing through the BeO moderator, heat generated by the fission process must flow from these rods into the stream of coolant steam at a rate equivalent to the rate of heat production. If the heat conductivity of the rods is low (say of the order of 0.2 BTU/hr/ft^2/^{o}F/ft), the temperature drop through the rod will be much greater than that across the steam film at the surface, whereas if the heat conductivity is high, the maximum drop will occur across the steam film. The fuel rods must be so designed that the temperature differences involved will not cause undue temperature stress in the materials and will not result in internal temperatures in the fuel rods above the melting point of the fuel matrix. For these reasons, it is necessary to know the heat conductivity over the temperature range of the pile as a function of method of preparation of the BeO and $BeO-UO_2$ before determining the final pile design.

Fragmentary data for the heat conductivity under certain conditions of BeO and $BeO-UO_2$ mixtures are available in the Metallurgical Project literature. These data tabulated in Table I below indicate that sintered BeO has an anomalously high heat conductivity in the range from 80° to 300°C and that this conductivity decreases linearly over the range measured. Since it is imperative to know the heat conductivity of the fuel rods at temperatures up to the highest contemplated for pile operation, an experimental program is now in progress to determine these values as a function of the method of preparation of the materials. Three types of experiments are being carried out:

(a) H. W. Russell of the Battelle Memorial Institute is determining the heat conductivity of sintered BeO rods up to 600°C and will prepare to determine the conductivity up to 1300°C. He is employing calorimeters in which the temperature gradient through the BeO is measured by thermocouples and the total heat flow is measured, in one case, by a water calorimeter, and in another, by the temperature gradient produced as a result of the flow of the heat

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Table I

Heat Conductivities

Material	Temperature, °C	cal/cm²/sec/°C/cm	BTU/ft²/hr/°F/ft
1. Sintered BeO prepared by McDanel Porcelain Refractories Company Data from CT-750			
	80	0.33	80
	190	0.25	61
	300	0.17	41
2. Pressed BeO powder (100 lbs/in²) Report CP-192			
	100	0.0024	0.580
3. UO_2 and U_3O_8 Report CP-192			
UO_2 powdered pressed at 100 lbs/in²	100	0.0002	0.0485
UO_2 fused	100	0.004	0.970
U_3O_8	100	0.001	0.242
4. UO_2 and U_3O_8 CT-192			
U_3O_8	100-150	0.0013	0.314
powdered	200-300	0.0011	0.27
pressed	360-620	0.001	0.24
UO_2	100	0.004	0.970
UO_2 sintered	100	0.0049	1.20
UO_2 powdered & pressed	100	0.0003	0.0730
100 lbs/in²	270-610	0.0002	0.0490
5 T/in²	100	0.0003	0.0730

[redacted]

Table I (contd.)

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Material	Temperature, °C	cal/cm²/sec /°C/cm	BTU/ft²/hr/°F/ft
5. BeO-UO_2 mixtures Metallurgical Laboratory Notebook NB-660B			
100% UO_2	100	0.0037	0.90
90% UO_2 10% BeO	100	0.00934	2.26
50% UO_2 50% BeO	100	0.0121	2.90
100% BeO	100	0.0093	2.26

[redacted]

through a substance of known heat conductivity [redacted]

(b) Equipment is being prepared at the Metallurgical Laboratory for determining the heat conductivity up to 2000-2200°C by measuring the temperature gradient in the wall of a beryllia "box" by viewing holes drilled to different depths in the top of the "box" by means of an optical pyrometer and by calculating the total heat flow through the top of the box from a knowledge of the emissivity of the BeO at the temperature of the surface. The "box" will be internally heated by a metallic inductor

(c) Incidental to determinations on the erosion and corrosion of BeO and $BeO-UO_2$ tubes by steam streams passing through them, heat conductivities are being determined by the Angstrom method which is based on an analysis of the shape of the heat wave which flows to the outer surface of the tube following a change in the temperature of the steam passing through the center of the tube.

Table II below gives the temperature drops through fuel rods and pebbles of different dimensions for piles operating at 100,000 kw and 4000 kw and for assumed values of the heat conductivity of 0.6 BTU/hr/ft^2/°F/ft and 20 BTU/hr/ft^2/°F/ft. When accurate values of the heat conductivity as a function of temperature and the materials of construction of the pile are known, it will be necessary to couple these with the calculations of power distribution in the pile based on neutron physics to determine the temperature distribution throughout the pile. On the basis of these calculations, it may be found desirable to design coolant channels in such a way as to have greater steam flow through certain channels than through others.

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Table II

Temperature Gradient Through Fuel Pieces

Distribution of Fuel	100,000 kw Operation		4000 kw Operation	
	Heat Conductivity		Heat Conductivity	
	0.6	20	0.6	20
330 5 ft. channels filled with 1.5" rods	14,800°C	445°C	593°C	18°C
810 5 ft. channels filled with 0.5" rods	6,350	190	254	8
330 5 ft. channels filled with 1.5" OD, 1.25" I.D. tubes	1,300	39	52	2
Homogeneous 5' x 5' cylindrical bed of BeO-UO_2 pebbles (50% voids)				
a) 2" diam. pebbles	1,833	55	74	2
b) 1" diam. pebbles	466	14	19	0.5
330 5 ft. channels 2" in diam. filled with pebbles. (50% voids assumed)				
a) 1" diam. pebbles	1,390	42	56	2
b) 0.5" diam. pebbles	330	10	13	–
c) 0.25" diam. pebbles	79	2	3	–

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E. Coefficient of Expansion, Resistance to Thermal Stress

A knowledge of the coefficient of expansion of BeO and $BeO-UO_2$ fabricated under the conditions which will be used to make these materials for the pile is important because this property will determine the resistance of the materials to thermal stress and will also determine the probability of the disturbance of the alignment of the pile bricks by expansion and contraction. Qualitative tests indicate that pieces of BeO which are heated to 1000° and suddenly cooled by immersion in water are seriously weakened. However, it is not anticipated that pile operation will create as serious temperature gradients as this test. Data recorded in the literature give a value of $\sim 10^{-5}/^{\circ}C$ for the linear coefficient of expansion of BeO. Such a value would lead to an expansion of the top of a 7' diameter pile to 7'1" on heating from room temperature to 1500°C. The resistance to cracking as a result of thermal stress of proposed fuel rod materials will be tested by internal inductive heating of fuel rods. If no cracking occurs, it may be possible to determine whether the rods have been weakened by conducting crushing strength tests.

F. Mechanical and Structural Features of the Pile

The general design for an atomic power pilot plant has been outlined above. Since such a plant operating at 4000 kw will produce several thousand curies of radioactivity a day and hence must be capable of operating indefinitely without maintenance except by remote control, the details of construction must be even more carefully planned and tested than in the conventional power plants. This part of the work can best be done by qualified construction engineers. Some of the problems to be considered are listed below.

1. Pile Bed

The pile design, outlined in the sections above, calls for the construction of a bed of BeO moderator from bricks of BeO in the form of hexagonal nuts. The

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vertical channels formed by the holes in the nuts will be charged with $BeO-UO_2$ fuel rods. The BeO nuts must be so designed that the pile bed will not shift in such a way as to put the vertical channels out of line. This may possibly be accomplished by the use of interlocking joints on the bricks and/or by using bricks of different heights so that the joints between bricks in adjacent columns will not fall in the same horizontal plane. The design of the fuel rods must take into consideration the method of charging and discharging and the question of whether the rods must be provided with spacers to keep them centered in the coolant channels.

2. Reflector and Breeder Blanket

The pile will be surrounded by a reflector blanket for the purpose of reducing the critical mass of U^{235} required to produce a chain reacting structure. The outer portions of this blanket will contain ThO_2 for the purpose of forming U^{233} from excess neutrons. Provision must be made for separate charging and discharging of the ThO_2, or the ThO_2 pieces must be of different size than the U^{235} fuel rods and provision be made by separating them by screening before chemical processing. Detailed design of the reflector and breeder blanket is dependent upon further calculations of the neutron physics of the pile.

3. Outer Container of the Pile

It is planned that the pile proper and the surrounding reflector and breeder blanket will be contained in a large steel cylinder. This cylinder must be made of a steel capable of withstanding the mechanical and temperature stresses of the system. The bottom of the pile bed must be supported by a steel plate with provision for passage of the circulating steam and the operation of a mechanism for discharging the fuel rods. The junctions between the main pile jacket and the auxiliary conduits above and below the pile must be such as to remain absolutely gas tight for an indefinite period under conditions of pile operation.

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4. Charging and Discharging Mechanism

It must be possible to lower fuel rods into the fuel channels without damaging them by mechanical impact and without undue exposure of personnel to radiation. It must then be possible, after a period of operation of the pile, to discharge these rods and move them safely to the location for chemical processing. One possibility for charging the rods is that of lowering each rod or chain of rods by a loop of wire running through a small low melting hook on the rod. When the rod is in place, the hook could be melted by passing current through the supporting wire. Satisfactory provision must be made for the protection of personnel from radioactive materials picked up by any charging mechanism introduced into the pile, and for the sheathing of such mechanism when it is withdrawn to prevent scattering of radioactive material. One of the chief problems in the design of a charging mechanism will be to provide closures to the charging holes which will be absolutely leakproof against steam at high temperature and several atmospheres pressure. If the pile is so designed that the charging holes open on a header which carries 1500° steam special provision must be made to plug these holes during operation or to water-cool the inlet tubes.

One possible discharging mechanism would make use of the fact that the 330 fuel channels in the pile can be considered as arranged in concentric circles. Under each circle of channels would be placed an annular, flat wheel. This wheel would be arranged so that in one position the slugs would rest on it, while in a second position the slugs would be allowed to fall through holes into a hopper below. Such a mechanism would make it possible to discharge all the holes at a given distance from the center of the pile at one time without discharging those at other distances from the center. The design of a discharge system must take account of the problems of operating movable parts below the pile by controls which must extend through the shielding of the pile and through the wall of the

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19C-1

steam pressure jacket of the pile. The system must be leakproof and the action of the movable parts must be completely dependable even though they stand for months in an atmosphere of high temperature steam without the benefit of ordinary lubricants.

5. Coolant System

The steam coolant to be used in the pile must circulate at a constant rate. If the circulation becomes too slow, the steam will reach a temperature where it will endanger the materials of construction. If the circulation is too rapid, the temperature range through which the steam is heated will be too small with a consequent loss in the efficiency of the heat exchange cycle. In the cycle proposed, the steam will pass upward through the pile channels at a pressure of about 5 atm, increasing in temperature from 150°C to 1500°C. It will then pass through a steel conduit internally insulated with refractory to a locomotive type boiler where it will pass through the flue gas tubes giving up enough heat to produce an equivalent amount of steam for return to the cooling cycle. Passing out of the flue gas tubes, it will then go to an evaporator where it will give up its remaining superheat and heat of condensation to boil water in an external system for the purpose of running turbine and generator. The condensed steam from the pile will then return to the locomotive type boiler for evaporation and re-circulation as the pile coolant. The engineering calculations for the pile must include a careful balance of the heat exchange requirements at all points in this cycle and must provide for adequate control of the rate of steam flow.

6. Power System

It is proposed to use an easily obtained commercial turbine and generator for producing power from the pile coolant system. This turbine will not operate directly in the coolant stream but will use steam produced by the coolant in passing through an evaporator. This will avoid the problems of maintaining equipment with moving parts in an highly radioactive system. For the pilot plant installation,

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it is proposed to use readily available commercial power equipment rather than to seek to attain the highest efficiency of power production. It is expected that the turbine-generator system may be obtained on loan from the manufacturer. If a condenser is used in conjunction with the turbine, it will be necessary to construct cooling towers to provide the necessary flow of low temperature water.

7. Shielding

A pile operating at 4000 kw will produce of the order of 10,000-20,000 curies of radioactive elements per day. The activity produced in a given day will decay to ~4000 curies after two months. After one month of pile operation, the operating unit may be expected to contain ~200,000 curies of activity. Six to eight feet of concrete will be required to shield all parts of the pile system where an appreciable fraction of the total activity may deposit.

8. Safety Features

Each feature of the pilot plant design must be critically appraised for safety from the standpoints of mechanical engineering, neutron physics and health physics. For example, it is important that the hoppers for collecting the discharged fuel rods have a geometry such that if all the fuel in the pile were accidentally discharged at once and if at the same time steam should condense in the hopper to fill it with liquid water, the mass would not be chain reacting.

G. Pressure Drop Through the Pile

Because of the high level of radioactivity in the pile coolant system, it will be desirable if this coolant can be circulated without the use of pumps. This may be achieved if the pressure drop through the pile is sufficiently low so that flow may be maintained by a hydrostatic head of practical height. For a given power of pile operation, a constant weight of steam must be circulated per unit time regardless of the average pressure of the steam. Therefore, since the pressure drop is a function of the linear velocity of the steam, a low pressure drop is

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21C

favored by using a high average steam pressure. However, because of the serious consequences of leakage of the radioactivity in the system, it probably would not be wise to use very high pressures in the proposed pile. The calculations summarized below indicate that pressure drops which can be furnished easily by a hydrostatic head (of the order of 1 atm or less) can be obtained at relatively low average pressures in piles of the type under consideration.

(1) If 330 f' high, 2" diameter channels charged with 1.5" fuel rods are used with an average steam pressure of 5 atm, the pressure drop in a pile operating at 100,000 kw will be of the order of 0.2 atm.

(2) If 810 smaller channels, ie. 1" diameter with 0.5" fuel rods, are under the same conditions, the pressure drop will be only slightly greater. If the fuel rods in the 1" holes are 0.75" in diameter, the pressure drop will be about 1.5 atm.

(3) If the pile should consist of a 5' x 5' homogeneous bed of 1" diameter $BeO-UO_2$ pebbles, the steam could not be forced through it at an average pressure of 5 atm, but if the average pressure were 10 atm, the pressure drop would be only about 1.2 atm.

Calculation of the characteristics of steam flow through pile channels must take into account the fact that the temperature of the steam, and hence its density and linear velocity, changes rapidly in going through the pile due to the large temperature gradient. Empirical data on mock-up channels will be required to determine the effect of such factors as the surface characteristics of BeO and the alignment of fuel rods on pressure drops.

The average rate of flow through the channels at 100,000 kw operating power is of the order of 100 linear ft/sec.

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H. Vapor Pressure of BeO and UO_2

In order for a high temperature pile to operate satisfactorily over long periods of time, the temperature of the operation must be maintained sufficiently low so that the materials of construction will not be seriously altered by losses due to vaporization. Experiments are now in progress to determine accurately the vapor pressures of BeO and UO_2 as a function of temperature. Calculations based on the best available estimate of the vapor pressure of BeO (Brewer) lead to the values given in Table III for the rate of loss of BeO from the fuel rods and surfaces of the cooling channels as a function of the vertical distance in centimeters from the bottom of the pile. It has been assumed that a penetration of 1×10^{-3}"/month is tolerable. On the basis of this assumption, the values tabulated indicate that operation at a maximum pile temperature of 1500°C will be safe.

Available data of somewhat questionable accuracy from the literature indicate that serious volatilization of UO_2 will not occur. However, as indicated earlier, this volatilization is being redetermined under pile conditions.

I. Chemical Problems

In the course of full power pile operation, it may be necessary to discharge the fuel and chemically process it at rather frequent intervals. In this processing, the uranium which has not been consumed must be recovered in a pure form for use in the pile again, the beryllium must be decontaminated and prepared for use again, the plutonium which has been formed should be recovered, and the fission products should be segregated for disposal or use. Such chemical processing will not be required often in the course of operation of a low power pilot plant but preparation must be made for eventual processing of this type. Preparations must also be made for the recovery of Th and U^{233} from the neutron absorbing ThO_2 blanket of the pile.

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Table III

Height above Bottom of Pile (cm)	Penetration * (in/month)
0	1.24×10^{-51}
20	5.18×10^{-33}
40	6.18×10^{-23}
60	1.25×10^{-16}
80	2.53×10^{-12}
100	3.40×10^{-9}
120	7.97×10^{-7}
140	5.74×10^{-5}
152.4	5.27×10^{-4}

*It is assumed that 4500 lbs/min of steam at 5 atm pressure is circulated through 330 holes 5 ft long and 2 in. in diam. charged with rods 1.5" in diam. It is assumed that there is a linear temperature gradient with the steam entering at 150°C and leaving at 1500°C and that the steam is saturated with BeO vapor at every point. The density of the BeO is taken as 2.5.

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Although the problems of chemical processing will probably not be difficult to solve in principle, it will be necessary to carry out a program of investigation to establish the exact methods to be used. If this investigation is not completed at the time of the design of the pilot plant unit, adequate provision must be made for flexibility in methods of handling the discharged fuel rods under conditions providing adequate radiation shielding and equipment for remote control operation. After one hundred days of pile operation at 4000 kw and 60 d cooling, a six inch fuel slug from a pile of the type that has been described will have $>$ 100 curies of activity. As part of the auxiliary equipment for the pilot plant, a storage tank or vault must be provided to hold discharged slugs during their cooling period.

In addition to the chemical problems concerned with processing pile materials there are problems, some of which have been mentioned elsewhere, concerning the conversion of UO_2 to U_3O_8, the corrosion of steel by steam at high temperatures and the chemical disassociation of materials of construction by radiation.

J. Radiation Effects

It is important to anticipate, insofar as possible, the effects of radiation on the materials of construction of the pile. Such effects are potentially capable of making the whole pile structure inoperable. Among the possibilities are the following.

If the fuel rods contain a high concentration of UO_2 and BeO and if a sufficient fraction of the uranium is allowed to undergo fission before processing of the fuel, the fuel rods may crumble as the result of the effect of the fission recoil particles.

It is possible that sufficient oxygen will be liberated from BeO and/or from the steam in the low temperature regions near the bottom of the pile to cause conversion of UO_2 to U_3O_8 with consequent crumbling of the fuel rods. This

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phenomenon would not be expected to occur in the high temperature regions of the pile where the steam would achieve its normal thermal disassociation equilibrium and where the back reaction of Be with oxygen would be rapid, but might be serious throughout the bottom half of the structure.

Experiments are now under way to determine the evolution of exygen from BeO as a result of exposure to neutrons in the Argonne pile and to determine the effect of fission on the strength of $BeO-UO_2$ samples. It will be desirable to obtain similar tests at Hanford levels of radiation.

K. Fission Product Problems

From the standpoint of simplicity of pile operation and maintenance, it would be desirable to jacket the fuel rods in such a way that no fission activity would escape into the coolant stream and be distributed through the coolant circulating system. Because of the high temperatures of operation, the conventional type of metal jackets cannot be considered for this purpose. Tests are planned to determine whether it is possible to seal the pores of a $BeO-UO_2$ fuel rod by glazing the outer surface in such a way as to preclude fission product diffusion into the coolant stream. The advantages of such a procedure must be balanced against the advantages of accelerating the diffusion out of the fuel rods of poisons such as xenon.

It may be possible by the use of a suitable absorbent or by a bleeding mechanism to separate radioactive gases from the coolant system. After chemical separation from the U and Be of the fuel rods the fission activity may be disposed of in underground storage pits or may conceivably be of use as a supply of tracers or for radiographic work.

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L. Subdivision of Problems

Assuming that the necessary financial support and the authorization for the use of an adequate quantity of U^{235} is forthcoming, the program of development and construction of the high temperature BeO moderated pile may be subdivided as follows:

(1) Calculations and design from the standpoint of neutron physics engineering.

(2) Calculations and design from the standpoint of mechanical and power engineering.

(3) Development and testing of materials of construction.

(4) Development of chemical process and chemical engineering calculations and design.

(5) Procurement

(6) Construction

Work has already been started to a greater or lesser extent on the first five of these problems. The first four of these headings are further subdivided in Table IV which gives estimated manpower requirements for a program which contemplates the initiation of full scale activity on October 1, 1945, and completion of the pilot plant by June 30, 1946. The estimates cover the period of October 1 to January 1, at the end of which time it will be necessary to initiate procurement of the major items of equipment if construction is to start on, say, April 1. It is probable that the manpower figures suggested are underestimates rather than overestimates.

M. Major Items for Procurement and Construction

The major materials and equipment pieces for construction of the high temperature pile pilot plant are listed below together with estimates or guesses as to their cost.

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Table IV

Classification	Subclassification	Estimated No. of men	Estimated Months	Total man months	Possible allocation of work
Neutron physics engineering	Critical mass and critical size. Control rods. Power production as a function of position and temperature. Pile operating characteristics. Optimum reflector blanket. Optimum ThO_2 blanket. Possible safety hazards in contemplated design. Shielding required	?	?	?	Theoretical physics group
	Neutron age in BeO	?	?	?	Argonne
	Absorption Cross section of BeO	?	?	?	Argonne
	Absorption cross section of fission products as function of energy	?	?	?	Borst at Clinton

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28C 27

Table IV (contd.)

Classification	Subclassification	Estimated No. of men	Estimated Months	Total man months	Possible allocation of work
Mechanical and Power Engineering	Shape and size of fuel & moderator pieces to give stability of bed and adequate heat transfer.(including tests)	2	1	2	
	Mechanism for charging fuel to pile	1	2	2	
	Mechanism for discharging fuel	1	2	2	
	Separation of ThO_2 from $BeO-UO_2$ in discharging	1	1/2	1/2	
	Design of outer shell of pile				
	Design of bottom support of pile bed	2	1	2	
	Design of dome and conduit to receive 1500°C steam at top of pile (with provision for charging mechanism)				4 engineers and 2 draftsmen

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29 C 27

Table IV (contd.)

Classification	Subclassification	Estimated No. of men	Estimated Months	Total Man months	Possible allocation of work
Mechanical and power engineering (contd.)	Heat transfer in coolant cycle Regulation of coolant flow-pressure drops	1	1	1	
	Choice of power equipment	1	1/2	1/2	
	Engineering features of shielding	1	1	1	
	Engineering design of control rods and safety devises	2	1	2	
	Design of buildings and of excavation at Argonne	2	2	4	
				17	
Development and testing of materials of construction	Fabrication of satisfactory BeO and $BeO-UO_2$	2	3	6	Crawford Hutchison Malm Walling
	Physical and chemical effects of steam on BeO and $BeO-UO_2$ specimens	2	3	6	
	Heat conductivities	1	1.5	1.5	Seifert
	Vapor pressures	1	1.5	1.5	Seifert
	Analysis of raw materials	1	2	2	Analytical group
	Effects of radiation	1	3	3	Allen-Gordon
	Diffusion of fission products from fuel rods	2	2	4	Rubinson's group
				24	

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30 C 27

Table IV (contd.)

Classification	Subclassification	Estimated No. of men	Estimated Months	Total Man months	Possible allocation of work
Chemical process development and design	Chemical processing of BeO-UO_2 fuel	4	3	12	2 new men Goeckerman Gilbreath
	Chemical processing of Tho_2	(2)	(3)	(6)	(sufficient information may be available from work in Section I and at Clinton)
	Design of chemical process equipment	1	3	3	New chemical engineer
				15 (21)	

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31C 27

(1)	45 kg of U^{235} as 20% enriched U	
(2)	15 T of BeO @ $7.50/lb	$225,000.
(3)	4 T of ThO_2 @ $10/lb (?)	80,000.
(4)	Locomotive type boiler	10,000.
(5)	Evaporator	10,000.
(6)	Shell and dome for pile	10,000.
(7)	Special fabrication of loading and unloading mechanism	10,000.
(8)	Fabrication of BeO bricks and rods	1,000.
(9)	15,000 cu ft of concrete @ $0.50/cu ft	7,500.
(10)	Instrumentation	5,000.
(11)	Chemical processing equipment	15,000.
(12)	Buildings	10,000.
		$383,500.