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Current Status of Work on BeO Moderated High Temperature Pile

The purpose of this memorandum is to summarize the current status of development work and procurement directed toward the design and construction of a beryllia moderated high temperature pile for the production of useful power from nuclear energy. The status of this work as of September 14, 1945, together with a discussion of problems involved, was summarized in MUC-JEW-33, and a proposed time schedule for the remaining development, procurement and construction was given in MUC-JEW-44, October 18, 1945.

1. General Features of Design

The proposed pile unit utilizes BeO as moderator and sintered rods of BeO mixed with uranium oxide as the fuel. The structure will be a cylinder about 6 ft. in diameter and 6 ft. high containing about 580 2 in. diameter vertical channels constructed from hexagonal beryllium oxide bricks. These bricks, which measure 3 in. between parallel sides, are constructed with a 2 in. diameter hole whose axis is parallel to the edges of the hexagon. The fuel rods which will be 1½ in. in diameter and 4-6 in. long will be placed one on top of the other in the vertical channels. The 1/4 in. annulus between the fuel rods and the moderator bricks will serve as a channel for a gas coolant which will carry the heat produced by the nuclear reactions in the pile to a boiler where it will be used to produce steam in an external system. This steam will be used to run a turbine which is connected to an electric generator. After leaving the boiler, the cooling gas will be recirculated to the bottom of the pile by means of a centrifugal pump. It is contemplated that the gas will enter the pile at about 500°F and leave at 1800°F. The average pressure in the circulating system will be 1 atm and the pressure drop through the system will be < 0.005 atm when operating at 4000 kw. Any one of several gases, such as steam, carbon dioxide or helium, might be used as the coolant.

Operation at 4000 kw is planned for standard operation of the proposed experimental unit but it is expected that the auxiliary equipment can be made sufficiently flexible to allow tests up to 40,000 kw. The efficiency of fuel utilization expressed in kw/kg of U^{235} will be about 3500 kw/kg at 40,000 kw and 9000 kw/kg at 100,000 kw. It appears probable that 100,000 kw operation would be practical in a similar unit provided with a larger heat exchanger and gas circulation equipment.

Earlier designs of the proposed unit contemplated the use of a coolant cycle wherein gaseous steam removed heat from the pile, gave up most of its superheat in a boiler which served to evaporate more steam for circulation into the pile and then gave up the remaining superheat and heat of condensation to produce low pressure, low temperature, secondary steam for operation of a turbine. The condensate from the coolant steam then went to the primary boiler where it was re-evaporated for recirculation through the pile. The condensation step was included in order to allow for the circulation of the coolant by means of a hydrostatic head or by pumping the liquid. The necessity for using the superheat of the steam as it came from the pile for evaporating the coolant prior to recirculation made it impossible to produce high pressure, high temperature steam in the auxiliary power system and therefore severely limited the thermodynamic efficiency obtainable in power production. In recent conversations, a representative of the Ingersoll-Rand Company has assured us that his Company can provide a centrifugal blower

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adequate to circulate the coolant gas through the pile system without condensation, We were assured that such a pump can be made leak-proof and sufficiently dependable to need no maintenance over a period of many months' operation. The earlier design of the cooling system has therefore been changed to provide for complete circulation of the coolant in the gas phase without condensation at any point. This change makes it possible to produce steam in the auxiliary power system at any desired temperature and pressure and hence to employ a conventional turbine-generator system of whatever efficiency is desired.

Elimination of the condensation step in the coolant cycle has made it possible to lower the maximum temperature in the cycle to 1800°F (1000°C) or lower. This change simplifies problems of design and operation in the following respects.

1. Less stringent requirements are placed upon the materials of construction. As you have pointed out, it was found in connection with the development of the high temperature nitrogen fixation furnaces at Madison that no difficulties attributable to temperature of operation were found when operating at 1500°C or below.

2. Any tendency for uranium oxides or fission products to vaporize from the fuel rods is reduced.

3. The required degree of flexibility in control of the pile imposed by the temperature coefficient is reduced.

2. <u>Size of Unit</u>

The critical dimensions for a bare cylindrical pile having 20% voids and using BeO of bulk density of 2.7 are 5.6 ft. diameter and 5.2 ft. high. The weight of BeO in the pile will be 7,160 kg (2,580 kg of Be). The weight of $U^{235}O_2$ will be 13.8 kg (69 kg of UO_2). The proposed pile dimensions will be slightly larger than these stated in order to provide for a BeO reflector on the top and bottom of the pile and extra channels around the circumference containing ThO_2 rods for the purpose of conversion or breeding.

The table below gives the figures (derived from calculations by M. L. Goldberger) for critical dimensions and weights of materials in pile utilizing beryllia of different densities. Beryllia shapes with a density of 2.7 have been produced in quantity by a relatively rapid process at the AC Spark Plug Division of the General Motors Corporation and this company believes that it can produce structural bricks of this density for the proposed pile.

Size and Weight of BeO Moderated Piles Operating on Uranium Containing 20% of $U^{235}O_2$
(Critical Values for Bare Piles)

Density of BeO (g/cc)	Voids for Coolant (%)	Spherical Piles					Cylindrical Piles					
		Diam. (ft)	Vol (ft^3)	BeO (kg)	UO_2 (kg)	$U^{235}O_2$ (kg)	Ht. (ft)	Diam. (ft)	BeO (kg)	Be in BeO (kg)	$U^{235}O_2$ (kg)	U^{235} in UO_2 (kg)
3.0	0	4.4	41	3480	31.3	6.3	3.7	4.04	3970	1430	7.2	6.3
2.7	20	6.1	111	6730	60.5	12.1	5.2	5.6	7160	2580	13.8	12.2
2.2	20	7.5	201	10100	91.1	18.2	6.3	6.8	11500	4150	20.8	18.4

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3. Heat Conductivity

When the use of BeO as the structural material of the pile was first considered, it was feared that such a refractory oxide might have so low a heat conductivity as to limit the power of operation due to the difficulty of removal of heat. However, early Project determinations of the heat conductivity of BeO from 50° to 300°C by Krats, recently confirmed and extended to 600°C at the Battelle Memorial Institute, indicate that BeO is equivalent to metallic iron in its heat conductivity in this temperature region. Using the Battelle value for 600°C (1100°F) it may be estimated that the temperature gradient within a 1.5 in. BeO-UO_2 fuel rod in the proposed type of pile operating at 100,000 kw would be of the order of only 600°C. The gradient would then be 300°C at 50,000 kw operation or 24°C at 4,000 kw operation. The table below summarizes the heat conductivity data. Determinations of the heat conductivity up to 1500°C are now in progress at Battelle and work on this problem is also being done at Chicago.

Heat Conductivities
(cal/sec/cm²/°C/cm)

Determinations by Krats on Sintered BeO Sample from McDanel Company		Determinations by Battelle Institute			
			Sintered BeO Prepared at Battelle		Armco Iron
T°C		T°C	Density = 2.22-2.24	Density = 2.11	
50	0.23	300	0.127	0.085	0.131
[illegible]	0.25	400	0.096	0.079	0.117
300	0.17	500	0.08	0.067	0.104
		600	0.067	0.060	0.090

4. BeO Procurement

Representatives of the Metallurgical Laboratory, of the Chicago Area Engineer's Office and of the Madison Square Area have visited the two main BeO producing companies in the country, i.e., the Brush Beryllium Company of Cleveland, Ohio, and the Clifton Products Company of Painesville, Ohio, to investigate the availability of oxide for pile construction. It was found that the Clifton Products Company could supply about 1.5 tons of 200 mesh refractory grade oxide within 3 weeks and thereafter could supply 2 tons/month of 60 mesh refractory grade or 1.5 tons/month of 200 mesh refractory grade. The production capacity for the low fired fluorescent grade is greater than that for the refractory grade. Representatives of the Brush Beryllium Company stated that they could produce 1.5 tons/month of refractory grade oxide, 5 tons/month of low fired SP grade oxide, and 1.5 tons/month of the highly purified low fired GC grade oxide. These figures indicate that without increasing the production capacity of the companies it should be possible to obtain adequate BeO for the construction of a pile within a period of 3-4 months.

Spectrographic analyses have been made by the Chemistry Division and neutron absorption analyses by the Argonne laboratories on the low fired and high fired oxides and on different mesh sizes of the high fired oxide from both vendors. These indicate that careful control must be maintained to prevent boron contamination but that either vendor should be able to supply oxide which will be satisfactory from the purity standpoint. The results of the analyses are reported in MUC-JEW-48, November 1, 1945

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The placing of orders for large quantities of the oxide is awaiting the results of fabrication tests by the AC Spark Plug Division using low fired oxide.

5. Fabrication of BeO Bricks for Moderator

The Norton Manufacturing Company of Worcester, Massachusetts, the McDanel Refractory Porcelain Company of Beaver Falls, Pennsylvania, and the AC Spark Plug Division of the General Motors Corporation, Flint, Michigan, have all had experience in the commercial fabrication of beryllium oxide shapes. Arrangements have been made with each of these companies to fabricate a test order of hexagonal bricks of the type proposed for the pile. This work is now in progress and the first shipment is expected in next week. When the bricks are received, they will be subjected to a series of comparative tests to determine which are best suited to be used in the pile.

Preliminary indications are that the AC Spark Plug Division will be able to produce nonporous bricks with a density of 2.7 using low fired BeO. Such bricks should be highly satisfactory from the standpoint of resistance to erosion, heat conductivity and cost of starting material, as well as density. A preliminary test on the erosion of BeO from the bore of a 1/8 in. I.D. BeO tube by steam at about 3 atm pressure passing at a rate of about 100 linear ft/sec. showed a satisfactory penetration rate of less than .001 in/month. Crushing strength tests are currently in progress to determine what limitations must be placed on heating and cooling rates of BeO in the pile in order to avoid deterioration as a result of thermal stress.

6. Fabrication of BeO-Uranium Oxide Fuel Rods

Development work on the fabrication of BeO-uranium oxide rods for use as the fuel in the proposed pile is in progress at the Metallurgical Laboratory, at the Battelle Memorial Institute and at the AC Spark Plug Division. It has been shown that rods of the mixed oxide may be made by sintering mixtures of BeO and UO_2 or mixtures of BeO and U_3O_8. When UO_2 is used in the starting powder, the rods tend to crumble when heated in the presence of air. This is believed to be due to the conversion of the UO_2 to the lower density U_3O_8. When U_3O_8 is used in the starting material, the rods produced may be repeatedly heated and cooled in air with no apparent deterioration of the physical structure. When initially heated in steam or vacuum, these rods have occasionally shown some tendency to lose a small fraction of their uranium at about 1000° and have shown higher losses at 1500°C but recent experiments on repeated heating at 1000°C have shown no further loss. In a recent firing of such a mixture at the AC Spark Plug Division, loss of uranium was experienced in a very thin surface skin but not below this skin even though the firing was carried out in an open kiln at over 1700°C. It appears that there are conditions which can be readily obtained under which loss of the uranium at contemplated pile operating temperatures is negligible. A careful investigation is being made of conditions under which volatilization may occur.

If it is possible for the AC Spark Plug Division to produce nonporous mixed oxide shapes comparable to their nonporous BeO, it may be possible to reduce fission product loss from the rods to a low value. Experiments on the rate of loss of fission products from irradiated samples and on methods of minimizing this loss are in progress. It may be that a fused refractory oxide skin will serve to essentially eliminate escape of activity.

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Centrifugal Blower for Gaseous Coolant

The Ingersoll-Rand Company produces centrifugal blowers for exhausting high temperature gases from blast furnaces. Their representative has indicated that they can produce a blower adequate for the purposes of the proposed pile which can be guaranteed to operate without loss of any of the coolant gas through the bearings. Engineers of the company are preparing a preliminary design and estimate.

8. Boiler to Produce Secondary Steam for Operating Power Equipment

Both the Foster Wheeler Company and the Babcock-Wilcox Company are preparing preliminary designs of boilers to fit the needs of the proposed pile unit and will give cost and time of delivery quotations in the near future. The plan is to remove the heat from the coolant gas as it leaves the pile by means of a unit containing a superheater, evaporator and economiser which will produce steam for the auxiliary power system at 600 lbs/sq.in. and 850°F. The coolant gas will circulate at 1 atm pressure, but it is hoped that the equipment can be designed with sufficient flexibility so that 5 or 10 atm pressure can be employed if it is desired to increase the power of the pile operation at a later date.

9. Turbine-Generator System

Representatives of the United States Navy have suggested that the Navy might be able to supply a standard Navy turbine-generator system operating with inlet steam at 600 lbs/sq.in. and 850°F. This or some other readily available turbine-generator system will be suitable for the proposed unit.

10. Efficiency of Conversion of Heat to Power

With a suitable turbine-generator system of conventional design, it should be possible to obtain at least 1000 kw of electrical power from 4000 kw of heat produced in the pile (see page 53, Progress Report #1, Locomotive Development Committee, by Yellott).

11. Control System

Detailed specifications of the control system for the pile must await final determinations of the age and diffusion length of neutrons in BeO and subsequent calculations of the neutron physics of the pile. Various control mechanisms may be possible. One of the more attractive possibilities is that of moving a cylindrical central section of the pile in and out of the pile. The piston supporting this system may be operated from the outside of the pressure shell while hermetically sealed within the pressure shell by means of a metal bellows. Such metal bellows have been developed in large sizes for various applications during the war.

12. Charging and Discharging Mechanisms

It is proposed that the pile may be charged through a central opening at the top using an adjustable device which allows a flexible tube to be centered over each hole in turn. The slugs may be lowered through the flexible tube. When charging is completed, the charging device can be stored under the concrete shielding of the pile. As a means of discharging, circular annular plates may be used under the concentric circles of fuel holes at the bottom of the pile. During operation of the pile, the fuel rods will stand on solid portions of

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the plates. At the time of discharge, each plate may be moved independently to a second position which will bring a large hole in the plate directly under the fuel hole in the pile and so allow the slugs from the fuel hole to fall into a hopper from which they can be run by gravity into an underground tank for chemical processing.

13. Pressure Drops and Flow Rates

The estimated pressure drops for a unit of the type outlined above are quite low. The estimated values for 4000 kw and 40,000 kw operation are given below. These are calculated for the pile channels and do not take into consideration the heat exchanger system. The drop in the heat exchanger system is not expected to be as great as that in the pile.

Average Pressure (atm)	Pressure Drops (atm)	
	4000 kw	40,000 kw
1	<0.002	<0.2
5	<0.0004	<0.04

The values for the linear velocity of the gas under different pile operating conditions are given below.

Flow Rates*

Pressure (atm)	Temperature (°F)	Volume (ft³/min)	Linear (ft/sec)
1	500	13750	45
	750	17400	58
	1000	20800	68
5	500	2740	9
	750	3470	11
	1000	4150	14
10	500	1370	5
	750	1740	6
	1000	2080	7

*For pile 6 ft. in diameter with coolant entering at 500°F and leaving at 1800°F and removing heat at rate of 4000 kw

14. Chemical Processing

At such times as it is desirable to recover the enriched uranium in the fuel rods, it is proposed to discharge the pile into a hopper from which the fuel rods can fall by gravity into a steam jacketed underground tank. Exploratory tests at Chicago indicate that the rods can be dissolved with sulfuric or nitric acid if allowed to stand for a few days at elevated temperatures. Although sufficient manpower has not yet been made available to test a chemical decontamination process, it appears probable that the uranium can be precipitated from the acid solution in the conventional manner as sodium uranyl acetate. This precipitate settles well so that the supernatant may be decanted off through a steam jet to another underground tank for storage. It is probable that essentially complete decontamination of the uranium can be obtained by dissolving and repeated reprecipitation of sodium uranyl acetate. The active supernatants will be stored in underground waste tanks.

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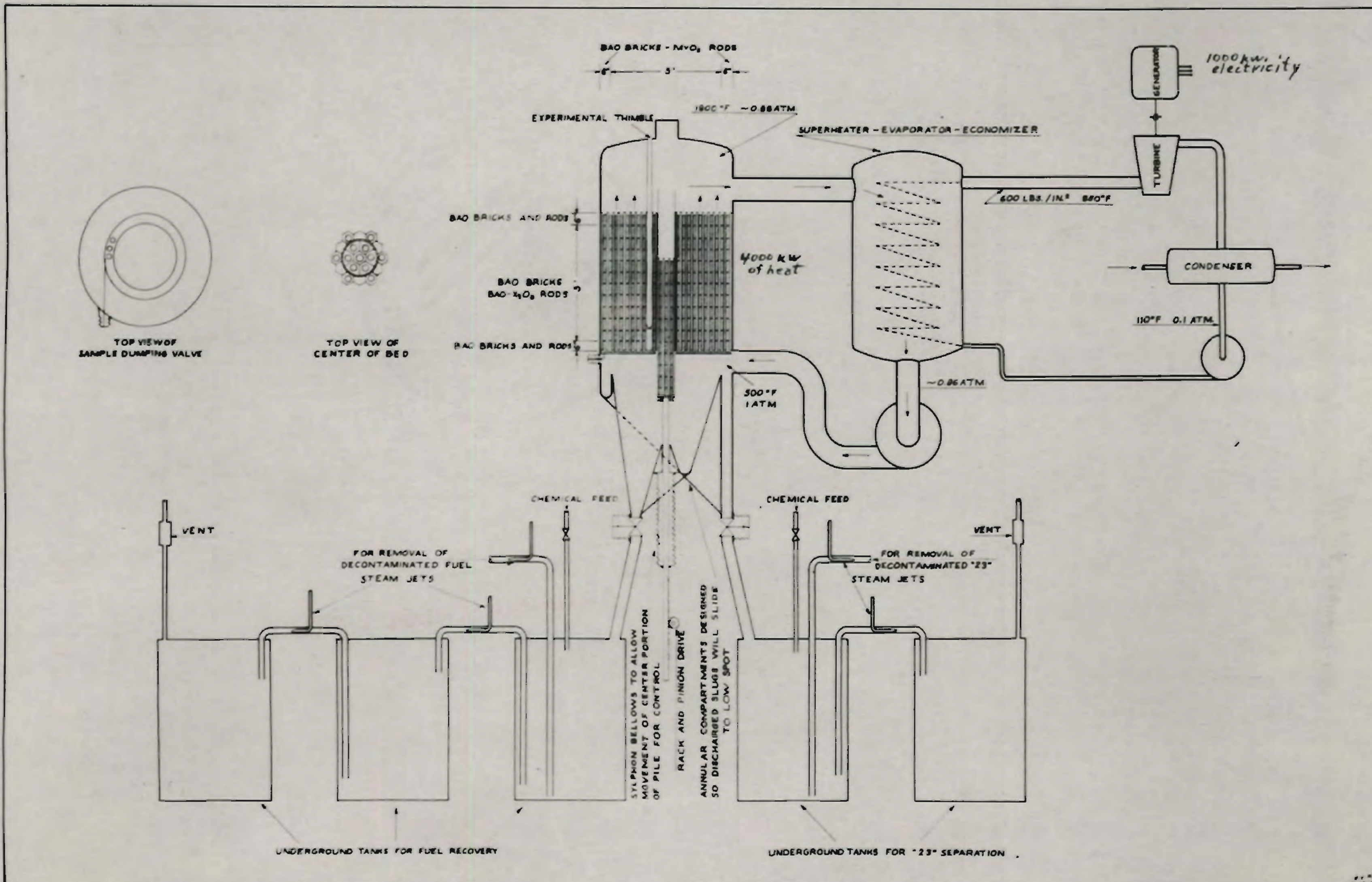

BAO BRICKS - NiO_2 RODS
6″
3′
6″
EXPERIMENTAL THIMBLE
1800°F ~0.88 ATM
SUPERHEATER - EVAPORATOR - ECONOMIZER
GENERATOR
1000 kw. electricity
TURBINE
600 LBS./IN.² 850°F
CONDENSER
110°F 0.1 ATM.
BAO BRICKS AND RODS
BAO BRICKS
BAO-ZrO_2 RODS
3′
BAO BRICKS AND RODS
4000 kw of heat
500°F
1 ATM
~0.86 ATM
TOP VIEW OF SAMPLE DUMPING VALVE
TOP VIEW OF CENTER OF BED
CHEMICAL FEED
CHEMICAL FEED
VENT
VENT
FOR REMOVAL OF DECONTAMINATED FUEL
STEAM JETS
FOR REMOVAL OF DECONTAMINATED "23"
STEAM JETS
SYLPHON BELLOWS TO ALLOW MOVEMENT OF CENTER PORTION OF PILE FOR CONTROL
RACK AND PINION DRIVE
ANNULAR COMPARTMENTS DESIGNED SO DISCHARGED SLUGS WILL SLIDE TO LOW SPOT
UNDERGROUND TANKS FOR FUEL RECOVERY
UNDERGROUND TANKS FOR "23" SEPARATION