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PRELIMINARY DESIGN PROPOSAL

DANIELS EXPERIMENTAL POWER PILE

BOOK 1 NOV. 1, 1946

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PRELIMINARY DESIGN

PROPOSAL

DANIELS EXPERIMENTAL

POWER PILE

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By

C. ROGERS McCULLOUGH
Director

And Members of the

POWER PILE DIVISION.

Nov. 1, 1946.

SERIES A RECEIVED: 11/1/46

SERIES A ISSUED: 11/1/46

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DANIELS EXPERIMENTAL POWER PILE

I. ABSTRACT

The work on the Experimental Power Pile has proceeded along the following lines: (1) an examination of the problems of producing useful power from the energy of nuclear fission; (2) a preparation of essential specifications for a power pile to accomplish this purpose; (3) development of the design schedule for the pile; (4) an analysis of the technical problems incident to this choice, and (5) detailed solutions of specific problems.

In selecting the design schedule the following decisions were made:

A. The pile will be a high temperature power unit designed and built especially to study experimentally the engineering features of a nuclear power plant.

B. The pile will be run initially at 4000 KW of heat and will be designed to operate at power levels up to a maximum of 40,000 KW of heat if operating experience proves this possible.

The results of the work are summed up in a brief description of the pile as it is now proposed. The central portion of the pile will be the cylindrical reactor 6 feet in diameter and $5\frac{1}{2}$ feet high. Most of the reactor will be composed of beryllium oxide moderator bricks, hexagonal prisms which are 3 inches across flats, have a 2 inch axial hole, and are $4\frac{1}{2}$ inches long. The axial holes in the moderator bricks, when they are assembled, will form 517 channels, 504 of which will be filled with fuel rods to a height of 5.55 feet. There will be 6 safety rods and 7 control rods in the remaining 13 channels. Six of the seven control rods will be placed on a 15 inch radius around the center of the reactor and the s eventh at the center.

Fuel rods initially will be made of 2% UO_2 enriched to 50% in U^{235} and of 98% BeO, other types of fuel rod materials are under development. All fuel rods will be hollow cylinders, $1\frac{1}{2}$ inch O. D. by 1 inch I. D., by $4\frac{1}{2}$ inches long. Fuel will be used to 10% depletion before reprocessing.

Both moderator and fuel rod materials and design are being investigated. The reactor will contain about 15 kg of U^{235} and 10-3/4 tons of BeO.

Helium gas as a coolant, will flow through the annular spaces between fuel rods and moderator bricks, and will be distributed by orifices among channels according to heat production. It will be circulated through the pile and through two external steamboilers which have a total steam capacity of 110,000 lb/hr. by 4 blowers requiring 150 KW driving power each. For the maximum anticipated heat output the pressure of the helium will be 10 atmospheres and the maximum mass flow rate 34 lb/sec. Equipment will be in duplicate so that the system may be run at half power in case of partial failure.

Power accessories have been designed for an output of 40,000 KW of heat of which 10,000 KW is to be obtained as electrical energy.

Coolant will enter the reactor at 500°F and leave at 1400°F. The highest temperature within the reactor will be 1750°F and the average reactor temperature will be 1200°F (650°C).

Surrounding the reactor there will be an 18 inch thick reflector composed in part of beryllium oxide bricks and in part of graphite bricks. The channels of the reflector will be used partly for helium coolant flow and partly for thorium rods for conversion to U^{233}. Facilities for exposing experimental samples will be provided.

Outside of the reflector there will be a 1/4" thick liner of steel, then an 8 inch heat insulating layer and a pressure shell of $1\frac{1}{2}$ inch steel plate, 11 feet in diameter by 21 feet high. The reactor will be supported within the pressure shell by a 5 inch thick steel diaphragm 12 feet in diameter.

A fuel loading and unloading mechanism has been proposed and will be located in the pressure shell below the reactor.

A radiation shield will surround the pressure shell. It will have the following construction: 2 inch air space, iron shell 10 inches thick, 2 inch air space and 10 feet of concrete or $4\frac{1}{2}$ feet of alternating iron and Masonite layers.

The pile structure will be supported on a concrete foundation.

Schedules for procurement of materials and for increase of pile power from 0 to 4000 KW and later up to a possible maximum of 40,000 KW have been worked out.

The necessary experiments which must precede the construction of the pile have been planned and some of these are presently proceeding.

II. INTRODUCTION

Studies of high-temperature, power pile were begun by Dr. Farrington Daniels in 1944. The feasibility of the proposed pile was established shortly thereafter by theroetical calculations made by Dr. Daniels and his associates. Investigations of anticipated problems were then carried out at the Metallurgical Laboratory in Chicago until early in 1946, when a committee, acting for General Nichols, reviewed the work which had been done and issued a directive to the Monsanto Chemical Company, operator of the Clinton Laboratories, to assume responsibility for the design and construction of the pile. It was also decided that because of the scope and importance of the project, technical men should be borrowed from cooperating industries and that these men should actually develop and design the pile. Knowledge of piles would thus be spread to industrial companies of the United States.

The group was formed about the middle of 1946 and has since carried the major part of the responsibility for the pile with the active cooperation of the Argonne National Laboratory.

The subject report summarizes the status of the power pile project as of November 1, 1946.

The purpose of the present Experimental Power Pile program is the design, construction and test of an experimental unit which will operate at elevated temperatures and convert the heat of fission into useful mechanical and electrical energy. It is important to demonstrate peaceful applications of atomic energy as soon as possible, and it has been decided to build this pile with careful attention to engineering details so that it can be operated safely, with ample tolerances, even when pushed to high energy outputs. Information is sought concerning the probable behavior of a power pile under practical operating conditions. Provisions will be made for testing samples of construction materials proposed for future high temperature piles under the expected operating conditions of high flux and high temperature.

This pile is to be built as an engineering experiment to contribute to our general knowledge along the lines indicated in the following paragraphs:

1. <u>High Temperature.</u> Although it has long been recognized that if piles are to be run for useful power they must be operated at high temperatures; no piles, as yet, have been operated above approximately 200°C. The reactivity of the pile falls off rapidly at high temperatures coefficient. It is important to actually operate a pile at temperatures well above 500°C in order to determine how serious these difficulties are and how they may be overcome.

2. Conversion of Thorium to U^{233}. It is important to start experiments on the conversion of thorium to U^{233} and to use this isotope of uranium in a pile so as to test practically its nuclear constants. Accumulation of a stock of U^{233} should be started as soon as possible for testing the breeder power pile.

3. Beryllium. Beryllium and its compounds have favorable properties as moderators and it is now time that a pile should be built to study these possibilities.

4. Elimination of Canning. All piles considered thus far have used an impervious metal coating to confine the highly radioactive fission products and prevent contamination of the coolant. The aluminum jackets, which have been used, prevent operations at high temperatures. Other metals can possibly be used at somewhat higher temperatures, but it is desirable to test a pile at much higher temperatures under conditions such that neither the temperature nor the neutron absorption can be limited by the presence of a metal. The sacrifice which must be made in order to eliminate canning is the radioactive contamination of the cooling medium - but this challenge must be met sometime. In the present pile it is proposed to circulate the cooling gas in a closed system with machinery which can operate without repairs and which can be replaced by remote control.

5. High Gas Pressures. For efficient cooling, the circulation of gas at high pressures is attractive but there are increased leakage hazards and difficulties of operating the controls and loading mechanisms. A pile should be built to explore the solution of these difficulties.

6. Neutron Flux Experiments. Future progress in the development of high temperature power piles requires a knowledge of the effect of intense neutron radiation on construction materials at high temperature and over long periods of time. The proposed pile will be provided with some experimental thimbles where samples can be exposed at temperatures up to 1400°F. to a neutron flux, it is hoped, up to ten times that now available at Hanford, No other pile now operating, or under consideration, is equipped to make such tests. This feature of the pile will be of great value for facilitating and expediting the design and construction of large and dependable high temperature power piles.

7. Tests of Extreme Conditions. It will be possible to push the pile to extreme energy levels and temperatures for experimental purposes, because no close tolerances are involved in the design and because only materials with high melting temperatures will be used in the construction. Hence, no serious consequence is to be feared in case the temperature should rise unexpectedly by several hundred degrees.

The concept of the design, originally, was for a heat output of 4,000 KW, with the hope that this could be increased. Study shows that the pile itself may be pushed to output of as much as 40,000 KW. The additional design requirements and difficulties are relatively minor and it is considered wise to design the integrated unit so that the limit of heat output will be the pile itself rather than any accessory equipment.

8. Operating Experience. Finally, it is necessary to design, construct and operate a high temperature muclear power unit so that the inter-relation of all factors concerned with the production of power from nuclear fission may be realized and the problem solved.

III. GENERAL SPECIFICATIONS

III. GENERAL SPECIFICATIONS

The primary purpose of a high temperature power pile is to produce useful mechanical energy from the energy which is evolved in nuclear fission as heat. It must produce heat at a high enough temperature to make possible good thermal efficienty of heat engines which are eventually operated by this heat.

If a pile is to be a prototype of an industrial power source, it should be capable of producing large amounts of electrical or mechanical energy for long periods of time without involuntary interruptions. Periodic voluntary shutdowns may be necessary, but these should be capable of being scheduled and should not occur too frequently.

It should be possible to control the pile easily during normal operation, fuel loading and unloading, startups and shutdowns.

A power pile should convert ~~throium~~ thorium or other material into fissionable material at a rate approximating the rate of destruction of U^{235} in the pile. This is necessary to conserve the available supplies of uranium.

It is very important that this, or any power pile, should be safe. It should contain a minimum number of potential hazards both to itself and to operating personnel. For example, uncontrolled reaction resulting in rupture or explosion, even if destructive only in the immediate neighborhood of the pile, would create a difficult disposal problem, in addition to the loss of life and property which it would entail.

The overall dimensions and weight of the pile should be as small as possible. The absolute lower limit on the size of the reactor will be determined either by the amount of heat which may be removed per unit volume or by the volume which is critical for the nuclear chain reaction, whichever is larger. The dimensions of all other parts of the power pile are derivable from the choice of reactor size and its consequences.

The materials which will be used in the pile, when they are other than ordinary engineering materaial, are described in the sections on specific components of the pile which follow.

Definitions of Terms

A power pile is a system in which the energy of the nuclear fission process may be released and converted into energy useful for producing mechanical work.

The names of important components of a power pile which are not specifically defined elsewhere in these specifications are given the following definitions for the purpose of these specifications:

Fuel - The fissionable isotope within which the nuclear energy is released as heat energy,

Fuel Matrix - The material in which the fissionable isotope is distributed. It contains non-fissionable isotopes and moderating material.

Fuel Units - The units into which the fuel matrix is divided in order to facilitate fabrication, handling and use.

Reactor - That portion of the pile in which the main nuclear reaction takes place.

Moderating Materials - The substances used in a pile whose primary function is to decrease the energy of neutrons which traverse them.

Reflector - The portion of the pile immediately surrounding the reactor. Its primary function is to return to the reactor those neutrons, which might have otherwise been lost. The reflector is composed almost entirely of moderating material.

Coolant - The medium by which heat is transferred from the reactor to the external circuit.

Thermal Insulation - A layer of material of low heat conductivity which is placed outside of the reflector and inside of the pressure shell or container. The primary functions of the thermal insulation are to decrease heat losses from the reactor and reflector and to diminish the amount of heat flowing into the pressure shell.

Pressure Shell - The metal shell or container which contains the reactor, reflector, coolant, and thermal insulation. Its functions are to withstand pressure differences between the inside and outside of the shell, to keep coolant and fission products in, and the atmosphere out.

Shield - The wall of material outside of the pressure shell and other components of the power pile within which radiation is generated. Its primary function is to absorb radiation escaping from the pile to a level which will not endanger personnel in the vicinity.

Definitions of Terms - Continued

Control Equipment - The equipment which is used to start the pile, stop it, and adjust operating variables. It may be manual or automatic or both, and it may use primary elements which are shared with indicating and recording instruments.

Instrumentation - The instruments which give visual indication of operating variables of the pile. They may also provide records.

Chemical Processing - The chemical treatment of the components of the pile including those processes which are required after the pile has initially been put into operation, but not those required before operation. These processes which are discussed include fuel processing and coolant purification.

Conversion - The transformation of thorium into uranium 233 by neutron bombardment. When the number of atoms of uranium 233 produced is greater than the number of atoms of fuel fissioned, the process is called breeding.

A. Fuel

The fuel shall be fissionable material. The fuel matrix may also contain non-fissionable isotopes in a concentration as determined by its effect on pile size and by the availability of highly enriched material. The fissionable material and inactive isotopes must be distributed in a support of moderating material in order to provide sufficient surface to remove the heat which is generated almost entirely in the fissionable material. The mixture of fissionable isotopes, non-fissionable isotopes and moderating material shall have the following characteristics:

1. It shall be sufficiently free of substances which absorb neutrons but do not produce them, that pile reactivity shall not be decreased materially thereby.

2. In choosing fissionable material and its degree of enrichment, available information as to supply and economy shall be taken into account.

3. Fuel can be in any of four forms: (1) self supporting solid, (2) granular or powdered solid, (3) liquid, or (4) gaseous. If the fuel is of the first type, it shall be possible to fabricate the material into individual units of required shape and specified tolerances and surface finishes. If the fuel is of one of the other three types it must be enclosed in a container. It must be possible to fabricate this container in the required shapes and to the specified tolerances.

4. The dimensions of the fuel units, if units are used, shall not change by more than a specified quantity on exposure to temperature and radiation or by corrosion, erosion or solid reaction with adjoining substances. The allowable amount of such change shall be determined by its effect on the structure and reactivity of the pile. If liquid fuel is used, it shall not corrode, erode or react with any substances with which it is in contact under the conditions of temperature, pressure and radiation which exist at that point, nor shall it undergo decomposition under these conditions.

5. The fuel units, if units are used, shall be and remain of sufficient strength to withstand without failures, stresses due to loads which may be imposed upon them at maximum operating temperatures and radiation levels.

6. The fuel material shall withstand any continuous or transient thermal stresses which may be set up within it, as shall canning material if used.

7. The fuel material shall have maximum thermal conductivity consistent with other requirements, and the conductivity shall not decrease to an unacceptable value between the time at which the fuel is placed in the pile and the time at which it is removed.

8. The surfaces of the fuel units, if units are used, shall not powder or chip under operating conditions.

9. When the pile is in operation objectionable fission products will be formed in the fuel mixture. In addition to acting as poisons within the fuel material, they are radioactive and if allowed to escape to other parts of the pile assembly would make operation and maintenance difficult. This is considered tolerable, but if escape of fission products to other parts of the pile is to be avoided, the fuel unit must be encased either by a glazed, non-porous surface or by a non-porous can. The material of the glazed portion, or of the can, must conform with the requirements of items 1, 2, 3, 4, 5, 6, 7, 8.

10. After the pile has been in operation for some time, it becomes inefficient because the fuel has been depleted and neutron-absorbing products have been formed, or the physical properties of the material of the fuel unit may have been so altered by the radiation or fission recoils as to make the fuel unit unfit for further use. The fuel material must then be removed for reprocessing. It should be so constituted that fissionable materials may be efficiently separated and recovered from toxic and radioactive products.

If solid material is chosen, it shall be fabricated into units whose geometric shape is dictated in part by the following considerations;

1. The unit shall be of a shape that can be fabricated.

2. The shape of the unit shall be such as to maximize mechanical strength, minimize thermal gradients, and minimize powdering and chipping.

3. The shape should provide maximum heat transfer area consistent with minimum thermal gradients, reasonable coolant pressure drop and adequate mechanical strength.

4. Units shall be of such size and shape that they may be distributed throughout the moderator and that they may be conveniently and safely inserted and removed from desired locations in the pile.

5. Each unit must contain considerably less than that quantity of fissionable material which can, under any conceivable circumstances, become critical.

6. Units must be of size and shape which are appropriate to the fuel handling and fuel storage equipment of the pile.

B. Fuel Handling

For convenience in discussion, the requirements for fuel handling will be divided into two classes; the first will include a description of the manner in which the fuel must be handled, and the second, requirements which must be met by the fuel handling mechanism. The general manner of fuel handling shall be as follows:

1. The fuel units shall be introduced into the reactor through gas locks suitable for the pressure and atmosphere within the pile.

2. While going through the locks and before insertion in the pile reactor, the fuel units shall be freed of undesirable gases.

3. The openings in the reactor container through which the fuel units are introduced shall be as small as possible to minimize the difficulty of sealing against leaks.

4. The fuel units shall be inserted, maintained within, and removed from the pile in such a manner and on such a schedule as to give maximum uniform fuel utilization and to minimize the rate of change of pile reactivity.

5. The fuel units shall be positively held in position in the reactor during other than loading or unloading times.

6. Fuel units shall at all times be handled in such a manner as to reduce the possibility of mechanical damage to a minimum.

7. The fuel units shall be introduced into the reactor in such a manner as to keep thermal shock to a safe value.

8. The fuel shall be handled in such a manner as to insure that a critical mass of fuel shall not be formed at any time outside of the reactor.

The fuel handling mechanism shall conform with the following:

1. It shall be simple, rugged and reliable. This is particularly true of any parts which are exposed to radiation and heat and which cannot readily be repaired in place or removed for maintenance.

2. Any parts of the mechanism which are subject to wear to a degree sufficient to prevent proper operation should be replaceable without danger to personnel.

3. Provision should be made to prevent or compensate for misalignment of parts of the mechanism relative to each other, or to the reactor, due to temperature variations or other causes, transient or permanent.

4. The mechanism shall be capable of automatic and manual operation according to any desired schedule.

5. It is desirable that operation of the mechanism should not require shutdown of the pile.

6. The mechanism shall occupy minimum volume and offer minimum resistance to coolant flow.

7. The mechanism should be capable of inserting fuel into or removing fuel from any position in any single channel.

8. It should, by itself or with the aid of auxiliary attachments, be capable of readily removing any obstruction in a fuel channel of the reactor.

9. Positive means shall be provided to prevent the insertion of fuel units into control rod channels.

10. The mechanism shall be capable of completing a loading or unloading operation in the shortest time which is consistent with the maximum permissible rate of change of reactivity.

11. If, during a fueling operation, it is necessary to remove and replace fuel units, reflector plugs, orifices, or other such items, provision shall be made for doing this, for storing the items, and for replacing them.

12. It shall be possible to remove depleted fuel units from the reactor, pass them through a gas lock or locks of minimum size in the reactor container wall and into the chemical treatment plant.

C. Moderator

In a power pile which operates with thermal neutrons, a moderator is required to reduce the kinetic energy of the fission neutrons to thermal levels where they can be more readily absorbed by fissionable materials and thereby continue the chain reaction. The material used in a moderator must have the following characteristics:

1. Low atomic weight.

2. Overall absorption cross section for neutrons which is extremely low compared with its scattering cross section.

3. High density, if minimum reactor size is desired.

4. Freedom from impurities to the extent that increase in absorption due to these impurities is as small as possible, consistent with the best manufacturing techniques.

5. Sources of supply adequate to fulfill the quantity requirements of the pile at the time of fabrication.

6. Reasonable cost.

7. Such physical and chemical properties, in addition to those specifically described elsewhere in this section, that units fabricated from the material shall remain chemically, dimensionally, and mechanically stable under the conditions of pressure, temperature, radiation, and coolant flow and in contact with the substances to which it may be exposed.

8. The moderator material shall not undergo phase changes under the conditions of temperature and radiation to which it will be exposed.

9. The moderator material shall not have an appreciable vapor pressure in the range of operating temperatures and pressures.

10. The moderator material shall be capable of being fabricated within the specified tolerances, in the shapes required and with the surface finishes required.

11. Chemical and physical properties of the moderator material shall be conducive to ease of fabrication and of chemical processing, and reprocessing.

12. The heat conductivity of the moderator material shall be sufficiently high for such heat transfer as may be required.

The moderator units shall be fabricated in accordance with the following requirements:

1. The form of the units shall facilitate assembly and also structural stability.

2. The forms shall, when assembled, permit insertion of plugs, fuel rods, control rods, conversion material, instrumentation and other auxiliary equipment.

3. The form of the units should offer maximum heat transfer area to the coolant, and shall be adequate to remove the heat generated at maximum power production of the pile.

4. The units shall have a surface roughness determined by a balance between the following considerations:

    a. Surface finish obtainable in fabrication.

    b. Minimum friction with respect to coolant flow.

    c. Maximum surface for heat transfer and heat radiation.

    d. Minimum friction to moving parts.

5. The technique used in fabrication shall provide optimum crystal orientation as determined by nuclear considerations.

6. Unit dimension changes when the pile is put in operation and

after a specified time of pile operation shall be such that pile operation will not be hindered by mis-alignments, shifting or expansion.

7. The unit shall be so fabricated that the surface presents maximum resistance to erosion, corrosion, chipping, and powdering.

8. The unit shall be of such design as to withstand the strains incident to high temperature and pressures, and sudden changes in these.

9. Fabrication technique shall be such as to result in units of high density.

D. Coolant

A continuous flow of fluid must be supplied to absorb the heat which is generated within the reactor and transfer the heat to an external point where it is utilized. The properties required of the fluid may be divided into two classes; ordinary physical properties, and those required because of the presence of intense radiation. For the first class, the fluid must have the following characteristics:

1. It should be a fluid within the operating limits of temperature and pressure.

2. It must not undergo decomposition at these temperatures and pressures nor can it be corrosive to the materials which contain it. Preferably it should not be toxic.

3. The fluid shall not change in phase while it is within the pile.

4. A high specific heat and a high heat transfer film coefficient are desirable.

5. It is desirable that the fluid have high density and low viscosity in the operating range of temperature and pressure in order to minimize pumping power requirements.

For the second class of properties, the fluid must have the following characteristics:

1. A low neutron absorption cross-section.

2. Its chemical and physical properties must not be altered adversely by high neutron, gamma, alpha or beta ray bombardment.

3. The coolant must not contain enough impurities to act as

appreciable neutron absorbers in the pile. If it acquires such impurities in passing through the pile, the coolant must be of such a nature that the impurities are easily removed at some point in the circulating system.

4. The coolant with good moderating qualities is to be desired.

E. Reflector

A considerable reduction in the cost of constructing and operating a pile can be achieved by the use of a reflecting blanket of moderating material. The effect of such a blanket is to reduce the size of reactor required to produce chain reaction, to reduce the loss of neutrons by escape outward and to produce a more uniform power production distribution throughout the reactor. The reflector may also be used to provide convenient locations for the exposure of conversion material.

The general requirements for the material of which the reflector is to be constructed are the same as those for the moderating material. The section of the reflector which immediately adjoins the moderator should be composed of the same material as the moderator because it is necessary to permit adjustment of the moderator-reflector boundary according to operating needs. Since the reflector will not be subjected to as severe conditions of temperature and radiation as the moderator, economic considerations should play a greater role in the choice of the outer sections of the reflector.

With the exception of changes described in the preceding paragraph, the reflector material and units shall conform to the requirements for moderating materials and units.

B. Pile Control

The purpose of pile control is to reach and to maintain a desired pile power level and to rapidly reduce the pile power level to zero before damage results in case of pile failure or failure of auxiliary equipment. The pile power level is proportional to pile neutron density. It is this neutron density that is directly controlled by the pile control rods. Factors affecting the pile neutron density are:

1. Voluntary changes in neutron density due to desired changes in power level.

2. Small involuntary changes in neutron density due to change in temperature, formation of neutron poisons, reduction of fuel enrichment due to depletion and poison unintentionally introduced.

3. Involuntary changes in neutron density of such magnitude that they require immediate reductions of neutron flux to zero.

The control rods may be divided into two classes according to function: safety and regulating. These functions are as follows; the regulating rods are to perform the control functions described under items 1 and 2 above, and the safety rods functions as described under item 3 above. Within the limits of rate of change of reactivity necessary to perform the assigned function, each rod may be used for either of the functions. A description of the rate of change of reactivity required by the functions of the rods are roughly as follows:

1. For safety rods - fast insertion.

2. For regulating and safety rods - slow insertion and slow removal when used for regulating rods, and fast insertion when used as safety rods.

The total poisoning effect of all the rods performing a given function shall be as follows:

1. The safety rods shall be capable of causing sufficient decrease in neutron density to shut down the pile before undue damage is caused even when the power level is increasing at the maximum probable rate and the maximum conceivable number of control rods fail to operate due to unforeseen circumstances.

2. The regulating rods shall be capable of causing sufficient decrease in neutron density to completely prevent the pile from being reactive when the fuel is undepleted, the temperature is a minimum, poisoning effects are at a minimum and the number of fuel units in the pile is a maximum.

The pile theoretically can be controlled by means of a single large central control rod but several smaller rods symmetrically placed with respect to the center are more practicable and offer great advantages from the safety standpoint. The effect of these rods individually on the reactivity is a function of the material and size of the rods, the size of the hole in the moderator, and the rod position in the pile. The total effect is not equal to the sum of the individual effects because of shadowing effects. For all operating conditions the change in the distortion of the neutron flux should be kept to a minimum. This can be accomplished by locating control rods symmetrically around the pile center and inserting equal amounts of poison with each rod. The physical considerations such as mechanical difficulties favor a small number as does the fact that control rods use space in the moderator that would otherwise be used for fuel. The extra safety factor provided by a larger number of rods together with the distribution of distortion of neutron flux favor a larger number. The number chosen should be a balance between these two opposing factors. The factors in choosing control rod material are:

1. The absorption cross section for thermal neutrons should be high at all temperatures which the pile may reach and without serious variation due to temperature.

2. The physical characteristics must be adequate in the following respects:

    a. The material must withstand temperatures in excess of those which will cause destruction of some other vital part of the pile.

    b. The material must have good mechanical properties, including strength, ease of fabrication and resistance to fatigue and creep under all pile conditions.

    c. It must be chemically stable under all pile conditions.

3. It must withstand neutron bombardment.

4. The nuclear absorption should not produce a material which escapes and is a poison, is corrosive, or reduces the heat transfer.

5. The material must become as little radioactive as possible to facilitate handling and shielding when out of the pile.

6. The material should be such, if possible, that absorption of neutrons produces a useful material rather than useless ones. For example thorium would be a desirable control rod material from this point of view.

The location of control rods should be determined by the following considerations;

1. It should be such as to cause minimum undesired distortion of neutron flux.

2. It should be symmetrical with respect to the pile center.

3. Spacing should be such as to give optimum characteristics with respect to interaction between rods and to leakage between rods.

4. The control rods, operating mechanisms, and other appurtenances shall be accessible for removal and maintenance.

G. Rate of Change of Reactivity

The change in reactivity is a function of the change of the amount and concentration of the fuel, temperature of the pile, poisons in the pile, and position of the control rods in the pile.

While the pile is being brought from zero power level to an operating power level an auxiliary source of neutrons should be introduced. This will permit the oper.tor to measure the neutron flux by means of a counter even before the pile has become reactive. Consequently the control rods can be stopped while the excess reactivity is still very small, following which the pile can be brought up to full power in any desired period.

In addition, the rate of increase of reactivity caused by withdrawing the control rods must be limited. This limit is determined by the ability of the operator or the automatic control devices to detect the neutron flux level and reinsert the control rods before the neutron flux reaches a dangerous value. The rate of increase of reactivity should not be so great as to cause the pile period to be so small that the safety rods can not shut the pile down in the event the operator or automatic control devices fail to operate. Inasmuch as the rate of change of reactivity is a function of the position of the control rods, the maximum allowable outward rates of motion of the control rods shall be calculated for the position of the control rods at which the rate of change is a maximum. Therefore, for all other positions of the control rods the rate of increase of reactivity will be below this maximum value.

In determining the time required for the safety rods to shut the pile down it shall be assumed that they fall with the acceleration of gravity and that only the minimum number of safety rods fall that are necessary to prevent the pile from starting. For example, if there are nine safety rods and six of these are sufficient to prevent the pile from becoming reactive, then it shall be assumed that only six of the safety rods fall.

The regulating rods shall be capable of sufficiently rapid insertion to prevent the power level from rising when the fuel loading mechanism is inserting fuel into the reactor at the maximum rate or when the temperature is decreasing at the maximum rate. The control of the rods shall be adequate to prevent undue power level oscillation under the above conditions.

The following is a list of events which will require automatic shutdown of the pile by the control mechanism.

1. Neutron flux overload
2. Limit on flux buildup rate (pile period)
3. Blower failure - short circuit, bearing failure, breakage of vanes (vibration pick-up detector)
4. Temperature overload
    a. Coolant (helium and steam); inlet to pile, outlet from pile.
    b. Pile hot spots
5. Pressure drop-out and overload limit
    a. Helium coolant
    b. Steam coolant
6. Power Failure
7. Load drop out (sudden)
8. Voltage drop off
9. Hydrogen, - Oxygen, Nitrogen, water content of coolant.
10. Excessive vibration.
11. Failure of vital control component for which automatic transfer to spare unit is not provided.

H. <u>Thermal Insulation:</u>

A layer of thermal insulation external to the reflector but internal to the pile pressure shell shall be provided. The thermal insulation has two purposes:

1. To minimize heat losses

2. To protect the pressure shell from excessive temperatures.

The thermal insulation shall have the following characteristics:

1. It shall have a low heat conductivity coefficient.

2. It shall retain adequate mechanical strength and thermal properties when subjected to radiation at the levels encountered immediately external to the reflector.

3. It shall be resistant to powdering and crumbling under the influence of age, coolant flow, temperature, pressure or changes in temperature or pressure such as may occur in use, if solid.

I. Container and Pile Support

The reactor, reflector, and thermal insulation of the pile should be enclosed in a container. This container must be gas tight and serves as a means for confining fission products and coolant, and for excluding undesirable substances from the pile. It may also serve as mounting base for certain pile auxiliaries and must be equipped with gas tight locks for entrance into the pile. It should withstand required pressures, above or below atmospheric conditions. Means should be provided for removing from the container walls, the heat which is generated by the absorption of radiation, and that which is transmitted through the thermal insulation. The material which is used in fabrication of the container must withstand the temperature, radiation level and corrosive action of materials with which it may be in contact. The container may be required to support the reactor, reflector and thermal insulation or it may not. In either event a structurally adequate support is required, which shall remain adequate to carry its load when exposed to high radiation levels. The support must not interfere with provisions for fuel entrance, fuel handling equipment, coolant entrance and metering, instrumentation and other auxiliary equipment.

J. Shielding

When the pile is in operation, the total radiation level in the vicinity of the outer surface of the active pile is about 1% of that within the pile. This amount of radiation which is found outside the active pile is still many orders of magnitude larger than that which can be tolerated by operating personnel. It is necessary, therefore, to surround the pile with a shield whose function is to reduce the radiation level below the amount which presents a hazard to the operating personnel. The established tolerance level is 0.1 Roentgen per day, usually assumed to be 8 hours.

The radiation which must be absorbed has three important components:

1. Gamma-radiation. This is most efficiently absorbed by material of high atomic weight and high density.

2. Fast neutrons. These are not easily absorbed in any materials and must, therefore, be converted into thermal neutrons which are easily absorbed by many materials. The necessary reduction in energy is accomplished by causing the fast neutrons to pass through moderating material.

3. Thermal neutrons. These come from two main sources (1) from the active pile by leakage through the reflector, thermal insulation and container and (2) from the fast neutrons mentioned in sub-paragraph 2 above which have been reduced to thermal energies. Thermal neutrons may be easily absorbed by relatively thin plates composed in part or entirely of cadmium, boron, or certain other elements.

It is important to note that in most materials gamma-rays are formed when thermal neutrons are absorbed and create an additional radiation problem.

The total shield shall be designed so as to reduce the radiation level outside the shield to less than a specified tolerance limit. Thickness and weight of shield shall be kept to a minimum.

The following considerations will affect the distribution of materials in the shield:

1. Each material has in addition to its primary function of absorbing a given type of radiation some effect in reducing the intensity of other types of radiation.

2. Radiation of one kind may be generated when another kind is absorbed.

3. The requirement of minimum thickness may be fulfilled by shields in which the various materials are distributed homogeneously throughout the entire volume or by a laminar structure in which there may be more than one layer of a given material and the layers may be arranged in any order.

In addition to its primary function of reducing the radiation level with maximum economy of thickness and weight, the shield must conform with the following requirements:

1. The materials for any portion shall be chosen, if possible, to act as efficient absorbers for some component of the radiation.

2. The materials used shall not change in physical properties to a significant extent on continuous exposure to the radiation levels to which they will be exposed.

3. The shield shall completely enclose, except for necessary apertures, all portions of the pile and its associated equipment which would otherwise cause the radiation level in the immediate surroundings to be higher than human tolerance.

4. Apertures in the shield must be provided for introduction of instruments, fuel and auxiliary equipment. These apertures shall be so constructed as not to cause a higher radiation level in the vicinity outside of the aperture than is found outside of the unbroken shield.

5. Cooling shall be provided where necessary to remove the heat generated within the shielding and means must be provided for disposing of any radioactivity generated within the cooling fluid.

6. If gases are generated by any of the shielding materials under exposure to radiation, means shall be provided for venting them and, if radioactive or toxic, for disposing of them.

7. Because a large volume and weight of materials are required for the shield, considerations of economy and supply are important.

K. External Power Generation System and Auxiliaries

A system must be provided for producing useful power from the heat which the coolant absorbs in the pile. Such a system will be composed of ducting or pipe, valves, blowers or pumps, heat exchangers or turbines and appropriate auxiliary equipment and controls. Heat exchangers are required if it appears that the coolant can not be used directly as working fluid in a turbine. In this case means must be provided for converting the heat contained within the secondary fluid of the heat exchanger into electrical energy. These means will consist of ducts, valves, motor, generator and auxiliary and control equipment and since they will conform to standard engineering practice, will not be described in the present specifications. The word "system" will in the following, be used to refer to the equipment between the coolant exit ducts from the pile proper and the secondary fluid exit ducts from the first heat exchanger. The system must provide the following:

1. Means for pumping the coolant at the design pressure and against the design pressure drop at the rate which is required to remove sufficient heat so that the upper temperature limit of any portion of the pile is not exceeded when the pile is being operated at the maximum power level.

2. Every effort must be made to so design and construct the system that its reliability is a maximum.

3. The system must be designed for continuous operation without failure at the existing conditions of temperature, pressure, flow and radiation.

4. Alternate or standby equipment must be provided for all components of the system whose failure would significantly affect the operation of the system or of the pile and it must be possible to connect the alternate equipment in case of failure.

5. Sufficient and completely effective valving should be provided, insofar as possible, to isolate any desired portion or portions of the system and to direct the flow of coolant along alternate flow paths.

6. Automatic and manual safety features must be provided to insure against excessive pressure rise, temperature rise or rise in radiation level.

7. The system should provide for operation at continuously variable power levels from zero to full load without excessive temperature changes within the pile.

8. The pumping power requirements must be reasonable as compared to the final mechanical or electrical output.

9. Provision must be made for charging the pile and circulation system with coolant of specified purity both initially and after the pile has been operated, and appropriate coolant storage facilities must be provided.

10. It shall be possible to remove harmful fluid or solid impurities from the coolant either continuously or intermittently as often as is required.

11. Leakage of any harmful substances into the system must be prevented and means should be provided for the disposal of leakage out of the system so that it does not present a health hazard.

12. Means must be provided for replenishing coolant lost by diffusion or leakage.

13. Means for decontamination of the system or portions of the system which have been contaminated should be provided where possible.

14. Provision should be made for proper coolant flow distribution through the pile so that maximum heat may be extracted with minimum overall pressure drop and within the maximum temperature.

15. Appropriate controls, instruments and recording instruments must be provided.

L. Instrumentation

The successful operation of the power producing system consisting of the pile reactor, coolant system, heat exchanger and associated equipment depends to an unusual degree upon the correct operation of each component because of the closely interacting functions of many of the components. It is therefore necessary to provide instruments for indication of operating temperatures, flows, pressures, neutron densities and radiation levels so that manual or automatic adjustments may be made to hold the operating conditions constant or to regulate these conditions.

Instruments which are used for indication may also be used to obtain records. It is desirable that the primary elements used to operate the indicators should also supply information for use in control circuits in order to minimize space and installation difficulties which will be encountered in some portions of the pile.

The primary elements of all instruments shall be continuously able to perform their functions when exposed to the radiation levels which will be encountered at their respective locations in the system.

Duplicate primary elements should be installed at such points in the pile at which failure of a single element would seriously affect pile operation.

The minimum of instrumentation and the location of elements for instruments is described as follows:

1. Temperature elements shall be located at many points throughout the moderator, reflector, in each fuel channel, in each breeder channel, at the coolant entrance and exit to the pile and at the entrances to and exits of the heat exchanger, at appropriate points in the thermal insulation, pile pressure shield, in the control rods, and at all entrances and exits of cooling fluids.

2. Pressure elements shall be located at points where they are exposed to entrance and exit coolant pressures, within entrance and exit ducts for heat exchangers, within boilers, and in general at several points within any part of the pile which contains fluid, static or flowing.

3. Flow elements shall be located at entrance or exit and possibly at other specified points within all systems which contain flowing fluids.

4. Radiation elements sensitive to neutrons shall be located at various points throughout the reactor to serve as power level indicators. Radiation elements sensitive to total radiation level shall be provided.

various points throughout the reactor to serve as power level indicators. Radiation elements, sensitive to total radiation level, shall be provided at specified points outside of the shielding where radiation hazards to personnel exist.

M. Chemistry

Continuous operation of a power pile requires two types of chemical processing; (1) the purification and recovery of fissionable isotopes from used fuel material and (2) the purification of coolant, if in pile operation the coolant becomes contaminated with impurities which are radioactive or harmful to components of the pile.

The general requirements for the chemical processing of fuel are as follows:

1. The process must be extremely efficient with respect to loss of fissionable material because the material is extremely expensive.

2. For the same reason, hold-up of recoverable fuel must be kept to the lowest possible value above unavoidable hold-up required by "cooling-off" periods.

3. It shall not be possible under any conceivable circumstance or combination of circumstances for a sufficient amount of fissionable material to be collected within a small enough volume to become critical, with or without the presence of moderating material such as may occur in processing chemicals.

4. The process must separate fission products from the unused fissionable material sufficiently completely to enable the recovered fuel to be refabricated into fuel material.

5. Means of disposing of fission products must be provided.

6. The process shall not be hazardous to operating personnel.

During normal operation of the pile, the coolant may be contaminated in the following ways:

1. By gaseous, radioactive fission products

2. By solid radioactive fission products.

3. By powder from materials of which the pile is constructed.

4. By gases which are unavoidably introduced when components of the pile are removed or replaced.

It is desirable to remove radioactive contaminants from the coolant so that the portions of the cooling system outside of the pile may remain accessible for maintenance and replacement. Solid particles and dust should be removed to prevent their interference with blower operation. It is necessary to remove some gases, such as oxygen, nitrogen and water vapor because they attack material within the pressure shell.

The requirements for the coolant purification system are therefore as follows:

1. Means should be provided for continuously removing gaseous fission products from the coolant as soon as possible after the coolant leaves the pile reactor. Provision should be made for safe handling and disposal of the products.

2. Filters or precipitators, which have as high efficiency as is consistent with allowable pressure drop shall be provided to continuously remove solid particles from the coolant stream as soon as possible after the coolant leaves the pile reactor. Provision must be made for handling and disposing of the material which has been removed.

3. Provision shall be made for continuous chemical treatment of the coolant before it enters the pile reactor to remove the gases which react with pile components.

4. Sufficient processing equipment to purify a complete charge of coolant for the pile shall be provided in addition to the continuous processing equipment described above.

IV

DESCRIPTION AND DISCUSSION

OF POWER PILE

DESIGN FACTORS

IV-A PILE PHYSICS CONSIDERATIONS

Work on the Daniels experimental pile started at the Argonne National Laboratory. A considerable number of reports and memoranda dealing with estimates of power pile component sizes and quantities have originated there. These reports set forth methods which have guided the calculations leading to the design presented in this report. The calculations in the Argonne reports and memoranda were not entirely applicable to the Daniels power pile design because:

1. Many of the constants used have since been more accurately determined through continually improved techniques employed in obtaining experimental measurements.

2. Configurations and tentative designs proposed for which comparative figures were required, differed from those of the present design.

The calculations of these reports were considered as illustrative examples of the application of the methods outlined, and the results of the calculations were used as guides to improve the design. The following portion of this report summarizes, revises and extends information presented in the Argonne National Laboratory reports. The reports considered are listed in Appendix I, Page 129 along with the general notes as to their contents.

1. Shape and Size of Reactor

The shape and volume of a power pile are the result of a compromise among many factors, the more important of which are: cost of fuel and other materials, temperature, heat transfer limitations, ease of mechanical construction, space and weight.

a. Shape

The geometrical shape of a power pile should be chosen such that each portion carries as nearly as possible an equal share in the generation and removal of power. A spherical construction for a pile offers the greatest equality of power distribution and economy of materials for obtaining heat energy from nuclear power. However, the necessity for control features, fuel renewal and heat extraction destroy the symmetry and reduce the theoretical advantages of a spherical pile. When construction difficulties and the cooling problem are also considered, the theoretical advantages are outweighed by practical considerations.*

From the viewpoint of mechanical construction, symmetry relationships, anc coolant problems, a rectangular geometry such as a cube would be desirable. But in this construction, the corners, eight in number, are uneconomical and inefficient in their use of material, particularly the uranium fuel. These corners are so far from the center of the reactor that the neutron density is small and hence the power generation is small in these corners as compared to the center of the reactor.

* Physics considerations of the spherical geometry are found in reports MUC-WC-MLG-7 and MUC-WHZ-318.

A compromise between the economy of materials and ease of construction results in the selection of a right cylinder for the shape of this pile. In this way the corners of the cube are elimimated and each portion of the reactor is more efficiently utilized for power production. The base of the right cylinder affords good mechanical support for the pile structure. The pressure shell can also be made in cylindrical form, and for the same thickness of material will be much stronger than for the rectangular shape. Furthermore, the cooling ducts are straight, and throttling requirements for the distribution of cooling can be simple. The construction of the pile from elementary blocks such as hollow hexagonal prisms is more readily accomplished than when a sphere is used.

An additional consideration of the shape which provides economy of materials is the ratio of the height to the radius of the right cylinder. For a bare cylindrical pile having a fixed ratio of fuel weight to moderator weight the minimum volume of material required is reached when the height is 1.85 times the radius. Thus economy in cost and weight of materials is obtained from shape considerations.

b. Reactor Size

The size of the reactor is determined by a compromise between amount of fuel and heat transfer considerations. The proportion of fuel to moderator by weight, and the temperature of the mixture determine the multiplying factor of the chain reaction. The size of the reactor influences the leakage of neutrons from the pile. The balance between the leakage and the excess production of neutrons by the chain reaction determines whether the system can maintain itself. Thus, for each fuel concentration and temperature, a critical volume or critical radius of the reactor is determined. For a given temperature, the variation of critical radius, weight of fuel, and weight of moderator with fuel concentration is shown on Figures 1, 2 and 3 for a bare reactor. It will be noted that the weight of fuel required passes through a minimum at a given concentration. If economy in the amount of the fuel is of primary importance, the size of the pile, and weight of fuel and moderator are thus determined. Figures 1 and 2 compare two moderators each having 20% voids, one of these is beryllium oxide of density 2.9 and the other is graphite with a density of 1.64. Figures 1 and 3 compare a beryllium oxide moderated pile operating at two temperatures. It can be seen that the higher temperature operation requires a larger pile, and more fuel and moderator.

It is thus seen that final determination of pile size is a compromise between thermodynamic efficiency, which requires a high operating temperature, and economy in the amount of initial fuel, which requires a low operating temperature.

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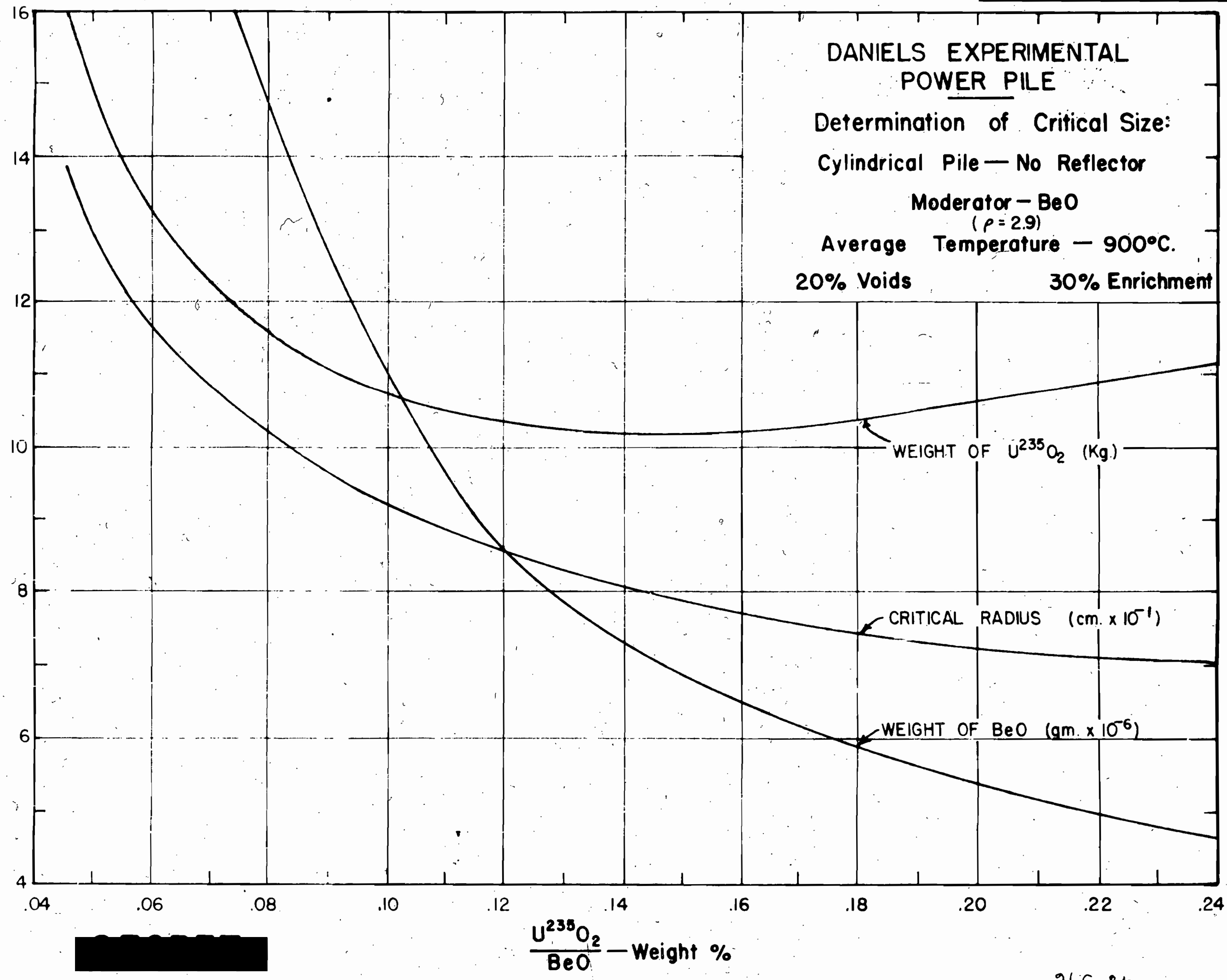

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Figure 1

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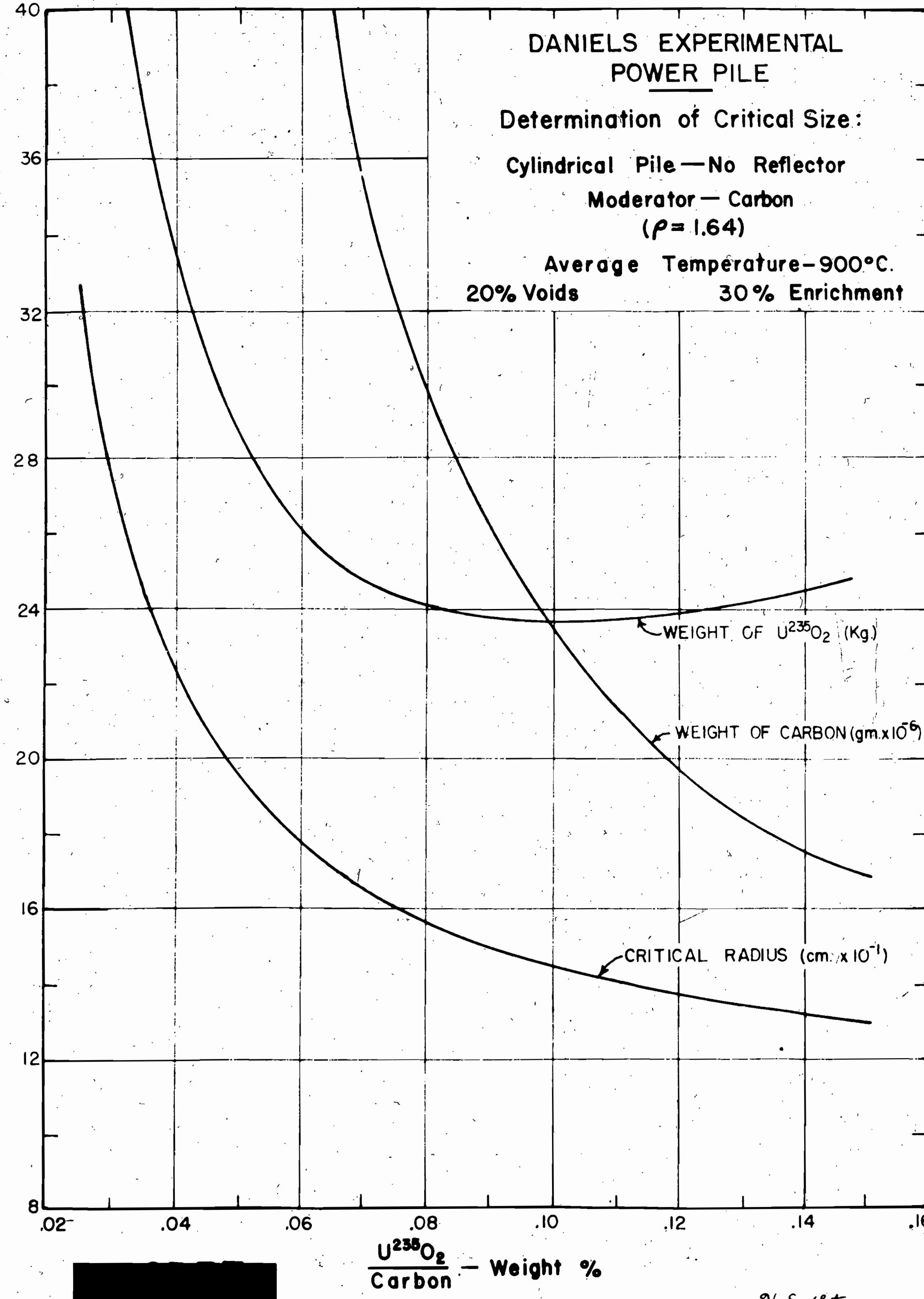

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Figure 2

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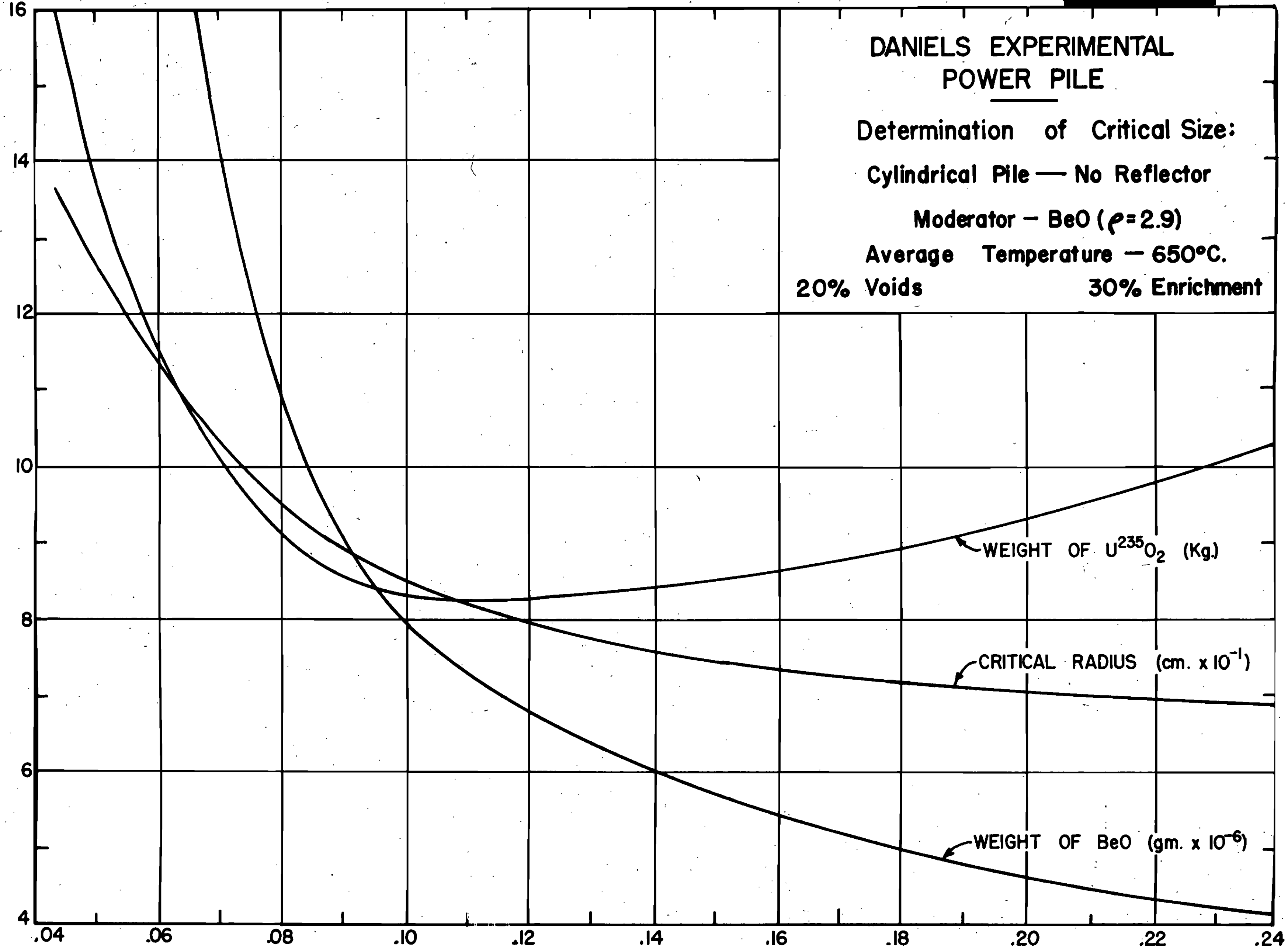

$\frac{U^{235}O_2}{BeO}$ — Weight %

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Figure 3

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A lesser factor affecting reactor size and fuel quantity is the presence of voids. These are necessary as passages for the coolant, and thus cannot be made too small, or excessive drops will occur and the pumping power for the coolant is increased. The presence of voids, however, decreases the effective density of the moderator and increases the size of the pile. The critical radius of the pile is inversely proportional to the density; the critical volume is inversely proportional to the cube of the density; and the critical weight of fuel and moderator inversely proportional to the square of the density. The presence of twenty percent void volume in the reactor increases the weight of fuel required by about forty percent. Therefore, the size of the voids is a compromise between the amount of fuel and large coolant pumping power requirements of high power outputs.

Further physics calculations on the critical size of the BeO pile may be found in other reports. *

2. Reflector Considerations

The reflector serves two useful purposes. First, it saves on fuel and moderator and second, it produces more uniform power production throughout the reactor.

The saving in fuel and moderator is obtained from the reduction in the critical size of the reactor. The reflector must be made of a moderating material, though not necessarily the same material as that in the reactor. The absence of fuel in the reflector makes possible a minimum of cooling since the material is not exposed to the heat of fission. Thus, most of the cooling holes may be filled and voids are almost eliminated from the radial reflector. However, voids must be maintained in the top and bottom reflectors to permit the flow of the coolant to and from the reactor. With these conditions imposed, the choice of material and thickness of the reflector is a compromise between the cost of the material and the volume of the reflector as compared to the savings effected in the cost and size of the reactor.

Figure 4 shows the effect of the reflector thickness on the weight of fuel and the total weight of moderating material required with a BeO moderator and reflector having 20% voids throughout. These curves are plotted against the radius of the reactor so that the optimum volume of the pile may be determined. For increasing thickness of reflector the size of the reactor becomes smaller, and a saving of fuel results, but the overall size of the pile and the total weight of moderator increase. A point is finally reached where the saving in cost of the fuel is no greater than the additional cost of the reflector. This is the optimum design on a cost basis. The excessive volume of the pile which might result may dictate use of a smaller reflector with a larger quantity of fuel.

Considerable improvement in savings of fuel and overall volume may be obtained by eliminating the voids in the reflector. Figure 5

* MUC-KW-58, MUC-KW-60, MUC-KW-61, MUC-RGS-AVM-5, ANL-RGS-2, and ANL-RGS-3.

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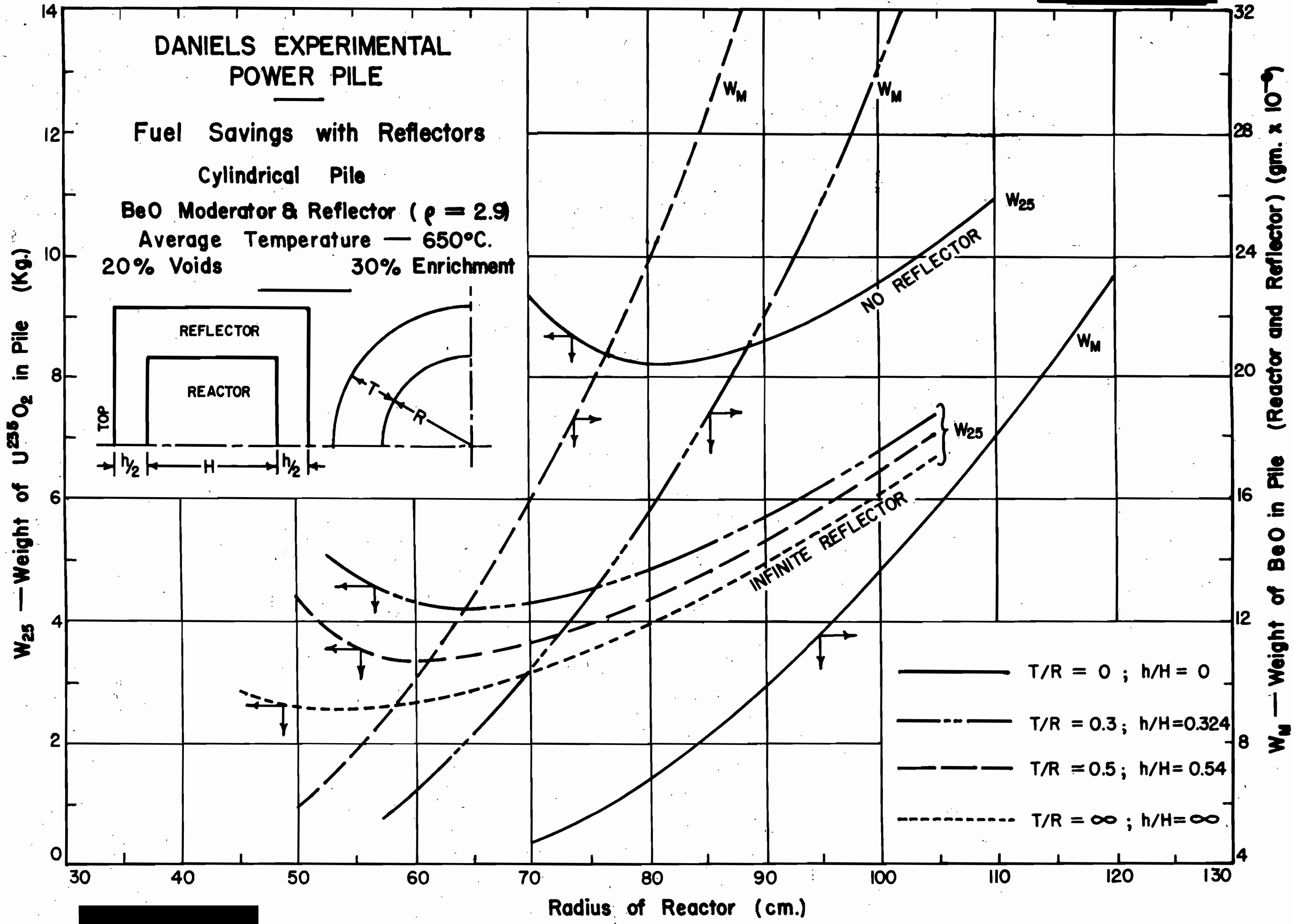

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Figure 4

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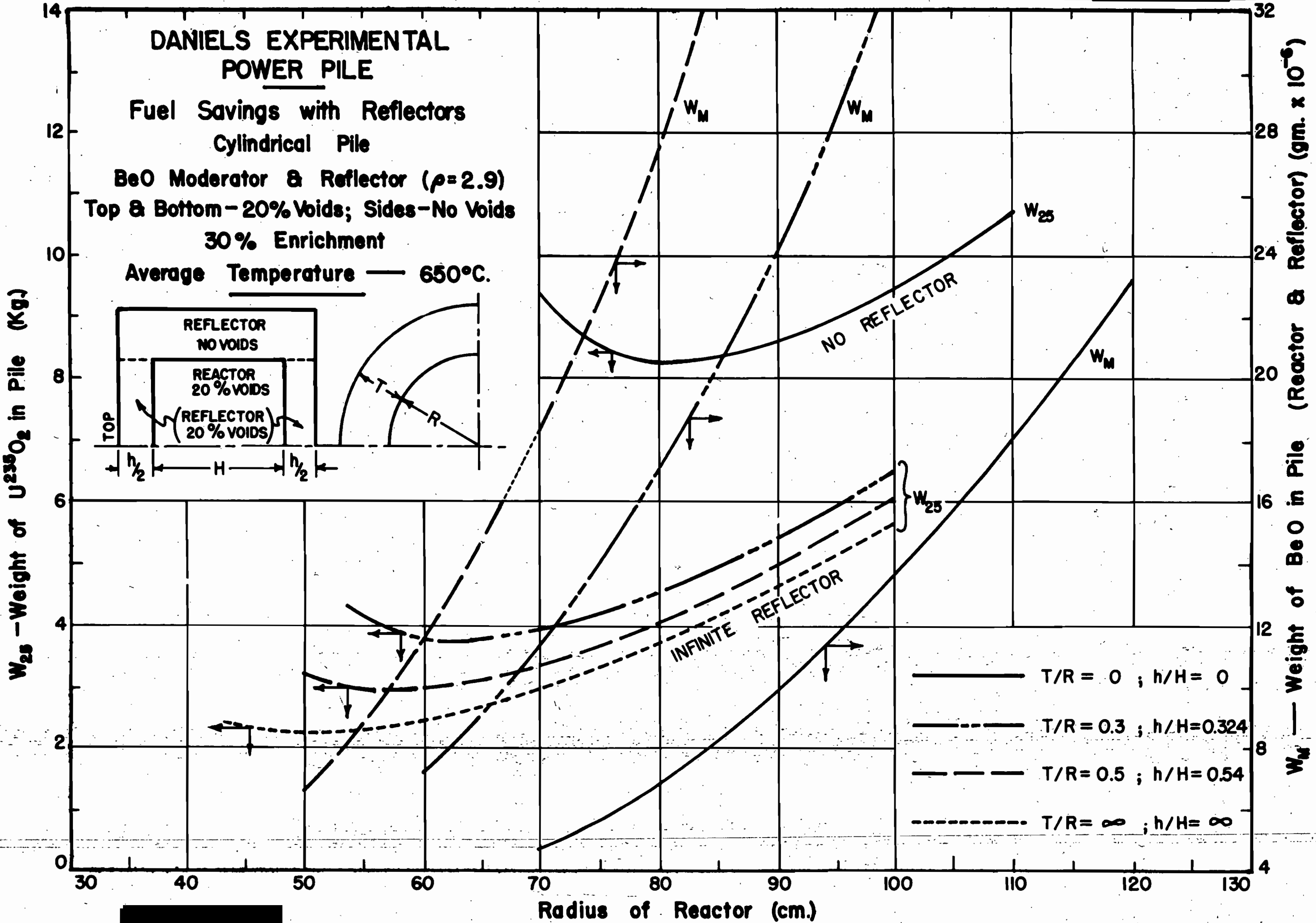

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Figure 5

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shows a family of curves for a BeO moderator with 20% voids but with a BeO reflector having no voids. The same trend in fuel and size is here also apparent; for clarity this is plotted on Figure 6 for the optimum design, that, is for the minimum fuel investment.

Because of its lesser cost a graphite reflector, though larger in volume, may produce an overall reduction in the cost of materials. Figure 7 represents a similar family of reflector thickness curves for a BeO moderator of 20% voids, but with a graphite reflector having no voids. It should be noted that a considerable increase in thickness of the graphite over the BeO reflector is necessary to obtain the same fuel saving. Because of this, the volume of the overall pile is greater. However, after a certain value of the fuel saving is reached the total cost of the graphite reflector, being many times thicker, may exceed the cost of the much smaller BeO reflector.

In connection with the BeO reflector design, it may not always be advantageous to utilize the optimum design for the reactor because the resulting smaller volume increases the problem of heat transfer. The temperature gradients may become so great as to cause portions of the pile to reach excessive temperatures. Thus, a compromise between optimum theoretical considerations and practical pile conditions may be necessary. The reflector also causes a more uniform power production throughout the reactor by flattening the neutron density distribution.

From a consideration of the above, a suitable design is a BeO moderated reactor having a diameter of 6 feet, a reflector of 18 inch thickness, and an average pile temperature of 650°C.

The factors discussed above plus many other factors must be taken into consideration in making a final decision as to the exact size and composition of the pile and reflector. Further study is required on this point. It has been tentatively decided that the BeO moderated reactor will have a diameter of 6 feet. A reflector will be provided 18 inches thick. For economy of BeO it is planned that the 6 inches of reflector nearest the reactor will be made of BeO and the outer 12 inches of graphite.

3. Conversion

Many of the neutrons which enter the reflector from the reactor never return. The net neutrons lost are called leakage and may be either absorbed by the reflector or pass through the reflector into the shield. An efficient use of the leakage neutrons is to produce more fuel. This may be accomplished by inserting thorium rods in the reflector so that the leakage causes capture and converts thorium to uranium 233 which is a fissionable fuel.

For the pile previously considered, the conversion ratio is .8* which means that for every ten neutrons absorbed by the fuel U^{235} eight neutrons leak from the reactor. If the thorium were placed as as a cylindrical sheet surrounding the entire reflector, all neutrons

* See Reports MUC-RGS-AVM-5, MUC-KW-58.

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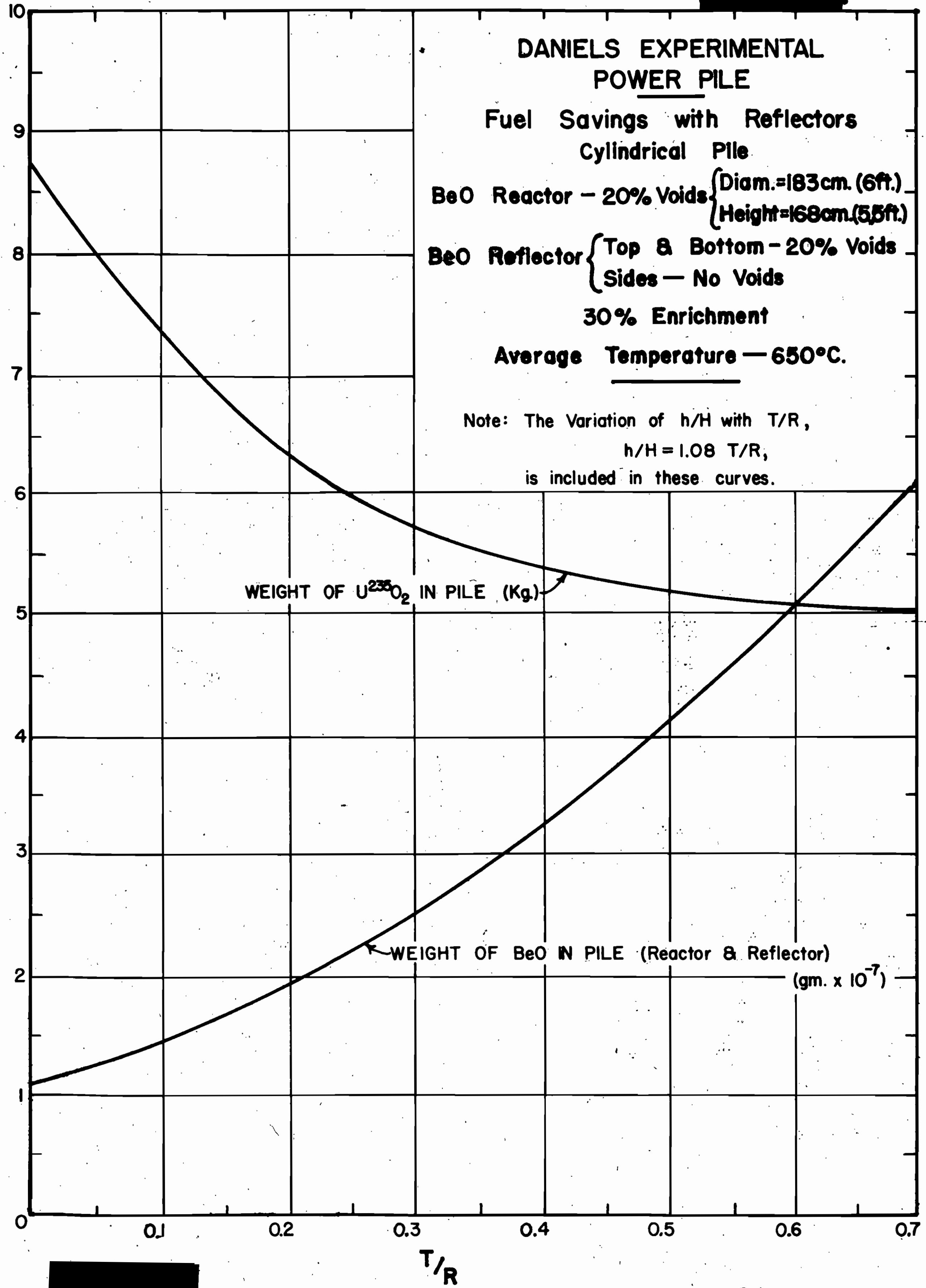

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Figure 6

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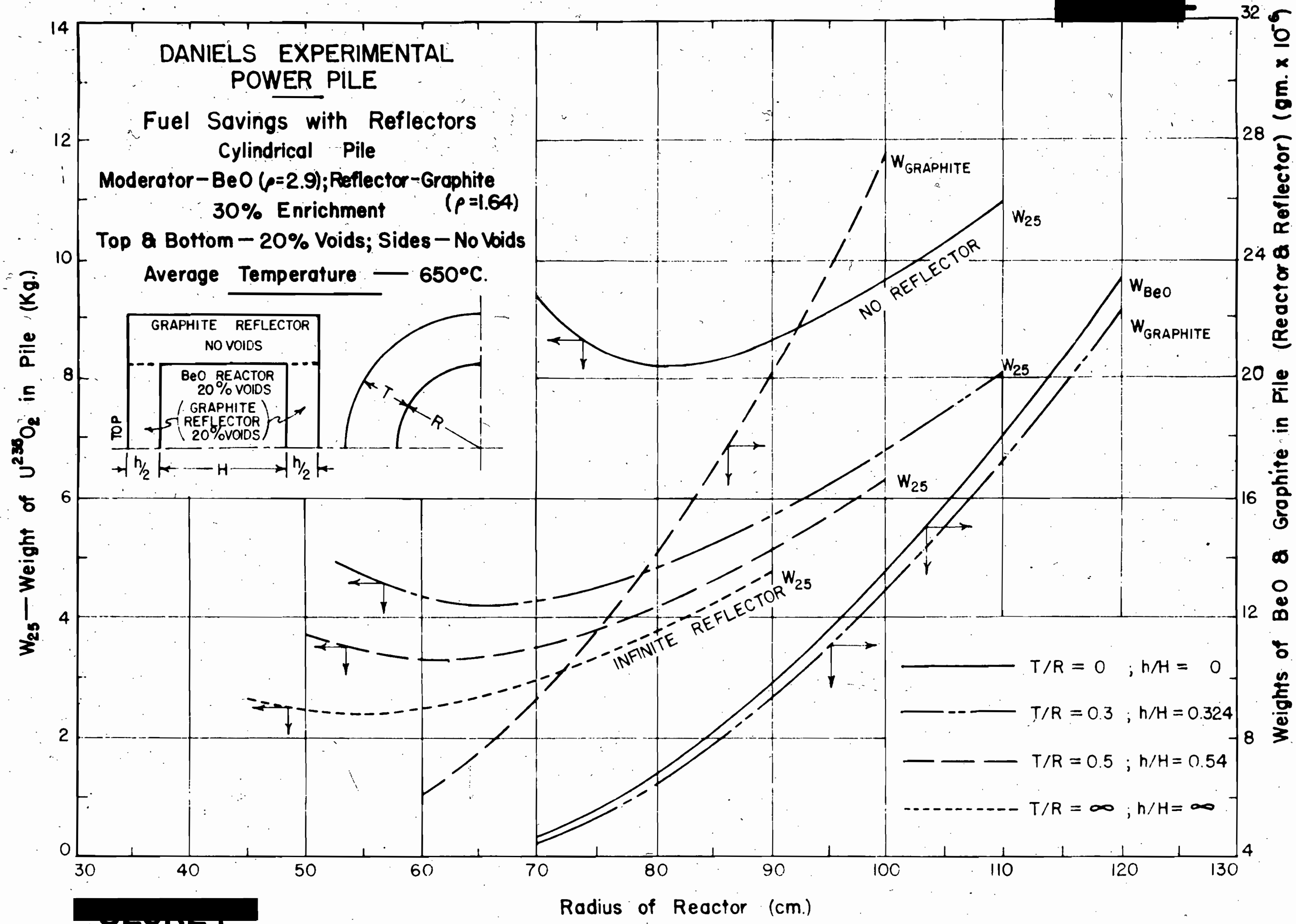

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Figure 7

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which leak from the reflector would pass through the thorium. This would be a very poor design because a large portion of neutrons leaking from the reactor would have been absorbed by the reflector and would not be available for conversion of the thorium. Furthermore, the thorium sheet would have such a large diameter that thickness sufficient to stop the larger portion of the neutrons would require a considerable volume of a very valuable element.

There are two advantages in placing the thorium within the body of the reflector. First, the diameter of the thorium sheet would be smaller. Second, the thickness of the sheet would be less for the same number of neutrons absorbed as in the external case. The reason for this difference is that the reflector on the outside of the thorium reflects a portion of the neutrons leaking through the thorium back into the thorium. Both considerations reduce the required volume of this valuable conversion material.

A sacrifice is made in moving the thorium closer to the reactor because the outer portion of the reflector is partially shielded from the reactor. This decreases the effect of the reflector upon the saving of fuel in the pile, as mentioned in previous sections. Thus a compromise between the conversion, volume of thorium, and increase in fuel must be made. No theoretical calculations relative to this point have yet been made but are planned.

4. Fuel Quantity

The total weight of fuel in the pile is well in excess of the critical amount of 5.2 kilograms, (See figure 5) required for a 6 ft. diameter, 5.5 ft. high BeO moderated pile, surrounded by an 18 inch reflector with no voids, and operating at an average temperature of 650°C. Two factors must be considered in determining the amount of this excess, namely, (1) Allowance for depletion and (2) Compensation for poisoning.

As power is taken from the pile, the fuel is consumed, reducing the quantity of fuel remaining in the unit. Sufficient fuel must initially be present in the pile to permit this depletion during operation, without allowing the amount of fissionable element to fall below the minimum required to support the chain reaction. The extent of this depletion allowance depends upon the refueling interval employed and the average level of power operation. A typical value is 1.5 kg. for 40,000 kw for 30 days, as shown in the table of Section V-A, Part 1, Page 89 .

The poisoning of the pile results from the fission products, which absorb neutrons without producing a commensurate amount of energy. These products are of two types, stable and radioactive. The stable "poison" products accumulate throughout the life of the pile and theoretically necessitate a constant though gradual increase in the quantity of U^{235}, in the pile as its age increases. Initially, this is a minor factor, but its importance grows with the use of the pile. The unstable poisons, on the other hand, reach equilibrium in a matter of a few hours; the equilibrium is attained when their rate of decay plus the rate of destruction by neutron absorption equals the rate of formation as fission products. The major unstable poison is Xenon of mass 135 occuring in the decay chain from Iodine (I^{135} is formed in about 5.8% of the fissions, and decays with a half-life of 6 hours). The resulting concentration of Xe^{135} with its extremely large cross section necessitates the addition of about 0.5 kg. of U^{235} in order to offset the poisoning effect. This amount of material has been adjusted to take care of stable poison as well.

The figure of 5.2 kg. of fuel is based upon BeO containing 1/2 part per million of boron and negligible amounts of other neutron absorbing materials. Although BeO of this purity has been produced, difficulty may be experienced in obtaining the large quantities of BeO required with this purity. It is considered wise, therefore, to tentatively allow an additional 0.8 kg. of U^{235} for impurities in BeO equivalent to two parts per million of boron.

Study of the reduction in effectiveness of the reflector by locating thorium in it has not yet been completed. It is estimated approximately that an additional 0.5 kg. of U^{235} should be allowed for this effect.

Further design study may also show the desirability of deliberately adding neutron absorbers in the pile for leveling power production and adding additional thorium for increasing conversion, both increasing the amount of depletion. An additional amount of fuel of 6.5 kg. of U^{235} should be allowed for this.

Summarizing the amount of U^{235} to be allowed for the initial pile charge:

Min. Hot Critical	5.2 kg.
Min. Depletion Allowance	1.5 kg.
Fission Product Poisons	0.5 kg.
Moderator Impurities	0.8 kg.
Conversion in Reflector	0.5 kg.
Allowance for design changes	6.5 kg.
Total	15.0 kg.

5. Power Generation Distribution

Power generation in the pile requires the presence of fissionable material in a region of neutron flux density. Thus the first requirement is to establish the flux density distribution. Figure 8 a compares the flux density distribution along the diameter of the pile for a 6 ft. diameter BeO reactor with and without an 18 inch BeO reflector having no voids. The ratio of peak to average value of the bare reactors is 2.31 while the ratio of peak to average of the reflector covered reactor is 1.59. Thus the addition of the reflector flattens considerably the distribution of flux across the diameter of the pile. Neglecting the effect of temperature variation the flux density along the axis of the pile is shown on Figure 8b. The ratio of peak to average flux density of the bare reactor is 2.16 while the ratio of peak to average of the reactor with the 18 inch BeO reflector of 20% voids at top and bottom of pile is 1.62. The improvement provided by the reflector is apparent.

Power production from nuclear fission is proportional to the product of the neutron density and the concentration of the fuel. In the reflector, where there is no fuel, no power is produced by fission unless breeding is considered. (See Section VI.) In the reactor the fuel concentration is uniform so the power distribution in the pile is proportional to the flux density in the reactor. This is shown on Figures 8a and 8b.

A small amount of heating is produced in the reflector from high radiation of gamma rays produced in the reactor causing (γ, n) reactions and from the absorption of some of the reactor neutrons by the reflector. Insufficient information prevents a direct calculation of these quantities at present.

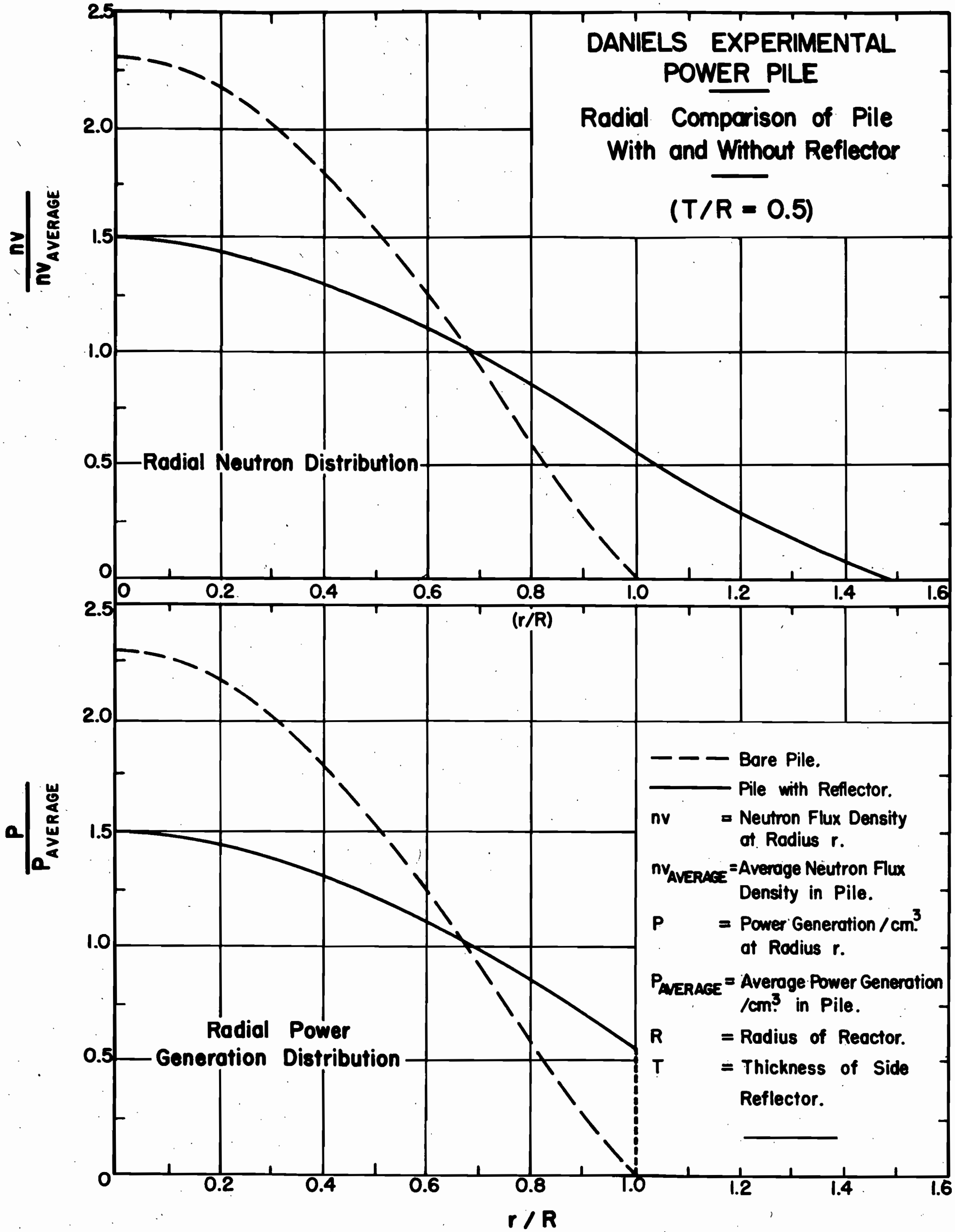
6. <u>Control Rod Considerations.</u>

A pile is in an equilibrium state of power generation when production of neutrons equalsthe absorption and the leakage of neutrons. The purpose of the control rods is to equalize the production and the losses.

The loss of neutrons can be increased by introducing "poison" (neutron absorbing materials) into any region of the pile in which neutrons exist. The absorption will be proportional to the neutron density and surface area of the control rod if the thickness of the rod is great enough to stop all neutrons. The thickness depends upon the density and absorption characteristics of the material. The absorption of a given construction of control rod is greatest if placed in a region of high flux denisty. From Figure 8a the center of the pile is the most effective position for a control rod. However, the poison reduces the flux density in the neighboring vicinity and the absorption is not as great as might be expected. Thus if a pile were to be controlled entirely by absorption of the neutrons, the poison should be distributed over a major portion of the reactor. A multitude of small control rods would require a cumbersome control mechanism which is a distinct disadvantage.

Fortunately, the disturbance of the flux density by a central control rod causes an increased leakage of the neutrons into the reflector. This increased leakage may be made many times greater, than the absorption. A design based thereon has the increased simplicity of lesser numbers of control rods and of increased conversion. Again the most effective position of the control rods exists toward the center of the reactor for the flux density is

[redacted]



[redacted]

Figure 8a

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[redacted]

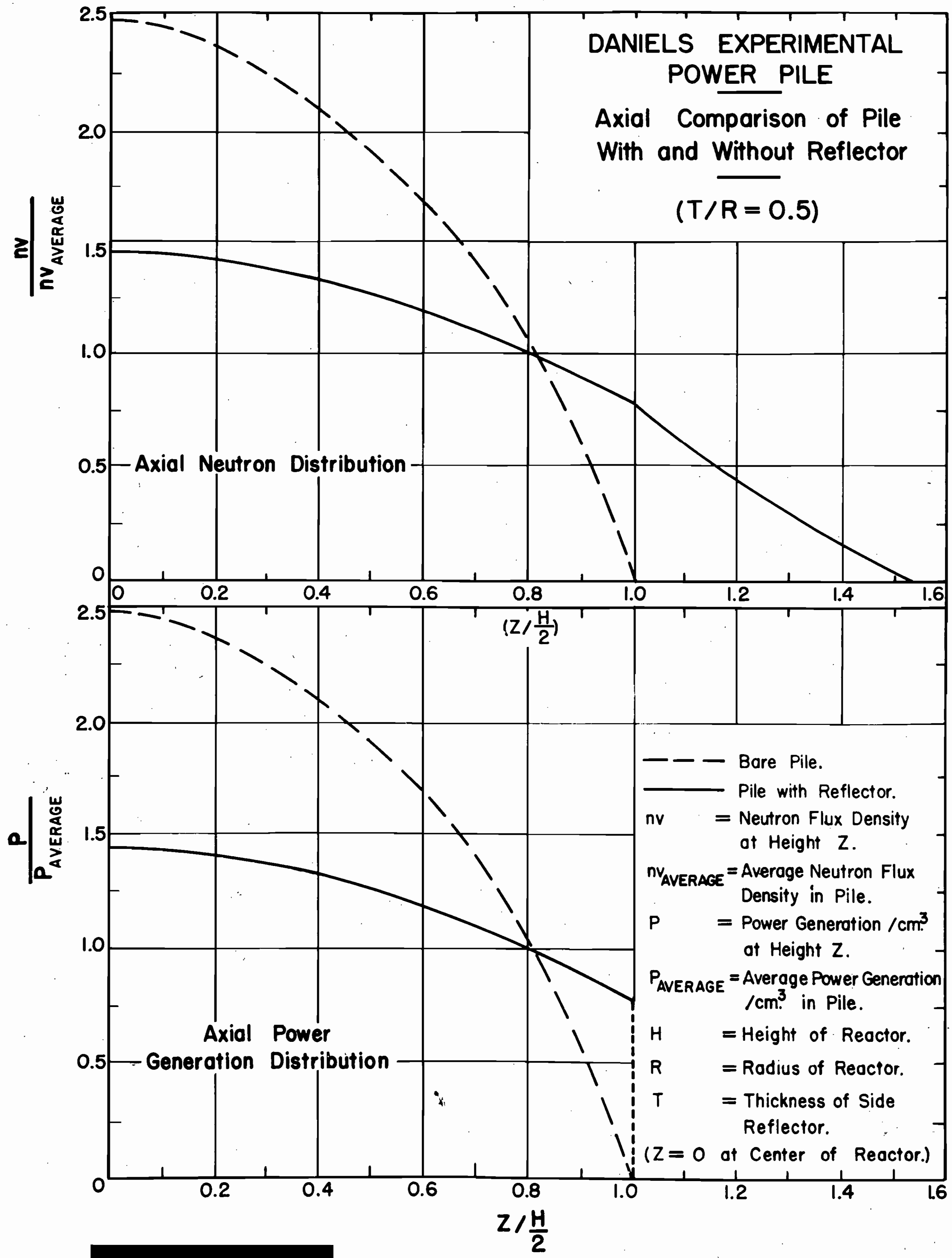

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Figure 8b

H.E. Stevens
10-29-46

greatest there and any distortion has a greater effect. The effectiveness of the control rod is dependent upon its surface; ie. the larger the radius, the greater the circumference, and the greater the control. Since a large control rod would rob the entire center of the reactor of fuel channels and hence increase the size of the pile, an array of small rods arranged in a ring about the center of the reactor may be substituted which will provide approximately the same circumferential area and the same control as a single large rod. The advantage obtained is that the central region inside the ring may be filled with fuel and a small pile size maintained. The control rods forming the ring need not be tangent but may be separated a distance many rod diameters apart. This will help isolate the rods from each other, minimizing the interaction of one rod upon another. However, with this spacing, the diameter of the rods influence their control upon the power.

The range of control is determined by the leakage of neutrons that will bring the pile below the critical multiplication of neutrons at the ambient temperature of the pile environment (room temperature). The required leakage at room temperature may be calculated from the size of the pile and the ratio of fuel to moderator by weight. The control rod array must distort the neutron flux in such a degree as to exceed this leakage if the pile reaction is to be stopped. These calculations have been made.* A seven control rod array, six rods in a 15 inch radius ring and one rod at the center of the ring, made up of $2\frac{1}{2}$ inch diameter rods of high absorption material provides sufficient loss of neutrons to bring the pile below critical at a temperature of 20°C. Further control rod calculations are necessary.

* See MUC-RGS-AVM-5

IV- B. PILE DESIGN

The production of useful power from a chain reacting pile is contingent upon successful operation of the pile at a sufficiently high temperature to provide efficient operation of one of the common forms of heat engine. A gas temperature of 1400°F. is high enough to make possible the production of steam suitable for a turbine. Operation at a gas temperature, from the pile, of 1400°F. will require the use of pile materials with suitable high temperature properties, and a high temperature heat transfer medium capable of withstanding exposure to radiation.

Availability of fissionable materials and the desire to employ a practical minimum quantity of fuel decree that the "fuel" for the pile should be uranium enriched in the U^{235} isotope to a concentration well above that in natural uranium. What chemical form the uranium must take, however, hinges upon its stability at high temperatures, and resistance to attack by the heat transfer medium selected. Metallic uranium is potentially usable as a fuel, but the accumulation of fission products during operation would lead to physical deterioration. Of the various compounds possible, only the dioxide and carbide are stable and non-volatile under these conditions, and of these the dioxide is more readily prepared and processed. Hence, the fuel used in this pile will be uranium dioxide, containing approximately 50% of the U^{235} isotope.

The weight of uranium used in the pile is such a small percentage of the reactor weight (approximately 0.3%) that in order to remove the heat generated it must be dispersed over considerable volume. For ease in handling this finely dispersed uranium, it must be mixed with a matrix material which should have moderating properties. The matrix material must provide a high thermal conductivity in order to conduct to the surface the heat generated throughout the mixture. The surface must be large enough to assure ample heat transfer. Accordingly the fuel is mixed with BeO and formed into hollow cylindrical tubes in short lengths This configuration permits charging and discharging of the fuel while leaving the bulk of the pile untouched. The concentration of the fuel in a relatively small portion of the moderator reduces to a minimum the mass of material that must be reprocessed when separating the uranium from the fission products.

The moderator, which reduces neutron energies to thermal levels for more ready absorption in the U^{235}, must combine low atomic weight, low neutron absorption and reasonably high density with stability under intense radiation and high temperatures. These requirements are met, at least in part, by graphite and beryllium oxide, and while the former is by far the cheaper of the two (about $.25 per pound for graphite, as against $3.50 to $4.00 per pound for beryllium oxide) the latter actually results in a lower expenditure for a pile, since the quantity of uranium-235 is reduced from about 15 kg with graphite to about 8.5 kg with beryllium oxide. Further, beryllium oxide is inert to almost all coolants (except steam at high temperature) whereas graphite can be used only with inert or reducing coolants.

The beryllium oxide is fabricated into hollow hexagonal bricks, which are assembled into a roughly cylindrical unit 6 feet in diameter and $5\frac{1}{2}$ feet high. The bricks are stacked end on end, thus providing a series of vertical channels into which the fuel tubes are inserted with space provided for coolant passage between the tubes and bricks.

The choice of helium as the coolant was based upon its stability under irradiation, its low neutron absorption, chemical inertness and high heat conductivity. Although the initial cost is high in comparison with nitrogen and carbon dioxide, which could also be used, its low molecular weight produces a saving in pumping costs that, in part at least, offsets this disadvantage. Economy of pumping power at 40,000 KW heat output dictates the use of a pressurized system. Accordingly the system is operated at 10 atmospheres pressure, thus reducing heat exchanger dimensions as well as pumping power. The discussion of factors influencing this decision is fully set forth in section IV-C page 62 entitled "Coolant and Coolant System."

The effect of pile size on the quantity of U^{235} required is discussed under the heading of "Pile Physics Considerations" page 32. It is fortunate that in the neighborhood of the minimum amount of U^{235} the quantity is not sensitive to changes in pile size, and that this minimum range occurs near the size at which the gas flow problem assumes reasonable proportions. Thus, the selection of 504 channels permits a reasonable pressure drop through the pile without increasing significantly, above the absolute minimum, the quantity of U^{235} required.

Surrounding the reactor will be a reflecting blanket of moderator bricks. Its chief function is to conserve neutrons by returning to the pile most of those neutrons that would otherwise be lost. It also provides a location for the thorium oxide used for converting to U^{233}, one of the desired functions of the pile. While beryllium oxide bricks must be used for the inner portion of the reflector to permit adjustment of the outer dimensions of the active portion found necessary in operation, the outer portion may be safely and economically assembled with graphite bricks.

With operation at pressures of 10 atmospheres an enclosing shell of steel must be used. In order to avoid the cost and uncertainities involved in employing high temperature alloys, thermal insulation must be provided between the reacting pile and the pressure shell. Sufficient insulation is provided to maintain a maximum temperature of the shell in the neighborhood of 500°F.

During operation of the pile, radiation at the surface of the shell is intense. To permit operation, shielding must be employed which will absorb this radiation consisting of fast and thermal neutrons and gamma rays. In view of the fact that the effectiveness is largely a matter of mass, the entire pile must be surrounded in a thick layer of absorbing material.

1. Fuel

Although the subject of fuel is discussed in detail in section V of this report, a brief review of the subject is appropriate at this point. The actual fuel of the chain reacting pile must be one of the fissionable elements at the heavy end of the atomic table. Of those elements known to fission with release of large amounts of energy (U^{233}, $U^{235}m$, Pu^{239}) only U^{235} is today available in sufficient quantity.

The amount of fissionable element actually used is so small that it is mixed with a moderating type of material to obtain sufficient dispersion for removal of heat. Since the fuel is intermixed with the matrix, heat is generated throughout the unit, thus imposing the requirements of (a) ability to conduct the heat from the central portion of the fuel rod to the outside and (b) ability to transfer the heat to the helium. The temperature gradient necessary for item (a) introduces thermal stress in the unit which must not cause fracture and failure. Item (b) imposes the requirement of a large surface-to-volume ratio.

Thus, the material selected must combine a high thermal conductivity with high tensile strength at operating temperatures in the region of 1700°F. The problem of obtaining these qualities is of such magnitude that it has been made the subject of an intensive investigation which is reported in section V-A-1, Page 79.

2. Moderator

The low atomic weight material which must be used for moderators may be elements or compounds, provided that in the compound form the density of nuclei is not adversely affected. When the requirements of low neutron absorption and high density are condidered, the field is narrowed to such possibilities as graphite, beryllium and its oxide, light and heavy water, fluorcarbons and hydrocarbons. However, of these potential moderators, all but the first three are subject to vaporization or decomposition at the operating temperatures encountered, and are therefore unsuitable.

Of the remaining three, pure beryllium metal has an appreciable vapor pressure at these operating temperatures. In addition, the refining process for obtaining the pure element raises the cost to several times the cost of an equivalent weight of beryllium oxide. Thus, the choice is probably narrowed at this time to but two materials for a moderator, namely, graphite and beryllium oxide.

The decision to use BeO for the moderating material was based largely on the fact that the amount of fissionable element required for a critical pile with this material is approximately half of that required when using graphite as a moderator. With suitable reflectors containing thoria rods, the critical quantity of U^{235} for a BeO pile is of the order of 8 or 9 kilograms whereas for a graphite-moderated pile this rises to around 15 kilograms. With BeO powder costing four dollars ($4.00) a pound and fabrication by the hot press firing method costing approximately $10.00 a pound, the cost of the BeO moderator will approximate $500,000. Even neglecting the cost of a graphite moderator, the saving due to reduced quantity of U^{235} will more than offset the investment in BeO. Beyond the monetary value of the uranium thus saved, there is the abstract value of the uranium thus freed for other experimental work in the broad pile development program.

It must not be inferred from the above that this is the only factor supporting this decision, nor, on the other hand that graphite is unsuitable for use in a high temperature pile. Indeed, from the standpoint of availability, graphite is highly desirable. It is more readily available than BeO and with a comparable purity. There exists a broad background of manufacturing experience, * and its machinability and fabricating characteristics surpass those of BeO. In the region of intense radiation existing in the reacting portion of the pile, however, the graphite is subject to physical deterioration due to the impact of fast neutrons on the carbon nuclei removing atoms from the crystal lattice structure. While this effect is of minor importance at the outer regions of the reactor and in the reflector, it is of such magnitude at the center that the use of a graphite moderator in a pile designed for permanent installation of the moderator needs further investigation and research, to study the effect of high temperature in counteracting these effects.

BeO, on the other hand, is outstanding in its resistance to neutron bombardment. Exposure of samples in the Hanford piles at radiation levels equal to those encountered in this pile at 4000 KW produced no significant change in dimensions over a period of 63 days. (Exposure tests of 120 days duration had been completed at the time of writing this report, but final measurements had not yet been taken). The modulus of elasticity was affected to a minor extent, dropping about 1% during the 63 days. Crushing strength showed no significant change. Thermal conductivity was the most seriously affected, suffering a 33% reduction in the course of 63 days exposure. This effect is, however, of no serious consequence, since the heat generation in the moderator is a negligible quantity.

It is interesting to note at this point that while BeO is a refractory material it has a thermal conductivity comparable with that of cast iron. In contrast, common refractory materials have conductivities of the order of 1/30 of that of BeO.

Fabrication of required forms from BeO can be accomplished in two different ways. The method favored to date has been that known as "hot-pressing", and consists of applying several tons per square inch pressure on the powdered BeO while constrained in a graphite die, at the same time heating the die electrically to a temperature of about 1900°C. The resulting product has a density ranging between 2.8 and 2.9 g/cm^3 or approximately 95% of the theoretical density of 3.02. Parts fabricated by this method have a high degree of uniformity, but the

* It is appropriate to point out that there is a considerable experience in the fabrication of BeO refractories, though familiarity with this fact has been, until recently, more or less restricted to certain phases of the chemical industry.

fabrication cost is high, being in the neighborhood of $10 per pound. Such a cost is inherent in the process since it requires 2 or 3 hours for heating to sintering temperature and cooling to the point where the brick may be removed. Breakage of dies contributes to the expense. Only one company (the Norton Abrasive Co.,) is equipped to produce parts by this method, and even at the full capacity of their present equipment, the time required for fabrication of the moderator units for the pile is one of the major items in the scheduling, being in the neighborhood of two years if all the reflector is made of BeO.

To accelerate the program, negotiations have been underway for some time with the A-C Spark Plug Company who are applying the ceramic-firing method to the fabrication of bricks. In this method, the BeO powder is formed into the desired shape while cold, allowance being made for the 30 to 40% shrinkage occuring during the firing process. Firing is done in batches of 30 to 35 bricks at a temperature of 1800°C.

While this process is far more rapid than the brick-by-brick hot press method, the product is not yet up to expectations. It is possible to attain a density of 2.6 to 2.7 g/cm^3. by this method which is sufficient for satisfactory operation in a pile. The uniformity of the product is, however, not yet satisfactory. Firing at such high temperatures softens the powder to the extent that a noticeable taper exists in the vertical direction, due to lack of sufficient strength to support fully its own weight. Further, the variation between batches of raw powder produces wide variations in the shrinkage experienced in firing. To overcome this it is necessary to run several tests to determine the shrinkage of each batch before the dies can be fabricated. On a large quantity it would therefore be necessary to accumulate the entire stock of powder before tests could be run and the dies cut.

It must not be concluded that this method should be abandoned. The low cost of fabrication (about $2 per pound) and the potential production capacity with this method make it desirable to pursue the problem further. It should be remembered that this is a new approach to the problem, and that time is necessary to overcome the difficulties.

Both methods are limited by the length-to-diameter ratio that can be produced. In the hot press method the limitation is imposed by the inability to produce uniform density throughout the length of the piece. In the ceramic fired method, the settling of the brick during firing produces the limitation. The satisfactory height in the latter case is about one half of that in the former case.

3. Reflector

Since the desired properties in a reflector material are almost identical with those of a moderator, the process of elimination applied to potential moderating materials may again be employed, arriving at a consideration of the same two materials, graphite and beryllium oxide.

In the reflector, however, the requirements may be somewhat relaxed due to the fact that operating conditions are not so severe as those obtaining in the reacting portion. The neutron flux density is less than that in the reactor, both in number of neutrons and in the average energy of those neutrons. Thus, while physical deterioration of graphite under neutron bombardment in the reactor was one of the major reasons for eliminating it as a moderator, this objection no longer holds in considering materials for use in the reflector.

The reflector design actually chosen consists of two layers of material; the inner one is of beryllium oxide and the outer of graphite. The two part construction is dictated by the following considerations. Immediately outside the reactor zone it is desirable to use the beryllium oxide to allow a margin for adjusting the size of the active portion. It is impossible to calculate with absolute accuracy the required size of the reactor; this is particularly true in the case of the high temperature pile, where the exact effect of temperature cannot be predicted. Final knowledge of the size can only be obtained by a slow approach to actual operation of the pile, feeling the way experimentally.

The outer portion of the reflector can safely be made of graphite, thus saving a large amount of beryllium oxide. This saving is important from the financial standpoint, but is rendered particularly important by the critical BeO supply problem. As has been remarked earlier, this promises to be a major factor in the pile construction time element, so that savings in time on this item may well be reflected directly in the overall fabrication time of the pile.

Inasmuch as one of the objectives of the pile program is to obtain information on the conversion of Thorium to U^{233} for future use as a fuel, provision is made for incorporation of thorium oxide in the beryllium oxide portion of the reflector. Since this thorium oxide must be removed at intervals for separation of the U^{233} formed, it must be formed into rods similar to the fuel units to permit handling by the fuel loading mechanism. While two concentric rows of reflector bricks are considered as the conversion zone, the actual number of bricks to contain thorium can be decided only after further determination of the nuclear characteristics involved.

The introduction of thorium into the reflector reduces the effectiveness of the latter to an extent dependent upon location and amount of thorium introduced. This reduction ranges from zero where the thorium is installed around the outside of the reflector (where it is exposed only to neutrons having already escaped from the reflector) to some maximum when installed in the innermost portion of the reflector. In this latter position the pile proportions approach those associated with a bare pile since the thorium absorbs a large portion of the thermal neutrons. Selection of the middle portion of the reflector strikes a compromise between the inefficient conversion at the outer periphery and the increased pile size required with thorium at the inner portion.

The reduced neutron flux density in the reflector is associated with reduced heat generation. The consequent reduction in gas cooling requirements permits use of the channels in the reflector bricks for additional reflector material thereby increasing the effectiveness of the reflector which is proportional to the mass of reflector material. Accordingly, the passages are filled with graphite plugs of such dimensions as to permit only a small leakage path through the channels. The cooling so achieved will be sufficient to maintain satisfactory operating temperature.

4. Pressure Shell and Insulation

The container for the pile must be capable of withstanding internal pressure ranging from a small fraction of an atmosphere up to 10 atmospheres. The reason for the upper limit of pressure has already been mentioned and is enlarged upon under "Coolant and Coolant System" page 62 . The low pressure is introduced by the purging process at time of pile start-up. Simultaneously with the reduction in pressure to the lowest attainable value, the entire system is heated to the lower temperature (500°F) of the operating cycle. It is hoped that maintaining these conditions for several hours will be effective in outgassing the materials used in construction.

In addition to confining the helium, the pressure shell serves as the supporting structure for the entire pile and its operating mechanisms. Settling of the structure must be prevented from interfering with the pile operation; hence the foundation must be adequate to reduce settling to a minimum.

Numerous holes through the shell are required for controls, instrumentation and fuel handling. These apertures must be so designed as to reduce helium leakage to a very low value, in order to minimize the disposal problem and to conserve helium. Any leakage must be diluted with such large quantities of air as to achieve sufficient dispersion of contaminated gases.

Insulation of the pile is required in order to reduce heat loss. Such insulation must be installed between the pile and the pressure shell, in order to make use of low alloy steel in the shell. The absorption of gamma radiation in solid insulating materials generates heat so that care must be exercised to select a material wherein this heat generation will not be excessive. Accordingly, investigations are planned which will lead to a satisfactory method of insulating the shell. Until the results of these investigations become available, it is planned to include the insulation between the shell and the pile, with a helium cooled inner lining of a high temperature alloy to prevent any possibility of dust from the insulation entering the helium stream.

With the present design the pressure shell will operate at about 500°F. The moderator bricks at the hot end of the pile will operate at about 1400°F. From room to 1400°F. the moderator will expand approximately 1" in diameter. The design will allow for this expansion without imposing stress on the lines separating the insulating section from the pile proper.

5. Shielding

The necessity for shielding the active pile is obvious. That shielding will be required for all elements of the heat transfer system is not so readily apparent. The need arises from radioactive contamination of the helium. This contamination consists of active fission products from the fuel, gaseous impurities in the cooling medium as originally supplied, and traces of gases remaining in the system after purging. While this radioactivity is but a fraction of that in the pile, it is of sufficient intensity to require appreciable amounts of shielding.

The shielding of the active pile presents the most difficult problem since the activity at this point is many times that in the outer helium circuit. Furthermore, while the activity at points removed from the pile is mostly of gamma radiation, that at the reactor includes thermal and fast neutrons as well as gamma radiation.* As has been explained previously, the absorption of gamma rays is accomplished more effectively by elements of high atomic weight. Fast neutrons must be slowed down by collisions with light atoms to thermal levels, whereupon absorption is achieved through the use of absorbing elements. In the neutron absorption process, however, gamma rays are emitted which must be absorbed just as those originally emitted.

With these facts in mind, a practice of pile shielding has been developed which has led to a two part shielding; the first part, a thick layer of iron which is effective in absorbing gamma rays and thermal neutrons, and the second part, a construction providing for moderating the fast neutrons to thermal levels, absorbing them and the secondary gamma radiation incident to the absorption process**. In the second part of the shielding, two types of construction are useful; (a) concrete mixtures and (b) a laminated construction of alternate layers of hydrogeneous material (such as Masonite) and iron.

The use of concrete is satisfactory where space limitations are not severe. It is relatively cheap, readily available and easily formed into desired shapes. For a given reduction in intensity of radiation, however, it is only about one-third as effective per unit thickness as the laminated construction. Hence, where space is important the laminated construction is used, although cost and difficulty of

* For a brief discussion of the effects of various types of radiation and the tolerance limits, refer to Appendix II, Page 134

** For a table of the effectiveness of various absorbing materials refer to Appendix II, Page 134 .

fabrication are increased thereby.

In view of the fact that approximately 1 percent of the power generated in the pile "leaks" (in the form of radiation) through the container, the shielding immediately adjacent to the pile will receive energy at the rate of about 400 KW when the pile is operating at maximum power of 40,000 KW. A 10" layer of iron, adjacent to the pile will absorb about 95 percent of this energy, as a large percentage of the radiation is in the form of gamma rays and thermal neutrons. The rate of absorption is high enough that cooling must be provided for the iron to prevent excessive temperatures. This is conveniently accomplished by water which not only cools the iron but has a moderating effect on the fast neutrons.

In the second part of the shielding the heat generation is at a low enough rate that, except for the innermost portion, the heat dissipation through the material is adequate. At the inner surfaces it is probable that cooling will be required; this may be accomplished by cooling water passages.

The use of water as a coolant introduces an additional, though minor, shielding and disposal problem. Impurities in the water may become radioactive and thus the water lines must be shielded. Disposal of the active cooling water can be done only after a sufficient decay period has elapsed to reduce the activity to safe levels.

Operation of the pile at pressures of about 10 atmospheres introduces a helium leakage problem. The pile presents many potential leakage paths due to control, instrumentation and fuel handling facilities. Any leakage of helium must be disposed of in such a manner as to prevent exposure of personnel. This may be achieved by provision of an air gap immediately around the pile shell; which is vented through a stack and maintained under a slight negative pressure. This negative pressure can be achieved by an exhaust fan, and will ensure that any gas passage through the shielding will be inward. This air will also serve to cool the pile shell, outer surfaces of ducts, and auxiliary equipment within the shield.

A similar air gap must also be provided in the outer portion of the shielding, since there is a possibility of evolution of small quantities of toxic gases in the material of this part of the shield. This is the case when Masonite is used. While the amounts of such gases produced are minor, care must be exerted to prevent their escape into operation areas.

Communication with operating mechanisms must be maintained through the shielding in order to control the pile, and such communicating passages present potential radiation leakage paths. Provision must, therefore, be made to prevent leakage at these points by incorporation of suitable shielding plugs or labyrinths.

In the interests of shielding problems in general, thought and calculations are being directed toward the inclusion in the concrete of materials with exceptional absorbing ability. Boron, with a cross section of about 700 barns, is one such material under consideration. Investigations are also under way on using a hydrogen bearing iron ore as the aggregate in the mixture. It is thought to be possible to improve concrete effectiveness by such methods to the point where the required thickness will approximate the laminated construction.

6. Provision for Exposure of Experimental Samples

One of the important functions of the high temperature pile will be the testing of construction materials for proposed new high temperature piles under conditions of high neutron flux and high temperature. For this purpose two channels near the center of the pile will contain thimbles extending into the pile through the upper shield and through the pile shell. These will be made of either high melting steel or c columbium and will be similar to the metal guide sheaths planned for the control rod channels. They will permit the exposure of samples at a neutron flux up to ten times that now available at Hanford and at temperatures up to 1400°F.

7. Neutron Physic Experiments

To predict pile size for a new pile design, the amount of fissionable material required, the size of the reflector, and the temperature coefficient of pile reactivity, it is necessary to know numerous fundamental physical quantities which describe the behavior of neutrons in a pile. Since certain of these quantities are not known with sufficient precision for other than preliminary calculations, they must be determined by experiment before final dimensions in the pile design can be settled.

These quantities which we shall consider here fall naturally into groups.

Group I - Properties of Pure Materials.

A. Neutron Age in BeO

B. Neutron Diffusion Length in BeO

Group II -Properties of Sub-critical Pile Assemblies

A. Buckling and neutron reproduction constant

B. Pile temperature coefficient of reactivity.

The following treats in succession the experimental measurement of the above quantities.

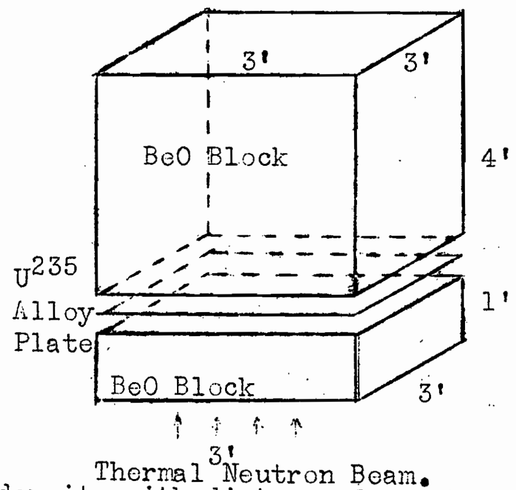
a. Neutron Age

The pile discussed in this report is a thermal pile, ie, the vast majority of the fissions are produced by slow, or thermal, neutrons.

Since neutrons born in the fission of a nucleus are in general fast, it is necessary to slow these neutrons down to thermal energy to maintain the chain reaction in this type of pile. Since no two materials are the same in their ability to slow down neutrons, it is necessary to have a quantitative measure of this ability. The measurement used is called the neutron age or Fermi age and it is commonly denoted by the Greek letter τ. Specifically τ has the dimensions of cm^2 and $\sqrt{\tau}$ is the average distance a neutron diffuses through the pile in slowing down from fission energy to thermal energy. In general material composed of light atoms is more effective in slowing down neutrons than materials composed of heavy atoms. The purpose of the Fermi age measurement is to determine the slowing down distance.

The importance of τ in pile design may be seen in the fact that the larger the distance a neutron must diffuse in slowing down, ie, the larger the value of τ, the larger the critical size of the pile.

The experimental technique for the measurement of τ is as follows. A sheet of U^{235} alloy 3 feet square is placed between two blocks of BeO as illustrated. The whole assembly weighing about 4 tons is then placed in a thermal neutron beam. The beam of slow neutrons produces fission in the U^{235} sheet and the fast fission neutrons enter the BeO blocks and are slowed down.



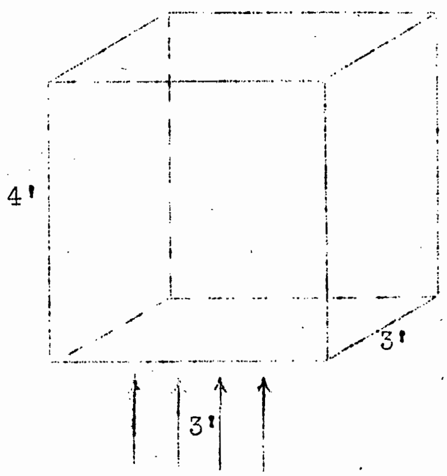
As the neutrons are slowed down, they move away from the U^{235} source sheet; but, even so, the density of neutrons slowing down and becoming thermal is much greater near the source than it is far away. There is a mathematical equation relating this decrease of density with distance from the source to the neutron age, τ. By measuring the density decrease with suitable foils and plotting the curve of density against distance from the source, one can calculate the neutron age by a curve fitting process.

b. <u>Neutron Diffusion Length</u>

In the foregoing section, we discussed the neutron age, which is a measure of the distance a neutron goes in slowing down. When a neutron has slowed down to thermal energy, it will not be captured immediately but will diffuse a considerable distance through the pile as a thermal neutron. The distance a thermal neutron will go before capture will then depend on the "transporency" of the pile material to the passage of neutrons, and on the tendency of the material to absorb neutrons. The physical unit used to measure this distance is the diffusion length commonly denoted by the symbol, L . . A large value of L for a material like pure graphite or pure BeO, means that that material is very free from strongly absorbing impurities such as boron. It is clearly important that the moderator material be free from such impurities since the latter absorb neutrons that could otherwise be used to maintain the chain reaction or to convert Th to U^{233}. Thus a good moderator material will have a large diffusion length L as well as a small τ .

The experimental measurement of L is very similar to the measurement of τ . A block of BeO of approximately the dimensions shown is placed in a beam of thermal neutrons. As the neutrons move up through the block, some are captured by the BeO. Thus the density of neutrons will decrease as the distance from the neutron source increases. There is a mathematical equation relating this decreasing neutron density to the diffusion length L. By measuring the decreasing density of thermal neutrons with suitable foils and making a graph of the data, one can obtain the value of L by a curve fitting process.

Block of BeO



Beam of Slow Neutrons

c. Exponential Test

The primary purpose of an exponential experiment is to improve the estimate of the pile critical size. The fundamental calculations are based on physical constants of an assumed mixture and moderator. The exponential pile simulates the actual construction and permits the determination of these values to a higher degree of accuracy. The concentration of fissionable material is kept well below that necessary to make the system chain reacting, the neutrons for the experiment being provided by an external Radium-Beryllium source. By this procedure the danger from radiation and fission products is kept at a minimum and the danger (always present in studying actual critical systems) of a neutron chain reaction getting out of control is removed. Very little shielding or personnel protection is necessary and the parts are readily accessible if the arrangement of the lattice needs to be changed.

The actual data consist of measurements of the relative neutron flux as a function of position. Such measurements are made by activating (making artificially radioactive) foils calibrated for the purpose. Analysis of these curves gives the "buckling" (B^2) from which the critical size can be calculated. Also by combining the value for the buckling with measurements of the Fermi age τ and the diffusion length L, discussed previously, the reproduction constant (k) can be determined. By arranging the assembly so that it can be heated the effect of temperature on the critical size and reproduction constant can be measured and thus knowledge of the temperature coefficient of the pile can be obtained.

The reproduction constant (k) in pile theory is the number of thermal neutrons produced per thermal neutron absorbed in an infinite extension of the pile material. If k is less than unity even an infinitely large pile could not be made chain reacting. For any finite pile there is loss of neutrons due to leakage through its boundaries and k must be greater than one for the system to be chain reacting. The "buckling" (B^2) is just the negative of the curvature per unit neutron flux at each point in the pile. It can be measured directly by measuring the relative neutron flux as a function of position in the pile with reference, say, to the neutron flux at the center. The quantity determines the critical size or critical mass of fissionable material for the pile.

The reproduction constant and the " buckling" are related mathematically by an expression containing also the "age" (τ) and the diffusion length L so once B^2, τ and L are known k can be computed. This is necessary for calculating the size of the reflector and its effect in turn on the critical size of the pile.

d. Transport Cross-section.

Measurements of transport cross-section in BeO are planned at several different temperatures, using blocks of BeO containing a known amount of boron as a neutron poison.

IV-C. COOLANT AND COOLANT SYSTEM

1. Capacity of Plant Equipment

The critical size of the pile as explained in "Pile Physics Considerations " Page 32, is determined by the physical contents of the moderator, reflector, and fuel rod. This critical size is the same for 0 heat output as it is for 4,000 KW or 40,000 KW heat output, providing the pile temperature is the same in all cases, and the pile temperature is fixed by other considerations. The amount of U^{235} consumed is proportional to the power of operation, but the amount of U^{235} in the pile is independent of the power. Thus for higher power levels of operation more make-up U^{235} is required and the work of chemical processing for U^{235} recovery is increased proportionately.

In order to make a suitable design of the gas handling and generating system for the pile, it is necessary to evaluate the maximum power level of operation to be expected. One of the first steps was to analyze the pressure drop and the pumping power requirements. * For pile output from 4000 to 10,000 KW heat, the helium pressure in the system should be from 3 to 4 atm. Since it is generally assumed that it will be desirable to operate the pile up to 4000 KW heat output or more, it is concluded that the pressure in the system must be above atmospheric pressure. Recent calculations have confirmed this. It is very little more difficult to operate at 10 atm. pressure than at 3 atm. pressure, and the entire gas handling and power generating equipment will not be much more complicated for operation at 40,000 KW than for operation at 4000 KW. The only difference between these two power levels will be in the size and capacity of the equipment and not in the general design. Engineering judgement at the present time dictates that pressure much in excess of 10 atm. will cause major structural problems in the design of the gas handling apparatus.

The construction of the pile for operation at 40,000 KW heat output involves very little additional expense for eqipment over that required for a pile whose output is limited to 10,000 KW or 4000 KW The known factors involve slightly thicker shielding, larger capacity driving turbines for helium circulation, larger boilers to obtain the larger area of heat transfer surface required, a larger cooling tower to dispose of waste heat, thicker walls on the ducts, boiler, blowers, pile shell, etc., and slightly better seals on the blowers, fuel charging appartus and control rods. In all cases, it does not require any additional equipment; just largerequipment, in some cases having some more elaborate features.

The plan of operation of the pile is to start with very low heat outputs, and test for the effects of high temperature on the pile and auxiliary equipment. The heat output will be slowly increased, until after about seven months, the power level will be up to 4000 KW heat output. If the test data indicates that higher

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* Pressure Drop in Daniels' Pile by D. D. Streid, 17 July, 1946, and supplement to this report, 9 August 1946.

power levels can be achieved, the heat output will be increased until the test data indicates that the maximum reasonable power level has been reached. This conceivably may be as high as 40,000 KW heat output, and it would be undesirable to have the plant designed so that the auxiliary equipment limits the maximum power level; this should be limited by the reacting pile. It would delay the progress of the entire overall program if the operation of the entire plant should be marginal at 4000 KW heat output, and operation at higher powers could not be obtained without completely rebuilding the entire plant.

Based on the above, the auxiliary equipments of the plant, such as boilers, blowers, ducts, steam plants, etc., are being designed to handle a maximum pile heat output of 40,000 KW. This will consist of duplicate equipment, so that continuous operation of the pile up to 20,000 KW will be assured, even when half of the equipment is shut down for servicing, inspection, or repairs.

2. Choice of Helium

Early study indicated that cooling of the pile by a gas was preferable to liquid cooling as liquid cooling introduced a major problem because of reaction between the coolant and the pile and because most liquid coolants have a very high neutron absorption cross-section. For a high temperature pile, water cannot be used as a coolant, except at the tremendously high pressure required to prevent evaporation. Other liquid coolants are mercury, NaK, bismuth, lead, etc. Very little is known about the practical use of any of these liquids as coolants in piles. Therefore it appears that gas cooling will intordduce fewer problems in the pile design than liquid cooling.

Of the common gases, air, steam, hydrogen and helium are the most reasonable choices for this application. Oxygen in air reacts with UO_2 at high temperatures converting it to U_3O_8 which then sublimes out of the pile. Steam reacts with BeO causing a physical deterioration and sublimation of BeO at high temperatures. Hydrogen introduces an explosion hazard and is so light that the problem of pumping large quantities is very difficult.

Helium has none of the disadvantages of the above gases, and thus offers a good possibility. It is well suited for this application; it is physically inert to the high α, β, and γ radiation and the neutron bombardment of the pile. It is chemically inert in that it does not affect BeO, UO_2, or graphite, even at very high temperatures. It is not corrosive, and it does not embrittle steel. It is one of the best gases known for heat transfer because it has a combination of a high specific heat and a good thermal conductivity.

Helium has the disadvantage compared to air and steam in that it is difficult to pump because of its low atomic weight. This requires relatively high pumping power for a given mass flow. Also the design of the blower becomes difficult because it requires an extremely high tip speed to supply the necessary energy for compression. For example, in this application, a centrifugal compressor impeller with a tip speed of 700 ft/sec. is required to obtain a compression ratio of 1.02, whereas, pumping normal air, this tip speed would produce a compression ratio of 1.4.

Helium is available in sufficient quantities at reasonable cost so that it can be considered for use in the pile. For the above reasons, it is concluded that helium is a good gas for this application.

3. Power Generating System

The arrangement for converting the heat generated in the pile to electrical energy is shown on Figure B-2. Helium is pumped through the pile and removes the heat; it is then cooled in a boiler and returned to the pile by a blower. Thus the helium is circulated in a closed system. The steam generated in the boiler is expanded through a turbine which drives a generator, producing the useful electrical output of the system. The turbine exhaust is condensed, and is returned to the boiler by a feed pump.

The helium system is operated at approximately 10 atm. pressure. The gas leaves the pile at 1400°F. This temperature was selected because it is considered the practicable upper limit for operation of materials in the pile, ducts, and boiler based on current engineering experience. The use of a higher temperature would introduce high temperature metal development problems which might prove to be very difficult and unduly delay the entire project. The use of 1400°F will allow the production of steam at high enough temperature and pressure to be used efficiently in a standard steam turbine with a reasonable boiler area. If the temperature were decreased much below 1400°F the amount of helium circulated would have to be increased with a considerable increase in pumping power. Also, a reduction in this temperature would reduce the maximum steam temperature and pressure which could be generated in the boiler unless more area is added. These two factors in combination would increase the power requirements of the blower and at the same time would reduce the power output of the turbine generator. It is considered desirable to keep this temperature as high as is technically feasible because the ultimate performance of atomic piles will depend on high temperature operation and it is desirable to obtain experience as soon as possible with high temperature operation.

The low temperature (500°F) in the helium system has been chosen because this is the upper limit for operation of materials presently available for blowers. The use of a higher temperature would require special materials in the blower and would complicate the blower design because of strength limitations of material at higher temperatures. An increase in this temperature would require a higher rate of circulation of the helium which, as explained above, is undesirable.

The schematic diagram (Figure B-2) shows a direct heating boiler in which the heat from the helium converts the water to steam. Should a leak develop in the boiler, water will be introduced into the helium circuit. At the temperature and pressure there existing, the water will be immediately vaporized. This has two results, (1) the vapor will react with the BeO in the pile causing it to deteriorate, and (2) the vapor will increase the reactivity of the pile. In case of a very large leak in the boiler, or a sudden boiler tube failure, a considerable quantity of vapor will be introduced into the helium; about 1/2 second later this vapor will enter the pile causing an extremely rapid increase in the pile reactivity, which must be checked by the safety rods.

If the rate of increase of power due to this increased reactivity is sufficiently fast compared to the speed of operation of the control rods, an explosion may occur. Present calculations indicate that when half of the helium is displaced by water vapor, the pile period is seven seconds which means that seven seconds is available for operation of the control rods; this is within the speed capacity of the control rods. Therefore, it is reasonable to proceed on the basis of using a direct heating boiler for the design of equipment.

There is some uncertainty in the physical data used as the basis for the calculation of a pile period of seven seconds when water vapor enters the pile. In case later information indicates that there is too much danger of an explosion in the pile being caused by a boiler failure, it may be necessary to design the system to protect against this possibility. At least three methods of doing this have been considered and are discussed in detail in the "Boiler" section Part V, Page 101 of this report. First of these consists of the use of a mercury boiler to take the heat out of the helium and a mercury condenser which heats water and makes steam. A second idea is the use of a secondary helium system in which the heat from the boiler is transferred to the secondary helium system through a gas-to-gas heat exchanger. The heat is then removed from the secondary helium system by means of a steam boiler. These systems have the disadvantage of requiring two heat exchangers each of which is larger than the single heat exchanger required in the direct heating system. They also have the disadvantage of the power required for the circulation of the mercury or helium in the secondary system. The third idea consists of a boiler constructed of double walled tubes with a space between the tubes filled with a gas or liquid. In case of a tube failure, water is introduced into this space, and not into the helium. These ideas are discussed in more detail in Section V, Page 108.

Figure B-2 is a schematic diagram of the power system. It does not, however, show all the details of this system. It is planned to use two boilers each having a steam generating capacity of 55,000 lbs/hr; each boiler will be capable of operating with up to 20,000 KW heat output from the pile. The two boilers in parallel will be required for experimental operation up to the maximum heat output of 40,000 KW.

It is planned to install two blowers per boiler or a total of four, each capable of handling one-half the maximum flow of a boiler. Duplication of equipment is required to insure continuous operation. For example, if a boiler or a blower is being inspected or repaired the pile can be operated on the other one. This has the structural advantage of reducing the sige of the individual helium ducts. It is planned to install the boilers and blowers in individual cells so that any one of them will be accessible for inspection or servicing while others are being used.

The following is a tabulation of the conditions in the various parts of the pile power system.

Maximum Pile Output	40,000 KW heat
Helium Flow	34 lb/sec.
Helium from pile to boiler, temp.	1400°F
Helium from pile to boiler, pressure	147.5 lb/^{2}in a
Helium from boiler to blower, temp.	500 °F
Helium from boiler to blower, pressure	147 lb/in^2 a
Helium from blower to pile, temp.	514°F
Helium from blower to pile pressure	150.6 lb/in^2 a
Helium blower shaft power	600 KW
Steam at boiler, temp.	775°F
Steam at boiler, pressure	450 lb/in^2 g
Steam at turbine throttle, temp.	750°F
Steam at turbine throttle, pressure	415 lb/in^{2}g
Steam Flow	110,000 lb/hr.
Generator Output	8,000 KW
Feedwater temperature	220°F

A more complete flow diagram showing all the equipment involved in the power gas system is shown in Figure B-1. This shows the functional relationship of the two boilers and the four blowers. This diagram does not show details of the auxiliary systems, such as the helium supply system, the helium purification system, the gas deoxidation system, and the gas de-humidifaction system.

4. Ventilation

It is planned to design the entire helium system so that all of the components including boiler, blowers, ducts, etc., are ventilated by an induced draft fan. Any leakage of helium containing radioactive fission products, thus will be picked up in this air and will be discharged from a high stack. In case of a sudden increase in the activity of the ventilating air the pile automatically will be shut down. The details of this ventilating system cannot be worked out until the complete plant is designed.

IV- D. CONTROL

1. Control for Power Pile Generation System

There are several factors which would make manual control of this pile difficult. There is a complicated interdependance of such factors as neutron flux density, pile temperature, coolant flow, steam flow and pressure. Also, the large excess reactivity would make it possible for an operator inadvertently to make changes in the control rod positions in such a way as to cause the neutron flux density to rise with a very short period. The control will, therefore, be almost completely automatic.

The control system is shown schematically in Fig. C-1. This diagram shows only the fundamentals of the control scheme and particularly not those required by a standard power generating plant.

This system is one which will deliver electrical power at substantially constant voltage and frequency to either an isolated system having a variable load or to a system whose frequency is determined by other large connected generators.

A detailed analysis of the control system is being made to determine the stability, transient response and required speed of operation of safety mechanisms. It is felt, however, that experience on similar control problems makes it possible to determine the general requirements of the system in advance of this detailed analysis. The information obtained from the analysis, it is expected, will confirm present opinions on the system in general and will give the necessary data for the design of the individual components of the system.

a. Control Rods.

The criterion determining the control method is the necessity for the most immediate response of the pile control to the processes going on inside of the pile. It is proposed to make the control rods responsive to neutron flux, detected by an ionization chamber, and to such functions of its rate of change as will effectively limit the power generated in the pile to an adjustable maximum value, and which also will limit the pile period to safe values and provide transient stability. At all times the control rods will also be responsive to a predetermined limiting pile temperature as determined by the maximum temperature indicated by any one of several thermocouples located at various points in the pile.

b. Power Level Reset by Steam Pressure

The maximum power generated in the pile will not be allowed to exceed at any time a value determined by a manual setting of the control system. The pile will be operated at the power level necessary to maintain the steam pressure substantially constant. However, the attempt to maintain constant steam pressure will not be allowed to cause the pile period to decrease below a given value.

c. Blower Control.

The temperature of the helium gas leaving the pile is to be controlled by the rate at which the helium is circulated. The exit from the pile is the most logical point for such control because it is the point where the least lag in coolant temperature consequent to a variation in rate of flow is encountered. The type of blower control to be selected will depend upon the type of blower drive chosen. Means will be included to prevent oscillations in the temperature and it may be necessary to supplement variation of blower speed with the use of dampers to obtain suitable rates of change of helium circulation. Calculations indicate that the temperature of the helium entering the bottom of the pile will vary slightly with load, dropping from 500°F at full load to approximately 375°F at 5% load. It is not believed that this variation in entrance coolant temperature will lead to any difficulties in control.

d. Turbine Speed Governor

The turbine is controlled by a normal speed governor which opens or closes the steam admission valves to maintain substantially constant speed regardless of load variation. This is a conventional type of turbine control which has proved satisfactory. If the generator is to be tied into an existing constant frequency system then the power output will be determined by adjustment of the turbine speed governor.

e. Boiler Feed Water Controls.

The normal boiler feed pump and make up water controls are excluded from this discussion as they need not be of a new type peculiar to this generating system.

f. Helium Control.

A gas analyzing control system provides for by-passing helium through the purification system in the event that the oxygen, nitrogen, or water vapor content of the main circulating system rises above specified limits. This will be a manual control, based on readings from a gas analyzer, but a means of automatically shutting down the pile will be provided in the event that appreciable amounts of these impurities are in the helium gas.

Variation of operating gas pressure in the system is controlled manually by pumping helium to or from the low pressure storage tank as shown in diagram B-1 .

A relief valve is included in the main circulating system to insure that the helium pressure does not increase above a safe value.

2. Emergency Safety Controls.

It is of the utmost importance that the control circuits be reliable and, for this reason, the use of three control circuits in parallel is being considered. Only one will be connected so as to be in actual control at any one time. The output of all three, however, will be compared automatically and any deviation of one from the other two, which exceeds allowable limits, will be taken as an indication that that circuit is faulty. If the circuit in actual control becomes faulty, then control will be automatically transferred to one of the other circuits.

It is also desirable that the failure of a control component which does not immediately affect the operation of the pile, does not cause the pile to shut down, but instead first causes an alarm to operate and, if no corrective measures are taken within a predetermined time interval, then causes the pile to shut down.

a. Pile

Safety rods are to be provided to shut down the pile should the power exceed the maximum setting, should the pile temperature exceed the normal limiting value, or should the pile period be less than the prescribed value. All of these factors will be set to operate the safety control rods at values a given percentage from the normal operating values. In addition the safety rods will be caused to drop upon loss of control power, excessively low speed of helium blower or upon a combination of low steam pressure and low water level in the boiler. Operation of the safety rods will cause the control rods to enter rapidly to the fullest extent.

b. Steam Pressure

Steam pressure in excess of normal pressure by a fixed amount will cause a safety valve to discharge to atmosphere and at the same time reduce the power level of the pile.

c. Turbine Overspeed

The emergency governor of the turbine will cut off steam to the turbine in the event of overspeeding by a fixed amount, and decrease the pile power to a minimum value under influence of the control rods.

3. Design Considerations.

a. Control Rods.

Preliminary calculations indicate that at least seven regulating rods will be necessary with additional safety rods.

Changes in reactivity may be obtained either by moving one rod or by moving a group of rods in parallel. In either case it would be necessary for the maximum rate of change of reactivity not to be exceeded. If the rods were actuated one at a time, it would be necessary to provide means for controlling the relative positions of the various rods. This would involve switching mechanisms, such as position actuated transfer switches and limit switches. For this reason all of the regulating rods probably will be operated in parallel.

b. Operating Range and Speeds of Control Rods.

The rate of removal of the regulating rods is limited by the maximum allowable rate of increase of reactivity. The rate of removal of the extra safety rods is not limited, because sufficient regulating rods will be provided to prevent the pile from becoming reactive under all conditions. The excess reactivity which must be compensated for by the regulating rods is about 50 per cent.

The sensitivity of a control rod varies approximately as the square of the neutron flux. This flux in turn varies along the vertical axis according to a cosine function. This means that motion of the rod at the top of the pile causes relatively little change in reactivity. As it is desirable for a safety rod to cause the greatest decrease in reactivity in the shortest time, the combination regulating and safety rods should never be withdrawn completely from the pile. A design value has been chosen as nine inches from the top of the pile. Using a similar limit at the bottom gives a four foot working range of the regulating rods to change the reactivity by 50 per cent.

An allowable maximum rate of increase of reactivity of one tenth of one per cent per second has been set, based on minimum pile period considerations. This corresponds to one tenth of an inch per second. (average) The maximum rate of change is, however, approximately 150 per cent of the average, because of the variation of rod sensitivity over its working range; therefore, the rate of movement of the regulating rods should not exceed 0.066 inches per second.

c. Design of Control Rods.

It is at present contemplated that the control rods will be made of boron steel which will be cooled by the circulating helium. However, consideration is being given to control rods which will stand very high temperatures. Such a rod might consist of graphite impregnated with boron and having a reinforcing rod through the axis. The rod might also be enclosed in a boron steel tube to prevent troubles caused by flaking or breakage of the graphite. Even if the temperature did reach a value above the melting point of the boron steel, the graphite-boron core could still control the pile. The control rod holes may be lined with thin tubes of a suitable material to prevent the control rods from sticking.

The control rods will be enclosed in steel thimbles which extend from the pressure chamber through the shielding with suitable enlargements for the actuating mechanism. Sufficient helium would be fed in through the top of the thimble to provide cooling and prevent diffusion of radio-active fission products into the actuating mechanism.

d. Methods of Actuating Control Rods

The actuation of the regulating rods will be by means of a rack and pinion. The pinion will be driven by an electric motor through a reduction gear and a magnetic clutch. This system has many advantages. It permits accurate positioning, permits any desired rate of motion and immediate disconnection by means of the magnetic clutch when it is used as a safety rod. The position of the rods can be indicated remotely from the pinion without being affected by the disconnection of the magnetic clutch. Limit switches can be used to re-energize the clutch to absorb the shock when the safety rod falls freely after a safety trip.

The method of actuation of the safety rods has not yet been determined. It is expected, however, that the operating mechanism for the safety rods will each be a different type. This will reduce the probability of two of the rod mechanisms failing at the same time due to similar causes such as high temperature, corrosion, etc.

IV- E. FUEL HANDLING

The "fuel", composed of U^{235} mixed with a matrix of BeO or graphite is formed into hollow cylinders $1\frac{1}{2}$" ID x 1" O.D. x $4\frac{1}{2}$" long.* It is contained in the channels provided in the moderator bricks and supported by adequate retainers located in the pile support.

The $U^{235}O_2$ depletes at a rate proportional to the operating power level of the pile, producing objectionable poisons, necessitating removals of the "fuel" when depletion of approximately 10% has been reached.

A fuel handling mechanism is required to insert the fuel into the pile, rearrange the fuel in various channels of the pile, and remove the fuel to a decay chamber. A proposal for such a mechanism is discussed in the following section. This proposal is the first attempt at a solution to the fuel handling problem and requires extensive analysis and development before a final approved design is obtained.

1. Insertion Through Pressure Shell

The fuel units will be inserted in the rectangular loading case shown in Figures C-2, C-3. The fuel will be inserted only in the holes which correspond to those in the loading tray in which it is desired to insert fuel. The outer gas seal is opened and the loading case is inserted into the pressure lock and decontamination chamber. After the decontamination process has been completed the inner gas seal will be opened and the loading case then moved to a position over the loading tray. When the case has reached the proper position a latch will be released and the fuel will be dropped into the loading tray. The tray is then moved to such a position as to line up an adjacent row of holes; the process is repeated until the tray has been loaded as desired.

2. Loading into Pile Reactor.

The rammer moves the loading tray into the positioning rack beneath the pile. For the initial loading all of the fuel racks will be filled with reflector plugs and with nozzles for controlling the flow of the coolant. After these have been loaded into the pile the loading trays will be withdrawn in succession from the positioning rack and loaded with fuel as described in the preceding section.

The rammer, shown in Figure C-2, C-3, can be positioned under any fuel channel. During the initial loading the rammer will ram each of the fuel units into the pile. The loading trays will hold one fourth of the total fuel units of the pile. Thus, if the six trays are all fully loaded, one fourth of the height of each channel can be loaded at a time. After four fuel loading operations on a sixty degree sector, the required amount of fuel will have been inserted in the pile, the next operation will consist of inserting reflector plugs. The above procedure is then repeated for each of the sixty degree sectors.

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* See Section V-A-1, Page 79

If it is desired to remove depleted fuel units and replace them with new ones, the new units are loaded into the trays in the appropriate positions, the reflector plugs and the units below the depleted ones are removed and stored in the empty trays. The new units are then loaded into the pile and the stored units are replaced. If two of the trays are filled with new fuel units and four are empty, then the middle one half of the pile can be loaded without removing any of the trays from the pile. The reflector plugs and the bottom three-fourths of the fuel units of one sixty degree sector are stored while the new fuel units are loaded. The bottom one quarter of the fuel units and the reflector plugs are replaced and the depleted fuel units are removed from the pile and sent to the chemical treatment plant.

If the loading operation is performed while the pile is in operation, the loading described above should be done in succession for individual channels until the reloading of a sixty degree segment has been completed. New fuel is then inserted in the trays from which the depleted fuel has been removed and the operation is repeated for another sixty degree segment.

If it is desired to replace the top one fourth, then fuel is loaded into only one tray, four trays are used for storing the three fourths of the fuel that will be replaced and the reflector plugs, and the sixth tray is used for the depleted fuel that is removed.

The above description is based on completing the reloading of an entire horizontal layer consisting of any one or two vertical one-fourths of the pile fuel. If the reloading is accomplished when the pile is shut down, then time is saved by operating in succession on all the units in one horizontal sixty degree sector. If the reloading is accomplished when the pile is operating, it may be necessary to operate on each channel within the sector in succession, completing the entire reloading operation on a given channel before proceeding to the next channel.

The same procedure outlined above applies to reloading in any given horizontal pattern as well as to reloading an entire horizontal layer.

The details of an actual loading operation will now be described. The rammer is positioned under the desired channel by means of the angular and radial control provided. The rammer is then moved upward from its normal position beneath the loading trays by means of a rack and pinion drive. The rammer moves the fuel upward past the retaining latch in the steel base plate. When the fuel has moved to a position somewhat above the retaining latch, shown in figure C-4 , the latch falls into the retaining position and the rammer is withdrawn. The latch is moved out of the way by the fuel and must remain in that position until the fuel has been moved above it. The rammer is so designed that the latch is free to fall and retain the fuel in position when the rammer is withdrawn.

The following is a detailed description of an unloading operation. When it is desired to unload units from the pile, the rammer is raised high enough to move rod A upwards. This rod lifts the fuel retaining latch out of the way after the weight of the fuel units in the pile are supported by the rammer. The rammer is then withdrawn and the fuel is lowered into the tray. When the fuel has almost been lowered to its final position in the tray, the rammer releases the auxiliary rod A and the latch is free to fall between the last fuel unit to be removed and the bottom unit to be retained in the pile. A rough schematic drawing of accomplishing this is shown in Figure C-4. The final design will be much simpler and more positive in action than here indicated.

3. Removing the Fuel through the Pressure Shell

When a loading tray has been filled with as much depleted fuel as it is desired to remove at a given time, the tray is withdrawn from the positioning rack. The tray is moved in succession over a series of unloading chutes and at each position of the tray the fuel is automatically dumped into the chutes, passing into a pressure lock. The inner valve is then closed, the lock purged of radioactive helium, the outer valve opened, and the fuel passed on to the chemical processing plant.

F. POWER GENERATING EQUIPMENT

The electrical power generating equipment of this project is very similar to standard steam driven electric power generating equipment. In this section is described the equipment which takes the energy from the steam delivered by the power pile boiler and converts it to three phase electrical power at the alternating current generator terminals. A flow diagram of the proposed plant is shown in Figure D-1 of Book 2. Because this is a new method of producing steam, standard power plant practice will be deviated from in some respects to provide for variations and unexpected happenings. A discussion of contemplated deviations follows:

1. After all necessary tests at zero power level have been conducted, it is planned to raise the power level to 4000 Kw. Since the initial starting heat load will be at very low levels and may be unsteady while the pile characteristics and control are being investigated it is proposed to take the small amount of steam generated into a simple steam condenser; this will be called a "steam killer". One can picture the initial startup as one where the power level is increased to some value and immediately reduced to zero and then increased to a new higher value with another immediate reduction to zero until one learns how the pile must be operated. During this period one would not want to operate the turbines, and opportunity would be given to study the characteristics of the steam generated in the boiler.

2. Under normal conditions the turbines will operate to use all the steam generated in the boiler. In event that the steam generation does not conform to the requirements for power generation and excess steam is produced it can be absorbed in the steam killer and returned as condensate into the normal condensate circuit. There is always the possibility of one of the operating turbines kicking off the line at which time the throttle valve will close instantly and allow steam to pass into the steam killer, so that interruptions due to turbine shutdowns or excessive steam production can be automatically handled without disturbing pile operation.

3. There is a possibility that the boiler steam will vary in pressure and temperature; it is therefore proposed to take the boiler steam into a header, called the variable pressure and temperature steam header. This header will deliver steam through pressure reducing and de-superheating equipment to a constant pressure and

temperature header providing suitable steam for turbine operation. If the pressure and temperature fall below that required for the turbines there will be no serious effect other than a reduction in the rate of power generation.

4. The power generating equipment and auxiliaries can possibly be obtained from the Navy, so the problem exists of adapting marine equipment to land use. The turbine condensers for marine use are not designed for the water pressures normally used on land equipment but since a cooling tower will probably be used, a layout will be made which will permit the cooling water to flow by gravity through the condensers after which it can be picked up by the circulating pumps.

5. Parts of the steam system such as the boilers must be protected against excessive steam pressures. Relief valves are necessary and since this is a closed system means will be provided to take relief valve discharges into the steam killer.

6. Regardless of precautions taken, steam or water will be lost from the system and it is proposed to handle this by means of an evaporator together with a distilled water storage tank. Only distilled water will be used in the boiler. However, there is always the danger of a leak in the turbine condenser. To overcome the danger due to passing raw cooling water into the condensate, detecting equipment will be installed and means provided to discard the contaminated condensate until the fault has been corrected. During the time the condenser is out of operation water will be drawn from the evaporator storage tank.

7. As the power pile boiler cannot be inspected without first being decontaminated there will be times when it is not possible to inspect it. Therefore, it is vital that the feed water be of a purity beyond anything encountered in standard power plant practice. The feed water filtering equipment will be installed in the line ahead of the boiler.

8. Where deemed necessary both steam and electric drives will be provided for auxiliaries.

9. The question of drives for the pile gas blowers is important because of the effect on the pile operation. A continuously variable controlled speed range from zero to full speed is desired. For extremely light loads during initial startup the DC motor may be the most desirable drive.

10. We propose to connect our switchboard to a large outside electric system from which we may obtain power as well as deliver power as operating conditions require. All necessary electrical protective devices will be provided.

11. The marine equipment has been laid out as a land plant and after providing ample room for operation, dismantling, etc. we find we will require a turbine room approximately 35 feet wide and 67 feet long. The building will have two floors. The lower floor as shown in figure D-3, of Book 2, will accommodate the condensers, circulating pumps, and possibly the gas blower drives. The second floor as shown in figure D-2 of Book 2, will be approximately 12 feet above the first floor and will accommodate the two main turbo-generators, the two auxiliary turbo-generators, the exciter units, emergency Diesel units and the switchboard. The deaerating feed water heater, the evaporator, and the steam killer can be installed outside and adjacent to the power plant building.

12. The marine equipment which we propose to use is designed for steam at 410 pounds/square inch and 750°F. If we were purchasing new equipment we would design for higher pressures and temperatures.

G. Chemical Process Design.

Since the chemical steps involved in recovering and decontaminating the uranium from the depleted fuel rods from the power pile are essentially the same as those for processing the uranium-aluminum alloy fuel for the proposed heterogeneous pile to be built at the Clinton Laboratories (1000 project), it appears feasible to use the same chemical plant for both piles. This suggestion has been made in the Preliminary Design Report on the 1000 Project (MON-N-108) in which a tentative design for the chemical plant is given. The proposed process as described is still the best known except for minor modifications incorporating subsequent experimental findings.

The detail requirements of the chemical plant on buildings, personnel, and equipment are given in the 1000 Project Report and need not be repeated here. A brief resume covering the process for handling the fuel rods will be given.

The $BeO-UO_2$ fuel rods will be dissolved in nitric acid. The subsequent solution may be then clafified by filtration or centrifugation.

Separation of the uranium from solution will then follow by extraction with hexone. The presence of large amounts of beryllium nitrate will act as a salting out agent. Decontamination of the organic extract can be accomplished by washing withan aqueous salt solution and the uranium can be recovered by stripping it from the extract with water. The desired degree of decontamination can be attained by repeating the extraction, washing, stripping cycle; by sodium uranyl acetate precipitation or by an adsorption-elution cycle on the synthetic resin, IR-100. Both batch and continuous operation appear feasible for the extraction-washing-stripping cycles.

The uranium which has been separated from beryllium oxide and decontaminated must be reconverted to U_3O_8, so that it can be mixed with beryllium oxide for fabrication of new fuel rods. This may be accomplished by precipitating uranyl peroxide from the uranyl nitrate solution obtained from the separations process. Ignition at 700°C may then be used to convert the peroxide to U_3O_8. A similar procedure is routinely used at the plants producing the enriched U^{235}. Since the weight of uranium to be processed per day when the pile is run at 4000 KW will be only 80g* and the weight when it is run at 40,000 KW is only 800g, it will probably be possible to obtain the purified decontaminated uranyl nitrate from the solvent extraction process in only a few liters of solution. This can be processed on a small scale by either the peroxide precipitation outlined above or by evaporation and ignition.

While it is known that these conventional methods of chemical separation can be successfully used, an attractive alternate method developed in the course of research on the beryllia power pile is being investigated. In this method, the daily process batch of beryllium oxide fuel tube (about 7.9 kg at 4000 KW operation and 79 kg at 40,000 KW operation) is treated in a stream of oxygen at 1200-1500°C. The uranium is volatilized and condensed in a cooler portion of the apparatus, leaving the beryllia and the bulk of the fission activity behind.

* Assuming 50% U^{235} and 10% depletion.

V-A. PILE DESIGN DETAILS

The general construction of the pile is shown in figures A-1 and A-4, which are vertical and horizontal sections through the pile. In the vertical direction the structure is seen to consist of three zones. At the bottom is the entrance plenum chamber, through which the helium enters the pile at 500°F. Immediately above the inlet plenum chamber is the active pile wherein the power is generated. Above the pile is the outlet plenum chamber, from which the 1400°F. helium is led, by ducts, to the heat exchanger. The upward flow of helium was chosen in order to place the pile supporting structure in the coolest zone possible.

The bulk of the pile consists of a large number of hollow hexagonal moderator prisms, stacked on end to form a 9' diameter cylinder 8.55' high. In effect, this produces a large block of moderator material providing approximately 1100 channels, spaced on 3" centers. In the central 6' diameter core are 517 channels, of which 504 are occupied by fuel for a height of 5.55'; the remainder are occupied by control rods, safety rods, and experimental thimbles. This portion is known as the reactor.

The portion of the moderator bricks wherein there is no fuel (18" on all sides of the reactor) is the reflector. Since there is little heat generated in this region, the channels around the outside of the reactor are filled with plugs of moderating material. Sufficient helium passage is permitted to remove the small quantity of heat generated. In the portions of the top and bottom reflector layers that index with reactor channels, the reflector plugs must provide for passage of the helium quantity required by the fuel rods; hence, they are not close fitting plugs.

Certain of the channels located in the middle third of the radial reflector are not plugged. Here it is planned to introduce thorium rods to produce U^{233}. The thorium rods will have the same general dimensions as the fuel rods, permitting the required helium flow to remove the heat generated in conversion.

1. Selection of Fuel Rod.

The fuel rod consists of a fissionable material which will be called the "fuel", and a supporting "fuel rod material" to provide structural stability and heat capacity.

a. Choice of Fuel

The known fissionable materials which may be used for running a power pile are ordinary uranium, enriched uranium 235, plutonium and uranium 233. Ordinary uranium requires very large quantities of uranium and moderator, accentuating the problem of chemical processing and recovery, and rendering impractical the use of the power pile on portable units such as ships. Moreover, it is difficult to utilize all of the U^{235} contained in the natural uranium.

Plutonium probably will not be available. Moreover, because of its highly poisonous properties, special health precautions would have to be followed in processing and preparing plutonium and the development of the present power pile would be slowed down.

U^{233} is not available now, but as soon as sufficient thorium has been converted to U^{233} in a year or so, it should be tried. Its constants for breeding i.e., converting thorium to U^{233}, are better than those of U^{235} which makes it ultimately a very desirable material for power piles. However, it does not exist now in sufficient quantity.

U^{235} in enriched form is the best atomic fuel to start with, considering availability, safety for health and early operation of the pilot plant. Ordinary uranium containing 0.7 percent of U^{235} requires a lattice arrangement of the pile, but when the concentration of U^{235} is increased to several percent, (by the diffusion process, for example) a lattice arrangement is no longer necessary.

The higher the percentage of U^{235} in the enriched uranium, the better because:

a. There will be smaller quantities of uranium to reprocess.

b. There will be a greater conversion of thorium to U^{233} on account of less capture by U^{238}.

c. There will be a smaller accumulation of plutonium, thus reducing the health hazard.

It is hoped that the enriched uranium made available for this pile will contain 50 percent or more of U^{235}.

b. Chemical Form of Atomic Fuel.

The U^{235} (or U^{233}) can be used in the pile as the metal or combined with non-neutron-absorbing elements in a thermally-stable chemical compound. Fluorides and sulphates decompose thermally at the high temperatures of the pile. Nitrates and chlorides, and certain other compounds, absorb neutrons and, moreover, they are thermally unstable. Oxygen and carbon do not absorb neutrons, and the oxide and carbide of uranium are stable at very high temperatures. The oxide is chemically stable toward neutrons and it is assumed that the carbide is stable also. The oxide is much easier to prepare and process than the carbide.

Metals are chemically stable because they do not involve chemical combination with any other elements, and they should be physically stable. The accumulation of fission products in metallic uranium will lead eventually to physical deterioration. The accumulation of fission products may be serious in compounds but the escape of these fission products is easier from porous refractory oxides or graphite than from the impervious metals.

When the uranium or uranium compound has undergone sufficient fission to be seriously weakened in physical structure or badly poisoned with accumulated fission products, it is necessary to remove the fuel rods, dissolve them in acid, decontaminate from the fission products, purify chemically, and restore the material to its original form. Additional U^{235} can be added after the fuel has been reprocessed several times. It will be much easier to supply the reprocessed fuel in the form of the uranium oxide than in the form of the metal because the step involving the reduction to the metal is not required. The purification process involves the nitrate, which can be easily converted to the oxide by heating, but the further conversion of the oxide into the metal requires an expensive metallurgical process which may lead to losses of the valuable U^{235}.

These considerations led to the choice of the oxide as the form of uranium fuel to be used in the present design because of its stability, its ability to withstand high temperatures and the ease with which it can be dissolved, purified and reconverted to the oxide.

c. The Fuel Rod Material

The desired properties of the fuel rod material carrying the U^{235} are that it shall have no properties detrimental to the functioning of the pile; that it shall contribute to moderation of fast neutrons; that it shall have physical properties suitable to the conditions of operation, and conducive to low thermal stress; and that its desirable physical properties shall be sufficiently maintained under the influence of neutron bombardment and fission product recoil.

The interior of a fuel rod is hotter than the surface by an amount that depends on its thermal conductivity and geometric form. The temperature difference causes stress; and failure of the fuel rod by cracking under this thermal stress is one of the conditions that may place a practical ceiling on the rate of power generation in the pile.

The overall problem is to find the best geometric shape and the best material under the conditions of service. Investigations of materials and shapes are being continued to develop an improved fuel rod for high power output.

1. Fuel Rod for Initial Operation.

For the initial six months of operation at 4000 KW and below (page 89 .) the fuel rod will consist of beryllia mixed with 2 percent uranium dioxide enriched to 55 percent U^{235}. The mixture will be hot-pressed into tubular sections 1 - 1/2 in. O. D. by 1 in. I. D. by 4 - 1/2 in. long. Availability and methods of fabricating beryllia have been discussed in Section IV -B -2 page 51. Numerous test samples have been made of hot-pressed beryllia containing up to 10 percent of uranium oxide, and it has been established that such mixtures are readily hot-pressed and the important physical properties of the resulting shapes are essentially the same as for pure beryllia. Reprocessing will be necessary when the reactivity of the pile becomes impaired by fission product poisons or when the physical properties of the fuel rod material are too far deteriorated for continued functioning. It is hoped to operate to 10 percent depletion of U^{235} and experiments are continuing to determine the rate of deterioration over long periods.

Beryllia has been chosen as a fuel rod material because its physical properties have been well established by an extensive research program carried out prior to this project and continued since the start of the project. The cylindrical form has been adopted because of manufacturing and handling simplicity, and a tube has been adopted in preference to a solid cylinder because calculation has shown that the thermal stress in a solid rod would be excessive.

Analysis of thermal stresses in a tubular fuel rod indicates that the stress distribution is most favorable when the inside and outside temperatures of the tube are equal. In practice, it will of course not be possible to assure equal temperatures, but the design will provide an approach to this ideal. Stress analysis indicates that to obtain low thermal stress the tube wall should be made as thin as possible. A very thin wall would of course be fragile and the tube would have low heat storage capacity leading to rapid change of temperature with changing load. The specified tube dimensions provide a satisfactory compromise between these conflicting requirements.

2. Alternate Fuel Rod Materials.

Beryllia has been chosen for the initial period of operation because it is known to have properties generally suitable for use as a fuel material at temperatures covering an even wider range than the proposed operating temperatures.

Graphite is believed to have properties considerably more favorable than those of beryllia, in its resistance to thermal stress; but this belief is based on evidence obtained at room temperature and does not have the support of such extensive experimental investigations as have been made for beryllia.

Beryllium metal has properties which indicate a calculated resistance to thermal stress of the same order of magnitude as those for beryllia. It is known that the metal can be alloyed with uranium. Unlike beryllia or graphite, beryllium has some degree of ductility; this makes the metal worthy of careful consideration as a fuel rod material, but its high temperature properties have not yet been sufficiently explored to justify its use in fuel rods. Data on the vapor pressure of beryllium shows that in the circulating helium stream a metal temperature of 945°C is the maximum due to the sublimation of the beryllium metal. This is based on a vapor pressure of 10^{-5} mm. considered maximum allowable. Figures 9a and 9b include data on the vapor pressure versus temperature of Be metal and the pounds of Be lost per year versus operating temperature for a helium flow of 34#/sec. These data, in the latter case are based on maximum theoretical values. Further investigations of beryllium will be made.

Another interesting composition for fuel rods is BeO plus 10 to 20 percent graphite. This mixture is molded by the hot pressing method as easily as pure BeO, and on testing showed a factor of improvement of about 4 over pure hot pressed BeO in resistance to cracking by thermal stress.

It has been found experimentally that the fuel rod materials considered for this pile suffer considerable loss of thermal conductivity under neutron and fission product bombardment. This loss of conductivity increases thermal stress, and must be allowed for in fuel rod design. Experimental evidence shows that when beryllia fuel rods are heated to 900°C part of the initial loss in conductivity is restored. Initial design however cannot be predicated on annealing until further data become available.

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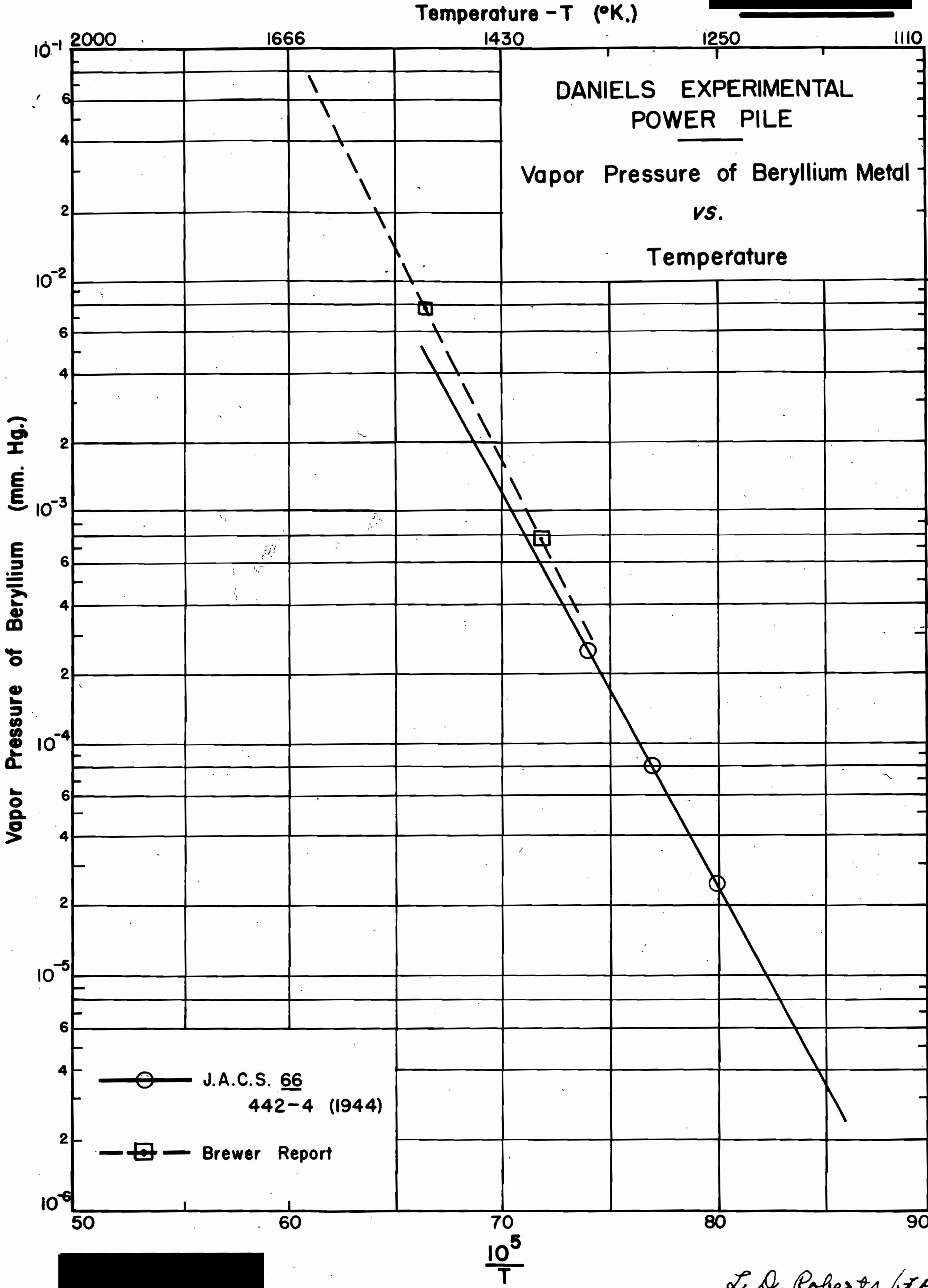

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Figure 9a

L. D. Roberts /J.P.
10–30–46

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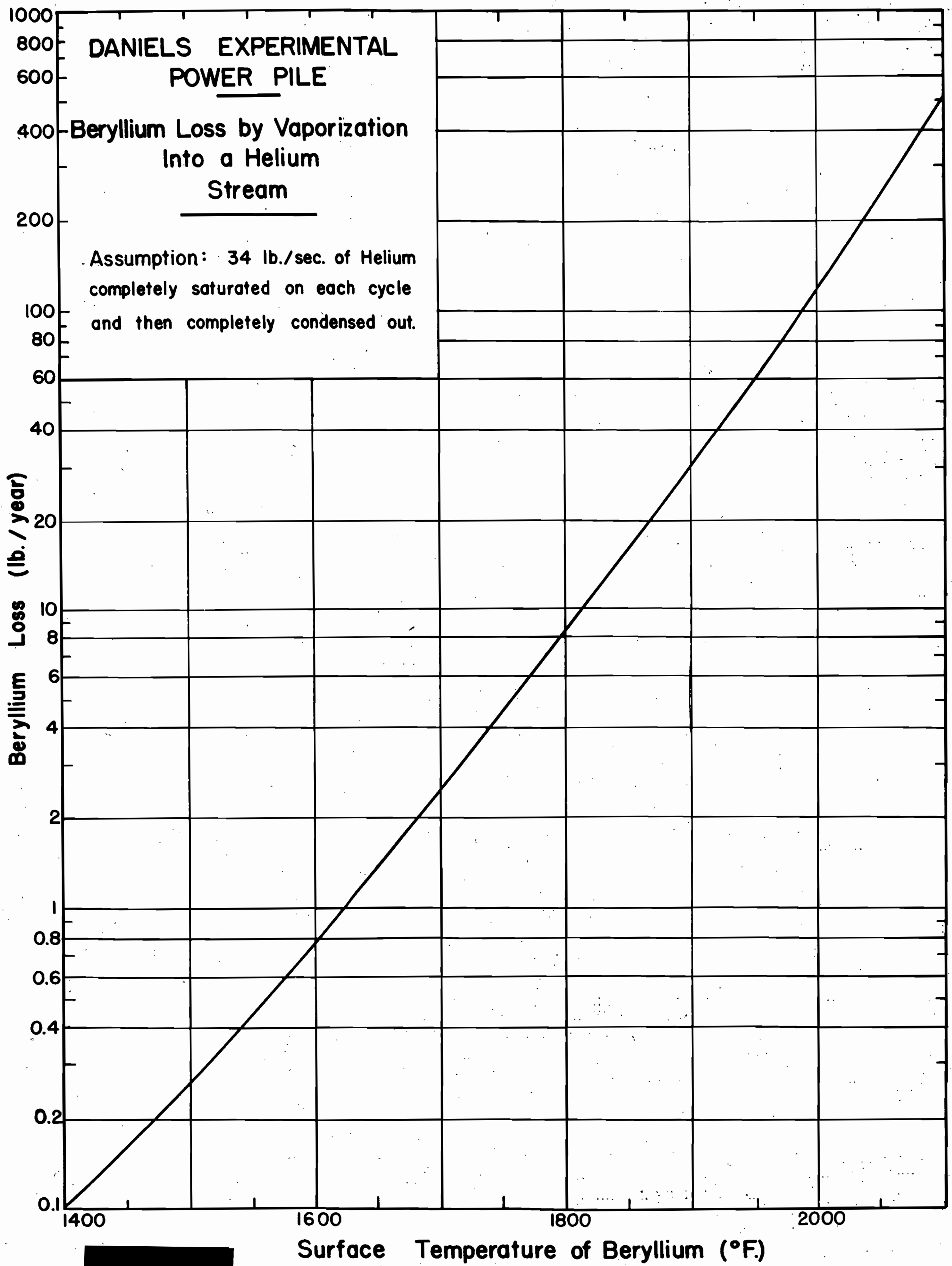

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Figure 9b

W. L. Silbitt
10-30-46

Graphite

At room temperature graphite has a combination of physical properties that would make it capable of operating without failure at about fifteen times the power output obtainable with beryllia under the same conditions. Graphite has not been considered as a first choice because there is in sufficient information concerning its properties under operating conditions. Qualitatively, it is known that graphite has high resistance to thermal shock and has good mechanical properties at high temperatures; this is shown by such applications as carbon electrodes in electric furnaces and carbon filament lamps. In the Hanford piles, graphite has been shown to suffer severe loss of heat conductivity and some dimensional growth as a result of neutron irradiation. This graphite, however, is at a temperature of 200°C or less.

A program has been started to explore the possibilities of graphite as a fuel rod material. Arrangements have been made to test strength and thermal conductivity at high temperatures, and the effect of irradiation on the thermal conductivity of impregnated samples. This will test the effect of fission recoils on the graphite. The growth experienced at Hanford is not expected to be serious because the fuel rod will be designed with adequate clearance, and it will remain in the pile only for a limited period. Experiments have indicated that a high degree of self annealing at operating temperatures may moderate the severe loss of heat conductivity experienced at Hanford.

Impregnation of Graphite with Uranium Oxide

Uranium oxide can be incorporated in the graphite by admixture with the carbonaceous material used in moulding the fuel rod. Present research at the Argonne National Laboratories, however, has indicated a much more convenient method of adding the uranium oxide. The graphite tube is impregnated with a solution of uranyl nitrate, $UO_2(NO_3)_2$, and this is subsequently fired in an inert atmosphere. Essentially the process as now used is as follows: The fuel tube is boiled in distilled water to remove powdered graphite adhering to the surface, heated to 800°C. in a helium atmosphere to remove water, and cooled and weighed. The piece is then refluxed for 30 minutes in a solution of uranyl nitrate in an organic solvent, dried and dipped in dibutyl cellosolve to remove any uranyl nitrate deposited on the surface. The impregnated uranyl nitrate is then converted to uranium oxide by heating for 30 minutes at 800°C in a helium atmosphere, and the piece is cooled and reweighed. The increase in weight is taken as a measure of the amount of uranium oxide impregnated.

It has been found that the curve of amount of uranium impregnated per cycle as compared with concentration of the impregnating solution is essentially a straight line over the ranges of solution concentration (3 to 35 grams of uranyl nitrate per 100 C.C. of solvent) investigated thus far. Lengthy refluxing of the graphite piece in the impregnating solution has little effect upon the amount impregnated. It has further been found that, for any one concentration of impregnating solution, the total amount of uranium impregnated as compared with the number of cycles is also a straight line over the range of impregnating cycles thus far investigated. It is possible therefore to obtain any desired amount of impregnated uranium by varying solution concentration and number of impregnating cycles.

The problem of the recovery of the uranium from the graphite fuel tubes has been very briefly studied, but it is known that 90% of the impregnated uranium can be redissolved by digesting with dilute nitric acid at about 90°C. Further investigation, now under way, will indicate whether a better degree of dissolution is possible. Of course the uranium can be recovered by combustion of the graphite; but this is less desirable since it prohibits re-use of the graphite.

d. Alternate Fuel Design

Whether graphite is superior to beryllia as a fuel rod material will be shown by research now in progress. Investigations on beryllium metal are also being conducted;there is a possibility that the metal may prove to be superior to graphite or beryllia at high temperatures. Finally, consideration is being given to the re-design of the beryllia fuel rod for operation at high power levels. Several methods are available for reducing stress by design changes.

One method consists of making the cylindrical tube in short lengths (about one quarter inch long) and moulding these "washers" to include a series of radial cuts extending part-way through the thickness. In this way discontinuities are provided in regions that would otherwise be subjected to high stress. This art of preventing cracking by providing artificial discontinuities has important prece dents in industrial equipment. The "washers" could be bonded together into lengths of a few inches for handling purposes.

Another method is to replace the tubular fuel rod by a slug having a plurality of parallel axial holes. This device simulates a bundle of small cylindrical fuel rods within a single moderator channel; estimates show that stress can be reduced in this way by a factor of three or four. Such a solution would probably increase the pressure drop in the reactor.

e. Estimated Schedule of U^{235} Purchases

The quantities shown in Table A were estimated for the following plan of pile operation; The pile is to start operations at practically zero heat output and gradually increase until it reaches 4,000 KW in about 7 months. If pile operation is satisfactory the power level will be increased approximately 4,000 KW per month until the maximum power level of 40,000 KW is attained.

1. The fuel will be discharged or loaded only at the completion of a month's operation when all fuel channels with depletion greater than 5% will be discharged and new fuel charged.

2. Power generation in the radial direction will be represented by a Bessel function of zero order going to zero at a point 20 cm. outside the reactor.

3. The inventory shown in Table A page 89 is based on a radiation decay period of four months and one month for processing, totalling five months for operation above 16,000 KW. These decay and processing periods are very conservative and it is believed that the time can be reduced to two months. This would decrease the inventory of U^{235} by approximately 36 Kg.

SCHEDULE OF U^{235} PURCHASES

TABLE A

Date	Power Level as Heat KW	Total Purchased U^{235} Kg.	Inventory U^{235} Kg.	Total Fissioned U^{235} Kg.	Total KW days x 10^6 Operation
A. Essential Study of Experimental Power Pile					
(1) Period of Physics Experiments and Construction					
Start	None	2.51	2.51	None	None
2nd Week	None	6.00	6.00	None	None
5th Week	None	15.00	15.00	None	None
17th Week	None	25.00	25.00	None	None
34th Week	None	25.00	25.00	None	None
(2) Period of Initial Pile Operation					
Start	4,000	25.00	24.85	0.147	0.120
1st Mo.	4,000	25.00	24.71	0.294	0.240
2nd Mo.	4,000	25.00	24.56	0.441	0.360
3rd Mo.	4,000	25.00	24.41	0.588	0.480
4th Mo.	4,000	25.00	24.26	0.735	0.600
5th Mo.	4,000	25.00	24.12	0.882	0.720
B. Proposed subsequent study of Capacity and Life (dependant upon results of A and on further approval of allotment of requesite U^{235}).					
(1) Period of Power Capacity Study					
Start	8,000	33.49	32.31	1.176	0.960
1st Mo.	12,000	41.08	39.36	1.617	1.320
2nd Mo.	16,000	43.87	41.66	2.205	1.800
3rd Mo.	20,000	51.30	48.28	2.940	2.400
4th Mo.	24,000	57.53	53.61	3.822	3.120
5th Mo.	28,000	60.47	56.44	4.851	3.960
6th Mo.	32,000	75.47	69.44	6.027	4.920
7th Mo.	36,000	77.93	70.23	7.350	6.000
(2) Period of Maximum Power Operation					
Start	40,000	84.56	75.39	8.820	7.200
1st Mo.	40,000	84.56	73.77	10.29	8.400
7th Mo.	40,000	84.56	72.23	11.76	9.600
15th Mo.	40,000	84.56	70.67	13.23	10.800
(3) Cleanup and Recovery Period					
Start	None	84.56	70.53	13.23	
1st Mo.	None	84.56	70.42	13.23	
2nd Mo.	None	84.56	70.28	13.23	
3rd Mo.	None	84.56	70.17	13.23	
4th Mo.	None	84.56	70.03	13.23	

1st Year of Operation

Subsequent Operation

2. Moderator and Reflector

The data concerning the properties of the two materials considered for moderator bricks, beryllia and graphite, are so extensive that they cannot be presented in detail. Therefore, the reader is referred to Appendix III, where he will find a list of properties and references. All those properties which are important to the operation of the power pile have been investigated. Some remarks concerning the results of the investigations are made below.

a. Properties of Beryllia

Two methods of fabrication of the beryllia are under consideration:

(1) Hot pressing.
(2) Ceramic firing.

A moderator brick of density 2.8 g/cc is produced by hot pressing and of about 2.6 g/cc by ceramic firing. There is a correlation between density and the principal physical properties, ie: the thermal conductivity and crushing strength are greater for the higher density type brick.

More complete tests have been made on the hot pressed beryllia. The important properties have been determined and are available. The effects of irradiation on the elastic moduli, thermal conductivity, crushing strength, and linear dimensions, have been investigated. For this investigation samples were subjected to neutron irradiation in the Hanford Pile at intensities which simulate pile conditions at about a 4000 KW power level.

The results of the various investigations indicate that hot pressed beryllia will make a satisfactory moderator brick. The important results are outlined in the following paragraphs.

The compressive strength is about 10^{10} dynes/cm^2 and no significant change was noted after 60 days irradiation.

The tensile strength is about 10^9 dynes/cm^2.

The heat conductivity is about the same as for cast iron. It is 0.129 cal, sec^{-1} cm^{-1} $^oC^{-1}$ at 400^{o}C and decreases to a value of 0.035 at 1000^{o}C. Twenty-four day and 63 day irradiation decreased the thermal conductivity to 80% and 60% respectively.

The elastic modulus is about 3×10^{12} dynes/cm^2 and decreases only 10% in going from room temperature to 1000^{o}C.

The resistance to spalling and thermal cracking is good as long as severe thermal shocks are avoided. Heating and cooling at the rate of 10^{o}C per minute is safe.

The coefficient of thermal expansion is $6.45 \times 10^{-6}/^{\circ}C$ in the temperature range of 100°C-200°C. Its values have been established as a function of temperature up to 900°C, where the value is $11.7 \times 10^{-6}/^{\circ}C$.

The vapor pressure as a function of temperature is known. It is 6×10^{-8} mm at 1500°C. The rate of loss of beryllia due to volatilation in the power pile will be negligible.

The resistance to chemical attack by the coolant gas, helium, is great. Oxygen, air, nitrogen, and helium have no detectable effect at 1400°C. Water vapor attacks BeO at 1400°C but the attack falls off with decreasing temperature. Under power pile conditions the effect of these gases on the moderator bricks will not be serious.

The fact that more complete tests have been made on the hot pressed type brick in no way implies that the ceramic fired brick would not be satisfactory. There has also been considerable investigation of the properties of the lower density type brick. From the standpoint of physical properties, sufficient is known (See Appendix III, Page 136) to indicate that a satisfactory moderator brick can be produced by ceramic firing. Irradiation tests have been made on low density BeO. However, some further investigation is required to be certain since the ceramic brick is not as strong as the hot pressed brick.

b. Properties of Graphite

While much has been learned about graphite moderators through operation of existing piles, this experience has been obtained only at low temperatures. In the interests of employing graphite for a portion of the reflector, investigations have been made of some of the important high temperature characteristics. In particular, vapor pressure and volatilization rates have been found to be satisfactorily low even at temperatures well in excess of those encountered in the pile. Hence, the use of graphite in the reflector is considered safe, but its use in the reactor requires further investigation.

c. Moderator Units

The moderator units illustrated in Figure A-6 will consist of beryllium oxide, molded and fired into hexagonal bricks. Each unit will be three inches across flats with a two inch diameter central hole, provided with three equally spaced longitudinal ribs for centering the fuel elements. The ends of the bricks will be provided with circular tongues and grooves to effect alignment. Bricks made by the hot-press method will be approximately 4½ inches long, while those made by ceramic firing will be about 2¼ inches long.

Where beryllium oxide bricks are used for the reflector, they will be identical with those used in the moderator. The graphite reflector units, will have the same general shape (hollow hexagonal prisms) but since manufacturing limitations are not so severe, the length will be made greater in order to reduce the number of pieces to be handled at assembly. In both types of reflector bricks, plugs of similar material will be inserted into the central hole, to increase the effective density and to prevent excessive helium flow. A sample drawing of these plugs is shown in figure A-8.

3. Pressure Shell and Insulation

The various elements of the power pile assembly and its fuel loading and control apparatus will be assembled within a structural steel pressure shell. This shell is in the form of a vertical cylinder with convex dished heads attached at each end by a continuous welded girth joint. The overall dimensions are approximately 11 ft. diameter by 21 ft. high. The cylindrical shell is formed of steel boiler plate $1\frac{1}{2}$ inches thick to withstand the internal helium pressure of 10 atmospheres. This thickness is adequate for the stresses imposed by the evacuation during purging.

The lower section of the pressure shell houses the fuel loading and pile control mechanism which is described in detail under "Fuel Handling", Section IV, Page 72. This section also forms the plenum chamber for distribution of the helium, entering the shell through two 24 inch diameter ducts, to the flow passages in the pile assembly. The relatively cool (500°F) helium being pumped from the boilers to the pile by blowers is thus circulated around the loading mechanism removing the heat generated in the metal parts by neutron and gamma ray absorption. Loading apertures and mechanism operating rods extend through this section of the pressure shell through the requisite gas seal. This lower end of the shell is slightly more than 7 ft. in length and is entirely surrounded by the concrete foundation for the power pile assembly.

The upper end of this section of the shell is welded to the lower surface of a circular steel diaphragm 5 inches thick by 12 feet in diameter which forms a bed plate to support the fuel rods, moderator bricks and reflector members of the power pile assembly. The outer edge of the bed plate, which extends beyond the upper and lower sections of the pressure shell, constitutes the foundation ring which engages the concrete foundation for support of the entire pressure shell assembly. The fuel rods are loaded and removed from the reactor, through 2 inch diameter holes provided in the bed plate under each column of moderator bricks. An annular groove is provided in the upper surface of the bed plate around each fuel rod hole. These grooves are proportioned to register with an annular ridge molded on the bottom surface of each brick in order to maintain these units in proper position with relation to the fuel rod loading holes and mechanism.

The top section of the pressure shell serves as the container for the active pile and also as a plenum chamber for distribution of the heated helium issuing from the fuel tubes to two 27 inch diameter helium discharge ducts welded to the shell. The ducts convey the helium to the boilers.

Provision is made for insulating the pressure shell, taking the form of an 8 inch thick space around the pile and upper plenum chamber. Insulating brick composed of Alumina may be a suitable heat insulation for this purpose as this material has a relatively low thermal conductivity. In addition, it combines good neutron transparency with relatively low energy absorption from gamma radiation. Experiments are presently u under way for determining the most suitable means of insulating the shell.

In order to prevent contamination of the helium circuit by particles of the insulating mmaterial a $\frac{1}{4}$ inch thick liner constructed of stainless steel is provided. This inner liner completely envelops the hot gas space above the bed plate and provides a gas tight barrier betwenn it and the insulation above the bed plate. The two 27 inch diameter helium discharge connections extend through the surface of the pressure shell to the surface of the inner liner, with welded joints at each surface. The inside diameter of the inner liner is 1-1/8 inches larger than the outside diameter of the pile assembly in order to provide clearance space to accommodate the calculated one inch thermal expansion of the top of the pile as it heats to operating temperature.

The lower portion of the pressure shell through which the 500°F helium flows to the pile will be provided with 4 inch thick insulation as a heat conservation measure. Circulation of air past the exterior surface of the pressure shell will be relied on for removal of the heat which leaks through the insulation and the heat generated in the $1\frac{1}{2}$ inch thick steel walls of the pressure shell due to gamma ray and neutron absorption.

4. Shielding

The shielding of the high temperature pile presents no problems that are different from those already successfully solved in building piles already in operation. This being the case, there is a background of information which has been drawn upon in the design of shielding for this pile.

Immediately surrounding the pile will be a 2 inch air space maintained at a pressure .75" of water below atmospheric in order to insure that any leakage through the shielding will be inward rather than outward. The air flowing through this space will be discharged through an exhaust stack about 200 feet high to assure satisfactory dispersion of contaminated gases. While the air flow will be used in cooling the pile pressure shell, and will thereby absorb heat, the resultant natural draft created may be insufficient to produce the desired reduction in air pressure. To assure this, the air will be drawn through the passage by a motor driven exhaust suction fan of conventional design. Exact specifications for this equipment must await decision as to the number of experimental access holes in the pile, in order to evaluate the air flow requirements.

The first layer of shielding will take the form of an iron shell 10 inches thick, which will reduce thermal neutron and gamma ray intensity about 1000 fold. In so doing the shield will absorb on the order of 95 percent of the radiation energy emanating from the pile and will thus require cooling which will be supplied by water flowing through pipes encased in the iron shielding. This cooling water, due largely to mineral impurities, will become radioactive and will require retention in a storage basin before disposal, in order to permit decay. The size of this retention basin will be such as to provide the requisite decay period based upon the purity of the cooling water finally selected.

Surrounding the iron shield will be another air space 2 inches in width whose function is to remove any toxic gases created in the Masonite portion of the shielding. Air will be drawn through this space by the same exhaust fans as are used for the inner space, maintaining the same sub-atmospheric pressure.

Outward of the second air gap will be a massive shield structure for absorption of the penetrating fast neutrons and gamma radiation. Where space limitations are of no consequence 10 feet of concrete shielding will be employed. However, where space limitations are important, as for instance in the zone where loading will take place, a laminated construction 4 feet thick of alternating layers of iron (3-3/4 inches thick) and Masonite ($4\frac{1}{2}$ inches) will be employed. This produces the same reduction in intensity as the 10 feet of concrete, although it is a more expensive construction and will therefore not be used for the entire shield.*

In the consideration of shielding requirements, no allowance has been made for the reduction in neutron leakage occasioned by the thorium conversion, since the final decision on the amount of thorium to be included in the pile has not yet been reached. Omission of this factor in shielding considerations results in a shield that is on the conservative side.

In that part of the helium circuit external to the pile proper, the radiation is almost entirely in the form of gamma rays, and is of the order of 0.1% of that emanating from the pile. To shield these portions of the circuit, a concrete shield 6 feet thick will be provided. Air passages, similar to those around the pile will be required only in the case of such items of equipment where leakage may occur such as the blowers. Here again 2 inch air space will be provided which will be connected to the aforementioned exhaust fans.

5. Experiments

a. Exponential Test

This equipment consists of a miniature pile constructed of the regular BeO bricks to be used in the actual pile, arranged as shown in Dwg. A-11. There will be 121 channels 8 bricks high. The fuel rods will be hollow BeO cylinders filled with mixtures of UO_2 enriched in U^{235}, and powdered BeO of varying concentrations to approximate actual fuel rods to be used in the final pile.

Figure A12 of Book 2, shows an elevation view of the assembly. This assembly will rest on a 36 inch thick bed of graphite bricks which will contain a radial channel to permit insertion of a 4 gram Radium Beryllium neutron source on the axis of the pile from the

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* Figure A-14 of Book 2 shows the absorption rates in the shielding used in the Hanford Pile.

exterior of the unit. This chamber is water cooled in the vicinity of the source to keep the source cool when the temperature of the assembly is raised by circulating hot CO_2 gas through it. The BeO channels and fuel rods are supported on the graphite bricks by graphite disks, in such a manner as to permit CO_2 gas to circulate around the fuel rods, thus giving uniform heating of the assembly.

A double wall stainless steel jacket containing Boron-carbide surrounds the unit to absorb all escaping neutrons so that reflection of these neutrons back into the pile will be avoided. This procedure is necessary to make the neutron flux density go to zero at the boundaries, thus making the measured flux distribution easy to analyze. The shield also provides protection for the observer by preventing escape of slow neutrons from the system.

Six narrow slots between columns of BeO bricks are provided on each of three sides, 120° apart as shown in A-11. Foils for measuring the neutron flux can be inserted at any desired height along the axis.

The whole assembly is surrounded by a four inch jacket containing lamp black for heat insulation. The jacket containing this heat insulation will be 3/16 inch steel and will be provided with a steel cover containing holes to give access to test slots between the BeO bricks.

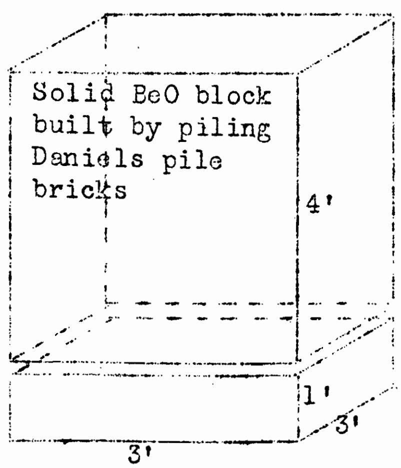
Figure #13 shows the whole unit with means for heating the CO_2 and circulating it through the unit to vary the temperature up to about 800°C.

It should be mentioned in conclusion that the BeO bricks can be used in the final pile and the enriched UO_2 can be easily recovered from the simulated fuel rods for use later in the final pile.

b. <u>Neutron Age and Diffusion Length Measurements</u>

Essentially the same equipment will be used for both the neutron age and diffusion length measurements. Beryllium oxide bricks of the same type as those to be used in the Daniels Pile will be piled up to form two solid blocks as illustrated. The holes in the bricks will be filled with BeO plugs in order to form a solid mass, thus making the total weight of the assembly about four tons. The upper block is supported on the lower one by an aluminum structure, and will be separated from the lower block by about 1/2 inch. This slot is left open so that a sheet of Al-U^{235} alloy containing 18% U^{235} and which is 3 feet square may be

1/2" separation



slipped between the two blocks. This assembly of BeO will be placed on the thermal column of the Clinton graphite pile. The neutrons from the thermal column will diffuse up through the lower block, through the 1/2 inch gap and into the upper block. The measurements are made by placing ten sets of metal foils about 3/8 inch square and 0.006 inch thick (certain combinations of indium and cadmium as required) uniformly spaced along the vertical axis of the upper block. When the foils are in place the neutron flux from the thermal column is turned on for about 20 minutes. The foils are then removed from the BeO block and their induced radioactivity determined. Since the induced activity will be proportional to the neutron flux that was in the BeO block, a graph of the foil activities will transform directly to a graph of the neutron flux in the BeO block. To measure the neutron age, the $Al-U^{235}$ alloy sheet is slid between the blocks and the measurement is made using cadmium shielded indium foils. The neutron age may be obtained from this data through a curve fitting process. To measure the diffusion length, several combinations of indium and cadmium foils are used with the $Al-U^{235}$ sheet removed. The diffusion length may be obtained from this foil activation data by a curve fitting process.

In preparation for these experiments the Clinton thermal column is now being rebuilt to obtain a pure spectrum of thermal neutrons. It is expected that this construction job, involving about 15 tons of graphite will be completed in November, 1946. The material for the BeO blocks is expected in December and the measurements will probably take about four months so that a final report on these two properties of BeO may be expected early in May, 1947.

V-B. COOLANT AND COOLANT SYSTEM

1. BLOWERS

a. Specifications.

The following tabulation gives the specifications for the blowers. These specifications are based on a maximum pile output of 40,000 KW divided between two boilers. It is planned to have two blowers in parallel, supplying each boiler by means of valving. Any one of the four blowers can be used with any other one and with either of the boilers. This will provide flexibility for low power operation, and permit inspection and servicing of the blowers.

Blower Specification Data

Gas	Helium
Inlet Temperature	500°F
Inlet Pressure	147 lb/in.^{2}a
Pressure Rise	3.61 lb/in^2
Gas Flow	8.5 lb/sec.
Inlet Volume Flow	8900 ft^3/min.
Drive	Steam turbine
Shaft Power	600 KW

The pressure rise of 3.61 lb/in^2 consists of a maximum of 2.68 lb/in^2 in the pile, 0.48 lb/in.^{2} in the boiler, and 0.45 lb/in.^{2} in the ducts. However, the most likely design of fuel rods (1 1/2" OD and 1" ID) will result in a pressure drop in the pile of but 1.56 lb/in^2 instead of the maximum of 2.68. This will allow larger pressure loss in either the boiler or the ducts.

The gas flow of 8.5 lb/sec. is only the flow through the pile and boiler, supplied by each blower. It may be necessary to increase this flow by about 10% to supply helium to the deoxidation and dehumidification systems, but the blowers will have adequate capacity to handle this additional flow.

b. Blower Drive.

In order to cover the power range from very low powers to the maximum of 40,000 KW, pile heat output, it will be necessary to have variable speed drives on the blowers. Because of the low pressure rise of the blowers the flow cannot be controlled over a very wide range by throttling at the inlet or discharge of the blowers. Such a method of control is practicable only when the blower compression ratio is in the order of 1.5 instead of the 1.02, which is here the case.

A variable speed blower drive can be obtained by DC electric motors, Ward-Leonard System, hydraulic transmission, or by steam turbine. Of these, the steam turbine seems the most advantageous since the speed is controlled by a simple governor and since steam is generated by heat from the pile. The use of a steam turbine requires an auxiliary boiler for starting of the pile power plant and for emergency stand-by in case of failure of the primary steam system. The steam turbine has the further advantage that it can be designed for a wide range of speeds. Indications are that the blower speed will be 5,000 to 6,000 RPM which is somewhat high for direct connected DC motors of the power required. The turbine can be designed to operate directly from the steam produced by the boiler at 725°F and 415 lb/in^2 gauge and can operate either condensing or non-condensing. The exhaust from these turbines will not be completely wasted as a portion of it can be used in the deaerating heater for the feed water, improving the thermodynamic performance of the overall plant.

c. Seals.

An important problem in the blower design is the seal arrangement for containing the helium gas. Since the gas will contain radioactive fission products it must be very tightly sealed to protect the health of the operators and public. Some information on this problem has been supplied by the Allis-Chalmers Mfg. Company, who reported that with sealing pressure of 4 to 10 atm., helium leakage of 100 to 1000 cc/min could be expected, using viscosity plate seals similar to those employed in the blowers at the gaseous diffusion isotope separation plant (K-25). Leakage from 10 to 100 cu. ft/min can be expected with carbon ring seals. Gas leakage will be negligible with refrigerator type seals using oil lubrication, although some oil leakage can be expected with this type of seal. The possibility of using refrigerator type seal depends on finding an oil which will be sufficiently stable under the radiation from the fission products in the helium to insure adequate lubrication of the seal for extended periods of time. The development of a suitable seal will be an important research problem in the program for the pile.

Most schemes for blower seals, other than the refrigerator type, involve the introduction of helium into an intermediate space in the seal so that pure helium flows into the system and the seal leakage to the atmosphere is pure helium. In this arrangement the helium leakage to the atmosphere will be into the bearing housing which then will be vented to a stack. It remains to be determined how much helium can be allowed to leak into the operating system through such seals and how much can be lost to the atmosphere.

d. Lubrication.

Oil lubrication of the bearing adjacent to the impeller in the blower will be an important problem because of the breakdown of standard lubricating oils under the radiation from the fission products in the helium. It is expected that a sleeve bearing will be used near the impeller which can be lubricated with a forced flow of lubricating oil. This lubricating oil can then be passed through a filter and any sludge caused by radiation removed. Nevertheless, the breakdown of the oil in the bearing may be sufficient to impair operation. It may be possible to protect the bearing and the seal from some of the harmful effects of this radiation by installing a shield of lead, 2" to 4", thick between the impeller and the seal and bearing.

In connection with the problem of oil stability, Allis-Chalmers is planning to test oils with the radiation generated by a betatron, checking hydrocarbon oils, prestone oils, and silicone oils. The work is to be done in connection with another program which Allis-Chalmers already has underway.

e. Shielding.

It is expected that the blowers will be installed inside of shielding, probably concrete about 6 ft. thick. It is expected that arrangements can be made so that the turbines which drive the blowers are out in the open and directly available for servicing and inspection. It is planned to ventilate the space between the shield and the blower by means of induced draft fans which discharge to a stack.

f. Vendors.

The following Companies have been requested to prepare proposition designs of blowers for this application:

American Blower Company
Allis-Chalmers Mfg. Company
Buffalo Forge Company
Fredric Flader, Inc.
DeLaval Steam Turbine Company
Spencer Turbine Company
Westinghouse Electric Corporation

1. American Blower Company.

They do not have standard equipment which will meet the requirements for this application, and under present conditions they cannot willingly undertake to develop special equipment.

2. Spencer Turbine Company.

They do not have standard equipment which will operate at as high a temperature as 500°F, and they are not in a position to undertake a special development for this application at this time.

3. Allis-Chalmers Manufacturing Company.

Allis-Chalmers is very interested in this proposition and is preparing a proposition for the engineering design of the blowers, seals, driving means, and control. This will include the necessary research and development of lubricating oils and seals. Their original proposition will not cover the cost of units for installation. Orders for equipment may be placed later on the basis of the results of the research and development being proposed. They have been asked to schedule the research and development program for completion by 1 July 1947. They estimate that a single stage centrifugal compressor will give the required performance and they are thinking of either a 23" to 30" diameter radial blade impeller operating at 700 ft/sec. tip speed or a backward sloped impeller of 26" to 36" diameter running at 800 ft/sec. tip speed. They are generally disposed toward a viscosity plate seal since they developed and manufactured the blowers with this type of seal which are used in K-25.

4. Buffalo Forge Company.

This company has investigated this proposition in detail and expected to quote on the proposition. However, the management decided not to submit a proposal because they could not give this project the individual engineering, design, and fabrication that should be given such an important project, without seriously interfering with other commitments.

5. DeLaval Steam Turbine Company.

They are preparing proposition designs for this application. They are particularly suited for this job because they have built many blowers for similar pressures, and temperatures and because they build steam turbines and governors in this particular size range. Their suggestion is for a single stage centrifugal compressor using a 27" diameter impeller running about 6000 RPM. They are tentatively thinking of using a refrigerator type oil cooled seal. This would consist of a graphite runner on a nitralloy disk cooled with oil. The turbine they propose to furnish would be designed for operating either condensing or noncondensing and they are recommending an oil governor in order to have close speed regulation over a wide range. (See appendix IV page 138).

6. Fredric Flader, Inc.

They have prepared a design for a blower for this application using a three stage axial flow compressor running at 20,000 RPM. The pitch diameter of the blades is 9" and the blades are 1" high. It is estimated that this compressor would have an efficiency of 80%. They have made a proposition without the turbine drive and are willing to change it to include the turbine drive if it is decided that their compressor design is promising. (See appendix V page 145).

7. Westinghouse Electric Corporation.

They have been asked to make a proposition for this application. They have indicated an interest in supplying this equipment and have referred this request to their Sturtevant Blower Division.

2. STEAM BOILER

a. Specifications

It has been decided to provide two boilers of equal capacity to convert the heat energy of the helium into steam, as shown in figure B-1 Book 2. The helium circuit is therefore divided so that half of the total flow can be circulated through each boiler. The cooled helium discharging from each boiler is pumped back to the pile for reheating by a pair of blowers, thus completing the closed helium circuit. The basic specifications for each of the two boilers are presented below and this presentation is followed by a discussion of the choice of these conditions:

1. Helium Conditions:

Helium flow	- 17 lbs/sec
Helium temperature to boiler	- 1400°F
Helium temperature leaving boiler	- 500°F
Maximum helium pressure drop in boiler	- $\frac{1}{2}$ lb/sq. in.

Helium carries radioactive fission fragments.
Low conductivity film, approximately .001" thick, is expected to form on heat transfer surfaces.

2. Steam Conditions:

Steam Pressure	= 450 psi g
Steam Temperature	= 775°F
Feedwater Temperature	= 220°F

Feedwater distilled and deaerated

3. Boiler Control:

Flow of helium circuit varies with load.
Superheat to be controlled to produce 725°F at turbine.
Boiler to be operable down to 10% of full load.

4. Shielding:

The helium circuit of the boiler will be enclosed in 6 ft. thick concrete to provide protection against radioactivity of this circuit. All parts subject to routine inspection or repair must be located outside of this shield.

The fission fragments which are carried by the helium may decompose pump packing, motor insulation, lubricating oil and therefore these materials must not be used in the vicinity of the helium circuit.

It is believed that the steam circuit beyond the boiler is not contaminated with radioactive materials and ther fore no special precautions need be taken in designing this circuit against radiation.

5. Safety Precautions:

Each boiler will be built to operate as nearly as possible without a failure which may result in steam flow into the helium system, since steam which enters the helium circuit will be carried into the pile and may damage it. This problem is being currently investigated.

b. Choice of Design Conditions

The design conditions for the steam plant were chosen based on considerations of safety, size, efficiency, and availability of equipment. These lead to a choice of 775°F, 450 psig for the boiler, so as to provide standard 725°F - 415 psig turbine conditions by means of an automatic desuperheater and pressure regulating valve. This conforms with modern power plant practice for good turbines of this size. A design for higher pressure and higher temperature is not appreciably more efficient, (see figure ten page 103), while the possibility of boiler failure is increased. The size of the equipment for 775°F, 450 psig is but 10% larger than that for a higher pressure and temperature design such as 800 psig, 950°F. The compactness of the chosen plant can be seen from figures B-6 and B-7 of Book 2. If the design pressure and temperature were decreased, little gain in safety would be obtained while the size of the machinery would increase appreciably and the efficiency of the plant would be reduced. Therefore, the design conditions, 775°F, 450 psig, are indicated from a consideration of safety, compactness and efficiency. Fortunately turbines, condensers, and electrical generators, for these conditions are available from Navy surplus for this use.

A feedwater inlet temperature of 220°F is used for two reasons. The first is that it is desirable to deaerate the water and to do so at a pressure above atmospheric to insure supply of oxygen free (and hence non-corrosive) feed to the boiler. Corrosion would lead to tube failure, resulting in a steam leak and damage to the pile. The outlet temperature from the deaerator will be approximately 220°F. since it is operating slightly above atmospheric pressure. The second reason is to provide feedwater heating to improve steam plant efficiency. Sufficient auxiliary steam is available from the blower turbines and other auxiliaries to accomplish this.

The helium inlet temperature of 1400°F to the boiler was dictated by pile considerations. 500°F outlet temperature was chosen because of serious blower design problems involved if a higher temperature was chosen. These choices provide sufficient temperature difference between the helium and the steam, when employing counter-flow heat exchange, so that the average temperature difference available for heat transfer is satisfactorily large, being approximately 450°F. The top temperature does not impose any serious problems on boiler design. In fact full top temperature can be withstood by the boiler so that tube failure due to overheating

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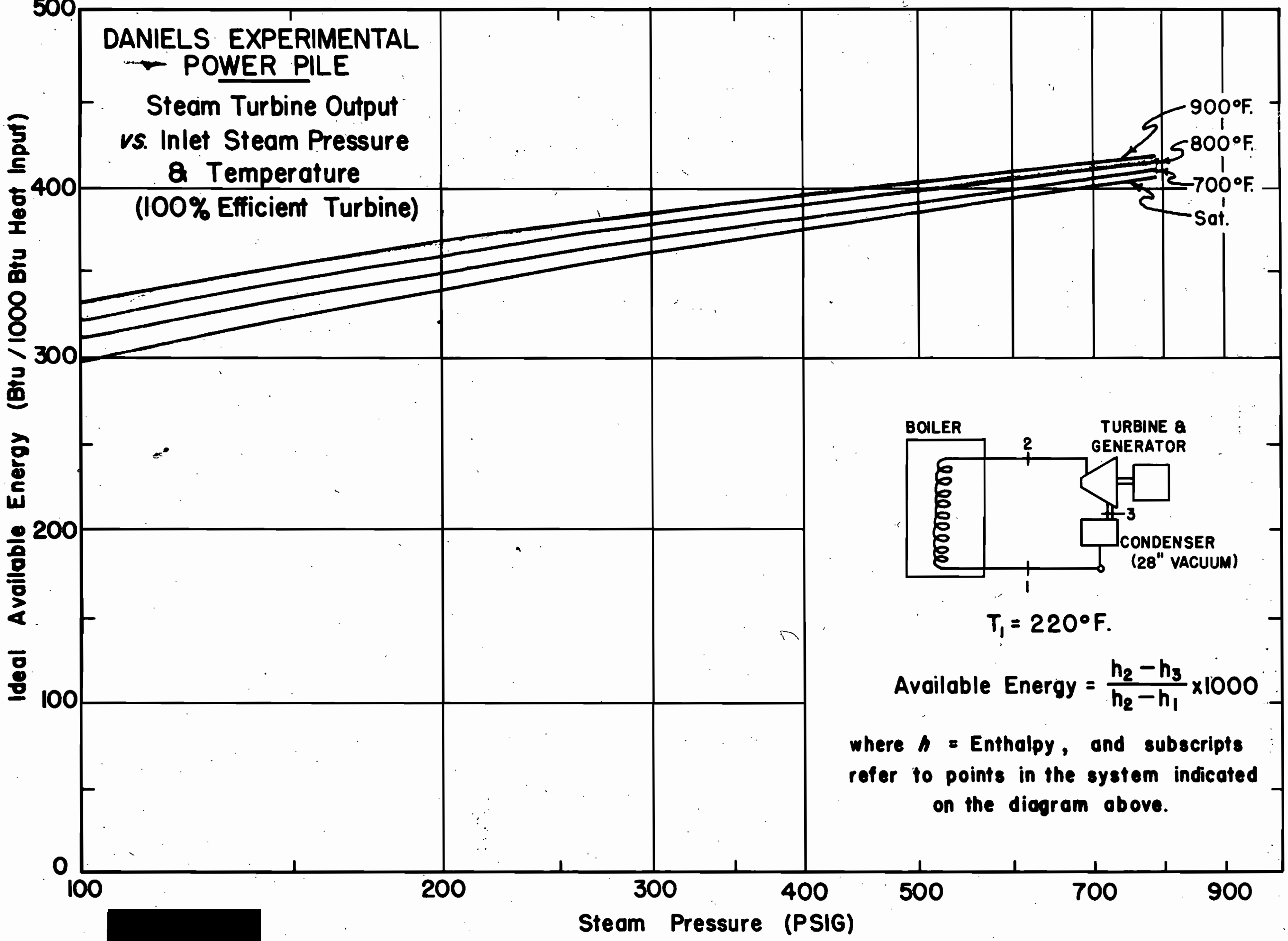

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Figure 10

A Amorosi
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should not be encountered, even in the event of failure of feedwater supply.

Ten atmospheres (150 psi) helium operating pressure was chosen to provide a high heat transfer rate with minimum frictional losses. Some problems have been introduced by the choice of 150 lb/sq.in. pressure for the helium at a temperature of 1400°F, but these have already been faced and solved in gas turbine work. The relation between frictional losses and heat transfer rate for a given gas tube geometry, and temperature is as follows:

$$F = \frac{kh^{3.1}}{p^2} \quad \text{where}$$

F = friction energy loss in ft. lbs/lb.
h = transfer rate in Btu/°F/sq. ft/hr
p = absolute pressure in lbs/sq. in

This relationship shows that the heat transfer for a fixed frictional loss is 4.4 times greater at 10 atmospheres than at atmospheric pressure. The 1/2 psi pressure drop allowed through the boiler produces 800 ft. lbs of friction energy loss per pound of helium flow. With a 70% efficient blower drive and a 20% efficient steam turbine drive, the energy required is 1% of the thermal energy transferred. This represents approximately 4% of the plant steam output, a reasonable figure.

However, if the boiler were designed for the same heat transfer rate at atmospheric pressure as at 10 atmospheres, the frictional losses and power required for the blower drive would amount to 100 times the above figures. Since the pile pressure drops are approximately eight times that allowed in the boiler, its frictional losses are sizeable but reasonable. However, if the pile were run at atmospheric pressure the frictional losses would consume a majority of the plant output at full load. Therefore from a balance of frictional losses, equipment size, and mechanical problems involved, 10 atmospheres operating pressure and 1/2 psi pressure drop through the boiler has been adopted.

c. Preliminary Investigation of a Boiler Design

The boiler is sufficiently different from conventional boilers or heat exchangers that no "measuring stick" is available to evaluate the designs submitted by manufacturers. Therefore a preliminary investigation was made to determine the magnitudes of heat transfer coefficients, the size of boiler, and the problems which may have to be faced from such considerations as radiation effects and steam contamination of the pile due to a steam leak.

From the specifications given in Section 2-A page 97 , the following design factors were determined:

	*Θm	**AU
Superheater	700°F	15,700
Evaporator	450°F	105,000
Economizer	250°F	50,000

The quantity of steam which will be generated by the boiler under these conditions is 56,500 pounds per hour.

Based on this rate of steam flow, a natural circulation boiler, with 1" OD tubes on $1\frac{1}{2}$" staggered centers, as shown in figures 4 and 5, is visualized. The boiler contains 900 tubes each having an active length of 10 feet. The transfer rates are 100 Btu/sq ft/°F/hr for the economizer and evaporator surfaces, and 33 Btu/sq ft/°F/hr for the superheater surface. The pressure drop through the boiler is estimated as 0.4 psi. The weight of the boiler dry is approximately 20,000 lbs; wet 23,000 lbs. The approximate dimension of the unit is 5 ft diameter and 16 ft overall height.

The design was chosen so that natural circulation could be used in order to eliminate a forced circulation pump with connected problems of piping the water to the outside of the six foot thick shielding and to minimize the possibility of boiler derangement which might be encountered in the event of failure or maloperation of the forced circulation pump. The water and steam drums are placed inside of the helium pressure shell to eliminate the differential expansion problem which would otherwise be encountered at the seal between the tubes and this shell. A thin inner shell is used so that the helium pressure shell can be held at a uniform temperature in order to minimize stresses in the pressure shell. The active sections of the tubes are straight but the tube and sections connected to the headers are curved in the evaporator and the tubes are hairpin shaped in the superheater and economizer to allow for differential expansion.

The above design is presented only to give an approximation of the size and weight and it is not to be considered a "working" design. The size of the complete boiler could be reduced by some 20% if finned tubes were used. Even though the boiler itself is not large, it can be seen that the addition of 6 foot thick shielding will present a massive structure.

d. Manufacturers Proposals

Various companies considered best qualified to supply boilers and heat exchangers for the power pile application have been contacted concerning their interest in supplying this equipment. These contacts have resulted in conferences with the representatives of four companies. These have afforded the opportunity for presentation and discussion of

* Logarithmic mean temperature difference, i.e. the temperature gradient available for flow of heat from the helium to the water and steam in the boiler.

** The product of heat transfer surface and rate; this is directly proportional to the amount of heat transfer surface for a fixed allowable frictional loss which must be provided in the boiler to obtain the specified performance.

the specifications outlined herein and an exchange of ideas as to the design of apparatus for generating steam at the desired temperature and pressure from the heat available in the helium circulated through the power pile.

1. The Foster Wheeler Corporation has declined to undertake the design of a direct heated boiler if serious consequences result from a boiler failure which permits entrance of water vapor into the power pile. The company is however, proceeding with the design of an indirect system of the type outlined in figure B-4, in Book II, wherein the heat contained in the primary helium circulated through the power pile is transferred to a secondary helium circuit through employment of a helium to helium heat exchanger. The secondary helium circulated through this heat exchanger constitutes the heating medium for the steam boiler.

This dual system has an obvious safety advantage over a direct heating boiler, as a boiler leak would discharge steam into the intermediate helium system rather than into the primary system, and leakage of steam into the pile could occur only in the event of simultaneous failure of both the boiler and the helium exchanger; an extremely improbable occurence.

The disadvantages of the dual system are that both the boiler and the heat exchanger are necessarily a great deal larger than the direct heated boiler and that the necessity for pumping helium through the secondary helium circuit causes an appreciable parasitic power demand with corresponding decrease in overall efficiency and net power obtainable from the plant. However, one advantage may be gained; that of reducing the size and complication of shielding for the hot heat exchanger.

The Foster Wheeler design is proceeding on the basis of using finned tubes in the helium-to-helium exchanger, and possibly in the boilers, with the view of decreasing the size and weight of these units. In view of the probable large size of the units it may be necessary to provide several units in lieu of the two boilers originally contemplated. Details of construction and arrangement of the units have not been fully developed as yet but the company has indicated that a fairly complete proposition design study will be furnished shortly.

2. The Babcock-Wilcox Company is proceeding with the design of a direct heating boiler on the basis that investigations now underway at Clinton Laboratories show that sudden introduction of water vapor into the pile will not result in immediate and uncontrollable increase in the reactivity of the pile. The boiler will probably be of the vertical tube type in order to preclude, if practicable, the necessity for forced circulation in the steam-water circuit. If the provision of extended surface on the boiler tubes should be found to necessitate forced circulation, it is likely that bare tubes will be employed in this design.

The control of superheat or final steam temperature will probably be accomplished by a direct contact desuperheater installed in the steam supply main close to the boiler; the company is also considering recirculation of part of the superheated steam through a coil installed in the steam drum and remixing this cooled steam with the superheated steam to provide superheat control. Some means for superheat control is essential in order to avoid excessive steam temperature under reduced power operating conditions. Superheat control through provision of adjustable baffles for controlling helium flow through the superheater has been considered and has been rejected to avoid the need for installing the necessary control apparatus under exposure to the temperature, pressure, and radioactivity of the helium gas.

Babcock and Wilcox is considering the feasibility of undertaking the experimental study of corrosion and deterioration under exposure to fission products of the various types of steel normally used in the construction of a boiler of this type. In this connection, Clinton Laboratories will attempt to supply representative fission products for this study.

A proposition design for a complete boiler is underway. Drawings and description of predicted performance and operating characteristics of a direct heated boiler will be submitted in the near future, together with an estimate of the time required for construction and delivery.

3. The Allis-Chalmers Manufacturing Company has agreed to proceed at once with a proposition design for a direct heating boiler and to present the complete study for review in the near future.

The type of boiler construction being developed is shown schematically in Figure B-8, Book 2. The heat transfer surface is composed of concentric layers of helically wound tubes assembled on a vertical axis and enclosed in a cylindrical shell. The tube nest is divided into three sections to comprise an evaporator, superheater, and steaming economizer. The superheater is placed between primary and secondary sections of the evaporator with relation to helium flow. Forced circulation through the evaporator is obtained by the boiler feed pump discharging at approximately 900 psi, so that no separate forced circulation pump is required. The feed water, in which a small amount of steam has been generated in the steaming economizer, actuates an ejector, thus providing for recirculation of water drawn from the boiler steam drum. This is shown in figure B-8, Book 2.

Adjustment of final steam temperature with variations in steam demand is secured through adjustment of steam drum water level. Raising the water level increases the static head in the line connecting the boiler drum to the ejector, thereby increasing the quantity of water recirculated from the boiler drum through the primary and secondary evaporator sections. This action, in turn, tends to increase heat removal from the helium flowing past the primary evaporator and thereby decreases the temperature of the helium traversing the superheater surface, with consequent decrease in the final superheated steam temperature. Decrease in steam drum water level, conversely, increases the final steam temperature.

The type boiler construction described is somewhat unconventional but the company has successfully built and operated boilers of this type for high steam temperature and pressure applications, and the geometry of the arrangement offers advantages for accommodation of the pressurized helium.

4. The Combustion Engineering Company is proceeding with a proposition design for a direct heating boiler for the power pile application. This design will conform generally to the arrangem shown diagrammatically in figure B-9. The company has built a large number of boilers of this general type; many of these have been used as exhaust gas heated evaporators in connection with diesel power plant installations.

The heat transfer surface is arranged in the form of layers of flat tube coils, and the surrounding cylindrical shell is designed to retain the pressurized helium directed through the superheater, evaporator, and economizer coil sections. Forced circulation through the evaporator is essential in this design, and the pump will probably have to be located outside of the boiler shielding to avoid radiation contamination of the bearing lubrication system and packing. Superheat control will be accomplished outside the boiler structure by use of a direct contact, spray type desuperheater.

The company has agreed to complete shortly a proposition design study along these lines and it is expected that construction and arrangement drawings together with operation and performance specifications will soon be available for review.

e. Dual Systems.

In event that a steam leak into the helium system may damage the pile or cause an explosion, various "dual" systems are being investigated. This is not being done at the expense of any delay in the design of the single system outlined herein, since all manufacturers, except Foster Wheeler Corporation, have been urged to proceed with single system designs and only to think of methods of preventing a steam leak into the primary helium circuit. The purpose of a dual system is to introduce an intermediary heat exchanger fluid between the steam and the primary helium so that a leak from the steam circuit will not introduce water vapor directly into the primary helium circuit.

1. Mercury Dual System. Figure B-5 depicts a system in which the thermal energy is absorbed by mercury in a primary heat exchanger and is transferred by the mercury to the steam in the boiler. By this means however, the pile helium circuit is safeguarded by the added mercury circuit. If mercury leaks into the helium circuit and thus enters the pile, it will cause no other damage than shut down of the pile because of the high neutron absorption cross-section of mercury.

Mercury in spite of its low heat capacity per pound and its low conductivity gives high heat transfer rates because of its high density.

Liquid mercury convection transfer rates are sufficiently high that it was used by Rhodes and Bridges to determine the fouling factors in boiling water transfer rates.* A finned primary exchanger could be built using either liquid mercury throughout as the transfer media or a system similar to that used in a binary mercury-steam cycle. In the latter case the mercury is evaporated and superheated in the primary heat exchanger and is condensed while evaporating the water in the steam boiler. Figure 11, page 110 shows the operating temperatures and pressures for such a system. This system could be designed so that the mercury boiler could operate on gravity feed thus eliminating the mercury pumping problem. The liquid mercury system has the advantage of being more compact but it requires pumps to circulate the mercury. Although some trouble was experienced with mercury boilers in early installations these boilers are now operating very successfully. ** The problem of containing and pumping mercury are completely solved.

For either the liquid or boiling cycles finned tubes can be used to obtain an overall transfer rate in the primary heat exchanger in the order of 500 to 1,000 Btu/°F/hr. per sq. ft. of tube surface.

This heat exchanger would contain less the 200 tubes 1" dia. 10 feet long and could be built rather compactly keeping the size of the "hot" heat exchanger to a minimum. The steam boiler can also be built very compactly because in this case the transfer rates for both fluids is high. Therefore the mercury dual system is entirely feasible.

2. Helium Dual System. A system employing helium in place of mercury as the intermediate heat exchanger fluid could be used, see figure B-4, Book 2 and Figure 12, page 111 . This system would afford the same safeguard as the mercury dual system. The secondary helium circuit would be operated at a pressure slightly higher than the pile helium circuit so that if a leak developed between the two "pure" helium would be admitted to the pile with no ill effect. Since the helium film is controlling in transferring heat, an introduction of two more helium films increases the resistance to heat flow some two to three times that of the single system. For a fixed transfer coefficient for the helium film the total area would have to be increased some 4 to 8 times since, as in an electrical circuit, the heat flow is proportional to the square of the resistance. The picture need not be this bad however since the primary heat exchanger (the helium to helium exchanger) could be made of a highly efficient type of surface namely the interrupted fin surface design. *** This construction will provide

* Trans. Ans. Inst. Chem. Engrs. - Vol. 35, 73-93 (1939)

** Page 625, through 656 1942 ASME Transactions.

*** "High Performance Fins for Heat Transfer" by R. H. Norris and W. A. Spofford, ASME Transactions Vol. 64, 1942 p. 489.

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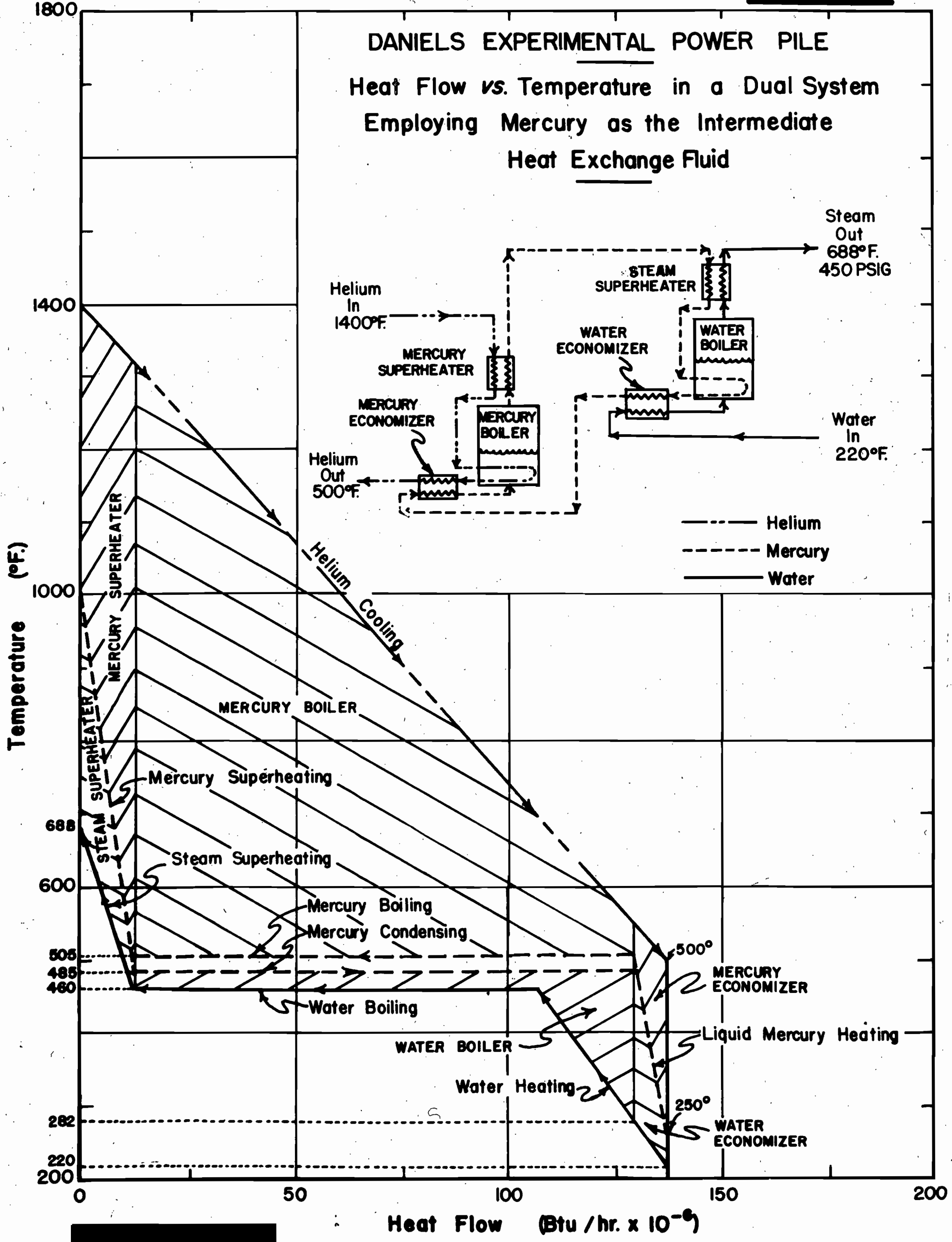

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Figure 11

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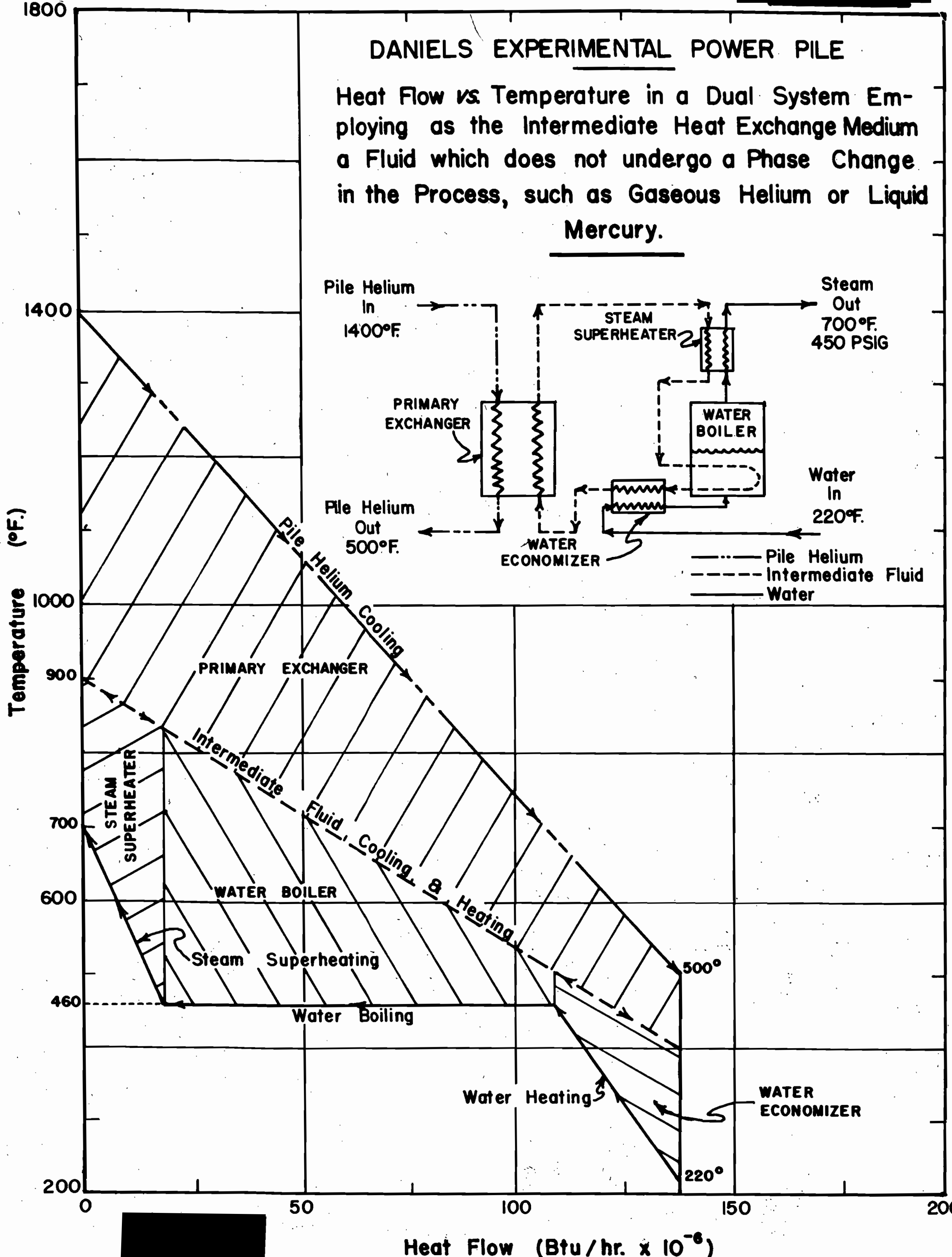

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Figure 12

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a transfer rate per unit frictional loss in the order of four times that obtainable in flow through tubes and twice that obtainable in transfer outside staggered tubes. * Furthermore, the surface area per unit volume is in the order of five times greater than a tubular exchanger. This system would still be considerably larger than the mercury dual system and would require more power to circulate the helium.

3. Double Wall Tube Construction. Among other means under consideration for decreasing the possibility of boiler steam being admitted to the pile helium circuit, the employment of double wall boiler tubes shows promise.

By use of the constructionsshown in Figure B-11, Book 2, it will be observed that under most conditions it is necessary that a leak in an inner tube or tube header joint be accompanied by a simultaneous leak in its companion outer tube or tube joint to permit direct steam leakage into the helium system, a quite improbable occurrence under any normal operating condition. Any ordinary imperfection in the inner tube occuring during operation results in leakage of steam or water through the leakage flow channels between the inner and outer tubes to the space between the primary and secondary headers. A connection is provided from this space to a leakage indicator observable by the plant operators who at the first convenient time after leakage is indicated can secure the plant for location and replacement or permanent plugging of the leaking tubes. The space between the inner and outer tubes may be subjected to periodic pressure tests for detection of possible incipient leaks in either the inner or outer tubes without danger while the plant is in full operation.

Double tube construction of this type has been widely used by the General Electric Company and General Motors Corporation in the construction of air coolers for large electric motor and generator closed air cooling systems installed aboard combatant Naval vessels where leakage of the sea water, used as the primary cooling medium, into the electric circuits would cause immediate and serious derangement of vital equipment. Little or no high temperature experience, however, is available in the use of this type of double tube construction or of alternate construction employing mercury between the outer and inner tubes in lieu of metal to metal contact. While use of double tubes results in no great increase in the amount of heat transfer surface required, the construction of the boiler is more complicated and more expensive. Should pile helium temperature circuit controls fail and very high helium temperatures result, the double tubes would soften and unless the high steam pressure were quickly relieved, there is a possibility of admitting steam to the pile helium circuit, even with the double walled tubes.

* Figure 3 of Buships Research Memo No. 5-43.

3. PILE GAS FLOW

a. Introduction

In order to remove the heat generated in the pile, sufficient coolant flow space must be provided for passage of helium without excessive pressure drop. This space is provided by use of tubular shaped fuel rods held concentrically in the moderator bricks by longitudinal ribs. Helium enters the channels at the bottom, flows upward through and around the fuel rods, and leaves the channels at the top.

A study of pressure drop through the pile showed that for operation at 40,000 KW heat output a pressure of 10 atm. is necessary to keep the pressure drop small in value. It was also shown that lower heat production levels permit the use of proportionately lower pressures; this tends to reduce leakage from the system.

b. Pressure Drop in the Pile.

Curve No. 13 page 114 shows the relation between pressure drop and helium flow in the pile for various operating pressures. Curve No. 14 page shows helium flow through the pile as a function of heat output. It will be noted that the pressure drop at 40,000 KW and 10 atmospheres is about 1.6 lb/sq. in.

The pressure drop at 4000 KW and 10 atmospheres is 0.023 lb/sq. in. The pressure drop increases to 0.23 lb/sq. in. when the pressure is reduced to 1 atmosphere. While this pressure drop is small compared to the value allowed at 40,000 KW it must not be concluded that 1 atmosphere can be used at 4000 KW. The power required to circulate the coolant must be considered in choosing the operating pressure. Such consideration indicates that the operating pressure at 4000 KW should be 3 to 4 atmospheres, and at 40,000 KW should be 10 atmospheres.

In calculating these pressure drops account was made of the fact that the helium flow is not uniformly distributed along the radius of the pile. This variation in flow is necessary to accomodate the variation in power generation with radial distance from the center of the pile. If the helium were passed through the pile uniformly, its temperature upon leaving individual channels would be widely different. Such wide variation is undesirable because it introduces additional problems of differential expansion and reduces thermodynamic efficiency.

To achieve uniformity in temperature, the flow through each channel is proportioned to the power generation in that channel, and since the power generated is a maximum in the center channel, that channel must have the maximum gas flow. For this reason the pressure drop through the pile becomes a function of the flow through the center channel.

In order to determine what portion of the total flow must be passed through the center channel it is necessary to know what portion of the total power is generated in the center channel. Since, for a cylindrical pile with reflector, an exact determination of this value is not possible, an approximation has been made.

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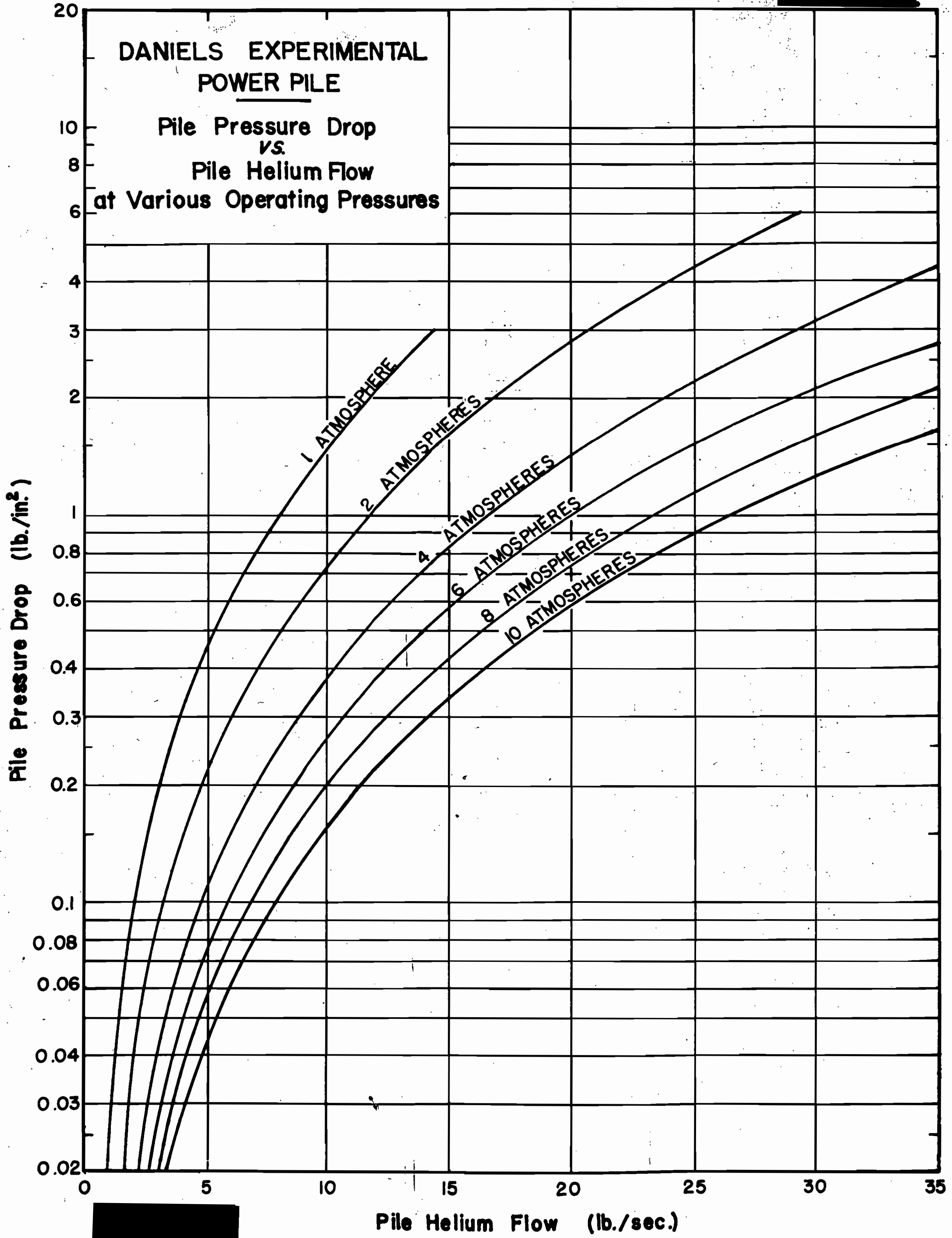

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Figure 13

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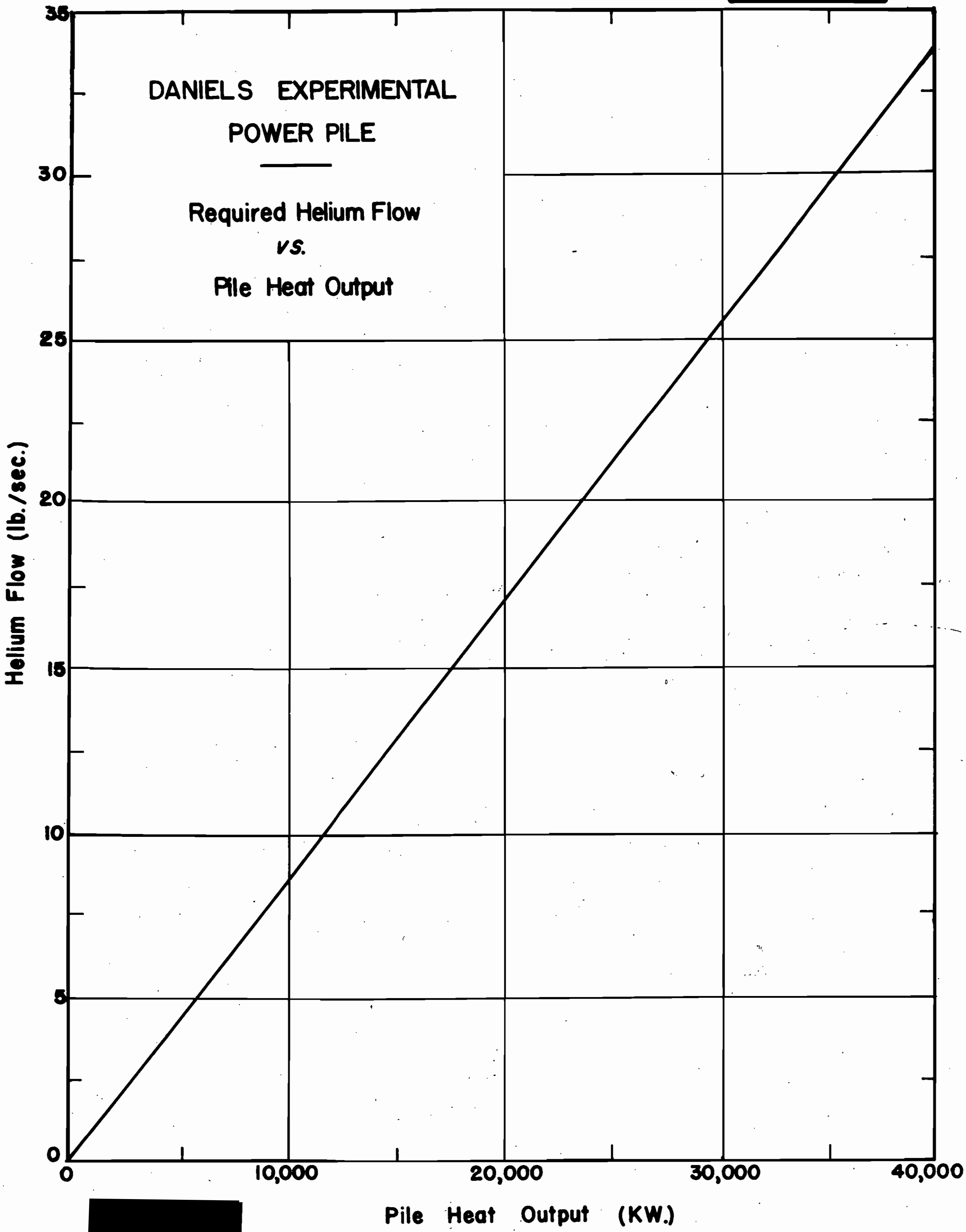

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Figure 14

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In calculating these pressure drops account was made of the fact that the helium flow is not uniformly distributed along the radius of the pile. This variation in flow is necessary to accommodate the variation in power generation with radial distance from the center of the pile. If the helium were passed through the pile uniformly, its temperature upon leaving individual channels would be widely different. Such wide variation is undesirable because it introduces additional problems of differential expansion and reduces thermodynamic efficiency.

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In order to determine what portion of the total flow must be passed through the center channel it is necessary to know what portion of the total power is generated in the center channel. Since, for a cylindrical pile with reflector, an exact determination of this value is not possible, an approximation has been made.

For a cylindrical pile without reflector, the power generation in the center channel is 2.31 times as much as would be the case if the power generation were uniform. For a cylindrical pile with reflector an analysis on the basis of simplifying assumptions, indicates that this factor should be 1.59. Experience on other piles, however, indicates that the power distribution curve might be such that, when extrapolated to the point of zero power production, it reaches zero in the reflector 20 cm. from the edge of the reactor. Computation on this basis indicates that the power generated in the center channel is 1.71 times as much as would be the case if the power generation were uniform. Curve No. 15 page 117 shows the radial power distribution in the pile for both cases.

To a sufficient blower compression ratio, the higher value of 1.71 was used for calculating pressure drops.

The pressure drops indicated by the curves are based on a flow channel 2" in diameter and 9' long filled with cylindrical rods having an inside diameter of 1" and an outside diameter of $1\frac{1}{2}$".

The pressure drops include the entrance and exit losses of the channels, friction losses therein, and acceleration losses due to heating of the helium. They take into account the resistance of the longitudinal ribs which hold the fuel rods concentrically in the moderator bricks. The losses in the plenum chambers at top and bottom of the pile are not included in these calculations, but are included in the duct system.

Tests will be conducted to check the calculated pressure drops over the expected range of operating conditions. Tests already conducted at Argonne National Laboratory on friction losses confirm the calculated pressure drop due to friction alone within $\pm$ 5%.

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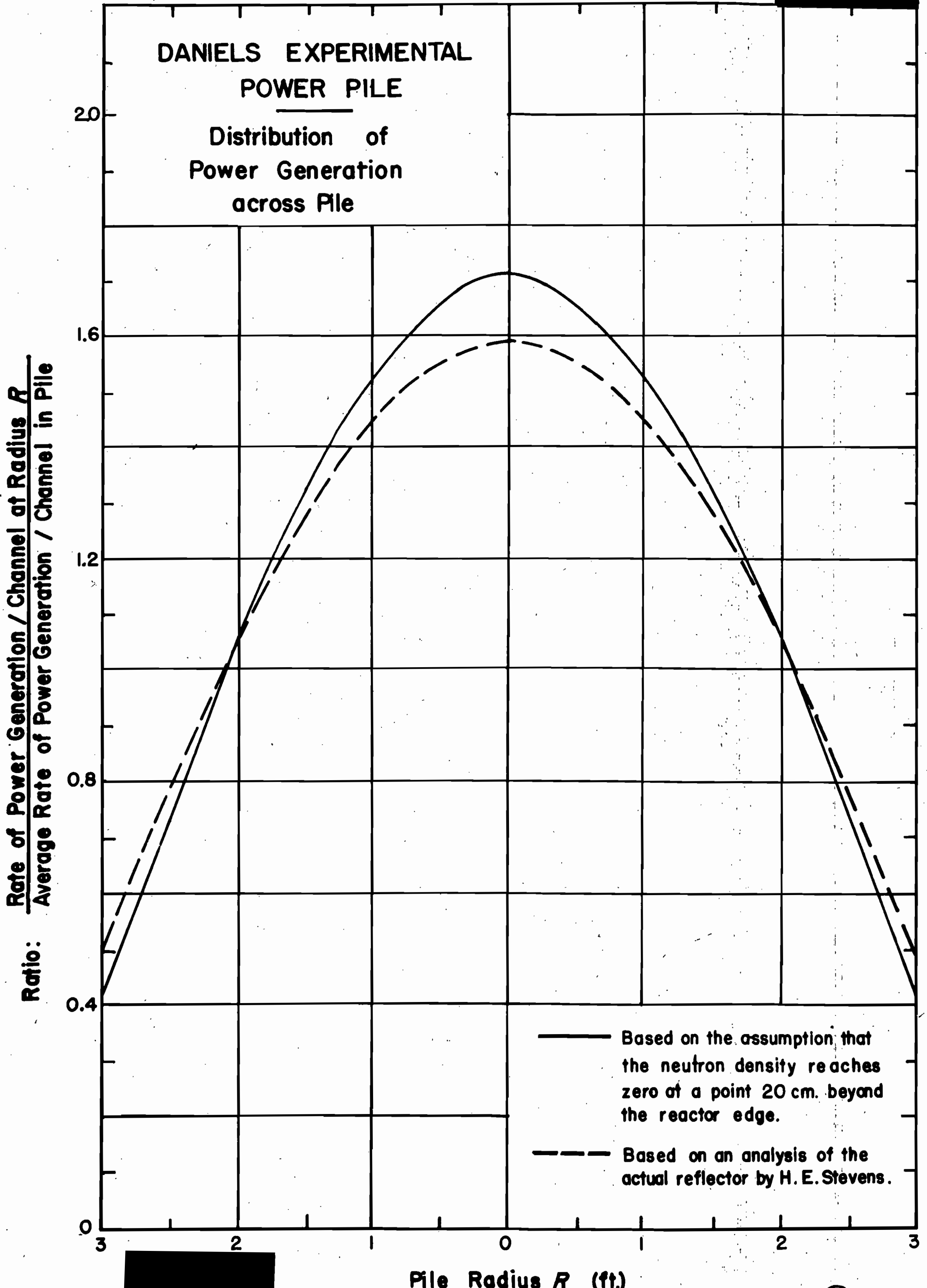

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Figure 15

N. J. Palladino
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c. Gas Flow Distribution

As was stated in the preceding section, to achieve uniformity in the temperature of the helium through individual channels the flow is to be restricted proportional to the power generated in that channel. The radial distribution of power generation in the pile is not uniform. Figure 15 (solid line) page 117 shows the expected variation of power generation with radial distances from the center channel.

The following methods of controlling flow of coolant through the pile were considered:

1. Sectional Control. Regulating flow by sectional control involves use of annular conduits on top of the pile to collect the helium from various zones in the pile. These annular conduits are individually piped to the main discharge duct so that the helium flow can be controlled by adjustable dampers. This construction is complicated and presents the problem of joining the annular rings to the moderator bricks.

2. Variation of Flow Channel Lengths. The control of flow by varying the flow channel lengths involves a design where the outer channels are five times as long as the center channels. This type of construction is objectionable because it does not permit maximum use of reactivity in the pile.

3. Variation of Channel Flow Areas. It is possible to control helium flow through the pile by varying the flow area from channel to channel. This method is not attractive because of the expense of making many sizes of fuel rods and moderator bricks and because it complicates the loading mechanism.

4. Use of Orifices, Top or Bottom. Orifices can be used to control the helium flow through the pile. They may be placed either at the top or bottom of the flow channels. If orifices are placed at the top they will be larger and easier to fabricate accurately than if they are placed at the bottom. They will be larger because the volume of the helium is greater at the higher temperature at the top of the pile. The disadvantage of using orifices at the top is that they are not accessible for easy replacement. Ability to replace orifices is desirable because the required distribution of gas flow cannot be exactly predicted in advance. The disadvantages of having orifices at the bottom are that they have smaller flow areas and that they must be removed and handled each time a fuel rod is changed in any channel.

Consideration of the above factors have lead to the decision to use orifices for control of helium flow. Whether they will be placed at the

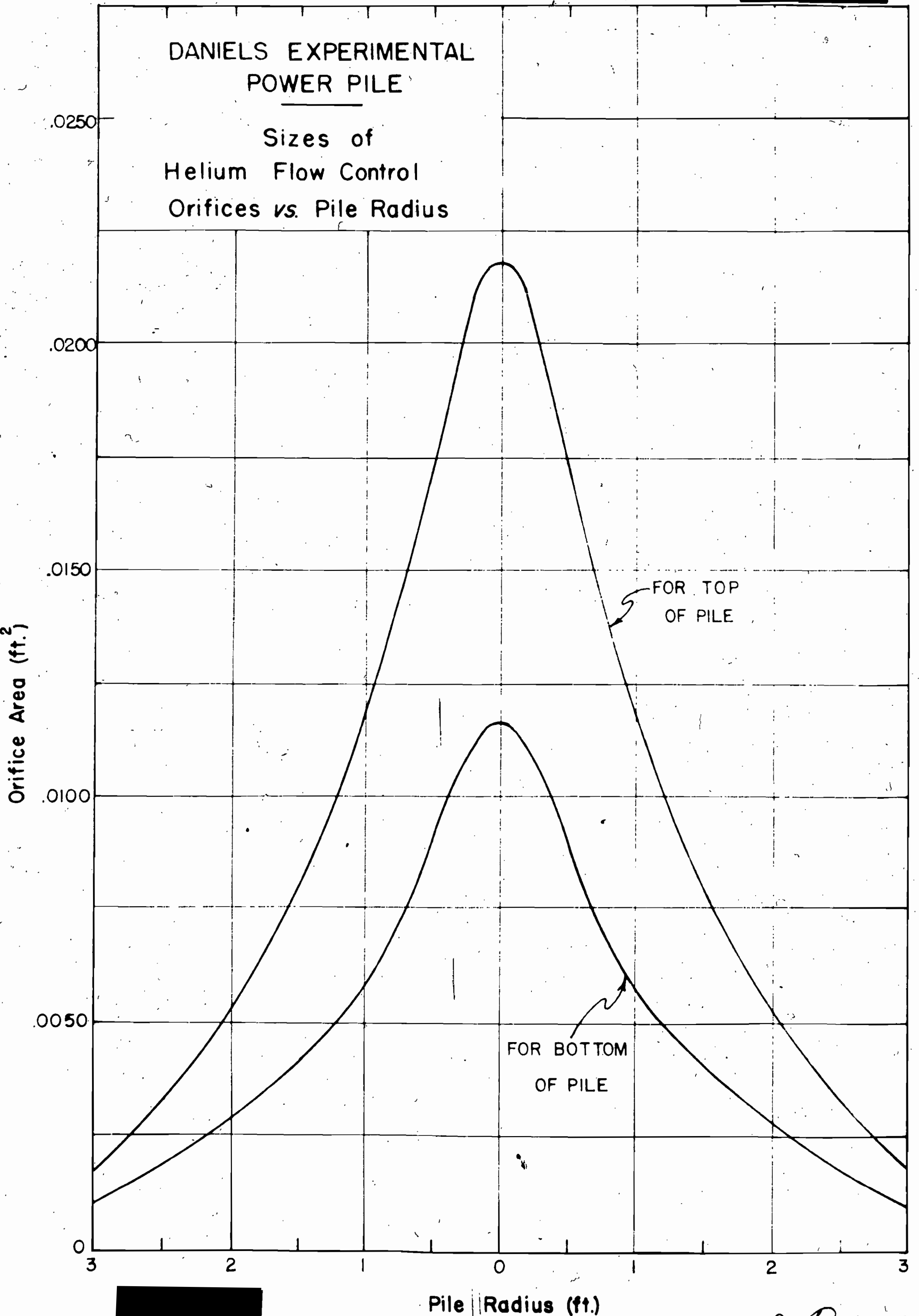

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Figure 16

N. J. Palladino
10-21-46

top or bottom has not yet been decided; both are feasible.

Figure 16 page 119 shows the area requirements for orifices at the top and for orifices at the bottom. In each case the center channel is designed to have no restriction. These curves are drawn for a continuous change in orifice size with distance from the center channel. Theoretically a different orifice size would be required for each set of channels at the same distance from the center; for engineering reasons however, a limited number of sizes will be used.

4. HELIUM SUPPLY

a. Source and Specifications

Helium gas for this project will be obtained from the Amarillo, Texas, Helium Plant operated by the Bureau of Mines, United States Department of the Interior, and will be purchased as "high-purity helium."

b. Purity

The purity of helium presently being distributed by the Bureau of Mines is 98.5% which is not sufficiently pure for this application. However, they are making improvements to their plant and will probably be able to supply bulk quantities of 99.9% helium early next year.

c. Shipment, storage

Shipment will be made in high pressure helium tank cars of the type used by the Navy. These are special railway cars carrying a bank of high pressure cylinders with suitable manifolds, valving, and charging connections. The capacity of one of these cars is about 200,000 cu. ft. at Standard pressure and temperature, when charged to 2000 psi.

Storage will be in banks of long steel cylinders manifolded together in racks similar to those used at Hanford.

d. Purification for use in Pile

Even though the purity of the helium received may be 99.9% it is anticipated that some purification will be necessary to remove any contamination which may have entered during shipment, and to remove all traces of moisture and oxygen from the gas before it is admitted to the pile.

Since the experimental data required for establishing helium purity tolerances is not yet available, details for the purification equipment have not been worked out. It is believed that when this data is available the design of the purification equipment will be a relatively straightforward chemical engineering problem.

e. Properties

The physical properties of helium are listed below:

Molecular Weight	4.0
Universal gas constant, R	386 ft/°R
Density (32°F and 14.7 lb/in²abs)	.0112 lb/ft³
Specific heat at constant pressure	1.242 Btu/lb°F
Specific heat at constant volume	.746 Btu/lb°F
$k = C_p/C_v$	1.667

The variation of viscosity and thermal conductivity with temperature are shown on Figure 17 page 123. The variation of specific film coefficient with temperature is shown on Figure 18 page 124.

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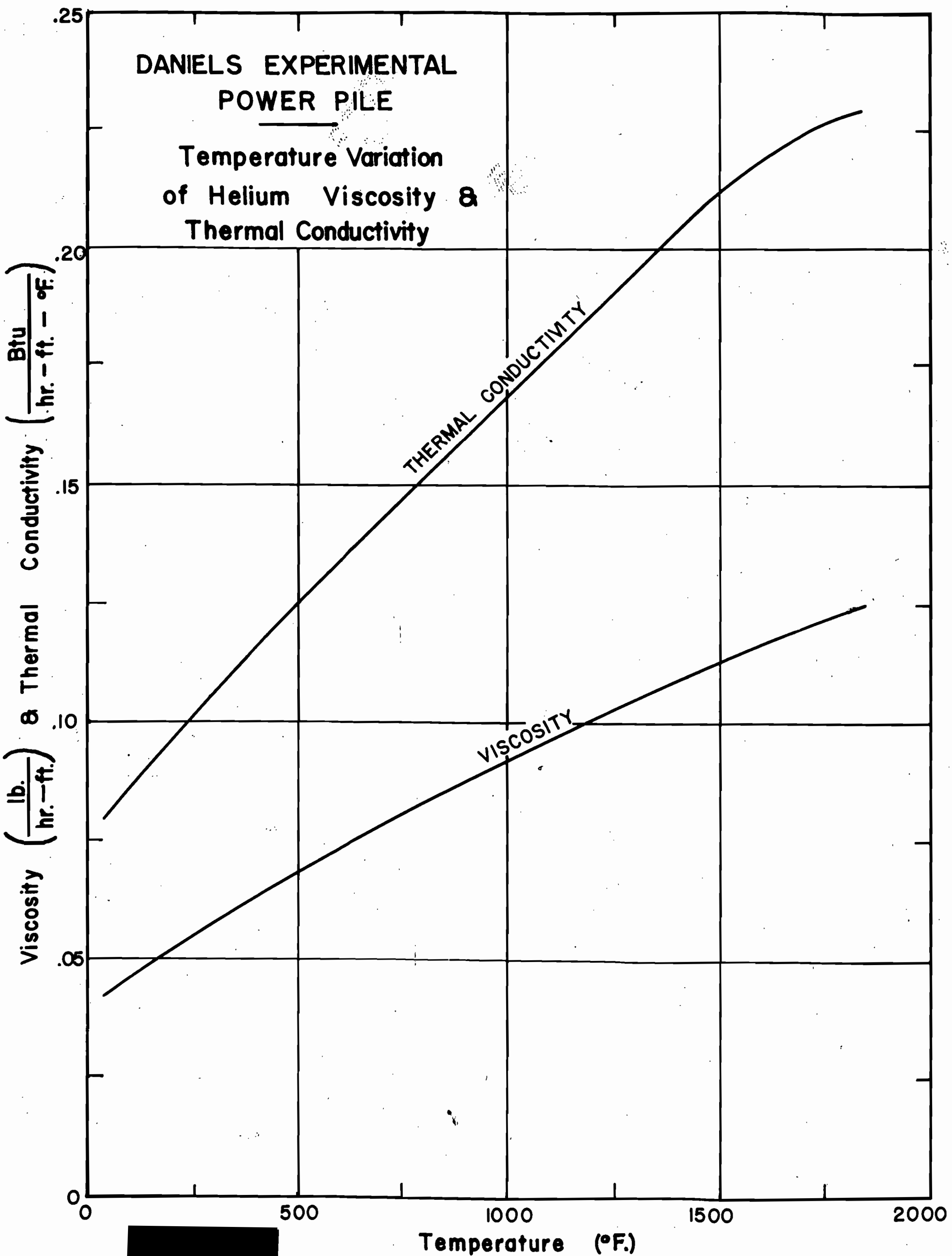

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Figure 17

A. L. Preston
10—21—46

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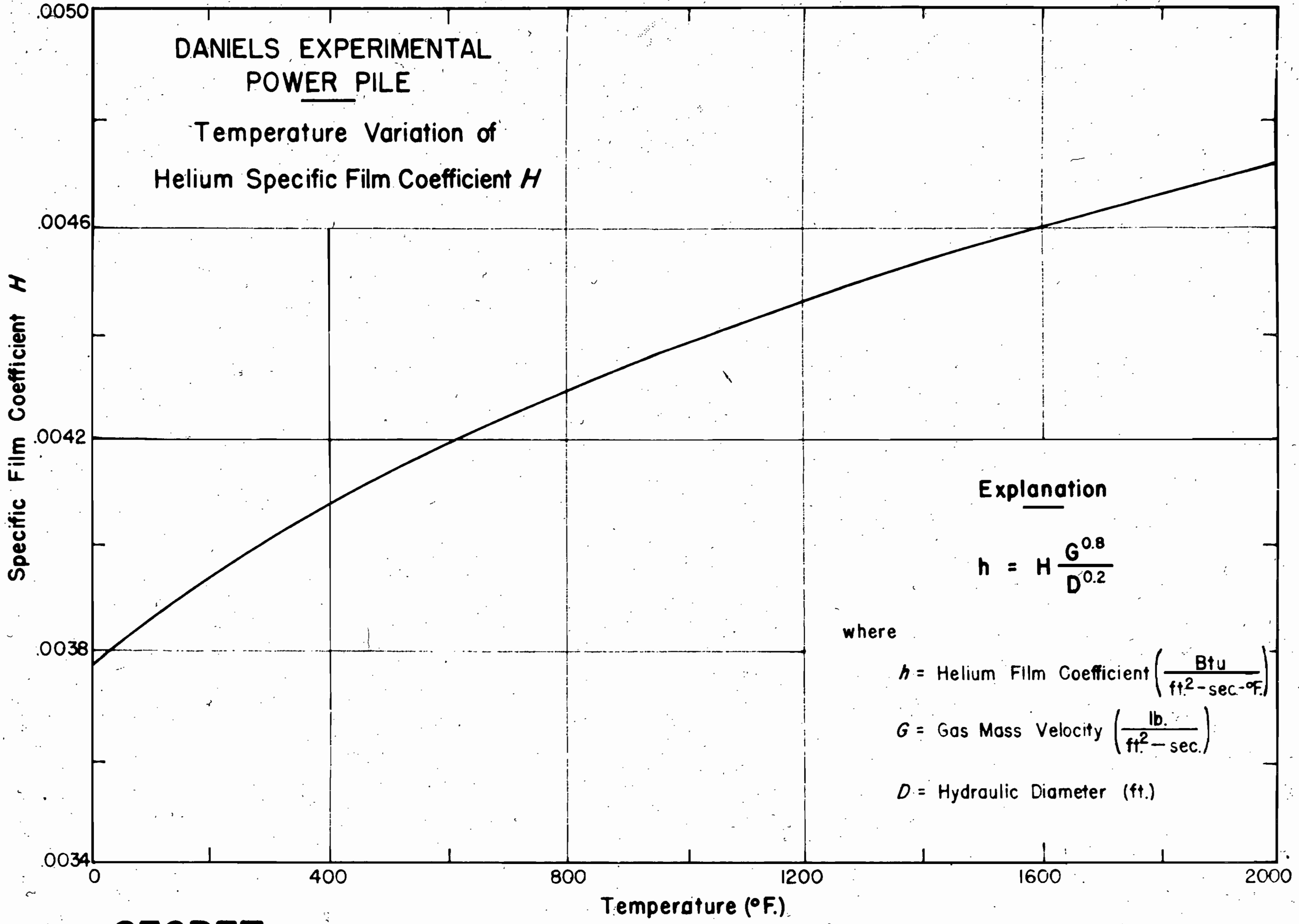

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Figure 18

A. L. Preston
10—21—46

5. HELIUM IN POWER GAS SYSTEM

a. Deoxidation and Dehumidification

Equipment to remove oxygen and moisture from gas in the main circulating system will be provided as shown in the flow diagram, Fig. B 12 Book 2 . Full details of this equipment have not been worked out since data on purity tolerances is not yet known. However, it is anticipated that the flow through this system will be ten percent of the main gas stream. Copper will probably be used to remove oxygen at 500°F and Al_2O_3 to remove moisture. Pressure drop will be balanced by the pressure rise in the main blowers, as shown on the flow diagram. This means that the blower flow rate will be ten percent greater than the main circulation rate.

Copper for oxygen removal is prepared and sold by Air Reduction Sales Company. It is apparently made from copper oxide pressed into pellets and reduced once with hydrogen by a patented process.

b. Discharge and Storage System.

It is anticipated that there will be some helium leakage from blower shaft seals and occasional discharge from the main pressure relief valve. This gas, together with any gas impurities removed in the dehumidifier and deoxidizer will be conducted to the discharge system. The discharge system will include a decay tank of sufficient size to allow time for decay of radioactivity in these gases before exhausting up a stack. Radioactivity of the stack gases will be measured and recorded by suitable instruments.

Storage will be provided in order to temporarily remove helium from the system as required during load changes and return the helium to the system later. A pump with suitable valving will be supplied for transferring the helium to or from the system. Storage will be in a large, low-pressure tank, possibly located underground for shielding.

c. Volume of System.

Preliminary estimates have been made of the volume of various portions of the helium system and tabulated below:

Pile	700 ft^3
Ducts	1600 ft^3
Boilers	1000 ft^3
Blowers & Separators	500 ft^3
Dehumidifier & Deoxidizer	300 ft^3
Total	4100 ft^3

d. Purging and Initial Charge

Before putting the helium circulation system into operation, it will be necessary to pressure test, leak test, purge, and charge the system with high-purity helium. The pressure testing can be done by conventional methods prescribed in the A.S.M.E. code. The leak testing must be very carefully done and will probably require the use of electronic leak detection apparatus of the mass-spectrometer type, such as is used in high vacuum work.

To facilitate the leak testing and purging, an evacuation system will be provided. This will include a large capacity oil diffusion pump backed up by a Kinney, Stokes-McLeod, or equivalent mechanical vacuum pump, or by a suitable steam jet exhauster. Such equipment is built by Distillation Products, Inc., Rochester, N. Y., and others.

In evacuating, it is anticipated that large volumes of occluded moisture, air, and gases will be encountered, so that it may be necessary to flush the system with pure helium and evacuate it one or more times to obtain a charge of the required purity. This flushing helium, as well as the full charge, will be admitted to the system through the makeup line and purification system from the fresh helium supply.

e. Helium Recovery.

Although it would be possible to recover and repurify helium from the discharge system, this would require quite extensive facilities and it is not considered economical to operate such a recovery plant in competition with the Bureau of Mines plants. New helium can be obtained from them at an estimated cost of about one cent per cubic foot. Recovery costs would probably be considerably greater than this, even without the radioactivity considerations.

6. DUCTS

The gas circulating system is composed of two major duct groups: One for 1400°F operation, and one for 500°F., both at about 150 psi abs. Several auxiliary duct systems are required for necessary components of the complete plant.

Fortunately, considerable information is available from gas turbine installations to assist in designing a reliable duct for 1400°F. This design consists of two concentric shells, with the annular space between filled with insulation as shown in Figure B-10 Book Two. As this annular space is maintained at slightly greater than internal (system) pressure the inner shell is not greatly stressed. This shell serves merely to prevent contamination from insulation into the system and to keep the insulation in place. An outer shell serves to support the structure and to retain the gas at 150 psi abs.

The inner shell must be gas tight in order to minimize in-leakage from the annular space. Longitudinal expansion is accumulated by bellows type expansion joints welded directly to this inner shell. Either 18-8 (stabilized) or 25-20 Stainless is suitable for the shell. As the shell is but slightly stressed (pressure on internal and external surfaces equalized, and surface temperatures equal), a thin walled 1/4" thick shell is suitable.

Thermal insulation will be placed directly around the inner shell. Either Eagle "66" (Eagle-Picher Co.) or Superex (Johns-Manville) will be acceptable for use at 1400°F. Radiation effects will have to be determined on these. Approximately 9 inches of insulation are required to insure a maximum surface temperature of 150°F.

A mild steel outer shell 3/8" thick will be provided to withstand internal pressure and to serve as a support for the structure. A clearance of 3/8" between outer shell and insulation is necessary to allow for difference in expansion of inner and outer shell. Longitudinal contraction and expansion is taken care of by either bellows or special gas turbine type expansion joints. As this shell is not exposed to 1400°F. no trouble will be encountered from thermal stress.

Average gas velocity is 150 ft/sec. at 1400°F and 147.5 lb/in^2a in a circular duct 2.25 ft. in diameter, which gives a pressure drop of 8 lb/sq. ft./100 ft. A duct 27 inches inside diameter (inner shell) and 47 inches outside diameter (outer shell) will meet these conditions of velocity and pressure drop.

There will be a separator in the 1400°F. duct to collect foreign particles, BeO chips, etc. Preliminary investigation indicates that a cyclone type separator is feasible. Provision will be made for periodic removal of the solids collected in the separator from a remote station for inspection and analysis.

The 500°F lines from the boilers will be 18 inch diameter pipes insulated on the outer surface. Longitudinal expansion will be afforded by means of expansion loops or bellows. These 18" pipes will give an average velocity of 100 ft/sec. with a pressure drop of 7 lb/sq. ft/100 ft.

Bolted connections will be used in the 500°F lines. No bolted connections will be employed on the 1400°F line; all welded joint construction will be used. None of the auxiliary piping will be larger than 12" and none hotter than 500°F, so that no trouble is anticipated.

The helium systems previously discussed are so arranged that values will be required only in the 500°F helium ducts and auxiliary lines. It is anticipated that valves similar in construction to those used in the K-25 plant may be applicable here. However, due to more severe operating condition of temperature and pressure, an extensive investigation and test program will be necessary before a final valve design can be accepted.

All valves will be double sealing with metallic sealing surfaces. Small valves 12" or less will be packless, ie. bellows seal. Larger valves may be bellows sealed or double packed. Many of the main and auxiliary valves will require remote control similar to that used at K-25.

VI APPENDIX

APPENDIX I

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Argonne National Laboratory Reports

A. Bibliography for Pile Physics Considerations. Section IV-A, Page 32.

B. General Bibliography - Report of Argonne National Laboratory.

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A. Bibliography for Pile Physics Considerations.

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3. "Slow changes in the Laplacian of a thermal pile," Way, K., MUC-KW-58, 12-28-45.

4. "Age in Be and BeO", Goldberger, M. L., MUC-WC-MLG-10, 1-12-46. Contains information on changes in basic data which affects the pile calculations.

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7. "Constants of Be and BeO, " Way, K., MUC-KW-60, 4-12-46. Summarizes most recent values of constants used in pile calculations.

8. "Change in Laplacian with change in temperature in BeO pile." Way, K., MUC-KW-61, 4-12-46. Indicates method whereby temperature variations may be incorporated in critical size calculations.

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11. "Changes in MUC-RGS-AVM-5 and MUC-RGS-2 resulting from new loading density and new transport cross section," Sachs, R. G., ANL-RGS-2. Modifies work of (6) and (9) to conform to recently redetermined constantsand new design proposals.

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(A), (B), (C), etc., denote associated groupings of reports. Each group pertains to a single subject:

(A) General surveys, summaries and status reports.
(B) Thermal Stresses in fuel rods.
(C) Thermal conductivity under radiation.
(D) Coolant pressure drop.
(E) Operating mechanism.

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(B) 4. "Temperature variations in fuel rods," Hutchison, C. A., MUC-JEW-64, 1-5-46.

(C) 5. "Report on thermal conductivity of low density BeO bodies." (Battelle), Linebrink, O. L., Nelson, H. R., CT-3437, 2-1-46.

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(D) 7. "Consideration relative to the gas flow, channels and heat transfer surfaces of a high temperature oxide pile," Robertson, A. F., MUC-CAH-2, 3-1-46

(A) 8. "Status of engineering problems on pile," Robertson, A. F., MUC-CAH-10, 4-9-46.

(B) 9. "Temperature and thermal stresses in pile fuel rods," Hutchison, C. A., MUC-CAH-7, 4-15-46.

(C) 10. "Experiments to determine the effect of neutron radiation on thermal conductivity of mixed oxide bodies." (A discussion of apparatus to be used.) Deem, H. W., Nelson, H. R., CT-3527. 4-20-46.

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(C) 18. "Recent heat conductivity data from the Battelle Memorial Institute," Willard, J. E. MUC-JEW-121, 6-15-46

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(E) 20. "Possible control rod actuation mechanism for Power Pile." Robertson, A. F., MUC-ACH-44, 6-25-46.

21. "Summary of information available on special thermocouple wire for neutron thermopile and boron-containing alloys for control rods," Robertson, A. F., MUC-CAH-45, 6-25-46.

22. "Volatilization of uranium from fuel rod material," Hutchison, C. A. and Malm, J. G., MUC-CAH-46, 6-25-46.

(C) 23. "Minutes of the Meeting, Friday, July 5, 1946", Dismore, P. F., ANL-OCS-5, 7-5-46.

(D) 24. "Observed pressure drops in fuel rod channels," Fairchild, H. B. ANL-OCS-29, 7-19-46.

(E) 25. "Fuel rod loading and unloading mechanism for top of pile operation," Fairchild, H. B., ANL-OCS-18, 7-26-46.

26. "Research on graphite impregnated with U_3O_8," Daniels, F., CL-FD-5, 8-6-46.

(A) 27. "Plans for nuclear measurements for the power pile," Daniels, F., CL-FD-5, 8-6-46.

(D) 28. "'Cane' and 'Bamboo' fuel rods," Fairchild, H. B., ANL-OCS-31, 8-7-46.

The Weekly Abstracts of Section C-II at Argonne National Laboratories supplements the subjects covered in the above reports, keeping the work progress and data up to date. These Abstracts are issued under the following codes:

MUC-OCS-33
ANL-OCS-1, -11, -15, -19, -25, -32, -37, -46, -51, -53, -57, -61, -69, -76, - 77

The first was issued on 6-27-46 while the last was issued 9-26-46.

Several valuable information sources originating at locations other than Argonne National Laboratory are included here for the sake of completeness:

1. Hanford Engineer Works Technical Manual.
2. Clinton Laboratories Project Manual.
3. Final Report on Production Test, No. 105-5-P, Survey of Shielding, Wende, C. W. J., 7-2822, 9-21-45.
4. Review of the High Temperature Power Pile Program, Daniels, F., 10-6-46.

The first design for Hanford was a helium-cooled pile of natural uranium and graphite. It was replaced by the water cooled piles. This proposal of a pile cooled with helium under high pressure is described by Moore and Leverett. CE-277, "Preliminary Process Design of Power Plant."

APPENDIX II

Abstracts From Hanford Technical Manual

Safe Radiation Limits

Experience with radium and x-rays has shown that the human body can safely absorb a distributed radiation dosage of 0.1 Roentgens per day for an indefinitely long period. All shielding arrangements are, therefore, desgined to reduce the radiation to a level whereby the possible absorption for an eight hour day cannot exceed 0.1 Roentgen in equivalent radiation from the shield.

The Roentgen is essentially a unit of gamma dosage defined as that quantity of gamma radiation which will produce one electrostatic unit of ions in one cubic centimeter of atmospheric air.

Equivalent radiations corresponding to 0.1 Roentgens per 8 hour day are listed in the following table:

Radiation	Flux (particles per sq. cm.per sec.)
2 Mev. beta particles	80
2 Mev. fast neutrons	200
2 Mev. gammas	3300
Thermal neutrons	15000

Types of Radiation Hazards

Beams. Assuming that direct radiation through the uninterrupted shield wall is at a level so low that no hazard exists, there still exists the possibility of concentrated rays escaping through cracks or access openings.

Inhalation. Radioactive gases or dispersions of active materials may be hazardous if inhaled.

Ingestion. When active materials are swallowed, the amount retained in the body depends strongly on the chemistry of the active substance. For instance iodine and cesium are 100 per cent absorbed but most fission products are less than 1 per cent absorbed.

Contamination. Radioactive material clings tenaciously to the hands or clothing and may be hazardous by direct radiation or subsequent inhalation or ingestion.

Effectiveness of Shielding Materials

Iron is effective in absorbing thermal neutrons and gamma rays and a layer 10 inches thick for the first barrier of a shield will absorb about 97 per cent of the total energy, converting it to heat. Fast neutrons are somewhat reduced but can be more effectively reduced to slow neutrons by a barrier of masonite. A subsequent barrier of iron will effectively absorb the resulting thermal neutrons. Thus, a laminated structure of alternate layers of iron and masonite operate in succession to reduce the neutron density to the desired degree and, at the same time, absorbing some gamma rays. A curve, figure A14(page 818 of section B, Hanford Technical Manual) illustrates the action of a composite shield of masonite and iron.

Residual radiation composed mainly of gamma rays are effectively absorbed by any material in sufficient mass. Therefore, the heavy materials require less thickness and ordinary concrete is economically suited for the purpose.

A table of thicknesses of shielding materials required to reduce the intensity by tenfold of various radiations follows:

Thickness in Inches Required For
Tenfold Reduction in Intensity

Material	2 Mev Gammas	Thermal Neutrons	Fast Neutrons (Approximately)
Water	20	2	4
Masonite	15	3	8
Graphite	12	45	15
Concrete	10	7	17
Iron	2.6	1.3	20
Lead	1.7	8	--

APPENDIX III

A. PROPERTIES OF BeO

1. Crushing strength OCS-33P2; CAH-25P2 & 8,9,10,11,12;
   JEW127-9; JEW63-5.

2. Tensile strength - JEW127-9; OCS11P6; 7/3/46P7; CAH.25P2;
   CAH-25P11 and P13,14

3. Heat conductivity (Annealing) OCS11 P3; OCS11p6; JEW127-8; JEW63-pl; JEW63-p4; 7/3/46p7; OCS33p7; OCS-32p3.

4. Thermal stresses and resistance to spalling)OCS11p6;OCS33p6;
   a. Steady heat))OCS32pl;94-1pl CAH25p2;JEW127-9 OCS-53pl;OCS-46pl OCS-46p5;

   b. Transient - OCS-32P1; OCS-32P4; CAH25P15, 16, 17;

   c. Annealing

   d. Additive

5. Elastic Modulus- 7/3/46P5; 8/15/46P3; JEW127-9,10;JEW127P5;

6. Vapor Pressure - 7/3/46P3; CAH-46P2; JEW217P1; JEW63-P3;
   JEW63P7;

7. Loss of weight on heating - 7/3/46P3; OCS-32P4; CAH-25P2;
   JEW127-7,8;

8. Shrinkage (Density, and linear dimensions-OCS32Pr; CAH-25P24, P4, 6, 7,19,20,21; 7/3/46P3: 8/15/46 P4 JEW-127-9,10; JEW63-4; JEW63-7; OCS57 JEW63P5,6:

   a. With heat.

   b. With irradiation

   c. Annealing

9. Effect of O_2, H_2, Air, H_2 or H_e, H_2O, vacuum - OCS11P7; 8/15/46P2 OCS57;94IP1; JEW127-10; OCS46P1;

10. Surfaces - JEW63-P4

11. Emissivity - OCS-33P6; JEW127-10

Appendix - Continued

12. Composition & Impurities - JEW127-13

13. Melting point - JEW63-P1

14. Thermal expansion - JEW63P5; JEW63P7

B. GRAPHITE

1. Energy stored due to irradiation - 7/13/46P2; OCS-11P1

2. Heat of sublimation 7/3/46P6; OCS11P6; OCS11P2

3. (Vapor pressure) 7/3/46P6
4. (Weight loss on heating) 8/15/46P2; CAH25P21;

5. Volatilization OCS-61P2; OCS-55

APPENDIX IV

(Copied with Permission)

DE LAVAL STEAM TURBINE COMPANY

TRENTON 2, N. J.

October 10, 1946

AIR MAIL - SPECIAL DELIVERY

Monsanto Chemical Company
Clinton Labobatories
P. O. Box 1991
Knoxville 11, Tennessee

Attention: Mr. Dale D. Streid

Gentlemen:

With further reference to your original inquiry of August 29 and in accordance with your letter of September 24 summarizing the discussion in Trenton on September 17, we are pleased to submit herewith preliminary information covering eight (8) turbine driven blower units for this project.

We have concentrated primarily on Proposition A as you suggested for which we understand the design conditions to be as follows:

Gas to be handled	- Helium
Specific Gravity	- 0.138 (air equal 1.0)
Ratio of specific heats	- 1.667
Volume at inlet	- 8950 CFM
Inlet temperature	- 500°F
Inlet pressure	- 147.0 psia
Pressure rise	- 3.61 psi
Initial steam conditions	- 415 psig - 725°F total temp.

The general arrangement of each of these units as illustrated on the attached outline drawing, E-18222, consists of a single stage double inlet compressor with two (2) sleeve bearings, connected through an extension shaft with flexible couplings to a single stage steam turbine, all mounted on a common bedplate.

Details of the proposed design are shown on the attached assembly drawing E-18224. This blower will have an impeller diameter of approximately 27" operating at 6000 RPM. At the above design conditions the blower will require 213 BH P. With the turbine exhausting against 5 psig exhaust pressure, the steam consumption will be 5100 lbs. per hour. It was mentioned that the turbine should operate either non-condensing or condensing, and with the turbine nozzled for the above design conditions, it will operate on lower absolute back pressures with the governor valve automatically adjusting the steam flow to the requirement.

AIR MAIL - SPECIAL DELIVERY

Our estimate has been made on the basis of using standard materials of construction which are semi-steel for the blower casing and $2\frac{1}{2}\%$ nickel steel for the impeller and if it is expected that these materials will not be suitable from a corrosion standpoint, then we will be very pleased to revise our proposal on the basis of using special materials for either the casing or impeller.

The assembly drawing shows details of the prpposed seal which was discussed with you and which consists essentially of a graphite runner operating against a nitralloy disc on the shaft. As you will note, the bearing housings are enclosed and can be connected to an evacuating system. If this is done, then the labyrinth seal where the shaft passes through the bearing housing should be adequate to prevent outward gas leakage at this point.

The turbine will be equipped with a variable speed oil relay type governor, which may be arranged for speed adjustment at a remote point. This could be done by attaching a reversible motor to the needle control valve of the governor, if manual speed adjustment is suitable, or by attaching an automatic pressure or volume control to the needle valve if automatic regulation is desired.

In connection with the variable speed operation, you mentioned that the inlet pressure may be varied from one to ten atmospheres. In this connection, we wish to point out that for any given speed and inlet temperature, the actual pressure rise of the blower will vary in direct proportion to the absolute inlet pressure, although the pressure ratio will remain constant.

The attached curve, No. 52047, shows variations of pressure rise and BHP plotted against the inlet volume for several speeds. As discussed with you, the characteristics of these blowers are well suited to parallel operation.

Our proposal includes a complete pressure lubricating system for the turbine and blower which would be separately located from the unit. This would consist of an oil reservoir with one turbine driven oil pump for continuous service, an alternate turbine driven oil pump to serve as an auxiliary with automatic pressure regulator, oil strainer, and the usual accessories. Because of the questionable location of this lubricating system, we believe it would be advisable for Monsanto to furnish the pipe between it and the units. Although our proposal is on the basis of one lubricating system for each unit, you may wish to consider the possibility of using a central lubricating system for all four units.

AIR MAIL - SPECIAL DELIVERY

On the above basis, the present selling price is $21,350 each unit, net f.o. b. Trenton, New Jersey. The weight of each unit will be approximately 10,500 lbs. This price is subject to revision to those prices which are in effect by the Company at time of shipment.

On the basis of present shop conditions, we estimate we could start delivery of these units in approximately ten to twelve months from date of order and approval of design, at the rate of approximately two (2) units per month. In view of the preliminary nature of this project, it would be advisable to check the delivery situation at the time you are in a position to place an order.

Our usual warranty on this class of machinery is for one (1) year from date of shipment. In view of the special nature of the installation and the probability that servicing will be either most difficult or impossible after the unit is placed in operation, we believe it would be advisable for us to arrive at some mutually agreeable basis for determining full acceptability of the units before they are placed in operation.

You will realize, of course, that each complete unit will be designed and manufactured by the same organization at the DeLaval Plant in Trenton, and hence we are able to provide complete overall responsibility for the design and manufacture. We believe you will agree that special emphasis in this instance should be placed on sound design and careful manufacture in order that the utmost in reliability will be provided. In this respect we are confident of being able to meet your requirements.

The alternate proposition B would consist essentially of the same unit, except with blower impeller diameter of 18" operating at 6000 RPM and requiring 36 BHP. You will note from the attached outline E-18223, that the overall size is practically the same as Proposition A. If you so desire, we will be glad to furnish further detailed information concerning Proposition B.

We are taking the liberty of sending a copy of this letter to Burford, Hall & Smith, 140 Edgewood Avenue, N. E., Atlanta 3, Georgia, who are our established Sales Representatives for DeLaval products and who are well qualified to serve you adequately on this project. We are asking them to communicate with you in order that they may make an appointment to call on you and carry on the discussions.

AIR MAIL - SPECIAL DELIVERY

We will appreciate the opportunity of discussing this matter further with you and making any revisions that may be required.

Very truly yours,

DE LAVAL STEAM TURBINE COMPANY

J. P. Stewart
Special Representative.

JS:EJ
Atts.

cc- Burford, Hall & Smith
140 Edgewood Avenue, N. E.
Atlanta 3, Georgia

cc- Regular Mail

D X 540

DE LAVAL ST[illegible] TURBINE COMPANY

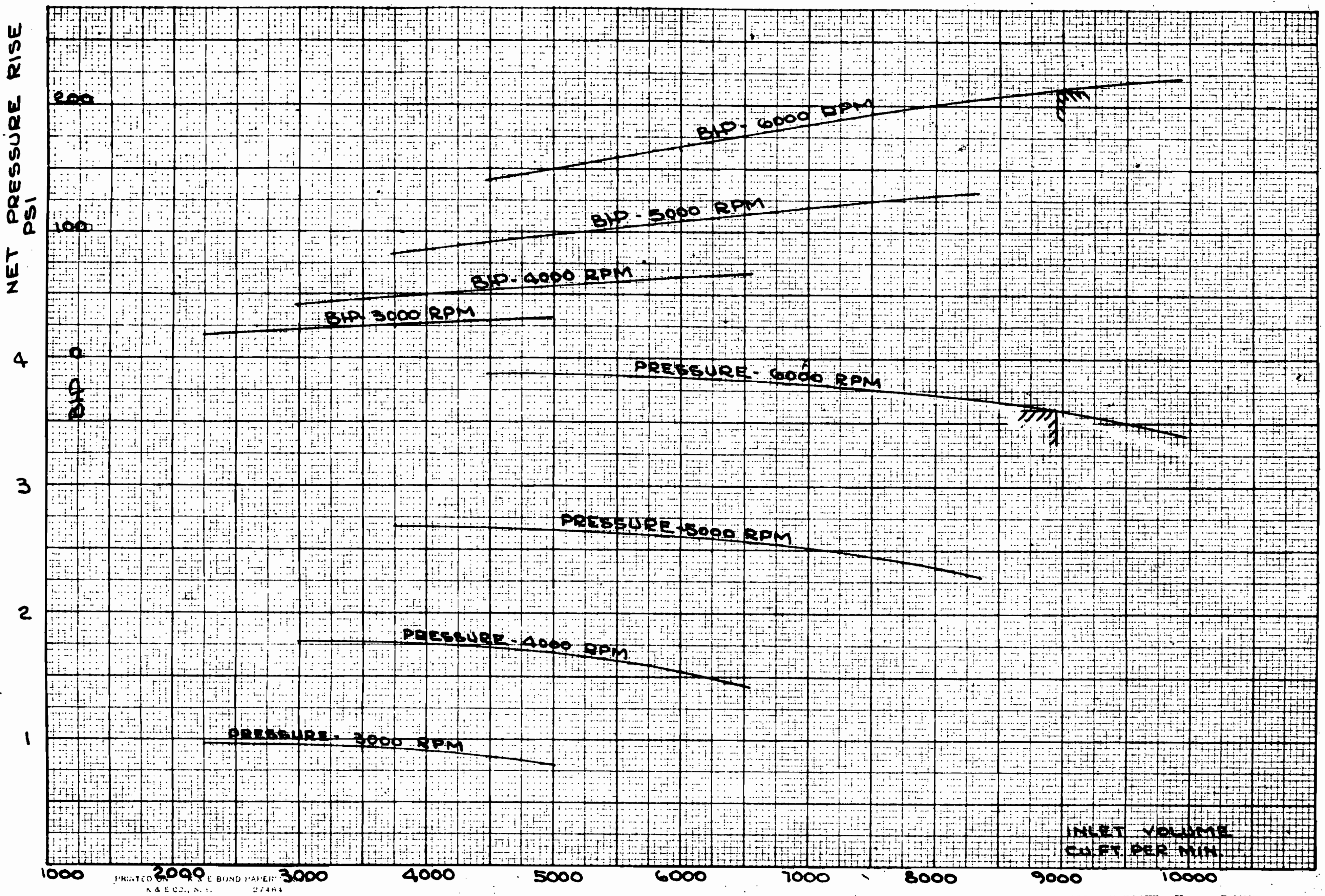
PROPOSED CHARACTERISTIC CURVE NO. 52047

FOR MONSANTO CHEMICAL COMPANY

CENTRIFUGAL BLOWER OR COMPRESSOR TYPE 215 KC-BL 16/14 P SPEED 6000 RPM DATE 10-7-46

INLET PRESSURE 14.7 PSIA INLET TEMPERATURE 500° F SPECIFIC GRAVITY 0.138

Curves are approximate and unit is guaranteed at indicated operating points only.



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K & E CO., N.Y. 27484

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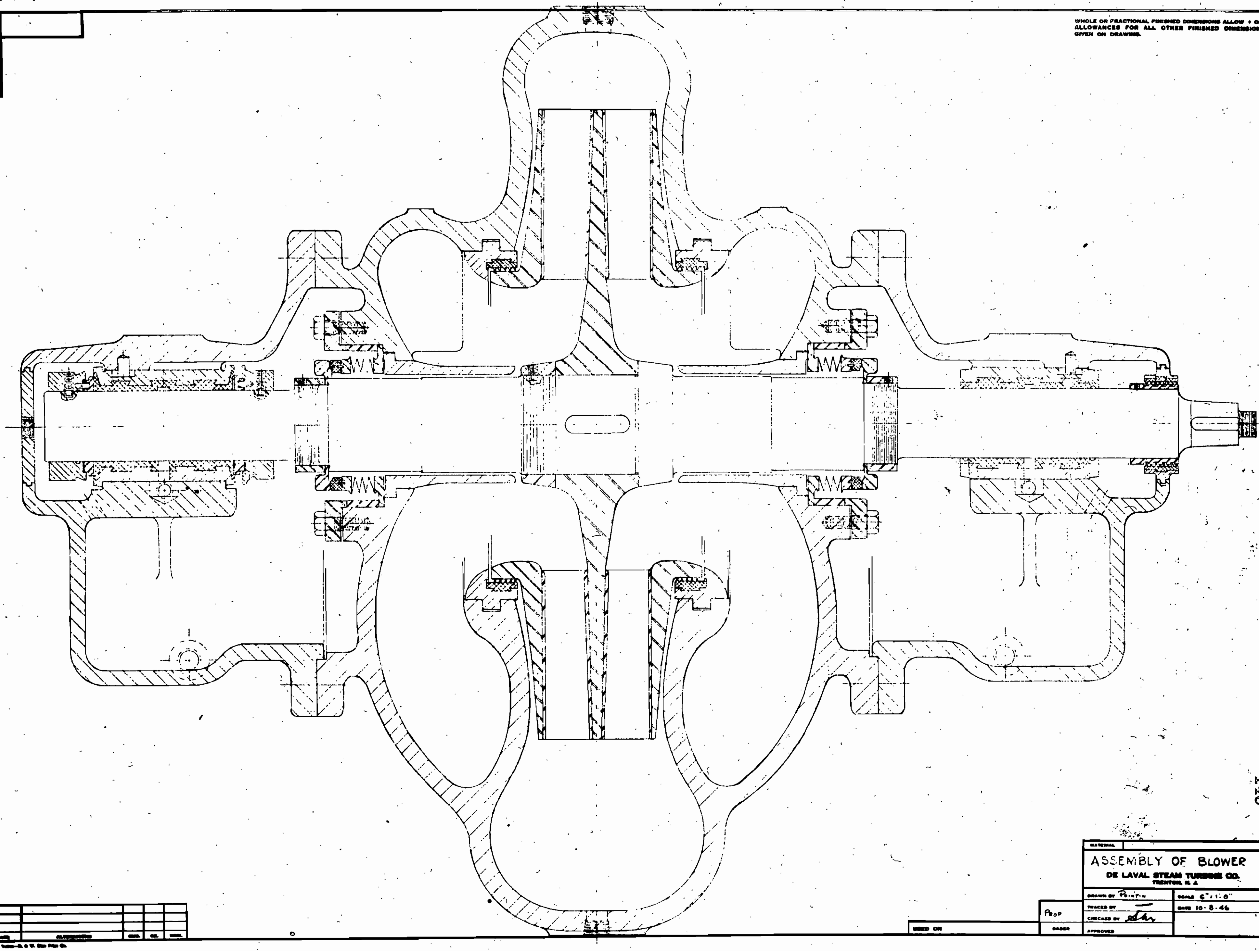
E-18224

WHOLE OR FRACTIONAL FINISHED DIMENSIONS ALLOW + OR − 1/64" ALLOWANCES FOR ALL OTHER FINISHED DIMENSIONS ARE GIVEN ON DRAWING.



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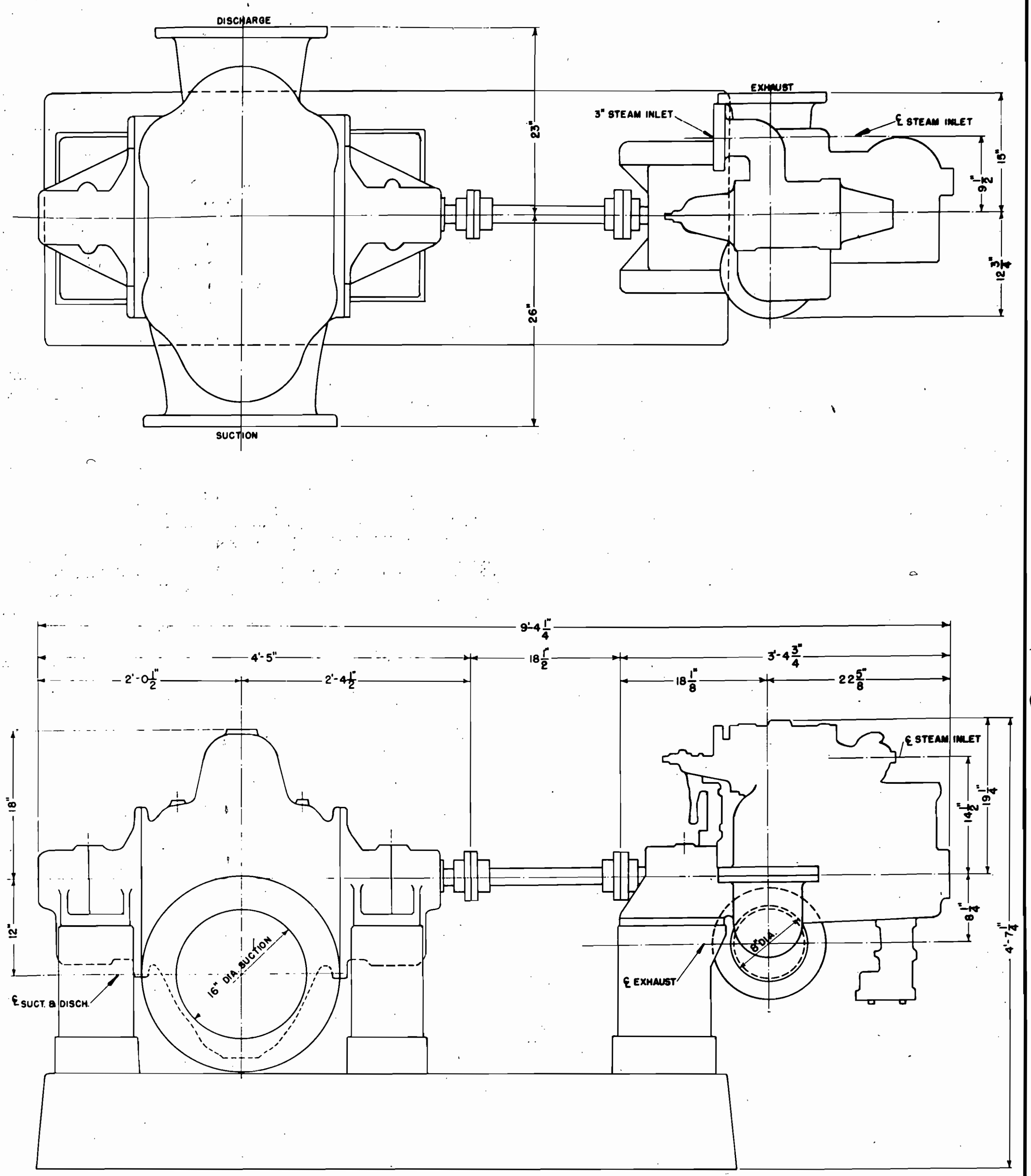
MATERIAL	
ASSEMBLY OF BLOWER DE LAVAL STEAM TURBINE CO. TRENTON, N. J.	
DRAWN BY Pointin	SCALE 6" = 1'-0"
TRACED BY —	DATE 10-8-46
CHECKED BY [illegible]	
APPROVED	

PROP

USED ON | ORDER

E-18224



MATERIAL	
TYPE 215 TC-BL 16/14 215 H.P. TURBINE DRIVEN BLOWER SPEED 6000 R.P.M. DE LAVAL STEAM TURBINE CO. TRENTON, N.J.	
DRAWN BY	SCALE - 1 1/2" = 1'-0"
TRACED BY B.F. EARLY	DATE - 10-24-46
CHECKED BY	
APPROVED	

USED ON

ORDER

E-18222

APPENDIX V

(Copied with Permission)

FREDRIC FLADER, INC.

483 Division Street North Tonawanda, New York Phone TON. 499 Phone DE. 2846

1 October 1946

Monsanto Chemical Co.
Clinton Laboratories
Post Office Box 1991
Knoxville 11, Tenn.

Attention: Mr. Dale D. Streid

Dear Mr. Streid:

This will acknowledge your letter of 24 September in which you confirm the specifications of two (2) blower designs in which you are interested.

Owing to the very short time available before October 4th, we have not had time to prepare a design layout showing the dimensions of these blowers and their installation. These sketches will be forwarded to you within the next few days.

Our specifications for blowers "A" and "B", in accordance with the requirements given in your letter, may be stated as follows:

Proposition	A	B
Gas Flow, lb/sec.	8.5	3.4
Inlet Pressure, atm.	10	4
Inlet Volume Flow, $ft.^3/min.$	8900	8900
Pressure Rise, $lb./ft.^2$	520	114
Power Required	200	40
Circulating Gas Temperature	500°F.	500°F
Length Rotor inches	9	6
O. D. Rotor inches	11.5	11.5
I. D. Rotor inches	7.5	7.5
Blade chord inches	1.4	1.4
Number of blades	21	21
Number of vanes	20	20
RPM	20,000	20,000
Efficiency per cent	80	80
Number of stages	3	2

Monsanto Chemical Co.

Due to the similarity in the two proposed types of blowers, we find that the outside diameter of each will be the same. Blower "A" will have three stages of axial flow and blower "B" will have two stages. We could design blower "B" in such a way that an extra stage could be added which would perform the service required of blower "A". We realize, of course, that you plan to procure only one of these.

Our quotation for either blower is $18,000 subject to revision or escalation according to changes in cost of material and labor. This quotation is without turbine drive and if you are further interested in our proposition, we will be glad to supply additional information and a quotation for the driving means.

If our proposal has sufficient merit so that you are desirous of proceeding further, we should like to request that design information be furnished to us concerning the type of shaft seals which were developed during the war and used on blowers produced for use at Oak Ridge, for study and possible incorporation in the design of these proposed blowers.

Yours very truly,

(signed)

Fredric Flader

FF/b

cc:Mr. R. N. Reams,
Purchasing Agent

24 September 1946

Mr. Fredric Flader, President
Fredric Flader, Inc.
775 Main Street
Buffalo 3, New York

Dear Sir:

This is to confirm our discussion during my visit to your plant 19 September 1946. I want to thank you for the courtesies extended me during this visit.

I discussed with you and Mr. P. Tauson, the requirements which we have for a blower for the Daniels Pile project. This blower is for circulating helium gas at temperature 500°F. The following table outlines the requirements of the two designs which are being considered:

Proposition	A	B
Gas Flow, lb/sec.	8.5	3.4
Inlet Pressure, atm.	10	4
Inlet Volume Flow, ft.^{3}/min.	8900	8900
Pressure Rise, lb/ft^2	520	114

As I told you, one of the most important problems in the design of this blower is the provision of an absolutely tight shaft seal. This is necessary because the helium gas will contain highly radioactive impurities which will be dangerous to operating personnel.

It is our desire that the company which furnishes the blower will also furnish the driving means and control units in a complete assembly. You said that you would make your proposition design on this basis. A small direct connected steam turbine seems to be the best drive means because of the ease of speed control and because steam will be readily available for this application.

This project is in a state of preliminary design and we would like to have preliminary design and performance estimates for blowers meeting Proposition A and Proposition B.

I have checked with Mr. R. N. Reams, our Purchasing Agent, who tells me that if we should obtain these blowers from your company we would like to buy them on a P. O. based on firm price quotation subject to escalation according to the cost of material and labor.

Please let me know if you have any further questions concerning this proposition. We would like to have a proposition design for the blower by 4 October 1946 in order to meet our design schedule.

Yours very truly,

(signed)
Dale D. Streid

DDS/em

cc: R. N. Reams, Purchasing Agent
McCullough/McArdle
Preston/Downing