UNCLASSIFIED

MonN-383
Piles-Thermal

Contract No. W-35-058.-eng-71

****

Classification cancelled (or changed to [redacted])
by authority of [illegible] by [illegible] date 6/3/55
by [illegible] date 6/22/55

SUMMARY REPORT ON DESIGN AND DEVELOPMENT OF HIGH TEMPERATURE GAS-COOLED POWER PILE

****

Price $ 2.40

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

By

C. ROGERS McCULLOUGH
Director

And Members of the

POWER PILE DIVISION

September 15, 1947

SERIES A RECEIVED: 10-14-47

SERIES A ISSUED: 10-17-47

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

UNCLASSIFIED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CONFIDENTIAL

SECRET

3

MonN-383
Piles - Thermal

DISTRIBUTION:

1. C. A. Hochwalt
2. E. J. Murphy
3. J. R. Coe
4. A. M. Weinberg
5. M. C. Leverett
6. W. A. Johnson
7. H. G. Rickover
8. Gale Young
9. Training School
10. H. G. Amerine
11. A. Amorosi
12. G. A. Anderson
13. E. B. Ashcraft
14. R. G. Berggren
15. R. O. Brittan
16. F. Daniels
17. J. R. Dietrich
18. G. G. Downing
19. H. Etherington
20. H. B. Fairchild
21. J. V. Fitzgerald
22. L. W. Fromm
23. J. W. Galbreath
24. L. P. Hunter
25. J. M. Harrer
26. R. V. Hurst
27. H. K. Jackson
28. K. Kasschau
29. E. L. Kelso
30. N. F. Lansing
31. C. R. McCullough
32. L. J. Marshall
33. W. T. Moore
34. J. F. Neely
35. N. J. Palladino
36. A. L. Preston
37. P. N. Ross
38. C. L. Segaser
39. W. L. Sibbitt
40. J. W. Simpson
41. A. W. Solbrig
42. F. W. Thalgott
43. T. H. Thomas
44. A. H. Toepfer
45. R. Umphries

46-57. AEC, Clinton Laboratories Division
58-63. Argonne National Laboratory
64-66. Atomic Energy Commission, Washington
67-72. Brookhaven National Laboratory
73-76. General Electric Company
77-78. Hanford Engineer Works
79-81. Los Alamos
82. Madison Square Area
83. Patent Advisor
84. Research Division (for NEPA), Oak Ridge
85-99. Research Division, Oak Ridge
100-103. University of California, Radiation Laboratory
104-140. Central File

CLASSIFICATION CANCELLED
DATE FEB 27 1957
For The Atomic Energy Commission
H. B. Carroll
Chief, Declassification Branch

UNCLASSIFIED

SECRET

UNCLASSIFIED

TABLE OF CONTENTS

Page No.

I. ABSTRACT 10

II. INTRODUCTION 13

History and Design Evolution of Power Pile 13

III. FACTORS AFFECTING PERFORMANCE OF GAS-COOLED THERMAL PILES. 19

A. Design Constraints of Chain Reaction 19

1. Economy of Fissionable Material 19
2. Neutron Economy and Critical Mass 19
3. Moderator Materials 21

B. Power Removal 22

1. General Considerations 22
2. Pile Geometry 25
3. Effect of Design Conditions 27
4. Example of Correlation of Heat Transfer & Physics Requirements 31

IV. DESCRIPTION AND STATUS OF DESIGN 33

A. General Description of Plant 33

1. Type of Plant 33
2. Rating of Plant 33
3. Nuclear Characteristics 33
4. Pile Construction 34
5. Coolant 34
6. Design Conditions 35

B. Detailed Design Description 36

1. Pile Structure 37
2. Fuel Elements 43
3. Fuel Handling 45
4. Nuclear Characteristics 53
5. Pile Control 60
6. Coolant System and Power Conversion Equipment 93
7. Chemical Processing of Fuel Elements 112

C. Status of Design 114

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U.S.C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

DECLASSIFIED

TABLE OF CONTENTS

Page No.

V. DESIGN AND DEVELOPMENT PROBLEMS 115

A. Physics 115

B. Heat Transfer 117

C. Pile Structure 126

D. Fuel Handling 136

E. Pile Control 142

F. Coolant System and Power Conversion Equipment . . . 150

G. Fuel Elements 199

H. Materials. 215

VI. DESIGNS FOR HIGH OUTPUT GAS-COOLED PILES 258

A. 250,000 KW Design 258

B. 60,000 KW Design 263

VII. RECOMMENDATIONS 265

APPENDIX A .. LIST OF CONSULTANTS 268

APPENDIX B .. LIST OF PERSONNEL 269

APPENDIX C .. PHYSICS CALCULATIONS. 271

APPENDIX D .. SUPPLEMENTARY NEUTRON PRODUCTION IN PILE . . . 276

APPENDIX E .. ALTERNATE DESIGN OF PILE STRUCTURE. 280

APPENDIX F .. PILE CONTROL - CALCULATIONS 282

APPENDIX G .. BOILER SPECIFICATIONS 307

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U.S.C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET
CONFIDENTIAL

LIST OF FIGURES

FIGURE NO.	TITLE
1.	Critical Radii & Masses of BeO Piles at 650°C.
2.	Neutron Economy in BeO-UO_2 Critical Reactor 650°C.
3.	Effect of Conversion Ratio on Consumption of Fissionable Material.
4.	Criticality Conditions for Cylindrical Bare Piles No Voids 650°C. H/R = 1.85 .
5.	Criticality Conditions as Function of Neutron Economy for Three Moderator Materials, Bare Cylindrical Piles.
6.	Radial Variation of Thermal Flux (nv_{th}) and Epithermal Flux (nv_f).
7.	Axial Variation of Thermal Flux (nv_{th}) and Epithermal Flux (nv_f).
8.	Critical Mass vs. Radius, BeO Moderator and Reflector, Cylindrical Pile, h/H = .32 T/R = .30.
9.	Critical Mass vs. Radius, BeO Moderator and Reflector, Cylindrical Pile, h/H = .54 T/R = .50.
10.	Critical Mass vs. Radius, BeO Moderator and Reflector, Cylindrical Pile, h/H = ∞ T/R = ∞ .
11.	Critical Mass vs. Radius, Be Moderator and Reflector, Cylindrical Pile, h/H = .54 T/R = .50.
12.	Critical Mass vs. Radius, Carbon Moderator & Reflector, Cylindrical Pile, h/H = .54 T/R = .50.
13.	Flow Arrangements for Heat Transfer.
14.	Effect of Gas Used on Specific Power of a Pile.
15.	Effect of Fraction Blower Power on Plant Shaft Output and Over-all Plant Efficiency .
16.	Locus of Pile Size from a Heat Transfer Standpoint for Various Pile Outputs vs. Physics Requirements, BeO Moderator and Reflector, Cylindrical Pile .
17.	Pile Output Based on Heat Transfer & Thermal Stress Limitations vs. Physics Requirements, BeO Moderator and Reflector, Cylindrical Pile .
18.	Schematic Arrangement of Components .

DECLASSIFIED
SECRET

CONFIDENTIAL

FIGURE NO.	TITLE
19.	Hollow Hexagon Type C-1.
20.	Typical BeO Brick Assembly.
21.	Pile Structure Sections.
22.	Bottom Plate.
23.	Fuel Channel Assembly.
24.	Sectional Elevation of Pile Structure.
25.	Cylinder with Rounder Ends, Type A-1.
26.	Fuel Units for 2" Dia. Channel.
27.	16 Hex.-3 Pentagon and 13 Hex.-6 Pentagon.
28.	Gas Lock Purging System I.
29.	Epicyclic Gearing Radius Selection.
30.	Charging Machine.
31.	Schematic Drawing of Control System.
32.	Fuel Latch.
33.	Fuel Latch-Working Model Photograph.
34.	Loading Patterns.
35.	Xenon and Samarium Poisoning During Steady Pile Operation.
36.	Xenon and Samarium Poisoning After Shutdown from Various Flux Levels.
37.	Xenon Poisoning After Decrease of Flux from Steady State nv = 5×10^{13} to New Flux Level (nv).
38.	Change in Xenon Poisoning with Time for a Sequence of Pile Operating Conditions.
39.	Shim Rod Mechanism.
40.	Control Rod Assembly and Safety Rod Details.
41.	Control Rods.
42.	Control Circuit Diagram.
43.	Basic Control Diagram.
44.	Differentiating Amplifier.

DECLASSIFIED

SECRET

CONFIDENTIAL

FIGURE NO.	TITLE
45.	Electromechanical Differentiator.
46.	Automatic Power Level Regulator, Schematic Block Diagram.
47.	Automatic Temperature Regulator, Schematic Block Diagram.
48.	Flow Diagram.
49.	Plant Layout Study.
50.	High Temperature Duct.
51.	Diagram of Boiler and External Piping.
52.	Proposed Arrangement of Atomic Pile Boiler.
53.	Proposed Arrangement of Atomic Pile Boiler.
54.	Arrangement of Power Pile Boiler.
55.	Proposed Blower.
56.	Diagram of Large Valves.
57.	Schematic Flow Diagram, Helium Surge System.
58.	Schematic Flow Diagram, Make-Up Helium Purification.
59.	Schematic Flow Diagram, Helium Purification.
60.	Steam Flow Diagram.
61.	Cooling Water Flow Diagram.
62.	Generating Station and Switchyard.
63.	Determination of Pile Voids and Pile Size for 12,000 KW Output, Helium-Cooled Pile.
64.	Tublar Unit, Fuel Element Temperatures, D_e = .048 Feet.
65.	Fuel Element Temperatures, De = .031 Feet.
66.	Fuel Element Temperatures, De = .0227 Feet.
67.	Average Temperature Difference Between Fuel Elements and Gas.
68.	Heat Transfer Data for Round Ducts.
69.	Depletion Time vs. Radial Position.
70.	Channels Requiring Change vs. Loading Interval.

SECRET

DECLASSIFIED

FIGURE NO.	TITLE
71.	Monthly Excess Consumption of Fuel Elements Channel Loading vs. Individual Elements.
72.	Gas Lock Purging System II.
73.	Alternate Indexing Machine, Fuel Handling.
74.	Effectiveness of Central Control Rods.
75.	Effective Radius vs. Radius of Zone of Influence for a Central Control Rod. Ref. N-2292.
76.	Change in K for a Central Control Rod using Position Factor. Ref. N-2292.
77.	Change in K for a Central Rod using Position Factor. Ref. N-2292.
78.	Variation in K with Diffusion Length Squared.
79.	Variation in K with Fermi Age - - for a Central Rod.
80.	Change in K for a Single Control Rod.
81.	Effect of a Single Control Rod on Pile Reactivity. Using Nordheim-Scalettar one Group Theory Approximation.
82.	Change in K for a Single Control Rod Using N-S Two Group Theory.
83.	Comparison of Methods for Calculating Control Effectiveness for One Rod - R-effective = 1.35 cm.
84.	Change in K for One Central and One Off-Center Control Rod.
85.	Change in K for an Array of Seven Control Rods: Six Placed with Zone of Influence Tangent to Central Zone Using Position Factor. - Actual Radius.
86.	Change in K for an Array of Seven Control Rods: Six Placed with Zone of Influence Tangent to Central Zone Using Position Factor. - Effective Radius.
87.	Effect of an Array of Seven Control Rods: Six Rods Uniformly Spaced about a Central Rod, Equating Effect to that of a Central Rod of Equal Area of Influence. Using Position Factor.
88.	Effect of Seven Control Rods, Eight Cm. In. Dia. on Change in K. Six Rods Uniformly spaced about a Central Rod.

DECLASSIFIED

FIGURE NO.	TITLE
89.	Effect of Seven Control Rods, Four Cm. in Dia. On Change in K - Six Rods uniformly spaced about a Central Rod.
90.	Schematic Diagram of Process for Separation of Uranium from Graphite. p 113
91.	Diagrammatic Arrangement of Type Boilers.
92.	Evaporation of Boiler Design III with Varying Gas Flow and Inlet Temperature.
93.	Performance of Boiler for Design III with Varying Operating Conditions With Helium Flow Constant at 30,600 Pounds per hour.
94.	Heating Surface Required in Boiler Unit vs. Varying Helium Inlet Temperature and Varying Steam Conditions.
95.	Half-Life Distribution of Radioactive Fission Product Nuclei.
96.	Locus of Possible Pile Designs for 250,000 Thermal KW Output for a BeO Moderated and Reflected Cylindrical Pile.
97.	Locus of Possible Pile Designs for 250,000 Thermal KW Output for a Be Moderated and Reflected Cylindrical Pile for 30% Enriched U^{235}.
98.	Locus of Possible Pile Design for 250,000 KW Output of a Graphite Moderated and Reflected Cylindrical Pile.
99.	Cross Section of Fuel Elements & Bricks of Design "A" 250,000 KW Unit, BeO Moderator.
100.	Cross Section of Fuel Element & Bricks of Design "B" 250,000 Pile.
101.	Cross Section of Fuel Element & Frame of Design "D" 250,000 KW Pile.
102.	Cross Section of Fuel Element & Bricks of Design "E" 250,000 KW Pile.
103.	German Thin Wall Structure - Natural Clay.
104.	Pile Support Arrangement.
105.	BeO Brick

DECLASSIFIED

FIGURE NO.	TITLE
106.	Pile Cross-Section Assembly.
107.	Bridge Tubes Section.
108.	Brick Assembly

DECLASSIFIED

SUMMARY REPORT ON DESIGN AND DEVELOPMENT OF HIGH TEMPERATURE GAS-COOLED POWER PILE

I. ABSTRACT

At the present time, the development of atomic energy is largely dependent on the solution of a number of problems in pile technology regardless of whether breeder or power piles are being considered. In fact, the development of breeder piles is intimately associated with power pile development for two reasons; first, since the supply of fissile material is limited, it is essential to use it economically and to increase the supply by conversion of fertile material. Second, production of significant amounts of fissile material by means of breeder reactors involves the production of large amounts of power. For example, a pile having a breeding gain of 0.1 would develop approximately 10,000,000 kw of power in producing 1 kg. of fissile material per day; it is highly desirable that this power be put to useful purposes rather than simply dissipated as heat.

As in the development of any new field of technology, there are a number of problems in pile technology the nature and importance of which can only be determined from actual experience in the construction and operation of piles. Moreover, all power piles regardless of the particular type being considered will present a number of similar technological problems, notably those associated with high temperature operation. Thus, the design construction and operation of an high temperature experimental power pile would provide technical information of considerable significance in atomic power development.

This report presents a description of a design for an experimental nuclear power plant utilizing a high temperature gas-cooled power pile as the energy source. The plant consists of the pile, a heat exchanger or boiler, a conventional steam turbine generator and their associated auxiliaries. Helium gas under pressure transfers heat from the pile to the boiler which generates steam for driving the generator. The plant is rated at a normal output of 12,000 kilowatts of heat and an electrical output of 2400 kilowatts. Provision is made for operation up to 20,000 kilowatts of heat (4000 kilowatts of electrical output) in the event operation of the plant proves this possible.

The pile operates on thermal energy neutrons using uranium enriched to 30 percent U^{235} as fuel. It is a right circular cylinder with its axis vertical and contains beryllium oxide as the moderating material and permanent skeletal structure. Removable fuel elements consisting of mixtures of enriched uranium and moderating material, which may be beryllium metal, beryllium oxide, or graphite, are located in vertical channels running parallel to the axis of the cylinder. Helium gas at a maximum pressure of 10 atmospheres flows through these channels where it is heated to a maximum temperature of 1400°F. The hot gas is then circulated through a boiler where it is cooled and generates steam, thence is returned to the pile at a temperature of 500°F.

The principal dimensional characteristics of the pile are summarized in Table I. It will be noted that the multiple channel construction provides

SECRET

TABLE I

PRINCIPAL DIMENSIONAL CHARACTERISTICS OF THE PILE

Mode of Operation*	1	2	3
Equivalent radius of reactor	62.2 cm (24.5 in.)	62.2. cm	54 cm
Height of reactor	114.4 cm (45 in.)	114.4 cm	100 cm
Radius outside reflector	91.0 cm (35.7 in.)	76.8 cm	76.8 cm
Height of permanent brick structure	193.3 cm (76 in.)	193.3 cm	193.3 cm
Diameter of fuel channels	5.1 cm (2 in.)	5.1 cm	5.1 cm
Total number of channels in pile	517	517	517
Number of active fuel channels	228	228	174
Critical mass of U^{235}, calculated at mean temperature 650°C, Kg	3.6	5.1	4.6
Initial inventory of U^{235}, Kg	5.0	6.7	6.0
Total weight of THO_2, Kg	0	6130	6130
Total weight of BeO, approx., lbs.	27000	27000	27000
Average thermal neutron flux	6.5×10^{13}	4.9×10^{13}	3.8×10^{13}
Volume percent of voids in reactor	28%	28%	28%

*Mode 1 requires least critical mass but gives negligible conversion; mode 2 gives considerable conversion with some increase in critical mass; mode 3 gives further slight increase in conversion with lower critical mass than mode 2, but at reduced power capacity. The same physical structure serves for all three modes of operation.

SECRET

DECLASSIFIED

considerable flexibility as to the amount and location of both the fuel material and the fertile material, i.e., the thorium conversion blanket. An accurate determination of the conversion ratio (number of atoms of new fissile material produced per atom of fissile material destroyed) including the effects of lumping, chemical processing losses, etc. has not been made but it is estimated to be of the order of 0.6. A breeding gain (conversion ratio greater than one) could possibly be achieved if U^{233} were available for use as fuel.

The design of this plant is still in the development stage. Accordingly, a description of the design status is presented in the report including therein a discussion of the nature and scope of the design and development problems which have been encountered, together with a description of the work which would be required in order to complete the design.

Solution of some of the problems depends on development and experimental work that has been in progress for some time. Still other problems, mostly of a minor nature, have not yet received detailed consideration. However, there appears to be no serious doubt that solutions can be found to all outstanding problems and that after a year of continued design and development work, it would be possible to proceed with working drawings for construction of a pile incorporating the general design features described in this report.

Two important aspects of the pile have been subordinated to the general design problem, and these aspects should receive careful attention in any further development of this design. Firstly, provision should be made for extensive high temperature test facilities, with adequate provision for instrumentation and test equipment. Secondly, the reactor should provide regions suitable for exploring the performance of a gas-cooled high temperature pile operating at the high power level expected of a commercial plant. Intensive study of materials should also be continued and directed towards design for high power output.

The report contains a brief general discussion of the factors which affect the power output and over-all economy of fissionable material, i.e., the performance, of gas-cooled thermal piles. This discussion shows the interrelation between such factors as neutron economy, critical mass, moderator and fuel materials, heat transfer phenomena, and their combined effects on the pile performance. Included also are the results of a preliminary investigation of the use of gas-cooled piles for production of large amounts of power (250,000 kilowatts of heat).

It has been concluded that the nuclear power plant described in this report can be built and operated successfully. A current directive by the Atomic Energy Commission provides for continued study of power reactors; on the other hand, it does not provide for early construction of a power reactor of any type. The Power Pile Division has, therefore, submitted recommendations on a program intended to further the development of power reactors within the scope of the Commission's directive. This program was submitted to the Administration of Clinton Laboratories as part of a letter dated September 12, 1947 and is presented at the conclusion of the report.

DECLASSIFIED

II. INTRODUCTION

Events of the past several months and in particular announcements by the Atomic Energy Commission relative to the future program at Clinton Laboratories together with termination of the Monsanto Chemical Company contract for operation of the Laboratories have made it desirable to prepare the subject report. This report has a two-fold purpose: (1) to record the work which has been done on the power pile project and to summarize its status as of September, 1947, and (2) to present information and recommendations which may be of assistance in formulating an effective program leading to the continued and rapid development of atomic power.

The formation and objectives of the Power Pile Division at Clinton Laboratories resulted from a directive issued by Brig. General K. D. Nichols of the Manhattan Engineer District to the Monsanto Chemical Company on May 16, 1946. This directive was, in part, as follows: "the Monsanto Chemical Company is directed to proceed as rapidly as possible with the design, construction, and operation of an experimental pilot plant of a high temperature power pile designed along the lines developed by Dr. Farrington Daniels and his associates at the Metallurgical Laboratory." The following description of the events and considerations which preceded this directive together with the chronological development of the program carried out pursuant to it is presented as an essential and integral part of the design and development work summarized in this report.

History and Design Evolution of the Power Pile

Early in 1944 a small group of scientists at the University of Chicago's Metallurgical Laboratory began to hold frequent informal meetings to discuss the application of nuclear energy for peacetime purposes. Of particular interest was the utilization of atomic energy for the generation of power. The group included Doctors S. K. Allison, E. P. Wigner, Leo S. Szilard, H. C. Vernon, Frederick Seitz, P. Morrison, Gale Young, E. C. Cruetz, F. Franck, William W. Watson, Charles M. Cooper, Thorfin F. Hogness, Alvin Weinberg, L. A. Ohlinger, Enrico Fermi and others who came in from time to time to express their ideas. In September, 1944, Dr. Farrington Daniels joined the Metallurgical Laboratory from the University of Wisconsin. He had conceived the idea of a high temperature pile using beryllium oxide as a moderating material. It was concluded to be the most feasible solution of the problem that had been considered up to that time. During the remainder of 1944 and the early part of 1945 frequent conferences were held between Dr. Daniels and Doctors Wigner, Hogness, and Compton of the Chicago Project. On frequent visits to Chicago Colonel Nichols talked with Dr. Daniels and encouraged the idea of developing a power pile.

UNCLASSIFIED

In April, 1945, the Manhattan Engineer District's budget for research and development at the University of Chicago's Metallurgical Laboratory included a provision for the expenditure of approximately $20,000 in the Chemistry Division for power pile research work. The group continued studies and discussions until July, 1945, and at that time a "Power Pile" section under the Chemistry Division was organized and actual experimental work was begun on problems relating to the construction of a chain reacting pile to be operated at high temperature. Dr. J. E. Willard, then of Hanford Eng. Works, was brought to Chicago to take charge of this section.

During the Autumn of 1945 several conferences were held among Colonel K. D. Nichols, Major General L. R. Groves and Dr. Daniels (who at the time was Director of the Metallurgical Laboratory) as to the scope and importance of the problems which were being encountered in the proposed high temperature pile. Colonel Nichols felt that the problem was becoming too big for the Metallurgical Laboratory and that, since the pile was intended primarily for power purposes, its development should be the responsibility of an industrial organization rather than a research group. Moreover, Colonel Nichols was opposed to the Metallurgical Laboratory negotiating additional subcontracts. He believed that a power pile should be built as soon as possible but that it should be built at Oak Ridge. It was decided that Monsanto Chemical Company (operators of Clinton Laboratories at Oak Ridge) should be approached regarding the undertaking of a contract for the design and development of the power pile.

In December, 1945, Dr. C. Rogers McCullough of Monsanto Chemical Company went to the Metallurgical Laboratory to confer with Doctors Daniels and Willard and to study their work on the power pile. In January, 1946, Messrs. Rutter, Gronemeyer, Buford and Colley of the Monsanto Chemical Company, General Engineering Department and Dr. C. Rogers McCullough met with Dr. Daniels and the Metallurgical Laboratory staff and reviewed the problem.

Colonel Nichols formed an Advisory Committee comprising Doctors R. C. Tolman, John Wheeler, A. K. Compton, W. K. Lewis, and C. A. Thomas to review the Daniels Pile. At a meeting March, 1946, in Washington this committee agreed that the design and construction of the Daniels Pile should be undertaken at Oak Ridge. Dr. C. A. Thomas, Vice-President of Monsanto Chemical Company agreed to undertake the job. It was further agreed that, inasmuch as the purpose of the unit was primarily power generation, appropriate industrial concerns in the field of power generation should be brought into the program on a cooperative basis to assist the Monsanto Chemical Company.

These conclusions were made known to Dr. C. Rogers McCullough and he was appointed Director of the Power Pile Division to be located at Oak Ridge. On April 11, 1946, a meeting was called by Dr. McCullough. This meeting was attended by Edwin H. Brown of Allis-Chalmers, K. H. Kingdon, C. G. Suits, and H. A. Winne of General Electric, L. W. Chubb and M. W. Smith of Westinghouse, Dr. Farrington Daniels of the Metallurgical Laboratory, Brigadier General K. D. Nichols and Lt. Col. A. V. Peterson of the Manhattan District, Rear Admiral T. A. Sollberg, Commodore P. F. Lee and Captain R. D. Conrad of the U. S. Navy, Major General E. M. Powers, Brigadier General A. R. Crawford, Brigadier General L. C. Craigie, Colonel H. A. Shepherd, and Colonel D. J. Kiem of the AAF, Dr. J. H. Lum, C. J. Colley, and F. G. Gronemeyer of Monsanto, and Dr. Gale Young of Clinton Laboratories.

UNCLASSIFIED

At this meeting the plan for the design and construction of the Daniels Pile was endorsed and the industrial companies, Navy and Army Air Forces agreed to cooperate with Monsanto in the program especially by the loan of men from the industrial companies. It was understood that the program would get under way just as soon as possible. On May 16, 1946, Brigadier General Nichols issued a directive to the Monsanto Chemical Company, operators of Clinton Laboratories, to assume responsibility for the design, construction and operation at Clinton Laboratories of an experimental pilot plant of a high temperature power pile designed along the lines developed by Dr. Daniels and his associates at the Metallurgical Laboratories. At this time, Dr. McCullough began to negotiate with the various industrial companies and universities for the loan of engineers and scientists, on a leave of absence basis, for the design work on the proposed pile.

The essential objective of the program as visualized at this time was to demonstrate the application of atomic energy to peaceful purposes as soon as possible. This, therefore, entailed the design, construction, and operation of a nuclear power plant of such a type as to assure a high probability of success even though it would have to be based on the limited amount of knowledge available at the time and could not depend on any extensive development and research programs of a long range nature. It was recognized, of course, that, while such a plant had a rather limited objective, its operation would, in some degree at least, disclose the nature of, and provide technical data on many of the problems which must be solved to assure maximum dependability and usefulness of future nuclear power plants. In this respect, then, the objective was essentially the same as that in building the first model in any new field of technology.

Shortly after receipt of the directive from Brigadier General Nichols contracts for consultant services were entered into by the Power Pile Division and the companies and men listed in Appendix A. Loaned employees were secured on a "leave of absence" basis from various industrial companies under a "no-profit-no-loss" policy agreed upon by Monsanto, the parent company and the individual. A list of these employees, their parent companies, and previous fields of work is given in Appendix B. The loaned employees, none of whom had prior experience in the field of atomic energy, were afforded the opportunity of classes in the Training School at Clinton Laboratories to enable them to obtain some knowledge of Nuclear Physics, Pile Theory, Chemistry of Heavy Elements, etc. A general educational program ensued for all members of the Division, together with actual design and experimental work on the proposed pile.

The preliminary studies of the engineering problems involved in construction of a nuclear power plant were based on a set of tentative specifications prepared at the Metallurgical Laboratory in Chicago as a result of the analytical and experimental work done there prior to formation of the Power Pile Division. These specifications envisioned a high temperature, helium-cooled pile, operating on thermal energy neutrons, with beryllium oxide as a moderator and permanent structure, enriched uranium as fuel, a boiler for cooling the helium and generating steam, and a conventional steam turbine generator to produce electric power. In arriving at these specifications primary emphasis had been placed on a type of plant which appeared most feasible for successful construction and operation in a relatively short time.

DECLASSIFIED

In addition, consideration had also been given to the fact that piles have great potentialities as high efficiency heat engines because the production of heat does not depend on the presence of an oxidizing atmosphere with its consequent limitations on the operating temperature. This was one of the reasons for the selection of beryllium oxide, a high melting point refractory, as the pile structural material.

By September, 1946, plans and experimental work were far enough advanced to enable the Division to begin work on a formal preliminary report (MonN-188), which was published in November, 1946. This report was prepared for a Pile Review Committee which was understood to have been appointed by the Manhattan Engineer District. The report described a preliminary design for a nuclear power plant utilizing a helium-cooled pile with beryllium oxide as the permanent structure and moderating material. The maximum pile rating was 40,000 kw of heat at a maximum coolant temperature of 1400°F and an operating pressure of 10 atmospheres.

While this report was being prepared Dr. Wigner asked that a study of an all-beryllium metal pile be undertaken. It was his belief that beryllium metal had not been given adequate consideration in any study of power piles up to this time, and he felt that before proceeding further with the beryllium oxide pile, it should be given a design evaluation at least comparable to that of the beryllium oxide pile. Consequently, although the directive which had been issued to Monsanto Chemical Company for the work of the Power Pile Division had stressed speed, it was agreed by Drs. Thomas, Wigner, and McCullough on October 30 that nine men from the Power Pile Division would make this study of an all-beryllium metal pile for a period of thirty days, even though it might interfere somewhat with the design of a beryllium oxide pile. This study was in accord with the second directive given the Power Pile Division "to make a long-range study of power from atomic energy". Actually, the beryllium metal pile study was not completed until February, 1947, and had involved the activities of many more than nine men for the intervening period. It was felt that once the job was started it should be an adequate one, and the additional time and manpower was allocated for that reason.

On February 3, 1947, the results of this study were published in a memo entitled "Design Study for a Beryllium Metal Power Pile." The study had disclosed that there were no outstanding differences between Be metal and BeO insofar as their use as the permanent structure and moderating material in a power pile of the type and rating being considered in this development was concerned. This factor together with the poor tensile, creep, and stress rupture properties of Be at high temperatures as well as the very limited state of knowledge regarding the technology of its fabrication led to the conclusion that no advantage would be gained by the use of Be metal as the permanent structure of the pile. At a series of meetings on February 26 and 27 and on March 3 and 5, Dr. Wigner concurred in the decision to continue the design development based on the use of beryllium oxide as the permanent structure. During the period following completion of the beryllium metal study report three factors assumed particular significance in the development.

UNCLASSIFIED

First, it became apparent that an appreciable saving in the critical mass of fissile material together with some gain in conversion ratio could be achieved by reducing the volume of the pile to approximately 0.3 of that used as the basis for the design covered by MonN-188. This also meant not only a considerable saving in the cost of the moderator but also a reduction in power output commensurate with the reduction in volume and, consequently, a reduction in thermal neutron flux.

Second, data was received indicating that samples of beryllium oxide containing fissile material suffered a loss in thermal conductivity by a factor of as much as 5.5 when irradiated in the Hanford piles. Moreover, there were also indications that the degree of damage was less if the irradiation occurred with the sample at high temperature. Since reductions in conductivity would cause a corresponding increase in thermal stresses in fuel units using BeO as the fuel-bearing material or matrix, this data on radiation effects introduced a large factor of uncertainty in estimates of the pile performance. In addition, it was also evident that this uncertainty could not be removed until tests could be made in the pile itself under conditions of simultaneous high temperature and high fission product, gamma, and neutron radiations. Fortunately, it had also been found that beryllium oxide which did not contain fissile material suffered only a relatively small loss in thermal conductivity after irradiation at Hanford and that almost all of this loss could be annealed out at high temperature. Thus the design of the permanent structure of the pile could be carried through with a reasonable degree of certainty.

As a result of the above two factors design work proceeded on the basis of a pile of reduced size and with a rating of 12,000 kw of heat in lieu of 40,000 kw. In addition, the need for data on the effects on materials of radiations at high temperature indicated that the pile should provide an effective facility for this purpose. Therefore, work was begun on re-evaluating the design with greater emphasis on this objective.

The third and perhaps most significant factor which became evident at this time was that the development and design of many of the mechanical features of the pile such as the supporting structure, the high temperature gas ducts, the fuel handling equipment, the control mechanisms, etc. presented problems of such magnitude that their successful solution would require a far greater expenditure of time and manpower than had been contemplated when the Power Pile Division was formed. In addition, it was apparent that an understanding and knowledge of the problems involved comparable to that acquired by the personnel of the Division up to this time would be needed if the design work was to be continued effectively. These considerations together with the large amount of theoretical and experimental work yet required in physics and materials development led to a decision to request the companies having men in the Division on a leave of absence basis to extend the stay of these men to another year or more. In most cases the leaves of absence were extended.

DECLASSIFIED

On July 3, 1947, the Division Director, Dr. C. R. McCullough, was notified by Dr. C. A. Thomas, Project Director, representing the Contractor, that a communication dated June 25, 1947, had been received from Mr. Carroll Wilson, General Manager of AEC, which affected the future of the Power Pile Division program. This letter stated that the AEC was not prepared to authorize the design or make any commitment concerning the construction of the power pile. It stated that it considered the investigation of basic problems or components should continue to be a part of the program at Clinton Laboratories but should be at a lower priority than work on another reactor not designed for power. The Commission felt that if men on loan to the Power Pile Division from various industries and institutions could contribute to this higher priority program and were prepared to remain for an additional year and work on this program, or partly on it, and partly on the study of components of the power pile, they would materially strengthen the technical group at Clinton Laboratories.

This information was contrary to the May 16, 1946, directive to design, construct and operate a power pile, on which basis the Division was formed. As previously stated, it was this information that prompted the writing of this report. In addition, letters were immediately initiated to all parent companies informing them of the status of the Division, and asking them their wishes regarding whether their men should remain to work under this new directive or be returned to their companies. Some of these companies immediately informed us that it was their desire that their men remain for an additional year to work in any capacity that the Commission and Management of Clinton Laboratories might decide. Most of the companies, however, decided that they would not make a positive decision until after a summary report was completed, hoping that by that time more positive information would be available.

The following sections of this report summarize the design and development work of the Power Pile Division on a high temperature gas-cooled power pile carried out pursuant to the original directive of May 16, 1946.

DECLASSIFIED

III. FACTORS AFFECTING PERFORMANCE OF GAS-COOLED THERMAL PILES

Before the design of a specific power pile can be considered, some discussion of the factors affecting power pile performance is necessary. By performance here is meant the net power output of the pile, and the over-all economy of fissionable material. These characteristics can be predicted by studies of the physics of the nuclear chain reaction in the pile, and of the heat transfer phenomena involved in removing the power from the pile. In general, the necessity for maintaining a self-perpetuating chain reaction will establish certain design constraints, which will become more rigorous if high economy of fissionable material is specified. Specification of high power output will establish further design constraints that may not always be compatible with those previously mentioned. In the following sections the interaction of these design constraints to establish the basic design of the pile is discussed. Since this discussion is of general interest, specialized language is avoided as much as possible. For a concise description of the calculation methods and physical constants used, see Appendix C.

A. DESIGN CONSTRAINTS OF CHAIN REACTION

1. The Meaning of Economy of Fissionable Material

Inasmuch as the supply of fissionable material is limited, the achievement of economy in its use is of the first importance. There exist in fairly large quantities materials, such as thorium and U^{238}, which, although they are not fissionable by thermal neutrons, can be converted to thermally fissionable materials by the absorption of one neutron per atom. These materials are called fertile materials. The possibility, therefore, exists of using surplus neutrons from the pile chain reaction to produce fissionable materials from fertile materials, and some types of piles might be developed in which the net consumption of fissionable material is very small, or even negative. In the types of service where such conversion or breeding of fissionable material is practicable, the achievement of a high conversion ratio (number atoms of new fissionable material produced per atom of original fissionable material destroyed) may well be the most important consideration in the design of the pile. One would expect this to be the case for large stationary power plants. There are other conceivable applications for power piles, such as for propelling water - and air-craft and missiles, in which the pile must be considered susceptible to loss, or even as expendable. In such cases, conversion may be of less importance, or of no importance, and the design may be determined by the necessity for keeping the minimum inventory of fissionable material in the pile. For such applications a minimum over-all pile weight may also be a design factor of great importance.

2. Neutron Economy and Critical Mass

The chain reaction in the pile proceeds by means of free neutrons that cause fission of the uranium 235 nuclei. When a neutron is absorbed by a uranium 235 nucleus it may cause fission of the nucleus. When the nucleus splits it liberates a number of neutrons. We designate by η the average number of neutrons liberated by the fissionable material per neutron absorbed.

DECLASSIFIED

Evidently, one of the emitted neutrons must replace the absorbed neutron if the chain reaction is to continue. However, not all of the emitted neutrons will be available for this purpose, as some will leak from the pile and others will be absorbed by non-fissionable material. When the size of the pile and the relative concentrations of the various pile materials is such that exactly one of the η emitted neutrons is available for carrying on the chain reaction — the remaining $\eta - 1$ neutrons either leaking from the pile or being absorbed by non-fissionable material — the pile is said to be critical. The fraction of the neutrons absorbed by non-fissionable materials depends upon what materials are contained in the pile and the relative amounts of each material. Since neutron leakage occurs through the pile surface, the geometry of the pile is related to the neutron leakage, and the fraction of the neuttrons that leak is determined by the pile shape, size, and composition. For any given pile shape and composition there is a single pile size that fulfills the critical condition. Critical piles, can, however be made over a range of shapes and sizes if the composition is suitably adjusted.

As an illustration of the variation of critical size, a cylindrical pile composed entirely of BeO and uranium oxide may be considered. The uranium is considered to be enriched in the fissionable isotope (U^{235}), containing 30% U^{235} and 70% U^{238}. The composition of the pile can then be specified by a single variable, Z, defined as the ratio Weight of $U^{235}O_2$/Weight of BeO. The pile is assumed to be a uniform mixture of BeO and UO_2 at a uniform temperature of 650°C. The pile has the shape of a right circular cylinder, of height 1.85 times the diameter. For a bare pile, this ratio of height to radius requires the minimum mass of fissionable material for criticality. Curves A and A' of Fig. I show the critical size, in terms of the critical radius and the mass of $U^{235}O_2$ (W_{25}) in the critical pile, as functions of the composition - variable Z. It may be noted that the values of W_{25} are proportional to the product of $Z \times R^3$, and that the cruve of W_{25} has a minimum value.

If the average density of the pile is decreased, as for example by piercing the pile with holes for cooling passages, the neutron leakage increases, and if the pile is to remain critical, either its size or its composition, or both, must be changed. Curves B and B' of Fig. I show the critical conditions for the same pile as that of curves A and A', but with 20% void spaces, uniformly distributed.

Neutron leakage from the pile can be greatly reduced by surrounding it with a reflector — a layer of material having low neutron absorption but relatively high neutron scattering power. Curves C and C', D and D' show the resulting critical conditions when a reflector of BeO, of thickness 1/2 the radius of the pile, is placed around the piles of curves A and B respectively. The radial reflectors have no voids; the axial reflectors have the same fractional voids as the reactor.

Of the η neutrons produced in an average fission, one must be used in the chain reaction if the pile is critical. The remainder either leak, or are absorbed in $U^{235}O_2$ or in $U^{238}O_2$ or in BeO. Fig. 2 shows the distribution of neutrons among these various categories, as a function of the composition - variable Z for a pile composed entirely of BeO and 30% enriched UO_2. In the figure, A_{25} designates the number of neutrons absorbed in U^{235}, A_{28} the number absorbed in U^{238}, A_m the number absorbed in the moderator (BeO plus .5

DECLASSIFIED

parts per million of B), and $\mathcal{L}$ the number leaking, as the result of the capture of one neutron by U^{235}. Obviously, $A_{25} + A_{28} + A_m + \mathcal{L} = \eta \cdot A_{25}$, which represents the neutrons returned to the chain reaction, always has the value 1. Of the η -1 neutrons not required for perpetuating the reaction, those absorbed by U^{238} (A_{28}) convert the U^{238} into Pu^{239}, a fissionable material. The neutrons leaking from the reactor ($\mathcal{L}$) are available for conversion if they can be captured after they leak from the reactor by surrounding it with a blanket of U^{238} or thorium. The neutrons absorbed by the moderator (A_m) are entirely lost. A_m may be termed a parasitic absorption.

$A_{28} + \mathcal{L}$ specifies the total number of neutrons available for conversion per neutron absorbed in U^{235}. Since each neutron absorbed in U^{235} destroys a U^{235} atom either by causing fission or by converting it to U^{236}, which is not thermally fissionable, the quantity $A_{28} + \mathcal{L}$ represents the maximum possible number of fissionable atoms that could be produced per U^{235} atom destroyed. The actual number of fissionable atoms produced will, of course, be less than $A_{28} + \mathcal{L}$, and will be determined by the efficiency with which the $\mathcal{L}$ leakage neutrons can be captured by fertile material.

It is evident that for the cases where breeding or conversion is practicable, economy of neutrons is equivalent to economy of fissionable material, and the quantity $A_{28} + \mathcal{L}$ is of primary importance. Fig. 2 shows that this quantity increases as the ratio U^{235} to moderator increases, but that the rate of increase is small at large Z. Small increases are, however, worth striving for. If an over-all conversion ratio (number of atoms of new fissionable material produced per atom of fissionable material destroyed) of one can be achieved, the pile will run indefinitely with no net consumption of fissionable material. Even if a conversion ratio of one cannot be achieved, small differences in conversion ratio can have large effects on consumption of fissionable material. The case of an over-all conversion ratio, β, may be considered. β is to incorporate all losses of neutrons and fissionable material, such as those that occur in the capture of leakage neutrons, processing of fissionable and fertile material, etc., as well as those lost by parasitic absorption in the pile reactor. β will be smaller than $A_{28} + \mathcal{L}$, but will depend upon $A_{28} + \mathcal{L}$. Over a long period of time, the amount of energy released in the pile per net fissionable atom destroyed will be proportional to $1/1 - \beta$. This function is plotted in Fig. 3. It is, of course, quite sensitive to β in the vicinity of $\beta = 1$; therefore, small variations in $A_{28} + \mathcal{L}$ may be of considerable importance.

3. Moderator Materials

The moderator material performs the functions of slowing down the neutrons formed in fission and of impeding their leakage from the pile. It will, in general, also be utilized as a diluent for the fissionable material in order to increase heat-transfer surface, and as a structural material. The three materials, Be, BeO and graphite, presently under consideration as possible moderators for high temperature piles, vary widely in physical and chemical properties. The choice of one of these materials for a given pile application will be based on a great number of considerations, such as high temperature properties, structural properties, heat-transfer properties, chemical reactivity, susceptibility to fabrication methods, as well as upon nuclear properties. Of these properties, the nuclear properties are among

DECLASSIFIED

the few that can be given a general evaluation. The characteristics of the three materials with respect to the fission chain reaction can be compared qualitatively by curves of the criticality conditions and the neutron economy of bare cylindrical piles employing the three moderators along with 30% enriched uranium. Fig. 4 shows the critical radii and masses of U^{235} for cylindrical piles as functions of the composition - variable Z. Fig. 5 shows the same quantities as functions of the neutron economy. The (γ, n) and $(n, 2n)$ reactions in Be are neglected in these calculations. The magnitude of these reactions are estimated in Appendix D. It is evident that Be requires a somewhat larger, and graphite a considerably larger, critical mass of U^{235} for a given neutron economy than does BeO. These relations alone do not specify the relative merits of the moderator materials. They must be considered in relation to the other properties of, and demands on, the materials. It has already been pointed out, for example, that both the criticality conditions and the heat-transfer relations are involved in determining the size and critical mass of a power pile. It is, therefore, not possible to predict, from curves similar to those of Fig. 4, which of the three moderators will give a pile of, say, the lowest critical mass of fissionable material when the neutron economy and power output are specified.[1] Furthermore, the importance of certain properties of the materials may be emphasized by certain specific pile applications. There are conceivable applications, for example, where beryllium metal would be useless because of the rather low limit to its maximum permissible temperature, in spite of its good heat transfer properties. At the present time one can say only that all three moderator materials show promise of great usefulness in the power pile field.

B. POWER REMOVAL

1. General Considerations

a. Distribution of Heat Sources. The energy released by fission of the uranium nucleus is removed from the pile in the form of heat, by a cooling fluid that flows in passages provided in the pile for that purpose. The distribution of the heat sources must be considered before heat removal can be discussed.

The energy appears initially as kinetic energy of fast moving particles and as radiation (γ-rays). By far the larger part of the energy is in the form of kinetic energy of charged particles, and is degraded to heat in the very near vicinity ($< 10^{-3}$ cm) of the fissioned atom. The smaller fraction of the energy that appears as radiation and kinetic energy of neutrons is converted into heat over a wide region (cm to meters) surrounding the fissioned atom. Table II summarizes the energy that is degraded to heat in a BeO - moderated pile using enriched UO_2.

---

[1] In Section VI the heat-transfer and criticality conditions are combined to give comparisons of BeO, Be, and Graphite piles for specific cases.

DECLASSIFIED

TABLE II

ENERGY ORIGINATING IN REACTOR OF STEADILY OPERATING PILE[1]
(EXCLUSIVE OF NEUTRINO ENERGY)

FORM OF ENERGY	MEV PER FISSION	DEGRADED TO HEAT
Kinetic energy of fission fragments	165	Within $\sim 10^{-3}$ cm of point of fission
Kinetic energy of particles	7	
Kinetic energy of neutrons	5	
γ – rays from fission and radioactive decay	10	More or less exponentially from point of origin, with decay constants of the order of centimeters.
γ – rays from capture of neutrons in Be and U^{238}	2	

It is evident from Table II that all but about 10% of the energy of fission is degraded to heat in the very near vicinity of the fissioned atom. The distribution of heat production throughout the pile will, therefore, be essentially the same as the distribution of the rate of fission, which is proportional to the product of the thermal neutron flux and the density of fissionable material. In Figs. 6 and 7, the solid curves show the distribution of thermal neutron flux and epithermal flux (flux of neutrons of energy higher than thermal) for a pile consisting of a BeO moderated reactor with uniform distribution of UO_2 containing 30% $U^{235}O_2$, and a BeO reflector (the pile corresponds to loading pattern A of Table IV). The relative value of the flux at any point in the pile is equal to the product of the values from the radial and the axial distribution curves at the corresponding coordinates, and the distribution of heat production will be about the same as the thermal flux distribution. Usually the UO_2 is concentrated in short lengths of identical elements which also contain moderator material and are designated as fuel elements. If these fuel elements are located in channels formed by a structure of moderator material with the channels running through the structure in the axial direction and distributed uniformly with small spacing over the radial cross section, the heat production will be concentrated largely within the fuel elements; but the gross distribution from element to element, and along the length of a given element, will be essentially proportional to the thermal flux distribution of Figs. 6 and 7. Inasmuch as the

[1] Values other than those for the (n,γ) reactions taken from Lecture 16 (K. Way) of Pile Technology Course at Clinton Laboratories.

DECLASSIFIED

distribution is not flat, suitable arrangements must be made for removing the proper amount of heat from each portion of the pile. In general, such arrangements result in lowered pile output or increased coolant-pumping work, or both, and it is desirable to keep the flux distribution as flat as possible. An effective reflector flattens the distribution considerably as is shown by comparison of the solid and the dashed curves of Figs. 6 and 7. The dashed curves give the thermal flux distribution for a bare pile.

b. Effect of Voids. Heat transfer in a gas cooled pile essentially consists of the following processes and restrictions:

1. Transfer the heat by conduction to the heat transfer surfaces without incurring damaging thermal stresses.

2. Transfer the heat to the gas coolant (a) without requiring excessive temperature difference between the gas and the fuel elements, and hence, without exceeding the maximum allowable pile material temperature, and (b) without requiring excessive gas pumping power.

3. Absorb the heat in the gas in such a way that the desired outlet gas temperature is obtained.

These requirements can be met by incorporating in the pile coolant passages of appropriate size, shape, number, and distribution. If the gross distribution of coolant passages over the pile cross-section is uniform and if the neutron absorption in the coolant gas is negligible, the effect of the passages and the coolant on the criticality conditions of the pile is, to a first approximation, just the effect of the average decrease in density of the pile materials represented by the coolant passages. Treating the coolant passages (voids) in this way, families of curves can be constructed relating pile radius, critical mass of fissionable material, and fraction voids for specified reflector constructions. To facilitate computation, it is convenient to express the reflector thickness as a fraction of the reactor radius. Several such families of curves are given in Figs. 8, 9, 10, 11, and 12. The fraction voids (= volume of coolant passages/volume of pile including coolant passages) is designated as α. All the curves are for reactors of axial length 1.85 times the radius. This length-radius ratio is approximately that for minimum critical mass of fissionable material. Figs. 8, 9, and 10 are for $BeO-UO_2$ piles of different reflector thickness ratios and Figs. 11 and 12 are for Be-U and graphite-UO_2 piles, respectively. In all cases the uranium is 30% enriched in U^{235}. Families of curves of this type may be used to relate the criticality requirements and the power removal requirements of piles in order that an optimum design may be achieved as described later in this section. It is evident from Figs. 8, 9, 10, 11, and 12 that low mass of fissionable material is required for criticality if the heat-transfer surfaces are so designed that a minimum of pile volume is devoted to gas passages. The following discussion is directed toward the achievement of this desirable end.

DECLASSIFIED

2. Pile Geometry

As in any heat exchanger, various surface arrangements of the pile structure should be considered. The arrangements are classified in the following groups: (1) Continuous channels in which the gas flows parallel to the channel wall; (2) Pebbles; (3) Interrupted fins.

a. Non-Split Flow Designs. In order to compare the various types of surface, consideration will be given first to a heat exchanger or pile in which the gas flows continuously in one general direction from one face to the opposite face. The conclusions drawn from such a comparison will provide some fundamental information on the characteristics of these surfaces but will not give the relative advantages of a pile designed with one type surface as compared to another except in the case of a single pass non-split flow design. For such a restricted design, pebble piles provide less than 1/2 the KW output of continuous channel piles of the same size under similar operating conditions. This is because of the very low heat transfer rate per unit of friction power obtainable from a pebble bed. Under operating conditions expected in power piles, interrupted fin surfaces of the type shown in Fig. 13 (a) provide approximately twice the heat transfer rate per unit of friction power of a continuous channel (flow inside of pipes). However, these surfaces are based on interrupting the gas flow so that the stagnant boundary layer is never permitted to build up. In order to accomplish this action effectively, these fins should not be thicker than 1/64" nor longer than 1/2 " and the channels must be small. There are two reasons for rejecting this type design at present. The first is the difficulty of manufacturing such fuel elements. The second is that these small shapes provide tremendous surface area, and thus impose restrictive pumping power in a single flow design. This type design is applicable, however, to the split flow arrangements discussed in the next paragraph.

b. Split-Flow Designs. Each of the type surfaces described above has a very high heat transfer rate per unit volume if very small equivalent diameter channels are used. Such operation can only be obtained in a very thin heat exchanger bank. This is achieved practically by splitting the flow into many parallel channels, for instance, by wrapping the surface into tubes using the core as the inlet header and the outer annulus as the outlet header as shown in Fig. 13 (b). This leads to the question of whether the cooling stream should be one pass, multipass or split flow. A multipass design requires more gas passage volume than a single or split-flow design and is, therefore, of no interest for piles because of the consequent sacrifice in economy of fissionable material.

Now consider a split flow design. If the thermal stresses are ignored for the moment, analysis shows that a pile designed for turbulent flow and for fixed operating conditions and fixed output requires a fixed gas passage area. If the flow is split and header losses are ignored, the gas passage area per side is halved as shown in Fig. 13 (c). In general, the active gas passage area is cut in half for each split. Thus, a two-circuit design requires only 1/2 the active gas passage area of a single flow design and a four circuit design requires 1/4, etc. However, headers must be provided within the reactor to get the gas to the active surface. These headers require a good part of the active volume saved by splitting the flow, if the

DECLASSIFIED

velocity head loss in the active channels is in the order of 10 to 20. If it is greater, a split flow design may show considerable saving.

Consider now the case with thermal stress. The reduction in active gas flow area occasioned by the use of a split flow increases the local percentage moderator material in the fuel elements. However, the equivalent diameter of the gas passages is proportional to the length of the gas path. Thus, with a single split the equivalent diameter of the gas passage is cut in half but the total number of channels is increased and the thickness of the fuel elements is reduced. For most cases, these effects tend to compensate for each other. It is evident, therefore, that the design of a pile with extremely small channels and with a potentially high power output may be practically obtainable by the use of a multi-split flow design.

It is evident from the above discussion that in a split flow design the active pressure drop and active area required for heat transfer is no longer predominant so that it does not matter whether the surface is small pebbles, continuous channels, or any other type shown in Fig. 13 (b). The predominant pressure drop and volume devoted to the gas in the pile is in the headers. Such a design may not be too sensitive to the heat transfer properties of the cooling gas and as a result may allow the choice of a gas which can be more easily compressed than a good heat transfer gas. Investigation of this type design has not been carried far enough to adequately evaluate it. It is discussed to show one line of possible future development for high output piles. Because of the lack of information on this type design, further discussion will be limited to piles in which the gas flows continuously from one face to the opposite face.

c. Arrangement of Moderator and Fuel Elements. If there were no thermal stress limitations in the pile, the gas passage area and, hence, percent pile voids, would be independent of the length of the pile as indicated by Equation 1. In this case, the length of the pile would be set by physics or other requirements. If thermal stresses are serious, a short length is preferable as shown by Equation 5. The examples given in Figs. 16 and 17 and in the section on high output piles is limited to an $L/D = .925$ which is the ratio requiring minimum critical mass of fissionable material for a given ratio of fissionable material to moderator.

Both heat transfer and pressure drop is expressed as a function of equivalent diameter (four times the cross-section area divided by the wetted perimeter of a channel). This method of representation is fairly good for any shape of channel for both turbulent and streamline flow. As a consequence, the shape of the channel has little effect on the heat transfer and pressure drop. From this standpoint flat plates will give approximately the same results as square or circular channels. The thermal stresses in a flat plate (except at the supports) is less than in a unit in which holes are drilled and also slightly less than in an egg crate design. However, these stress differences are small. As a result, ease of fabrication will dictate to the greatest degree the shape chosen. For metals such as Be, a plate design is preferable. Therefore, any shape of channel can be used and the generalized comparisons made later will apply.

DECLASSIFIED

As pointed out above, approximately 90 percent of the energy of fission is generated within a distance of 10^{-3} cm of the fission. Therefore, most of the heat is generated in the immediate vicinity of the fissionable material. The rest of the energy is degraded into heat in a distance of cm to meters. Since thermal stress varies as the square of thickness of the fuel element and only as the first power of the heat generation per unit volume, any fuel element could be halved in thickness, thus doubling the heat generation per unit volume but halving its thermal stress. This consideration leads to the design of a pile in which the fuel is not homogeneously distributed throughout the moderator but consists of fuel elements (with fissionable material and moderator) and other elements with moderator only. The quantitative effect of this distribution on pile size is given in Equation 5. Since something less than 10 percent of the heat is generated in the moderator plates, there is an optimum ratio of moderator plate to fuel plate thickness. This is dependent on the allowable thermal stresses and on the radiation damage factor for the two plates. The optimum ratio of moderator plate thickness to fuel plate thickness is usually between 3 to 15.

The fuel elements and moderator elements do not necessarily have to be separated by a gas space. The design of the removable fuel containing units could be sandwiches with a moderator plate sandwiched between two fuel plates or could be tubular fuel inserts in a moderator block as brought out later in the heat transfer discussion of Section V, B-4.

3. Effect of Design Conditions

For the case of a cylindrical pile in which the gas flows in continuous channels parallel to the axis from one face to the other, a simple relationship representing heat transfer requirements can be obtained between pile voids, pile diameter, D, and the pile design conditions. The basic equations required are the heat transfer rate equation, the pressure drop equation, the energy balance equations (heat generated equals heat transferred to the gas, equals heat absorbed by the gas). The relationship obtained is:

(1)

$$\alpha D^2 = \frac{1}{\sqrt{\theta}} \left[\frac{KW \times \sqrt{F_x^2 F_y F_c F_L}}{336 P \sqrt{R \eta_b} \sqrt{\frac{\Delta T^2}{T_b T_b}} \left(\frac{\gamma}{\gamma - 1}\right) \sqrt{\frac{9\gamma - 5}{2(\gamma - 1) m w}}} \right]$$

The following expression gives the equivalent diameter of the gas channels:

(2)

$$\rho_e^{1.2} = \frac{4.55 \times 10^{-3}}{F_y \cdot F_x^{-0.2}} \left[\frac{(9\gamma - 5)\mu^{0.2}}{\gamma^{0.8} \left[m w (\gamma - 1) \right]^{0.2}} \right] \left[\frac{\frac{\pi}{4} D^2 \alpha}{KW} \right] \frac{\theta L}{\Delta T^{0.8}}$$

DECLASSIFIED

Or approximately by:

(2.1) $$D_e \cong \frac{.01L\theta}{\Delta T}$$

Where

KW = Pile thermal output in kilowatts.

α = Fraction pile voids.

D = Reactor diameter in Ft.

θ = Temperature difference between the fuel elements and gas at the center of the pile.

P = Operating pressure in atmosphere.

F_x = Maximum to average radial heat release ratio.

F_y = Maximum to average axial heat release ratio.

$F_c \cdot F_L$ = Ratio of pressure drop in complete gas circuit to that devoted to heat transfer in pile.

R = Fraction of pile thermal output devoted to driving blower.

η_b = Efficiency of converting blower thermal energy to gas pressure energy.

$\Delta T = T_2 - T_1$ = Gas temperature rise in pile, °F.

T_p = Gas temperature at center of pile, °F.

T_b = Average gas temperature in blower, °R.

γ = Specific heat ratio of gas.

mw = Molecular weight of gas.

D_e = Equivalent diameter of gas channels; all channels are assumed to be similar.

μ = Viscosity of the gas at center of the pile in lb/hr ft.

These equations have certain design limitations, such as their application to turbulent flow only. These limitations are given in MonN-299. However, they are satisfactory for preliminary evaluation studies. From these equations it can be seen that neither the length of pile nor the equivalent

DECLASSIFIED

diameter of gas channels is required to determine the pile diameter and percent voids. However, once the length is specified, the equivalent diameter of the gas channels is automatically established.

Equation (1) shows how the design conditions affect αD^2. By examination of this equation, the design conditions described in the following paragraphs are indicated to give a pile of maximum thermal output.

a. Operating Pressure. The thermal output is directly proportional to the operating pressure.

b. Pile Temperature. Equation 1 shows that the thermal output of the pile is proportional to $\sqrt{\theta \cdot \Delta T^2 / T_b}$. For the optimum division of temperature, the output goes up approximately as the 3/2 power of pile temperature. However, the problems associated with increasing pile temperature are usually much more severe than those associated with corresponding increases in pressure.

c. Gas Characteristics. All the gas properties of interest in heat transfer can be related to gas molecular weight and specific heat ratio as shown in Equation 1. Examination of this equation indicates that a gas of low molecular weight and low specific heat ratio is desirable. Fig. 14 shows the ratio of thermal power obtainable with various gases compared to air as 1.

d. Nuclear Physics. The pile should be designed with as small maximum to average heat release ratio as possible since the output is indirectly proportional to this ratio.

e. Gas Pumping Power. Since the pile thermal output is proportional to the square root of the blower power, the blower power should be as large as possible for high thermal output. For piles used to produce mechanical power, however, the effect of blower power on shaft output and plant efficiency is of primary importance. The shaft output is proportional to $\sqrt{R}\,(1 - R)\eta$ where R is the fraction of pile thermal output devoted to driving the blower and η is the efficiency of conversion of thermal energy to mechanical energy in the power cycle. It can be seen from this relationship that there is a point beyond which an increase in (fraction) blower power actually reduces the shaft output. Furthermore, the over-all efficiency of the plant drops as R increases since it is equal to $\eta(1 - R)$. Fig. 15 shows the effect of varying R on both shaft output and the efficiency of a power pile. It appears tha 0.10 to 0.20 fraction blower power is a reasonable design value.

The thermal power output is proportional to $1/\sqrt{F_c \cdot F_L}$. These factors take into account all pressure drops not directly contributing to heat transfer in the pile. The factor, F_c, is the ratio of total pressure drop to that in the pile; therefore, it takes into account the pressure drop in the ducts and heat exchanger. The size and cost of this equipment will have a bearing on the value to use for F_c. As a preliminary design value, it is reasonable to use 1.4. The factor, F_L, is the ratio of pressure drop across the pile to pressure drop used to produce heat transfer. It takes into account entrance and exit losses, acceleration effect, losses between fuel element joints and friction drop in the axial reflector.

DECLASSIFIED

f. Physical Properties of Pile Materials. In the case of some moderating materials there are stress limitations. Therefore, another limitation on pile power output as imposed by the thermal stress equation must be introduced. By solving equations (1), (2.1) and the following two equations simultaneously,

(3)

$$\frac{w}{D_e/2} = \text{Const.} \frac{(\text{Vol. fuel elements solids})}{(\text{Vol. voids})}$$

(4)

$$S_z = \text{Const. } pw^2 \frac{E\,b}{k\,(1-\sigma)}$$

Where

w = Fuel element thickness

p = Heat generation per unit volume

the expression for α and D taking into account thermal stress results:

(5)

$$\frac{\alpha^6 D^9}{(1-\alpha)} = \frac{.0185KW \cdot F_x \cdot F_y \cdot F_d \cdot F_v}{\Delta T^2} \times \frac{E\,b}{kS_z\,(1-\sigma)} \times \left[\quad\right]^4$$

Where:

The [ ] quantity is the [ ] quantity in Equation (1).

k = Thermal conductivity of the fuel plates in Btu/ft F hr.

S = Allowable stress in the fuel elements, psi.

E = Modulus of elasticity, psi.

σ = Poisson ratio.

F_d = Ratio of length reactor to diameter of reactor.

F_v = Ratio fuel element volume to total material volume.

Other symbols are defined under "Effect of Design Conditions".

This equation is based on the stresses in the fuel elements using the flat plate stress equation with cooling on both sides. It is assumed

DECLASSIFIED

that values of F_v will not be chosen to make the fuel elements too thin to fabricate. The equation, therefore, is not rigorous for all designs, but is an excellent first order guide from which to design piles. It shows that the pile output per unit volume is favorably affected by a small length to diameter of pile ratio, by a small ratio of fuel element volume to total material volume and by a large value for $D\alpha R(1-\sigma)/E\beta$, the thermal stress figure of merit. Values of this quantity are given for various materials in the properties of materials section.

4. Example of Correlation of Heat Transfer and Physics Requirements

From the general considerations on heat transfer and nuclear physics pile designs can be obtained which show the effect of design conditions on critical mass of fissionable material, conversion and KW output per Kg of fissionable material. To illustrate, the following design specifications are assumed:

$P = 40$ atmos.

$T_1 = 500^\circ F.$

$T_2 = 1400^\circ F.$

Maximum pile temperature = $2000^\circ F.$

Gas = helium.

Maximum to average heat release ratio = 1.9

Fraction blower power = .15.

As pointed out in the previous section, heat transfer can be expressed as a function of α, fraction pile voids, diameter or R, radius of reactor in centimeters, and moderator material.

If the moderator material has no thermal stress limitation, the heat transfer is only dependent on α and R. For the above design specifications, the following values of αR^2 are obtained for the heat outputs listed:

Pile Rating, KW	Value of αR^2
50,000	318
100,000	637
250,000	1595
500,000	3180

The locus of the αR^2 for each pile output can be plotted on the nuclear physics curves for critical mass and conversion versus α and R to determine the most satisfactory design point. This is done for BeO moderator in Fig. 16. It should be remembered that these curves represent operation with no thermal stress limitations.

DECLASSIFIED

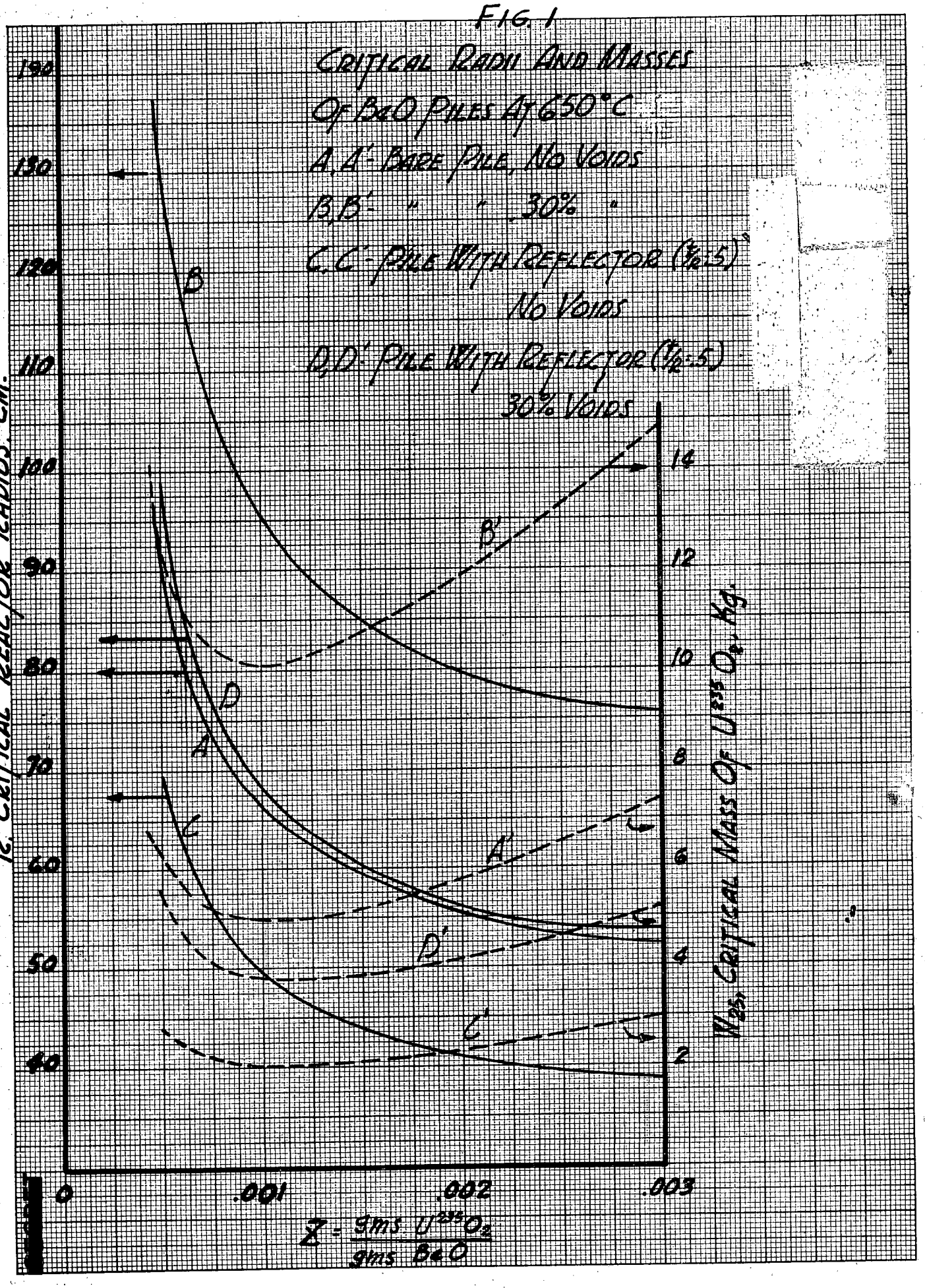
However, in the case of BeO or graphite, there are thermal stress limitations. As an example of the locus of pile designs with thermal stresses, assume a BeO moderator of density 2.87, with an allowable stress of 900 psi in the fuel elements. This design stress was chosen to provide a radiation damage factor of 5, transient operating factor of 2.0, and an eccentric fuel element position factor of 1.5. Assume also that the length of the pile = .925D. All other design specifications are the same as above except the maximum pile temperature which is less than 2000°F and is dictated by the stress limitations. The locus of designs for this condition are shown in Fig. 17. It should be emphasized that the available data on the properties of BeO are extremely meagre and of quite uncertain accuracy as discussed in Section V of this report. This, together with the fact that the stress analysis methods used were necessarily very approximate, makes the results useful only for preliminary evaluation purposes.

Assume that the pile designs are given by Fig. 17 and examine the information therein presented. Suppose a pile of 250,000 KW output is desired with high conversion. The design point would be chosen to the left of the curve at point A. Suppose a low critical mass was desired, then the minimum point of the curve, point B, would be taken as the design point. Similar curves are presented for Be, graphite and for BeO for other densities than 2.87 and for other allowable stresses in Section VI, "Discussion of High Output Piles". In Figs. 16 and 17 the specific power KW/Kg, is obtained by dividing output by the ordinate value.

The comparison of high output piles using BeO, Be and graphite moderator covered in Section VI, indicates that all three of these moderators are sufficiently promising from a nuclear physics and heat transfer standpoint to warrant investigation.

DECLASSIFIED

FIG. 1



DECLASSIFIED

SECRET

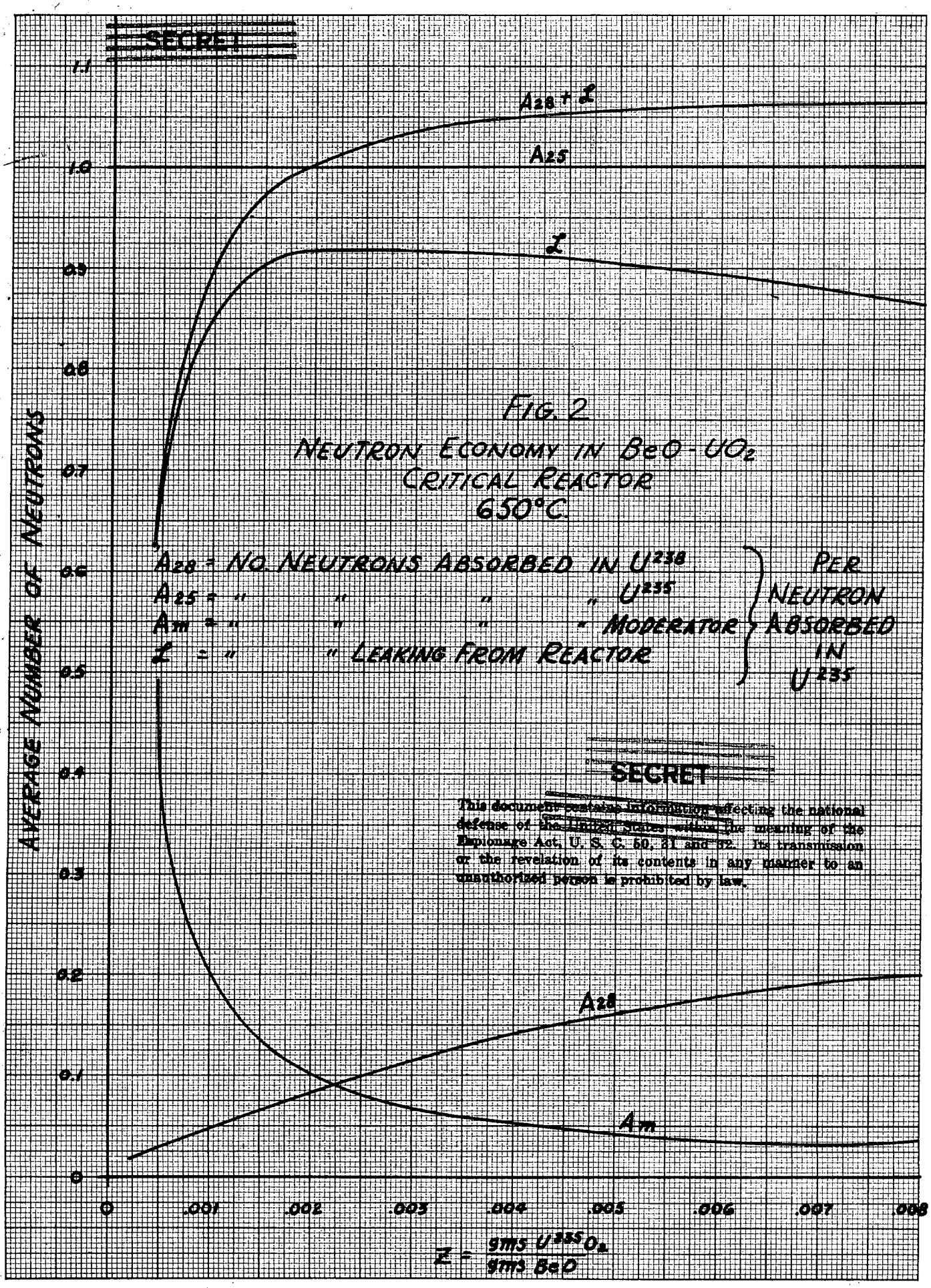


FIG. 2

NEUTRON ECONOMY IN $BeO-UO_2$ CRITICAL REACTOR 650°C.

A_{28} = NO. NEUTRONS ABSORBED IN U^{238}
A_{25} = " " " " U^{235}
A_m = " " " " MODERATOR
$\mathcal{L}$ = " " LEAKING FROM REACTOR

} PER NEUTRON ABSORBED IN U^{235}

SECRET

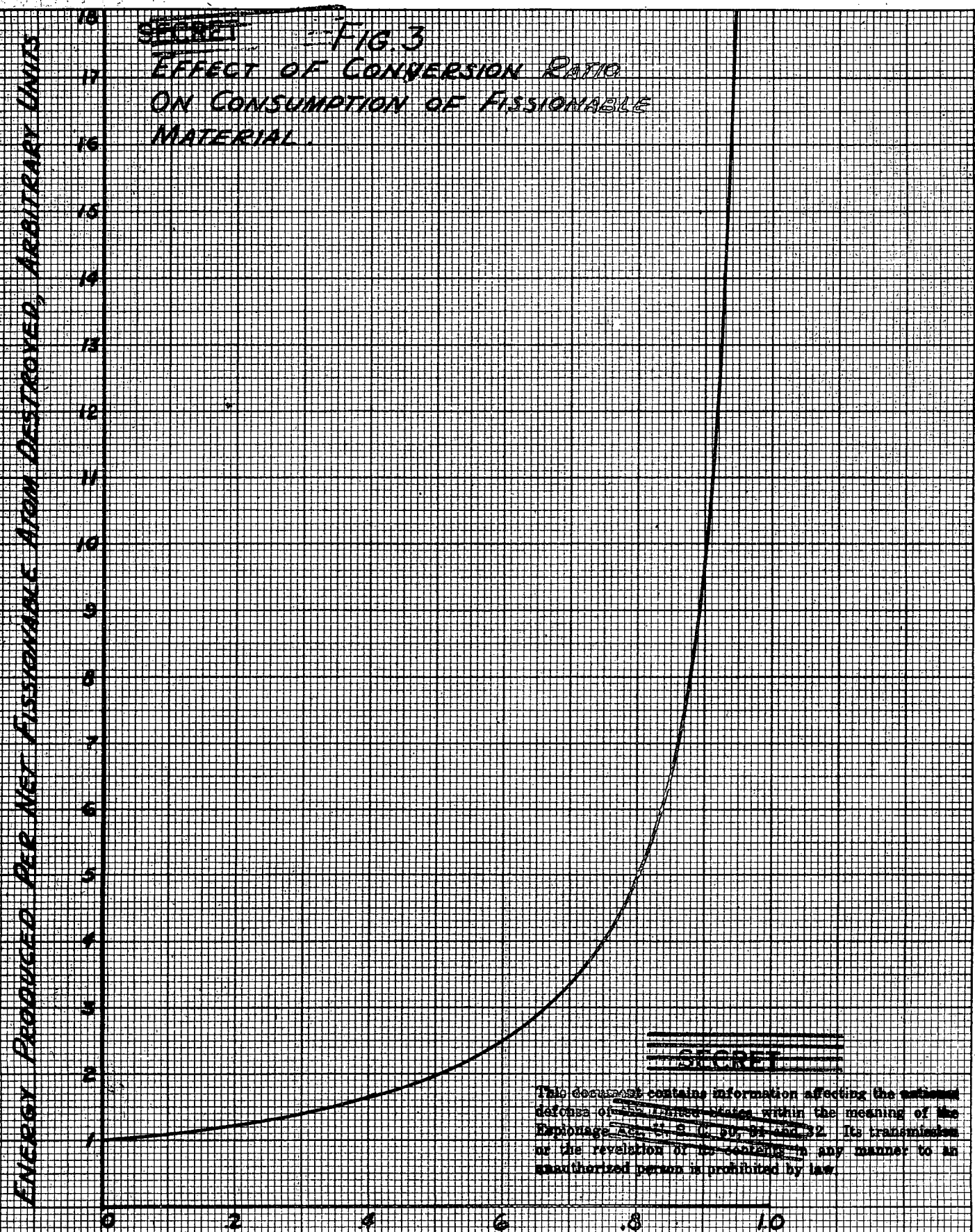
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET

FIG. 3

EFFECT OF CONVERSION RATIO ON CONSUMPTION OF FISSIONABLE MATERIAL.



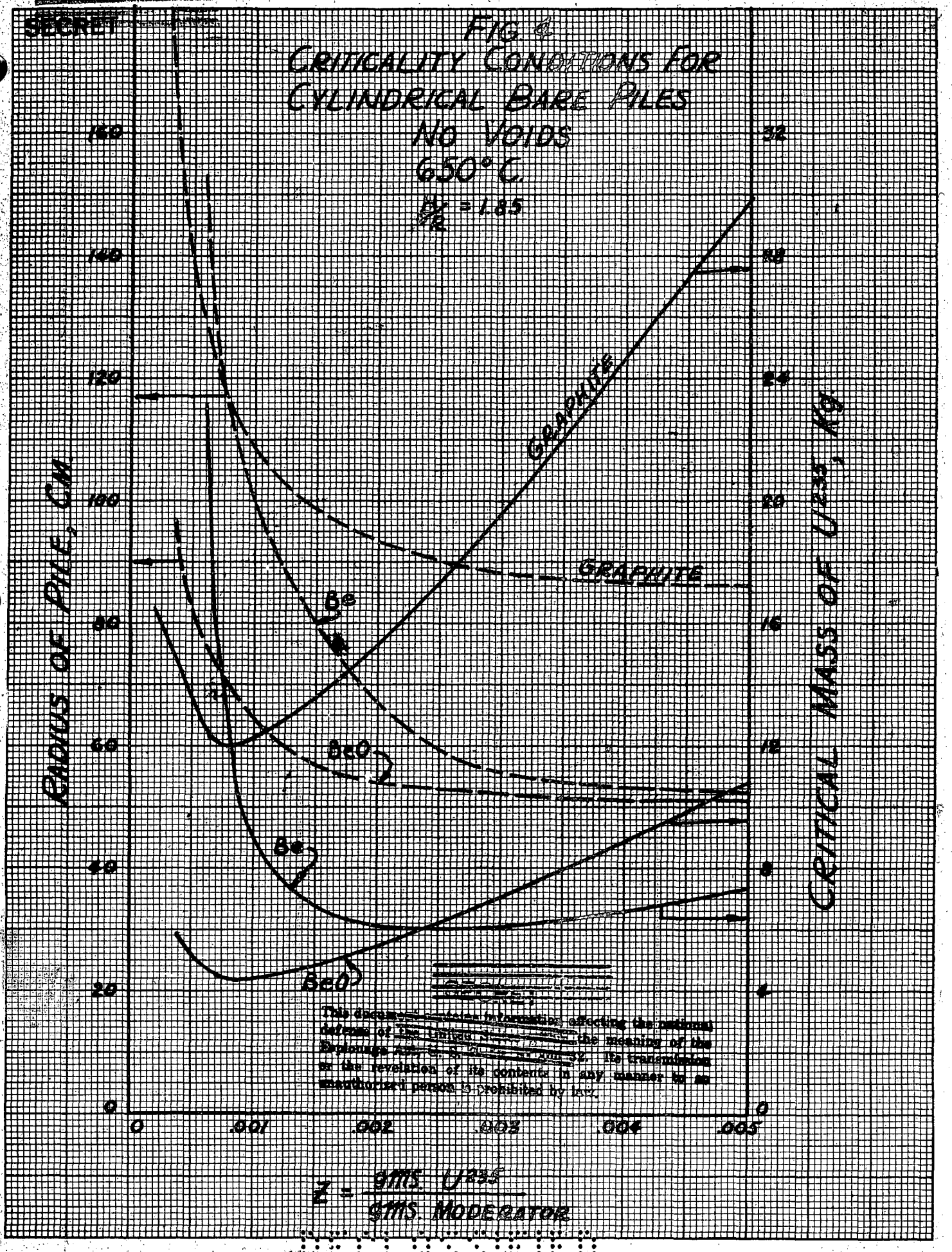
SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

β = CONVERSION RATIO = $\frac{\text{NO. NEW FISSIONABLE ATOMS PRODUCED}}{\text{NO. FISSIONABLE ATOMS DESTROYED}}$

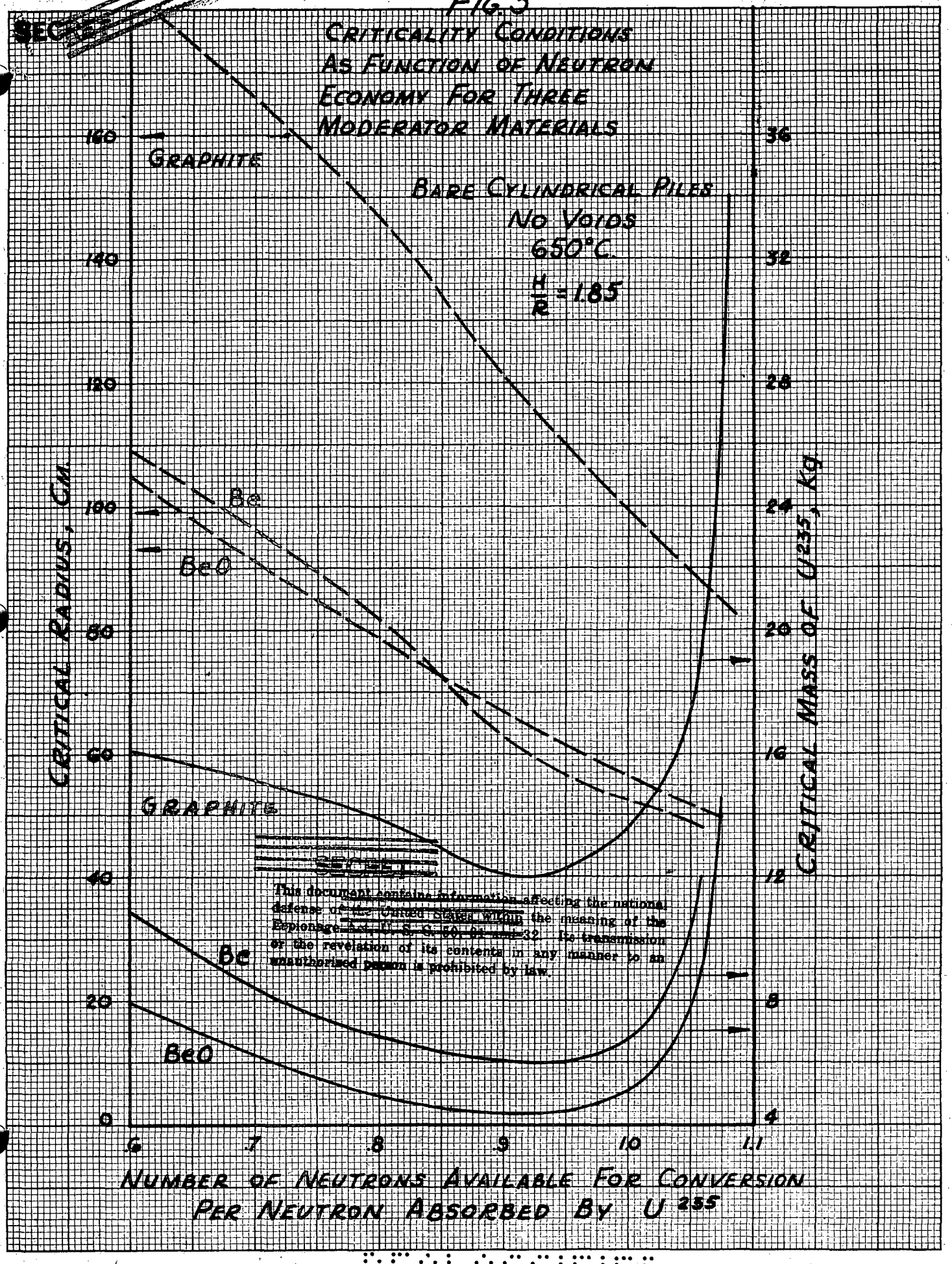
DECLASSIFIED

SECRET



This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C., 50:31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FIG. 5



SECRET

SECRET

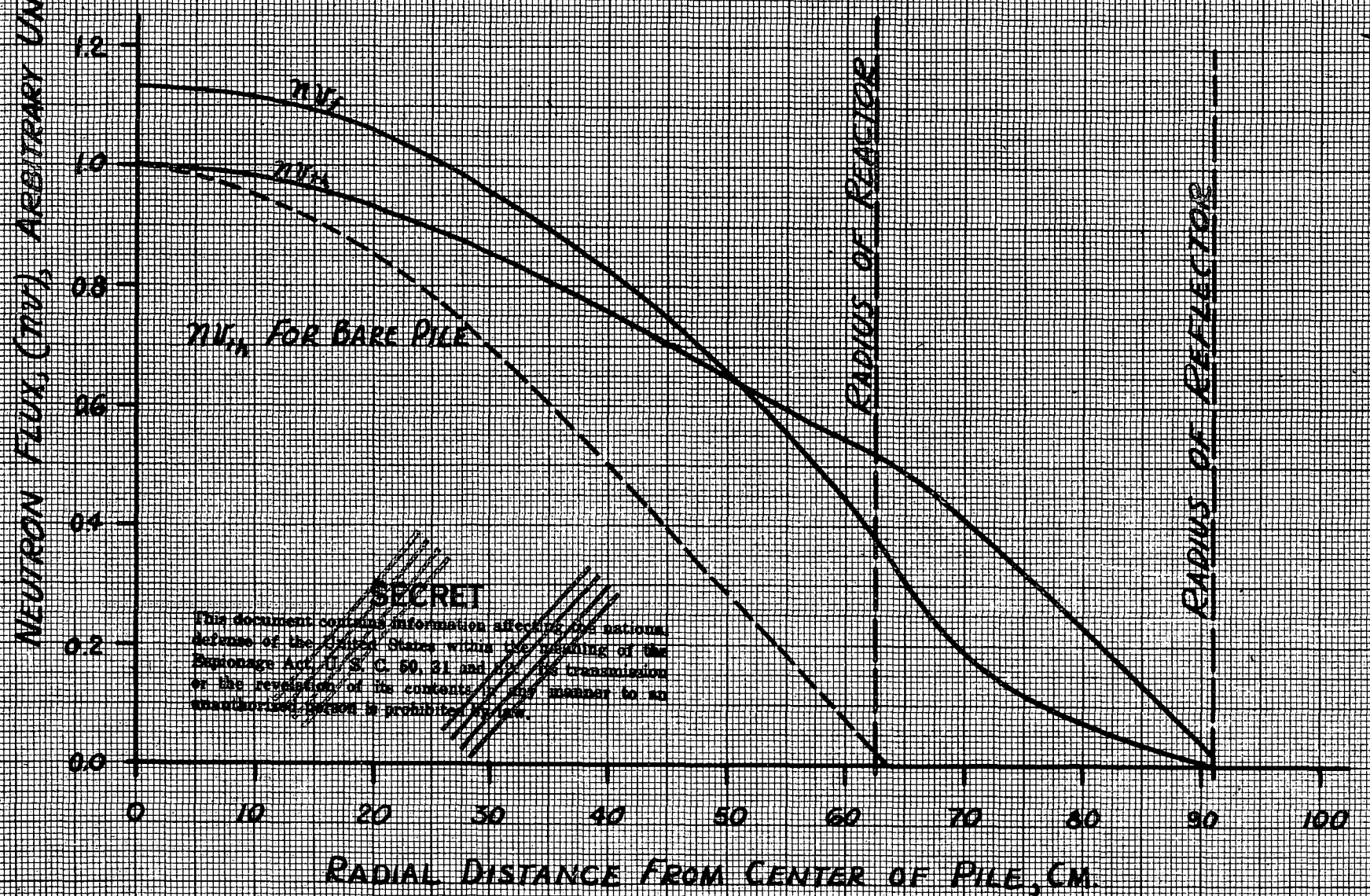
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50:31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET

FIG. 6

RADIAL VARIATION OF THERMAL FLUX (nv_{th}) AND EPITHERMAL FLUX (nv_{ϵ})



SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

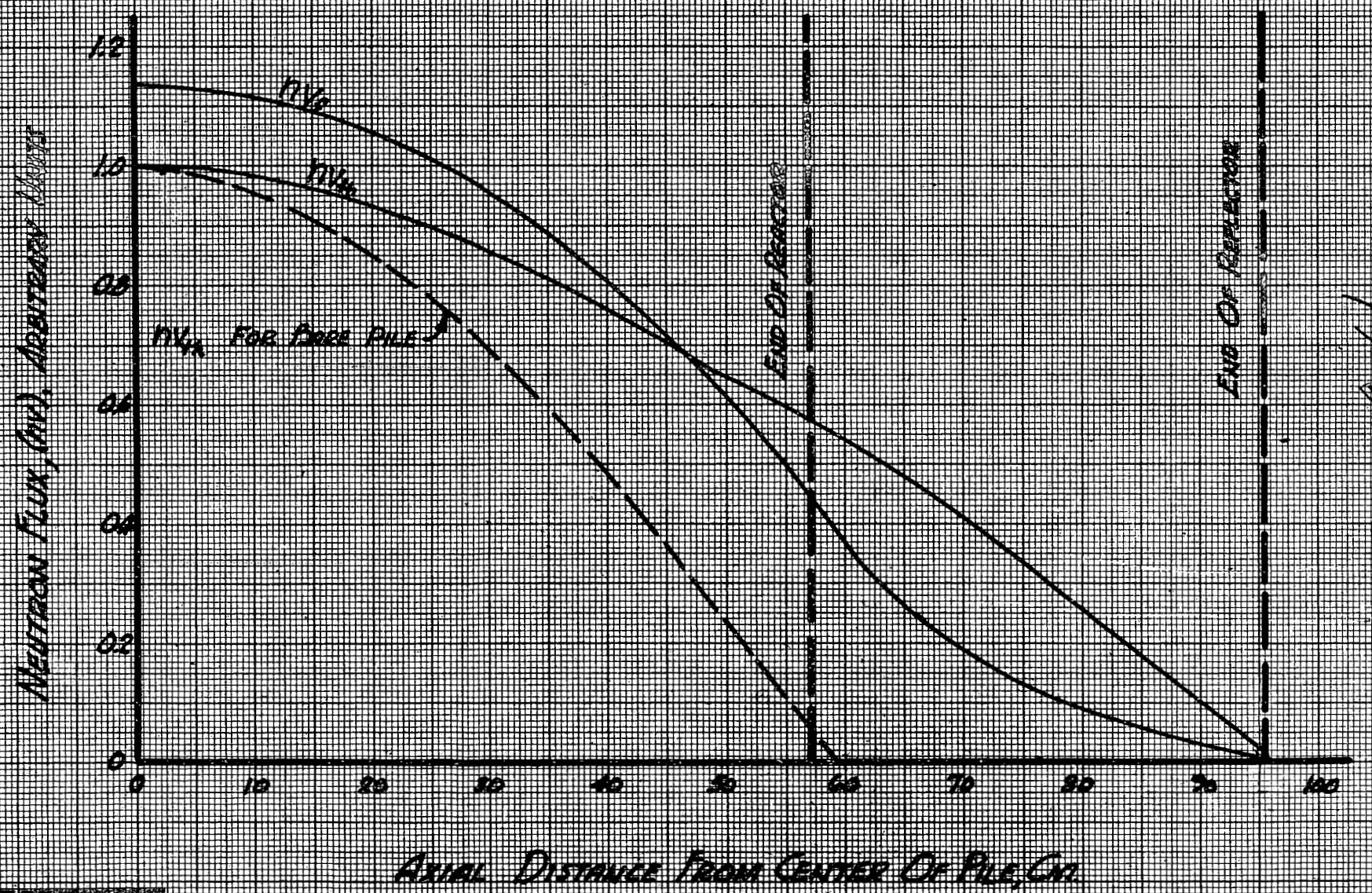
DECLASSIFIED

SECRET

FIG. 7

AXIAL VARIATION OF THERMAL FLUX (nv_{th}) AND EPITHERMAL FLUX (nv_e)

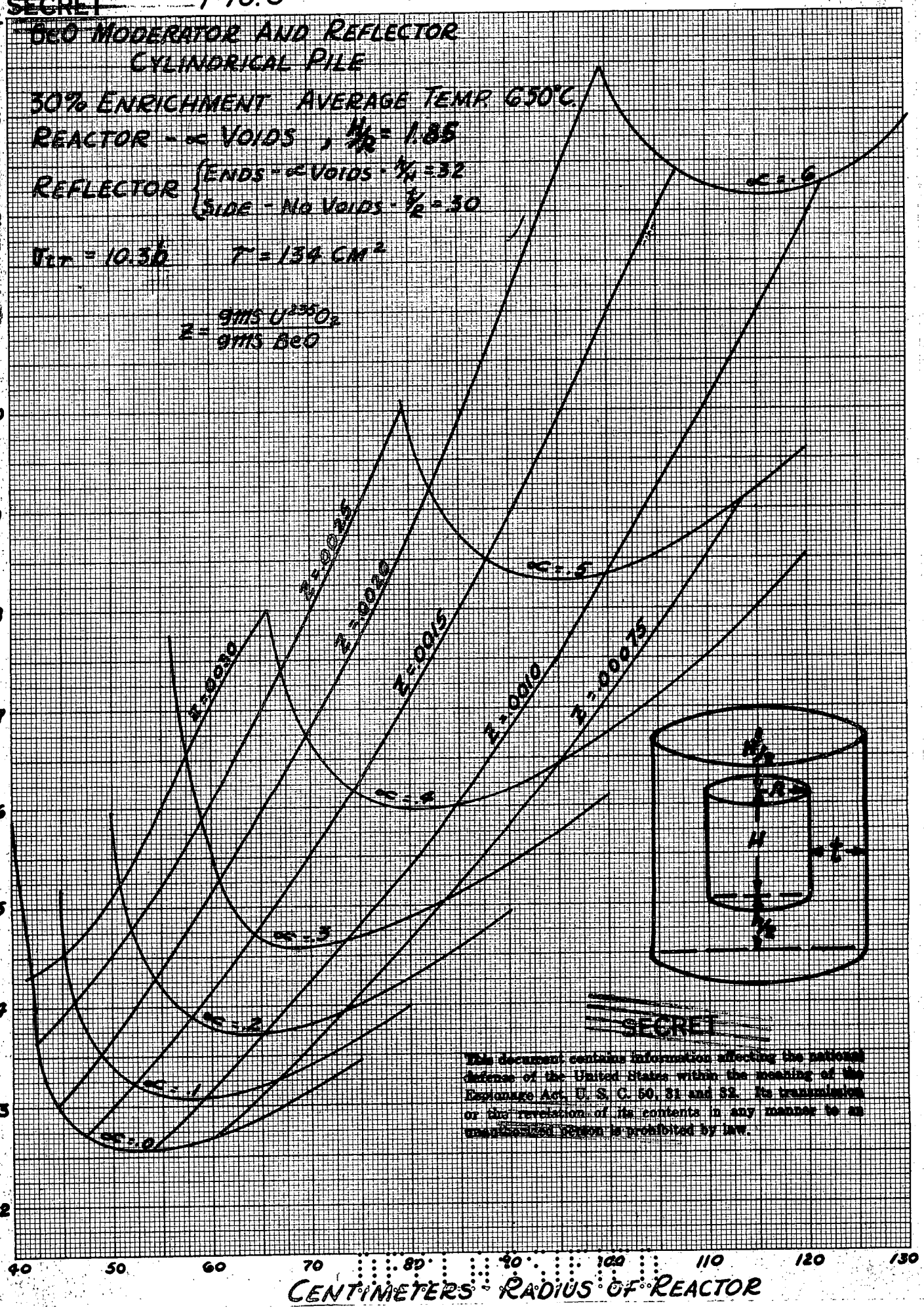
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.



SECRET

SECRET

FIG. 8



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FIG. 9

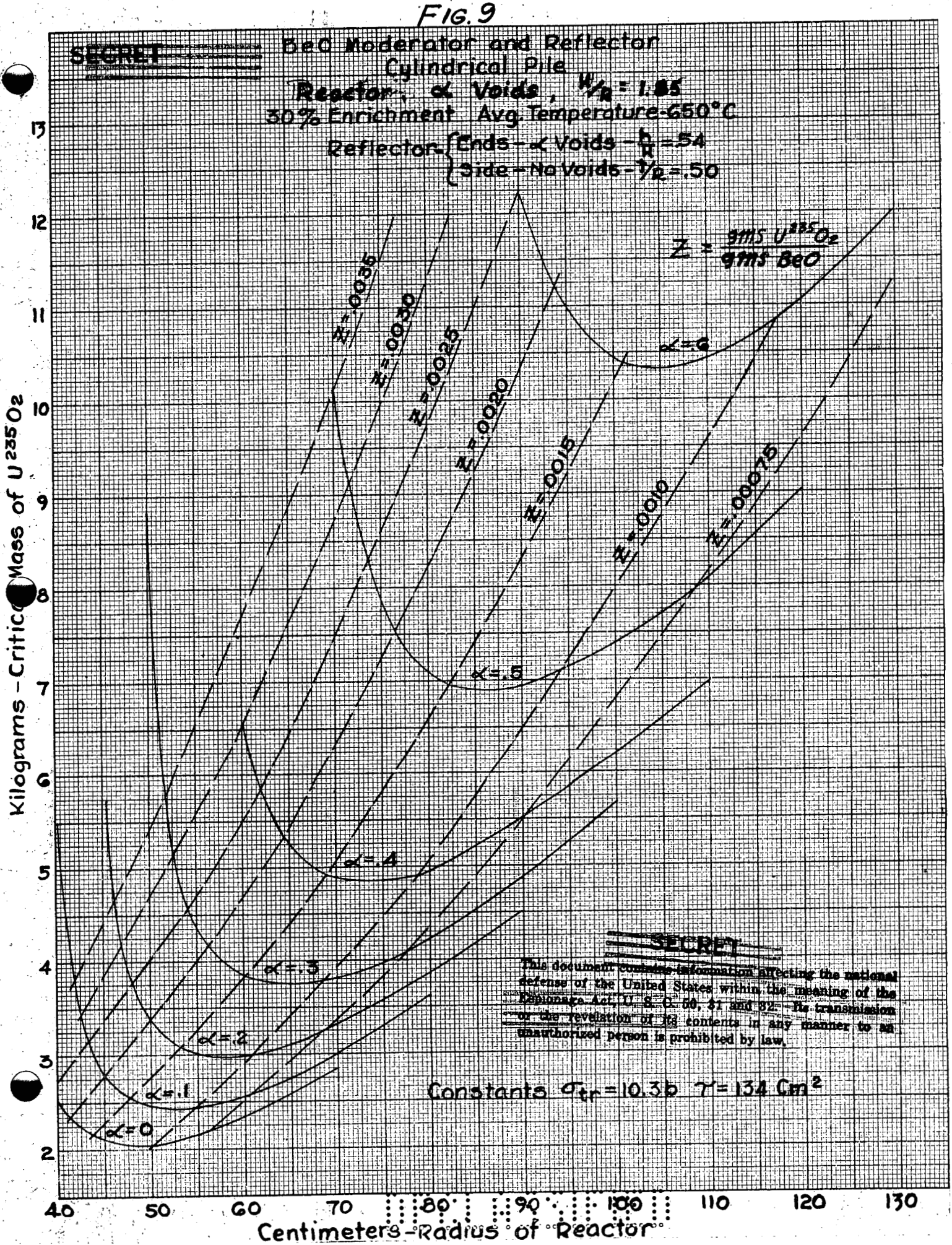
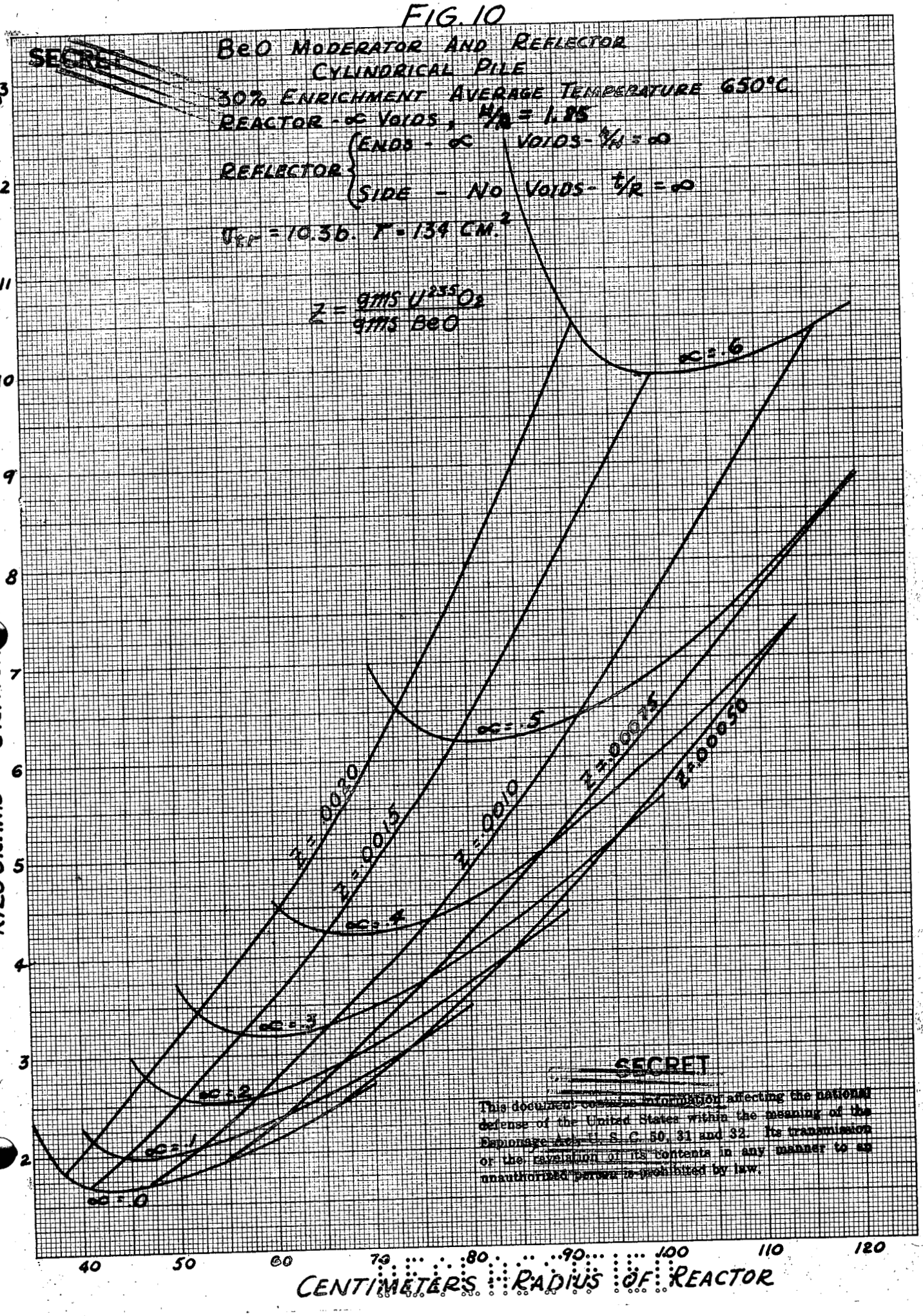
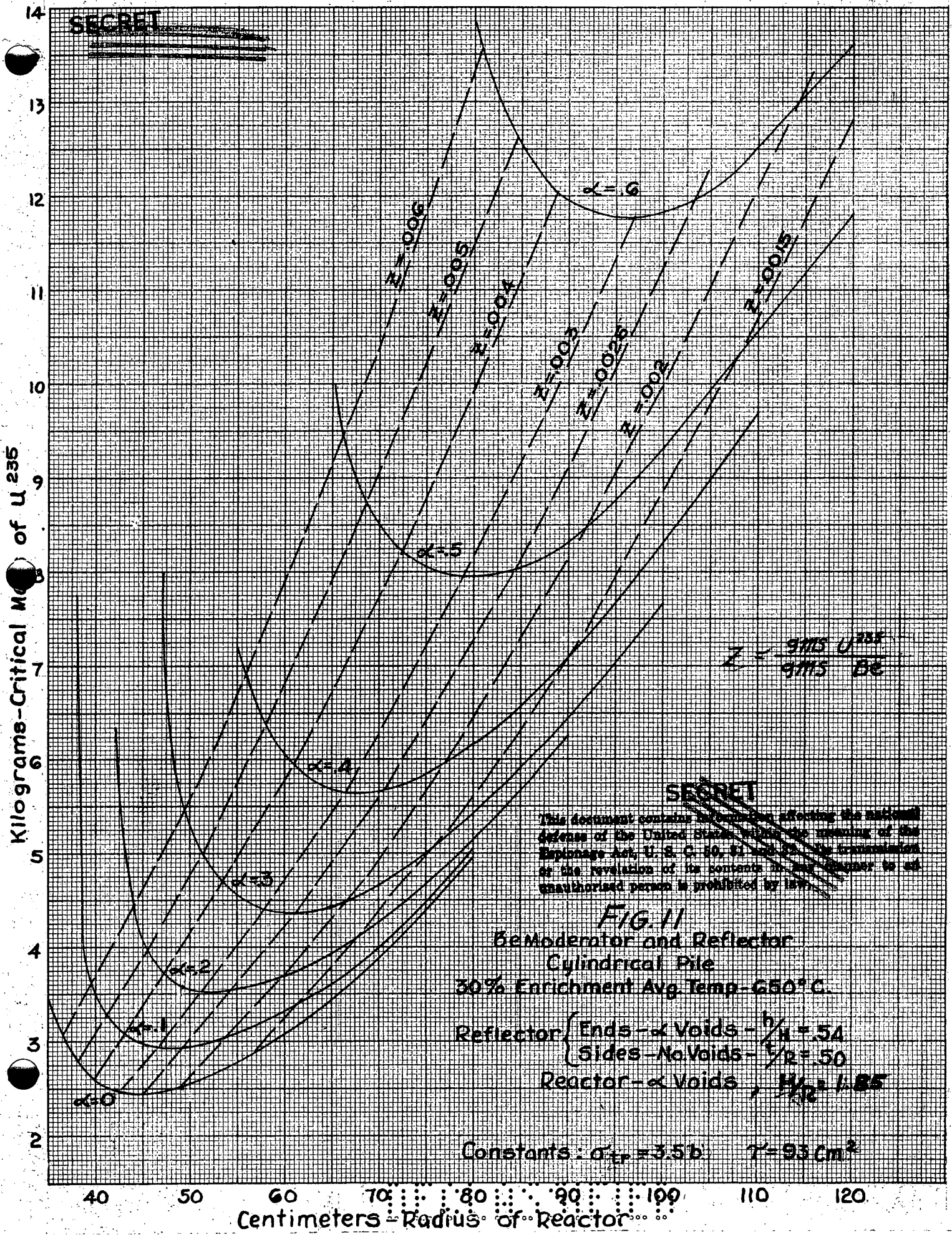

SECRET
BeO Moderator and Reflector
Cylindrical Pile
Reactor, α Voids, H/R = 1.85
30% Enrichment Avg. Temperature-650°C
Reflector-{Ends-α Voids-h/R=.54
Side-No Voids-t/R=.50
Z = gms U235O2 / gms BeO
Z=.0035
Z=.0030
Z=.0025
Z=.0020
Z=.0015
Z=.0010
Z=.00075
α=6
α=.5
α=.4
α=.3
α=.2
α=.1
α=0
Kilograms-Critical Mass of U235O2
Centimeters-Radius of Reactor
Constants σtr=10.3b τ=134 Cm²
SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FIG. 10

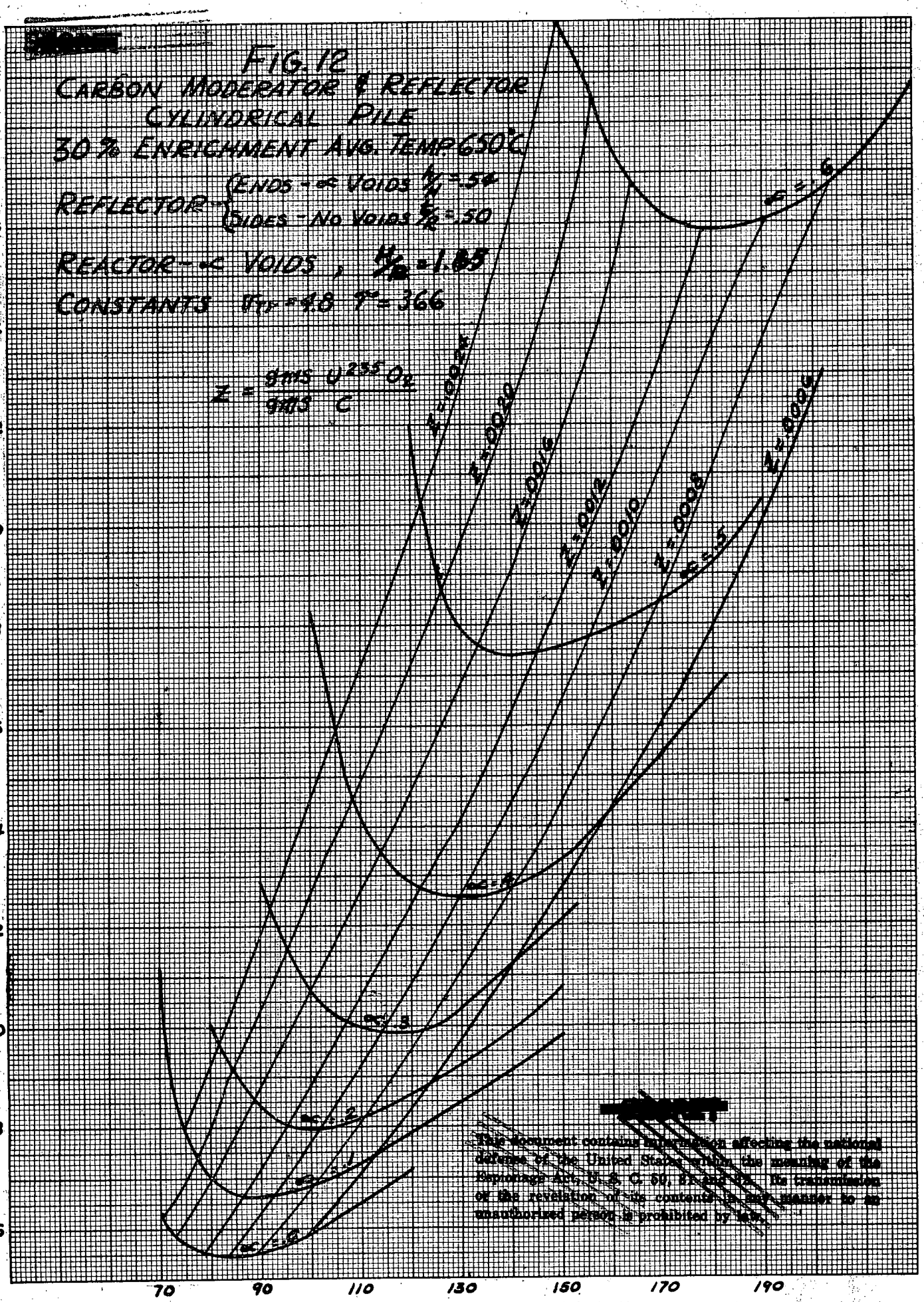

SECRET
BeO MODERATOR AND REFLECTOR
CYLINDRICAL PILE
30% ENRICHMENT AVERAGE TEMPERATURE 650°C
REACTOR - α VOIDS, H/R = 1.25
REFLECTOR { ENDS - α VOIDS - t/H = ∞
SIDE - NO VOIDS - t/R = ∞
σ_EF = 10.3b. T = 134 CM.²
Z = gms U²³⁵O₂ / gms BeO
α = .6
α = .5
α = .4
α = .3
α = .2
α = .1
α = .0
Z = .0020
Z = .0015
Z = .0010
Z = .0025
Z = .0050
KILOGRAMS - CRITICAL MASS OF U235O2
CENTIMETERS RADIUS OF REACTOR
40
50
60
70
80
90
100
110
120
2
3
4
5
6
7
8
9
10
11
12
13
SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

PD CURVE 2

Dr. 4080

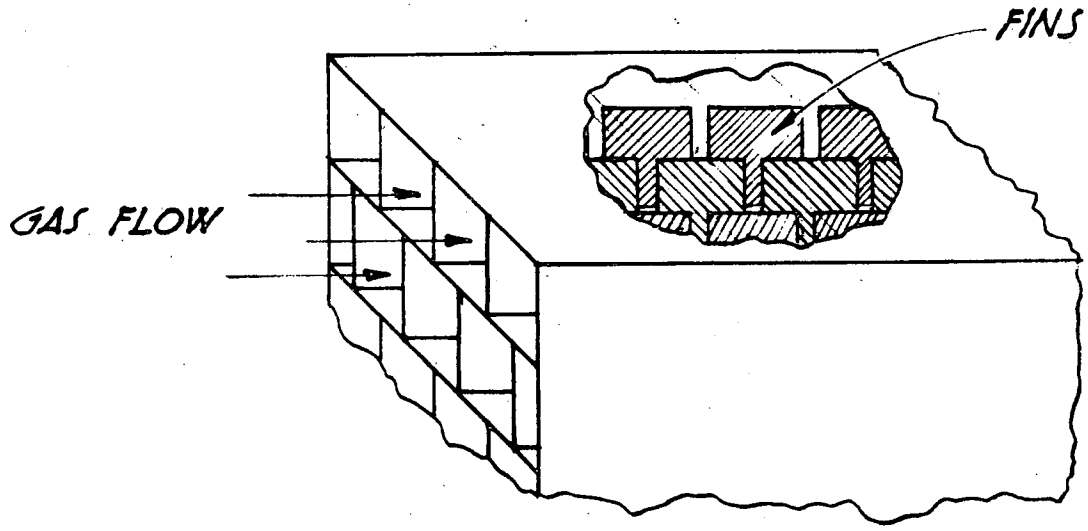


[redacted]

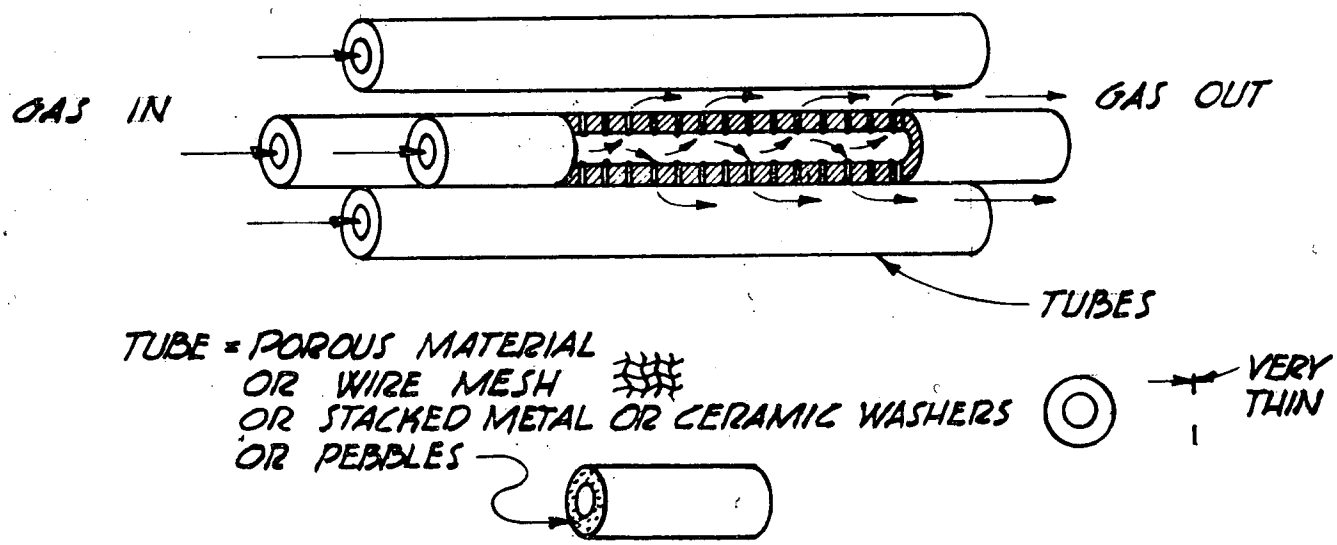


[redacted]

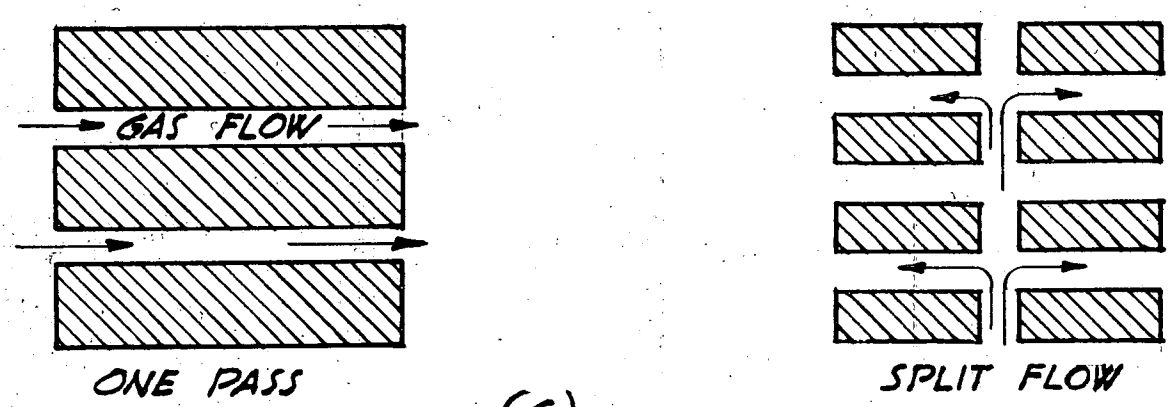
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.



(a) INTERRUPTED FINS



(b) MULTI-SPLIT FLOW DESIGN



(c)

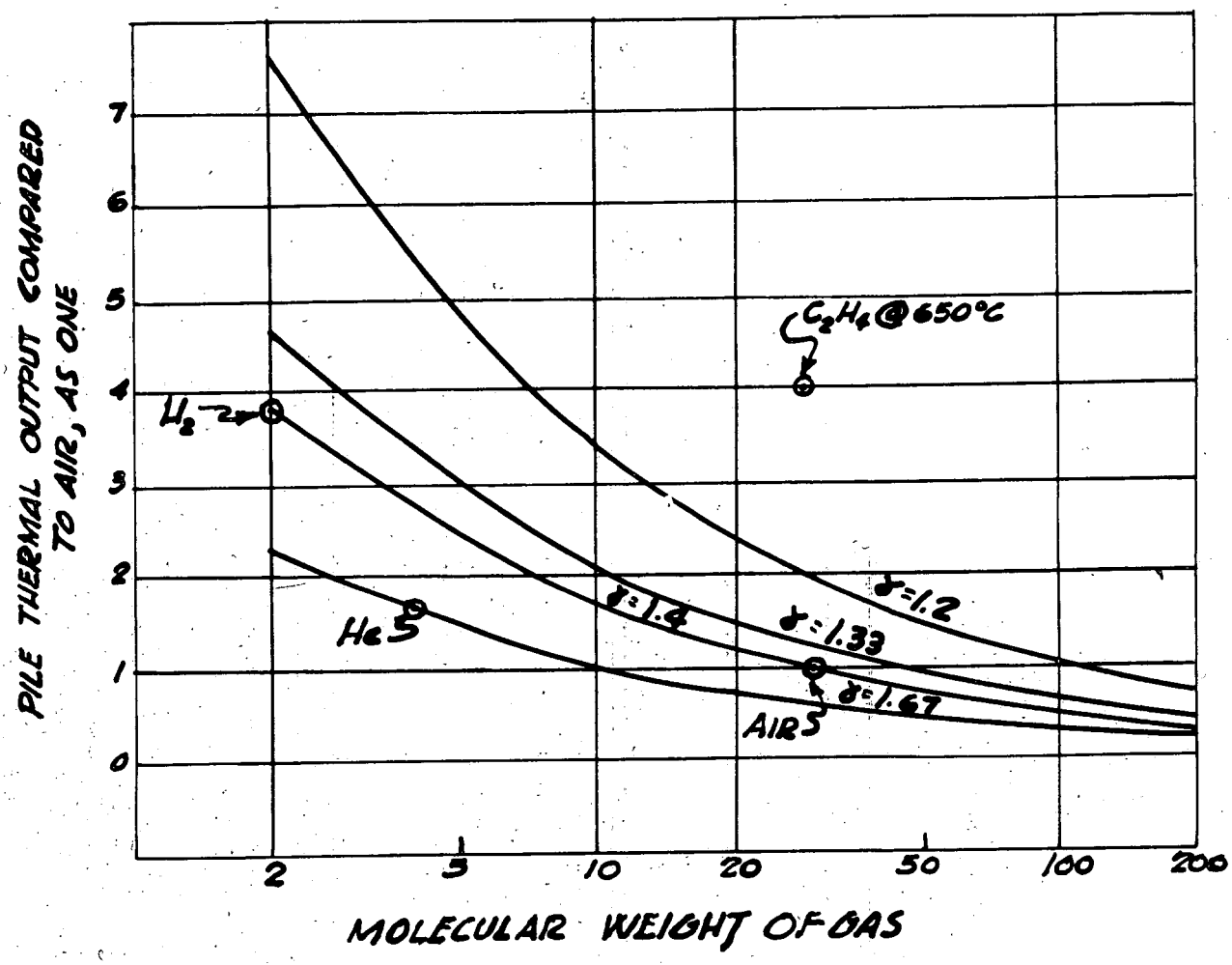
FIG. 13

FLOW ARRANGEMENTS FOR HEAT TRANSFER

~~CONFIDENTIAL~~

FIG. 14

EFFECT OF GAS USED ON SPECIFIC POWER OF A PILE
CURVE SHOWS THE RATIO OF PILE THERMAL OUTPUT OBTAINABLE WITH VARIOUS GASES COMPARED TO AIR, AS ONE, FOR A FIXED SIZE OF PILE WITH SAME OPERATING PRESSURE, TEMPERATURE & SAME % BLOWER POWER WHERE γ = SPECIFIC HEAT RATIO OF GAS.



This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50; 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

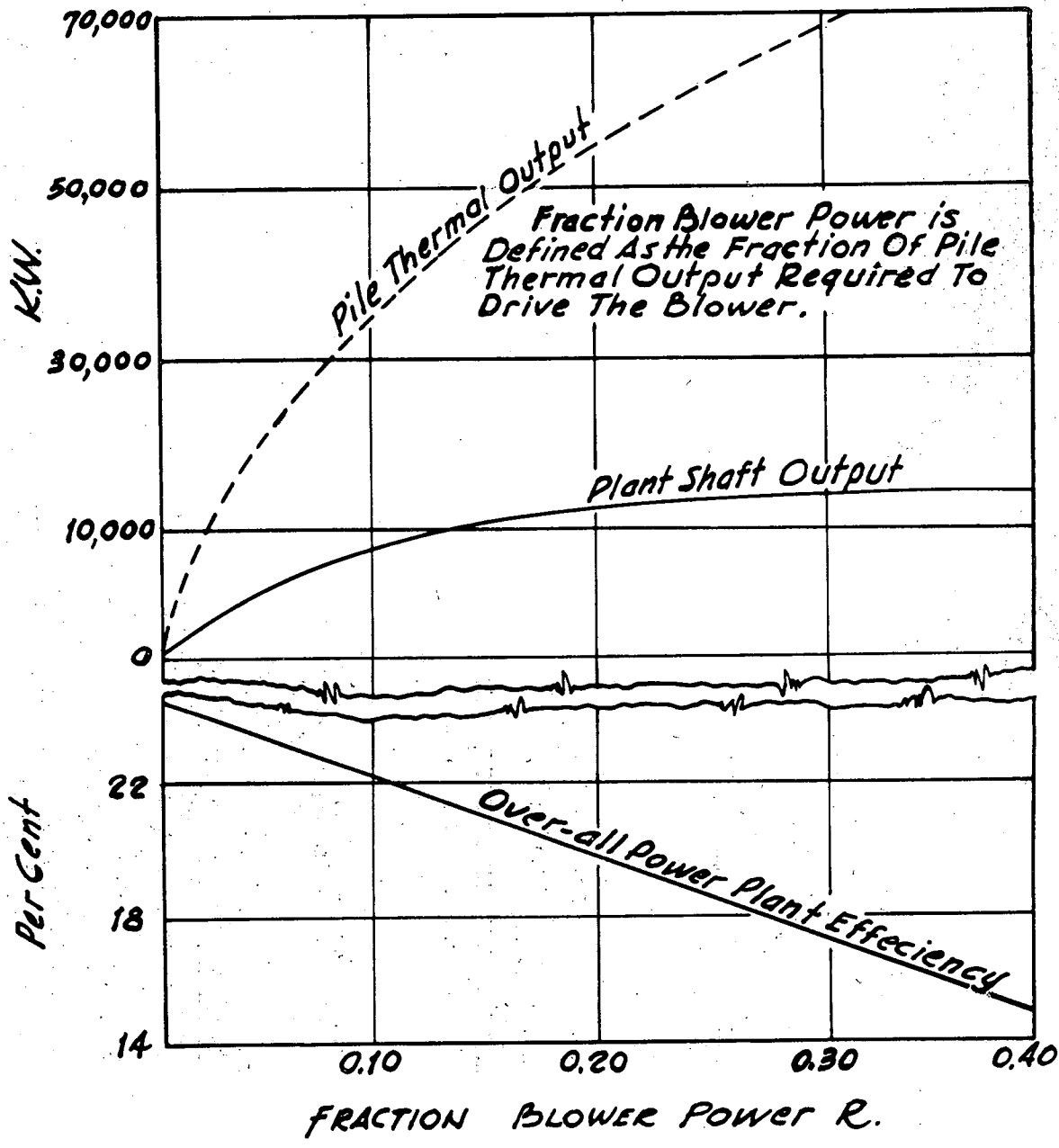
DECLASSIFIED

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

FIG. 15

EFFECT OF FRACTION BLOWER POWER ON PLANT SHAFT OUTPUT & OVERALL PLANT EFFECIENCY Based on 25% effeciency Of Conversion Of Thermal Energy To Mechanical Energy in The Power Cycle and A Pile Output Of 40,000 K.W. @ .10 Fraction Blower Pile



~~CONFIDENTIAL~~

~~This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.~~

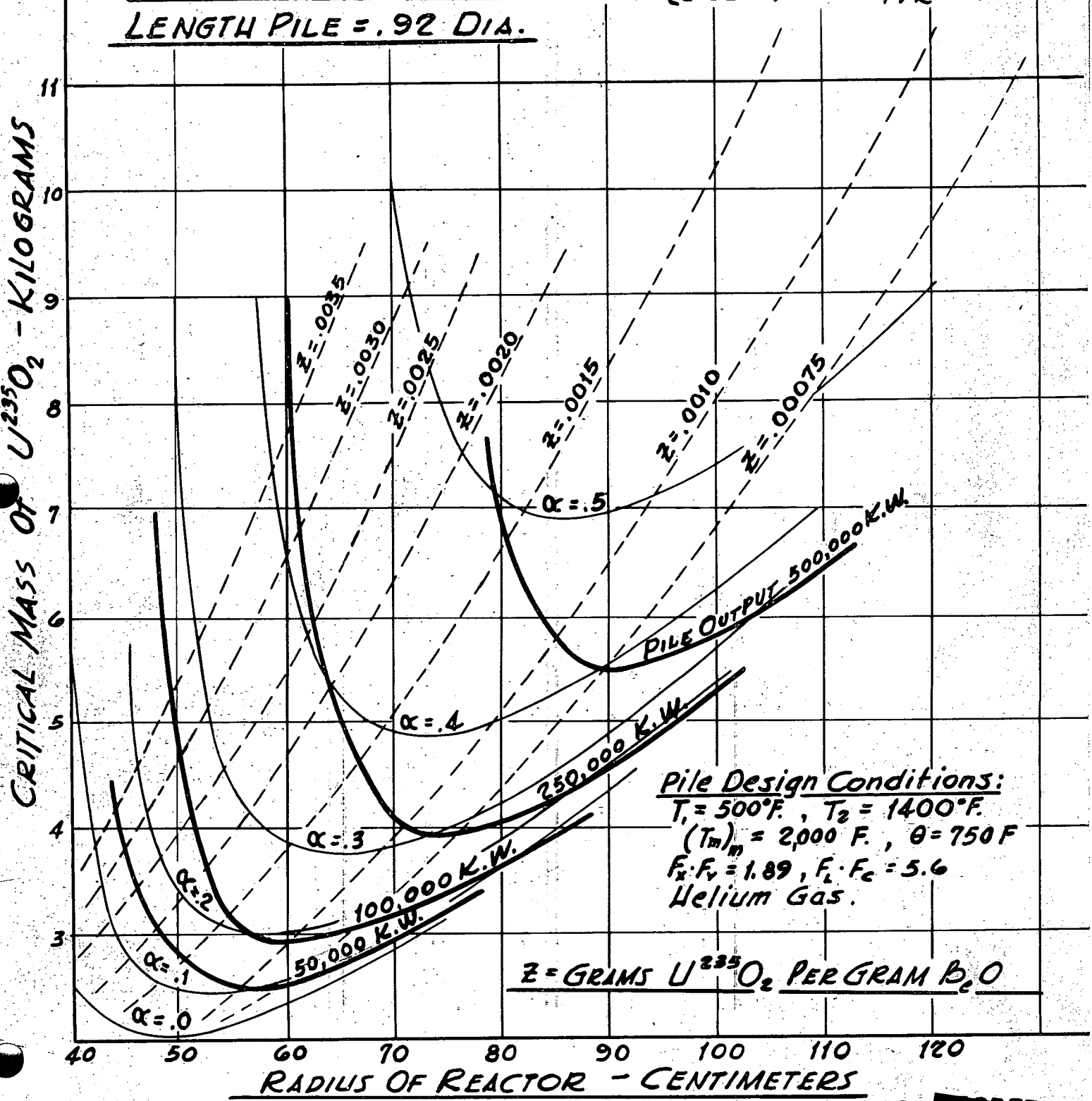
UNCLASSIFIED

SECRET

FIG. 16

LOCUS OF PILE SIZE FROM A HEAT TRANSFER STANDPOINT FOR VARIOUS PILE OUTPUTS VS. PHYSICS REQUIREMENTS FOR B_eO MODERATOR and REFLECTOR, CYLINDRICAL PILE, 30% ENRICHMENT, REFLECTOR = {ENDS = α VOIDS, h/H = .54; SIDE = NO VOIDS, T/R = .50}

LENGTH PILE = .92 DIA.



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET

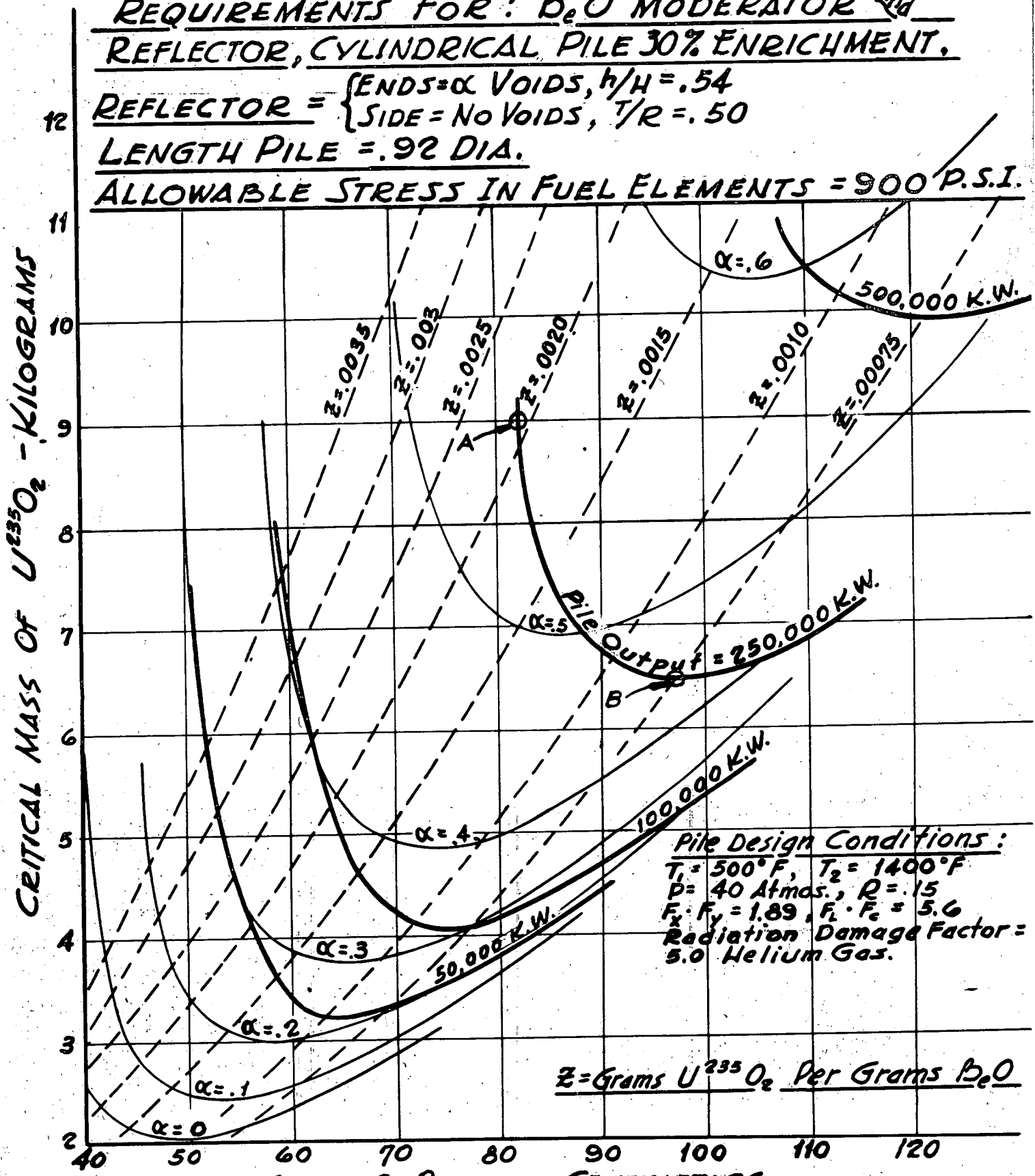
FIG. 11

PILE OUTPUT BASED ON HEAT TRANSFER AND THERMAL STRESS LIMITATIONS VS. PHYSICS REQUIREMENTS FOR: B_eO MODERATOR and REFLECTOR, CYLINDRICAL PILE 30% ENRICHMENT.

REFLECTOR = { ENDS = α VOIDS, h/H = .54 ; SIDE = NO VOIDS, T/R = .50 }

LENGTH PILE = .92 DIA.

ALLOWABLE STRESS IN FUEL ELEMENTS = 900 P.S.I.



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

IV. DESCRIPTION AND STATUS OF DESIGN

A. GENERAL DESCRIPTION OF PLANT

1. Type of Plant

The principal components of the nuclear power plant which has been visualized for utilizing a high temperature gas cooled pile for the experimental production of power from atomic energy are shown schematically in Fig. 18. Two essentially closed fluid circuits are used as the heat transfer media. The primary fluid is helium gas which serves to transfer heat from the pile to a steam boiler. The secondary fluid is water and is used in a conventional steam cycle for generating electric power by means of a conventional steam turbine generator. The system operation is briefly as follows. The helium at a maximum pressure of 10 atmospheres is circulated between the pile and boiler by means of single stage centrifugal blowers. The temperature of the gas entering the pile is 500° F. and that of the exit gas 1400° F. The hot gas flows through a suitable duct from the pile to the boiler where it is cooled to 500° F. and generates steam at 450 psi. and 735° F. This steam is used to drive the turbine generator, producing electric power.

2. Rating of Plant

The design rating of the pile is 12,000 KW of heat output. With an overall efficiency of 25 percent, this would produce an electrical output of 3000 KW. However, not all of the pile thermal output is available for producing electric power. Approximately 18 percent of the pile output is needed to drive the blowers which reduces the net electrical output to about 2400 KW.

The boilers and blowers are designed for a maximum continuous rating of 20,000 KW. This is done to provide a suitable margin above the pile rating to avoid limiting the pile output by the auxiliaries. Moreover, although only one boiler and blower are shown in Fig. 18 for purposes of clarity, actually two boilers and four blowers are included in the design, thereby making it possible to operate the pile at almost its full rating with only one boiler and two blowers in service.

3. Nuclear Characteristics

The pile depends on thermal energy neutrons for producing fissions, i.e., it is a thermal pile. The fuel is uranium enriched to approximately 30 percent in the fissionable isotope U^{235}. As described later, the pile construction provides considerable flexibility as to the size and arrangement of the reactor and reflector and also of the conversion blanket. For this reason the amount of fissionable material required for pile operation varies depending on the particular loading pattern used. For the case giving the maximum kilowatts per kilogram, the operating charge is 5.0 kilograms of U^{235}, which, for a power level of 12,000 KW, corresponds to an average thermal neutron flux of 6.5×10^{13}.

DECLASSIFIED

SECRET

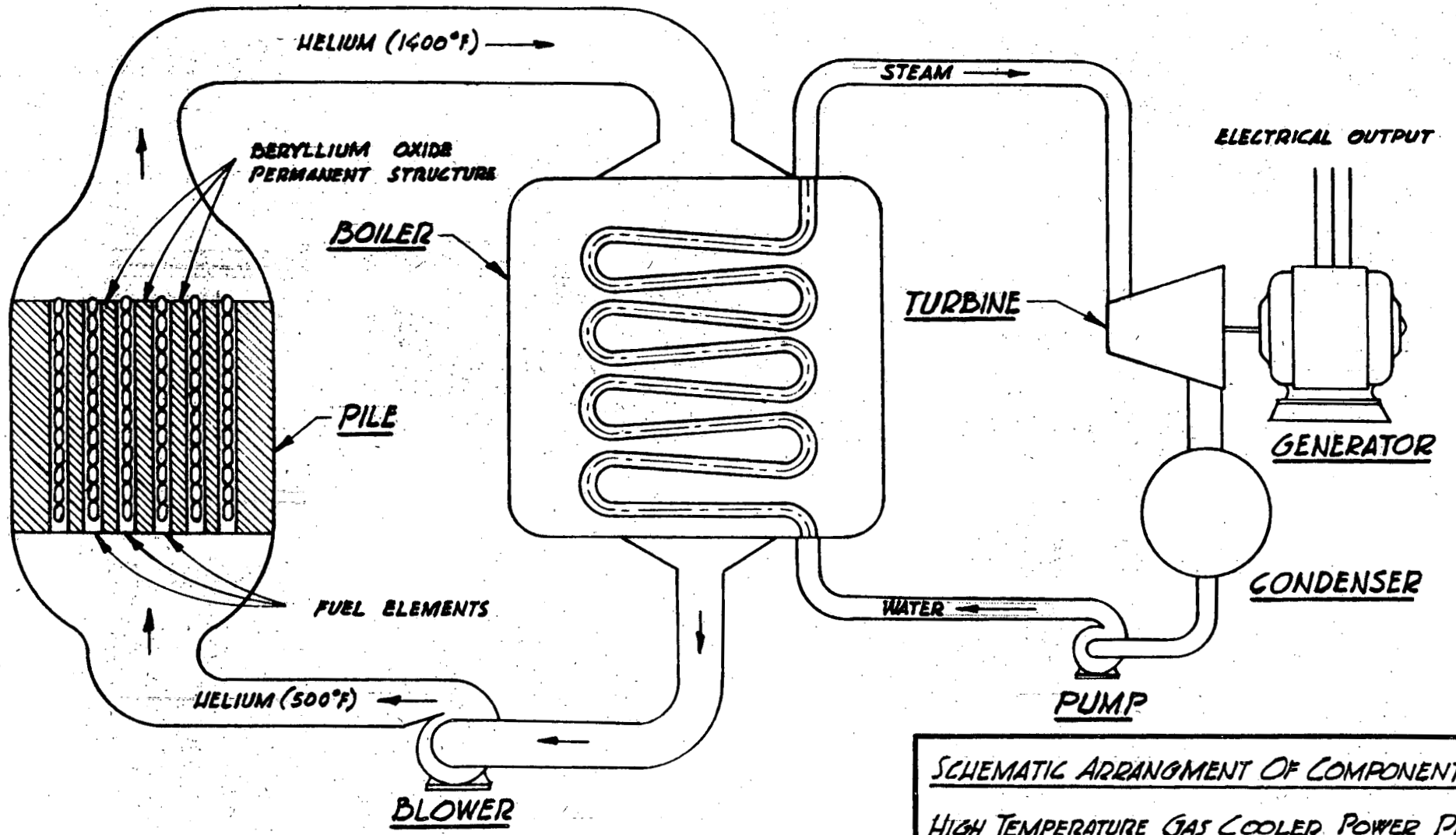


FIG. 18

SCHEMATIC ARRANGMENT OF COMPONENTS

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.N.L. 8-28-47	C. A.L.S. 8-28-47	A. K.E. 8-28-47	REP 9-16-47			
PROJ. C-222M						
SCALE: NONE				A-2951		

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

As noted in Section III of this report, the attainment of an overall conversion ratio (atoms of fertile material produced per atom of fissionable material destroyed) of close to one is extremely difficult when using U^{235} as the fissionable material. Exact determination of the conversion ratio for the pile design described herein has not been made particularly with respect to including the effect of chemical losses but it is estimated to be in the order of 0.6.

4. Pile Construction

The permanent structure of the pile consists of hexagonal beryllium oxide bricks, each 3" across flats with a 2" circular hole, assembled to form a cylinder approximately 72" in diameter and 76" high with its axis vertical and pierced by parallel vertical channels. This assembly is enclosed in a steel pressure shell. The central channels of the cylinder contain short removable slugs made up of the fissionable material incorporated in a matrix of moderating material which may be graphite, beryllium metal, or beryllium oxide. The channels containing these fuel elements form the reactor portion of the pile. Surrounding the reactor are additional channels which are loaded with BeO plugs forming the reflector. Thorium conversion can be achieved by replacing some of the BeO plugs with similar ones containing thorium.

a. Selection of Pile Structural Material. Beryllium oxide has a number of properties which make it very suitable as the moderating material and permanent structure of a high temperature gas cooled pile. Outstanding among these properties are its high melting point (2500° C.), high resistance to gamma and neutron bombardment (dimension changes have been found to be less than 0.1%, crushing strength to be practically unaffected, thermal conductivity reduced by a factor of 1.5, and the elastic modulus unchanged after irradiation in the Hanford Piles), and chemical stability (with the exception of its reaction with steam at temperatures around 1400° C.). In addition, BeO has a very high crushing strength (circa. 80,000 psi.) and moderately good resistance to thermal spalling. Finally, it may be noted that from the standpoints of critical mass, pile size, and neutron economy, there are not very great differences between beryllium metal and beryllium oxide as moderating materials.

5. Coolant

Helium has been selected as the coolant because it has low neutron absorption; it is not affected by alpha, beta, gamma, and neutron radiations; it is chemically inert in that it does not react with BeO· UO_2, or graphite; it is available at high purity and can be easily purified; it has the highest specific heat of any gas with the exception of hydrogen; it has good heat transfer properties; it imposes no temperature limitation on the design.

Gases, in general, are inferior to liquids as heat exchange media. This inherent characteristic of a gaseous medium requires that the conditions of operation of a gas cooled pile must differ from the conditions for a liquid cooled pile. For the gaseous medium, a relatively large temperature rise from gas inlet to outlet is necessary, the fuel elements may be required to

DECLASSIFIED

operate several hundred degrees hotter than the gas and the gas system will usually have to be under pressure. These design conditions are discussed in the following paragraphs.

6. Design Conditions

As pointed out in Section III, some of the more important design conditions affecting the pile performance are the maximum gas pressure, the inlet and outlet gas temperatures, and the gas pressure drop across the pile. In the selection of limiting values for each of these conditions, the choice has been dictated by a compromise among a number of conflicting requirements and the desirability of avoiding wide departures from established engineering practice and experience. The design conditions for this pile are listed in Table III and are discussed briefly in the following paragraphs.

TABLE III

DESIGN CONDITIONS

Design rating, KW of heat	12,000
Maximum rating of boilers (total KW of heat	20,000
Coolant gas	Helium
Maximum gas pressure, atmospheres absolute	10
Gas temperature at inlet to pile, °F	500
Gas temperature at outlet from pile, °F	1400
Percent of heat output used for pumping gas through pile	
Gas pressure drop through pile, psi	2.5
Material of permanent structure	Beryllium oxide
Fissionable material	Enriched U^{235}
Alternative matrix materials of fuel elements	Beryllium oxide, Beryllium metal, Graphite
Critical mass	Small
Thorium conversion	Design to be flexible

DECLASSIFIED

a. Selection of Maximum Gas Pressure. The design and fabrication of the pile and boiler pressure shells, the high temperature ducts, the blower shaft seals, and the gas locks in the fuel charging system become more difficult as the gas pressure increases. On the other hand, the pile output is directly proportional to the gas pressure, if other design conditions are fixed, as shown in Section III. The selection of 10 atmospheres as the maximum gas pressure was essentially a compromise among all of these factors. In addition, it was high enough for the rated output and made it necessary to solve some of the pressure problems of gas cooled piles without unduly delaying the development of this design.

b. Selection of Inlet Gas Temperature. The helium temperature entering the pile should be as low as possible consistent with a reasonable boiler size. The value of 500° F. for this temperature was chosen when this design was crystallized. There are advantages to a lower temperature; the possibility of using a lower temperature for this experimental pile is discussed in Section V.

c. Selection of Outlet Gas Temperature. The 1400° F. temperature selected for the helium leaving the pile is considered at the present time to be approximately the practicable upper limit from the standpoint of metal alloy parts in the pile structure, ducts, and boiler.

d. Selection of Pressure Drop in Gas System. Because of their inherent simplicity, the use of single stage centrifugal blowers is desirable. However, with this type of blower the blade tip speed is limited by stress to 700 ft. per second and is directly proportional to the square root of the pressure drop if the gas pressure is fixed. On this basis, then, the allowable pressure drop across the pile at rated load is limited to 2.5 psi. To reduce thermal stresses in fuel elements high surface to volume ratios are desirable but also result in increasing the pressure drop across the pile. It has been found that 2.5 psi. permits reasonable leeway in the design of fuel elements of complex cross section. Moreover, it limits the gas pumping power, i.e., the fraction of pile thermal output required to drive the blowers, to a reasonable value (18 percent of pile output).

B. DETAILED DESIGN DESCRIPTION

This section presents a detailed description of the design which has been developed thus far for each component of the nuclear power plant. Emphasis is placed on presenting an integrated design. Alternate designs of most of these components have been developed or studied, and these are discussed in Section V. In some cases the components described are believed to be the best of the designs considered. In other cases, the designs are presented because they are developed in greatest detail, although other designs in process are believed to be better. The tentative selections made have the purpose of presenting an over-all design and should, therefore, not be considered final. The relative merits of alternate designs are discussed fully in Section V.

DECLASSIFIED

1. Pile Structure

The permanent part of the pile consists of an assembly of hexagonal beryllium oxide bricks in the form of a right circular cylinder with its axis vertical. The hexagonal bricks are 3" across flats, and 6" long with axial circular holes 2" in diameter as shown in Fig. 19. These bricks are stacked vertically to form continuous vertical channels 2" in diameter and 76" long and are so laid that the horizontal joints between bricks of any one channel are staggered vertically by 2" relative to those of the adjacent channels, as shown on Fig. 20. This necessitates the use of bricks 4" long at one end of two thirds of the channels. The remaining third are assembled with an 8" brick at each end.

There is a total of 517 channels in the assembly forming a vertical cylinder with an over-all length of 76" and a mean diameter of 72". This cylinder is retained by a shell and supported from the bottom on a plate forming a sub-assembly which is encased in a pressure shell that is supported by a foundation. Fig. 21 shows a plan section of the pile. Helium gas at approximately 500° F. enters the pressure shell at the top and passes downward through an annulus just inside the shell into the chamber at the bottom, serving to cool the shell. The gas is then heated to 1400° F. in passing up through the fuel channels, and is collected in a plenum chamber inside the pressure shell. Exhaust ducts lead the hot gas to boilers where it is cooled and returned to the pile.

The vertical channels formed by the brick assembly described above contain a column of removable elements or slugs each 5" in length. These removable elements can consist of moderator material alone, (reflector plugs), or of moderator plus fissionable material (fuel units), or of fertile material (converter units). Thus the size, shape and location of the reactor, reflector, and conversion blanket can, by appropriate loading of the channels, be set at any desired values consistent with the over-all size of the brick assembly. Three possible loading patterns, along with their corresponding operating characteristics, are described subsequently in conjunction with the nuclear characteristics of the pile.

a. Supports and Retaining Means. A steel plate 82" in diameter by 6" thick serves as a foundation for the moderator-reflector brick. This plate, in turn, is supported on pads mounted on the pressure shell. Variations in temperature between plate and pressure shell are accommodated by this method of support. Holes are located in the plate to correspond to those in the brick assembly. The holes taper from 2" diameter at the inner face to 2-7/8" diameter at the outer face of the plate, as shown on Fig. 22. An annular groove is added at the 2-1/4" diameter point to serve as a catch for a latch mechanism used to support the column of removable elements, and described in more detail later. The inner face is shaped to receive the spigot end of a BeO brick in order to maintain at all times good correlation between brick and plate holes.

Weight is added to the top of the bricks to resist any force such as the pressure drop across the pile which may tend to lift the brick, and also to retain the removable elements in the channels. Tests have shown

DECLASSIFIED

that at high rates of helium flow in the channels the removable elements may be blown up through the top of the pile. The weight consists of cast steel blocks 10" thick, each of which covers 7 channels. The blocks contain channels which correspond to the channels in the brick, with radial lugs for retention of the column of slugs.

Each column of slugs is held up against the top weights by means of a replaceable spring element which has been charged into the channel along with the fuel, reflector, or converter units, and holds the slugs in a fixed position under all conditions of helium flow. This spring element is shown in Fig. 23 and consists of a steel coil spring carried in a steel tube approximately 5 inches long, designed to have a 1" deflection and to support 5 pounds weight.

Immediately below the spring element is a replaceable metal slug containing a latch mechanism which automatically engages in an annular groove in the bottom plate hole. A further movement of 1" up into the channel, permitted by the spring, will lock the latch into the body of the latch slug and permit free removal of the latch plug and column of fuel. A more complete description of this latch mechanism is given later in describing the fuel handling equipment.

Steel blocks around the outside of the brick structure are shaped to fit the irregular brick contour and form a cylinder. They consist of circular segments approximately 12" long with a mean thickness of 5". A one inch thick steel retaining shell is put around these forming blocks and serves to limit pile movement and prevent 500° F. gas from by-passing the pile. Cold clearance of 1/4" at the bottom and 3/4" at the top is provided between shell and brick to avoid over-stressing the parts under all conditions of temperature which may be encountered.

The retaining shell is fastened to the bottom plate, and closed at the top by a double flat plate assembly 37" above the weights at the top of the brick. The lower plate of this assembly is very thin and serves as a radiant heat shield and buffer plate to prevent the 1400° F. helium from impinging directly on the outer member. The outer 3/4" thick plate seals the hot gas plenum chamber, and withstands the 2.5 psi. differential between the incoming and outgoing helium. Control rod thimbles are welded directly to this outer plate and pass through to within 1" of the weights at the top of the brick assembly. Oversize holes in the lower plate provide clearance around the control rod thimbles so that this plate exerts no force on the thimbles. The baffle plate just below the incoming helium entrance has similar clearance holes around these thimbles for the same purpose.

b. Pressure Shell. The pile is encased in a cylindrical steel vessel 8 ft. external diameter, 1-1/2" thick, and 22'-6" overall length, with elliptical heads. It is designed for an operating pressure of 132 psi. gauge and a maximum pressure of 250 psi. gauge. The pile and other parts of the coolant system are protected by relief valves and rupture discs set to release at a pressure not greater than 250 psi.

DECLASSIFIED

As shown on Fig. 24, the incoming helium enters at the top of the shell through two 19" openings, and flows down the entire periphery of the shell to enter the pile from the bottom. Thus, all parts of the pressure shell are in contact with 500° F. helium. Two 27" openings for outgoing ducts are provided a little above the shell mid-point. Thermal sleeves are provided at the points where the outgoing ducts pass through the pressure shell in order to avoid stresses due to sharp temperature differentials at these points.

The loading mechanism enters the shell through a 31" eccentric hole in the bottom of the shell. An unloading tube enters the pile through a hole in the pressure shell and curves down into the loading face. This tube is indexed in the bottom plate and free to move through the pressure shell.

There are two 20" round manholes, one near the top, and one near the bottom, to provide access to the spaces above and below the brick assembly. Access is necessary in assembly, and for inspection after preliminary operation under temperature before introducing fissionable material. Manholes would then be welded to make a permanent and reliable seal.

The entire structure is supported by the pressure shell, which is mounted on a foundation at points along the periphery at the height of the outgoing ducts. The mounting provides for free radial expansion while maintaining center line location by means of radial lugs and slots.

c. Pile Gas Flow. The flow of the coolant throughout the pile structure may be seen from Fig. 24. Helium gas at 500° F. enters the pile through two 18" diameter ducts located at the top of the pile. A majority of the gas is directed by a baffle plate to the center portion, where it is directed down to the central portion of the top plate assembly. It then flows outward, and down the annular passage between retaining and pressure shells. After flowing to the periphery of the shell just above the top plate assembly, it flows downward through the annulus between the pressure and retaining shells, and into the space around the loading mechanism, thence upward into the reactor channels, reflector and former block cooling passages. It is then collected in the outgoing plenum chamber at the top of the brick assembly, where it enters the two outgoing ducts. The gas flow through the fuel channels is proportioned in accordance with the distribution of heat generation throughout the pile volume shown in Figs. 6 and 7, by means of removable orifices located at the lower end of each fuel channel.

Control rods are cooled by 500° F. helium bled into the thimbles at the top of the pile. The flow id divided, part going down the center of the hollow rod and part down the annulus between control rod and thimble. An orifice, in the form of a close-fitting ring immediately above the top plate assembly controls the amount of gas flowing in the annulus. Gas flowing down the center of the rod is discharged directly in the open brick space, and flows to the top of the pile. That flowing down the annulus is discharged at the pile face. Open control rod channels are provided with replaceable orifice plugs in the bottom plate to control the amount of gas flowing up the open channels for cooling purposes.

DECLASSIFIED

Flow of gas through the former blocks will be adjusted so the blocks are maintained at approximately 1000° F. maximum. The former blocks are extended to the top plate assembly so the retaining shell is protected in the region of the hot plenum chamber from 1400° F. gas. Helium flowing through the holes which run into the exhaust gas duct is collected in a ring around the ducts. The gas from the former blocks is discharged between the two plates of the top plate assembly, and allowed to leak into the hot plenum chamber around the control rod thimbles.

d. Pile Alignment. The pile shell is supported around its periphery in the plane of the exhaust duct center line as shown on Fig. 24, and expands freely up and down from this point approximately 0.33" and 0.57", respectively. A radial expansion of 0.17" from room temperature to 500° F. is allowed for by movement on pile support pads. This support point was selected as being most desirable from boiler and duct considerations.

The reactor-reflector assembly is supported by the bottom plate, which is centered with respect to the pressure shell and supported by it. The assembly is allowed to expand upward as the loading face must be fixed with respect to the pressure shell. Nothing need be carefully indexed longitudinally with respect to the hot end pile face except control rods, which are readily adjustable in this direction. This total upward movement is approximately 0.61" over the entire retaining shell length, or 0.38" over the reactor and reflector.

Line-up between retaining shell and pressure shell center lines is accomplished with 4 radial lugs at the top and 4 at the bottom fitted into slots on the pressure shell. This construction allows radial expansion while maintaining constant relative center line position. The top plate assembly is keyed in this manner to the retaining shell. It is sealed at the periphery by a thin, flexible sheet steel member. A small differential movement may occur between retaining shell and pressure shell due to a changing loading pattern, disrupting gas flow, or time lag of heat flow. This movement would shift the inner duct with respect to outer and do no harm. The outer duct is provided with a slip joint to allow for this as well as variations in radial movement.

Diametrical expansion of beryllium oxide and steel differ approximately 0.1" at the cold end when both are at 500° F. Due to a possibility of the brick becoming hotter, a cold total clearance of 1/4" is provided between the brick assembly and the retaining shell. This is equivalent to 1000° F. brick temperature and 250° F. shell temperature. A total clearance of 3/4" is left at the top, which is equivalent to a brick temperature of 1900° F. and a shell temperature of 550° F.

The nominal clearance of 1/4" at the bottom of the pile will cause no difficulty from loading and unloading operations. The top movement of 3/8" is not enough to distort channels to the point where fuel elements will jam, because individual brick alignment is well maintained by means of bell and spigot joints which have a clearance less than 1/32".

DECLASSIFIED

In the brick structure the control rod channels are of hexagonal cross section 3" across flats, each channel being formed by omitting a column of brick. Control rods are 1.55" diameter, which provides a 0.725" mean radial clearance between control rods and channels. The channels are aligned by the former blocks and retaining shell, which in turn are lined up with the pressure shell. The control rods are aligned partly by the pressure shell and partly by the control rod thimbles. These thimbles, which form channels for the control rods in the zone above the brick and top weights, are lined up with the pressure shell at the top and with the top plate of the top assembly just above the outgoing helium plenum chamber.

e. Test and Experimental Facilities. While the provision of adequate test and experimental facilities is a requirement of major importance, it has been necessary to devote almost all attention thus far to the other design features described previously. It seems probable, however, that special test channels would be needed, and it is considered feasible to provide them.

f. Shielding. The shielding indicated on the drawings is only approximate and is based on the same general consideration as that now in use for other piles.

g. Specifications for Beryllium Oxide Bricks and Reflector Plugs. The following tabulation presents the specifications tentatively selected for fabrication of BeO bricks and reflector plugs:

(1) Brick (Total weight 18,195 lbs.).

(a) 5730 hexagons as per Fig. 19 (weight 16,330 lbs.).

1. 6" length (about 6-7/16" overall to end of spigot).

2. 3" width of hexagon across flats.

3. 2" diameter of internal longitudinal channel.

4. 1/8" radius fillets along outer edges of the hexagon and 1/16" radius fillets at the ends.

5. Dimensional tolerances as listed on Fig. 19.

6. Bell and spigot as shown on Fig. 19. Dimensional tolerances for bell and spigot must be worked out with the manufacturer.

7. Density 2.85 average with 2.8 minimum. (This must be discussed with the manufacturer, and somewhat lower values may have to be accepted).

8. Brick to be made with any suitable powder which produces brick of suitable density with a boron content not to exceed 1 ppm.

DECLASSIFIED

(b) 345 hexagons identical with "(a)" above except 4 inches long instead of 6 inches. (weight 655 lbs.).

(c) 318 hexagons identical with "(a)" except 8 inches long instead of 6 inches (weight 1210 lbs.).

(2) Reflector Plugs (weight 5380 lbs.)

(a) 4140 cylinders with rounded ends as per Fig. 25.

1. 5" length.

2. 1-7/8" diameter.

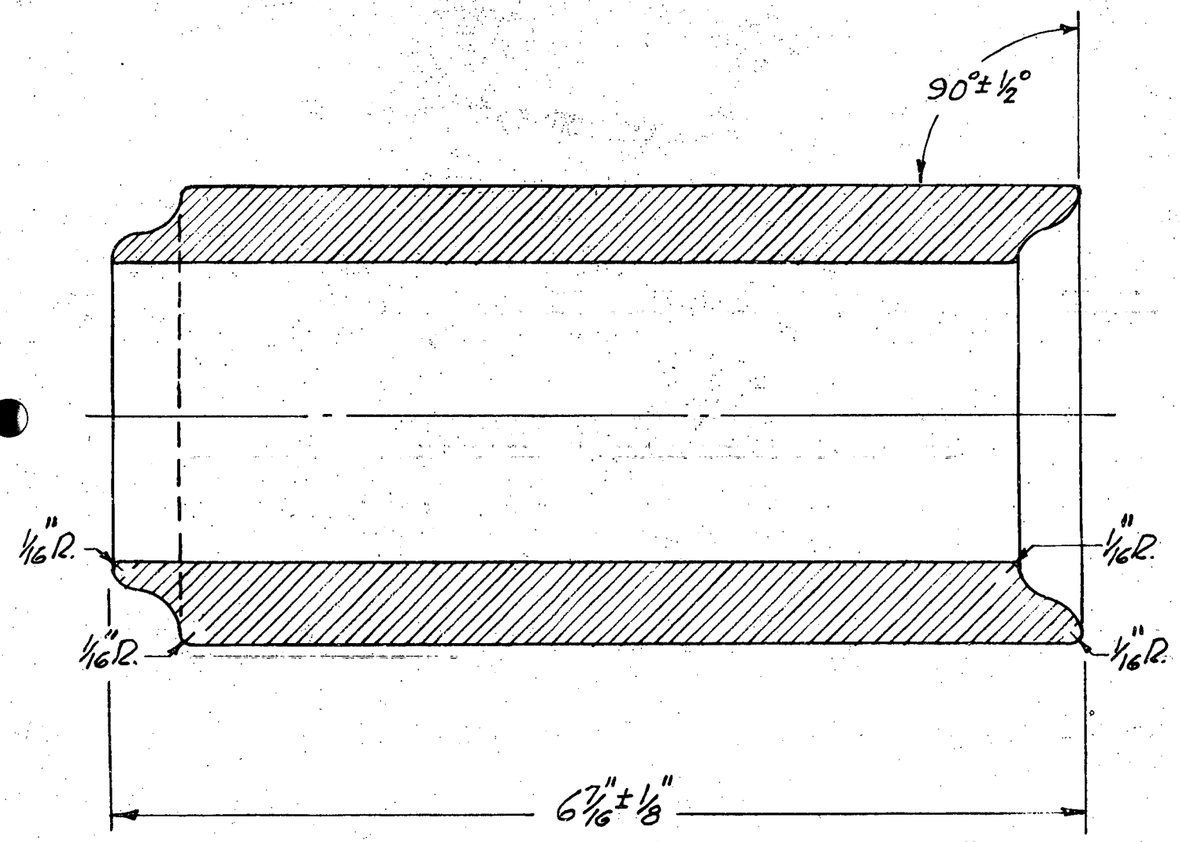
3. Rounded ends in accordance with Fig. 25.

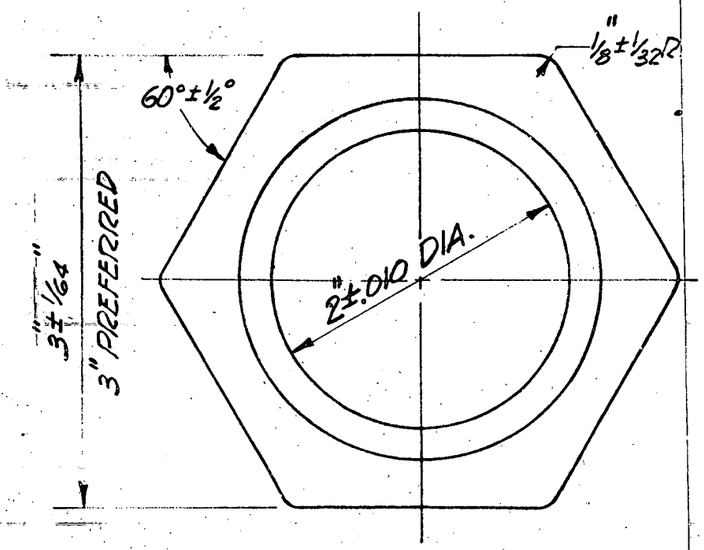
4. Dimensional tolerances as listed on Fig. 25.

5. Density 2.6 to 2.7 to be determined by discussion with manufacturer. (A density of 2.85 would be preferable).

6. Plugs to be made with any suitable powder which gives the required density with a boron content not to exceed 1 ppm.

DECLASSIFIED





NOTES:

1. ALL DIMENSIONS IN INCHES UNLESS OTHERWISE NOTED.
2. INFORMATION GIVEN APPLIES THROUGHOUT LENGTH, TO ALL FLATS & ANGLES & TO BOTH ENDS.
3. ALL SURFACES SHALL BE FREE OF VISIBLE CRACKS, FOLDS & CHIPPED AREAS. MINOR CHIPPED AREAS MAY BE BLENDED BY GRINDING SUBJECT TO FINAL ACCEPTANCE BY USER.

SPECIAL TOLERANCES - THESE LIMIT THE VARIATIONS PERMISSIBLE IN INDIVIDUAL UNITS.

ROUNDNESS OF HOLE - DIAMETRAL VARIATION IN ANY TRANSVERSE PLANE SHALL NOT EXCEED 1/64"

TAPER OF HOLE - DIAMETRAL VARIATION IN ANY LONGITUDIAL PLANE SHALL NOT EXCEED 1/64"

HEXAGONAL DISTORTION - "ACROSS FLATS" VARIATION ALONG ANY TRANSVERSE PLANE SHALL NOT EXCEED 1/64"

HEXAGONAL TWIST - HEXAGONAL FACES SHALL NOT BE TWISTED IN EXCESS OF ½° FROM END TO END. HEXAGONAL FACES SHALL BE FREE OF LOCAL HIGH SPOTS PROJECTING MORE THAN .005" ABOVE SURROUNDING SURFACE.

HEXAGONAL TAPER - "ACROSS FLATS" VARIATION ALONG ANY LONGITUDINAL PLANE SHALL NOT EXCEED 1/64"

FIG. 19

HOLLOW HEXAGON
TYPE C-1

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. L.C.L. 6-27-47	C. RER 6-27-47	A. [illegible]	REP 9-16-47	H.L.S. 9-16-47	
C-222M					
SCALE: FULL					B-2613

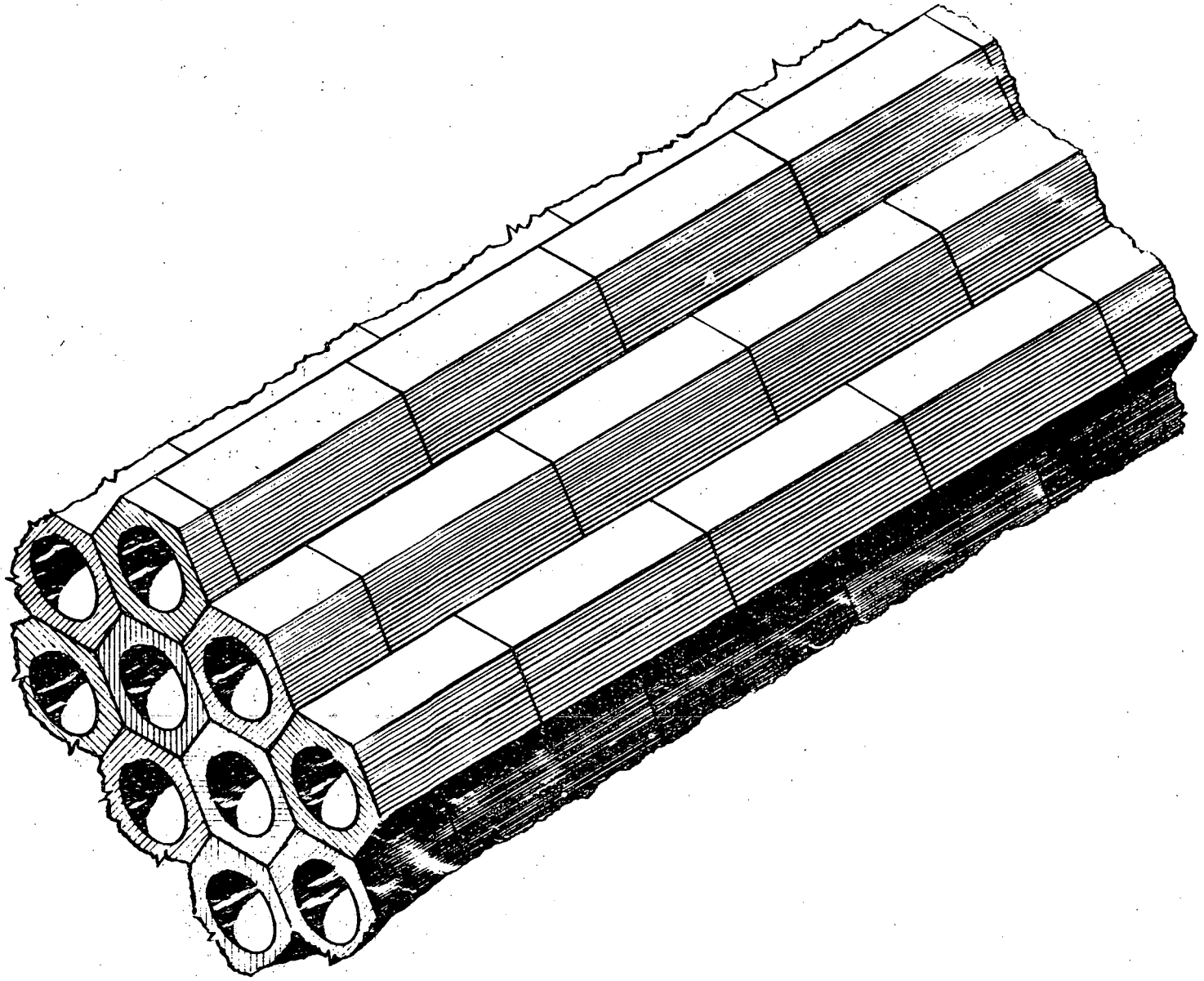


FIG. 20

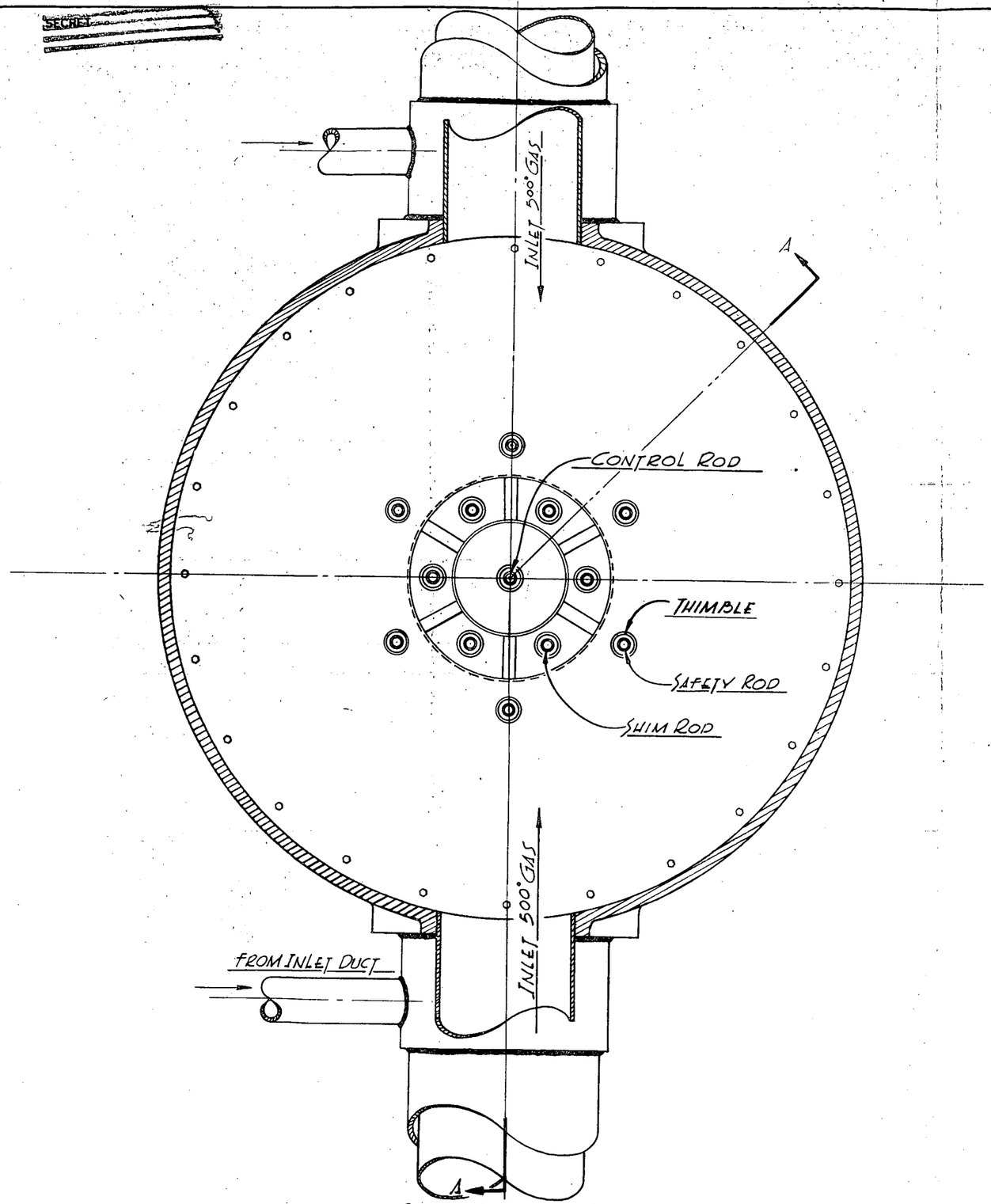
SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

TYPICAL BeO BRICK ASSEMBLY
HIGH TEMPERATURE GAS COOLED POWER A

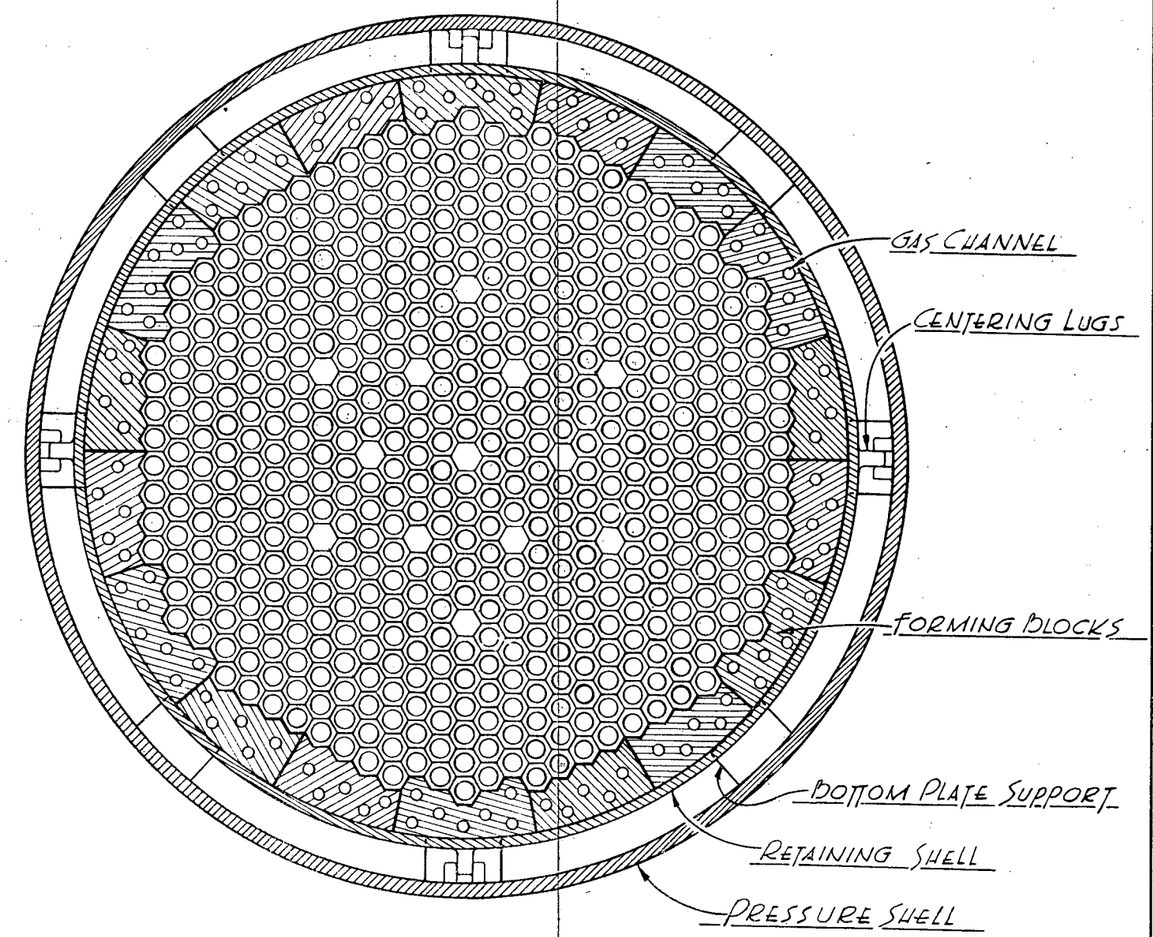
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. CNL 8-7-47	H.L.	A.	RSP 8-14-47		
DWG. C-282M					
SCALE: ½"=1"				C-2277	

SECRET



PLAN SECTION C-C



SECTION B-B

FIG. 21

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

PILE STRUCTURE SECTIONS

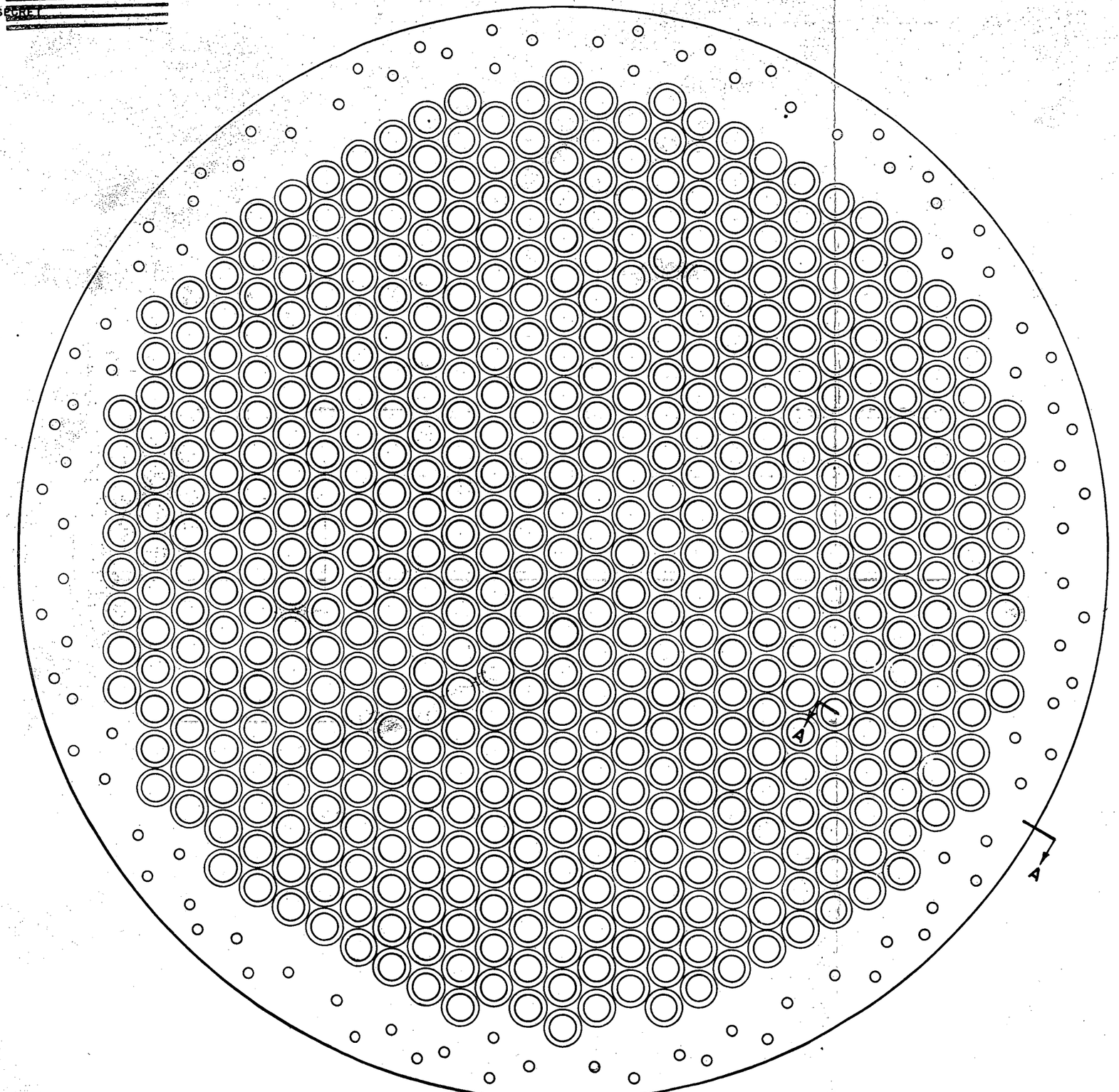
HIGH TEMPERATURE GAS COOLED POWER PILE

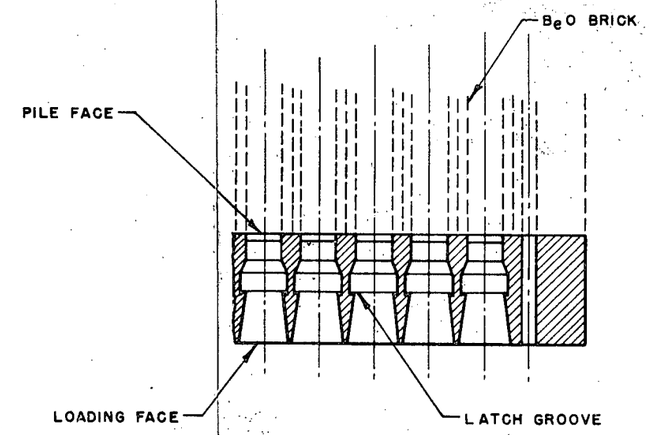
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Drawn by D. 8-14-47	Chk. G.L.S. 8-20-47	GAA 8-15-47	RWT 7-16-48	
Proj. C-882				
SCALE:				D-2275

DECLASSIFIED DECLASSIFIED DECLASSIFIED

SECRET





SECTION A-A

FIG. 22

[redacted]

BOTTOM PLATE
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

6-22-61					
SCALE:					D-2278

DECLASSIFIED

SECRET

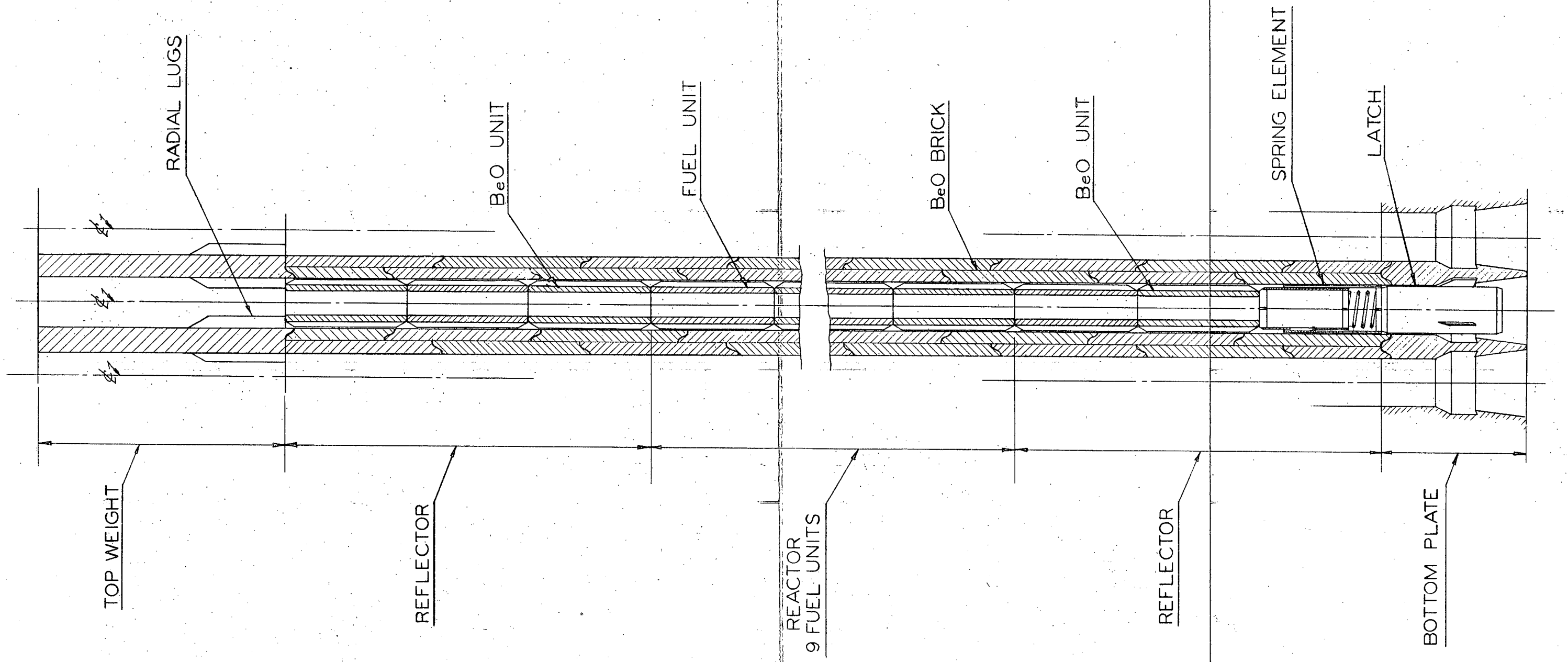


FIG. 23

SECRET
[redacted]
unauthorized person is prohibited by law.

FUEL CHANNEL ASSEMBLY

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. J.C.L. 9-5-47 | C. KRK 7-5-47 | AUDITED 8-9-47 | H.L.S. 9-17-47 | RSP 9-17-47

SCALE: 3/4"

D-2957

DECLASSIFIED
DECLASSIFIED
DECLASSIFIED

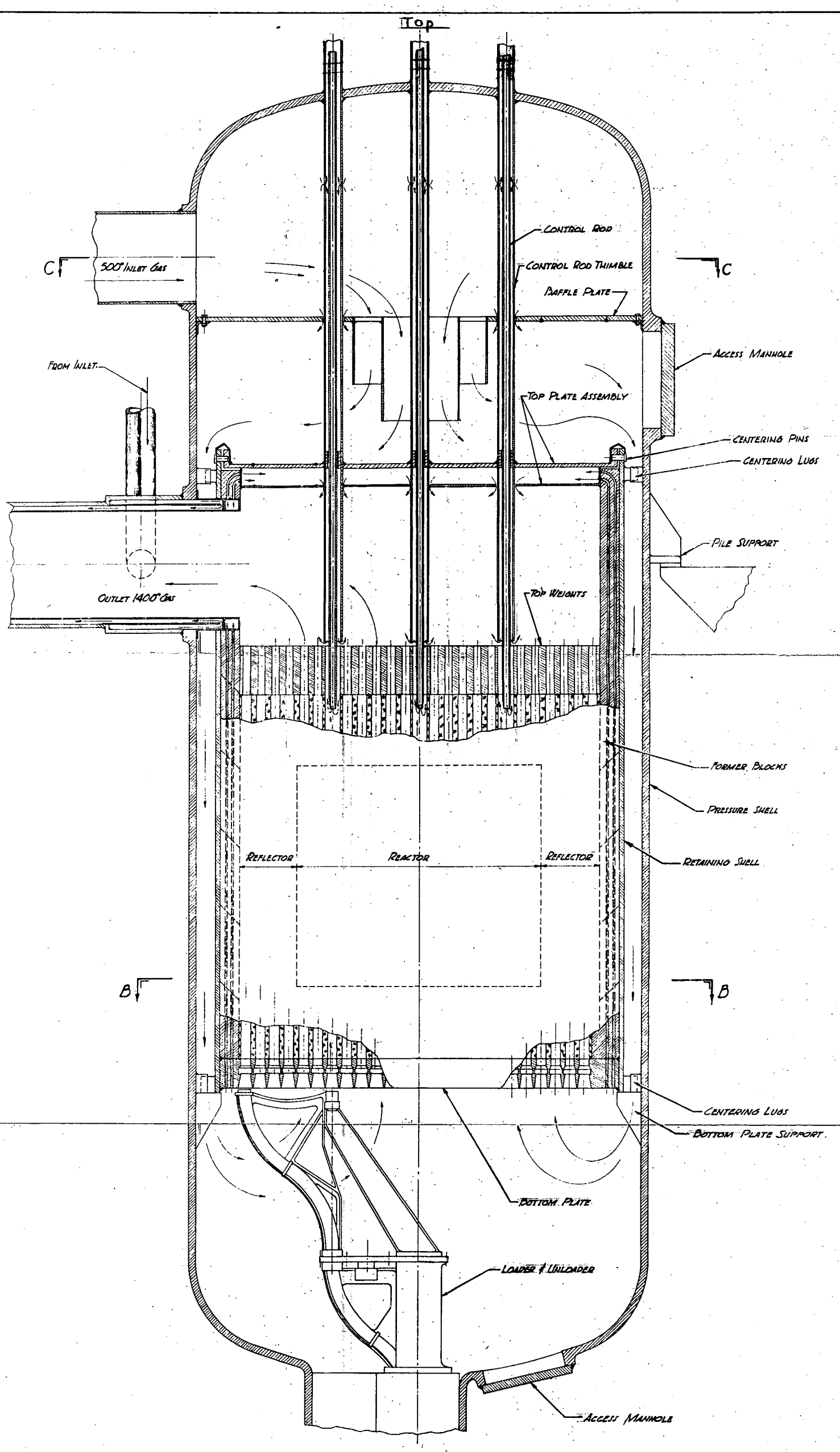


Fig. 24

SECRET

Section Elevation of Pile Structure
High Temperature Gas Cooled Power Pile
MONSANTO CHEMICAL CO.
Chemical Department
Dayton, Ohio

E-2274

NOTES

1. ALL SURFACES SHALL BE FREE OF VISIBLE CRACKS, FOLDS AND CHIPPED AREAS. MINOR CHIPPED AREAS MAY BE BLENDED BY GRINDING SUBJECT TO FINAL ACCEPTANCE BY USER.

2. CYLINDER MUST BE STRAIGHT FROM END TO END WITHIN $\pm \frac{1}{64}$

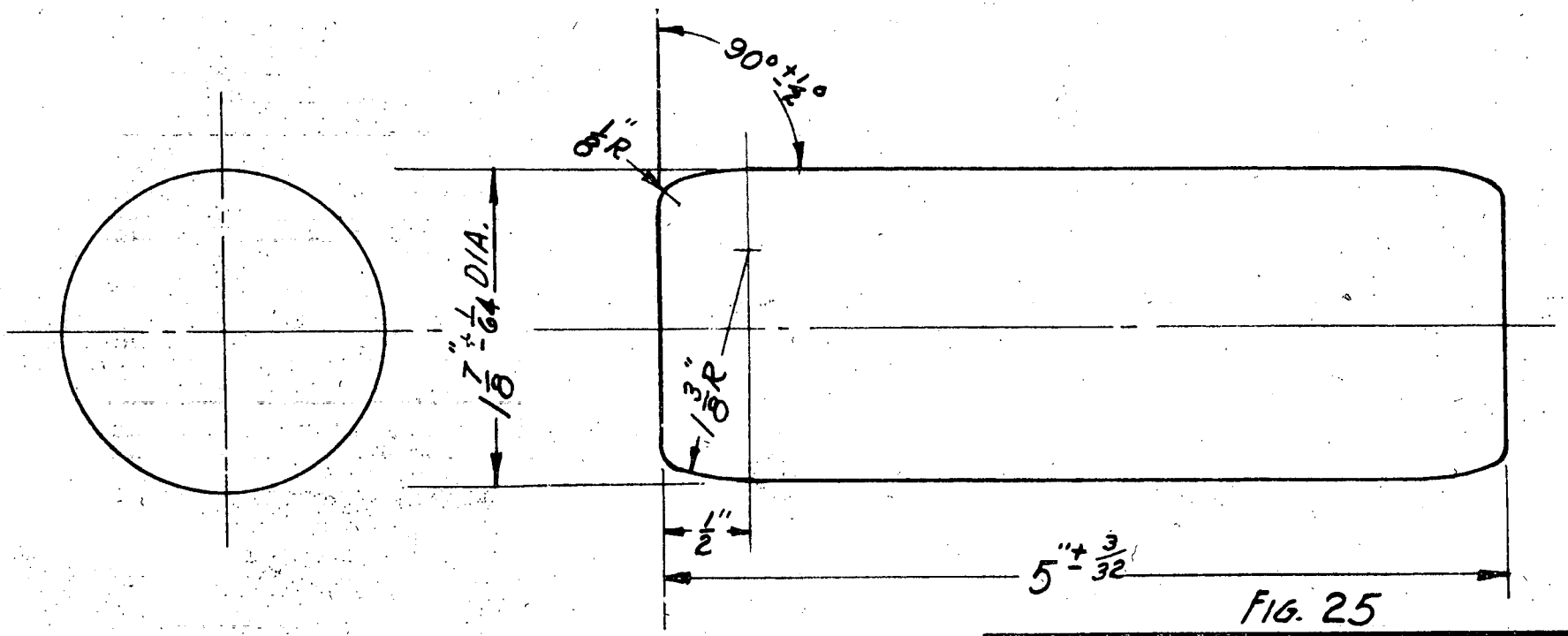


FIG. 25

CYLINDER WITH ROUNDED ENDS

TYPE A-1

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. L.C.L. 9-10-47	C. A.L.S. 9-15-47	A. W.J.M. 9/11/47	R.S.P. 9-16-47			
PROJ C-222 M						
SCALE: FULL						A-2279

2. Fuel Elements.

The fuel consists of uranium or a uranium compound, enriched to 30% U^{235}, dispersed uniformly in a relatively bulky matrix of beryllium oxide, graphite, or beryllium metal. Fuel elements of all three materials are believed to be capable, when suitably designed and fabricated, of sustained safe operation at 12,000 KW. The development program has not proceeded sufficiently to determine just how high the power level can safely be pushed for the various materials and designs.

The materials are fabricated into elements conforming, with suitable clearance, to the two-inch circular channels of the reactor. In current designs a minimum radial clearance of one-sixteenth inch is provided between the channel wall and the centering projections of the fuel elements, and for handling convenience the elements are five inches long.

a. Beryllium Oxide. Fuel elements have been made from a mixture of BeO and UO_2, hot pressed to a specific gravity of 2.9. Early development work in fabrication of this material yielded thick-walled simple tubes, and also similar tubes with the addition of centering fins as shown in Fig. 26-A. Such tubes can be fabricated in quantity, but their low resistance to thermal rupture limits them to relatively low power output. Later development work has shown that hot pressed material can be fabricated into shapes considerably more complex and with considerably thinner walls than the original tubes. The design shown in Fig. 26-D has been produced in hot pressed material, and still more complex shapes and thinner walls are being studied for sample production.

Other methods of fabricating BeO-UO_2 mixtures show that it is possible to obtain material having considerably better resistance to thermal rupture than the hot pressed material. Thermal rupture tests of first trial samples have indicated that for a given shape, ceramically-fired material can be operated at twice the power level possible with the hot pressed material. Fig. 26-B shows a shape that has been satisfactorily extruded and ceramically fired. Preliminary experiments indicate that it will be possible to make still more complex shapes of the type shown in Fig. 27 capable of still higher output.

To summarize, the current status of beryllium oxide fuel elements is as follows: The pile can be operated, although probably at reduced power, with fuel elements that have been developed to date. It is confidently expected that the current and proposed research programs described in detail in Section V will yield greatly improved materials and shapes, and so lead to fuel elements that will provide a wide margin of safety at the design rating of the pile.

b. Graphite. Graphite can be readily extruded or machined into suitable shapes. A sample element having the dimensions of Fig. 26-D was machined from graphite block. Methods of uniformly incorporating uranium into the matrix have been developed and also methods of making the graphite relatively impervious to gases.

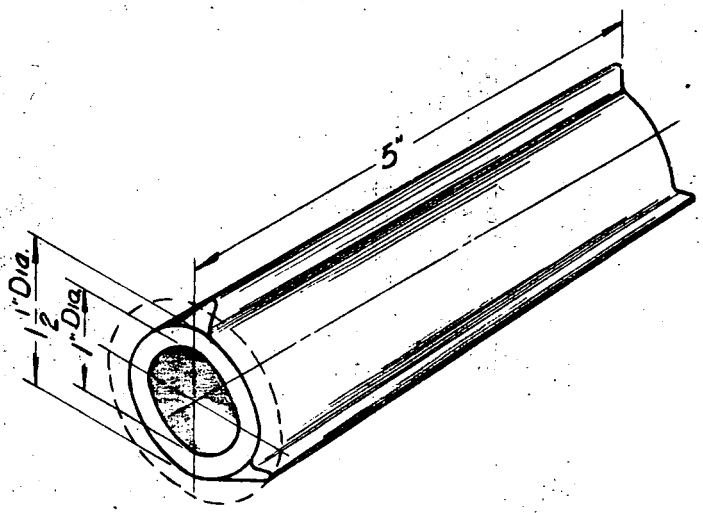
DECLASSIFIED

c. Beryllium Metal. Fig. 26-C shows a design for a beryllium-uranium alloy. This is calculated to permit continued safe operation at the rated output of the pile. Essentially, the element consists of parallel plates; fabricating problems dictate whether the element can be formed as shown (by hot bending), or whether it will be assembled and fabricated from separate plates.

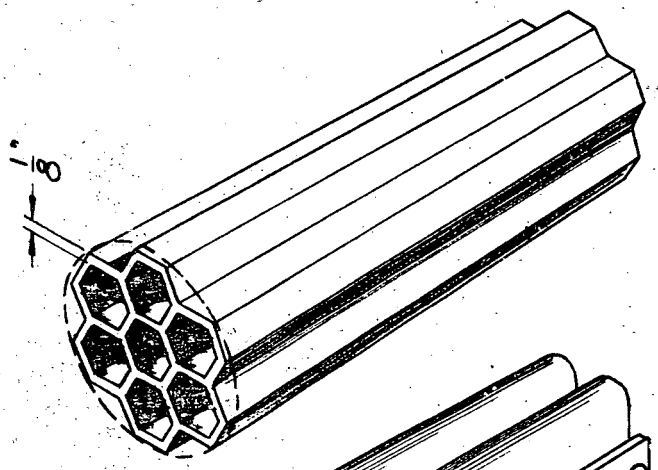
A more detailed discussion of fuel elements is given in Section V. In particular, that section shows the importance of temperature and irradiation on the properties of the matrix materials and consequently on the expected performance of fuel elements. In addition, information on the present technology of fabrication of the matrix materials and its effect on fuel element design is presented.

DECLASSIFIED

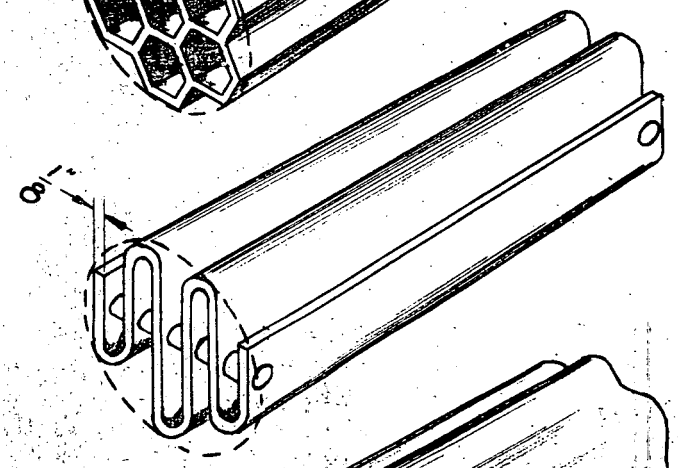
SECRET



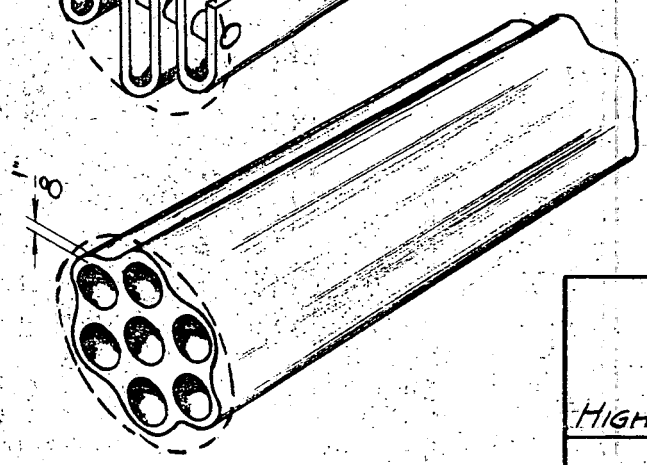
(A) Hot Pressed BeO



(B) Extruded BeO



(C) Be Metal Sheet



D { Bored Be or Graphite Casting
Extruded Be, BeO, or Graphite

FIG. 26

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FUEL UNITS
FOR 2" DIA. CHANNEL
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. G.E. 9-16-47	C. A.L.S. 9-16-47	A. N.J.P. 9-16-47				
SCALE:			A-2962			

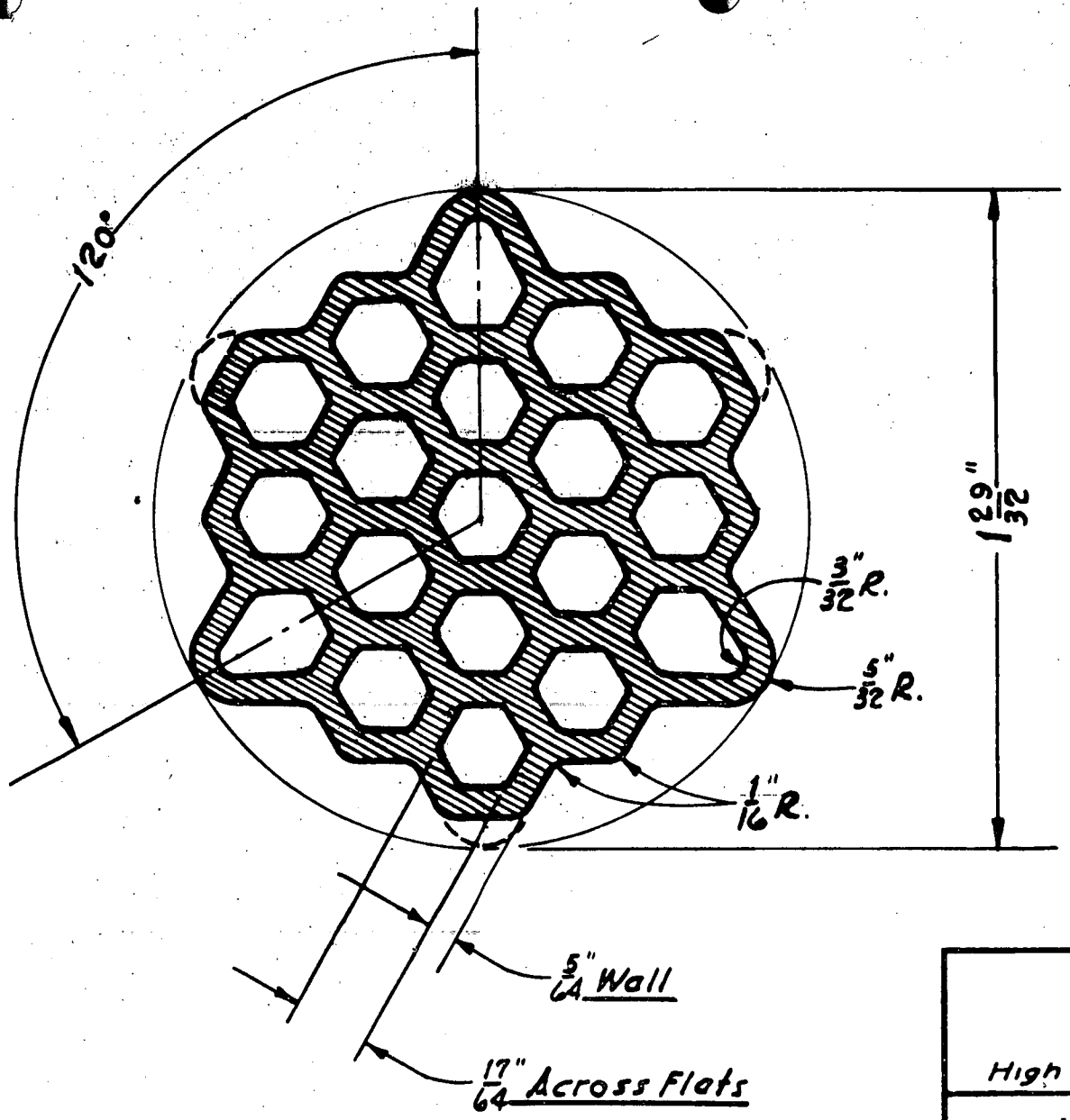


FIG. 27

16 Hex - 3 Pentagon
13 Hex - 6 Pentagon

High Temperature Gas Cooled Power Pile

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D A.E.S. 9-17-47	C R.E.R 9-17-47	A N.J.P. 9-17-47	A.L.G. 9-17-47	R.S.P. 9-17-47		
SCALE: 2" = 1"					A-2963	

3. Fuel Handling.

a. General. All fuel elements described in the previous section pass through approximately the same overall cycle which is, broadly, as follows: Sufficient fuel and reflector elements to fill a complete channel are assembled in proper order and inserted into a gas tight container which provides easy handling and maintains a low moisture content within the fuel elements. In this condition the elements are delivered to storage facilities to await subsequent use. The container is opened only after delivery to the pile loading area and immediately before the fuel elements enter the pile, the exposure to atmosphere being so short that moisture absorption is negligible. The elements are removed from the container and inserted into the pile where they remain until the allowable limit of fuel depletion has been reached. They are then removed from the pile and delivered to a decay chamber to permit decay of the fission products until the activity level has decreased to a low enough value that reprocessing may be initiated. At the reprocessing plant they are crushed, dissolved or burned to permit separation of the Uranium from the matrix of moderator material. The Uranium is purified and enriched in the 235 isotope and re-used in the fabrication of additional fuel elements as described in the previous sections.

Fuel handling, which is concerned with all handling of fuel elements external to the reprocessing and fabrication plants, resolves itself into two problems. All transportation between phases of the cycle is considered as external handling; insertion into the pile and removal from the pile are called the charging and discharging operations. This latter phase has received more attention since it represents the more difficult problem and is one which must be solved before operation of the pile. External handling equipment can successfully be investigated after charging and discharging equipment is well along in design since modifications and improvements can be made at any time during the life of the pile. Because of this the description and discussion of fuel handling equipment problems revolve largely around the problems concerned with the charging and closely related components.

Charging and discharging are accomplished by one machine located in the entrance gas plenum chamber below the pile. Control rods penetrating the exit plenum chamber at the top of the pile preclude the design of a machine to achieve either function at that end. A latch mechanism supports the fuel column in the pile, yet permits unlatching to withdraw spent channels.

Since this results in an entire channel being charged at a time, pile power is reduced to, or nearly to, zero. It is not necessary, however, to reduce the pressure in the helium circuit to achieve loading.

Fuel is introduced to the charging machine through a gas lock which prevents intermixing of the atmosphere and pile helium and provides a chamber in which gaseous contaminants may be removed from the new fuel elements. The "charging machine" consists of the indexing machine for

DECLASSIFIED

selection of the channels to be served, the indexing drive and its control and the charging ram to effect transfer of fuel between the indexing machine and the pile. In discharging, the machine removes the spent elements from the channel and delivers them to the discharge lock. During this operation the elements are cooled to remove sensible heat and the heat generated by decay of fission products. Subsequent removal from the discharge lock to the decay chamber is considered a phase of external handling although it is possible that the decay chamber may be so intimately associated with the discharge lock as to be difficult to distinguish physically.

b. Gas Locks. Fig. 28* shows a basic design of a charging gas lock and includes a step-by-step description of lock operating procedure. In essence, the lock consists of a cylinder 2-1/4" in diameter and 80" long, sufficient to hold the fuel and reflector elements to fill a complete channel. The fuel is introduced to the lock through the curved entrance passage by an external machine at the loading face which is so designed that it is impossible for an operator to stand in front of the open passage during the charging procedure. Incorporated in this passage is the primary valve used to seal the lock from the surrounding atmosphere. The secondary valve separating the lock from the pile is located at the inner (left) end of the lock. Transportation of the fuel elements from the lock to the charging machine is accomplished by the transfer plunger shown schematically at the right end of the lock. Construction and operating principals of this plunger are similar to those of the charging ram described later.

The purging system is comprised of a helium supply and an exhaust system. The former provides a supply of pure helium to match the lock atmosphere with that of the pile prior to the opening of the secondary valve for transfer of fuel into the charging machine. Included in the helium supply line is a constant pressure reducing valve which maintains a lock atmosphere of pure helium during pile operation and at a pressure slightly in excess of pile pressure. This slight pressure differential prevents leakage of contaminated helium from the pile into the lock.

The exhaust system is provided to reduce the oxygen content before pressurizing with helium and to discharge the contaminated helium entering the lock during the time that the secondary valve is open. Removal of the oxygen is achieved by the vacuum pump which will reduce the pressure to .001 atmospheres in 15 seconds. Since the estimated volume of the lock, with allowance for various passages, is about 1/2 to 2/3 of a cubic foot, the pump required to evacuate the chamber within the time limit is in the range of larger sized laboratory equipment. Discharge of contaminated helium, while it could be accomplished by the vacuum pump, is more readily accomplished by simple blow-down procedure. Accordingly, a by-pass is provided around the pump which delivers the contaminated helium directly to the stack discharge system. This by-pass valve remains open during the

* The time schedule noted is based on the loading of 58 channels in a two-hour shut-down as described under "Loading Schedule"

DECLASSIFIED

insertion of fuel into the lock as the negative pressure of the stack system induces a draft of fresh air through the lock.

The use of two valves in series in the exhaust system is worthy of mention. It is apparent that the by-pass valve must be operated three times per channel loading and is thus subject to wear over long periods of time. Replacement of this valve while the pile is operating is rendered possible by inclusion of the "main discharge valve" located between the lock and the by-pass valve. Since this valve is opened and closed only once per loading period its life is expected to exceed that of the pile. When it is closed it is possible to replace the by-pass valve without altering the lock conditions.

The essential requirements of the discharge gas lock are similar to those of the charging lock, but with the additional requirement of cooling the spent elements during and after discharge.

c. Indexing Machine. The indexing machine takes the form of a mono-tube capable of receiving from the charging gas lock an entire channel length of elements and so constructed that the delivery end of the tube may be indexed with any channel in the pile. Registry with the desired channel is achieved by adjusting the delivery end to the desired radius and rotating the entire unit to the required angular displacement from a fixed reference angle.

To achieve the radial adjustment, the mono-tube is constructed in two pieces each formed in the shape of a shallow letter S such that the center line of the tube is tangent at its extremities to two parallel lines separated by a distance equal to one-half the maximum radial displacement of the delivery end from the center line of the pile. The inner of these two tubes reaches from the center line of the pile to the mid radius and is free to rotate about the pile center line. The outer tube is so supported as to be capable of rotation about the outer extremity of the center line of the inner tube. By assuming various angular positions of the outer tube with respect to the inner, the free (delivery) end of the assembly is capable of reaching any radius from zero to the maximum desired radius.

The method of achieving the radial adjustment is most readily explained by reference to Fig. 29 which is a schematic end view of the charging machine. In this drawing, A is the inner tube and B is the outer tube with the delivery end denoted by letter C. The drawing pictures the unit in four radial positions. In view "a" the tubes are fully extended to form a straight angle and in this position the delivery end, C, is at the maximum obtainable radius. In "b", "c" and "d", as the angle between the two arms decreases, the delivery point C is shown successively at 2/3 R, 1/3 R and at zero radius.

Inspection of these four positions shows that the delivery end follows a straight line radial motion from R to zero. That this is possible may be seen considering A and B as the legs of a family of isosceles triangles with varying apex angle and having a base line equal to the distance between the pile center line and point C (in this case the vertical center line of the drawing).

DECLASSIFIED

A straight line motion is desirable in order to prevent the necessity of introducing into the angular adjustment a compensation for radial position. The necessary drive is provided by gears I, II and III. The reaction gear I may temporarily be considered as rigidly fixed in space. The drive pinion II is supported by tube A but free to rotate about its own axis as it meshes with reaction gear I. It also meshes with the driven pinion III which is rigidly attached to the outer tube B so that the motion of pinion III is transferred directly to the outer tube B. By making the radius of the drive pinion one half that of the reaction gear (regardless of the size of the drive pinion) it can be seen that the motion of gear III is such as to cause the outer tube B to move relative to inner tube A at twice the angular velocity of A and in the opposite direction. The angles noted in "a", "b" and "c" and "d" show that this produces the desired radial motion of the delivery end C.

In order to select the channel once the radial adjustment has been made the entire unit must be rotated to the proper angle. To accomplish this it can be seen that the reaction gear I can not be anchored but must be capable of rotation through 360 degrees. If, during this rotation of the reaction gear, a fixed relation between it and inner tube A is maintained, it will be noted that the machine revolves as a unit about the center line.

Fig. 30 shows a cross-section of a construction design. It must be borne in mind in reading this drawing that the center line of the pile is vertical whereas the drawing shows it as horizontal. When reading the drawing the right end must be considered as the top.

The tubes previously mentioned can be seen at the upper end of the machine and are supported by cast arms. The construction permits use of a heat treated alloy for the tube to obtain reasonable hardness for abrasion resistance. The outer arm is supported on two bearings which are in turn supported by the inner arm. Immediately adjacent to the lower of these two bearings may be seen the driven pinion which is rigidly attached to the outer support arm.

The driving pinion is supported by the inner arm, the lower end of which forms a long hollow shaft through which the radial drive is achieved. This shaft is supported on bearings by the outer shaft which is the angular position drive. The outer shaft, by means of an extension at the upper end supports the reaction gear of the planetary indexing drive. The lower end of this extension takes the form of several supporting fingers in order to prevent accumulation of dust around the dust shields over the upper bearings.

In both cases, the upper bearings are thrust bearings which take the weight of the entire machinery from the inner shaft through the outer shaft to the stationary main housing which is inserted in the extension of the pressure shell. The upper location is chosen in order to provide axial location as near the pile support plate as possible so as to minimize relative axial motion between the pile and the charging machine.

DECLASSIFIED

The shafts terminate at the lower end with the driving gears required for radial and angular drives. Above each of these gears there is a gas seal provided to separate the contaminated helium of the pile from the chamber in which these gears operate. These seals take the form of buffer seals in which an intermediate zone of pure helium is introduced between the two areas which are to be separated. This buffer helium is maintained at a pressure slightly above that existing in the zones on either side in order that any leakage which occurs will be outward from the buffer zone. Thus there is no possibility of contaminated helium passing into the operating chamber for the driving gears. The supply of helium to these seals can be observed near the left end of the drawing.

In the case of the angular adjustment drive gear the section shown on the drawing has been chosen to disclose the provisions made for ready replacement of the driving machinery which consists of relatively high speed electric motors and gear reducers. These units will probably require more frequent servicing than the slow moving parts of the indexing machine and are therefore incorporated in such a fashion that replacement of the units can be made without the necessity of reducing pile pressure.

The angular adjustment drive gear is in constant mesh with an idler gear supported in part by the main housing and in part by the pressure housing of the lower end of the charging machine. At the point where this gear is supported by the pressure housing, a seal of relatively simple construction is provided to separate the gear chamber from the driving motor chamber. When the driving unit is installed in this chamber, the pressures on both sides of this seal are equalized; the drive from the out put of the reducing gear to the idler gear being achieved by the splined connection shown. When it is necessary to replace the motor and reducer, the chamber in which the unit is installed may be depressurized and the entire unit removed from the chamber. The small seal around the shaft of the idler gear is relied upon to reduce helium leakage from the gear chamber to an acceptably low value. A similar provision is incorporated for the radial adjustment drive and for the ram drive mechanism.

d. Indexing Control. Fig. 31 is an electro-mechanical schematic drawing of the control system for the indexing machine. This system consists of two servo-mechanisms with a mechanical interlock which permits remote control of the angular and radial indexing of the machine.

The system is so designed that rotary movement of the index control shafts of the input differential imparts a proportional motion to the corresponding positioning shaft of the indexing machine. This is accomplished with master and follow-up selsyns coupled with rotating and electronic amplifiers. Any discrepancy between the desired setting as indicated by the master selsyn, and the actual setting, as indicated by the follow-up selsyn, is detected by the electronic amplifier as a phase difference. The output of the electronic amplifier provides excitation for the rotating amplifier which generates sufficient power to drive the machine until the selsyns are in again phase.

DECLASSIFIED

The input differential is necessary since the design of the machine requires that the radial positioning shaft be driven synchronously with the angular positioning shaft when indexing for angle only, and that it be driven independently of the angular shaft when indexing for radius.

In conjunction with the mechanical interlock an electrical interlock, not shown on the drawing, is provided for the purpose of preventing operation of the angular drive motor in the event that trouble develops in the radial drive system. This is needed to prevent damage due to over travel of the radial adjusting mechanism.

Control of the input differential will be provided by a mechanism which will enable the operator to select the desired channel by pushing a single button. Once motion is initiated, the machine will complete the indexing motion before subsequent operations (charging or discharging) can be started. This mechanism has not been designed to date since it offers no problems unique to this application, and ample experience is available to draw upon in the design.

e. Charging Ram. The ram for moving elements into and out of the pile is incorporated within the hollow central portion of the radial adjustment drive shaft to obtain the minimum overall length of the charging machine although at some expense in complication of the machinery. The ram is laterally flexible yet axially rigid in order that it be capable of passing through the entire length of the charging machine in any position that this machine may assume. The construction as shown on the drawing (Fig. 30) is in the form of a succession of elements 5" in length joined end to end by ball and socket joints. The elements are fluted in order to permit passage of cooling helium during discharge operations.

The ram is supported within a stationary housing which also encompasses the driving system used to impart the necessary axial motion to the ram. The driving means proposed on the drawing consists of a pair of chains disposed laterally on either side of the ram proper. A rigid link attached between these two chains engages an extension on the lowest element of the ram mechanism and transfers the drive from the chains to the ram. The chain is driven by the lower sprockets which are powered by a motor and gear reducer located at the lower end of the unit. A buffer type seal similar to those between the main driving shafts and the stationary housing is incorporated to provide for ready replacement of the drive motor and reduction gear.

The ram mechanism housing is supported on a framework which straddles the charging machine drives and is supported on the main housing. In order to prevent leakage of contaminated helium through the annulus between the ram housing and the inner shaft, a fourth buffer type seal is provided at this location.

DECLASSIFIED

f. Fuel Latch. Fig. 32 shows the design of a latch which is used once and discarded at the completion of its period of service. A working model, photographed in four important positions in the cycle, is shown in Fig. 33. It consists of a short cylindrical tube 2" in diameter and approximately 5" long so that it may pass readily through the charging machine. Incorporated within this tube are three latch fingers spring loaded in the outward direction in order that these fingers may engage the latch recess. To charge a channel it is necessary only to move the fuel elements and latch high enough into the pile for the latch fingers to engage the recess. Subsequent withdrawal of the ram leaves the fuel resting in the channel.

In order to discharge the channel the latch fingers must be retained in a closed position so that they cannot engage either the latch recess or the entering edge of the fuel charging mechanism. Provided within the latch is a locking ring so designed that when the fingers enter a 2" diameter cylindrical portion the ring falls by gravity into the internal recess on the latch fingers. In this condition the fingers are incapable of engaging any shelf in the charging system. In the pile this is achieved by pushing the channel upward 1" beyond the operating level causing the fingers to enter the 2" diameter portion of the support plate gas passage.

Locking during the insertion operation is rendered impossible, by so designing the entrance passage that no portion has a diameter less than 2 1/4". Although it is possible for one finger to be depressed to the locking position in passing through the loading machine, the three stabilizing fins incorporated on the locking ring prevent droping of this ring until all three fingers are simultaneously depressed.

The use of springs for actuation of the latch fingers is considered entirely safe since softening of the spring during insertion is impossible. Softening during operation will not cause failure of the latch since the spring is needed only during the insertion operation.

g. Charging and Discharging Procedure. With the charging machine located in a position 180 degrees from that shown on the drawing, fuel is introduced through the entrance passage provided between the gas lock, and the charging machine tube. (The flexible joint noted on the drawing is provided to accommodate the relative motion between the lock and the pressure shell caused by thermal expansion of the latter unit). Transfer of the elements is accomplished by the transfer plunger incorporated in the gas lock which moves the elements into the charging machine until the fingers of the latch engage the latch recess located slightly below the plane of the main thrust bearings. The fuel column is supported at this intermediate stage during withdrawal of the transfer plunger, and during indexing which is initiated as soon as the transfer ram has been withdrawn beyond the two main shafts. Once the proper orientation of the delivery point has been achieved, the charging ram transfers the fuel elements from the charging machine into the pile.

UNCLASSIFIED

SECRET

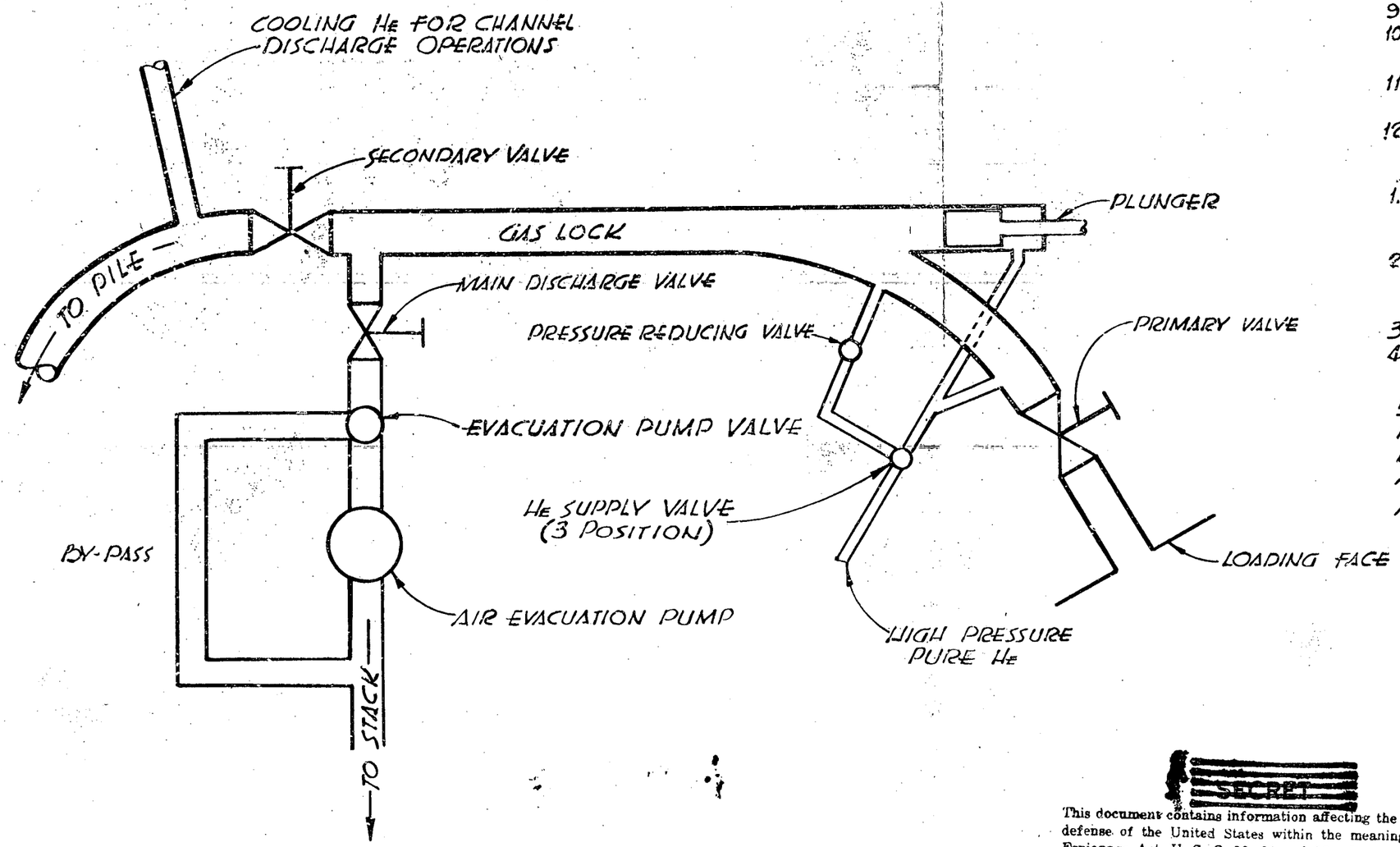
Discharging is achieved by raising the charging ram until the fuel and latch have been raised the necessary amount to achieve locking of the latch fingers in the retracted position. Retraction of the ram lowers the entire channel of fuel safely below the pile supporting plate, permitting indexing to the discharge passage through which the spent elements are delivered to the discharge gas lock. The discharge passage takes the form of a simple 90 degree elbow located immediately outside the reflector and opposite the charging lock so that when the machine has been discharged it is already in position to receive a new charge of fuel elements.

As has been mentioned, the fuel elements require cooling to maintain reasonable temperatures during the discharging operation. Fig. 30 indicates the supply of cooling helium in the fuel entrance passage which provides for cooling flow through the monotube while spent elements are in the machine. The helium flows from this supply line through the entrance passage into the annulus surrounding the charging machine shafts which is provided in order to permit free flow of helium regardless of angular location of the channel being discharged. Although not shown on the drawing, a gas entrance port is provided in the outer shaft immediately adjacent to the entrance channel in order to permit passage of helium in any radial position of the charging machine.

DECLASSIFIED

SECRET

SECRET



PREPARATION FOR CHARGING OPERATION

1. OPEN MAIN DISCHARGE VALVE.
2. TURN VACUUM PUMP VALVE TO "BY-PASS" POSITION TO DEPRESSURIZE LOCK.
3. START AIR EVACUATION PUMP.

CHARGING CYCLE

	TIME
1. OPEN PRIMARY VALVE & INSERT FUEL ELEMENTS.	10 SEC.
2. CLOSE PRIMARY VALVE & TURN VACUUM PUMP VALVE TO "PUMP" POSITION.	2 "
3. EVACUATE LOCK TO .001 ATMOSPHERE.	15 "
4. TURN VACUUM PUMP VALVE TO "OFF" POSITION.	1 "
5. TURN He SUPPLY TO "PRESSURIZE" POSITION. & RAISE LOCK PRESSURE TO 10 ATMOSPHERES.	2 "
6. TURN He SUPPLY VALVE TO "OFF" POSITION.	1 "
7. OPEN SECONDARY VALVE & TRANSFER ELEMENTS TO CHARGING MACHINE BY MEANS OF PLUNGER.	10 "
8. WITHDRAW PLUNGER INTO LOCK.	3 "
9. CLOSE SECONDARY VALVE.	2 "
10. TURN VACUUM PUMP VALVE TO "BY-PASS" POSITION & BLOW LOCK DOWN TO 1 ATMOSPHERE.	5 "
11. OPEN PRIMARY VALVE TO ALLOW STACK DRAFT TO PURGE CHAMBER & PERMIT FUEL ENTRY.	
12. REPEAT STEPS 1 THRU 10 FOR EACH CHANNEL.	

LOCK TREATMENT FOR PILE OPERATION

1. AFTER LAST CHANNEL IS CHARGED, REPEAT STEPS 1, 2, 3, 4, & 5 EXCEPT THAT NO FUEL IS INSERTED IN STEP 1.
2. TURN He SUPPLY VALVE TO "PRESSURE REGULATING" POSITION TO MAINTAIN LOCK PRESSURE SLIGHTLY IN EXCESS OF PILE PRESSURE.
3. CLOSE MAIN DISCHARGE VALVE.
4. STOP VACUUM PUMP.

NOTE:

PURGING SYSTEM FOR GAS LOCK IF PILE HELIUM ACTIVITY IS MAINTAINED AT OR BELOW 0.1 CURIE PER CU. FT. AT S.T.P.

FIG. 28

GAS LOCK PURGING SYSTEM I

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Strauchman				
D. 9-12-47	C. R.T.P. 9-12-47	A. 9-15-47	R.S.P. 9-16-47	A.L.S. 9-16-47

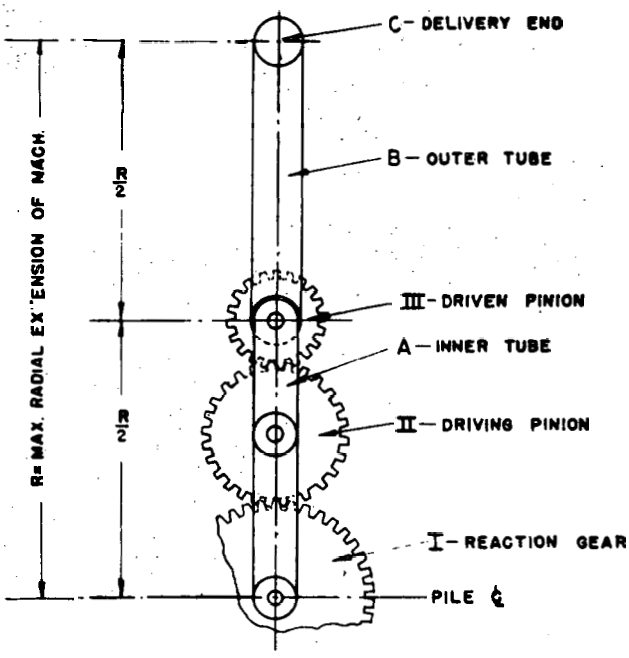
Proj: C-222M

SCALE:

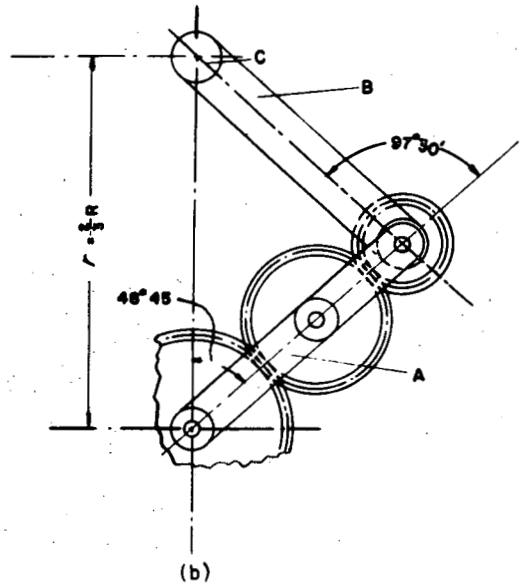
B- 2272

SECRET

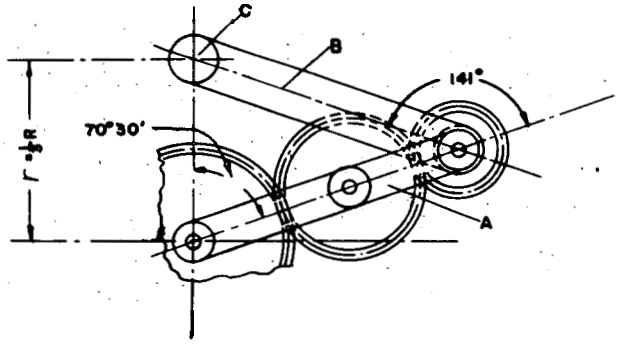
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.



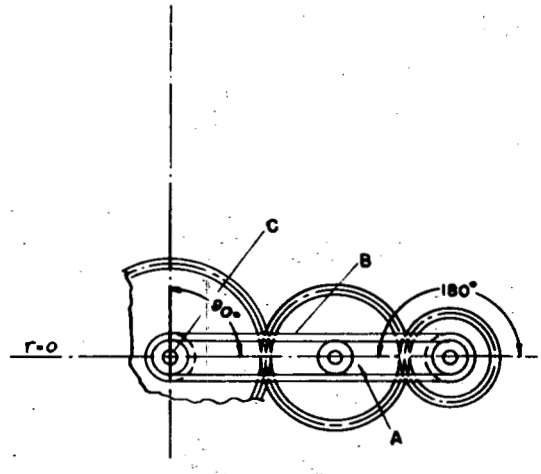
(a)



(b)



(c)



(d)

FIG. 29

[redacted]

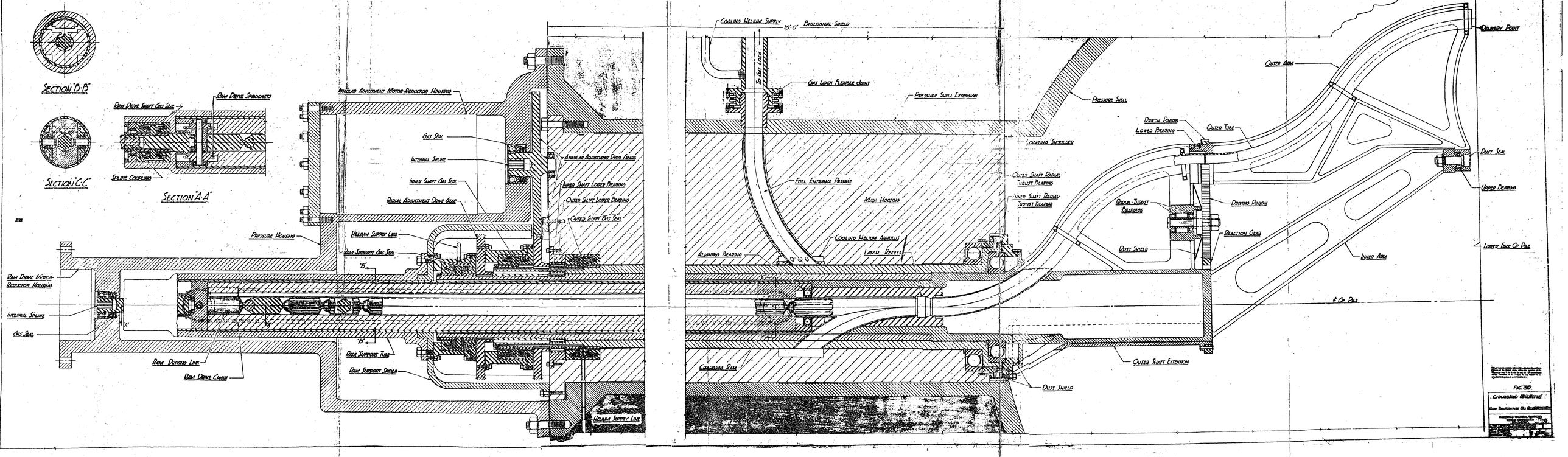
This document [redacted] defense of the [redacted] of the Espionage Act, U. S. C. 50, 31 and 32, as amended. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DANIALS EXPERIMENTAL POWER PILE
EPICYCLIC GEARING RADIUS
SELECTION

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. W.K.C. 7-14-47	C. R.L.S. 7-14-47	R. [illegible] 7-16-47			
PROJ. C-222-M					C-2239

DECLASSIFIED


SECTION "B-B"
SECTION "C-C"
SECTION "A-A"
RAM DRIVE SHAFT GAS SEAL
RAM DRIVE SPROCKETS
SPLINE COUPLING
ANGULAR ADJUSTMENT MOTOR-REDUCTOR HOUSING
GAS SEAL
INTERNAL SPLINE
INNER SHAFT GAS SEAL
RADIAL ADJUSTMENT DRIVE GEAR
ANGULAR ADJUSTMENT DRIVE GEARS
INNER SHAFT LOWER BEARING
OUTER SHAFT LOWER BEARING
OUTER SHAFT EXTR SEAL
PRESSURE HOUSING
HELIUM SUPPLY LINE
RAM SUPPORT GAS SEAL
RAM DRIVE MOTOR-REDUCTOR HOUSING
INTERNAL SPLINE
GAS SEAL
RAM DRIVING LINK
RAM DRIVE CHAIN
GAS SUPPORT TUBE
RAM SUPPORT SPIDER
HELIUM SUPPLY LINE
COOLING HELIUM SUPPLY
10'-0" BIOLOGICAL SHIELD
GAS LOCK FLEXIBLE JOINT
PRESSURE SHELL EXTENSION
FUEL ENTRANCE PASSAGE
MAIN HOUSING
COOLING HELIUM ANNULUS
LATCH RECESS
ALIGNING BEARING
CHARGING RAM
LOCATING SHOULDER
OUTER SHAFT RADIAL-THRUST BEARING
INNER SHAFT RADIAL-THRUST BEARING
PRESSURE SHELL
DOWN PINION
LOWER BEARING
OUTER TUBE
RADIAL-THRUST BEARINGS
DRIVING PINION
REACTION GEAR
DUST SHIELD
OUTER SHAFT EXTENSION
DUST SHIELD
OUTER ARM
DELIVERY POINT
DUST SEAL
UPPER BEARING
LOWER FACE OF PILE
INNER ARM
℄ OF PILE
FIG. 30.

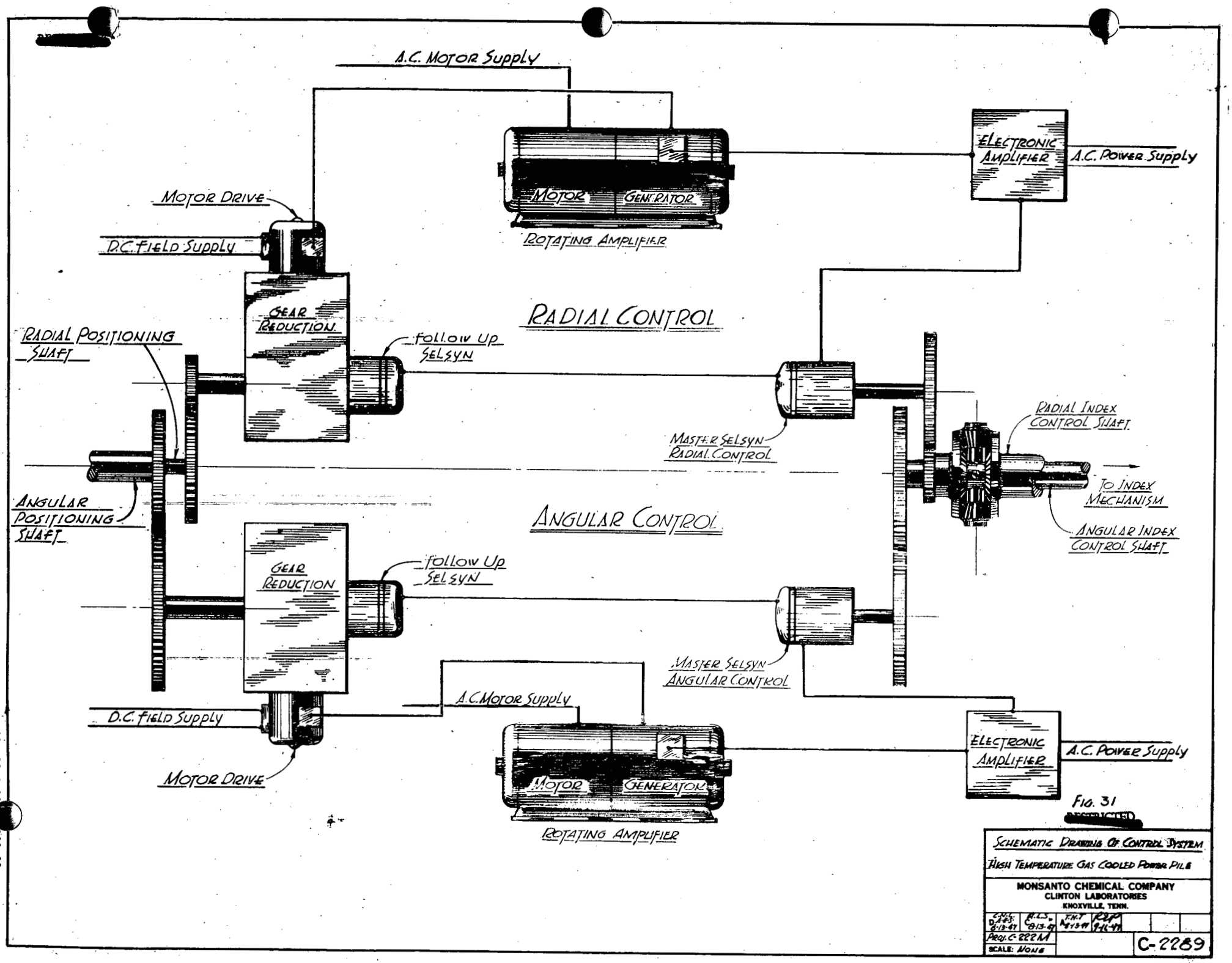


Fig. 31

[redacted]

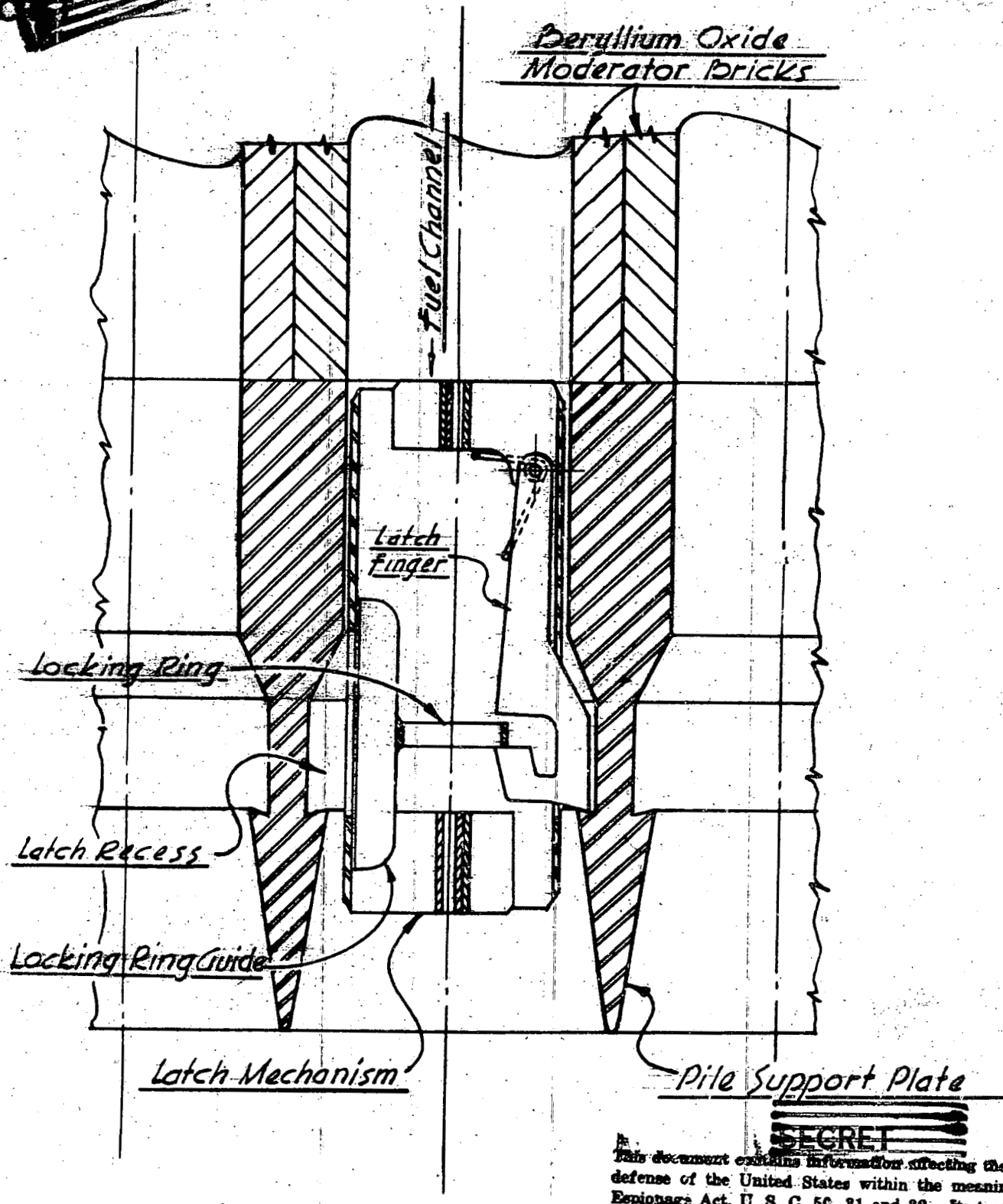
Schematic Drawing Of Control System

High Temperature Gas Cooled Power Pile

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

C.H.S. 8-13-47	D.L.S. 8-13-47	F.H.T. 8-13-47	R.E.P. 9-16-47			
Proj. C-222 M						
Scale: None						C-2289

SEC[redacted]



[redacted]

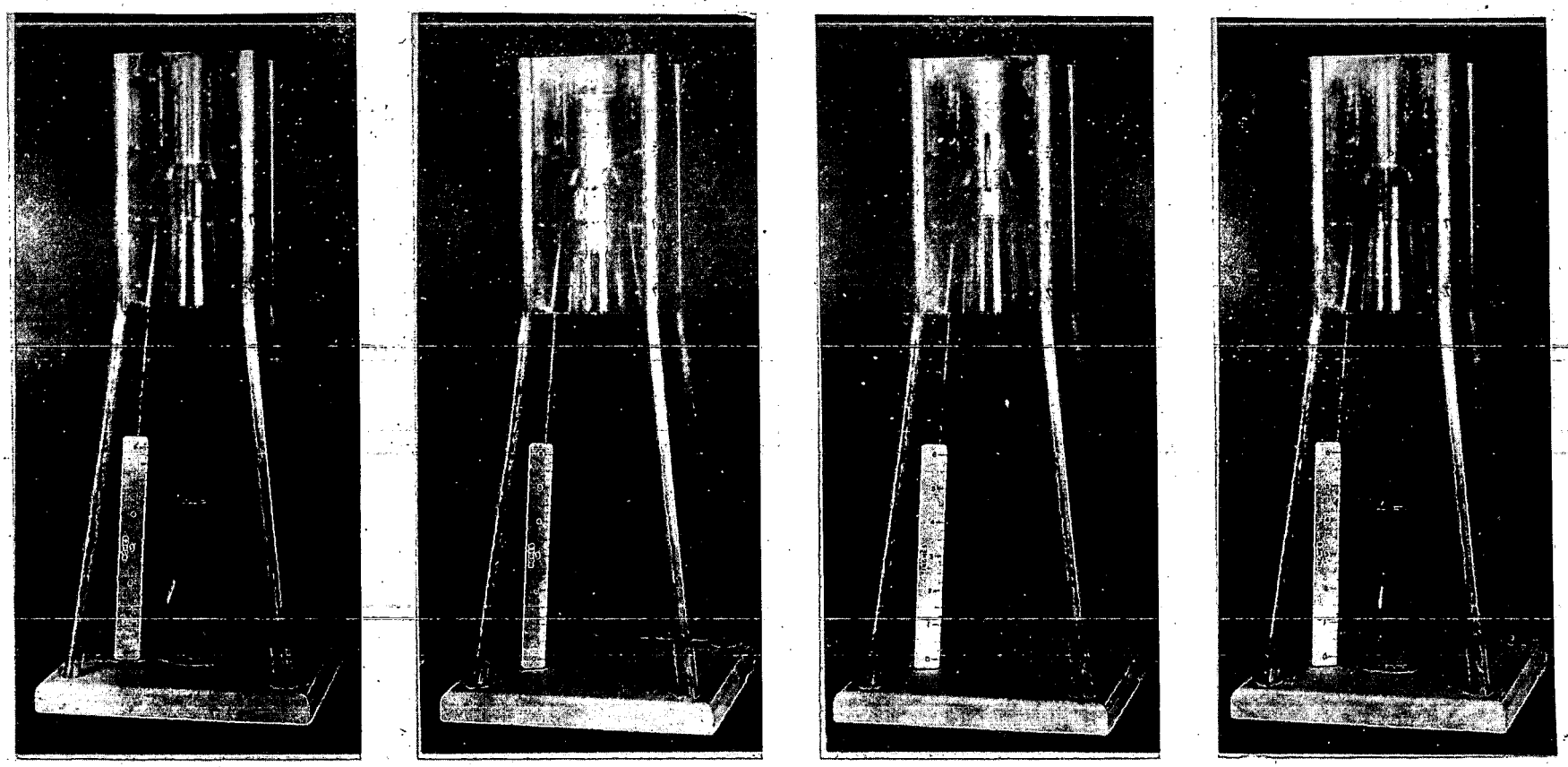
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FIG. 32

REF. DWG. D-2255

FUEL LATCH						
HIGH TEMPERATURE GAS COOLED POWER PILE						
MONSANTO CHEMICAL CO. CLINTON LABORATORIES KNOXVILLE, TENN.						
Structural D	A.L.S. C 9-8-47	A KJS 9/5/47	RLP 9-16-47			
Proj: C-222M						
SCALE: 3/8" = 1"				A-2271		

DECLASSIFIED



CHARGE LATCHED LOCKED DISCHARGE

FIG. 33

FUEL LATCH - WORKING MODEL

SECRET

4. Nuclear Characteristics

The essential nuclear characteristics of the pile are shown in Figures 8, 9, and 10. These show the amount of $U^{235}O_2$ required to make the pile critical as a function of the radius of the reactor, the thickness of the reflector, and the fraction of the reactor cross sectional area used for gas passages, i.e., the pile voids. It will be noted that for each value of voids, there is a reactor radius which gives a minimum critical amount of fissionable material.

The pile has been designed on the basis of minimizing the critical mass of fissionable material while at the same time providing a high degree of flexibility as to the kind and pattern of loading so that studies can be made on various shapes of fuel units, various fuel unit matrix materials and on conversion of thorium. Three possible loading patterns are illustrated in Fig. 34 and their corresponding operating characteristics are given in Table IV. Loading Pattern A results in the highest neutron flux, and the lowest critical mass of U^{235}, but provides no conversion except the small amount taking place in the U^{238}. Pattern C provides the highest neutron economy and provides a conversion blanket, but at a relatively low power and flux rating due to the reduction in the reactor volume. Pattern B gives a flux somewhat lower than Pattern A but at the same time provides a conversion blanket. In each of these cases beryllium oxide was assumed as the fuel unit matrix material. If fuel elements with beryllium metal as the matrix material and having the same voids as the BeO fuel elements are used in the pile, the chain reaction characteristics of the pile remain essentially the same because of the similarity of the nuclear properties of Be and BeO. If fuel elements of graphite are used, the critical mass of U^{235} increases somewhat. This case has not been calculated, but an upper limit to the critical mass has been set by considering the entire fuel element as void. The critical mass of $U^{235}O_2$ for case A on this assumption is 6.2 kg. The critical masses for cases B and C are impractically high when so calculated

SECRET

DECLASSIFIED

SECRET

TABLE IV

SUMMARY OF PILE NUCLEAR CHARACTERISTICS

Loading Pattern			
Average reactor radius, cm	62.2	62.2	54
Reactor height, cm	114	114	100
Number of active fuel channels	228	228	174
Average fraction voids in reactor	.28	.28	.28
Average outer radius of reflector, cm	91.0	76.8	76.8
Height, reactor plus reflector, cm	193.3	168.0	168.0
Average outer radius of conversion blanket, cm	----	91.0	91.0
Height, reactor plus reflector plus blanket, cm	193.3	193.3	193.3
Hot critical mass of $U^{235}O_2$, Kg	3.6	5.1	4.6
Initial operating charge of $U^{235}O_2$, Kg	5.0	6.7	6.0
$\frac{\text{gms } U^{235}O_2}{\text{gms BeO}}$ in reactor for criticality	.00132	.00186	.0024
$\frac{\text{atoms Be}}{\text{atoms } U^{235}}$ in reactor for criticality	8030	5700	4400
$\frac{\text{Neutrons absorbed in BeO}}{\text{Neutrons absorbed in } U^{235}}$ in reactor	.146	.105	.085
$\frac{\text{Neutrons absorbed in } U^{238} + \text{Neutrons leaking from reactor}}{\text{Neutrons absorbed in } U^{235}}$	.954	.995	1.015
$\frac{\text{Neutrons absorbed in } U^{238}}{\text{Neutrons absorbed in } U^{235}}$ (approximate)	.06	.08	.10
Design rating, heat output in kw	12000	12000	8100
Average Thermal-neutron flux	6.5×10^{13}	4.9×10^{13}	3.8×10^{13}

SECRET

DECLASSIFIED

SECRET

a. Operating Charge of Fissionable Material. At the time of initial start-up of the pile, the total weight of $U^{235}O_2$ in the pile must be considerably higher than the critical masses shown in Table IV. Extra fuel must be present to make up for fuel consumption during operation and for the effects of poisons - neutron abosrbing nuclei resulting from the fission of U^{235}.

The amount of extra fuel that must be included in the fuel elements to make up for the fuel consumed during the life of the fuel elements depends upon the life of the elements and the average power level of operating of the pile. If the pile operates continuously at 12,000 kw, .45 kg of U^{235} will be consumed in 30 days. At a power level of 8,000 kw the consumption will be .30 kg in 30 days.

The two main poisons formed in the pile are $Xenon^{135}$ and $Samarium^{149}$. $Xenon^{135}$ has an absorption cross section of 3.6×10^{-18} cm^2 and $Samarium^{149}$ has a cross section of 5.5×10^{-20} cm^2 for thermal neutrons. Neither the Xenon nor the Samarium is formed primarily from the fission process; both occur as products of the decay of less stable nuclei formed in fission. Samarium is a decay product of $neodynium^{149}$, which is formed in 1.4% of the fissions and Xenon is a decay product of $Tellurium^{135}$, formed in 5.9% of the fissions. $Xenon^{135}$ is itself unstable, while $Samarium^{149}$ is stable. The decay chains are:

$$_{52}Te^{135} \xrightarrow{2\ min} {}_{53}I^{135} \xrightarrow{6.7\ hr.} {}_{54}Xe^{135} \xrightarrow{9.2\ hr.} {}_{55}Cs^{136}$$

and

$$_{60}Nd^{149} \xrightarrow{1.7\ hr} {}_{61}Il^{149} \xrightarrow{47\ hr} {}_{62}Sm^{149}$$

Both Xenon and Samarium build up with time as the pile operates; both approach steady-state concentrations if the flux-level in the pile is maintained constant. The steady state is reached for Sm when the rate of formation by fission is equal to the rate of destruction by neutron absorption. This steady-state concentration is independent of the flux level in the pile, but the rate at which the steady state is approached does depend on the flux level. The steady-state concentration of Xe occurs when the rate of production by fission is equal to the sum of the rates of destruction by neutron absorption and natural decay to Cs. Both the steady-state concentration and the rate of approach to that concentration are functions of the flux level in the pile. The concentration of Xenon and Samarium in the pile can be expressed in terms of the fractional change ($\delta k/k$) they would produce in the multiplication constant of an infinite pile (see Appendix C for detailed definition of k). In Fig. 35, the growths of Xe and Sm are shown, in terms of $\delta k/k$, as functions of the operating time at various thermal flux levels (nv) for a pile having the average characteristics tabulated in Table IV.

SECRET

DECLASSIFIED

Because both poisons are formed by radioactive decay of nuclei that are less effective as neutron-absorbers, their poisoning effects continue to build up for a time after the pile has been shut down. Fig. 36 shows the build-up of Xenon and Samarium poisoning immediately after the thermal flux in the pile has been reduced from a value nv to zero. The curves apply to the case in which the pile has been operating long enough at the flux nv for the Xenon and Samarium concentrations to have assumed essentially constant values. A similar effect occurs if the flux level in the pile is reduced but not brought completely to zero. Fig. 37 shows the build-up of Xenon poisoning after the flux level in the pile is changed suddenly from 5×10^{13} to various lower values. Operation at 5×10^{13} is assumed to have lasted long enough for the steady-state concentration of Xenon to have been reached. It is evident from Figs. 36 and 37 that a large excess of fuel above the initial critical value is necessary if large and rapid changes in power are to be possible, or if the pile is to be restarted during the interval from, say, two to twenty-four hours after shutdown.

Fig. 38 shows the changes in $\delta k/k$ due to Xenon poisoning that would occur during a sequence of operating conditions, including instantaneous start-up of the unpoisoned pile, operation at a flux of 5×10^{13}, instantaneous shut-off, and instantaneous start-up at the peak of the poisoning curve. It may be noted that operation at a thermal flux of 5×10^{13} reduces the accumulated Xenon concentration quite rapidly.

The minimum fuel charges for operating the pile with the loadings previously discussed are given in Table V. The allowance for fission product poisoning is just enough to allow steady operation at the rated flux. Decreases in power could be made only at a very slow rate and restarting would have to occur either immediately after shutdown, or after a period of the order of 30 hours. A small fuel allowance has been made for possible effects of moderator impurities. The hot critical mass was computed on the assumption of impurities equivalent to .5 part per million of Boron, but it is not certain that this purity level can be attained.

TABLE V

Operating Charge of $U^{235}O_2$

Loading pattern	A	B	C
Hot critical mass, kg	3.6	5.1	4.6
Moderator impurities, kg	.40	.40	.40
Fission-product poisons kg	.55	.85	.70
Depletion, 30 days, kg	.45	.45	.30
	5.0	6.7	6.0
Reprocessing make up of UO_2 per month, kg	.482	.487	.327
Enrichment of make-up UO_2	93.4%	92.5%	91.7%

DECLASSIFIED

The reprocessing make-up listed supplies only the fuel actually consumed per month, and does not take into account chemical or fabrication losses. The make-up fuel must be enriched to 92 or 93% U^{235} (see table) if the average enrichment in the pile is to be held at 30%. If the pile is replenished with 30% enriched uranium, the monthly quantity of make-up U^{235} must be increased by about 20% to compensate for the increasing poisoning effect of the U^{238}.

b. Inventory of Fissionable Material. A schedule of the fuel, expressed in Kg of $U^{235}O_2$, required to operate the pile continuously is given in Table VI. Because it takes five months for the depleted fuel to be reprocessed and refabricated, a steady state between the fuel added to operate the pile and the fuel in process is reached in seven months from the start of operations. At this time the total inventory will be 40.2 Kg of $U^{235}O_2$. In order to maintain a constant isotopic concentration of 30%, it will be necessary to add quantities of 90% to 100% enriched UO_2 to the fuel during processing. The additions are tabulated and are 3.12 Kg per year after the first year.

The maximum average power level given (7000 KW) is not the maximum power level attainable. It is an estimated average that allows for decrease of the power rating of the fuel elements during their life because of fission damage. Both the power level and operating time, hence the fuel depletion, are limited by the fission damage which can be tolerated in the fuel rods. A maximum depletion of 7.5% was assumed in preparing Table VI. If the damage is small, it may be possible to leave the fuel in the pile a longer time without changing. If the fuel could be left in the pile 5 months, the inventory of $U^{235}O_2$ would then be only about 15.5 Kg, as is shown in Table VII.

Table VI assumes an operating mass of 6.70 Kg of $U^{235}O_2$ in the pile at time of loading. During the third month, the entire pile is refueled, thus the sudden appearance of 6.70 Kg in process. Both tables apply to the case wherein the entire pile is refueled at the same time. Some saving in inventory (at least in the case of the 7000 Kw-month fuel elements) could be achieved by a schedule of partial reloadings which would operate the fuel elements in the lower-flux region near the edge of the pile longer than those near the center of the pile. One method of accomplishing this, assuming 10% depletion, is described in Section V.

DECLASSIFIED

SECRET

TABLE VI

$U^{235}O_2$ INVENTORY

Fuel-element Life 7000 Kw - months

$U^{235}O_2$ in Fresh Pile, 6.70 Kg

Month	Average Power Level	Consumption per month	To Processing	$U^{235}O_2$ added during processing (90-100% enriched)	Accumulated total of $U^{235}O_2$ added during Processing	30% $U^{235}O_2$ in Process	Total 30% $U^{235}O_2$ Inventory (Pile plus process)
0	Start		---	---	---	0	6.7 Kg
1	1000 KW	.04 Kg	---	---	---	0	6.7
2	2000	.07	---	---	---	0	6.7
3	3000	.11	6.48 Kg	.22 Kg	.22 Kg	6.7 Kg	13.4
4	4000	.15	6.55	.15	.37	13.4	20.1
5	5000	.19	6.51	.19	.56	20.1	26.8
6	6000	.23	6.47	.23	.79	26.8	33.5
7	7000	.26	6.44	.26	1.05	33.5	40.2
8	7000	.26	6.44	.26	1.31	33.5	40.2
9	7000	.26	6.44	.26	1.57	33.5	40.2
10	7000	.26	6.44	.26	1.83	33.5	40.2
11	7000	.26	6.44	.26	2.09	33.5	40.2
12	7000	.26	6.44	.26	2.35	33.5	40.2

TABLE VII

$U^{235}O_2$ INVENTORY

Fuel-element Life 35000 KW - months

$U^{235}O_2$ in Fresh Pile, 7.75 Kg

0	Start					0	7.75 Kg
1	1000 KW	.04 Kg	----	---	---	0	7.75
2	2000	.07	----	---	---	0	7.75
3	3000	.11	----	---	---	0	7.75
4	4000	.15	----	---	---	0	7.75
5	5000	.19	----	---	---	0	7.75
6	6000	.23	----	---	---	0	7.75
7	7000	.26	----	---	---	0	7.75
8	7000	.26	6.44 Kg	1.31 Kg	1.31 Kg	7.75 Kg	15.50
9	7000	.26	----	---	1.31	7.75	15.50
10	7000	.26	----	---	1.31	7.75	15.50
11	7000	.26	----	---	1.31	7.75	15.50
12	7000	.26	----	---	1.31	7.75	15.50
13	7000	.26	6.44	1.31	2.62	7.75	15.50

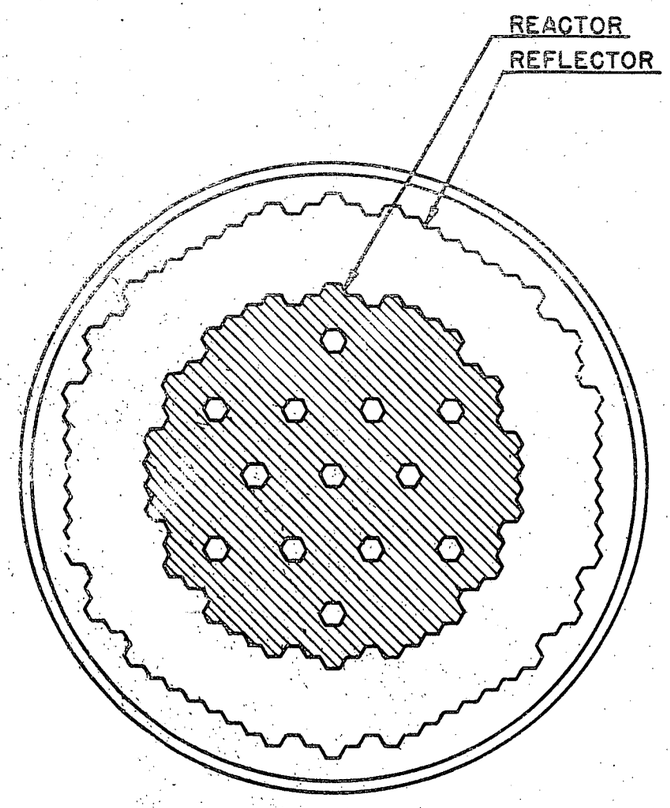
SECRET

DECLASSIFIED

c. Neutron Flux Distribution. The gross thermal and epithermal neutron flux distribution for the pile without the thorium blanket, i.e., loading pattern A, is shown in Figs. 6 & 7. Since the heat production per unit volume is approximately proportional to the thermal neutron flux in the volume, this figure also shows the gross distribution of power generation throughout the pile.

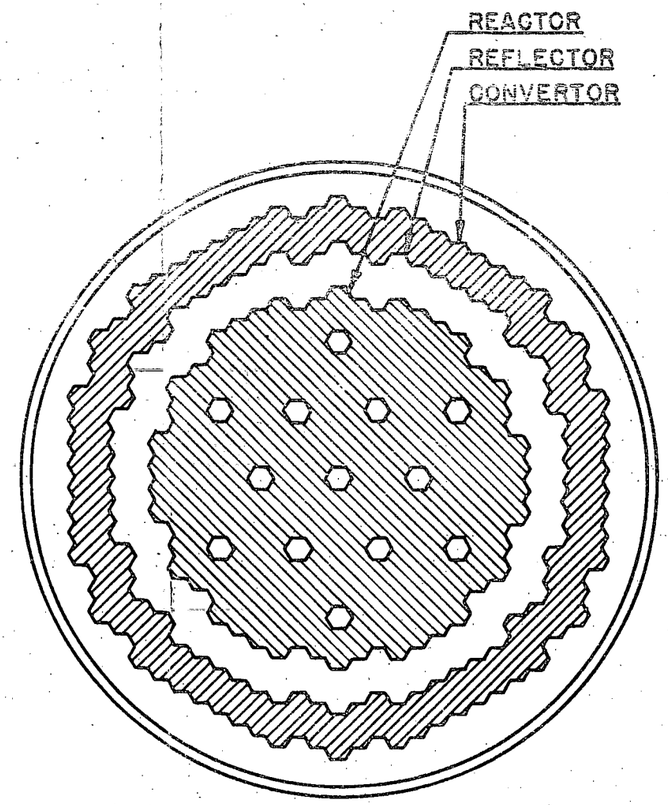
DECLASSIFIED

SECRET



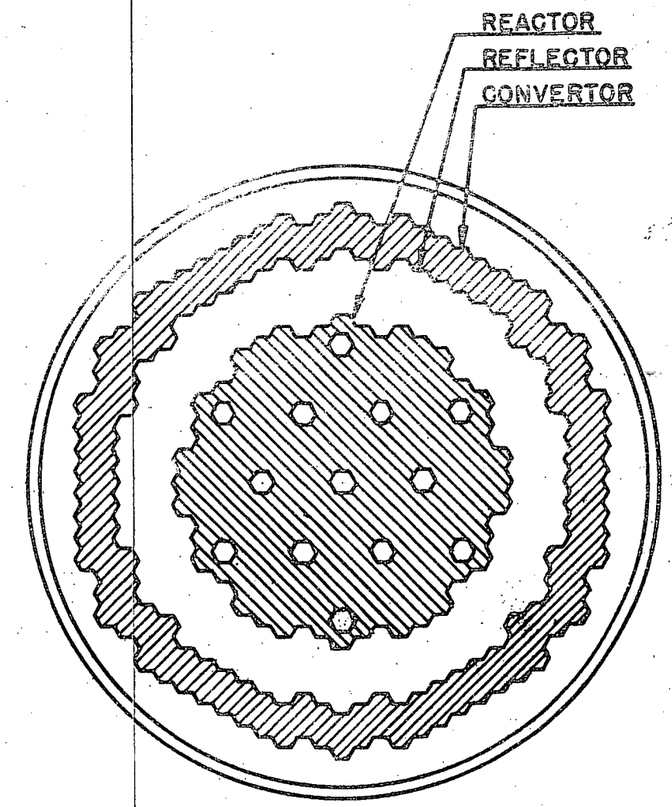
PATTERN A

228 CHANNELS, 62.2 CM. RADIUS
REACTOR WITH 28.8 CM. REFLECTOR
THICKNESS AND NO CONVERSION



PATTERN B

228 CHANNELS, 62.2 CM. RADIUS
REACTOR WITH 14.6 CM. REFLECTOR
THICKNESS AND WITH CONVERSION BLANKET



PATTERN C

174 CHANNELS, 54 CM. RADIUS
REACTOR WITH 22.8 CM. REFLECTOR
THICKNESS AND WITH CONVERSION BLANKET

FIG. 34

THREE POSSIBLE LOADING PATTERNS
HIGH TEMPERATURE GAS COOLED POWER PILE

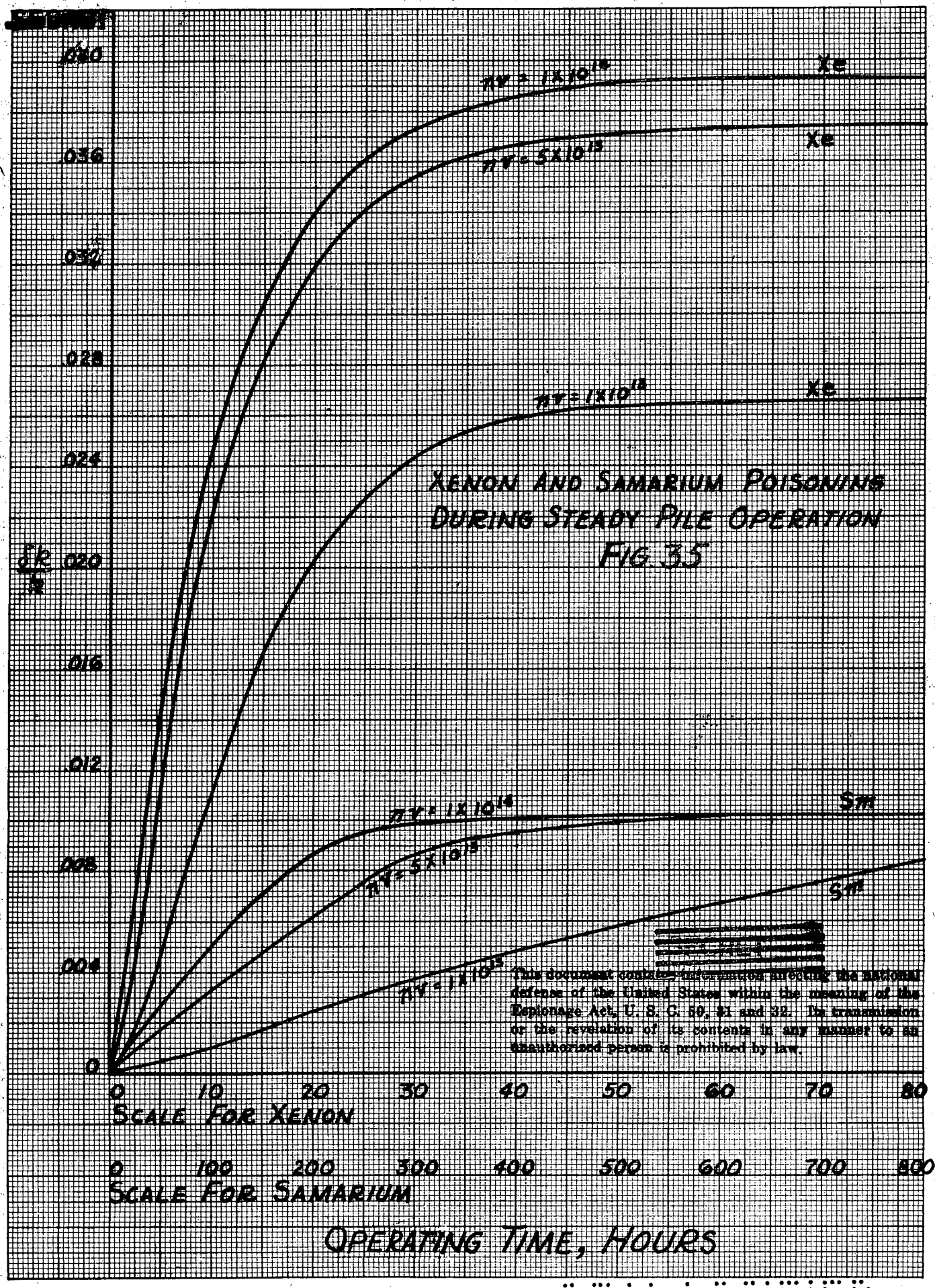
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D W.H.G. 8-12-47	C H.E.R. 8-12-47	A NPP 9-12-47	R.L.P. 9-16-47		
PROJ. C-222-14					
SCALE:					C-2961

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED



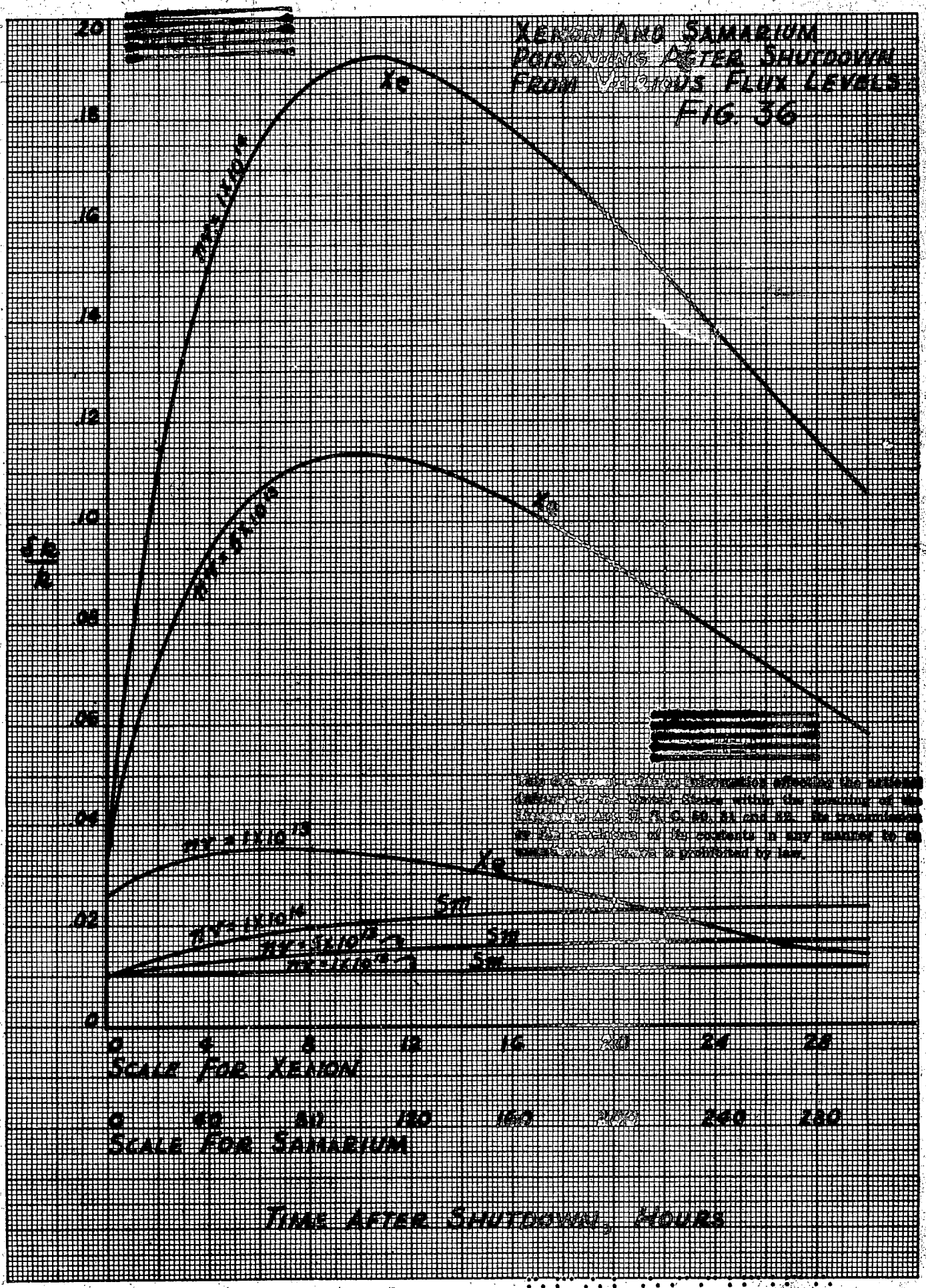
Xenon And Samarium Poisonins During Steady Pile Operation

Fig. 35

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED



Xenon And Samarium Poisonings After Shutdown From Various Flux Levels

Fig. 36

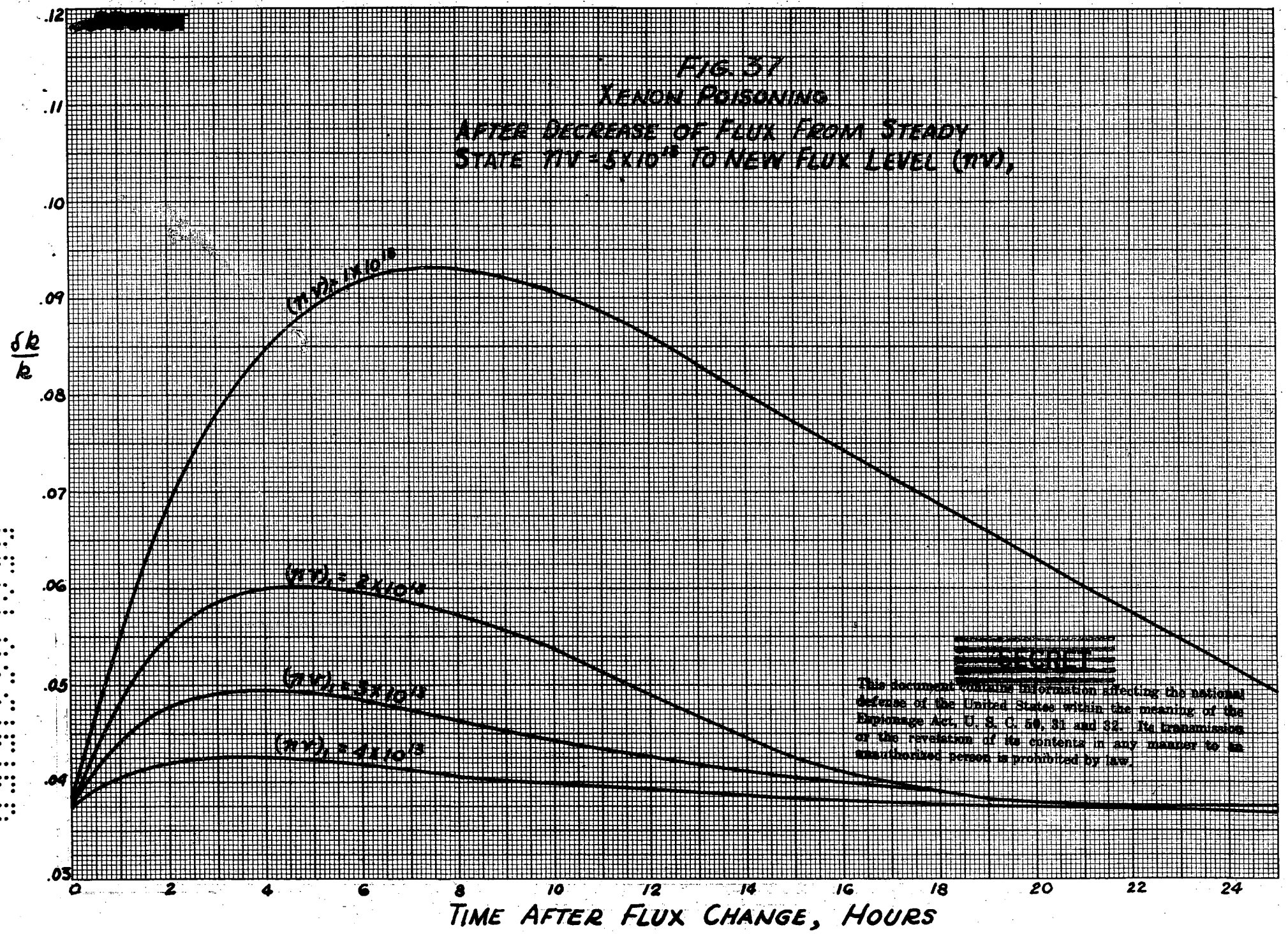
[redacted]

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U.S.C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

UNCLASSIFIED

[redacted]



[redacted]

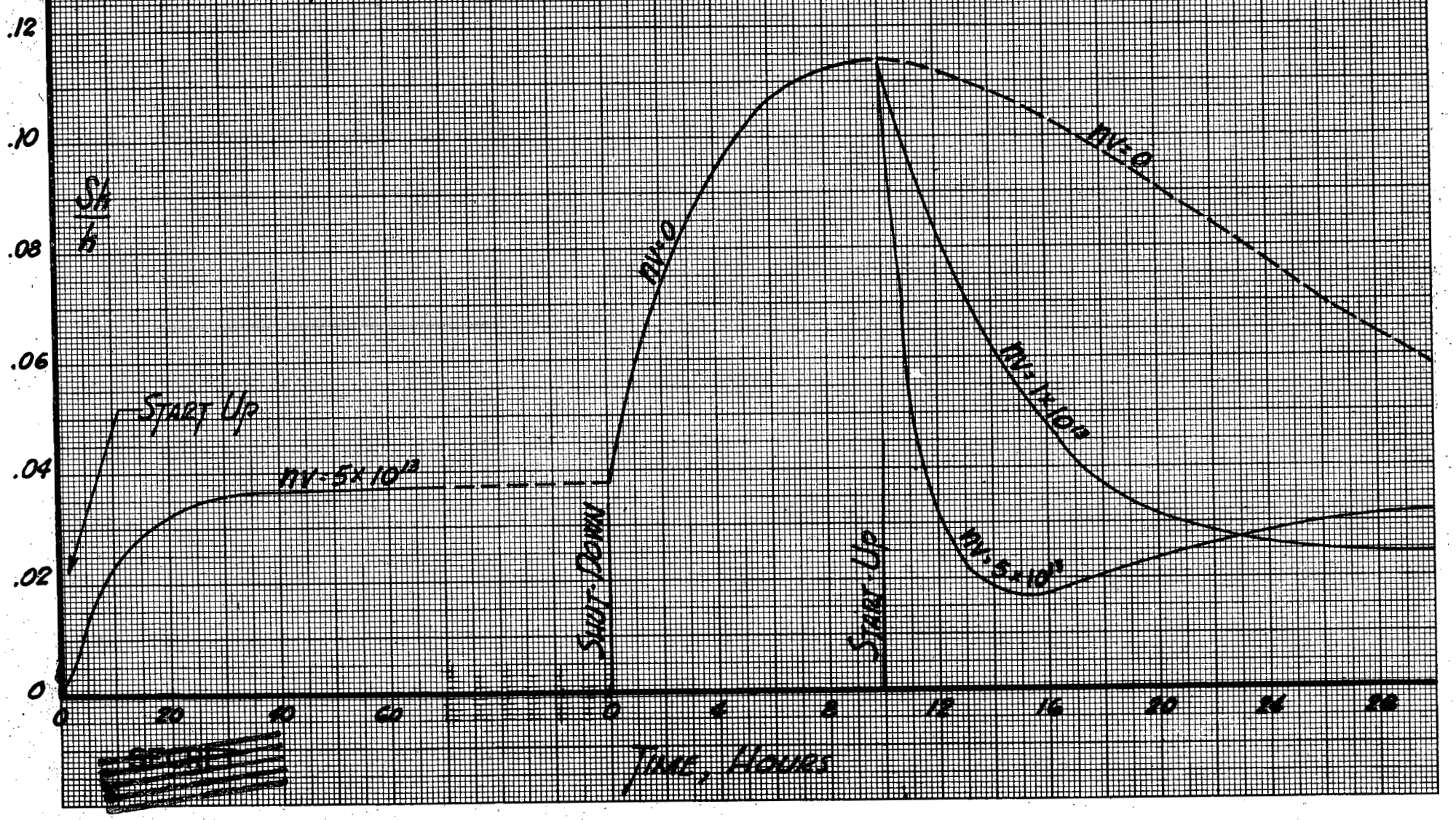
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FIG. 38

CHANGE IN XENON POISONING WITH TIME FOR A SEQUENCE OF PILE OPERATING CONDITIONS



[redacted]

5. Pile Control.

The purpose of pile control is to reach and maintain a desired 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 flux density. It is therefore, this neutron flux density that must be controlled. Factors affecting the pile neutron flux density are:

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

Small involuntary changes in neutron flux density due to changes in temperature, formation of neutron poisons reduction of fuel enrichment due to depletion, and unintentional introduction of poisons.

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

a. Control Rods. The reactivity of the pile will be controlled by means of rods which are highly absorbent to neutrons. These control rods are divided into three classes: 1. Safety, 2. Shim, and 3. Regulating. There are six safety rods, six shim rods, and one regulating rod located as shown in Fig. 21.

Preliminary calculations have been made as to the approximate control effect of these rods.

No. and Type of rods	k
Six shim and one regulating rod all the way in the Pile.	.458
Six safety rods all the way in.	.150
One shim rod all the way in (center)	.082
One safety rod all the way in	.025
(one outer shim rod)	.054

1. Driving Mechanisms.

(a) Power Units. The type of power unit for each control rod depends upon the function of the rod in controlling the pile reactivity. The rods must travel upward, out of the pile, to increase the reactivity and travel downward, into the pile, to reduce reactivity.

DECLASSIFIED

The regulating rod is driven both out and in by a direct current 1 H.P. motor, the speed and direction of which is controlled by the power level regulator.

The shim rods (Refer to Fig. 39) are driven out and in, for pile power regulation, by a 1/4 H.P. direct current motor. To drive the rods into the pile at high speed, for an emergency shutdown, 5 H.P., low starting torque, alternating current, three phase, full speed motors are used. These motors are equipped with electrically operated mechanical brakes, to stop the rods just above the lower limit of their stroke.

The safety rods (Refer to Fig. 40) are lifted by a conventional cable hoist. They are driven into the pile by the force of gravity when they are released from the magnet, which holds them out of the pile during operation. The downward force of the rods is absorbed by a special shock absorber when they are almost completely inserted into the pile.

b. Power Transmission. The active neutron absorbing section of the rod, which is in the pile, is welded to a driving rod which extends up through, the 1400°F. gas chamber, the 500°F. gas chamber, and the biological shield at the top of the main pressure shell where it connects to the main driving mechanism (rack and pinion or plunger). This mechanism and driving rod are enclosed in a thimble containing helium gas at about 500°F. and surrounded by cooling air under pressure. The complete assembly for each type of control rod is shown on Fig. 41.

The mechanism for the regulating rod is similar in all respects to the shim rod mechanism except that the high speed AC motor is omitted entirely and, as a result, the differential gear mechanism is not necessary. The DC motor is geared directly to the pinion gear drive shaft.

The mechanism for a typical shim rod is shown assembled on Fig. 39. The main driving mechanism is a rack (A) and a Pinion (B). This pinion is driven by a shaft (C) which extends horizontally out of the pressure thimble, through a contact type pressure seal, and then through a biological shield to the differential gear box. The shaft is fastened to one of the driven bevel gears (G). The variable speed D.C. motor is connected through the worm gear (J) to the differential carrier gear (H). This gear carries the spiders and spider gears (K). The full speed A.C. motor turns the High Speed bevel gear (F).

The rack speed is limited to 0.3 ft. per minute in an outward direction. The drive for this speed is the 1/4 H.P. D.C. motor. This motor turns a worm gear (J) which drives the differential carrier gear (G). The high speed gear (F) attached to the A.C. motor shaft (E) is held stationary by the motor brake and, as a result, all motion of the differential carrier (G) is transmitted to the shaft (C) which drives the pinion and rack.

Under normal conditions of reactivity control the rack speed inward is again about 0.3 ft. per minute. This is supplied by the D.C. motor exactly as described in outward motion except that the motor runs in the opposite direction.

DECLASSIFIED

SECRET

When a quick reduction in reactivity is required, the A.C. motor is energized and its brake is released at the same time. The motor drives its gear (F) at high speed. The spiders (K) transmit this motion to the driven gear (G) in the opposite direction driving the rack downward. The spider carrier (H) is kept from turning by the worm gear (J). It should be noted that even if the D.C. drive were energized and turning slowly at the time of an emergency shutdown the action of the fast A.C. drive would over-ride the slow speed drive and drive the rods downward into the pile, at high speed.

The safety rods (Refer to Fig. 40) are fastened to a selenoid plunger which is enclosed completely in a tube of non-magnetic stainless steel. The plunger, which fits loosely in the tube, is guided by a graphite bearing ring at the lower end of the plunger. A direct current electro-magnetic selenoid coil slides on the outside of this tube. When the rod is "all in" the plunger rests on the upper rod guide at the top of the biological shield. To lift the rod the coil is lowered around the plunger and energized. The coil is then lifted by the cable hoist, located outside of the upper biological shield, raising the plunger and rod along with it. The plunger engages the stop at the top of the tube and locks in place magnetically. In this position the magnetic holding force becomes very large and the current of the magnet can be reduced by a rheostat to just enough to hold the rod and plunger weight. The self centering construction at the top of the plunger aids in stabilizing the assembly when the rod is "all out".

When an emergency shutdown is required the magnet current is cut off, through a quick release circuit, and the safety rod falls due to the weight of the plunger and rod.

To reduce shock at the end of the fall, the internal diameter of the thimble is reduced for about one ft. above the stop; so that a gas cushion is formed between, the plunger, the stop, and the thimble wall.

c. Rod Stroke. The regulating rod stroke is limited to 4.5 inches. The stroke is limited by mechanical stops and by electrical limit switches located in the position measuring equipment.

The shim rods can travel a total stroke length of 70". The proposed assembly is shown on Fig. 41. This distance plus clearance and guide spacing makes the total required length of thimble, above the biological shield, about 10'-4". The rack has a mechanical stop at each end so that the stroke is definitely limited to 70". Electrical limit switches de-energize the drives near the mechanical stops. The final "all in" position is reached only by driving the rod slowly with the D.C. motor. The high speed drive is de-energized about 1 ft. above the lower mechanical stop. Hence, the stroke at high speed is limited to about 5'-10".

The safety rods have the same stroke (70") as the shim rods. The mechanical stops which confine the selenoid plunger provide the limits for this stroke.

SECRET

DECLASSIFIED

d. Speed of Rod Travel. The regulating rod is used as a fine control device and its speed is continuously variable from zero to about 2 feet per second, in either direction, as dictated by the power level regulator.

The shim rods are driven into and out of the pile at a constant speed of about 0.3 feet per minute when controlling power level.

When rapid insertion is required, to quickly decrease power level, the A.C. motor is energized. A directional motor starter is used for the A.C. motor so that this motor can only drive the rod into the pile. The average speed resulting at the rack from this drive is about 500 ft/min. in a full stroke travel of 70".

The average insertion speed for the safety rods is the speed resulting from the acceleration of gravity. If the rods are released they have a free fall of 5'-0" before they encounter any shock absorbing effect. The time of fall this distance is approximately 0.5 seconds or an average speed of about 400 ft./min.

e. Synchronizing and Interlocking. The method of interlocking and synchronizing the various rods is shown on Fig. 42 which covers the required basic electrical control system in block diagram form. The drawing can best be followed by considering, start up, normal operation, or an emergency shutdown and tracing the action of the relays and controls through that phase of an operation.

The first purpose of the control system is to prevent starting the pile if an unsafe condition exists. Before "start up" all the rods will be as far as possible into the pile. This rod position is the same as we would want after an emergency shutdown. Hence, the interlocks and signals which cause all the rods to run into the pile should also prevent the rods from being withdrawn to start the pile into operation.

On Fig. 42 the safety relay is shown receiving power from the control circuit power supply, through a number of contacts operated as follows. (The letters after each description are the letters used to designate the interlock on Fig. 42.)

1. Manual lock-out switch (M) can be opened by the operator when pile shutdown is desired. When locked open this switch will prevent start up.

2. Contacts; open upon steam pressure failure to both coolant blower, turbo-generators (SHTG #1;#2).

3. A contact which opens if helium pressure is below atmospheric. (HP). Air will leak into the pile if the helium pressure is below atmospheric.

4. A contact; open when the rate of helium pressure decrease is high (HPD). This indicates a bad helium leak.

DECLASSIFIED

5. A limit switch; is closed when either of two main helium outlet valves to the pile are open. (HMOV #1; #2). When neither valve is open helium cannot circulate.

6. A limit switch; closed when either of the main helium inlet valves to the pile is opened (HMIV#1; #2). When neither valve is open helium cannot circulate.

7. A contact; closed by one of four tachometers, one of which will be on each helium blower (HBS #1; #2; #3; #4). Below a set minimum speed these contacts are open. This insures that the blower capacity required for a minimum quantity of helium is available.

8.&9. Limit switches, on the inlet and outlet valves of the blowers; closed when the valves are open (HBOV #1; #2; #3; #4 and HBIV #1; #2; #3; #4). This insures that whenever a blower is running its valves are open and that helium can circulate to and from the pile.

10. A contact; open when the output helium temperature at the pile outlet duct is too high for the pile power level setting (HOT).

11. A contact; open when the helium temperature at the inlet to the heat exchanger is too high (HITE). This interlock is a check on 10, but it is felt that this is sufficiently important to warrant a duplicate indication of trouble.

12. A contact; open when the helium temperature at the heat exchanger outlet is too high for the pile power level setting (HOTE).

13. A contact; open when the helium moisture detector indicates that the moisture content of the helium is high. A steam leak from the boiler to the helium at a ruptured heat exchanger tube would cause this contact to operate (HMC).

14. A contact; open if the hydrogen content of the helium is high. (HHC)

15. A contact; open if the oxygen content of the helium is high. (HOC).

16. Several contacts in temperature sensitive instruments. These contacts open at high pile temperatures. The temperature sensitive elements are located at several points in the pile where hot spots are expected to develop. (PT 1; 2; 3; etc.)

17. A contact; open when boiler steam pressure is excessive. (SP).

18. A contact; open if the boiler feed pumps fail to operate (EW).

19. A contact; open whenever the fuel loading mechanism is energized (FL).

20. A contact; in the power level regulator, which indicates high neutron flux (NV).

21. A contact; in the power level regulator, which indicates a high time derivative of the neutron flux (NVD).

22. A contact; in the temperature regulator; open when essential components of the regulator are not operating properly (TR).

23. A contact; in the power level regulator; open when essential components of the power level regulator are not operating properly (RR).

24. The control circuit is energized from the main power supply. If the supply fails the circuit is de-energized and the safety rods drop into the pile. This protection is inherent in the circuit design.

With all the above interlock switch contacts closed no unsafe condition exists and the safety circuit is ready for the pile to operate.

The second purpose of the control circuit is to prevent performance of an improper operation sequence by the pile operator.

A safety control relay is energized through six limit switches. On Fig. 42 one switch is shown as 1TL, the other five rods and switches are not shown because all circuits are similar to #1 shim rod circuit. These switches are closed when the shim rods are "all in". Another similar limit switch (RL on Fig. 42), closed when the regulating rod is "all in", is also in series with the Safety Control Relay.

To complete the circuit a manual control switch and a contact from the Safety Relay must be closed. When the Safety Control Relay closes one of its contacts will by-pass the shim rod and regulating rod limit switches so that these rods can be withdrawn without opening this Safety Control Relay circuit.

This control circuit condition can be described as "ready for pile operation."

If the Safety Relay and the Safety Control Relay are energized as described, a contact from the Safety Control Relay will energize the lifting and holding magnet circuits for all the safety rods. On Fig. 42 one safety rod circuit is shown, the other five are similar. The magnet can be raised by the hoists; lifting the safety rods to their "all out" positions, where limit switches (1SRL on Fig. 42) will be closed.

The hoists are energized through a six position selector switch which will allow only any one of the hoists to operate at a time. This means that only one safety rod can be pulled out at any one time. Hoist travel is limited by hoist limit switches on the hoist shaft. (1SHR and 1SHL on Fig. 42.) When de-energized the hoist motor is prevented from turning by an electrically operated brake.

When the limit switch (1SRL on Fig. 42) on each of the six safety rods is closed, indicating that all six rods are "all out", the withdraw signal

circuit in the Power Level Regulator is completed, except for a false limit switch on the regulating rod travel limit (RR on Fig. 42). This switch will be closed until the Regulating rod reaches the limit of its travel outward. Its primary function is to stop the rod at that point. At start up, with the rod "all in", this switch (RR) is closed.

The movement of the regulating rod is determined by the power level regulator. The regulating rod's position in its stroke determines the positioning of the shim rods.

All six of the shim rods must be withdrawn or inserted the same distance in the pile and they must move together. To accomplish this a master voltage signal is taken from a potentiometer, which can vary a voltage signal from zero to maximum. The error between this voltage and a similar voltage signal from the shim rod remote position indicators is used to position the shim rods. This error signal is amplified and applied to the field of a D. C. generator the output, of which, in turn drives the D.C. motor on the shim rod drive gears. As a result, the rods are either inserted or withdrawn together and the same distance.

The potentiometer in the master voltage signal generator is driven by a constant speed motor which increases or decreases the voltage signal at a constant rate as long as the motor is energized.

At the limits of the shim rod travel the insert or withdraw signals circuits are de-energized by the insert limit switch (1TL on Fig. 42) or the withdraw limit switch (1TR on Fig. 42).

The power level regulator positions the regulating rod. When this rod is three quarters withdrawn, it energizes a limit switch. (RW on Fig. 42). This energizes the master signal motor and it starts to increase the master voltage signal at a constant rate. The shim rods respond to this voltage change and run outward, keeping their respective error signals zero. This causes the power level of the pile to rise until it exceeds the desired power level by a very small amount. The power level regulator responds to this condition and causes the regulating rod to run inward. When the rod is almost at the center of it's stroke a limit switch (RC on Fig. 42) is opened. The switch de-energizes the master voltage signal motor and the shim rods stop running outward.

When the power level regulator causes the regulating rod to run inward, to decrease the power level of the pile, far enough to reach another limit switch (RI on Fig. 42), the master signal voltage is decreased and the shim rods respond by running inward. The power level of the pile is thereupon reduced until the power level regulator withdraws the regulating rod far enough to open the limit switch RC and stop the shim rods.

A maximum and minimum limit switch (SMW and SMI on Fig. 42) limit the travel of the master signal potentiometer.

DECLASSIFIED

SECRET

The fuel loading mechanism should not be operated when the safety rods are "all out" of the pile. A limit switch on each rod (1SLL on Fig. 42) will close the circuit to the fuel loading mechanisms control circuit when all of the safety rods are "all in". Conversely when the safety are not "all in" the fuel loading mechanism cannot be operated.

If any of the safety contacts, in the safety relay circuit, are open, the relay opens. This de-energizes the holding magnet circuits and lets the safety rods fall into the pile. At the same time (if power failure has not been the cause of safety rod insertion) the high speed motors on the shim rod drive are energized and drive the shim rods into the pile at a high speed. A limit switch on each shim rod (1TFL on Fig. 42) will open when that rod is about one foot from the inward end of its stroke. This de-energizes the motor and applies a brake to stop the rod.

Simultaneously, with these actions, a signal simulating a high pile flux is applied to the power level regulator and drives the shim rod to the "all in" position through the normal regulating circuits. When the high speed drive on the shim rods is cut off they will still receive a signal from the regulating rod calling for them to run in. In response to this signal they run inward until the lower limit (1TL on Fig. 42) is reached where they stop. This last "drive in" signal is not necessary from a safety standpoint because the fast drive runs the rods beyond the depth of the pile reactor.

A manual switch, in this high flux signal circuit, allows the operator to lower the power level directly.

If a power failure caused the emergency shutdown, the safety rods alone should be inserted into the pile because the power to insert the shim rods would not be available. After power is restored the shim rods would run in.

This cycle of control circuit action causes a complete re-setting of all pile devices so that when the cause of a shutdown is removed the pile can be re-started.

f. Position Indicators. For the regulating rod, the position indicating mechanism consists of a worm driven traveling nut, along which the limit switches are installed and adjusted. Various standard makes of limit switches are suitable for this application. The position of the traveling nut is a measure of the position of the rod in the pile. This position indicator is geared to the drive shaft and is located in the drive compartment above the pile. By means of a pair of selsen motors, one in the drive compartment and one at the remote control location, the rod position is shown, for operating purposes, at the control board.

A similar arrangement is used for the shim rods. Here the follower selsen is part of the shim rod control system and is used for synchronizing. For the safety rods, an "all in" and "all out" position indication is required, but rod position between these limits need not be known for normal

SECRET

DECLASSIFIED

operating purposes. Specially designed limit switches are installed at the top and bottom of the safety rod thimble, where the plunger can operate them, and indicate the presence of the rod at either extreme. The design of those switches has not been worked out but they must be totally enclosed against the helium atmosphere and cooled by a draft of cold air or a flow of oil.

g. Seals. A typical seal is shown as part of Fig. 39 and is generally referred to as a, refrigerator type, contact seal. This seal is oil cooled, the pressure of the oil being higher than the pressure of the helium inside the thimble. The experimental work on this seal is described under the "blowers and seals" section of this report. Seals are required for the six shim rod drive shafts and the one regulating rod drive shaft.

2. Description of Control Rods.

a. Number and location. The location pattern is shown on Drawing Fig. 40. One regulating rod is installed in the center channel of the pile. Six shim rods are installed in a ring around the center regulating rod about $10\frac{1}{2}$" from the center of the pile.

Six safety rods are installed in a ring outside of the shim rods, 18" from the center of the pile.

b. Rod Material. The rod material is 1% boron steel. The physical properties of this material are similar to standard types of steel except that it is somewhat more brittle. Tests of this alloy must be run before design work can be completed. The principle tests needed are stress vs. strain curves and creep vs. stress curves for various temperatures up to about 1600°F.

c. Rod Size and Shape. The part of the shim and safety rods which enter the pile and have an effect on reactivity is an annulus in cross section. The outer diameter is 4 cm. and the inside diameter 2.54 cm. The regulating rod has a 1 centimeter outside diameter and a solid cross section. Refer to Fig. 41 for rod assemblies. The reactivity control portion of the rods is welded to the drive rod. A port is provided near this joint to allow 500°F. helium gas to enter the rods. This helium inlet port is shown on Fig. 41.

d. Cooling. The temperature of the rods, while the pile is operating, is between 500°F. and about 800°F. The temperature is due partly to radiated and conducted heat from the pile channel surfaces and partly to neutron absorption. The temperature of the helium gas, available for cooling, is 500°F. Exact calculation of the resulting rod temperature has not been made but they must be kept below 800°F. to retain sufficient mechanical strength. The 500°F. gas from the chamber above the pile will be allowed to enter the rods through the helium inlet ports in the rods. Some gas flows between the rods and the inside surface of the BeO bricks. The quantity of gas flow depends upon the construction of the pile channels in which the rods operate.

DECLASSIFIED

SECRET

3. Shielding of Control Rods.

The control mechanisms are located above the 5' biological shield which is directly above the top of the pressure shell. Refer to Fig. 40. A circular compartment with a wall of biological shield 2' thick contains the nest of thimbles. The drive shafts for the regulating rod and shim rods run through holes in this 2' of shielding. A space around this inner shield is left for the installation of the motors and the driving gears. Around the outside of this motor compartment is a biological shield about 5' in thickness. Above the motor compartment and thimble compartment there is another biological shield 5' thick. The hoists for the safety rods are located above this shield and lift the magnets by means of cables which run through holes in this shield. This is shown on Fig. 40.

4. Replacement of Rods and Mechanisms.

a. Regulating and Shim Rods. The sectionalizing of the shielding is shown on Fig. 40. The shielding is built so that, when the pile is shutdown, workers can enter the drive and motor compartment through manholes.

The drive and motor equipment can be removed by separating the shaft coupling in the motor compartment. This is a bolted coupling.

The coupling inside the inner ring of shielding is keyed and can be opened by pulling the shaft outward.

Remotely operated torches can be used to cut the thimbles loose from the biological shield if the thimbles are to be removed.

The 4' diameter section of shielding just above the thimbles is removable and the thimbles and rods together can be pulled up through this opening.

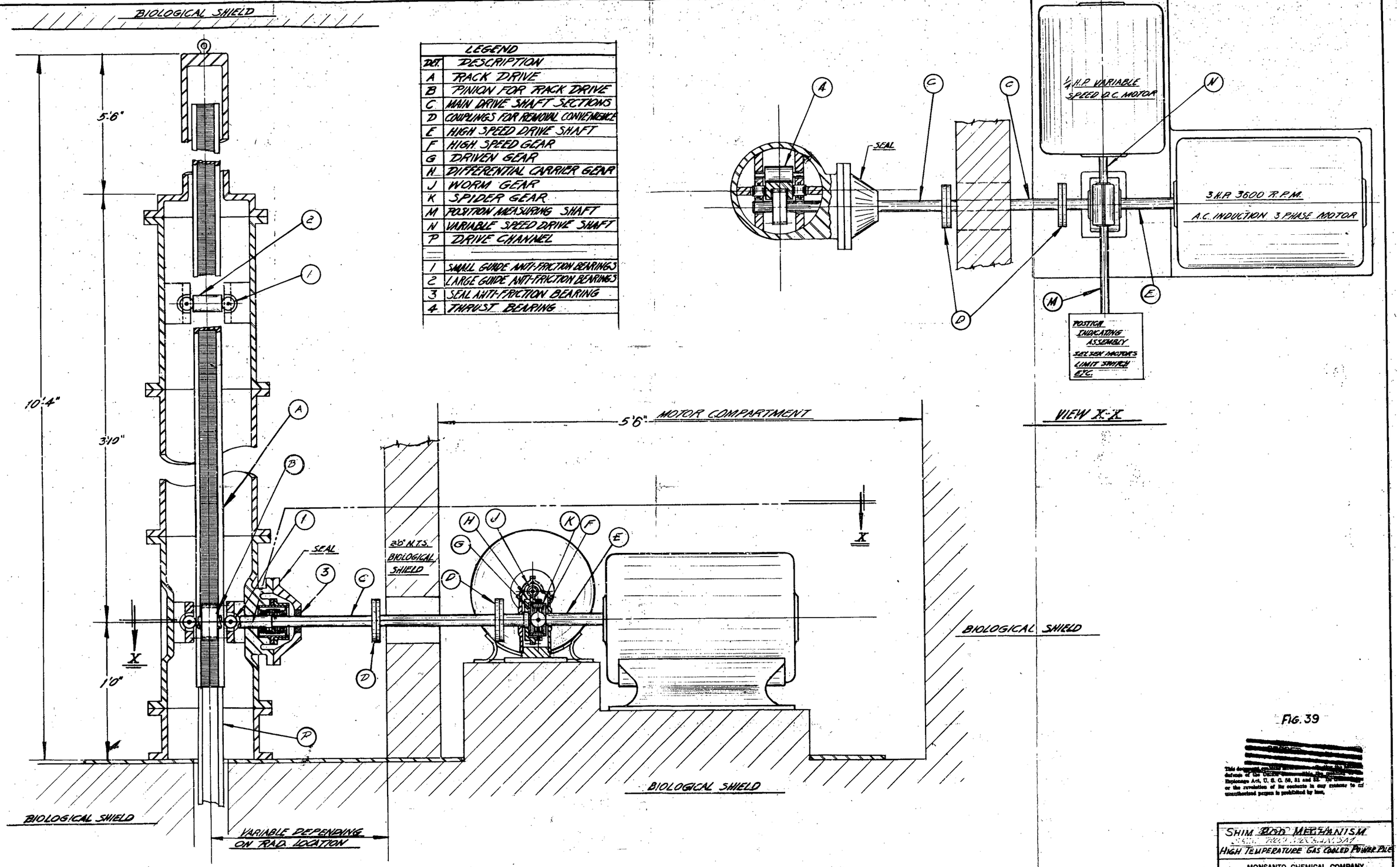
b. Safety Rods. The hoists are always available for maintenance because they are above the upper biological shield.

The hoists can be removed by pulling the magnets upward through holes provided above each thimble.

The thimbles can be cut loose and the thimbles and rods pulled up through the 4' opening, in the same way as the regulating and shim rod thimbles are removed.

SECRET

DECLASSIFIED



LEGEND	
DET.	DESCRIPTION
A	RACK DRIVE
B	PINION FOR RACK DRIVE
C	MAIN DRIVE SHAFT SECTIONS
D	COUPLINGS FOR REMOVAL CONVENIENCE
E	HIGH SPEED DRIVE SHAFT
F	HIGH SPEED GEAR
G	DRIVEN GEAR
H	DIFFERENTIAL CARRIER GEAR
J	WORM GEAR
K	SPIDER GEAR
M	POSITION MEASURING SHAFT
N	VARIABLE SPEED DRIVE SHAFT
P	DRIVE CHANNEL
1	SMALL GUIDE ANTI-FRICTION BEARINGS
2	LARGE GUIDE ANTI-FRICTION BEARINGS
3	SEAL ANTI-FRICTION BEARING
4	THRUST BEARING

FIG. 39

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

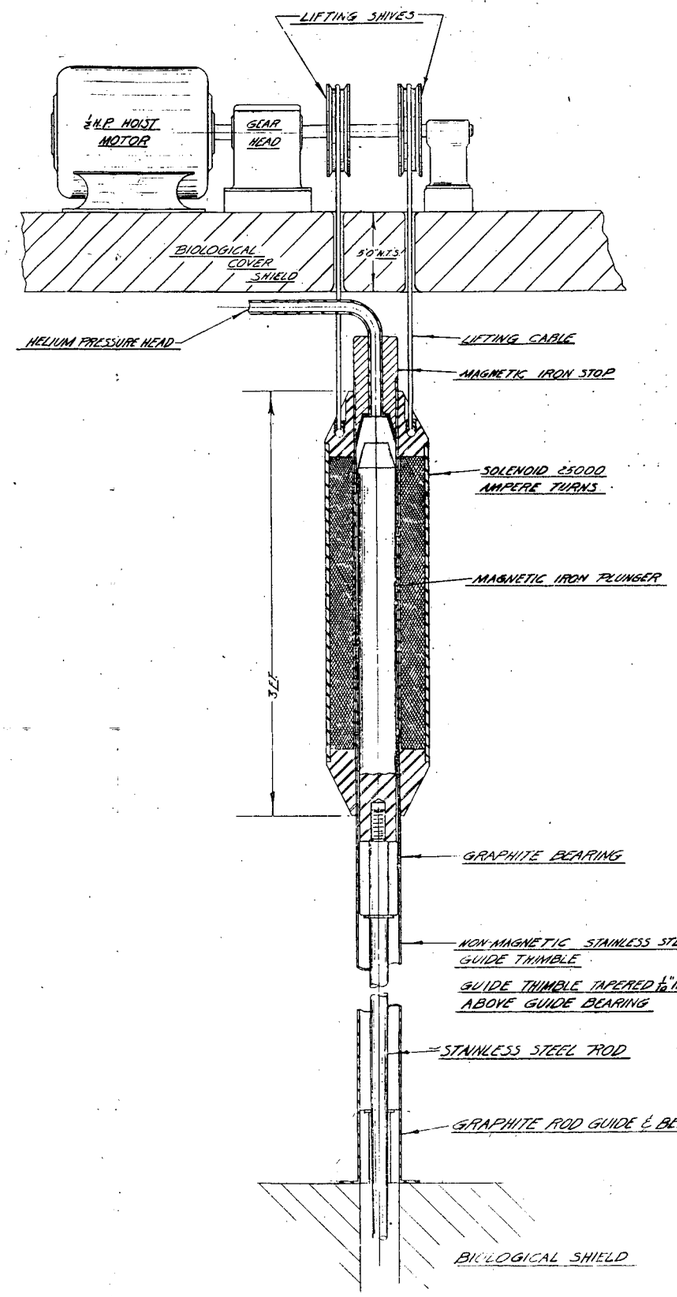
SHIM ROD MECHANISM
[redacted]
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

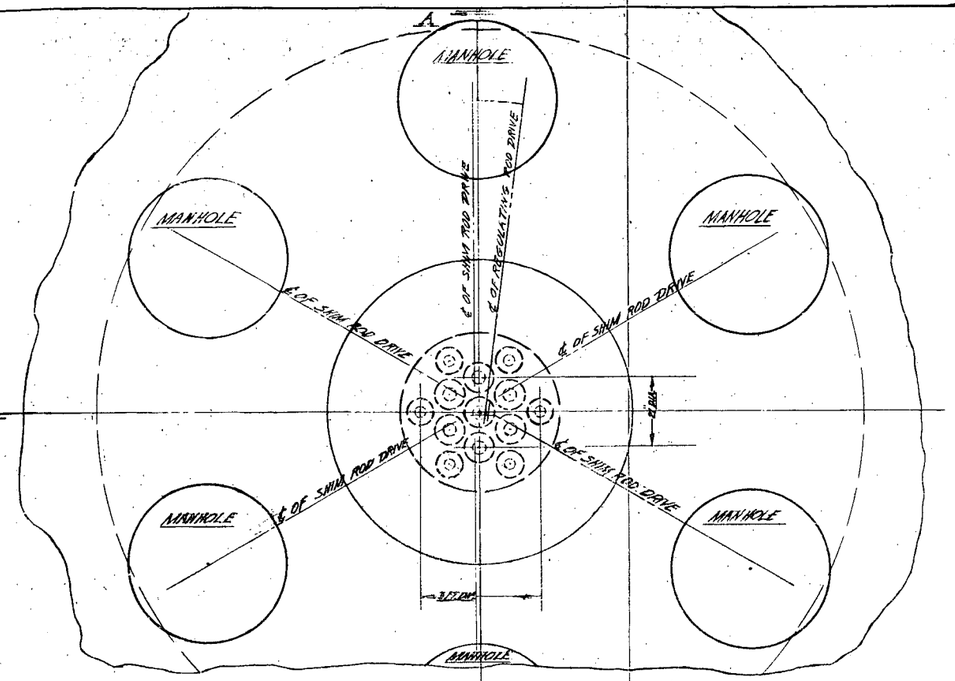
D. R.H. 5-8-47	A.B.D. 7-14-47	A. J.W.K. 8-11-47	R.D.P. 8-11-47		
T.P.M.J. 8-22-61					
SCALE: NONE					D-2282

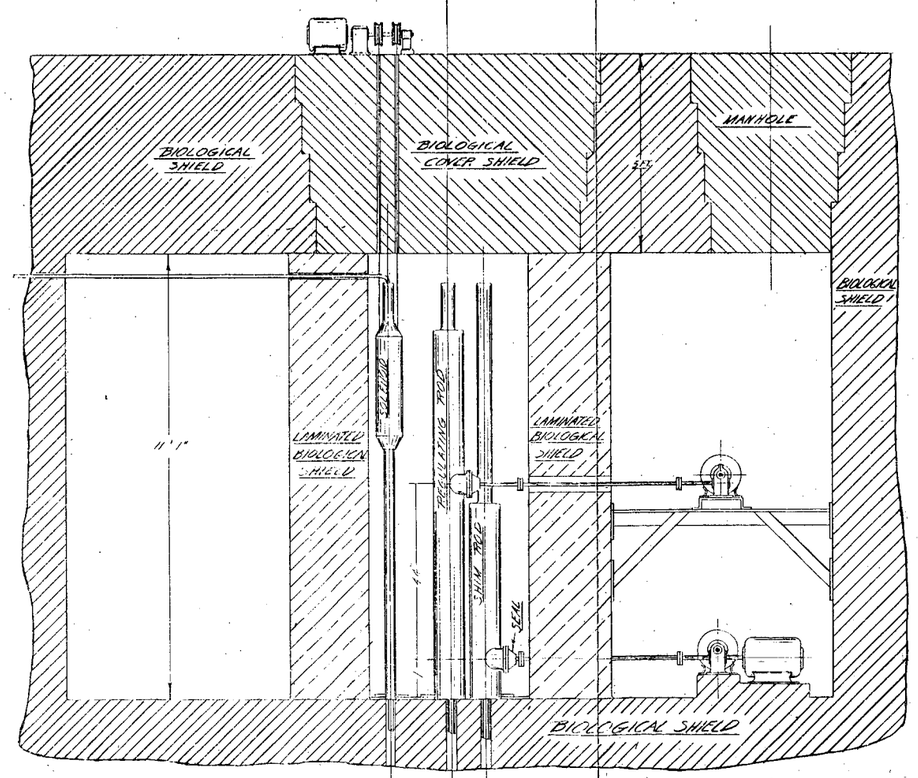
DECLASSIFIED DECLASSIFIED DECLASSIFIED

[redacted]



TYPICAL SAFETY ROD ASSEMBLY





SECTION A-A

[redacted]

This document [redacted] affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CONTROL ROD ASSEMBLY AND SAFETY ROD DETAILS
HIGH TEMPERATURE GAS COOLED POWER PILE
MONSANTO CHEMICAL CO.
CLINTON LABORATORIES
ENGINEERING DEPARTMENT

8-17-50	D.L.S.	J.A.M.	R.L.P.	
8-17-50				
	CHECKED			
	APPROVED			
	CHIEF ENGINEER			8-22-50

DECLASSIFIED DECLASSIFIED DECLASSIFIED

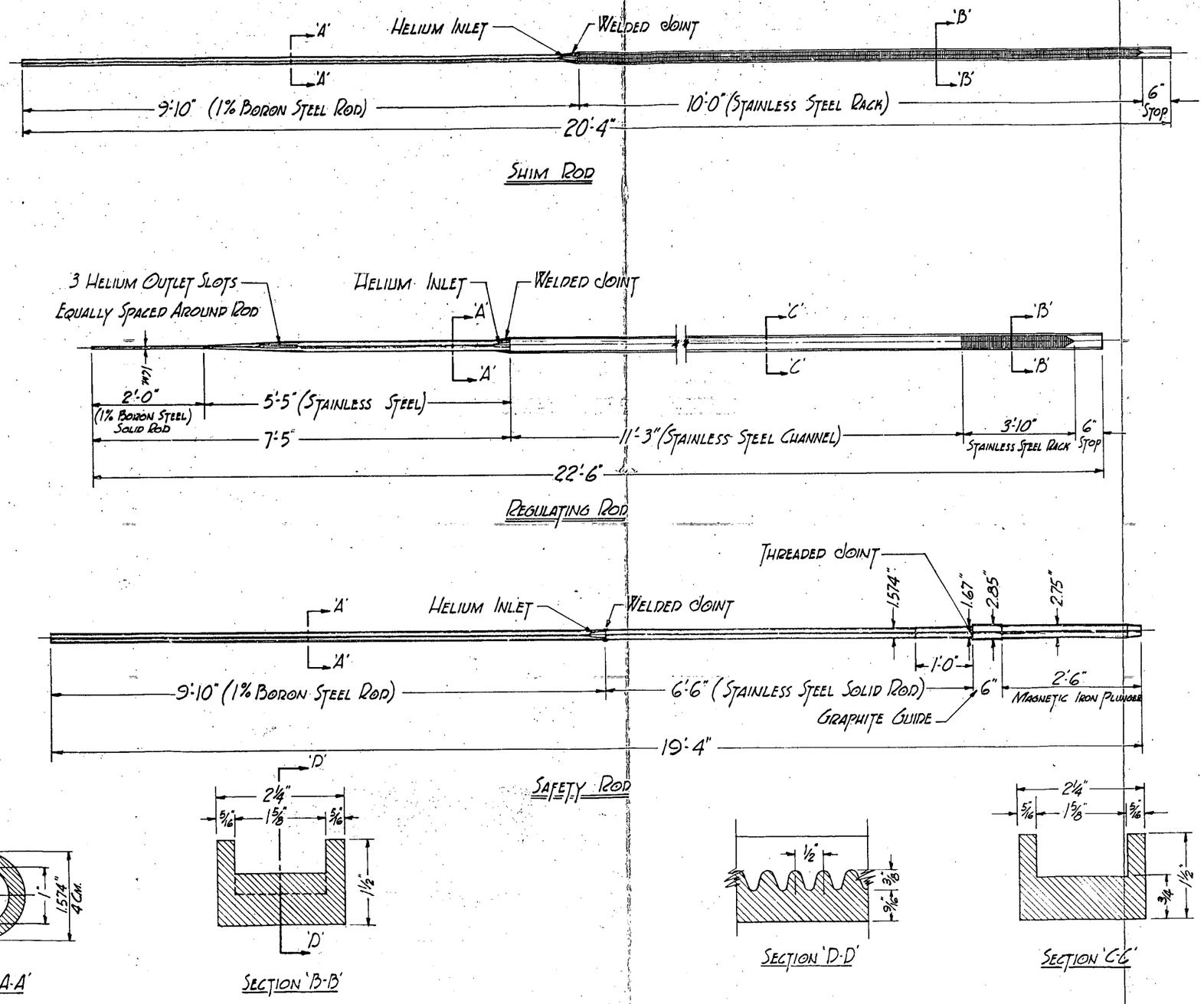


FIG. 41

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CONTROL RODS

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.N.L. 8-18-47	C. A.L.S. 8-14-47	A. J.M.H. 8-14-47	CLA 9-11-47		
Proj. C-2221A					D-2291
SCALE: Full & 1/2					

DECLASSIFIED

CONTROL CIRCUIT
HIGH TEMPERATURE GAS COOLED PILE

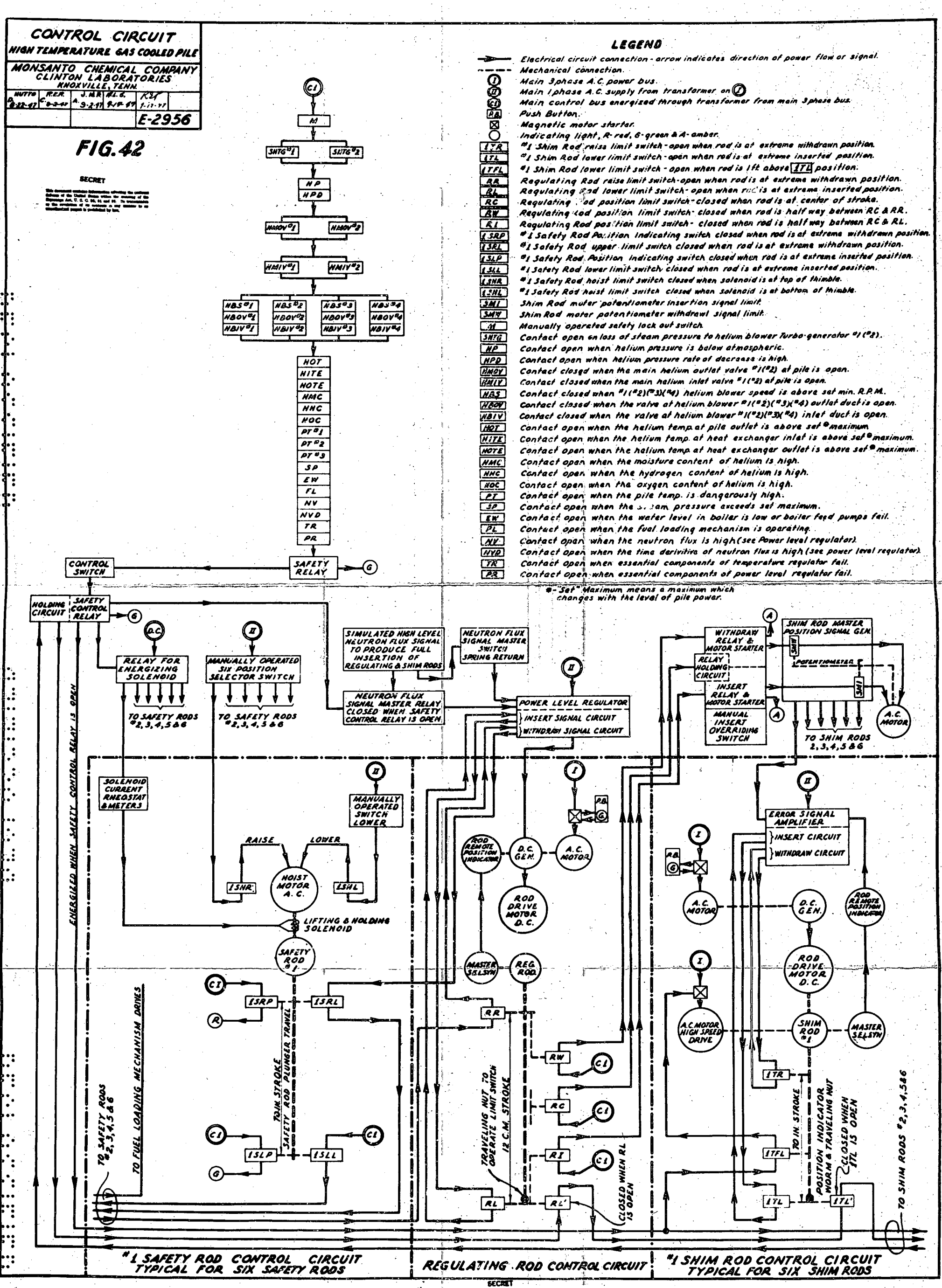
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

NUTTO	R.E.R.	J.M.R.	R.L.G.	RST
B 8-22-47	C 8-3-47	A 9-2-47	9-15-47	1-12-47

E-2956

FIG. 42

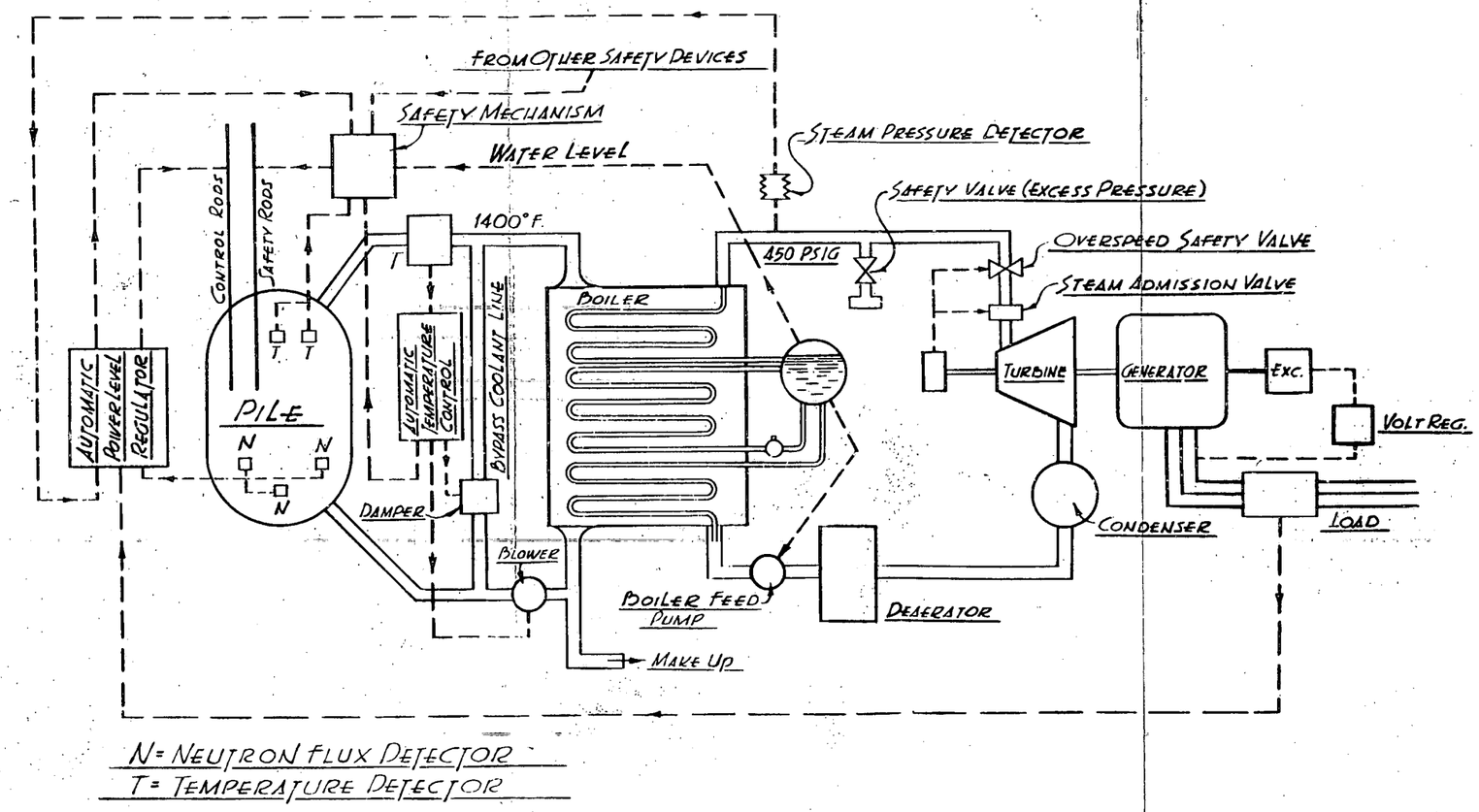
SECRET



SECRET

E-2956

SECRET



N = NEUTRON FLUX DETECTOR
T = TEMPERATURE DETECTOR

FIG. 43

BASIC CONTROL DIAGRAM

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

As Shown Above	R.E.P.	UBC	H.L.S.			
D. 9-3-47	9-9-47	9-3-47	9-9-47			
Prof. Engr.						
SCALE: None						E-2958

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

b. Automatic Power Level Regulator. Because of the high excess reactivity of the pile, and the complex interdependence of several control parameters, the power output of the pile is under the constant control of an automatic power level regulator throughout the normal processes associated with start-up, maintenance of power level, desired changes in power level, and shut-down. Manual control is not precluded in any phase of pile operation if safety requirements are not transgressed, although the design of the automatic regulator renders manual attention unnecessary excepting as a maintenance measure to insure that all equipment functions properly. Pile operation remains under the full control of the automatic power level regulator unless any one of various conditions arises which indicates abnormal danger to operating personnel, pile materials, or essential auxiliary apparatus. In such an event, control of the pile is transferred immediately and automatically to the safety circuit for its prompt action in causing pile shut-down, which the automatic regulator continues to assist.

(1) Objectives. The automatic power level regulator serves to control the complete system which is shown in functional form in Fig. 43. As major components the system includes the pile itself, the boiler or heat exchanger, and the turbine-driven electrical generator. The regulator is designed for the following detailed objectives:

(a) Start-up.

1. Increase of pile power output from zero to a selected value in the operating range.

2. Limiting of the rate of increase of pile reactivity to a safe value.

3. Stabilization at the desired power level within a minimum time consistent with safety requirements.

4. Absence of excessive overshoot or hunting in the regulator system.

(b) Maintenance of power level.

1. Essentially complete compensation for long-period variations in the nuclear constants of the pile, i.e.:

Change of pile reactivity with temperature.
Depletion of fissionable material with operating time.
Accumulation of fission-produced poisons.

2. Maintenance of full control sensitivity at any steady state power level.

3. Regulation of pile flux independent of short-period load fluctuations.

DECLASSIFIED

(c) Change in Power Level.

1. Increase or decrease in pile power output from one operating level to any other in the operating range, i.e.:

In response to a manual change of regulator setting.
In response to a maintained change in output load.

2. Change to stable operation at the desired power level within a minimum time consistent with safety requirements.

3. Absence of excessive overshoot or hunting in the regulator system.

(d) Shut-down .

1. Emergency: Automatic delivery to safety circuit under abnormal or dangerous conditions, with continued attempts to control on the part of the power level regulator, i.e.:

If logarithmic rate of increase of pile neutron flux exceeds a selected value.

In case of failure of any critical control component for which automatic change-over to an alternate unit is not provided.

2. Normal: Gradual decrease in pile power output from any operating level to zero under constant control of the regulator, i.e.:

Under manual control of power setting

Under automatic scheduling of power setting, following a time or a demand-operated control signal.

(2) Intelligence. In order to enable the power level regulator to perform the various control functions which have just been listed, the following quantities are measured and made continuously available as control parameters:

(a). Pile neutron flux, as an indication of pile power.
(b). Time derivative of pile neutron flux.
(c). Steam pressure in the boiler, to be held constant.
(d). Time derivative of boiler steam pressure.
(e). Averaged time derivative of electrical power demand of the load.

(3) Physical Description of Power Regulator.

(a). Classificati : of Regulator is Components. The complete power level regulator comprised of components which fall into four

DECLASSIFIED

SECRET

major classifications. Together with their functions, these classifications are as follows:

1. The control parameter instrumentation, which derives up-to-date information on the operation of the pile, the heat exchanger, and the turbine-powered electric generator.

2. Instruments which establish reference levels, derived either from a manual setting or from output demand upon the power pile system, which expresses the desired values of the control parameters.

3. A servomechanism which responds to the difference between desired and measured values of the control parameters, and delivers an output signal which reduces the difference toward zero by a direct adjustment of pile power output.

4. Instruments which serve to limit the magnitude or rate of change of control signals, or the degree or rate of response of control components.

Each of the above classifications includes instruments which warrant description in some detail.

(b). Control parameter instrumentation. Instruments in this classification make continuous measurements of pile neutron flux and its time rate of change, boiler steam pressure and its time rate of change, and an average rate of change of the electrical power demand of the load. For control purposes, these parameters are sufficient to specify the instantaneous behavior of the power pile system, although, of course, other parameters are required for limiting functions.

1. Neutron detector and amplifier. Over a range of approximately 10^6, instantaneous pile power level is measured by a calibrated neutron detector which responds in direct proportion to the thermal neutron flux level in the pile. Together with its associated amplifier, the detector is located outside the pile reactor where the neutron flux level is sufficiently low to permit measurement at the highest pile power levels which are used. To take full advantage of the entire range of sensitivity of the detector and of amplifier linearity, the amplifier is provided with a servo-operated gain control which maintains constant amplifier output and thereby avoid overload. The gain control servo also operates the slider of a potentiometer which is supplied with a constant voltage source, and therefore furnishes a control signal which is proportional to neutron flux, nv, or to instantaneous pile power. With the use of magnetic clutches, the speed of response of such a servomechanism can be made very much more rapid than anticipated changes in the power level of the pile.

2. Neutron flux differentiator. Either of two methods may be used to obtain a control voltage proportional to $\frac{d(nv)}{dt}$, the time derivative of pile neutron flux nv.

SECRET

DECLASSIFIED

The first involves use of the differentiating amplifier and servo circuit. According to this method, which is superior from the standpoint of speed of response, a differentiating amplifier (Fig. 44) operates upon the output control signal proportional to nv which is furnished by the neutron detector described in the preceding section. The differentiating amplifier supplies an output voltage proportional to d(nv)/dt, which is added directly as an anticipatory correction to the measured value of the neutron flux.

In the second method a electro-mechanical differentiator and servo circuit may be employed. A voltage proportional to d(nv)/dt may also be obtained electro-mechanically with a circuit such as that shown in Fig. 45. A voltage proportional to nv, the neutron flux, supplied by the output servo of the neutron detector amplifier, is applied in series opposition to a second voltage between one side and the variable arm of a parallel potentiometer. The difference voltage is applied as the input signal of an amplifier whose output furnishes field excitation for an electric generator, which is driven at constant speed by an auxiliary power source. The output of the generator powers an electric motor which is linked mechanically with the variable arm of the potentiometer in the amplifier input circuit to complete the feedback loop of a servomechanism which adjusts the potentiometer arm to reduce amplifier input toward zero. So far as time lags in the system permit, the motor therefore compels the slider of the input potentiometer to follow both the position and the velocity of the potentiometer slider which is set by the neutron flux servo. As a result, a generator tachometer driven by the motor shaft then delivers a voltage proportional to d(nv)/dt.

The electro-mechanical differentiator can be expected to perform satisfactorily only if the phase change around the servo loop from input to output is small. Expressed in other terms, the time lag in the servomechanism must be small in comparison to the period with which the pile neutron flux changes.

3. Steam gauge. Steam pressure in the boiler of the heat exchanger is translated directly into a proportional electrical control signal by actuating a spring-loaded piston, a stretched diaphragm, or a Bourdon tube which drives the variable arm of a potentiometer. A constant voltage is applied across the complete potentiometer winding, while the control voltage which is proportional to steam pressure is taken between the variable arm and the appropriate end of the winding. Inasmuch as boiler steam pressure is intended to remain constant at 450 Psi G during normal operation, the electro-mechanical steam gage is expected to operate with an output proportional to the excess of steam pressure over atmospheric pressure between 0 and 500 Psi.

4. Steam pressure differentiator. The time rate of change of boiler steam pressure is obtained as the output of a differentiating amplifier which operates upon an input voltage proportional to steam pressure. Amplifier output, proportional to dp/dt is used as an anticipatory correction to the measured pressure.

5. Power change indicator. A final control signal is

DECLASSIFIED

derived from the rate of change of kilowatt demand of the load, averaged over a period of 5 seconds. The instrument which derives the control signal involves a simple kilowatt movement which delivers a voltage proportional to instantaneous power demand. The time derivative of this voltage, obtained as the output of a differentiating amplifier, is applied to a series RC (resistance-capacitance) circuit with a time constant of 5 seconds. The control voltage then appears across the condenser of the RC circuit.

(c). Reference level instrumentation. The instruments of this classification establish voltages or potentiometer settings which represent the desired values of certain control parameters.

1. Reference voltage set for pile neutron flux. During manual operation, the desired level for pile neutron flux is set up between one side and the variable arm of a potentiometer which is supplied with constant voltage. The error signal voltage for neutron flux is then the difference between the voltage output of this potentiometer and the output of the neutron detector potentiometer, supplemented with rate signals as necessary for safety and stability.

In normal automatic operation, the desired level of pile neutron flux is determined jointly by desired and effective indicated levels of boiler steam pressure and by the rate of change of power output demand averaged over 5 seconds. It is clear that boiler steam pressure along cannot establish a voltage which will serve as a reference for neutron flux, since for any steady state the pressure is constant at the same value, while neutron flux varies with the load. In fact, any neutron flux level is satisfactory if the boiler steam pressure is maintained at a constant value. The only indispensable error signal for neutron flux under automatic operation must therefore come from the difference between the desired steam pressure and the effective indicated pressure--i.e., the measured pressure plus the anticipatory correction proportional to its time derivative. Such a pressure error signal cannot be applied directly to the input of the neutron flux servo amplifier because of the unavoidable time lags associated with the pile and boiler system. In fact, under otherwise constant conditions, a change in steam pressure results from the time integral of a change in pile neutron flux. Direct application of the pressure error signal would tend to produce a large and even dangerous change in neutron flux before the error signal could be appreciably decreased. Strong overcorrection and probably complete instability would follow.

Stable automatic control of the power pile system is achieved by a periodic reset adjustment of the reference level for neutron flux in proportion to the pressure error. In the course of eliminating the resultant neutron flux error signals between reset actions, compensating pressure changes are produced which progressively reduce the magnitude of reset corrections toward zero under conditions of constant load.

If expected changes in electrical power output demand were slow compared to the time constant of the pile and boiler system, a pressure error

DECLASSIFIED

signal would probably be adequate even from the practical standpoint. But because the time constant of the pile and boiler system has a value of some 20 seconds, a change in output demand may result in a very appreciable pressure change before steam is being generated in the boiler at a rate which begins to decrease the error signal. On the other hand, rapid response of the pile to changes in load is not necessary, inasmuch as the time constant of the pile and boiler system is great enough to maintain steam pressure essentially independent of variations in load so long as the time average power demand is not changed at a rapid rate. It is therefore desirable to add to the steam pressure error signal a voltage which is proportional to the rate of change of power output demand, averaged over several seconds to prevent undue influence of large but short-lived changes in load. Acting to oppose the time derivative of pressure (since an increase of load results in a pressure decrease), such an anticipatory signal causes a prompt change in pile power output which effectively lessens the undesired excursion of boiler pressure.

This anticipatory correction to the error signal voltage for steam pressure is obtained as the output of the power change indicator previously described. The complete steam pressure error signal, to which the reset adjustment of reference neutron flux is proportional, is then the difference between desired and measured steam pressures plus two correction terms which are proportional respectively to the time derivative of steam pressure, and the time derivative of the electrical load demand averaged over 5 seconds. The instrumentation for accomplishing periodic proportional reset of reference neutron flux is included in the block schematic diagram of Fig. 46 while its detailed operation will be described in Section d.

2. Reference level for steam pressure. Inasmuch as operating steam pressure is to remain constant at 450 Psi G, the reference voltage for steam pressure is equal in magnitude to the steam gage potentiometer output at a steam pressure of 450 Psi G.

The reference level for steam pressure is actually introduced, however, by a manual setting of the variable arm of a potentiometer connected across the output of one of the two multiplier amplifiers in the proportional reset circuit. The error signal for steam pressure is never explicitly derived. By means of the two multiplier amplifiers, two simple servo systems, and a cycling switch mechanism, the pressure error is used implicitly to introduce a periodic correction of the reference level for neutron flux in proportion to the ratio of desired to effective steam pressure levels.

(d). Power level servomechanism. Pile neutron flux and therefore instantaneous pile power is regulated directly by motor-driven control rods. The complete power level servomechanism is designed to operate from an input signal which depends upon the difference between desired and actual pile neutron flux levels, and to deliver an output signal in the form of a motion of the control rods which reduces the error signal toward zero. Between the input error voltage and the output displacement of the control rods are the following servomechanism components:

DECLASSIFIED

1. A power amplifier which furnishes an output voltage proportional to the input error signal.

2. A constant speed direct current generator, driven by an auxiliary power source, whose output voltage is proportional to its field excitation, which is supplied by the output of the power amplifier.

3. A direct current motor, driven by the generator output at a speed which is approximately proportional to the applied voltage.

4. The control rod driving mechanism, powered by the variable speed motor, which distributes any reactivity change between the regulating rod and the shim rods.

All of these components will be described later in substantially more detail from the functional standpoint.

(c). Limiting instrumentation. To achieve the desired degree of stability in the operation of the entire power level regulator and to provide adequate safety precautions, it is necessary to introduce a number of secondary control functions which serve only to limit the magnitude or rate of change of control signals, or the degree or rate of response of control components. These limiting control functions, divided according to their use for stability or safety, are as described below.

1. Stability. A tachometer voltage proportional to the speed of the d.c. motor which drives the regulating rod is subtracted from the neutron flux error signal.

2. Safety. In the region where pile neutron flux and its time rate of change can be measured, the value of $1/nv\ d(nv)/dt$, the logarithmic time derivative of neutron flux, is limited to a value which corresponds to a pile period of 10 seconds. As shown in Fig. 46 a voltage proportional to $1/nv\ d(nv)/dt$ is derived by applying $c_2\ d(nv)/dt$, the voltage output of the neutron flux differentiating amplifier, to a resistance that is set by the neutron flux servo motor to a value proportional to nv. Since the current in the series circuit is then proportional to $1/nv\ d(nv)/dt$ the voltage which appears across a fixed portion of the resistance in the series circuit also varies as $1/nv\ d(nv)/dt$. If $1/nv\ d(nv)/dt$ exceeds its limiting value, the power level regulator calls for emergency shutdown of the pile, with the full assistance of the safety circuits.

If the measured value of pile neutron flux, as indicated by the neutron detector should exceed a prescribed maximum value, the power level regulator causes emergency shut-down of the pile.

If the measured value of boiler steam pressure exceeds a selected upper limit, operation of the pile is transferred from "automatic" to "manual", and the reference level for neutron flux is reduced to a selected low value

DECLASSIFIED

where steam cannot be generated, but the pile is not completely shut down.

During start-up, and at any other time when steam pressure decreases below 210 Psi G, operation of the pile is transferred from "automatic" to "manual".

Neutron flux measuring equipment is provided in triplicate, with provision for automatic rejection of any one of the circuits if its operation becomes essentially unlike that of the other two.

(4) Operation of Power Level Regulator.

(a) Start-up. In order to minimize the control problems which are associated with safely traversing the wide region of low power below the useful range of the neutron detector, initial start-up of the power pile is to be carried out with the assistance of an auxiliary neutron source which produces a small measurable neutron intensity at the location of the neutron flux detector for the pile. Changes in this measured flux level as the pile approaches the critical state will then be readily detected and controlled. Use of the auxiliary neutron source for subsequent start-up operations is arbitrary. Under either circumstance however, the operation of the power level regulator is as described in the remainder of this section.

The increase of pile power from zero to a selected value in the operating range must be initiated manually, but may be transferred to "Automatic", if desired, by the increase of steam pressure past 210 Psi G. The schedule of events may be followed most clearly by referring to Fig. 46, a functional diagram of the automatic power regulator. With the regulator on "Manual" control and the pile neutron flux at zero, the start-up process is initiated by setting the reference voltage for neutron flux at a value which corresponds to the desired operating level.

Inasmuch as actual pile neutron flux is zero, the initial neutron flux error signal is large. The servo amplifier delivers a proportional output voltage to excite the constant speed generator G, which in turn energizes the d.c. motor which actuates the regulating rod. Since the regulating rod can introduce a total change in δk eff. of only 0.006, it is withdrawn to its full extent without appreciably affecting the criticality of the pile. As the regulating rod passes a position midway from the center of its operating range to its full limit of outward travel, however, a position-actuated switch starts the motors which withdraw the six shim rods. Then as the regulating rod is fully withdrawn, a limit switch is actuated which introduces cut-off bias on the servo-amplifier output tubes which control withdrawal of the regulating rod, leaving in operation other output tubes which control regulating rod insertion. The shim rods continue to be withdrawn at a slow constant rate which is chosen to limit the rate of change of reactivity to a safe value. Operation proceeds in this way until the pile becomes critical.

Once the critical condition of the pile is reached, the neutron chain

DECLASSIFIED

reaction becomes self-sustaining, and the neutron flux multiplies in time with a rapidity which depends directly upon the excess of reactivity over that which makes the pile critical. Since the pile neutron flux is initially very low compared not only to the desired value but also to the flux level which can be measured, however, the shim rods continue to move outward at the same constant rate until the effective value of neutron flux slightly exceeds the desired neutron flux level. Thereupon, the growing error signal of reversed algebraic sign operates through the active servo amplifier tubes to energize the regulating rod motor in the other direction, and drive the regulating rod in toward the center of its range, in opposition to the continued slow outward travel of the shim rods. As the regulating rod leaves its fully withdrawn position, the limit switch which imposed cut-off bias for withdrawal is operated in reverse, restoring full amplifier activity. Finally, as the regulating rod approaches the center of its operating range, it operates another position-actuated switch which stops the shim rod motors.

When, in the process of start-up as described above, the regulating rod returns to its central position and stops the outward motion of the shim rods, the condition of the pile is essentially critical. Due to the 0.7% delayed neutrons which participate in the chain reaction, however, pile reactivity tends to increase for several seconds. During this period, the neutron flux error signal keeps the regulating rod moving slowly into the pile, continually maintaining the excess reactivity of the pile at essentially zero at the desired level of measured neutron flux. If in this process the regulating rod passes a position midway from the center of its operating range to its full insertion, a position-actuated switch starts the shim rod motors in a direction to cause shim rod insertion. The same slow constant rate of motion of the shim rods is preserved as for their withdrawal during the earlier stage of start-up. If compensation of reactivity change is not achieved by the shim rods before the regulating rod reaches its full insertion, another limit switch is actuated which applies cut-off bias to the servo amplifier tubes which control regulator rod insertion, leaving in operation the tubes which control withdrawal.

The inward progress of the shim rods continues until the critical condition of the pile cannot be maintained without an outward motion of the regulating rod. This situation is made evident to the neutron flux servomechanism by the reversal of the algebraic sign of the input error signal. Energized through operating output tubes of the servo amplifier, the regulating rod leaves its position of full insertion and thereby operates the limit switch in reverse to restore full amplifier activity. It continues to move rapidly outward at a rate which essentially compensates for the continuing inward motion of the shim rods. Then, as it approaches the center of its range, the regulating rod again operates a position-actuated switch which stops the shim rod motors, leaving the pile essentially critical.

In subsequent operation, the neutron flux servomechanism responds to error signals of either sign by moving the regulating rod in a compensating direction within its extreme limits. Slow excursions of the regulating rod beyond mid-range are compensated by shim rod motion as already described, without the necessity of inactivating the servo amplifier for error signals

DECLASSIFIED

of either sign. In response to rapid errors of appreciable magnitude, however, such as would result from a decided change in the reference level for neutron flux, the regulating rod quickly moves to an extreme position and stays there until the error signal reverses in sign. Rate signals from the generator tachometer operated by the regulating rod motor and from the neutron flux differentiating amplifier furnish the stability necessary to prevent excessive overshoot or hunting of the servomechanism about the desired operating point. In addition, throughout all of these and subsequent procedures, safety precautions are taken by limiting the value of the logarithmic time derivative of neutron flux, $1/nv\ d(nv)/dt$.

The neutron flux servomechanism so far described in this section serves automatically to keep the pile neutron flux at a selected value, and therefore to stabilize the power output of the pile at a fixed level. When so operated, the power level regulator is under "Manual" control inasmuch as the reference level for power production--i.e., for neutron flux-- is set manually. As indicated functionally on Fig. 46, however the power level regulator is also capable of "Automatic" control, wherein the power generated by the pile is automatically adjusted to meet the requirements of a load which may change arbitrarily, between wide limits. Such operation is made possible by a periodic correction or reset of the neutron flux reference level in proportion to an error signal which is directly responsive to load demand.

Any disparity between the rate at which energy is produced by the pile and the rate at which it is dissipated in the load must result in a change of pressure in the heat exchanger, which holds most of the reserve energy in the power pile system. Conversely, any actual or anticipated departure of boiler steam pressure from the desired value of 450 Psi G is an indication that the reference level for neutron flux requires adjustment. The pressure error signal cannot be directly applied to the neutron flux servo amplifier. It is used instead to produce a periodic correction of the neutron flux reference level in proportion to the pressure error expressed as a fraction of the effective pressure.

In the terminology of Fig. 46, the following quantities are important in the reset function:

p = reference steam pressure, 450 Psi G

p_e = $p + c_3\ dp/dt - c_4\ d\bar{L}/dt$ = effective measured steam pressure.

p = actual steam pressure, Psi G

dp/dt = time derivative of actual steam pressure

dL/dt = time derivative of load demand averaged over 5 seconds.

c_3, c_4 = arbitrary constants which may be set as required for best operation

DECLASSIFIED

SECRET

$(nv)_o$ = operating neutron flux reference level before reset

$(nv)_r$ = operating neutron flux reference level after reset

Thus with a relative pressure error of $(p_o - p_e)/p_e$, the reset action changes the operating neutron flux reference level from $(nv)_o$ to a new value nv_r given by the reset equation:

$$(nv)_r = (nv)_o \left(1 + \frac{p_o - p_e}{p_e}\right) = (nv)_o \, p_o/p_e$$

which may be rewritten as:

$$p_o (nv)_o = p_e (nv)_r = (p + c_3 \, dp/dt - c_4 \, dL/dt)(nv)_r$$

Each term in the last equation excepting $(nv)_r$, the reset reference level for neutron flux, is made available by previously described components of the power level regulator. The equation may therefore be solved by two multiplier amplifiers which form the two products $p_o (nv)_o$ and $p_e (nv)_r$, and a servomechanism which adjusts their difference to zero by varying $(nv)_r$. As shown in Fig. 46, the inputs to the two multiplier amplifiers are $(nv)_o$ and P_e, while their gains are set in proportion to p_o and nv_r, respectively, by adjustments of the variable arms of their output potentiometers. Then as the reset equation is solved by the servomechanism and the input error signal $p_o (nv)_o - p_e (nv)_r$ is reduced toward zero, the reset servo motor is made to adjust not only the multiplier amplifier output potentiometer but also the neutron flux reference level potentiometer to the new value $(nv)_r$.

To make possible the operation just described in which the neutron flux reference level is reset with respect to its earlier value, two identical neutron flux reference level potentiometers are used. The slider of one potentiometer (also used to establish neutron flux reference level in "Manual" operation) is retained at nv_o during the reset operation which adjusts the slider of the other potentiometer (actually in control under "Automatic" operation) to the new reference level $(nv)_r$. Then, after the reset operation has been accomplished, a cycling switch actuator shorts the input of the reset servo amplifier and opens the input circuit of the follow-up servomechanism. Operating on an input error signal which is the reset correction, $(nv)_r - (nv)_o$, the follow-up servo amplifier drives a servo motor which adjusts the slider of the "Manual" reference potentiometer to nv_r, where the error signal disappears. Thus, during the next reset operation, when the follow-up servo is again inactive, the neutron flux reference level to be corrected by proportional reset is the corrected level of the preceding cycle.

The lowest frequency with which the cycling operation of reset and follow-up is repeated, is determined by the constant excitation supplied to one field of the constant speed generator which energizes the cycling switch actuator motor. Under conditions when the load demand and the steam pressure change slowly, there is no reason to make reset corrections at a rapid rate. The cycling operation serves under such circumstances as a monitor on proper performance. While steam pressure or load is changing

SECRET

DECLASSIFIED

rapidly, however, the reset cycling rate is increased by an aiding field excitation of the cycling switch generator. The variable aiding field excitation is provided by a reset cycling rate amplifier which delivers an output proportional to the absolute value of its input voltage, $c_3\, dp/dt - c_4\, \overline{dL}/dt$. In addition, if the input voltage exceeds a predetermined level, a trip relay in the amplifier output circuit immediately sets the cycling switch actuator to the beginning of the reset operation in order to correct with the full advantage of sudden large rates of change in pressure or load. A time delay prevents early repetition of the trip relay action.

The constant field excitation of the cycling switch generator accomplishes a complete cycling period in approximately 30 seconds. With increasing rates of change of pressure or load demand, the contribution to the variable aiding field excitation of the generator may reduce the cycling period to as little as 15 seconds. The time delay between possible actions of the trip relay is approximately 20 seconds.

(b) Maintenance of power level.

1. Long-period variations. Having compensated during pile start-up for the increase in reactivity over several seconds due to delayed neutrons, the neutron flux servomechanism is capable of maintaining the critical condition of the pile at a fixed or an automatically controlled flux level with comparatively little difficulty. If the desired operating level is not altered, only slow changes in pile activity remain to be compensated. It can be safely assumed that a regulator design which is satisfactory for controlling the pile through start-up as described in Section d, is also adequate to deal with the long-period variations in the nuclear constants of the pile which are now to be mentioned.

2. Change of pile reactivity with temperature. First to be observed among the reasonably long-period variations in pile activity is that due to the temperature sensitivity of the nuclear properties of the pile materials. The principal effect of a change in temperature is to change the diffusion length L for thermal neutrons as a consequence of the variation of Σ_a, the macroscopic absorption cross section, in inverse proportion to the rms velocity appropriate to a neutron of absolute temperature T on the basis of equipartition of energy. Then if E is the mean energy of thermal neutrons,

$$E = 1/2\, mv^2 \propto T, \text{ or } v \propto T^{\frac{1}{2}}$$

By definition,

$$L^2 = \frac{1}{3\Sigma_a \Sigma_\tau} = \frac{\lambda_t}{3} \frac{1}{\Sigma_a}$$

where $\lambda_t = \frac{1}{\Sigma_\tau}$ is the transport mean free path for the scattering of thermal neutrons. Therefore, since

$$\Sigma_a \propto \frac{1}{v} \propto \frac{1}{T^{\frac{1}{2}}}$$

DECLASSIFIED

SECRET

it follows that

$$L^2 \propto 1/\Sigma_a \propto v \propto T^{\frac{1}{2}}$$

Pile reactivity, ρ, may be expressed in terms of L^2, k, the neutron multiplication constant without leakage, τ, the neutron age, and B, the geometric buckling of the pile:

$$\rho = k - (1 + L^2 B)e^{\tau B}$$

It follows that since $L^2 \propto T^{\frac{1}{2}}$, the pile is stable with respect to temperature changes, for if T increases, L^2B increases, and ρ decreases. In other words, a small increase in pile reactivity results in the generation of more power, which raises the temperature of the pile material and thereby reduces the reactivity change toward zero.

Even though the pile tends to be stable with respect to temperature changes, regulator action is still necessary to maintain constant power output, especially since temperature stabilization of the pile requires several minutes. With the use of the neutron flux servomechanism, however, compensation is continually applied for reactivity changes due to temperature, and errors are not cumulative since the neutron flux level itself is controlled.

3. Depletion of fissionable material with operating time. Operation of the pile depends directly, of course, upon maintenance of the chain reaction by means of which fissionable atoms are continually destroyed with the release of energy.

Since only very small amounts of new fissionable material are formed in the pile reactor during normal operating processes, it is clear that continued operation must reduce the amount of fissionable material available to sustain the chain reaction, and that therefore the pile reactivity must decrease slowly with time. The maintenance of constant output power despite the depletion of fissionable material is solved by the power level regulator even more easily than problems already mentioned, because of the very long time constant of the process.

4. Accumulation of fission-produced poisons. Much more important changes in pile reactivity result from certain neutron-absorbing fission-produced products than from the regular slow decrease of the number of fissionable atoms present. The best known and most important example is Xe^{135}, which results very early in the radioactive decay chain of Te^{135}, produced directly from fission of U^{235}. The absorption cross section of Xe^{135} for thermal neutrons is 6000 times that of U^{235}. The available $\Delta k_{gl}/k$ which must be included in the pile to permit critical operation under certain possible conditions when large amounts of Xe^{135} may be present is approximately 11%. Despite its great importance as a factor influencing pile reactivity, however, the presence of Xe^{135} and of less serious poisons does not present an important control problem so long as sufficient excess k is available to bring the pile to the critical condition, and provided that adequate safety precautions are observed with respect to the rate of increase of pile reactivity. As before, the underlying reason for the small importance to the control problem of such large

SECRET

DECLASSIFIED

reactivity changes is that their time constants are very long.

5. Maintenance of control sensitivity. The neutron flux servomechanism is designed to maintain full control sensitivity at any steady state power level by so dividing any major reactivity change between regulator and shim rods that the steady state is reached with the regulating rod near the center of its operating range. With the regulating rod near its central position, it can be moved over half of its range of motion with full speed in either direction, i.e., in response to error signals calling for either increase or decrease of pile flux.

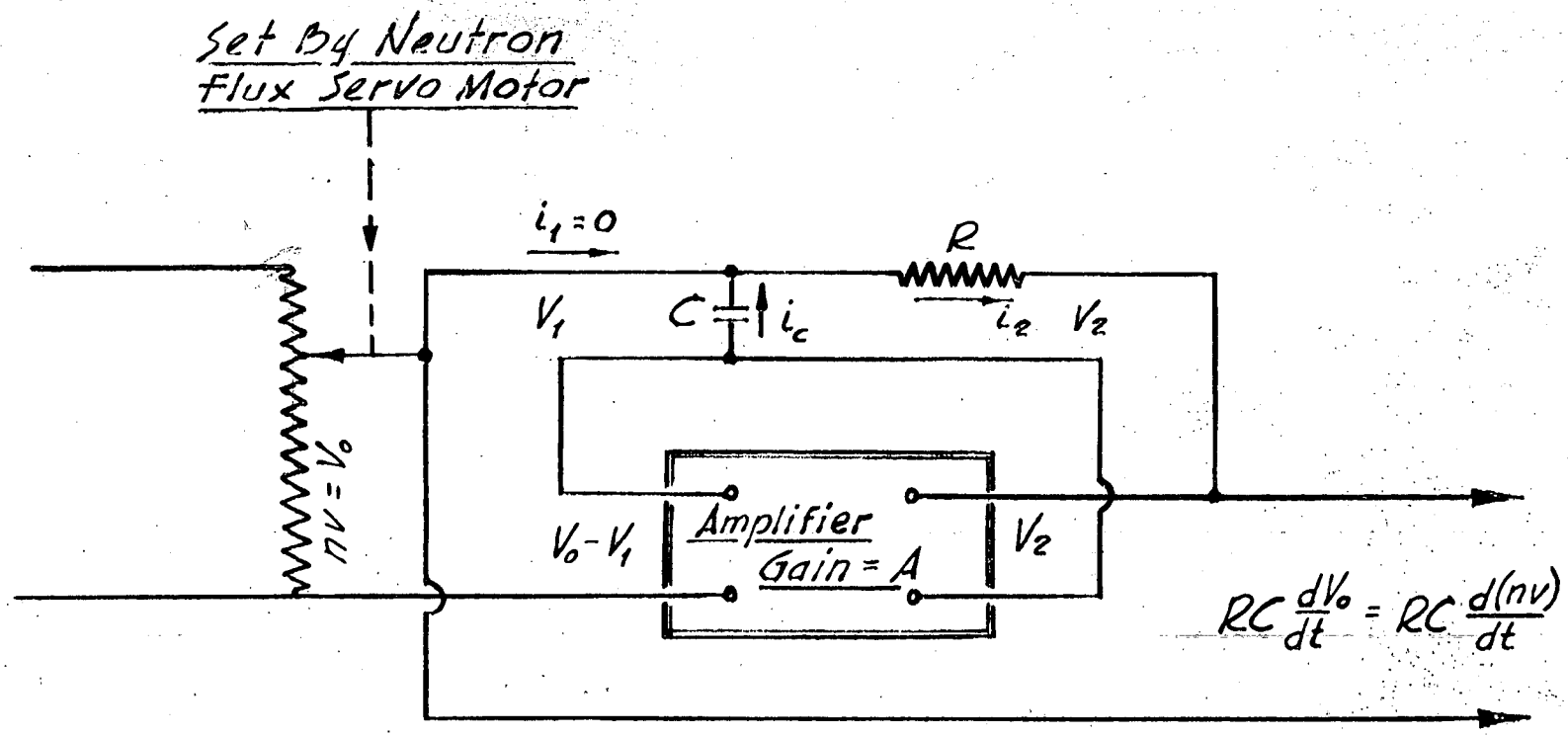
6. Regulator action independent of short-period load fluctuations. Short-lived changes in power output demand upon the power pile system should not affect the error signal for neutron flux so long as the average of the power output demand over a period comparable with the response time of the pile and boiler system is constant. By averaging the rate of change of power output demand over 5 seconds, a correction to the regulator error signal is obtained which is independent of short-period load fluctuations.

(c). Change in power level.

1. Manual change of regulator setting. When the power level regulator is operating under "Manual" control, the input error signal depends directly upon the difference between the manually set flux reference level and the effective measured flux level--i.e., upon the difference between the rate at which power is produced and the rate at which it should be produced. Thus, to change the operating power level under "Manual" control, the setting of the potentiometer which delivers the reference voltage for neutron flux is changed to the new desired value. The error signal which results operates through the servo amplifier, the constant speed generator, the regulating rod motor and the control rod mechanism to introduce the proper time schedule of change in pile reactivity to accomplish the change to the new operating level. Such reactivity changes are usually sufficiently large to call for a distribution in effect between the regulating rod and the shim rods, and a return of the regulating rod to the central part of its operating range when the new power level is reached. Throughout all of these changes, rate controls are applied for stability, and rate limitations are maintained for safety.

2. Maintained change in output load. When operating under "Automatic" control by steam pressure error and maintained change in output load, the power level regulator does not call for a change in the pile neutron flux level unless the steam pressure departs from its desired value or the average power demand of the load changes. A change in output load from one constant value to another obviously results in a change in steam pressure unless the power level of the pile is also changed. The anticipatory error signal obtained from averaging the rate of change of output power demand over 5 seconds causes a transient adjustment of pile

DECLASSIFIED



GENERAL THEORY

$V_2 = f(V_1) = A = (V_o - V_1)$

If A is very large

$V_1 \approx V_o$ and $V_2 \approx f(V_o)$

FOR CASE SHOWN ABOVE

$i_1 = 0 \qquad i_c = C\frac{dV_1}{dt} = i_2$

$V_2 = V_1 + i_c R = V_1 + RC\frac{dV_1}{dt}$

Output Voltage is:

$V_2 - V_o = V_1 - V_o + RC\frac{dV_1}{dt} \approx RC\frac{dV_1}{dt}$

FIG. 44

DIFFERENTIATING AMPLIFIER

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Strauchman D. 8-27-47	A.L.S. C. 8-27-47	A. 8-28-47	R.&P. 9-16-47			
Proj. C-222 M				A-2299		
SCALE: None						

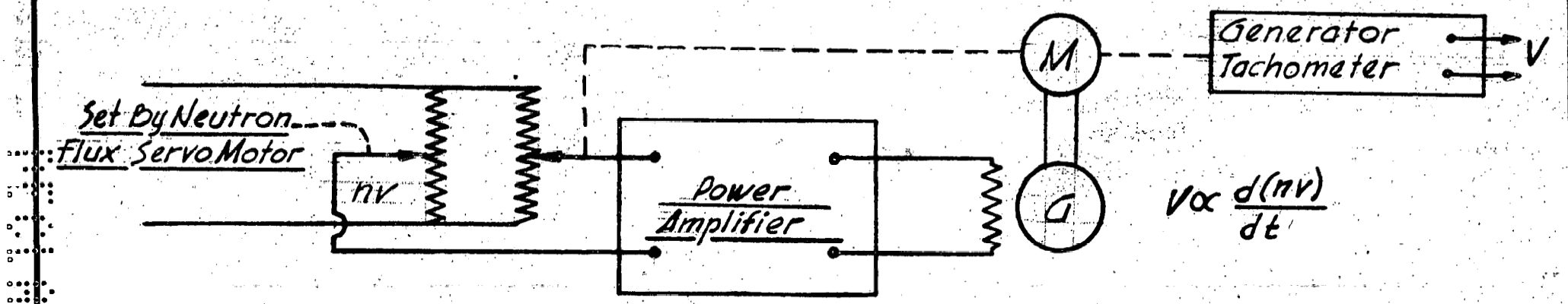


FIG. 45

ELECTROMECHANICAL DIFFERENTIATOR

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

J.E. Strauchman D. 8-27-47	A.L.S. C. 8-27-47	A 8-28-47	R.E.P. 9-16-47			
Proj. C-222 M				A-2300		
SCALE: None						

[redacted]AL

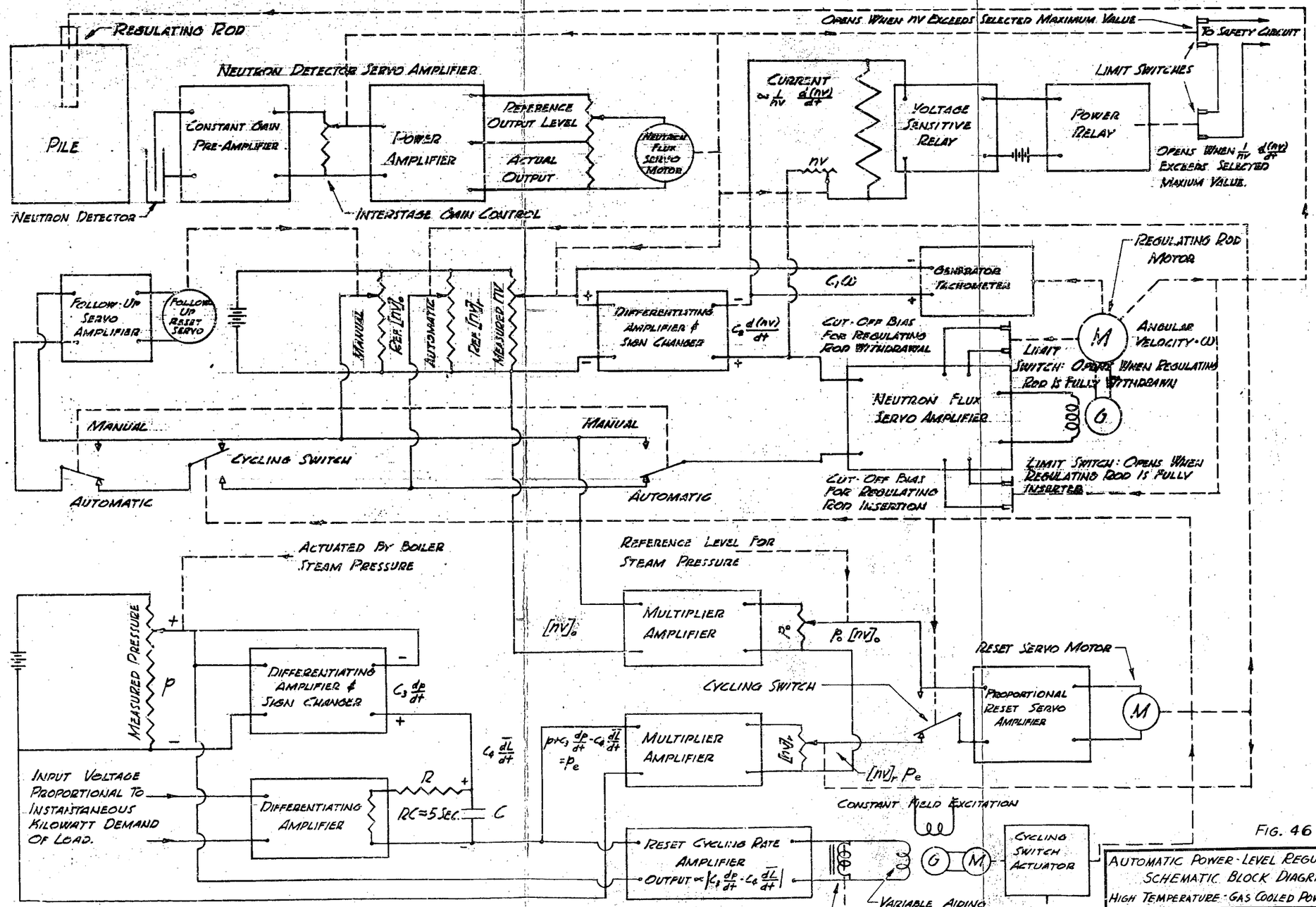


FIG. 46

AUTOMATIC POWER-LEVEL REGULATOR
SCHEMATIC BLOCK DIAGRAM
HIGH TEMPERATURE-GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Redrawn D 9-9-47	W.A.P. C. 9-9-47	Traced A 9-9-47	R.E.P. 9-16-47	D.L.S. 9-16-47	
Proj. C-222M					C-2294
SCALE: None					

CONFIDENTIAL
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

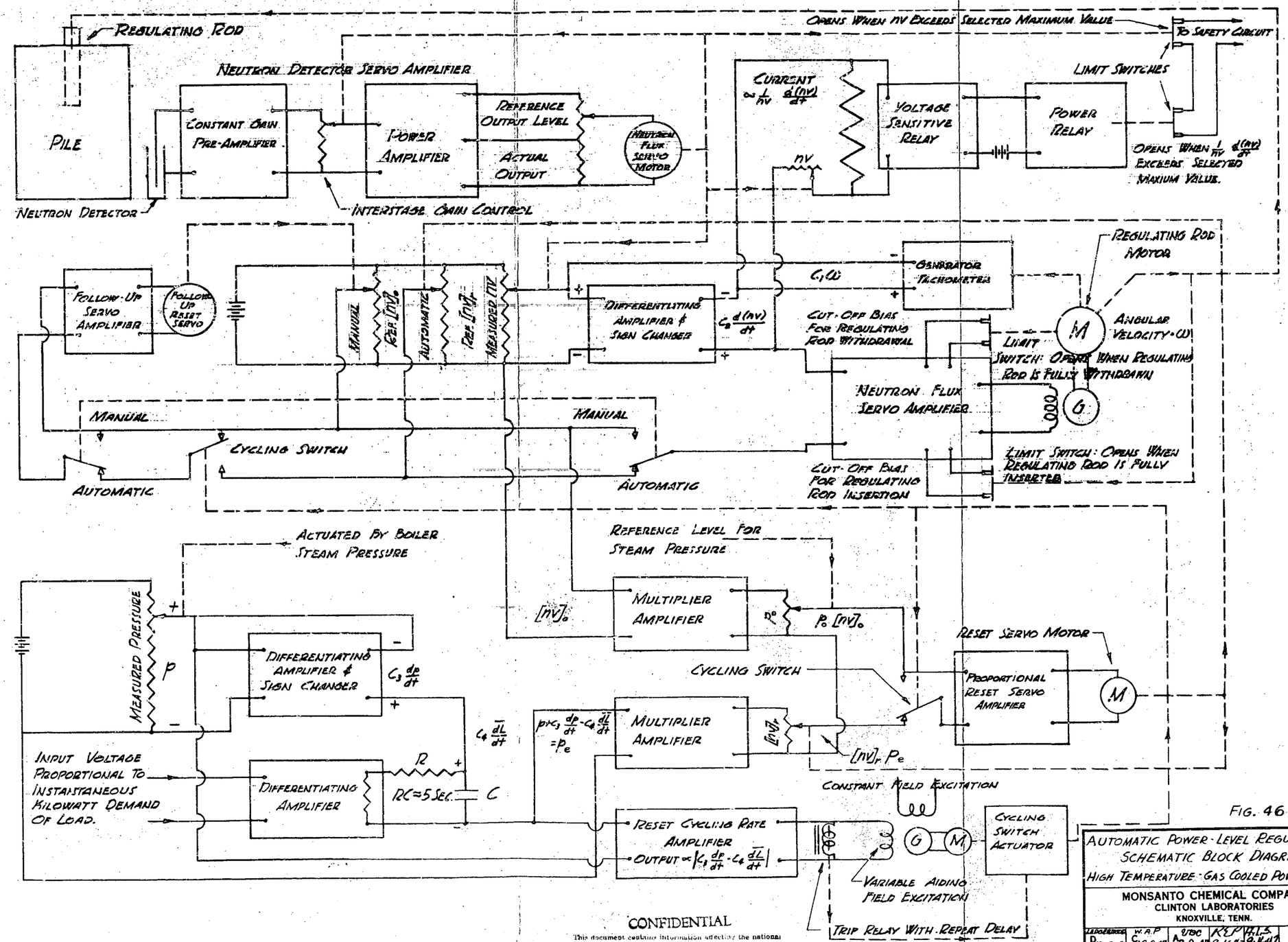


FIG. 46

AUTOMATIC POWER-LEVEL REGULATOR
SCHEMATIC BLOCK DIAGRAM
HIGH TEMPERATURE-GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

LABORATORY	W.R.P.	DRAWN	R.S.P.	R.L.S.	
D 9-9-47	C 9-9-47	A 9-9-47	9-16-47	9-16-47	
Proj. C-222M					C-2294
SCALE: None					

CONFIDENTIAL

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

SECRET

power toward the value which is required to maintain constant steam pressure at the new level of power demand. If the magnitude and duration of this transient error signal are properly chosen, the departure of steam pressure from its desired value is materially reduced. In any event, however, an error signal is maintained until the steam pressure itself has stabilized at the desired constant level of 450 Psi G under the new load. Rate controls and rate limitations are applied as described before to maintain stability and safety of operation.

(d). Shut-down.

1. Emergency. Under any of the following abnormal or dangerous conditions, the power level regulator opens the auxiliary safety circuit for rapid pile shut-down with the safety rods, and transfers major control of the regulating and shim rods to motors which drive them at high speed into the pile to their full extent:

If the value of pile neutron flux as measured by the neutron detector exceeds a prescribed maximum value.

If the logarithmic time derivative of pile neutron flux exceeds a value which corresponds to a pile period of 10 seconds.

In the event of failure of any critical control component for which automatic change-over to an alternate unit is not provided.

2. Normal. Under ordinary conditions, shut-down is accomplished under the full control of the power level regulator without any assistance from the safety circuits.

If the regulator is operating under "Manual" control, the procedure for shut-down is essentially identical with that for obtaining any other desired power level. The potentiometer whose output establishes the desired level of neutron flux is set to zero. The error signal which results can be reduced to zero only by pile shut-down, which is accomplished as usual by controlled motion of the regulating and shim rods.

Controlled shut-down of the pile can likewise be carried out according to a desired time schedule, or it may be carried out if desired by a control signal operating from the output power demand when the power demand goes to zero. The useful power output of the pile is also reduced to zero automatically if steam pressure becomes too high, although the residual neutron flux level retained in the pile permits rapid start-up to any desired power level under full regulator control.

SECRET

DECLASSIFIED

SECRET

c. Automatic Temperature Regulator.

(1) Objective. Throughout usual operation of the power pile system, the automatic temperature regulator maintains the outlet temperature of the coolant at 1400° F. within ± 10° F. by circulating the coolant through the pile and the heat exchanger at a rate which depends jointly upon the pile power and the power delivered to the heat exchanger.

(2) Intelligence. The only control parameter required to enable the temperature regulator to fulfill its objective is the temperature of the coolant as it leaves the pile, called the outlet temperature of the coolant.

(3) Physical Description of Temperature Regulator. The temperature regulator is comprised of the following fundamental components:

A sensing element which delivers a voltage proportional to the outlet temperature of the coolant.

A reference level instrument which supplies an output voltage proportional to the desired outlet temperature of the coolant.

A servomechanism which responds to the difference between desired and measured values of outlet coolant temperature, and delivers an output signal which reduces this difference toward zero by varying the circulating velocity of the coolant.

Limiting and rate control devices for stability and safety in operation.

A more detailed specification can be given for most of the above equipment.

(a) Sensing Element. An accurate, high-temperature, fast acting thermocouple is used to derive the control voltage which is proportional to outlet coolant temperature. It is expected that one of the thermocouple units recently developed by the Bureau of Standards for use in the control of gas turbines will be satisfactory for this application. The thermocouple voltage is applied to a constant-output amplifier with servo-operated gain control. The useful output, furnished by the same servo, is the setting of the variable arm of a potentiometer in proportion to the voltage from the thermocouple, and thus to the measured outlet coolant temperature.

(b) Reference Level Instrument. A potentiometer supplied with a constant voltage is used to furnish a voltage proportional to the desired outlet coolant temperature, by the setting of its variable arm.

(c) Coolant Temperature Servomechanism. Between the input error signal, which is proportional to the difference between desired and measured outlet coolant temperatures, and the output signal, which is a change in the circulating velocity of the coolant, are the following essential servomechanism components:

SECRET

DECLASSIFIED

A power amplifier, which delivers an output voltage proportional to error signal input.

A small motor, driven by the output of the power amplifier.

Two variable speed alternators driven by two steam turbines, each of which is provided with a constant flow of steam through one channel, and a variable steam flow through another, in proportion to the setting of a valve which is driven by the small motor mentioned above.

Four large squirrel cage induction motors, two of which are driven by each of the above alternators at a velocity which varies directly with the steam flow to the two turbines.

Four large centrifugal blowers, powered by these four large motors which circulate the coolant at a velocity which depends directly upon their speed.

Besides the above-named components, the following auxiliary equipment is directly associated with the coolant temperature servomechanism to improve its speed of response, which would otherwise be severely limited by the inertia of the large rotating machinery: A low-inertia butterfly damper in a low impedence coolant line which by-passes the pile, and which moves from its position of stable equilibrium to introduce a greater or a smaller area of obstruction in the by-pass line, in proportion to the output of the temperature error signal servo amplifier.

(d) Limiting and Rate Control Instrumentation. In order to provide for adequate operating stability and to insure that necessary safety precautions are taken, it is necessary to introduce the following secondary control functions, which serve only to limit the magnitude or rate of response of control signals, or the degree or rate of response of control components.

(1) Stability. A signal proportional to the time rate of change of indicated outlet coolant temperature subtracted from the temperature error signal input to the servo amplifier. This signal is obtained as the output of a differentiating amplifier which operates upon the voltage proportional to actual outlet coolant temperature. A tachometer generator voltage proportional to the speed of the small motor driven by the amplified temperature error signal is subtracted from that error signal.

(2) Safety. Blower speed is never allowed to decrease below a selected minimum value, either during start-up or in subsequent operation. Minimum blower speed is maintained by the constant steam flow supplied through one set of channels to the blower turbines. A position-actuated switch, operated by the mechanism which controls the variable steam flow to the turbines, introduces cut-off bias on the power amplifier output tubes which govern the reduction of steam flow, whenever the variable steam flow approaches zero. If the outlet coolant temperature reaches a selected maximum value, a position-actuated switch operated by the thermocouple output servo opens the safety circuit and causes pile shut-down. The safety circuit is opened and pile shut-down is initiated in case of the failure of any critical control component for which automatic change-over to an alternate unit is not provided.

DECLASSIFIED

SECRET

(4) Operation of Automatic Temperature Regulator.

(a) Constant Pile Power Level. During all normal operating circumstances, the circulation velocity of the coolant is varied to maintain the outlet coolant temperature at 1400° F. The action of the automatic temperature regulator in achieving this end may be followed clearly by referring to the diagram of Fig. 47.

The voltage proportional to the desired outlet coolant temperature of 1400° F. is set and maintained between one side and the variable arm of the reference level potentiometer, while the observed outlet coolant temperature is set up on a similar potentiometer through the adjustment of its variable arm by the thermocouple output servo. The difference of these two voltages is applied as an error signal to the temperature servomechanism. As a result of this input signal, the power amplifier supplies a proportional interstage voltage, through a second amplifier, to a solenoid which produces a proportional deflection of the butterfly damper in the bypass coolant line, in such a direction as to reduce the input temperature error by changing the circulation speed of the coolant through the pile. In addition, the power amplifier supplies a proportional voltage to the small motor in its output circuit, which proceeds to adjust the valves which control the variable steam flow to the blower turbines in a direction to reduce the input temperature error by changing blower speed. The complete effect of a temperature error signal is therefore two-fold:

A rapid reduction of the input temperature error through the action of the butterfly damper in changing the circulation speed of the coolant through the pile; and

A much slower but essentially unlimited reduction of the input temperature error through the change in blower speed, as effected by regulating steam flow to the blower turbines.

Both of these actions continue so long as the error signal persists. As the error approaches zero, the butterfly damper approaches its equilibrium position, where it is ready to respond rapidly with maximum sensitivity to error signals of either algebraic sign. With the disappearance of the error signal, the motor which operates from the power amplifier output is no longer supplied with a driving voltage. It stops, leaving the valves which control the variable steam flow to the blower turbines in position to maintain the temperature error at zero under steady state operating conditions. Throughout these regulating procedures, rate signals from the temperature differentiating amplifier and from a generator tachometer driven by the steam control valve motor, furnish the stability necessary to avoid excessive overshoot or hunting of the system about the desired operating point.

For operation under constant pile power level, it is likely that the temperature error signal will never be large. In such a case, the deflection of the butterfly damper from its equilibrium position as caused by the error signal is small. For the same reason, the rate of the steam control valve motor is small, but the correction it introduces is cumulative, and reduces the error signal to zero with the butterfly damper at its equilibrium position.

SECRET

DECLASSIFIED

(b) Change in Power Level. Operation of the automatic temperature regulator is essentially as already described for any condition of change in pile power level or load demand so long as the temperature error signal does not result in the reduction of the variable steam flow to zero. Large temperature error signals would appear to be unlikely even under conditions of changing power level, primarily because the speed of response of the temperature regulator is expected to be greater than the speed with which large changes of coolant temperature can take place due to the pile and boiler system, because of its very high thermal inertia. Whatever the degree of automatic temperature regulation which can be achieved under changing conditions of power production or load demand, however, the temperature regulator is continually effective in recognizing temperature errors as they occur, and in producing immediate as well as long period cumulative corrections. It is anticipated that the automatic temperature regulator will be capable of maintaining outlet coolant temperature within $\pm$ 10° F. of the desired value, 1400° F., under all normal conditions of operation of the power pile system during which the variable steam flow to the blower turbines is not reduced to zero.

(c) Start-up and Low Power Operating Conditions. As briefly described in Section 3 (d) , blower speed is never allowed to decrease below the value which is maintained by the constant steam flow supplied through one set of channels to the blower turbines. As a result, the automatic temperature regulator is made inactive so far as steam flow regulation is concerned under start-up or any other operating conditions when pile power level is insufficient to raise outlet coolant temperature above 1400° F. at minimum blower speed. The inactivation of the temperature servomechanism for low power operation is accomplished by a switch which is operated by the mechanism which controls the variable steam flow to the blower turbines, when that flow approaches zero. Operation of this position-actuated switch inactivates servo amplifier output for temperature error signals tending to decrease steam flow, but leaves the operation of the servo amplifier unchanged for error signals which would increase steam flow. Thus, as pile power increases to the point where the outlet coolant temperature exceeds 1400° F. at minimum blower speed with the butterfly damper in its equilibrium position, the servo power amplifier operates normally to increase steam flow to the blower turbines and therefore to correct the temperature error signal. As the variable steam flow increases from zero, however, the position-actuated switch is operated in the other direction, and the servo amplifier sensitivity is restored for signals tending to decrease steam flow. Operation of the automatic temperature regulator then continues as described in the two preceding sections until a period of low power operation again causes the variable steam flow to be reduced to zero.

Although blower speed is never allowed to decrease below the value which is maintained by the constant component of the steam flow to the turbines, the automatic temperature regulator is designed to keep the outlet coolant temperature at 1400° F. over essentially all of the useful operating range below the point where variable steam flow becomes zero. In this operating region, correction of the temperature error signal is accomplished altogether by the butterfly damper in the by-pass coolant line, acting in conjunction with the early stages of the temperature error servo amplifier as a true servomechanism.

DECLASSIFIED

It has already been stated that whenever the variable steam flow to the blower turbines approaches zero, a switch is actuated which renders the power output stage of the temperature error servo amplifier inoperative for error signals tending to decrease steam flow. If, at any time after this switch is operated, the butterfly damper is at its position of equilibrium or beyond in a direction to decrease the circulation velocity of the coolant through the pile, another switch is actuated to render the power output stage of the servo amplifier inoperative for error signals tending to increase steam flow to the blower turbines. When both switches are actuated, a transfer switch is operated to convert the action of the butterfly damper from a deflection proportional to error signal to true servo action which can reduce the temperature error signal to zero by affecting the circulation velocity of the coolant through the pile. In this condition, outlet coolant temperature is maintained at 1400°F. under minimum blower speed until pile power level becomes so low that the butterfly damper opens the by-pass coolant line to its full extent. Here another switch must be actuated to inactivate the new servomechanism for error signals tending to decrease coolant velocity through the pile if operation of the regulator is to continue. If this action is not taken, the sign of the correction introduced by the damper reverses, and the entire servomechanism becomes unstable.

If after operation under very low pile power as described above the power level is increased, the servomechanism which sets the damper to maintain outlet coolant temperature at 1400°F. eventually returns it to its position of equilibrium for high power operation. At this point the switch is operated which restores the output sensitivity of the servo amplifier for temperature error signals tending to increase steam flow, and restores the operation of the butterfly damper to a deflection, proportional to error signal, about its equilibrium position. If pile power increases still further, the mechanism which controls variable steam flow to the blower turbines opens the steam valves and operates the switch which restores full sensitivity to power amplifier output. This action places the automatic temperature regulator in normal operation for the control of outlet coolant temperature at ordinary levels of pile power.

d. Instrumentation.

The primary purpose of the system of instruments in the power pile is to indicate and record important information about pile operation. However, because the pile is experimental, some instruments will be added, so that additional information can be gathered for design improvements.

The instruments covered in this section are those which are necessary because nuclear energy is being used to supply heat for the boiler. Instruments usually found in a steam-electric power plant are omitted.

The hazard of radiation continually exists for personnel engaged in the pile operation and hence a control room will be located at a remote point, and all measurements channeled to this room, where indicating and recording instruments and indicating lights are conveniently arranged. These measurements can be classified as indicating and controlling, indicating only, and alarms.

DECLASSIFIED

(1) Indicating and Controlling. The flux level is measured by a specially designed ionization chamber. The design of this chamber has not been worked out, but it must be capable of operating in the 500°F. pile temperature and at a neutron flux level in the range of 10^6. Three such ionization chambers are located around the perimeter of the pile reflector. One of these units is always a standby, one is in use for flux measurement and the third is used by the power level regulator. The electrical current flow in these chambers is proportional to the flux level. The chamber in use for pile power level control is connected into the input circuit of the neutron flux amplifier in the power level regulator. The chamber in use for flux measurement is connected through a suitable electrical amplifier to a standard commercial voltmeter calibrated in units of neutron flux.

The temperature of the helium leaving the pile is measured by placing a platinum-alloy of platinum and ruthenium thermocouple in the outgoing helium chamber above the pile. The millivolt output of this thermocouple is measured by a commercial temperature recorder.

A duplicate thermocouple similarly installed is used in the temperature regulator circuit. A third thermocouple is installed for a standby. The leads from all three are arranged so that they are interchangeable.

A pressure gauge is installed on the outgoing steam line, which indicates and records the steam pressure. A similar pressure instrument converts the pressure measurement into a control voltage for use in the power level regulator. These instruments are interchangeable.

(2) Indicating and Recording. These measurements are quantities which have no direct relation to pile power regulation, through an automatic control circuit.

The regulating rod drive temperature is recorded by a standard temperature instrument. The hot junction of a thermocouple in the drive supports inside the rod thimble measures the drive temperature.

A similar thermocouple arrangement is located at each of the shim rod drives. A multiple temperature recorder instrument is used to record these temperatures at about 1 minute intervals.

The temperature of the six safety rod thimbles is measured by a thermocouple hot junction located inside of each thimble. The temperatures are recorded on a multiple temperature recorder.

The temperature of the seal oil is measured at the supply header by a standard temperature recording instrument.

Standard orifice type flow meters are used to measure and record the water flow to the boiler and the steam flow out of the boiler.

DECLASSIFIED

A venturi meter is used to measure and record the coolant flow through the pile.

Electrical current flow to each of the safety rod magnets is measured with a standard indicating ammeter.

Cooling air flow to the thimble chamber is indicated by a fan operated switch and a light at the control panel.

The speed of the coolant blower and the steam turbine in the coolant blower drive system are measured by electrical tachometers. The speed is recorded on the tachometer charts.

Standard electrical voltmeters indicate the voltages of, the main bus, the pile power system, the pile control system, and the D.C. alarm system.

The position of each of the safety rods is shown by a light. The lights are operated by limit switches which close when the rod plungers are "all in" or "all out". Two lights are provided for each of the six safety rods.

The position of the regulating rod is shown by a pointer dial, which is actuated by a follower selsyn motor, which in turn is connected to the master selsyn motor in the position indicating assembly for each shim rod.

A pointer is attached to the shaft driving the shim rod master signal potentiometer.

The position indicator dials for the shim rods and the master signal potentiometers are mounted together so that a quick comparison of the readings can be made and any error noted.

Suitable pressure gages are provided to read the helium pressure in the reserve tanks and the pressure of the oil for the shaft seals.

Indicating lights, turned on by the respective motor starters, show that the motor generator sets for shim and regulating rods are operating.

(3). Alarms. When the pile is in operation some dangerous conditions may arise which could cause damage to the pile or injure operating personnel. Such a condition must shut the pile down; as well as set off an alarm. Other dangerous conditions need only set off an alarm and call the operators attention to the troubles.

The safety relay circuit is described under the synchronizing and interlocking section of this report. This circuit contains twenty four contacts or sets of contacts; each of which indicates a condition dangerous

DECLASSIFIED

SECRET

enough to require immediate pile shutdown. All of these contacts except the manual lock out switch have back contacts connected into a shutdown alarm and annunciator circuit. This circuit is designed so that, when a contact opens and allows the safety rods to fall into the pile, it also closes a contact, energizes an annunciator light and sets off the alarm bell. The bell can be silenced by turning the manual lockout switch to silence. The light continues to burn until the trouble is corrected.

The radioactivity is measured at the entrance and exit to the ventilating stack. When this radioactivity is high an alarm is set off. This alarm cannot be silenced and the alarm continues to operate until the condition is corrected.

Another annunciator system with a silenceable alarm is used to indicate dangerously high radioactivity measured at a number of points around the pile and boiler equipments.

Radioactivity is measured in the ventilating space around the pile, each high temperature duct, each boiler, each helium suction and discharge header, each helium blower, each helium surge tank and the helium purifier.

Samples of the helium are drawn off and radioactivity measured at the inlet and outlet of each boiler, inlet and outlet of the helium purifier, each helium blower-motor housing, the helium gas holder and the helium decontamination system.

Steam and water samples are similarly monitored for radioactivity at the superheater steam outlets, the boiler drum water, the boiler blowdown water, the condensate line out of the condenser, the boiler feedwater pumps, the deaerators and air ejectors.

Each compartment or room, to which operating personnel has access, is monitored for a dangerous radioactivity intensity. When a safe limit is exceeded an alarm is set off at the room involved and an annunciator light is lit in the pile control room.

A meter continually measures the steam condensate conductivity and has a self contained alarm and annunciator to indicate an excessive quantity of impurities in the water.

All these alarm circuits are energized from an emergency battery power system so that power is available to operate the alarms even if the main supply fails.

SECRET

DECLASSIFIED

~~CONFIDENTIAL~~

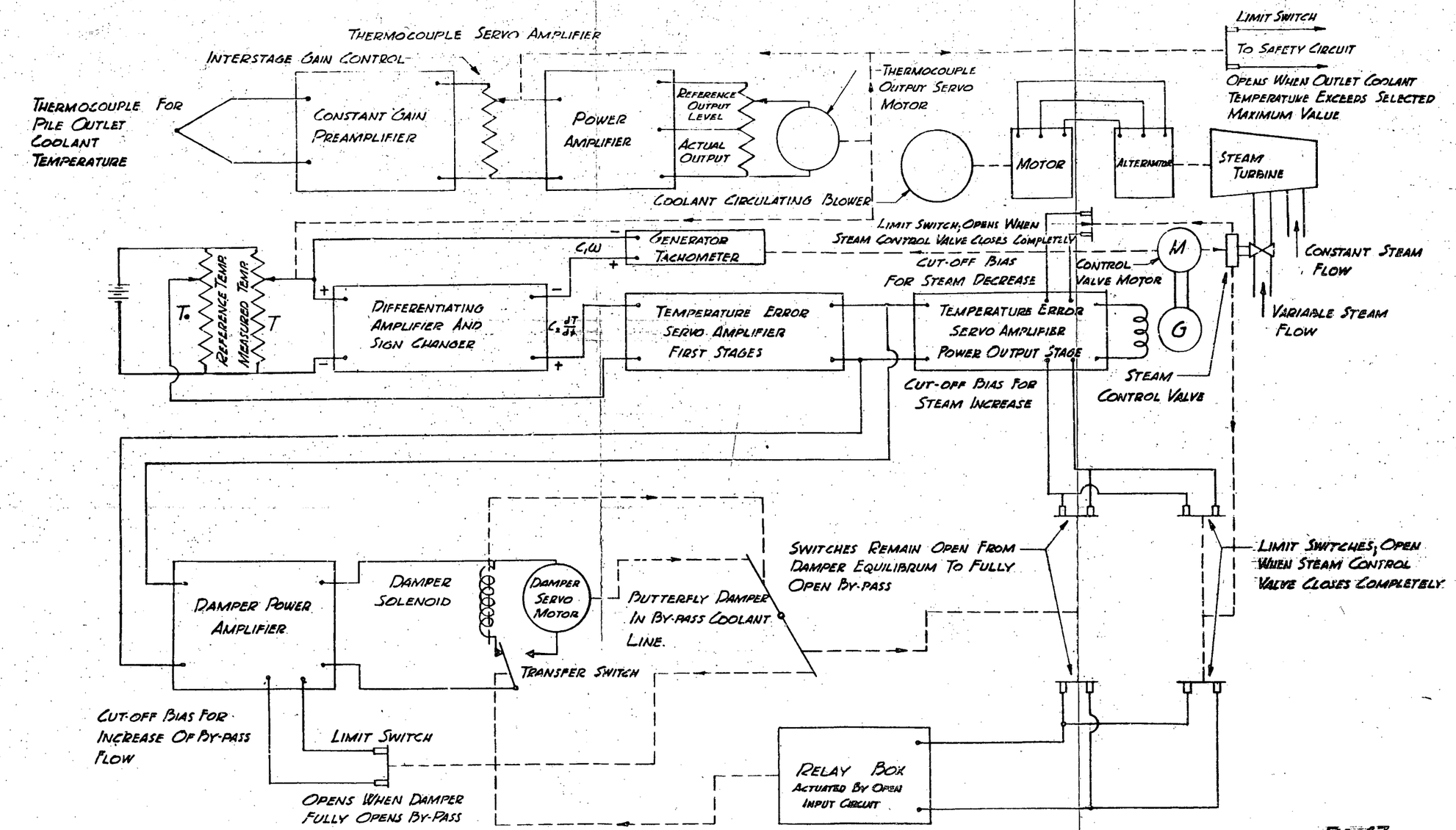


FIG. 47

~~CONFIDENTIAL~~

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

AUTOMATIC TEMPERATURE REGULATOR
SCHEMATIC BLOCK DIAGRAM
HIGH TEMPERATURE - GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D	C.N.L. 8-20-47	C	A.J.S. 8-8-47	A	8-21-47 8-18-47 7-11-47
Proj. C-222-A1					C-2795

SECRET

6. Coolant System and Power Conversion Equipment.

The main coolant circuit is connected to the pile with duplicate, high temperature, parallel-flow cooled, outlet ducts and with duplicate inlet ducts. The high temperature ducts connect to duplicate boilers, the discharges from which connect to a common header. Four blowers in parallel draw the helium from this header and discharge to another common header. Duplicate ducts return the helium to the pile. Arrangement of equipment is shown schematically in the Flow Diagram, Fig. 48.

Shut-off valves are located in the boiler discharge ducts and the pile inlet ducts. Each blower has valves on the inlet and discharge in the connections to the headers. The high temperature boiler outlet ducts have U-traps in lieu of valves. The U-traps are to be filled with some low melting point metal, such as lead-bismuth alloy, when they are to be shutoff, and this metal is to be melted out when they are to be opened. By suitable manipulation of the valves, it is possible to operate the pile with any single piece of equipment in the main-circuit inoperative.

Between the blower inlet and discharge headers is a by-pass connection containing a shutoff valve and an adjustable butterfly valve. This butterfly valve is used for achieving quick response in flow variation under varying loads and for controlling the by-pass helium flow at very low power operation.

At the points where the return ducts connect to the pile, 6" diameter lines containing damper valves are noted. These 6" diameter lines conduct the cool helium to the parallel flow cooled high temperature ducts and the dampers control this flow relative to the flow through the pile.

The piping for the main coolant circuit is indicated on the flow diagram showing the pipe size, helium temperature, helium pressure, and helium flow. The auxiliary systems such as supply, surge, evacuation, etc. indicate the approximate pipe sizes.

The dotted line on the flow diagram represents the shielding against radiation. Everything inside the dotted line requires shielding and everything outside does not.

The helium supply is connected to the blower suction header, which is at the lowest pressure in the main coolant circuit. By means of valves and pipes shown, the helium supply may be discharged directly into the main coolant circuit or it may be passed through a purification plant first. Until very high purity helium is available, a purification plant is required.

The blower inlet and discharge headers are shown with blanked-off ends. It is thought that at some future time these could be extended to connect to new, and possibly different, blowers. This could be done to increase the capacity of the system or to replace blowers which are inoperative, and which cannot be removed because of radioactivity.

SECRET

DECLASSIFIED

All equipment in the main coolant circuit is designed for a pressure of 250 psi gauge to allow for a margin of safety over the ten atmospheres maximum operating pressure. The system is protected by a pop safety valve and rupture disc so that the system pressure cannot rise above the design pressure.

All of the equipment in the main coolant circuit is designed for a maximum rating to match a maximum pile heat output of 20,000 KW. The expected normal full load heat output of the pile is 12,000 KW which gives a normal rating for all of the main coolant circuit equipment of 60% of the maximum rating.

The following table summarizes the coolant system performance at normal and maximum output:

	Normal	Maximum
Pile Heat Output, KW	12,000	20,000
System Operating Pressure, Atmospheres, Abs. (Pressures shown in Fig. 48 are psi, Abs.)	10	10
Helium Temperature Entering Pile, °F.	500	500
Helium Temperature Leaving Pile, °F.	1400	1400
Helium Flow Through Pile, Lb/Sec.	10.2	17
Duct Cooling Helium Flow, Lb/Sec.	2.1	2.5
Total Helium Flow Through Blowers, Lb/Sec.	12.3	19.5
Pressure Drop Through Pile, psi	.95	2.5
Total System Pressure Drop, psi	1.4	3.61
Velocity of Helium Through High Temperature Duct fps	66	110
Velocity of Helium Through Low Temperature Duct fps	51	85
Time Required for Helium to Complete One Cycle, Sec.	6.7	4

A plant layout has been made of the main circulating system showing the general arrangement of equipment. See Fig. 49. The details of design of the components of the helium system are described as follows:

a. High Temperature Duct. The general arrangement of the high temperature duct connecting the pile to the boiler is shown on Fig. 50.

DECLASSIFIED

SECRET

Helium gas from the pile is supplied to the inner core of the duct at a temperature of 1400° F. and under a pressure of 132 psi gauge. The casing of the inner duct is cooled by means of helium supplied to the annulus surrounding it. The maximum temperature of the helium used as duct coolant is 500° F. and its pressure is somewhat higher than the pressure in the inner core. Flow of the coolant is controlled to maintain the metal temperature in the external duct at 850° F. The duct, however, has been designed for a maximum temperature of 1000° F. It has no expansion joints. Duct expansion is provided for by having the boiler float and the pile rigidly fixed.

The U-loop shown in the duct provides means for sealing the pile by use of liquids or low melting alloys in the annulus and core when the pile is shutdown to obtain access to the boiler or to the high temperature duct between the seal and the boiler. Connections are to be provided for draining both annulus and core.

The duct liners forming the annulus are arranged to take the expansion caused by the difference in metal temperature between the liner and the main body duct. It is not intended that the joint be tight. Due to the higher pressure in the annulus any leakage would occur from the annulus to the inner core and would not be objectionable in small quantities.

The main or outer duct is constructed in sections. These sections are joined together by means of circumferential fusion welds to form a continuous pipe. Each section could be formed from 26" O.D. pipe (if procurable) or from so called "fabricated sections" of bends and piping. In either case the inside diameter should closely approximate 24-1/2".

(1) Table of Specifications - Outer Duct.

Inside Diameter	24-1/2"
Design Press	250 psi gauge
Maximum Metal Temperature	1000° F.

Material - Alloy Steel ASME Code Specs. S. A. 158 Grade P5a. Thickness - to be determined in accordance with the allowable stresses specified by the ASME code for power boilers plus 1/10".

The circular liner or inner sleeve acting as the partition between the inner core and the other annulus is constructed in short sections. Ends of each section would be fabricated to provide a sliding type expansion joint. Spacers are provided on the outside of the liner whose purpose is to maintain a uniform distance between the liner and the external duct. Spacers should be designed to allow for differential expansion between outer duct and inner liner and prevent any relative longitudinal motion of one end of the liner with respect to the duct.

SECRET

DECLASSIFIED

The length of the sections of the liners is substantially the same as the lengths of the sections of the main duct and the ends of the liners would be located approximately at the positions of the circumferential welds in the outer duct.

(2) Table of Specifications - Inner Duct.

Inside Diameter	22"
Thickness of Liner	1/8"

Material - Alloy steel ASME Code Specs. No. SA 158 Grade P5a.

b. Boiler. Each of the two boilers to be provided is designed to absorb one-half of the heat generated by the pile, based on pile heat generation at a rate of 20,000 KW with helium at 10 atmospheres heated to 1400° F. at the pile outlet connections. In passing through the high temperature duct between the pile and the boilers the helium temperature is reduced 55° F.; thus, at maximum design rating, the boilers receive helium at 1345° F. and the helium pressure at entrance to the boilers is 132 psi gauge. The primary helium flow through each boiler under these conditions is at a rate of 30,700 lbs. per hour, and the boilers are so proportioned that the helium pressure drop does not exceed 1/2 psi.

In addition to this primary helium flow, each boiler, at maximum designed rating, receives 4600 lbs. per hour of helium used for cooling the high temperature duct as described in the previous section. This duct cooling helium reaches the boiler at a temperature of 885° F. The primary function of the boilers, insofar as operation of the pile is concerned, is to cool the primary and secondary helium to 500° F. or lower, for return to the helium system via the low temperature duct work and the helium blowers.

The primary function of the boilers, as regards the production of useful power, is to generate steam. At maximum designed rating each boiler produces 29,200 lbs. per hour of steam at 450 psi gauge and 735° F. for discharge to the steam turbines, when supplied with deaerated feedwater at 235° F.

It has been decided that forced re-circulation type boilers best meet the requirements of this application. The boiler arrangement is shown schematically in Fig. 51. The boiler pressure shell enclosing the heating surface is located within the biological shielding. The steam drum and re-circulating pumps are mounted outside the shield with the necessary connecting steam and water lines passing the shield in such a manner as to avoid direct radiation paths through the shielding. The boilers are designed to meet the requirements of the ASME boiler code. The boiler pressure shell is designed for 250 psi gauge pressure with an added allowance of 1/10" metal thickness to provide for metal which may be dissolved from exposed surfaces during decontamination operations.

DECLASSIFIED

SECRET

Feedwater enters the economizer which is located at the lower end of the boiler pressure shell. At rated boiler output the economizer heats the incoming feedwater from 235° F. to 420° F. and this heated water is discharged directly to the boiler steam drum through connecting piping which traverses the biological shield. The recirculation pump takes suction from the boiler steam drum and discharges through the shield to the boiler evaporator inlet located above the economizer within the boiler pressure shell. The heat absorbed by the recirculated water during its passage through the evaporator converts part of the water to steam. This steam-water mixture is discharged from the boiler evaporator outlet to the boiler steam drum where the water and steam are separated. The water mixes with the incoming feedwater from the economizer and returns to the recirculation pump for another circuit through the evaporator. The steam passes through water separators provided in the steam drum and the resulting dry saturated steam is piped through the shielding to the superheater inlet. In the superheater the temperature of the steam is raised from 460° F. to 735° F. for discharge to the turbo-generator.

The primary helium flow enters the top of the boiler from the terminus of the central section of the high temperature duct. The 1345° F. helium first traverses the upper section of the boiler evaporator and reaches the superheater elements at somewhat reduced temperature. Proper proportioning of the amount of evaporator surface above the superheater results in maintenance of substantially constant superheated steam temperature throughout the normal boiler operating capacity range. If this arrangement were not provided and the superheater were located at the top of the boiler, the superheated steam temperature would increase with decreasing boiler output, and special precautions would be necessary to avoid overheating the superheater, and damage to the main steam system and turbines.

The primary helium flow, after traversing the superheater passes over the balance of the evaporator surface below the superheater. Part way through this lower evaporator section the primary helium stream is reduced to 885° F., the temperature which the duct cooling helium attains at the boiler end of this duct. The duct cooling annulus is extended into the boiler pressure shell to this point and the 885° F. duct cooling helium mixes with the primary helium flow. The combined streams then traverse the balance of the evaporator and pass on through the economizer elements located at the lower end of the boiler. Sufficient economizer surface is provided to cool the helium to 500° F. at maximum boiler output rating. At reduced boiler capacity the combined helium flow leaving the economizer is cooled to a temperature lower than 500° F., the amount of temperature depending on operating conditions.

The lower end of the boiler pressure shell, below the economizer, is arranged for removing water from the helium stream should a leak occur in the boiler. Large slugs of water fall to the bottom of the shell under the influence of gravity and the smaller particles are separated from the helium by separators provided around the periphery of the shell below the economizer. The separators are designed to reduce the liquid water content of the helium to 5% or less by weight under most adverse conditions of leakage.

SECRET

DECLASSIFIED

SECRET

During normal operation of the plant the moisture separators provide for extraction from the helium stream of BeO dust particles dislodged from the BeO moderator and fuel slugs in the pile. This material is collected in the lower end of the boiler pressure shell and blown out to decay tanks periodically.

The purified helium flows upward from the separators through an annulus provided between the inner casing of the boiler and the outer boiler pressure shell. By this means the pressure shell is maintained at a uniform temperature of about 500° F. and thermal stresses in the pressure shell are avoided without the need for using internal heat insulation which would complicate subsequent decontamination of the boiler for inspection or repair. At the upper end of the boiler pressure shell above the shell cooling annulus, the helium is collected and discharged through the low temperature duct to the pile via the helium blowers.

Detailed specifications have been prepared to describe the desired boiler arrangement as outlined above, and are included for information in Appendix G of this report. Two boiler manufacturers have submitted detailed design propositions complying with these specifications. Figures 52, 53 and 54 show the arrangements proposed with overall dimensions and details of various features.

c. Low Temperature Ducting. Ducting on the low temperature (500° F.) side of the main circulating system takes the helium from the boiler through the blowers and back to the pile. This ducting also provides for necessary valving to isolate boilers and blowers when desired; it also provides for necessary flexibility to take care of differential expansion between the hot side of the circulating system and the low temperature side.

The low temperature ducting is illustrated on the plant layout, Fig. 49. It consists of an 18" I. D. line in the form of an inverted U leading from each boiler to an 18" I. D. suction header. Each leg of the U contains two bellows type expansion joints operated in tandem so as to take care of both longitudinal and transverse motion. A valve is located at the top of the U in the horizontal run. From the header, a 16" I. D. line, also in the form of an inverted U as described above, is led to each blower. From each blower a 16" line is led to an 18" I. D. discharge header, again by use of an inverted U. From this header in a similar fashion two 18" I. D. lines return to the pile; a flow meter is located in each of these lines.

The low temperature ducting is anchored just beside each valve so that difficulty would not be encountered with motion of the valve stem extension in the concrete shielding. The headers are anchored in the center and are supported on rollers along their length. Rollers are installed at the top of each U to resist moments on the valves which are caused by the forces of the expansion joints.

SECRET

DECLASSIFIED

SECRET

Both the 16" ID and 18" ID ducts are 5/16" thick. All low temperature ducting is of carbon steel, SA-158 Grade 5a as described in "ASME Code Specification for materials, 1943", page 131.

The arrangement shown provides for valves in horizontal pipe runs as recommended by valve manufacturers, and places them so they are accessible during operation. Expansion joints are in vertical pipe runs so that acid used for decontamination can be drained out of them. Ducting is arranged so that any equipment it is intended to isolate is not in direct line with the valves which do the isolating.

d. Blowers. The single stage centrifugal compressor type of blower has been selected for this application. As seen in the flow diagram, Fig. 48, four blowers are used. Their inlets are connected to a common header. A valve is located in each inlet and discharge duct to and from each blower to isolate each blower either for operating reasons, or for inspection, repair, or replacement of the blowers. The capacity of blowers is such that the operation of all four in parallel matches the maximum pile heat output of 20,000 KW, with a system pressure drop of 3.61 psi.

The performance of each blower at maximum rated speed is as follows:

Volume Flow	5340 ft.^{3} min.
Pressure Rise	3.61 psi.
Inlet Temperature	500° F.
Inlet Pressure	147 psi. absolute.
Rated Speed	7200 rpm.
Range of Operating Speeds	4 to 1.
Rated Shaft Power	116 hp.

Each of the blowers is electrically driven by a squirrel cage induction motor close coupled to the compressor and totally enclosed with the blower in a common housing thereby avoiding the need for an absolutely tight shaft seal. The motor and blower are separated by a simple labyrinth seal, but the motor space is filled with helium and is helium cooled; the helium is in turn cooled by a helium-to-water heat exchanger. The motor is protected by a thermal shield from the 500° F. temperature existing in the helium stream. See Fig. 55.

The electric motor has a normal rating of 125 hp at 7450 rpm. The motor is a low voltage machine operating at 130 or 240 volts in order to minimize the possibility of insulation breakdown due to radiation. Silicone bonded glass insulation is used. The motor is capable of operating at variable speeds from 25% to full speed, from a variable frequency source.

SECRET

DECLASSIFIED

In order to supply the variable frequency current required for speed variation two 250 KW steam driven alternators are provided complete with all necessary controls, governing equipment, and switchgear. One alternator and turbine can take care of two or more blower units.

For operating the blowers with quick flow changes under varying loads, a by-pass line is provided (See Fig. 48) in which is located a butterfly valve. This valve is actuated automatically immediately upon load variation and the blower speed changed afterwards as the butterfly valve is returned to its steady state position.

e. Large Valves. The helium flow diagram shows that a number of large valves are required in the main flow system which contains radioactive impurities. These are as follows:

Location	Size	Number
Duct to Pile	18"	2
Boiler Outlet	18"	2
Blower Inlet and Discharge	16"	8
Blower Header By-pass	18"	1
Evacuation System Inlet	18"	1

The valves used in these locations are of the double disc, buffered, gate valve type, shown in Fig. 56, and having the following special features:

(1) Operation of the gate is achieved by a rising stem which passes through the 6' biological concrete shield. The stem is stepped to prevent any straight path for radiation leakage.

(2) The valve stem packing is outside of the shielding and so arranged that it can be changed with the valve in either the open or closed position.

(3) Helium under pressure is introduced into a lantern ring in the packing. Thus, pure helium would leak into the valve and pure helium would leak out of the packing. The out-leakage is collected in a second lantern ring and piped to a stack or suitable decay tank.

(4) The in-leakage of helium is limited by a back-seat when the valve is open. Thus, the stem and stem containing tube in the shield are full of pure helium, and the contaminated helium is restricted to the bonnet and valve seat.

(5) During opening or closing of the valve, there would be an inflow of helium between the stem and stem tube which would prevent contaminated helium from entering this space.

DECLASSIFIED

(6) When the valve is closed, pure helium under pressure is supplied along the stem into the bonnet. This would leak into the system through any leak in the valve seats. Thus, the two valve seats are independently sealed, and helium leakage would always be pure helium inward, even if one side of the valve is open to atmospheric air.

(7) The valve is of all welded construction using wrought materials to minimize leakage of radioactive helium.

(8) The valve is provided with electric motor operation. Provision is made for manual operation in case of an electric power failure.

(9) The main body of the valve is of plain carbon steel, ASME Code Spec. SA-158-P-5a. This is the same material used in the low temperature helium ducts which are welded to the valve.

(10) The valve is mounted rigidly on a suitable base foundation. Thermal expansion stresses in the low temperature ducts are relieved by expansion joints in these ducts so the valve can remain fixed.

Valve seats are made of soft stellite seating against hard stellite. The helium leakage through each valve seat is limited to that which would cause a pressure rise of 440 micron cu. ft. per hour on vacuum test of a single valve. This corresponds to a leakage of 1.65 cc/hr. at operating conditions.

f. Moisture Detector. The moisture detector is located in the helium stream, as shown in the Flow Diagram, Fig. 48, to detect small leaks of steam or water from the boiler into the helium system during operation and to shutdown the pile when there is a sudden increase in the moisture content of the helium stream.

The design which appears most satisfactory at the present time is that incorporating two instruments, a specially dehumidified Infra Red Analyser (Baird Associates) for measurement and detection of small amounts of water vapor and an instrument based on the change in electric surface conductivity with changes in moisture content to trip the safety rods in case of excessive moisture.

The Infra Red Analyser is designed to trip an alarm when the moisture content rises to 1-3% and the electrical conductivity instrument trips the safety rods into the pile when the moisture rises to 4-6%. A recorder is included with these devices to give a permanent record of the moisture content over a long period of time. The moisture detection and recording apparatus is designed to operate satisfactorily over a pressure range of 1 to 10 atmospheres and over a temperature range from 60 to 500° F.

Provisions are made in this device to permit putting in a drop of water from time to time to check the sensitivity of the instrument, after installation, particularly with respect to the effect of accumulation of dirt and impurities.

DECLASSIFIED

g. Surge System. The surge system is provided as an experimental facility for changing the operating pressure in the power plant. It consists of two sets of gas storage tanks, a low pressure set and a high pressure set, so arranged that gas pressure in the pile cooling system may be reduced by pressure transfer or equalization with the low pressure set of tanks, or may be increased by pressure transfer from the high-pressure set of tanks. A pump is provided within the surge system to transfer gas from the low pressure set to the high pressure set. A heat exchanger in the transfer line between the surge system and the pile cooling system serves to cool the hot gas being transferred to the surge system; this heat exchanger would be by-passed when transfer is in the opposite direction. A diagram of this system is shown in Fig. 57.

The high pressure storage facilities consist of four tanks, each having a volume of 750 cubic feet, and each capable of retaining helium gas at a pressure of fifteen atmospheres absolute and at temperatures up to 180° F. The minimum operating temperature would be that of the extreme weather at the final plant site, and can be assumed to be -10° F. if the installation is made in Oak Ridge.

The low pressure storage facilities include three tanks, each having a volume of 3300 cubic feet. Each of these tanks is capable of retaining helium gas at pressures up to 4 atmospheres and at temperatures not higher than 180° F. or lower than -10° F. One tank is also capable of operation at reduced pressure down to one tenth atmosphere.

Both the high pressure and low pressure tanks are of all welded construction, fabricated from low carbon steel and are free from any leaks detectable by an electronic leak detector.

The transfer pump has a capacity of 40 cfm at suction conditions of one atmosphere and 100° F. with a total compression ratio of fifteen. Two such pumps are provided, one for normal operation and one for standby. In addition to the main transfer pumps, two low pressure transfer pumps are provided to reduce the pressure in one of the low pressure tanks to one-half atmosphere or less. One of these pumps is for normal operation and the other for standby service. Either is capable of pumping helium at a rate of 40 cfm at suction conditions of one-half atmosphere and 100° F. with a compression ratio of four.

The heat exchanger in the transfer line from the pile cooling system is capable of cooling helium gas from 500° F. to 100° F., at a maximum rate of 20 lbs. per min. for five minutes, under conditions of decreasing gas pressure from 10 atmospheres to 1 atmosphere.

All piping in the surge system is extra-strong seamless steel pipe, with welded joints. Valves in these lines are of fabricated low carbon steel construction, bellows-sealed, globe or angle type, supplied with welding ends. Valves used for isolation of parts of this system for decontamination or maintenance work are installed in duplicate, i.e., two valves in series with provision for applying a buffer gas pressure between them.

DECLASSIFIED

All tanks, pumps, valves, and piping in the surge system are surrounded by biological shielding. The space inside the shielding is suitably ventilated and monitored to detect any radioactivity which might result from a small leak.

h. Gas Holder and Safety Device. As shown on the Flow Diagram, Fig. 48, a gas holder is supplied in the system to receive the entire helium charge from the system in event that circulating system must be dumped. Since the gas holder must have suitable radiation shielding for safety, it is underground with a concrete lid over it about 5 ft. thick and a large vent pointing straight up. The gas holder is of the usual water seal type with about 28,000 ft.^{3} NPT capacity. This is sufficient to hold the charge of the helium system at 10 atmospheres and room temperature. The design of the lid would have to be special to withstand the sudden acceleration due to sudden dumping of the pile. The discharge from this gas holder feeds into the gas decontamination system so the gas holder can be slowly emptied once it is filled.

Between the pile helium system and the gas holder, a safety device is provided consisting of a sealed bursting disc placed in the discharge line of a totally enclosed spring loaded pop safety valve which is provided with an excess flow check valve by-pass. The rupture disc is designed to break at a safe pressure for the system and the relief valve is set to close at some lower pressure. With this combination, the rupture disc would make the unit perfectly tight during normal operation of the pile. If the pressure should ever get out of control and rise to break the rupture disc only the amount of helium which must be discharged to lower the pressure to the setting of the relief valve would be lost from the system, i.e., the safety device would not dump the system to atmospheric pressure.

The excess flow check valve by-passing the relief valve insures the presence of the system pressure on the rupture disc at all times by remaining open as long as the disc is intact. In the event that the disc ruptures the rush of gas through the excess flow check valve closes the check and the differential between the system pressure and atmospheric pressure keeps it closed. The relief valve then opens and discharges helium to the atmosphere until the system pressure is blown down to the closing pressure of the relief valve. If a second pressure increase takes place before the disc can be replaced the relief valve reopens and operates in the same manner as the safety valve on any conventional steam or gas pressure.

In order to avoid leakage through the safety device after the disc has once ruptured it is necessary to shut down the plant and install a new disc.

Detail design of the gas holder and safety device has not been undertaken except to prepare the necessary specifications outlined above.

i. Ventilation of Shielding. The space immediately inside the shielding is to be maintained at a pressure slightly below atmospheric and continuously swept or ventilated by air drawn through an exhaust fan and discharged up a stack. The purpose is to sweep away any small amounts of helium that may leak into this space and prevent this leakage from coming

DECLASSIFIED

through the shield and endangering personnel. The air stream would be monitored at all times to detect any activity which would indicate a leak or imminent failure.

This ventilation system would include only standard industrial controls and is to be designed in detail after final layout of the plant is begun.

j. Helium Purification. Small concentrations of certain impurities in the helium coolant may interfere with efficient pile operation. Accordingly, since various impurities will be introduced into the system by commercial helium and by the formation of gaseous impurities from volatilization of and by chemical reactions between pile materials, provision is made for purification and detection facilities in the helium system, in addition to the moisture separator and detector previously described.

(1) Detection - The mass spectrometer has been selected as the instrument most suitable for analyzing the coolant for impurities. In Columns 4 and 5, Table XVI, are tabulated the limits of sensitivity of the mass spectrometer for a standard and also for a special type instrument. The mass spectrometer is not satisfactory for water vapor determination and it probably would not be sensitive enough for oxygen analysis. However, this instrument is useful for scanning the molecular weight spectrum and determining possible impurities (i.e., oxides of nitrogen) not now foreseeable. It is a valuable tool for studying the formation of gaseous impurities during pile operation. So far as oxygen detection is concerned the Air Reduction Sales Company makes a detector known as Airco Oxygen Method #8 which is recommended for this application. The Baird Associates Infra Red Analyzer and electric surface conductivity instrument discussed in Part B-6-f of this section are provided for moisture detection.

(2) Purification - The purification plant is composed of four parts, an Evacuation and Degassification System, a Make-up Helium Purification System, a Continuous Purifier and a Gas Decontamination System.

(a) Evacuation and Degassification System. The large quantity of gaseous impurities adsorbed on the surfaces of the various pile materials would have to be removed before the pile is started in order to minimize possible contamination of the coolant. This is done as follows:

1. Evacuate system with a multistage jet pump (Worthington Pump and Machinery Corporation).

2. Introduce helium into the evacuated system. Circulate and heat the helium by means of steam in the boiler or by means of electric heaters.

3. Evacuate hot system in order to desorb impurities.

4. Refill with purified helium, heat and circulate.

5. Evacuate.

6. Repeat as often as is necessary as shown by analysis of the coolant.

DECLASSIFIED

The foregoing procedure would remove most of the easily desorbed gaseous impurities. When the pile is started, additional gases would be desorbed. However, these gases would appear in lesser concentrations and would be removed by the continuous purifier.

(b) Make-up Helium Purification System. Commercial grade helium of purity 98.0 - 98.7% helium is supplied by the Bureau of Mines. A compilation of typical analyses is given in Column 2, Table XVI. Helium is delivered from the plant in Amarillo, Texas, in railroad tank cars at 1800-2500 psi, each tank car containing about 200,000 ft.^{3}. The Bureau of Mines claims that 99.6% high purity grade helium will be available the latter part of 1947. The high purity grade would be used in the high temperature pile if it is available. Purification facilities are provided, however, for using commercial grade purity.

A small low temperature activated charcoal adsorption plant would be used for this purpose. A dryer of the electrodryer type is used in conjunction with this unit. The capacity of the plant and dryer is sufficient to supply a daily make-up of 1000 ft.^{3} of helium per day. This figure may be revised downward. No shielding is required for this plant. A diagram of the make-up purification system is shown in Fig. 58.

(c) Continuous Purifier. A refrigerated, activated charcoal purification plant is used for continuous purification of the helium. Refrigeration is obtained from a closed nitrogen cycle engine similar to the type now being used by the Bureau of Mines at Amarillo, Texas. A diagram of the Continuous Purifier is shown in Fig. 59. The capacity of the plant has been set at 10,000 ft.^{3} of helium per hour. A plant of this size will maintain the purity of the helium well within the tolerances which have been established.

Tolerances for the design of the Continuous Purifier are listed in Column 3, Table XVI. They have been conservatively estimated from available information, and are for the pile operating at a level of 10,000 KW. Because some of the information was incomplete, the tolerances are tentative.

(d) Gas Decontamination System. Decontamination of radioactive helium gas which must be disposed of is provided by the following facilities all of which must be shielded.

1. Low temperature charcoal purification, if necessary.

2. Storage tanks for the decay of radioactivity. A tentative capacity of 100,000 ft.^{3} total has been chosen as adequate. This figure is subject to probable revision downward.

3. Dilution of radioactive gas for stack disposal.

DECLASSIFIED

k. Steam Power Generating System.

(1) Main Steam Power System - The steam power generating equipment is arranged to operate on the complete-expansion Rankine-cycle as indicated by Fig. 60, which shows the connections for the main and auxiliary steam system. Steam is conducted from the two boilers at 450 psi gauge pressure and 735° F. temperature to a common header located adjacent to the power generating equipment. Pressure drop and heat losses in the conducting pipe system are expected to reduce this pressure and temperature to 415 psi gauge and 725° F., respectively, at the header. Connections are then made from the main header to equipment as follows:

(a) Two connections are provided for each of the main turbo-generators. These turbine generators are Navy surplus units built by the General Electric Company for a rating of 4600 KW at 5600 rpm (93 cycles); they generate 1800 KW at 3600 rpm (60 cycles). The steam consumption with 410 psi gauge pressure and 725° F. temperature is 11.35 lb. per kw-hour, or 20,500 lb. per hour at 1800 KW. Since this steam plus that needed for auxiliaries, just about matches pile performance with a pile heat output of 12,000 KW, it is planned to install only one turbine-generator set initially. A second set and accessories will be installed in a standby condition such that it may be easily connected and put in operation if it is found feasible to operate the pile at a higher output.

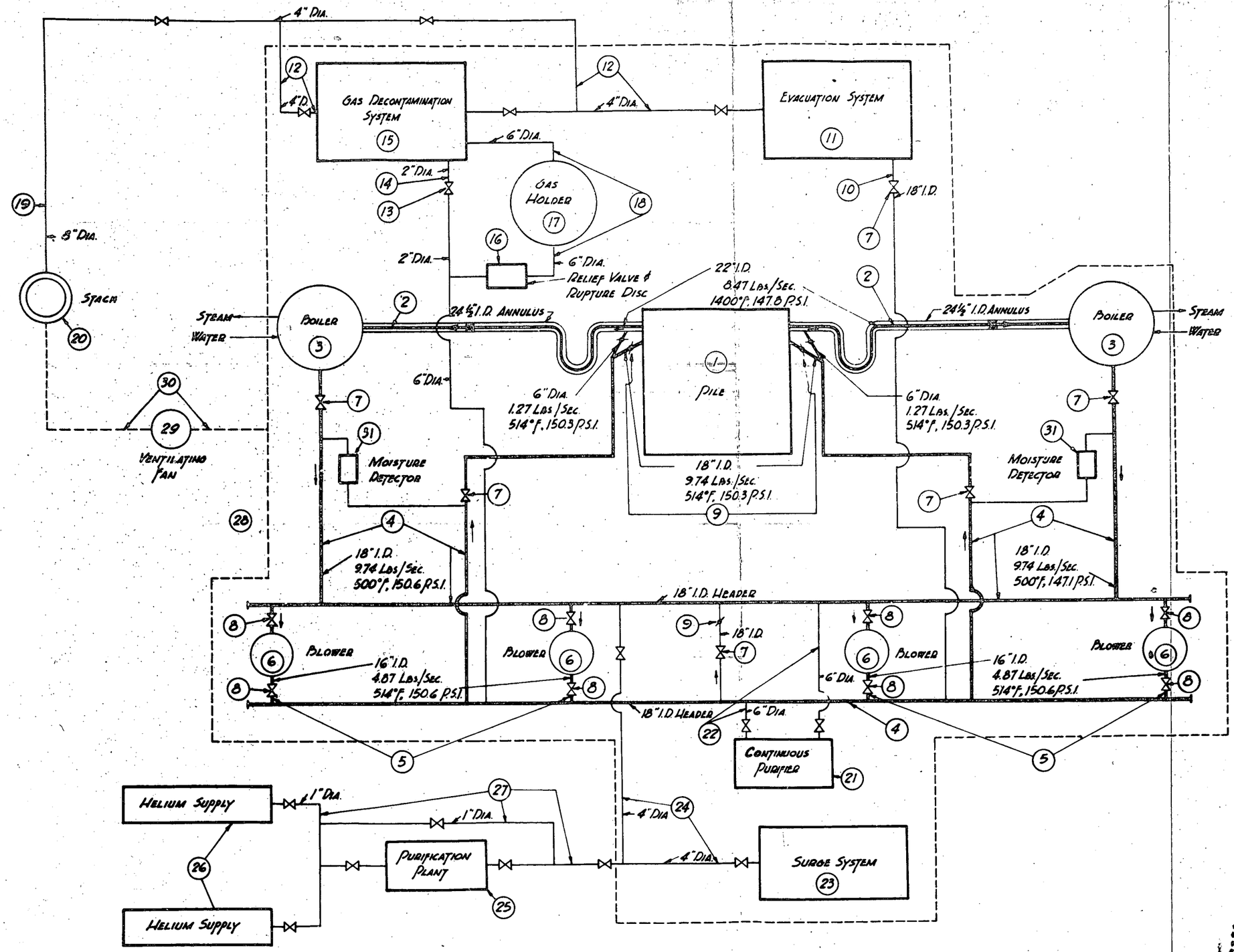
(b) One auxiliary turbine-generator set with accessories is installed for a rating of 300 KW 60 cycle AC and 40 KW DC. This is Navy surplus, built by the General Electric Company for a house supply in the DE-51 escort vessel. The turbine requires steam at 400 psi gauge, saturated, which is to be obtained from a reducing and desuperheating station installed in the feed line from the main header. This set is not to be operated under normal conditions, but is used for initial start-up of the plant for testing, and for standby power when neither main turbine-generator sets are operating. It may also be used for very low power operation when it is not deemed worth while to operate the main sets.

(c) Two emergency steam condensers or "steam-killers" are connected to the main header such that either will be capable of condensing steam from both boilers when operating at normal output of 12,000 KW. These emergency condensers are installed so that operation up to full power can be obtained even if both main turbine-generator sets are inoperative. Steam generated under these conditions can be condensed and returned to the system thus maintaining the high purity of boiler feed required.

(d) Since it is planned to use sealed or "canned" induction motors for the helium blower drives, it is necessary to provide connections on the main header for the two variable-speed turbo-alternators to energize these motors as described previously in the section on blowers.

(e) In addition to the connections for the above equipment, spare connections are provided on the main header for possible future installations and for a connection to an external source of steam for emergency operation if needed.

DECLASSIFIED



ITEM	APPARATUS
1	PILE SHELL
2	HIGH TEMP. DUCT
3	BOILER & CONTROL
4	LOW TEMP. DUCT 18" MAIN CIR. SYSTEM
5	LOW TEMP DUCT 16" MAIN CIR. SYSTEM
6	BLOWERS (SEALED) BLOWERS (CANNED)
7	SPECIAL VALVE 18" I.D.
8	SPECIAL VALVE 16" I.D.
9	DAMPER
10	EVACUATION SYSTEM INTAKE DUCT
11	EVACUATION SYSTEM
12	EVACUATION SYSTEM EXH.
13	BACK PRESS VALVE
14	GAS DECONTAMINATION SYSTEM DUCT
15	GAS DECONTAMINATION SYSTEM
16	RELIEF VALVE & RUPTURE DISC
17	GAS HOLDER
18	PIPING FOR GAS HOLDER & RELIEF VALVE
19	DECONTAMINATION EXHAUST DUCT
20	STACK
21	CONTINUOUS PURIFIER
22	DUCTS & VALVES FOR CONTINUOUS PURIFIER
23	SURGE SYSTEM
24	SURGE SYSTEM DUCTS
25	PURIFICATION SYSTEM
26	HELIUM SUPPLY SYSTEM
27	PIPING & VALVES LINKING PURIFICATION SYSTEM & HELIUM SUPPLY SYSTEM
28	VENTILATING SYSTEM
29	VENTILATING FAN
30	DUCTS FOR VENTILATING FAN
31	MOISTURE DETECTOR

FIG. 48

FLOW DIAGRAM

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D-2267

DECLASSIFIED

(2) Auxiliary Steam System - This system consists of a steam main carrying desuperheated steam at 400 psi gauge pressure and 500° F. temperature connected to the main header through a reducing and desuperheating station, and an additional main carrying steam at 150 lb. per square inch saturated, which receives its steam from a reducing and desuperheating station connected to the 400 psi - 500° F. main. The reducing and desuperheating stations receive desuperheating water from the boiler feed-water supply main. Steam is supplied from the 400 psi - 500° F. main to the 340 KW. auxiliary turbo-generator previously described and to the standby steam-driven centrifugal boiler feed pump. The 150 psi gauge, saturated, steam system supplies steam to the condenser air-ejectors, and is used as an emergency supply of steam through reducing valves to the 10 psi gauge, auxiliary exhaust system, which supplies steam to the deaerating feed heaters, distilling plant and turbine gland seals.

(3) Condensate and Boiler Feed System - Exhaust steam from the main turbine-generator sets is condensed in matched Foster-Wheeler 3800 sq. ft. surface condensers from the DE-51 vessels. These condensers are each capable of condensing the full output (20,500 lb. per hr.) of steam from the main turbines at 28 in. hg. of vacuum when using 6000 gpm of 85° F. cooling water. The condensate is then transferred by condensate pumps, installed in duplicate, to two Foster-Wheeler closed-type, single shell low-pressure feed-water heaters, one per each main condenser. Each low-pressure heater includes the main air-ejectors, inter-condenser for the main ejectors, after-condenser for the main and auxiliary ejectors, gland steam condenser and drain cooler. Cooling water for the inter and after coolers is supplied from the main and auxiliary condenser condensate pump discharge. The condensate leaves the low-pressure heaters at a temperature of approximately 120° F.

The exhaust steam from the 340 KW auxiliary turbine, and that portion of steam from the helium-blower turbo-alternators which is not needed for the deaerating feed-heaters, distilling plant and gland seals is condensed in two Allis-Chalmers 28 in. by 6 ft. surface condensers from the DE-51 vessels. These condensers are cross-connected so that either may be used to condense the exhaust from either turbine sets. The condensers are rated at 6600 lb. per hr. of steam at a vacuum of 25 in. hg. when circulating 500 gpm of 85° F. cooling water.

All condensers from the DE-51 vessels are to be reworked to eliminate leakage between the cooling water and the condensate, and a detection device similar to the Salinity Cells aboard the DE-51 vessels is to be installed in the system for warning if leakage does occur.

(4) Feed Water Heaters - Condensate from the main and auxiliary condensers is transferred by condensate pumps to the deaerating feed-water heaters. These heaters are installed for the three-fold purpose of conserving heat energy in the exhaust steam, supplying heated water to the boiler to minimize thermal stresses in the shell, and finally to insure that boiler-feed water is free of oxygen and dissolved gases in order that corrosion effects are reduced to a minimum. Exhaust steam from the auxiliaries

DECLASSIFIED

at 10 psi gauge is used for heating through adjustable reducing valves with ranges from 0 to 10 psi. The maximum attainable temperature of boiler feed with this steam pressure is thus limited to less than 240° F., and with this temperature it is expected that the oxygen in the feed-water can be kept to less than 0.005 cc. per liter. Each feed-water heater is mounted over an 875 gallon surge tank, hence, there is enough feed-water for 15 minutes of operation with a pile output of 12,000 KW for emergencies.

(5) Distilling Plant - In order to supply the initial boiler water, and make-up water lost from the system during operation, a connection is made from the demineralized water plant for the High-flux Research Pile to two Griscim-Russel Soloshell Distilling Plants of 8000 gallons per day capacity each installed at the Power Pile. Therefore, since water from the demineralizing plant is of a purity comparable to distilled water, the water entering the boiler-feed system is the equivalent of doubly distilled water. The distilled water from the distilling plants will discharge to 500 gallon distilled water storage tanks and hence to the feed-water heaters as needed. The water from the High-flux Research Pile demineralizing plant is supplied at a maximum rate of 35 gallons per minute and will be stored in 1000 gallon capacity storage tanks mounted on the roof to feed water to the distilling plant as required.

(6) Boiler Feed Pumps - From the feed-water heater surge tanks the boiler water is discharged to boiler feed pumps and hence into the boilers. These boiler-feed pumps consist of two electric motor driven pumps and one steam turbine driven pump connected in parallel. The electric motor driven pumps are for normal operation and the steam-turbine driven pump is for emergency standby in case of failure of both motor driven pumps. Each electric motor driven pump will be rated at 70 gal. per min. at 550 psi gauge discharge pressure. The steam-turbine driven pump has about the same capacity, and is built by Ingersoll-Rand for the DE-51 escort vessels. The capacity of each pump is sufficient to supply feed-water to each boiler when operating with pile outputs up to 20,000 KW.

(7) Cooling Water System - Cooling water is supplied from the Clinch River bounding the Clinton Engineer Works. Due to the comparatively large quantity of water required and the distance involved in pumping from the Clinch River, a closed cycle cooling system has been selected. Initially, the generating plant is to be installed with only one main turbine-generator and accessory equipment connected and ready to operate, which will represent the conditions of operation at 12,000 KW pile output. The cooling water requirements for the condensing and cooling equipment for power generation at 12,000 KW is 7600 gal. per minute. For pile operation, at 20,000 KW, the cooling water requirement is 13,550 gal. per minute. These figures are for the power generating system alone. The cooling water requirements for the remainder of the plant are estimated at 400 gal. per minute, making the total estimated quantity of cooling water required for the Power Pile approximately 14,000 gpm at maximum output. Therefore, a forced-draft cooling tower is erected adjacent to the plant with an ultimate capacity of cooling 14,000 gpm of water from 105° F. to 85° F. during the worst conditions of summer weather contemplated. Provision is made for pumping 1500 gpm of raw water to the plant for make-up. Fig. 61 shows diagrammatically

DECLASSIFIED

the cooling water circuit. The condensing and cooling equipment have individual pumps for circulating the water from an intake tunnel in the plant connected to the cooling tower basin. The water discharges to the outlet tunnel and is circulated by high-head large-acpacity centrifugal pumps through the emergency condensers and hence to the cooling tower. The intake tunnel also discharges to the outlet tunnel through a weir-type of level controller such that, should there be a failure of power equipment, the cooling water passes directly through the emergency condensers, bypassing the other equipment and, thus, condensing the steam which the boilers will continue to produce due to stored heat in the pile before shut-down can be completed.

1. Electrical Generating System. The electrical generating system is included in the pilot plant to provide facilities for testing the control characteristics of an integrated power plant under various load conditions. This system is also available for electrical power supply in the event that external power is temporarily not available. A diesel-electric generator is also provided for emergency electric service.

The electrical system has been designed around the main turbo-generators, excitation sets, auxiliary turbine generator sets, emergency diesel generators and switchgear which are to be obtained as surplus from the Navy.

Fig. 62, "Generating Station and Switchyard", shows the proposed arrangement of the electric generating facilities. The electrical system would be connected to the Clinton Laboratories distribution substation by two short 2300 volt feeder lines as indicated on the drawing. Breaker protection on each line would be provided at the distribution substation end.

Basically, the substation is divided into two sections; a "power out" bus, and a "load" bus. The main generator, rated at 1800 KW, feeds through the main 2000 KVA 1735/2300 volt transformer bank to the "power out" bus. The 300 KW auxiliary generator feeds through a generator breaker and a 450 KVA 440/2300 volt transformer bank to the same bus. A feeder from the "power out" bus takes the energy to the central distribution substation (not shown). The circuit breaker at the distribution substation in conjunction with the main generator breaker would be expected to protect the 2000 KVA transformer bank. The 450 KVA auxiliary transformer bank is protected by its own high side breaker and the auxiliary generator breaker. This arrangement is believed to provide adequate reliability and reasonable flexibility for the delivery of power from the generators.

The second section of the station constitutes the "load section". This section is normally supplied with power by another feeder connecting the central distribution substation. The direct load on the 2300 volt bus would presumably include induced draft fans for ventilating the power plant and pile, the circulating water pumps, and possibly power for the helium purification apparatus and the helium blowers.

DECLASSIFIED

A 1000 KVA 2300/440 volt transformer with a breaker on the high tension side takes power from the 2300 volt "load" bus and delivers it to the 440 volt "load" bus. This bus would supply all electrically driven equipment having motors of less than 100 hp capacity.

One group of feeds from the 440 volt load bus, that protected by circuit breaker 9, supplies loads that must be kept in operation for several hours after the pile is shut down. In the event of a power failure, these loads may be isolated by opening circuit breaker 9 and then be driven by the emergency diesel-generators.

The arrangement shown is intended to provide considerable flexibility of operation, including separation of the station into the generating section and the load section, so that generation would be independent from auxiliary loads and hence possible difficulties or instability in operating the generators would not result in disturbances of power supply to the station auxiliaries.

All equipment operating at 2300 volts, including the three transformer banks and circuit breakers 1 through 4, would be outdoor type, while the equipment and buses operating at lower voltage would be indoor type.

The drawing also lists the estimated requirements for the various air circuit breakers (ACB's), under the two tabulations headed "Air Circuit Breaker Ratings". The extreme righthand columns of these tabulations show the recommended characteristics for the breakers to be procured.

Proposed metering for the various circuits, and the protective relaying are also shown on the drawing. The metering consists of ammeter, voltmeter, wattmeter, watt-hour meter and frequency meter for each generator, and a voltmeter for each bus level, which may be connected to the various bus sections by means of a voltmeter transfer switch. A synchroscope is provided for synchronizing various combinations of generators and incoming lines.

Protective relaying for the main generator consists of over current, reverse power, phase balance and ground current. Differential protection would be desirable in lieu of most of that listed, but it now appears impractical to bring out the three phase neutrals, as they are interconnected inside the machine. The auxiliary generator relaying is similar to that for the main generator except no ground current relay is provided, as this machine is operated ungrounded. The bus tie breaker and the auxiliary load transformer breaker provide only over-current protection.

A major factor in station arrangement is the necessity for assuring operation of certain station auxiliaries under any emergency. It is a characteristic of the pile that there is appreciable heat production for a number of hours after shutdown. Facilities must be provided to remove this heat or the pile may be destroyed. This means that minimum gas coolant circulation must be assured, and that condensing water must be available to remove the heat from the steam produced in the boiler.

DECLASSIFIED

To assure power for the auxiliaries, four sources are provided; (1) the area substation, (2) the main generator, (3) the auxiliary generators, (4) the emergency diesel generators. The two lines from the area substation to the power pile substation are capable of independent operation.

The ultimate source of emergency power is provided by two emergency diesel generators, each with its own share of load. The generators will start automatically with the tripping of circuit breaker 9 (which occurs whenever the 440 volt bus is de-energized) and as the generators operate independently, synchronizing will not be required.

DECLASSIFIED

7. Chemical Processing of Fuel Elements

Operation of the pile will necessitate two major chemical processing operations; recovery of uranium from depleted fuel units, and separation of the U^{233} produced from thorium in the pile. In addition to the above operations, processes for the separation of beryllium and thorium will eventually have to be developed in order to conserve these materials.

a. Recovery of Uranium from Depleted Fuel Units. Early in the power pile program it was evident that the chemical process being developed by the Technical Division for the recovery of uranium from the Research Pile fuel assemblies could be applied to recovery of uranium from Power Pile fuel units. Research Pile fuel assemblies as processed consist of a uranium-aluminum alloy containing about 7% uranium. The separation of uranium from fission products is accomplished by the use of a continuous counter-current organic solvent extraction process, after preliminary dissolving of the fuel assembly in nitric acid. The aluminum in the assembly is utilized as a salting-out agent. Two extraction and stripping cycles are being considered, the first being carried out under oxidizing conditions and the second under reducing conditions, such that plutonium will remain in the aqueous phase during the second extraction. After the second stripping process, the uranium is precipitated, ignited and then delivered to the refabrication plant. On the basis of the present data it is estimated that the loss of uranium in chemical processing will be 0.2% or less per pass through the chemical processing plant. The total hold-up of fissile material due to processing operations alone will be about five days. About 45 days cooling, before chemical processing, would be required, and an additional cooling time of about 80 days would be required to allow decay of U^{237} produced in the pile in order that fuel unit refabrication operations could be performed without necessity of remote control. Allowing 10 days for fuel unit refabrication, the total hold-up of fissile material due to chemical processing and fuel unit refabrication would probably be about 140 days. Since beryllium is a better salting-out agent than aluminum, it is apparent that the process described above could be modified for the use of Power Pile fuel units containing beryllium.

b. Graphite Fuel Units. Since graphite fuel units may be used, considerable study was given to chemical reprocessing of graphite units. The use of graphite fuel units will effect a considerable saving in reprocessing costs. This saving is particularly significant because one of the major economic factors involved in the application of atomic power will be the cost of constructing and operating the chemical process plant.

The advantage of the graphite unit lies in the fact that it would be possible to recover the uranium, and to prepare a feed for the solvent extraction columns which is perhaps 100 times as concentrated as is possible in the case of the Be-U and $BeO-UO_2$ fuel units. In the Be and BeO units, the concentration of uranium is limited by two factors:

(1) In a solution which is more than 4 molar in beryllium, the beryllium is extracted into the organic phase with the uranium.

(2) At higher concentrations the solubility of $Be(NO_3)_2$ is a limiting factor requiring a relatively large volume of solution.

DECLASSIFIED

Specifically, the uranium solution recovered from graphite units will be of the order of 2 molar, while that recovered from beryllium units will be of the order of .02 molar. It is estimated that the cost of constructing and operating a chemical process plant for the graphite units would be 4 or 5 times less than the cost of the process using beryllium fuel units.

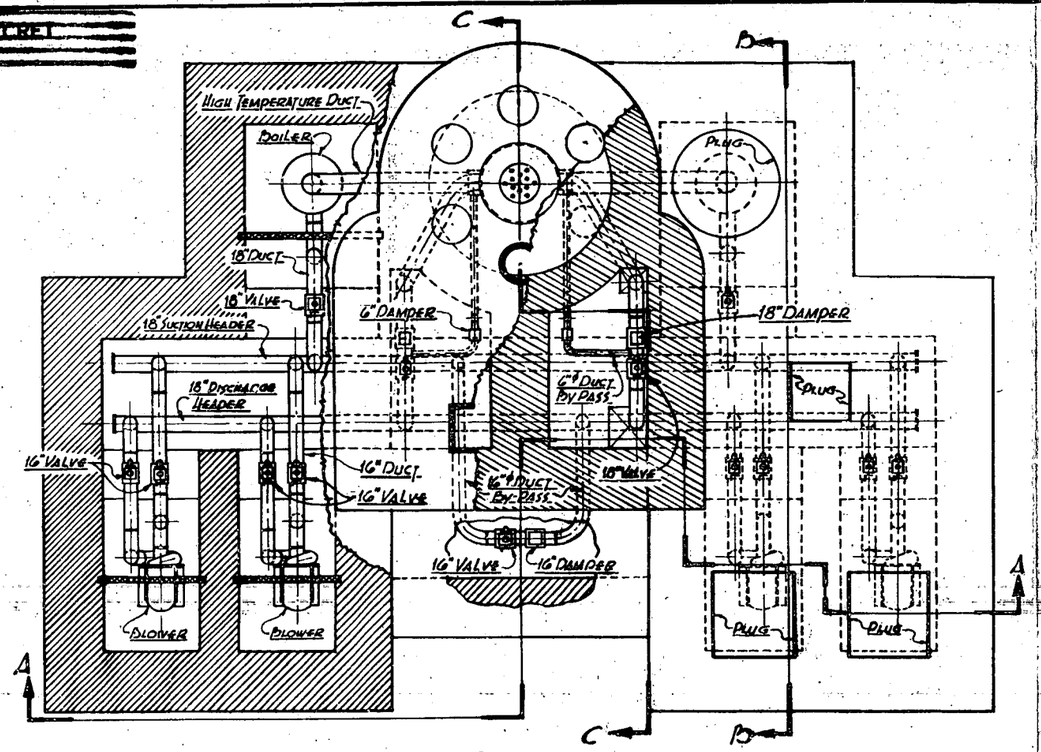
The responsibility of the Power Pile Division in connection with chemical processing is the development of a process for the recovery of uranium, together with the bulk of the fission products which will accompany it, from the graphite. The most promising process appears to be one involving the burning of graphite, and leaching of the residue with nitric. The residue should contain less than .001% of the original uranium if burning has been complete. Critical factors in the process will be the control of dusting during burning, the effecting of complete burning, the recovery of the small amount of dust which is now considered inevitable, and the performance of porous metal filters now being considered for use in the dust filtration step and the leaching operations. An experimental program has been outlined and is now awaiting procurement of personnel and facilities.

A schematic outline of the process is shown in Fig. 90. Graphite fuel units are ignited in a small combustion chamber, and the combustion gases containing perhaps 0.1% of the total uranium as dust are bubbled through a small packed vessel counter-current to nitric acid. The combustion gases then pass through the upper part of the filter and out the stack. The liquid level in the leaching vessel will be between the two levels indicated. The liquid level must be at least as high as the top of the downcomer. The liquid level cannot be higher than the top of the filter, because pressure caused by gases accumulating in the upper part of the leaching vessel will force the acid through the filter. Combustion could take place for probably 10 hours before it would be necessary to dump the ash down into the leaching vessel. At intervals, possibly every two days or so, it would be necessary to drain the leaching vessel and oxidize the unburnt carbon by soaking the whole vessel in oxygen at about 900°C. A filter is placed at the point where the acid enters the leaching vessel to minimize the possibility of combustion gases leaving through the condenser due to some inadvertent unbalancing of pressure. The uranyl nitrate solution in the HNO_3 still is periodically jetted to the solvent extraction process described above.

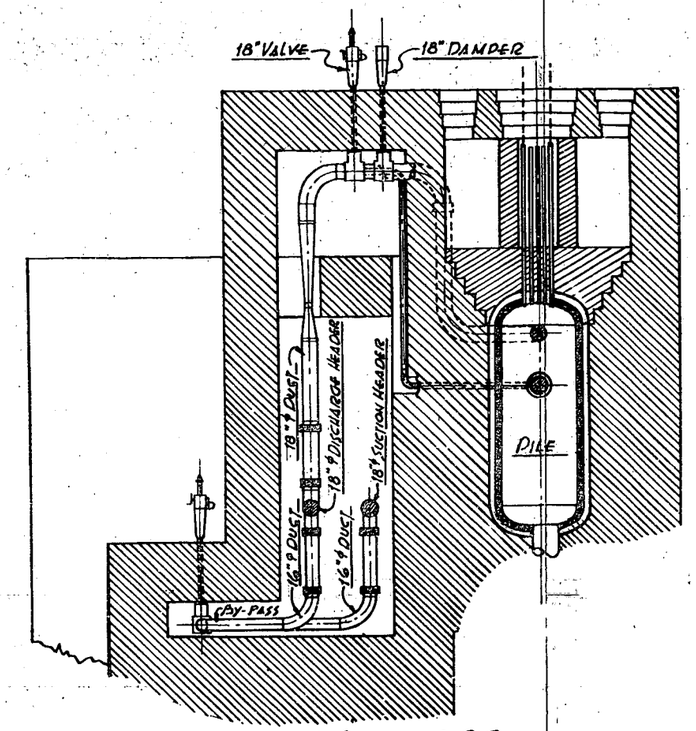
c. Separation of U^{233} from Thorium. The process for separation of U^{233} from thorium is being developed by the Technical Division, and is in the laboratory and semi-works state. A solvent extraction process similar to the fuel unit recovery process is being developed. It is expected that the process loss of U^{233} will be of the same order of magnitude as for the fuel unit process, about 0.2%.

DECLASSIFIED

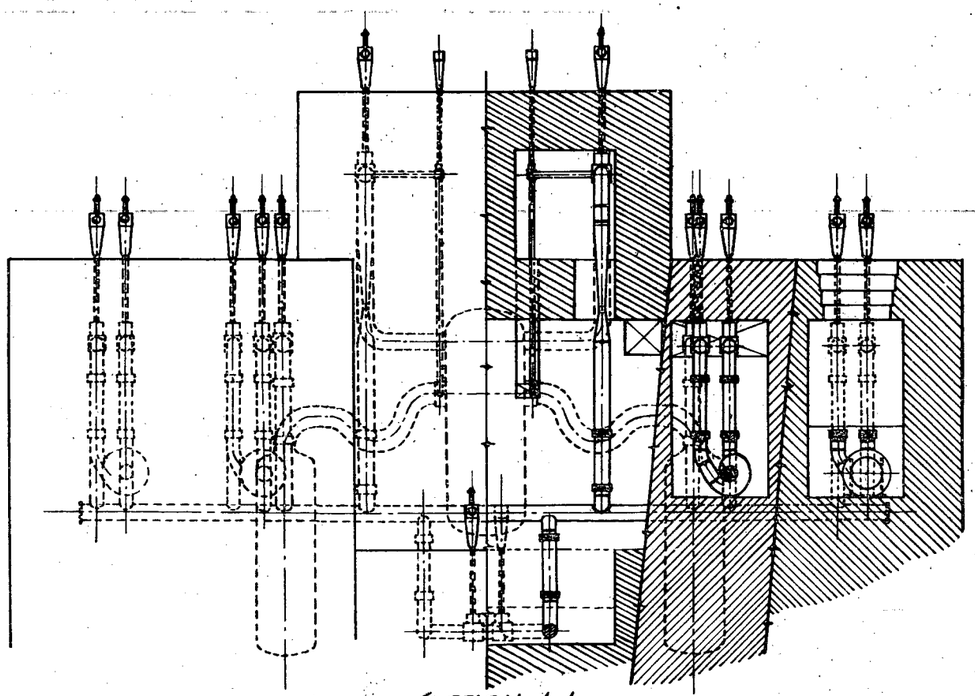
SECRET



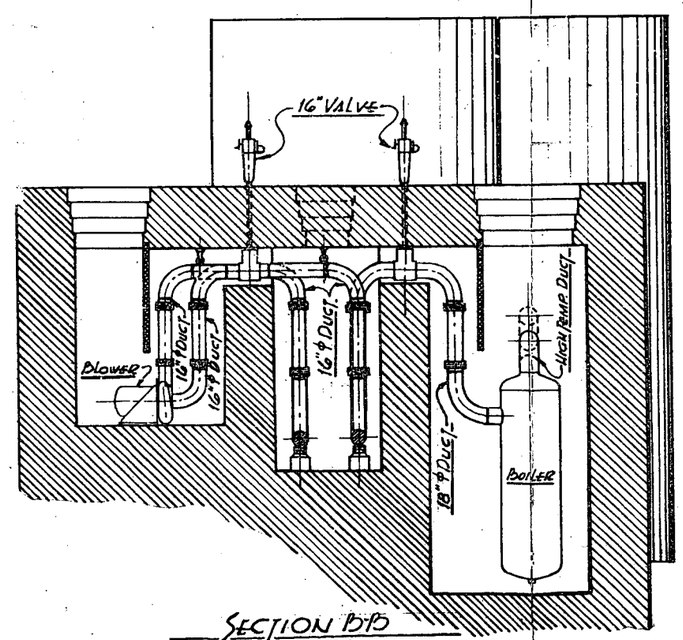
PLAN



SECTION C-C



SECTION A-A



SECTION B-B

FIG. 49

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

PLANT LAYOUT STUDY

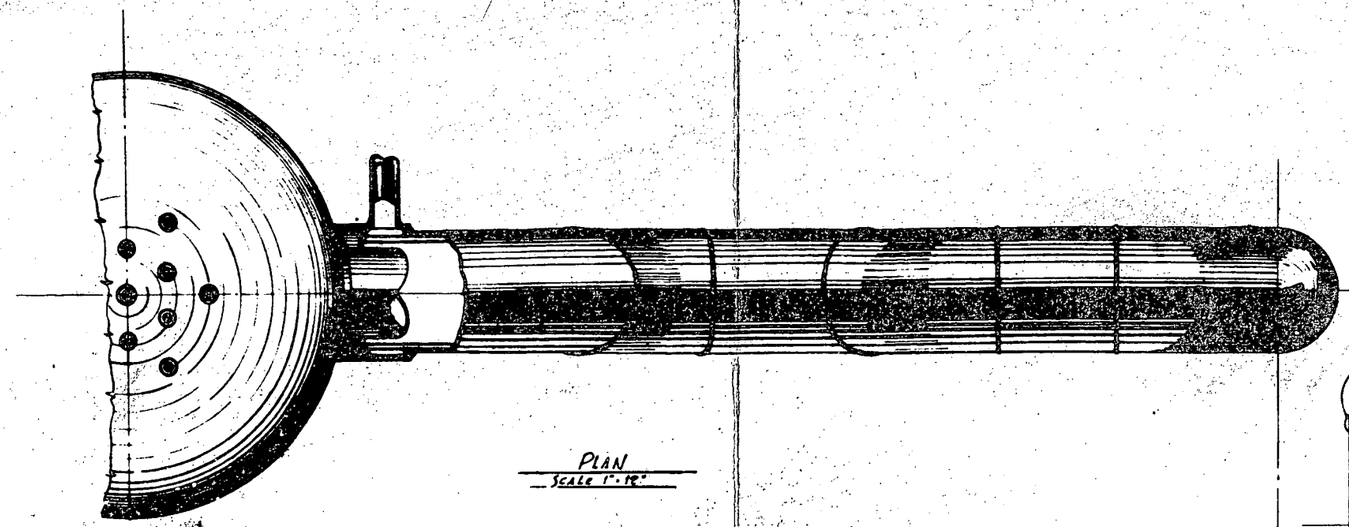
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

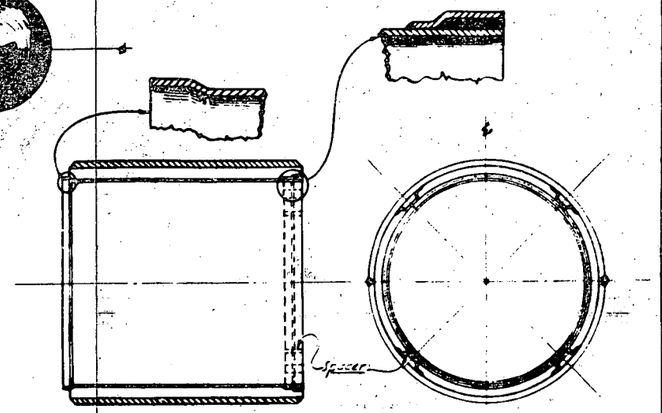
Nuclear Engineering	W.G.P.	MGP.	R.L.S.	CRP
D. 9-5-47	C. 9-11-47	A. 9-11-47	9-16-47	9-17-47
Proj. C-288M				C-2959
Scale:				

DECLASSIFIED

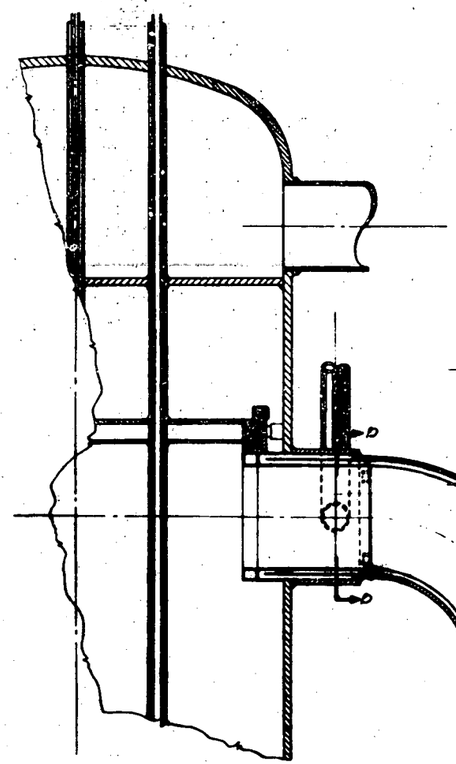
CONFIDENTIAL

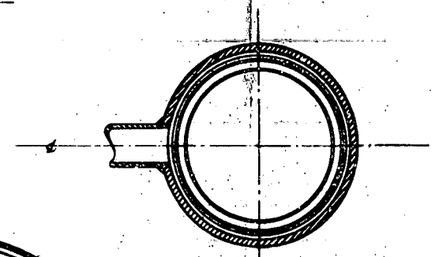


PLAN
SCALE 1" = 18"

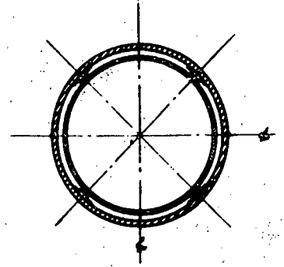


TYPICAL DUCT DETAIL
SCALE: NONE

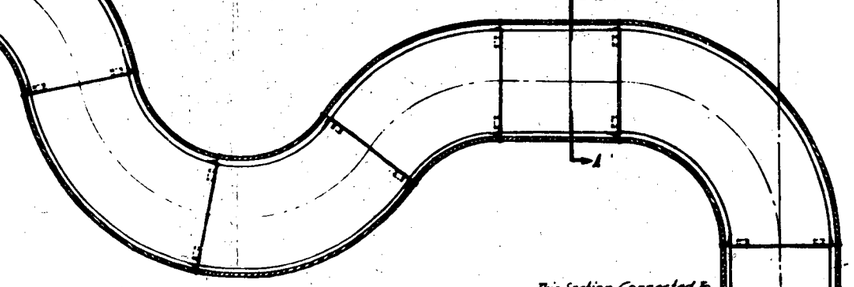




SECTION D-D
SCALE 1½" = 18"



SECTION A-A
SCALE: 1½" = 18"



SECTIONAL ELEVATION
SCALE 1" = 18"

FIG. 50

CONFIDENTIAL

HIGH TEMPERATURE DUCT
HIGH TEMPERATURE GAS CHECKER BOILER PLANT

MONSANTO CHEMICAL CO.

DECLASSIFIED

DECLASSIFIED

DECL

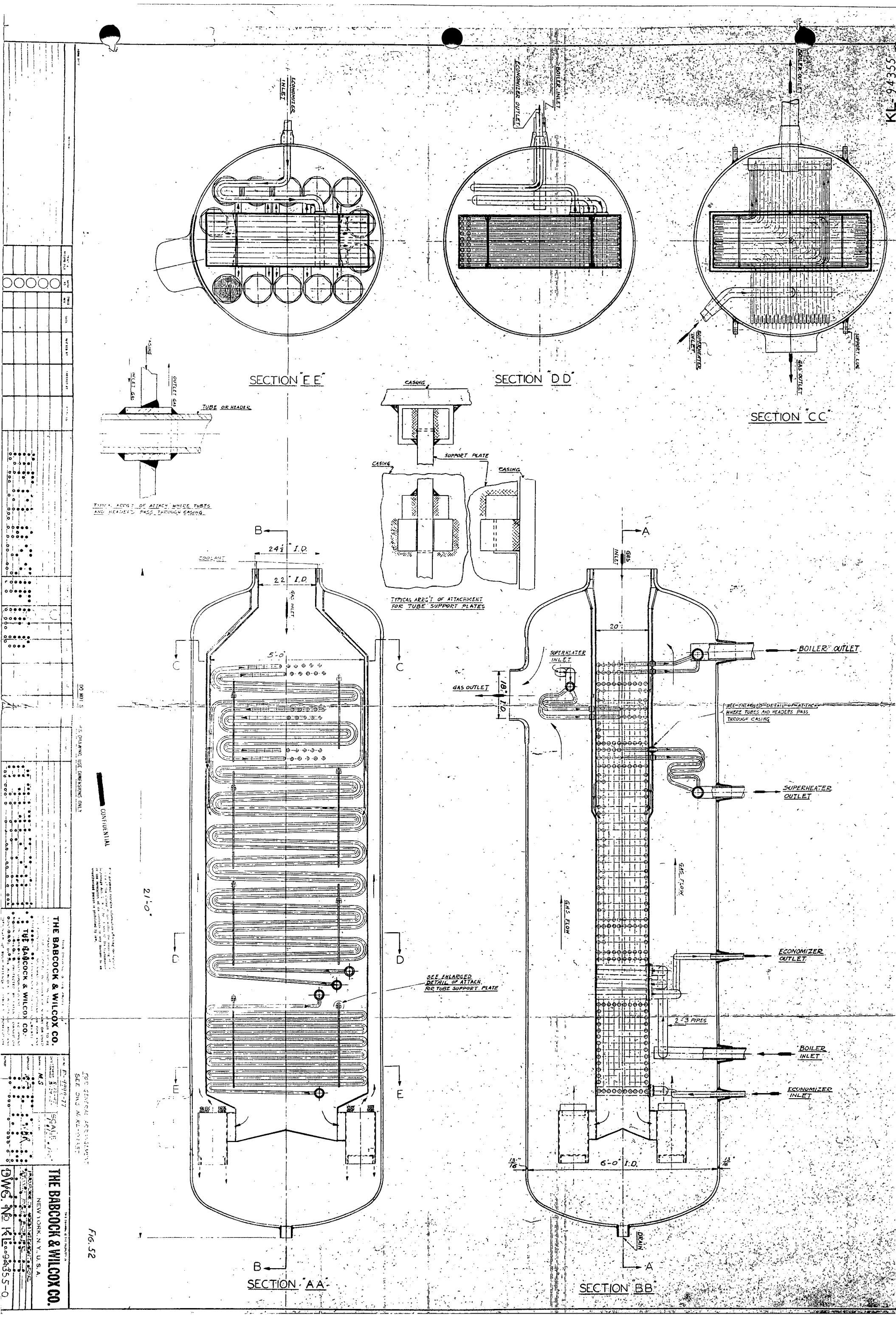

KL-94355
ECONOMIZER INLET
SECTION "E E"
ECONOMIZER OUTLET
BOILER INLET
SECTION "D D"
BOILER OUTLET
SUPERHEATER INLET
GAS OUTLET
SUPPORT LUG
SECTION "C C"
CASING
INLET GAS
OUTLET GAS
TUBE OR HEADER
TYPICAL ARR'G'T OF ATTACH WHERE TUBES AND HEADERS PASS THROUGH CASING
SUPPORT PLATE
TYPICAL ARR'G'T OF ATTACHMENT FOR TUBE SUPPORT PLATES
COOLANT
24½" I.D.
22" I.D.
GAS INLET
5'-0"
21'-0"
SEE ENLARGED DETAIL OF ATTACH. FOR TUBE SUPPORT PLATE
SECTION "A A"
GAS INLET
20"
SUPERHEATER INLET
GAS OUTLET
18" I.D.
BOILER OUTLET
SEE ENLARGED DETAIL OF ATTACH. WHERE TUBES AND HEADERS PASS THROUGH CASING
SUPERHEATER OUTLET
GAS FLOW
ECONOMIZER OUTLET
2"-3" PIPES
BOILER INLET
ECONOMIZER INLET
6'-0" I.D.
DRAIN
SECTION "B B"
THE BABCOCK & WILCOX CO.
NEW YORK, N.Y., U.S.A.
DWG. NO. KL-94355-0

FIG. 52

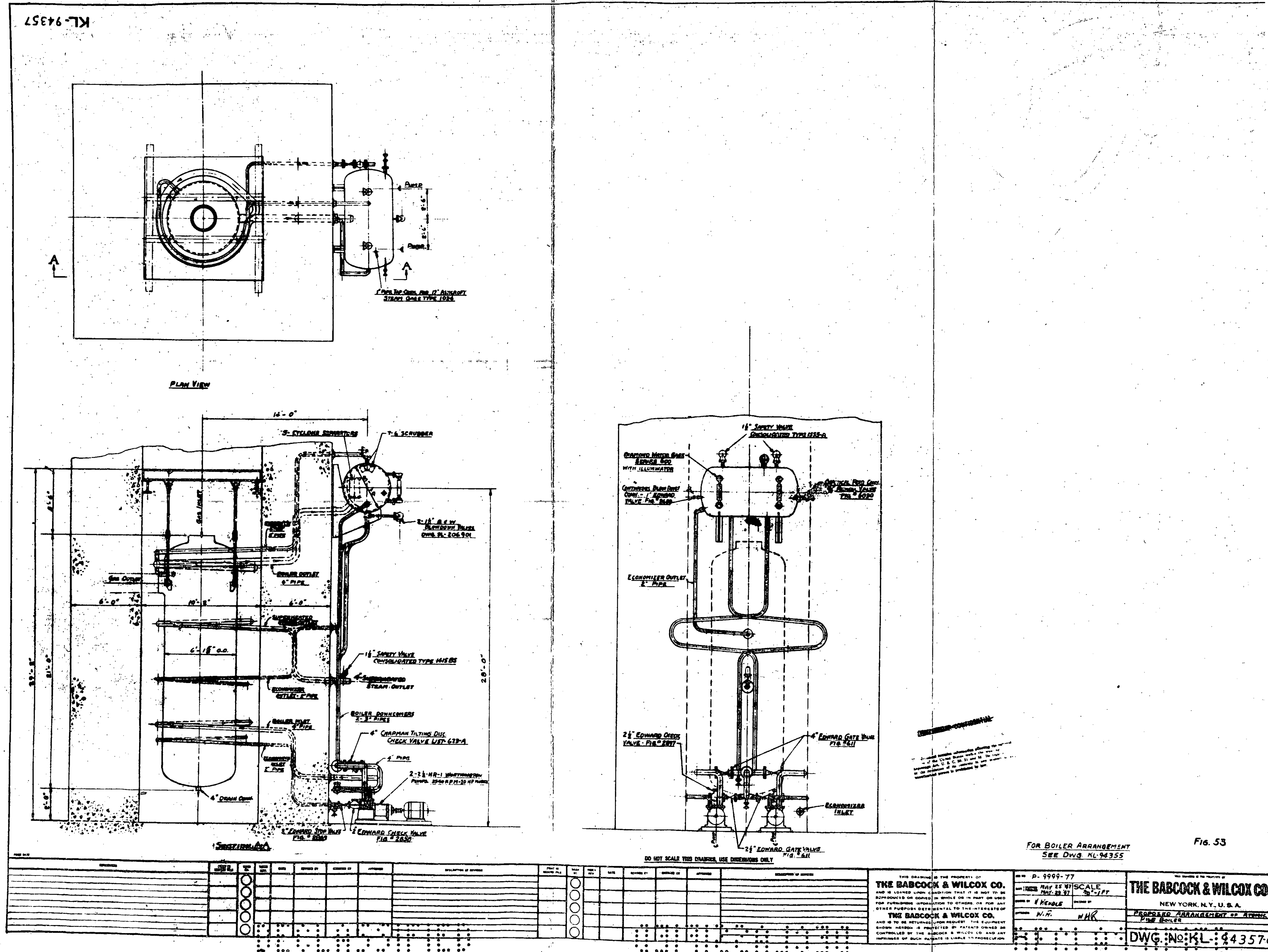
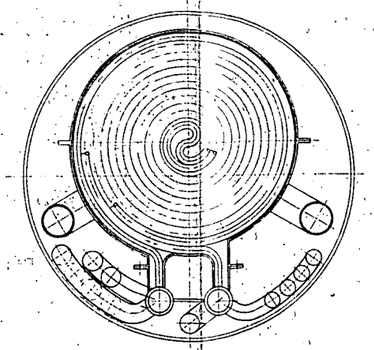
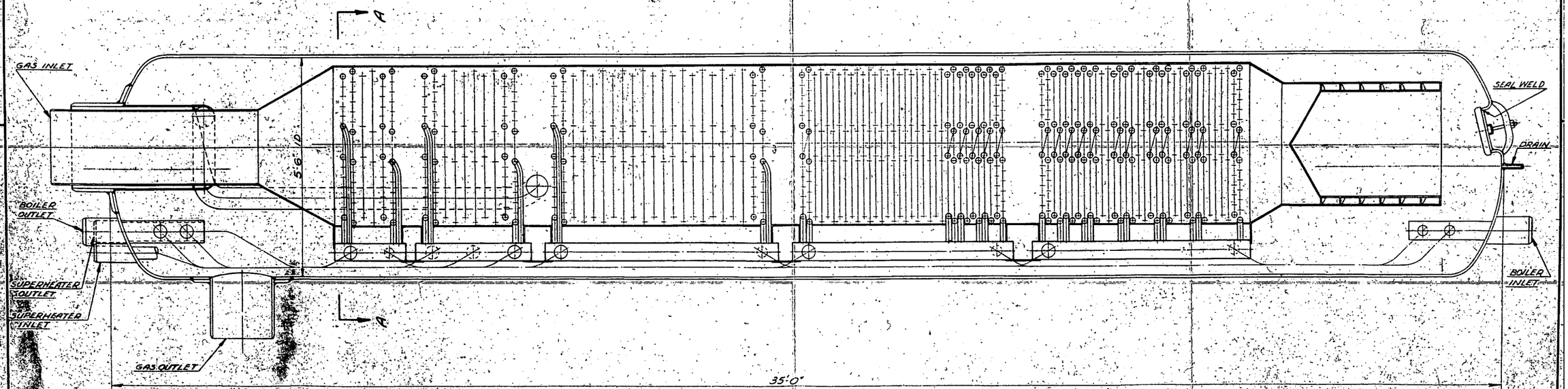
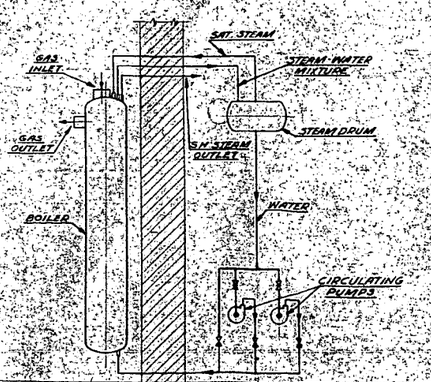

KL-94357
PLAN VIEW
SECTION A-A
14'-0"
5-CYCLONE SEPARATORS
T-6 SCRUBBER
2-1½" B&W BLOWDOWN VALVES DWG. KL-206901
GAS OUTLET
BOILER OUTLET 6" PIPE
6'-0"
10'-8"
6'-1½" O.D.
1½" SAFETY VALVE CONSOLIDATED TYPE 1415BS
4" SUPERHEATED STEAM OUTLET
ECONOMIZER OUTLET 2" PIPE
BOILER DOWNCOMERS 2-3" PIPES
BOILER INLET 2" PIPE
4" CHAPMAN TILTING DISC CHECK VALVE LIST 673-A
4" PIPE
ECONOMIZER INLET 2" PIPE
4" DRAIN CONN.
2-2½-HR-1 WORTHINGTON PUMPS
2" EDWARD STOP VALVE FIG. 2585
2" EDWARD CHECK VALVE FIG. 2850
28'-0"
1½" SAFETY VALVE CONSOLIDATED TYPE 1355-A
ECONOMIZER OUTLET 2" PIPE
2½" EDWARD CHECK VALVE FIG. 2897
4" EDWARD GATE VALVE FIG. 611
ECONOMIZER INLET
2½" EDWARD GATE VALVE FIG. 611
DO NOT SCALE THIS DRAWING, USE DIMENSIONS ONLY
FOR BOILER ARRANGEMENT SEE DWG. KL-94355
THIS DRAWING IS THE PROPERTY OF THE BABCOCK & WILCOX CO. AND IS LOANED UPON CONDITION THAT IT IS NOT TO BE REPRODUCED OR COPIED IN WHOLE OR IN PART OR USED FOR FURNISHING INFORMATION TO OTHERS, OR FOR ANY OTHER PURPOSE DETRIMENTAL TO THE INTERESTS OF THE BABCOCK & WILCOX CO. AND IS TO BE RETURNED UPON REQUEST. THE EQUIPMENT SHOWN HEREON IS PROTECTED BY PATENTS OWNED OR CONTROLLED BY THE BABCOCK & WILCOX CO. AND ANY INFRINGER OF SUCH PATENTS IS LIABLE TO PROSECUTION.
P-9999-77
MAY 25 '47
MAY 29 '47
SCALE ⅜"-1 FT
W.H.
WHR
THE BABCOCK & WILCOX CO.
NEW YORK, N.Y., U.S.A.
PROPOSED ARRANGEMENT OF PIPE BOILER
DWG. No KL-94357-0

FIG. 53



SECTION A-A





SCHEMATIC ARRANGEMENT

[redacted]

FIG. 54

ARRANGEMENT OF POWER PILE BOILER
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

T.C.	
F.S.T.O.	
E.E. UNFIRED	

The Drawing is the Property of Combustion Engineering Company, Inc. New York. Issued for information, offered to purchaser, but not forwarding for bidding or drawing on apparatus except where provided for by agreement with said company.

DRAWING No. MNF-10071-0

PRELIMINARY ONLY
NOT TO BE USED FOR CONSTRUCTION

UNCLASSIFIED

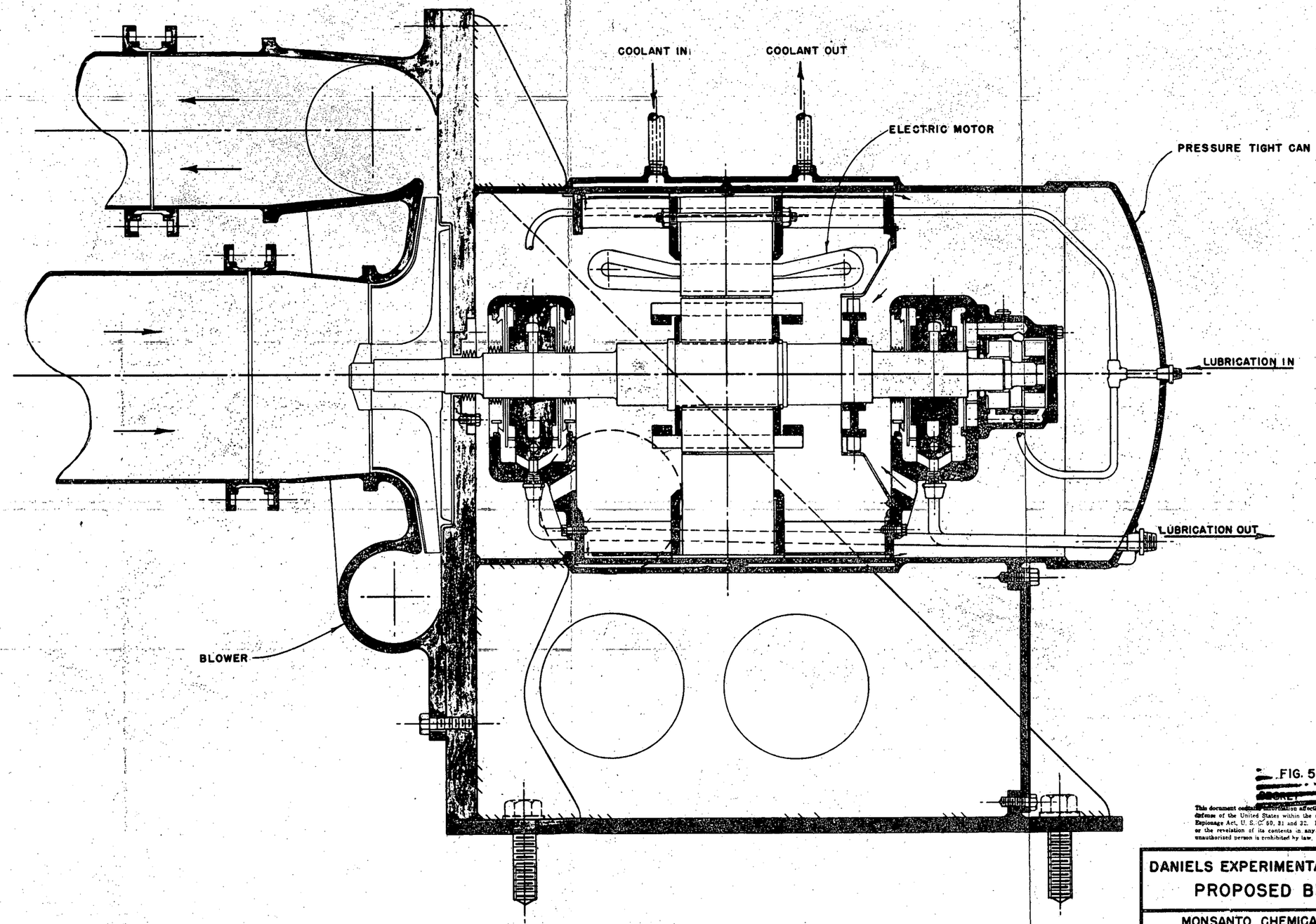


FIG. 55

[redacted]

This document contains information affecting the National Defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DANIELS EXPERIMENTAL POWER PILE

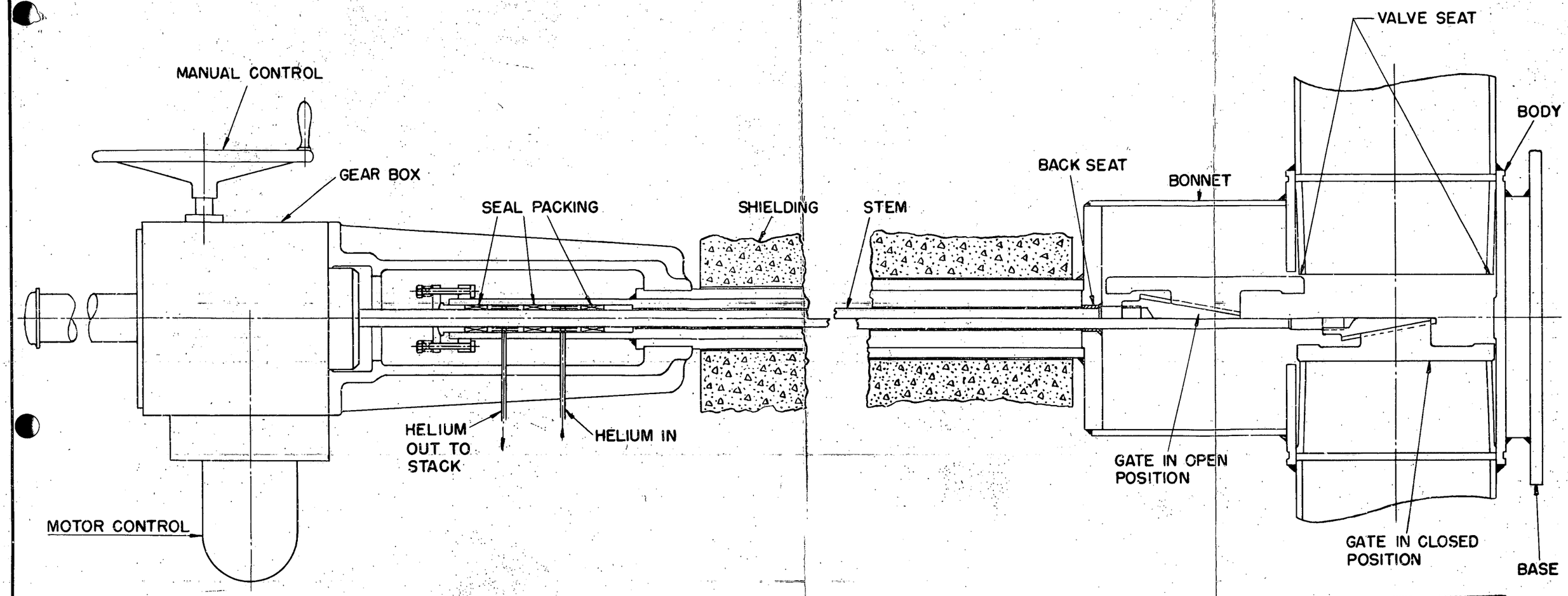
PROPOSED BLOWER

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. HUTTO 6/12/47	R.L.J. 6-12-47	D.S.	R.E.P. 6-12-47			
PROJ. C-222M				D-2703		

DECLASSIFIED DECLASSIFIED DECLASSIFIED

SECRET



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

THE DANIELS EXPERIMENTAL POWER PILE
DIAGRAM OF LARGE VALVES

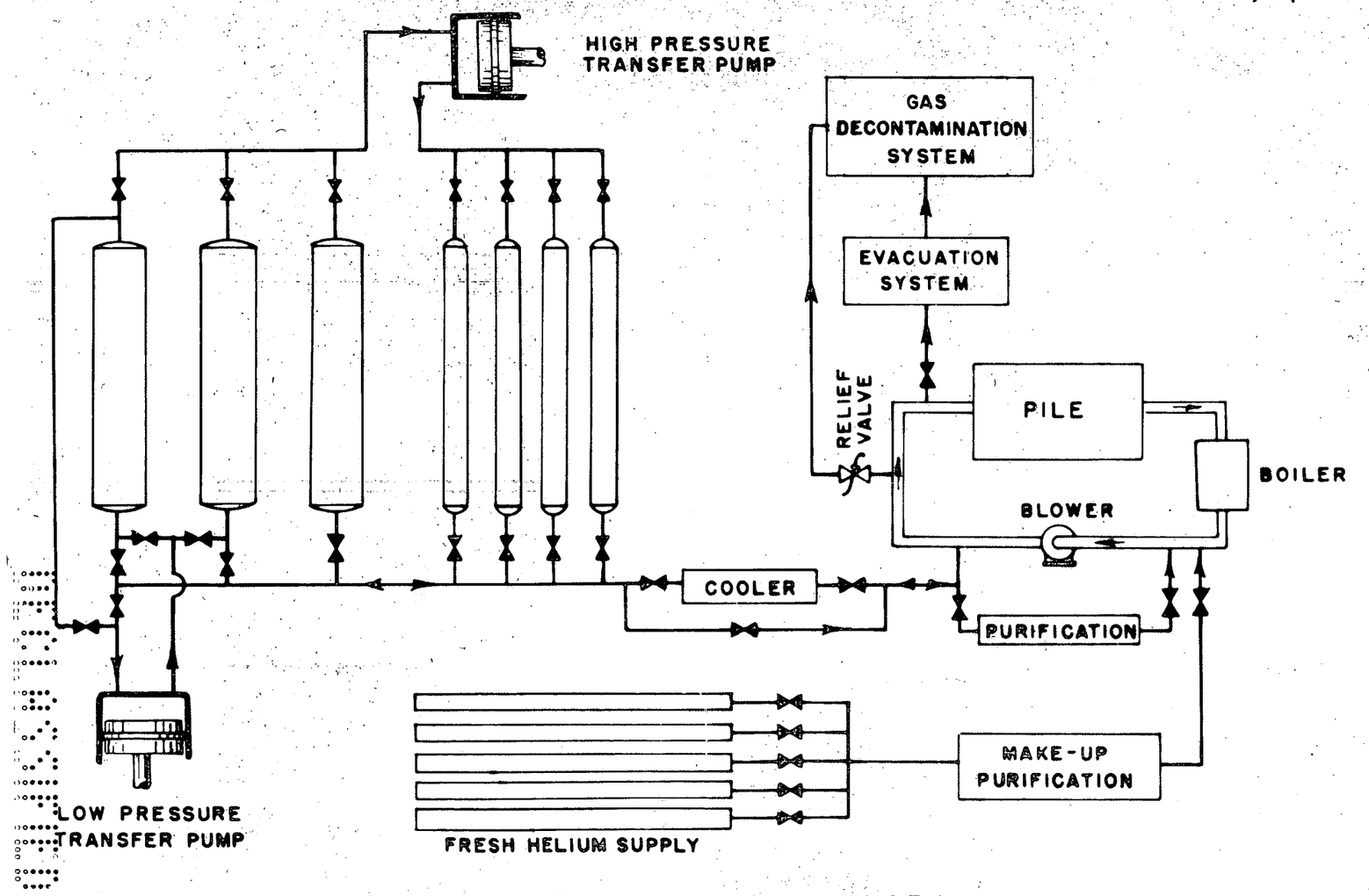
FIG. 56

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

EARLY D. 6/2/47	H.L.S. C. 7-11-47	A. RJP 7-14-47	REP 7-14-47			
PROJ. C-222-M				B-2394		
SCALE						

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.



SCHEMATIC FLOW DIAGRAM
HELIUM SURGE SYSTEM
FIG. 57

SECRET

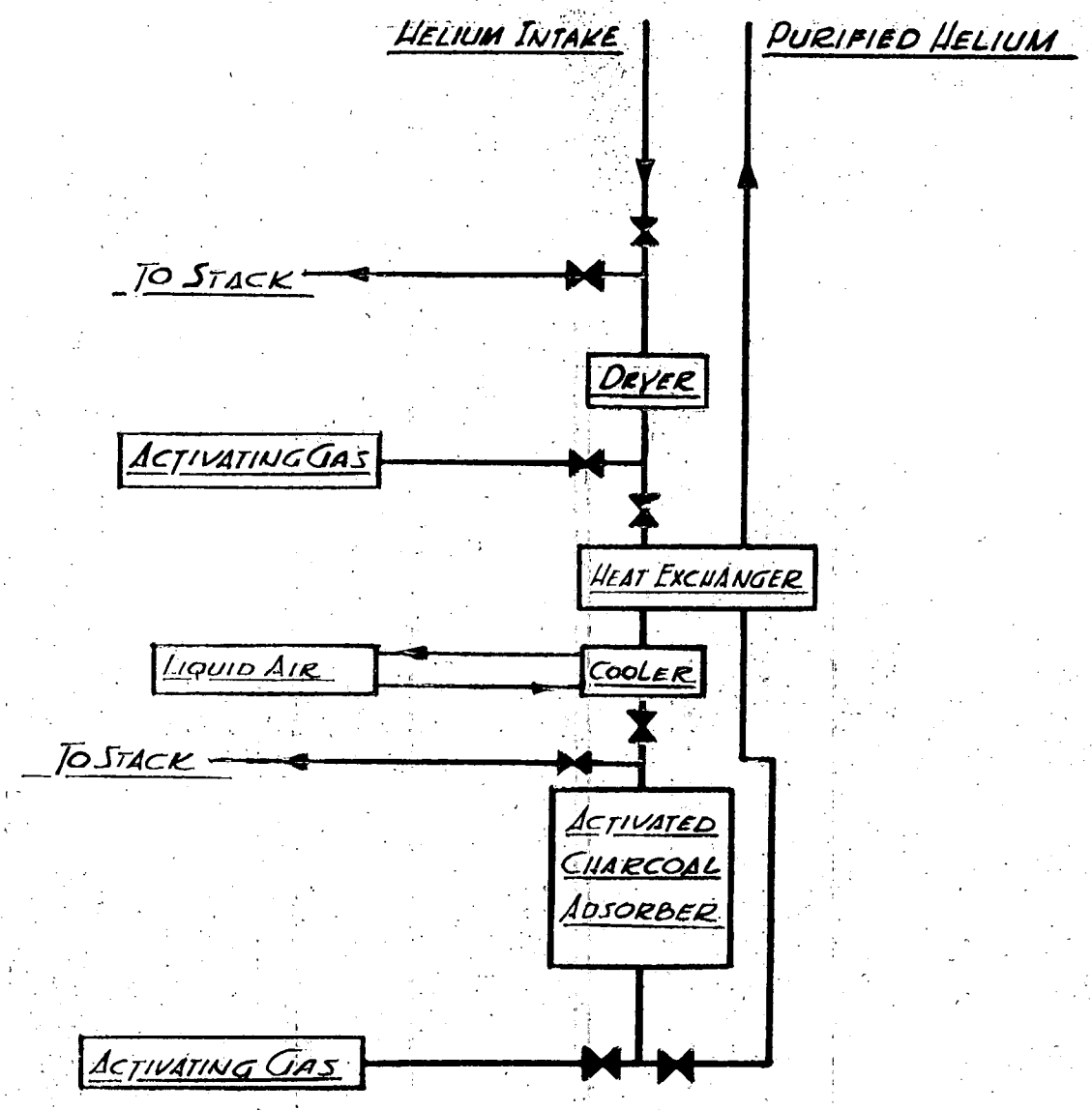


FIG. 58

SCHEMATIC FLOW DIAGRAM

MAKE-UP HELIUM PURIFICATION

DECLASSIFIED

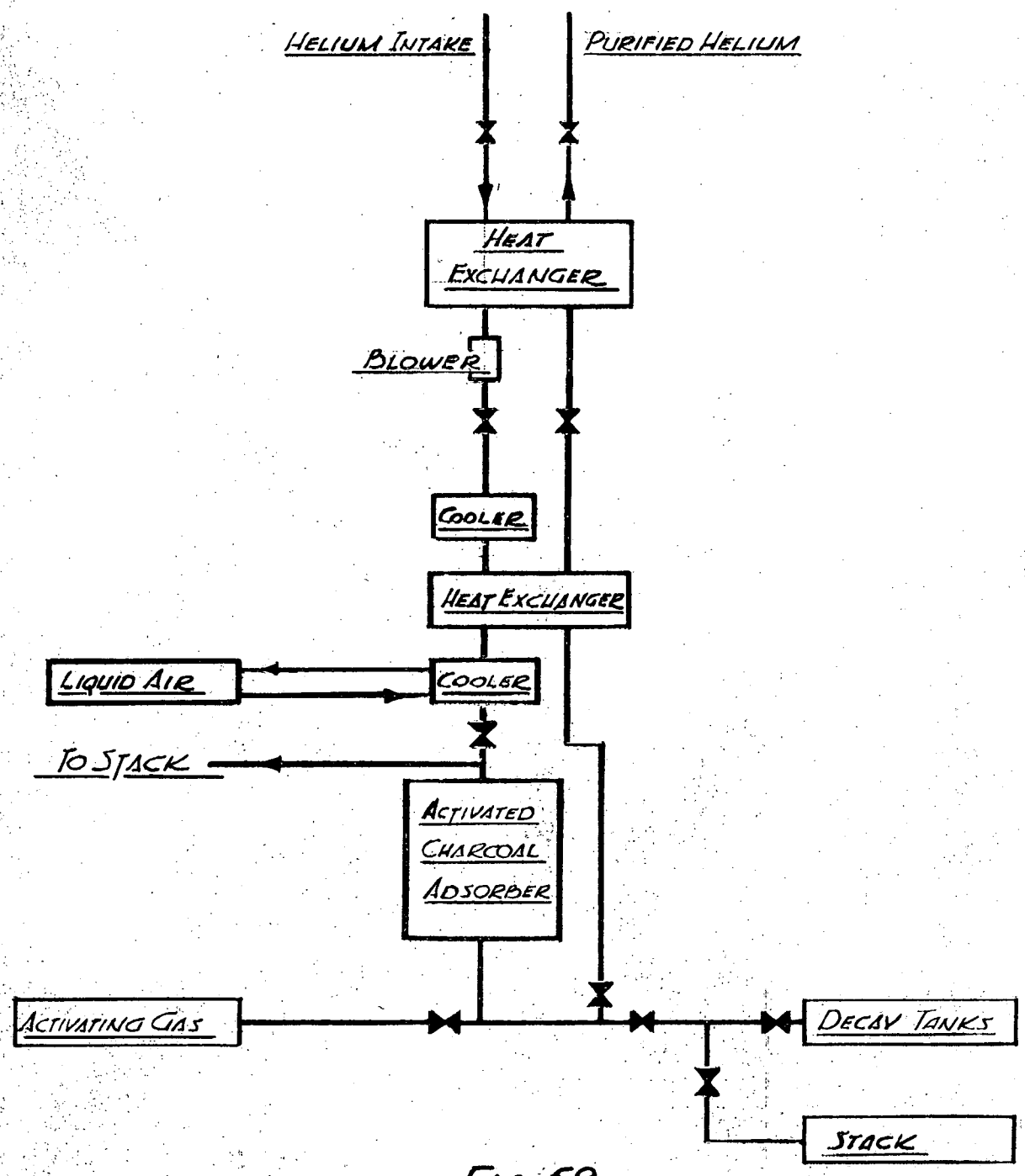


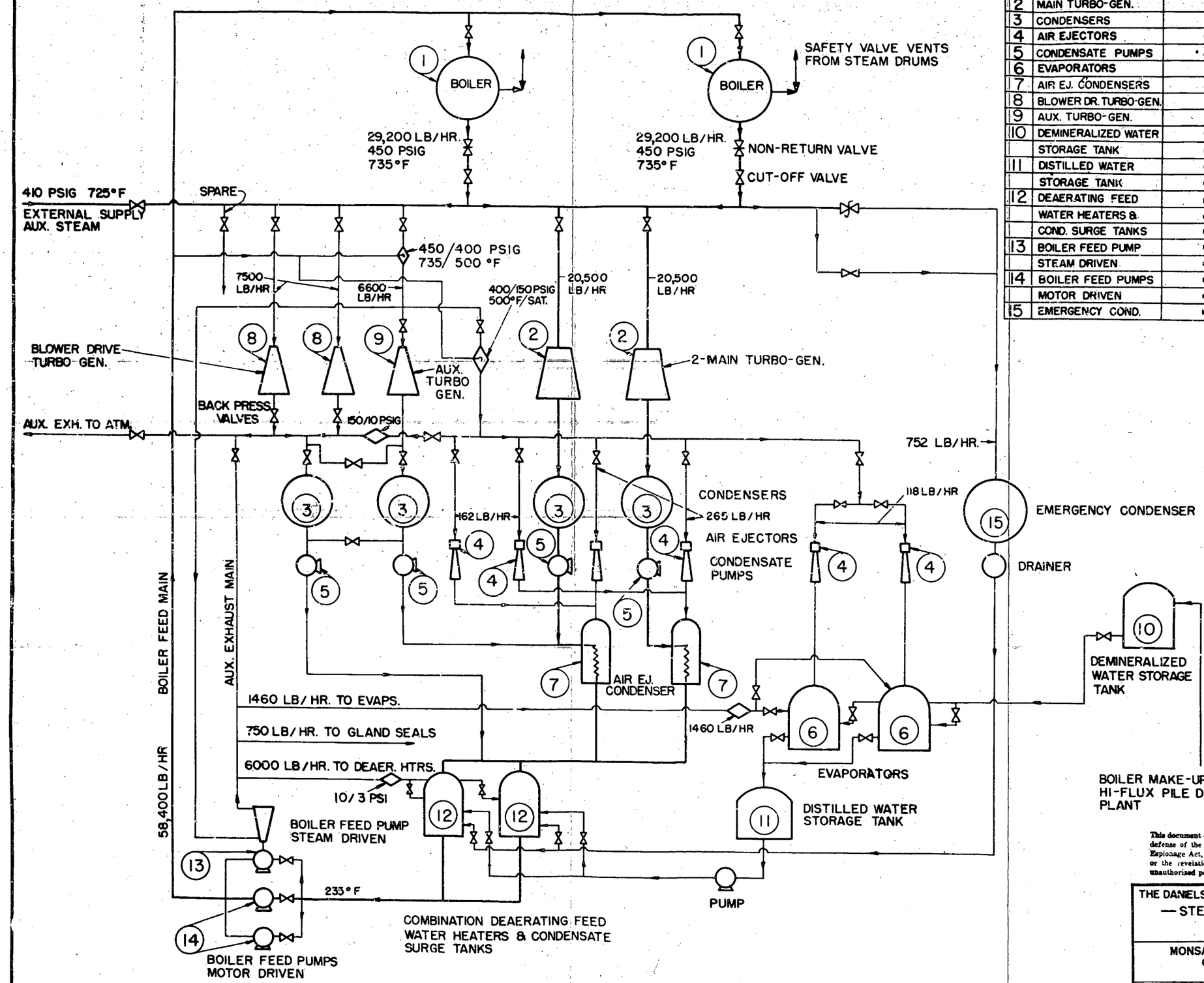
FIG. 59

SCHEMATIC FLOW DIAGRAM

HELIUM PURIFICATION

DECLASSIFIED

SECRET



ITEM	APPARATUS	SPECIFICATIONS
1	BOILER	SPECIFICATIONS TO GEN. ENG. MAY 6, 1947
2	MAIN TURBO-GEN.	" " " " " "
3	CONDENSERS	" " " " " "
4	AIR EJECTORS	" " " " " "
5	CONDENSATE PUMPS	" " " " " "
6	EVAPORATORS	" " " " " "
7	AIR EJ. CONDENSERS	" " " " " "
8	BLOWER DR. TURBO-GEN.	" " " " " "
9	AUX. TURBO-GEN.	" " " " " "
10	DEMINERALIZED WATER	" " " " " "
	STORAGE TANK	" " " " " "
11	DISTILLED WATER	" " " " " "
	STORAGE TANK	" " " " " "
12	DEAERATING FEED	" " " " " "
	WATER HEATERS &	" " " " " "
	COND. SURGE TANKS	" " " " " "
13	BOILER FEED PUMP	" " " " " "
	STEAM DRIVEN	" " " " " "
14	BOILER FEED PUMPS	" " " " " "
	MOTOR DRIVEN	" " " " " "
15	EMERGENCY COND.	" " " " " "

FIG. 60

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

THE DANIELS EXPERIMENTAL POWER PILE
— STEAM FLOW DIAGRAM —

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

EARLY D-5/28/47 C.7147 C.L.S. A.7-8-47 R.E.P. 8-14-47

PROJ. CE22M-

SCALE:

C-2393

DECLASSIFIED

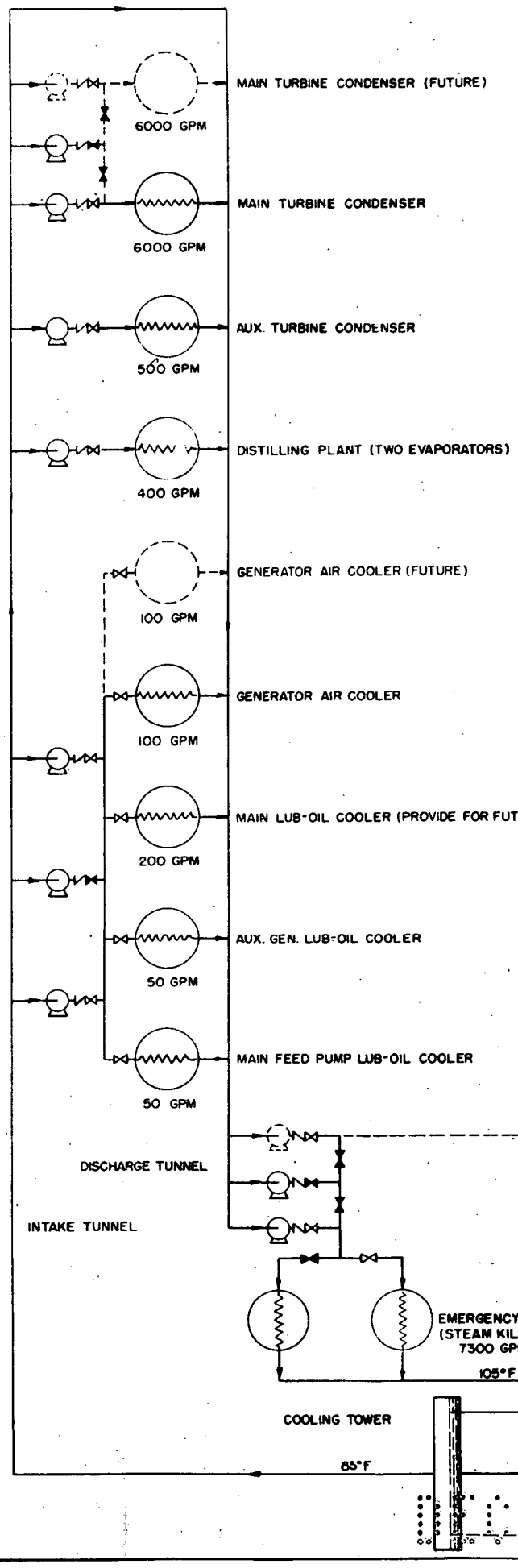


FIG. 61

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

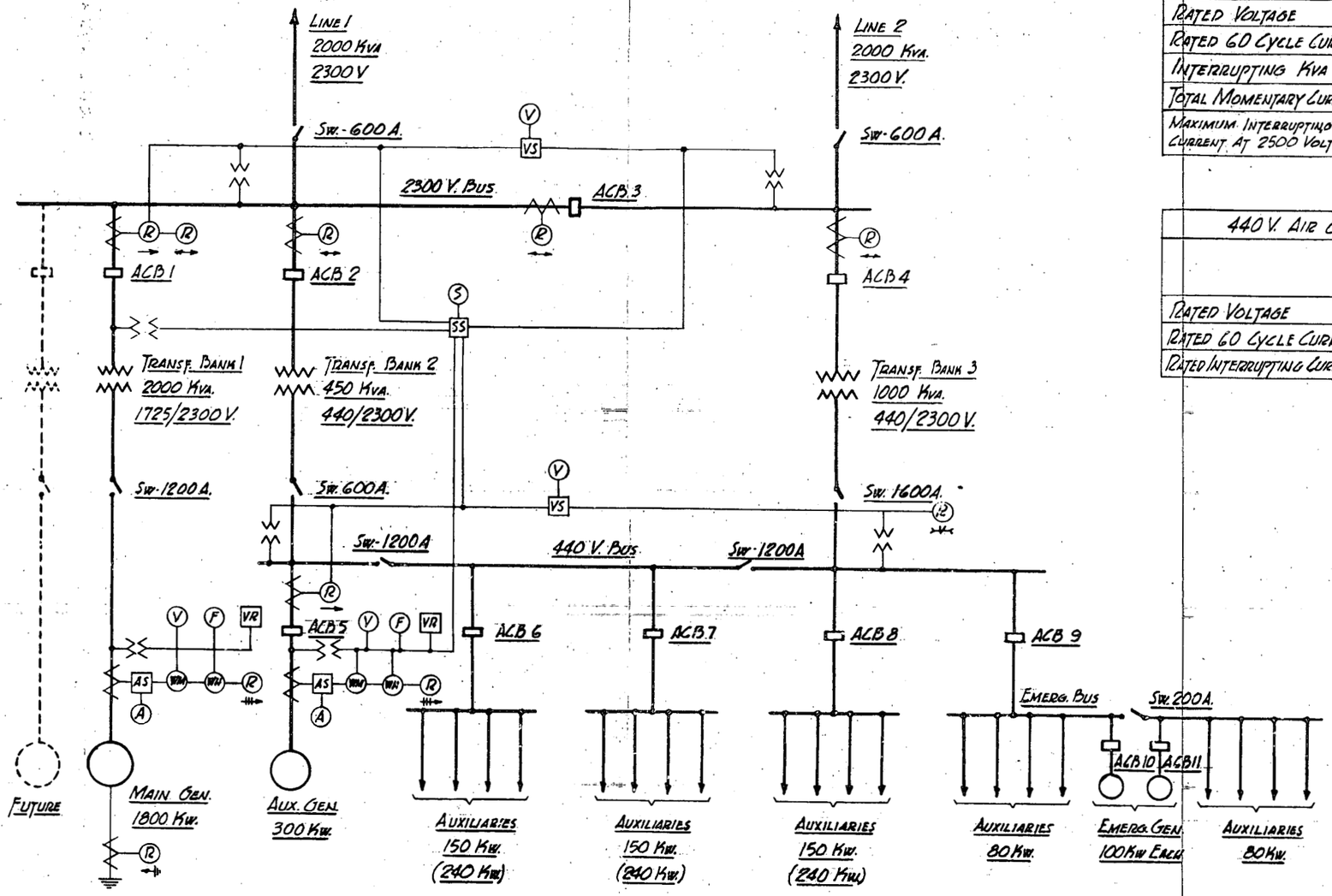
THE DANIELS EXPERIMENTAL POWER PILE
COOLING WATER FLOW DIAGRAM

MONSANTO CHEMICAL CO.
CLINTON LABORATORIES
KNOXVILLE, TENN.

PROJ. C 22 DM

C-2606

~~RESTRICTED~~



2300 V. Air Circuit Breaker Ratings

	Minimum Requirements				Proposed For All Breakers
	ACB 1	ACB 2	ACB 3	ACB 4	
Rated Voltage	2300	2300	2300	2300	2500
Rated 60 Cycle Current	500	120	600	250	600
Interrupting Kva	67,000	80,000	51,000	79,000	100,000
Total Momentary Current	27,000	32,000	21,000	32,000	40,000
Maximum Interrupting Current At 2500 Volts	17,000	20,000	13,000	20,000	23,000

440 V. Air Circuit Breakers Ratings

	Minimum Requirements			Proposed For All Breakers
	ACB 5	ACB 6, 7 & 8	ACB 9	
Rated Voltage	440	440	440	600
Rated 60 Cycle Current	600	400	200	600
Rated Interrupting Current	28,000	32,000	32,000	50,000

Notes:

1. Indicated Load Of Auxiliaries Is Estimated For A Pile Output Of 12,000 Kw. The Load Shown In Parentheses Is For 20,000 Kw.
2. ACB's 5, 6, 7, 8, & 9 Have Overload Trip Attachments.
3. ACB 9 Has Undervoltage Trip
4. ACB's 10 & 11 Will Be Low Capacity Breakers Not Required To Open Under Fault Conditions.

Legend:

- VR Voltage Regulator
- AS Ammeter Switch
- VS Voltmeter Switch
- SS Synchronizing Switch
- Ⓐ Ammeter
- Ⓥ Voltmeter
- Ⓦ Wattmeter
- Ⓦh Watthour Meter
- Ⓕ Frequency Meter
- Ⓢ Synchroscope
- Ⓡ Relay-Type As Follows:
  - Over Current
  - Reverse Power
  - Phase Balance
  - Under Voltage
  - Ground

Fig. 62

~~RESTRICTED~~

Generating Station And Switchyard

High Temperature Gas Cooled Power Pile

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

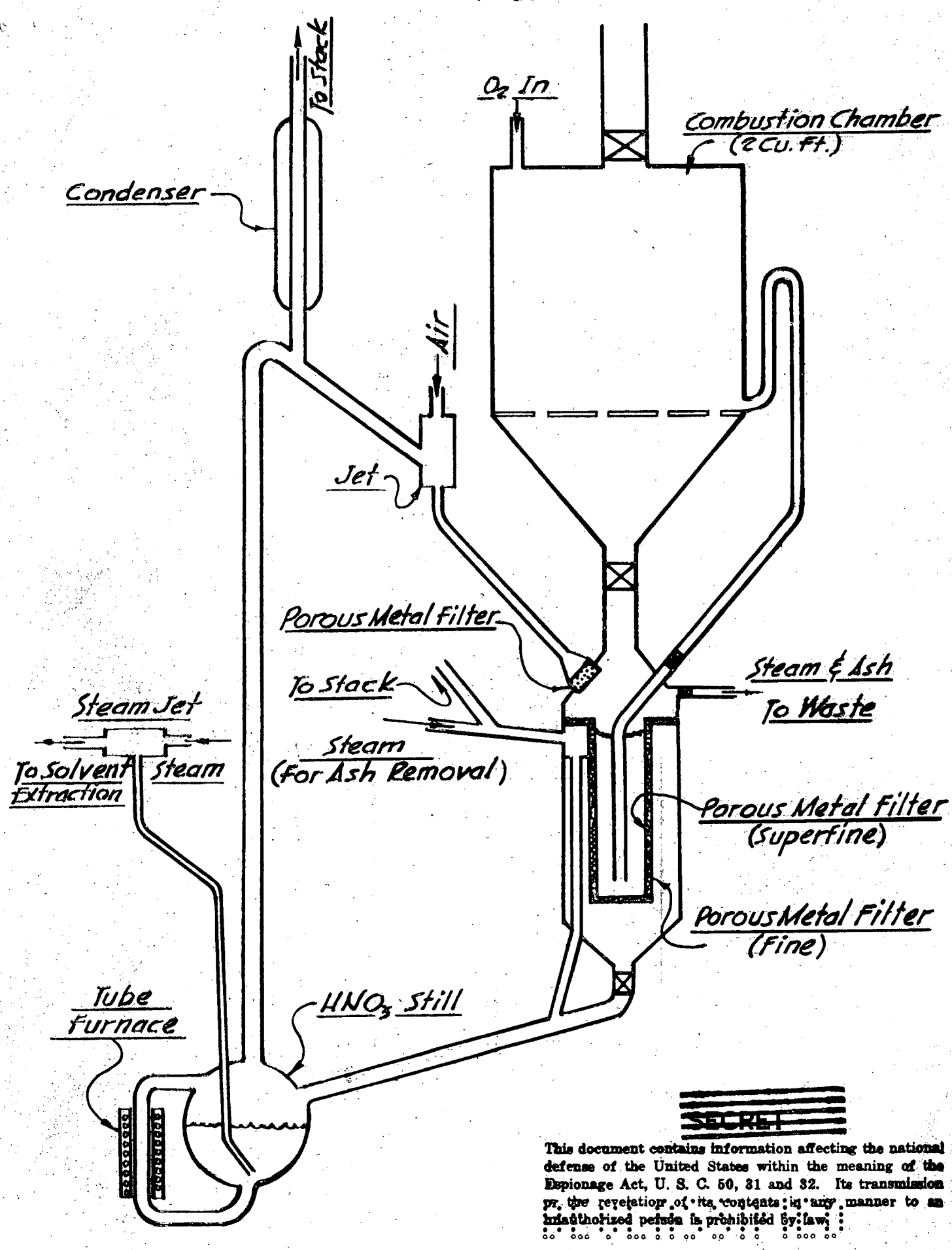
D. C.H.L. 8-13-47	C. W.A.P. 8-15-47	A. NJP 8-15-47	CEP 8-16-47	W.L.L. 8-16-47	
Proj. C. 222 M					C-2290
Scale: 1/4" = 1'					

~~RESTRICTED~~ ~~RESTRICTED~~ ~~RESTRICTED~~

SECRET

SCHEMATIC DIAGRAM OF PROCESS FOR SEPARATION OF URANIUM FROM GRAPHITE

FIG. 90



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

C. STATUS OF DESIGN.

The proposed design has reached a stage where satisfactory solutions have been found to most of the problems. These problems and alternate solutions are discussed in detail in Section V. Solution of some of the problems depends on development and experimental work that has been in progress for some time. Still other problems, mostly of a minor nature, have not yet received detailed consideration. There appears to be no serious doubt that solutions can be found to all outstanding problems and that after a year of continued design and development work, it would be possible to proceed with working drawings for construction of a pile in accordance with the principles outlined in this report.

Satisfactory solutions are in sight for the problems associated with differential expansion, accurate loading and unloading of fuel, positive retention of fuel elements during operation and the design of suitable auxiliaries. Final selections remain to be made from alternate solutions and, in some cases, much preliminary design and experimental work is required before selections can be made.

Two important aspects of the pile have been subordinated to the general design problem, and these aspects should receive careful attention in any further development of this design. Firstly, provision should be made for extensive high temperature test facilities, with adequate provision for instrumentation and test equipment. Secondly, the reactor should provide regions suitable for exploring the performance of a gas-cooled high temperature pile operating at the high power level expected of a commercial plant. Intensive study of materials should also be continued and directed towards design for high power output.

SECRET

DECLASSIFIED

SECRET

V. DETAILS OF DESIGN AND DEVELOPMENT PROBLEMS

A. PHYSICS.

1. Present Status.

At the present time, the first-order analysis necessary for arriving at a design point has been completed. The variables pile size, void content, and ratio of fuel to moderator have been investigated over wide ranges by approximate methods. The main approximations involved in the method are the use of one-group neutron theory and the assumptions of uniform temperature in the pile and uniform distribution of material. This analysis has shown the interrelation of the various factors involved in the design of the pile and has made possible the choice of a tentative design on a rational basis. The bulk of the work yet to be done consists of investigating the feasibility and characteristics of the design by more accurate methods. The investigation involves both experimental and analytical work. The main portions of the work are outlined in the following sections.

2. Experimental Work Required.

a. Neutron "Age" in BeO. No experimentally-determined value of the neutron "age", (1/6 mean-square slowing down distance) is available. An accurate value of this fundamental quantity is needed for all pile analysis.

b. Neutron Scattering in BeO. Measurements of thermal-neutron diffusion length in BeO as a function of temperature, or experiments giving equivalent information on scattering as a function of temperature are needed for prediction of the high-temperature behavior of the pile.

c. Xenon Cross Section. The neutron absorption cross-section of Xe^{135} should be measured as a function of neutron energy in the thermal and near-thermal regions in order to allow calculation of the temperature coefficient of reactivity of the pile at high power, and high temperature. The possibility of instability exists.

d. Cold Critical Experiments. A series of critical experiments at room temperature or slightly above is necessary to check analytical results and to provide information not readily obtained analytically. Some of the measurements to be made are as follows:

(1) Critical pile size and mass of fissionable material.

(2) Behavior of the pile size - critical mass curve in the vicinity of the design point.

(3) Flux distributions with and without control rods.

(4) Control - rod calibrations.

(5) Room - temperature coefficient of reactivity.

(6) Conversion measurements.

SECRET

DECLASSIFIED

SECRET

e. Hot Critical Experiments. Critical experiments will be necessary over the range of temperatures from room temperature to the design operating temperature of the pile, primarily to establish safe operating procedures. An engineering analysis is needed to determine whether the hot critical experiments can be conducted most efficiently on a special set-up or on the partially completed pile.

3. Analytical Work Required.

The major types of calculations remaining to be done are summarized below:

a. Criticality Calculations.

(1) Effect of non-homogeneity of pile on critical conditions.

(2) Effect of neutron streaming along coolant channels.

(3) Effect of temperature distribution.

(4) Accurate determination of effective pile radius.

(5) Correction for effect of control-rod channels.

(6) More extensive two-group calculations.

b. Flux and Power Distribution.

(1) Gross flux distributions for various operating conditions.

(2) Local flux and power distribution in: fuel slug, moderator bricks; control rods, vicinity of control rods.

(3) Conversion calculations.

c. Pile Operation.

(1) Determination of practical value of excess reactivity for pile.

(2) Determination of start-up, shut-down, and power-change procedures: Analysis of control demands and thermal effects.

(3) Investigation of pile stability and transient response.

d. Radiation Control.

(1) Design of pile shield.

(2) Design of shielding for associated equipment.

SECRET

DECLASSIFIED

SECRET

B. HEAT TRANSFER ANALYSIS

1. Design Conditions.

The general principles relating heat transfer to the design of a gas cooled power pile has been described in Section III. In the application of these principles to the particular pile design described in this report the following design conditions, including the restraints imposed by the chain reaction, were selected as a result of the considerations previously described in Section IV.

Inlet Gas Temperature, T_1 = 500°F.

Outlet Gas Temperature, T_2 = 1400°F

Maximum Operating Pressure, P = 10 atmospheres

Pressure Drop, Δp = 2.5 psi

Thermal Power Output, = 12000 kw

Pile Length to Diameter Ratio, L/D = .925

Heat Release Ratio, Peak to Average

Radial, F_x = 1.50

Axial, F_y = 1.26

Heat Generation in Structure, $= \frac{\text{mass structure}}{\text{Total mass}} \times 9\ \%$

Moderator Material - Hot Pressed BeO

The following allowable stresses were assumed for the fuel elements and the moderator bricks:

$$\text{Fuel elements} = \frac{15{,}000}{5.5 \times 2 \times 1.5} = 900 \text{ psi}$$

where 15,000 is the tensile strength of BeO

5.5 is a radiation damage factor

2.0 is a factor of safety to take care of transient conditions

1.5 is a factor to take care of the eccentric loading of the fuel elements

$$\text{Moderator bricks} = \frac{15{,}000}{1.5 \times 3.0} = 3{,}330$$

where 15,000 is the tensile strength of BeO

SECRET
DECLASSIFIED

1.5 is a radiation damage factor

3.0 is a factor of safety to take care of transient conditions

The thermal stresses were calculated using idealized stress equations for elastic deformation and the values of the physical properties for actual operating conditions given in the properties of materials section of this report. The values without radiation damage were used and the above factors were applied to take care of radiation damage. The conditions at the center of the pile were considered to be the most severe. The heat release at this point was taken as the peak to average heat release ratio of 1.50 x 1.26 = 1.9 for both the fuel elements and the moderator bricks.

The pressure drops of 2.5 psi for the pile and 3.61 psi for the complete system were chosen because the latter is the maximum attainable pressure rise with a single stage centrifugal blower operating at 10 atmospheres pressure and 500°F inlet temperature, and because it falls in the optimum range of .10 to .20 fraction blower power. The relationship between the fraction blower power, R, and pile pressure drop, Δp, is given in equation 16 page 74 of Mon N-299. From this relationship the value of $\frac{R\eta_b}{F_c} = .00726$ was obtained for $\Delta p = 2.5$ and other design conditions given above. This value was used in establishing the design point.

2. Selection of Percent Voids and Pile Size.

The pile of minimum critical mass and good conversion was selected by obtaining the values of α and D from equation 5 of Section III for various piles which satisfy the above design conditions. Then values were plotted on a curve similar to figure 4 from which the design point was selected.

The value of the [ ] quantity in equation 1 of Section III for the above design conditions was found to be 55, as follows:

$$\left[\frac{KW\sqrt{F_x^2 \cdot F_y \cdot F_L}}{336\,P\sqrt{\frac{R\eta_b}{F_c}}\sqrt{\frac{\Delta T^2}{T_p \cdot T_b}}\left(\frac{\gamma}{\gamma-1}\right)\sqrt{\frac{9\gamma-5}{2(\gamma-1)\,mw}}}\right] = \frac{12{,}000\sqrt{1.5^2 \cdot 1.26 \cdot 4.5}}{336 \times 10\sqrt{.00726}\sqrt{\frac{900^2}{960 \times 1450}} \times 3.42}$$

The value for the pressure drop through the pile to the pressure drop used for heat transfer, F_L, was taken to be 4.5. This was obtained from preliminary test results of fuel elements. It takes into account the losses discussed under Pressure Drop Design Information at the end of this section.

Referring to equation 5 of Section III, the value of the quantity $\frac{\alpha^6 D^9}{1-\alpha}$ was obtained as follows:

$$\frac{\alpha^6 D^9}{1-\alpha} = \frac{.0185\,KW \cdot F_x \cdot F_y \cdot F_\alpha \cdot F_v}{\Delta T^2\, S_z}\left(\frac{E_b}{2(1-\sigma)}\right)[\quad]^4$$

$$\frac{.0185 \times 12{,}000 \times 1.5 \times 1.26 \times .925 \times .2}{900^2 \times 900} \times 19 \times 55^4 = 185$$

DECLASSIFIED

SECRET

Where,

[ ] = 55 is the value found directly above
The ratio of fuel element material to total pile material mass, F_v, was taken as .2. This value should be made as small as possible providing the fuel elements do not as a result become too thin to fabricate or the fuel channel too small. It is primarily influenced by the allowable stresses in the fuel elements and permanent structure.

The value of $\left(\frac{E b}{k(1-\sigma)}\right)$ was obtained from the properties of materials section for an estimated fuel element temperature at the center of the pile of 1400°F to be 19.0

The values of α and D obtained from the above equation constitute pile designs which satisfy the design conditions. These were plotted on Fig. 63 to obtain the pile of minimum critical mass and high conversion. The design point was selected as $\alpha = .28$ and R = 61 centimeters, (D = 4 ft.). The design point could have been selected further to the left to attain higher conversion and a smaller pile size and hence also require a smaller amount of BeO. However under these conditions a slight error in the nuclear constants might result in a pile requiring very large quantities of fissionable material. The voids in the present design could be easily increased and the total channels requiring fissionable material reduced, if it proved desirable at some later date.

3. Design of Moderator Bricks.

Consideration was given to cooling the bricks on the outside but by such operation the outside of the bricks would be put in tension and more serious stresses might be caused at the corners than in a design with inside cooling only. This condition could be aggravated under certain conditions of brick stacking which would produce overcooling. It was therefore decided to design without cooling on the outside but to reconsider the design after stress analysis tests of various brick shapes were completed.

With cooling on the inside of the brick the inside surface is put in tension. It was therefore decided to use a circular fuel element channel because either a square or hexagonal channel would cause a serious "notch" effect on stress. Since the exterior of the brick is in compression it is considered that in this case the notch effect due to corners is not serious. A hexagonal brick was chosen because it best accommodates a circular hole and provides good structural stability.

The approximate thickness of the brick was determined by the following flat plate stress formula for heat removed from one side only to be .047 ft. or .57 inches, say 1/2".

$$S_z = \frac{1}{3} \rho \omega^2 \left(\frac{E b}{(1-\sigma) k}\right)$$

SECRET

DECLASSIFIED

SECRET

Where,

The heat generated per unit volume of moderator material, p, was based on this 9% heat generated in slowing down the gamma rays and neutrons. At the center of the pile it is 210,000 Btu/c.f.

$\frac{Eb}{k(1-\sigma)}$ @ say 1100° F = 21 (from prop. of materials section)

w = thickness in feet

The ratio of fuel plate volume to total moderator volume, F_V was chosen as .2 at the beginning of this section to minimize fuel element stresses. This value plus the percent pile voids establishes a minimum volume for the permanent structure of $(1-\alpha)$ $(1-F_V)$ = 57.5%.

A 3" hexagonal brick with a 2" hole was chosen because it meets the requirements of 1/2" wall thickness and at least 57.5% pile volume, being 60% of the pile volume. The stress in this brick was checked with the best formula presently available. It is the following formula for heat generated uniformly in a circular tube and removed from the inside only. The outside diameter of the tube is considered the average outside circle drawn between the flats and corners of the hexagonal.

$$S_z = q\left(\frac{Eb}{k(1-\sigma)}\right)f_2$$

Where,

q = heat generated per foot length of brick

$$= \frac{12{,}000 \times 3413 \times 1.9 \times .09 \times \frac{.60}{.72}}{228 \times 3.7} = 7{,}000$$

f_2 = stress factor which takes into account the tube diameter ratio = .024

$\frac{Eb}{k(1-\sigma)}$ @ 1100°F = 21

By use of this formula the brick stress was determined to be 3,380 psi which is close enough to the allowable value of 3,330 to be satisfactory. From the stand point of the total number of channels required it would be preferable to design for larger diameter fuel channels. However this would increase the size of the pile and the fissionable material required by a considerable amount as seen from equation 5. By using a smaller value for F_V a smaller pile and less fissionable material can be obtained but only at the expense of making the channels smaller than 2" and the fuel elements thinner. This does not seem desirable. It is therefore concluded that the choice of F_V = 0.2 is satisfactory.

4. Design of Fuel Elements.

A large number of factors affect the design of a specific fuel element subject to the restrictions imposed by the heat transfer design conditions described thus far, namely, a 2" circular channel, 2.5 psi

SECRET

maximum pressure drop, and not more than 12% of the pile volume in the fuel element material. The nature and importance of these factors are described in detail in a subsequent discussion on the design and development of fuel elements. However in order to show a form that the fuel elements might take the following preliminary analysis of the problem is presented.

Assume a fuel element having an egg crate cross-section. Its thickness can be determined to be .056" from the flat plate stress formula, using a factor of 2 for joint effects,

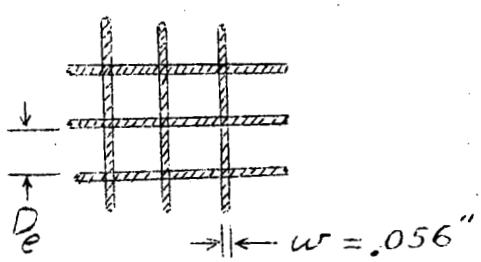
$$S_z = 2 \times \frac{2}{3} \times \frac{p w^2}{8} \left(\frac{E b}{k(1-\sigma)} \right)$$

Where $p = \frac{3413 \times 12{,}000 \times 1.9 \times .92}{4^2 \times .785 \times 3.7 \times .12} = 13 \times 10^6$ Btu/c.f.

$\frac{E b}{k(1-\sigma)}$ @ 1400°F = .19

S_z = 900 psi

Approximately 5% of the fuel element channel is taken up by clearance around the fuel elements and a slight space provided between the fuel elements to limit fuel element joint losses in the case of misalignment. Therefore the total volume within the fuel elements is approximately 40% - 5% = 35%. Since the fuel element structures contain 12% of the pile volume the equivalent diameter of the channels is



$$\frac{(D_e + w)^2}{D_e^2} = \frac{.35}{.35 - .12}$$

$$D_e = 0.24''$$

Assuming that this fuel element was used, the pressure drop in the pile is obtained by using the following standard pressure drop equation,

$$\frac{144 \Delta p}{\rho} = \frac{G_s^2}{2 g \rho^2} \frac{L}{D_e} \times 4 f \times F_L$$

Where, ρ = density = .039 lb/ft.^{3}

G_s = mass flow per sec. through center channel = $\frac{10.5 \times 1.5}{3.52}$ = 4.4

L = reactor length = 3.7 ft.

$D_e = \frac{.24}{12}$ = .02 ft.

F_L = ratio of total pressure drop through pile to pressure drop used for heat transfer = 4.5 as previously indicated

DECLASSIFIED

SECRET

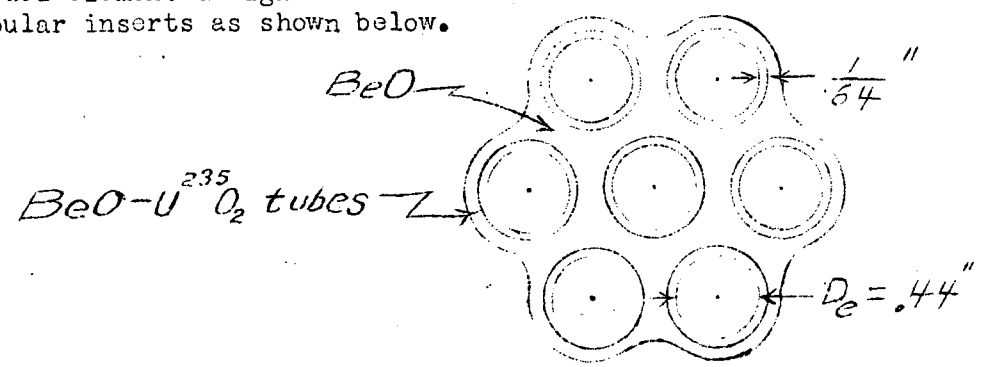
f = friction factor = .0105 as found from McAdams "heat Transmission" page 118 for center channel at a Reynolds number of 3,800

From which Δp is found to be
$\Delta p = 2.2$ psi

This is slightly less than the assumed value of 2.5 but in view of the uncertainty of the accuracy of determining pressure drop losses in the pile it is considered satisfactory. Fig. 27 shows a possible construction for a fuel element conforming to the foregoing design requirements.

The average design temperature differences between the gas and the fuel elements at the center of the pile was found from equation 2 of Section III to be $\theta = 250^{\circ}F$. Since the fuel channel wall does not transmit as much heat as the surfaces within the fuel elements an effectiveness factor of .86 must be used to obtain the true temperature difference therefore the true temperature difference between the fuel elements and the gas is $\frac{250}{.86} = 290^{\circ}F$. The maximum fuel element temperature was obtained as described in MonN-299, page 52 to be $(T_m)_m = 1535^{\circ}F$. Part load temperatures are given under "Temperature Distribution in the Pile".

An alternate fuel element design is a BeO fuel element with the fuel concentrated in tubular inserts as shown below.



This fuel element would have a pressure drop of 1.0 psi and a maximum fuel element temperature of 1700°F.

5. Temperature Distribution in the Pile.

The temperature distribution in the pile at various pile ratings is given in figures 64, 65, and 66 for fuel elements of .048, .031 and .0227 ft. equivalent diameter, respectively. All fuel elements, regardless of shape, having the same equivalent diameter will give the same temperature distribution. For instance, the flat plate, the 7 hexagonal and the 7 hole units shown on Fig. 26 all have the same equivalent diameter of .031 ft. and therefore their performance is given by Fig. 65. This curve also applies to the 7 hole tubular insert unit described in Section 4 above The 19 channel unit shown in Fig. 27 has .0227 ft. equivalent diameter and is therefore covered by Fig. 66. The fuel element with an egg crate cross-section described in the preceeding section on fuel element design has an equivalent diameter of .02 ft. and a gas to fuel element temperature

SECRET
DECLASSIFIED

difference, at the center of the pile at 12,000 kw output of 290°F compared to 350°F for the .0227 ft. equivalent diameter fuel element. The temperatures for the egg crate cross-section design can be taken as slightly smaller than those shown in Fig. 66. The pile ratings written on the left hand side of the parameters correspond to the fuel element surface temperatures in the center channel of the pile. The pile ratings written at the peaks of the parameters correspond to the cross-sectional average fuel element temperature across the pile. Since the maximum to average heat release ratio across the pile is 1.5 the center channel produces 50% more heat then the average channel. Therefore the average temperature across the pile is considered to correspond to the temperature in the center channel when the average pile heat generation per unit volume is equal to the center channel heat generation per unit volume.

The average gas temperature at any point in any channel is only a function of the inlet temperature, the outlet temperature and the heat generation along the channel. The heat generation is assumed to be a cosine curve with a maximum to average heat generation of 1.26 for all cases. Therefore the gas temperatures along the channels are the same for all fuel elements at all loads as shown.

The fuel element temperatures were determined by using the heat transfer rates given in Fig. 68. At a power output of 20,000 kw the Reynold's number, R_D, was 14,800, 10,000 and 7,400 for the fuel units of figures 64, 65 and 66 respectively. For the small equivalent diameter fuel channel of .0227 ft. an L/D ratio of 30 was assumed. Therefore as seen from Fig. 68 the heat transfer rate suffers a dip with reduction in load. This shows up in Fig. 66 as can be seen from the fact that the highest temperatures occur at 6,000 kw output. This dip also occurs in the friction factor curve. It indicates that uneven temperature rises will result in the pile when some channels are operating in the dip region.

The average temperature of the fuel elements as a function of load for the various fuel element designs can be obtained from the average temperature difference between the fuel elements and the gas given in Fig. 67 as indicated therein. The average temperature of the bricks will be about 1,000°F at low loads and 1050°F at high loads except for the case when the .048 equivalent diameter fuel element is used. When operating with this fuel element the average brick temperature will be approximately 50°F higher than the figures given above due to the higher fuel element temperatures and consequent higher radiation transfer to the bricks.

In determining the temperature distribution in the pile the suppression of the thermal flux and consequent lowering of the local heat generation was considered to be sufficiently localized near the control rods to have little effect on the temperature distribution.

SECRET

DECLASSIFIED

SECRET

The above discussed pile temperatures were calculated based on the following pile voids and surface effectivenesses

D_2 (ft)	% Voids	Surface Effectivenesses
.0227	26	.86
.031	26	.78
.048	27.4	.64

6. Heat Transfer Data.

The standard equations for heat transfer found in the literature was used in determining pile performance. The effect of shape on heat transfer is such that by use of the equivalent diameter concept a small error is introduced for flow in the turbulant region. For streamline flow the use of the equivalent diameter may lead to an error as high as 20%. By using short fuel elements the boundary layer is interrupted and the heat transfer rate is increased over that in a continuous channel. This effect has been ignored. It is estimated that the accuracy of the equations used is about ± 30%. This error has little effect on design since the fuel element temperatures are considerably below allowable. More work should be done in the range of very small channel size for various surface arrangements. The effect of growth dueto radiation damage on heat transfer and pressure drop should be investigated.

7. Pressure Drop Data.

Relatively simple methods of obtaining the pressure drop in the fuel elements are available from the literature. The equation which is used is as follows:

$$\frac{144\Delta p}{\rho_{avg}} = \frac{G_s^2}{2g\rho_{avg}^2}\left(\underbrace{\frac{4fe\,L}{D_e}}_{\text{Wall friction}} + \underbrace{k_e\,(N-1)}_{\text{joint losses}} + \underbrace{k_b(N_b-1)}_{\text{brick joint losses}} + \underbrace{k_1\left(\frac{T_1}{T_{avg}}\right)}_{\text{inlet shock loss}} + \underbrace{k_2\left(\frac{T_2}{T_{avg}}\right)}_{\text{outlet shock loss}} + \underbrace{\left(\frac{T_2-T_1}{T_{avg}}\right)}_{\text{Accel requirement}}\right)$$

Where

f_e is the equivalent friction factor for the series of parallel channels which constitute the fuel element and clearance space between the fuel element and brick wall

k_e = fraction of velocity head loss per fuel element joint

N = number of fuel elements

k_b = fraction of velocity head loss per brick joint

SECRET

DECLASSIFIED

SECRET

N_b = number of brick joints

k_1 = fraction of inlet velocity head loss

k_2 = fraction of outlet velocity head loss

The other symbols are defined earlier in this section.

This equation can be applied to any fuel element if the empirical coefficients f_e, k_e, k_b, k_1 and k_2 are known. The literature contains sufficient information on some of these coefficients and approximate values for the others. The following test work is now being conducted to complete pressure drop information:

1) the distribution of gas in parallel channels of various shapes and the determination of the value of f_e

2) joint losses and methods of minimizing them and eliminating differences in pressure drop due to misalignment

3) brick joint losses

4) methods of reducing outlet shock loss.

SECRET
DECLASSIFIED

[redacted]

FIG. 63

DETERMINATION OF PILE VOIDS AND PILE SIZE FOR 12,000 KW. OUTPUT, HELIUM COOLED PILE.

$P = 10$ ATMOS, $T_1 = 500$, $T_2 = 1400°F$

$\Delta p = 2.5$ psi, $F_x \cdot F_y = 1.89$

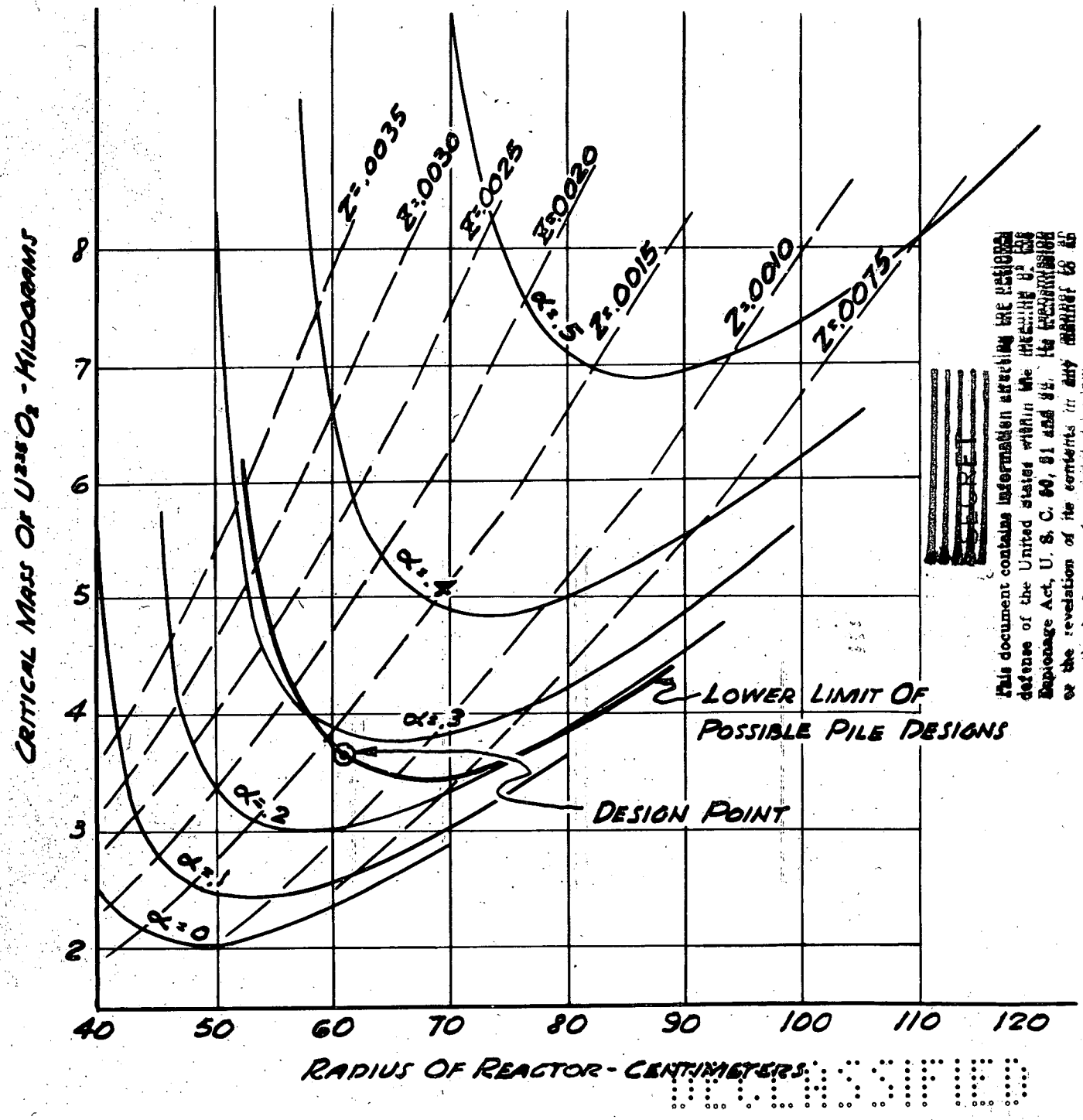
BeO MODERATOR

ALLOWABLE FUEL ELEMENT STRESS = 900 psi

REFLECTOR { ENDS = α VOIDS, $h/H = .54$; SIDE = NO VOIDS, $T/R = .50$ }

LENGTH PILE = .925 DIA.

Z = GRAMS $U^{235}O_2$ PER GRAM BeO



[redacted]

This document contains information affecting the national defense of the United states within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SE[redacted]

HIGH TEMPERATURE EXPERIMENTAL POWER PILE

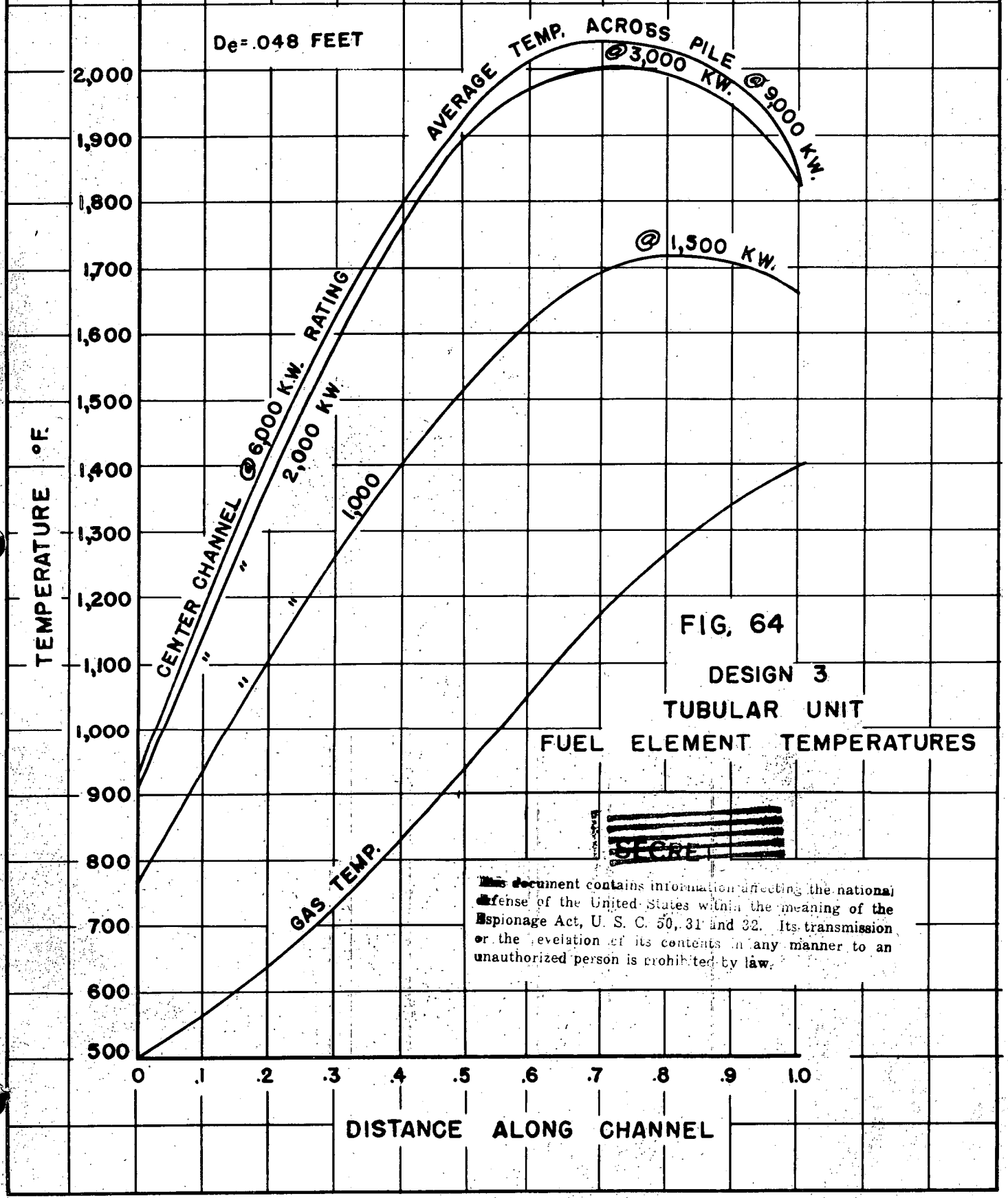


FIG. 64

DESIGN 3

TUBULAR UNIT

FUEL ELEMENT TEMPERATURES

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CURVE A

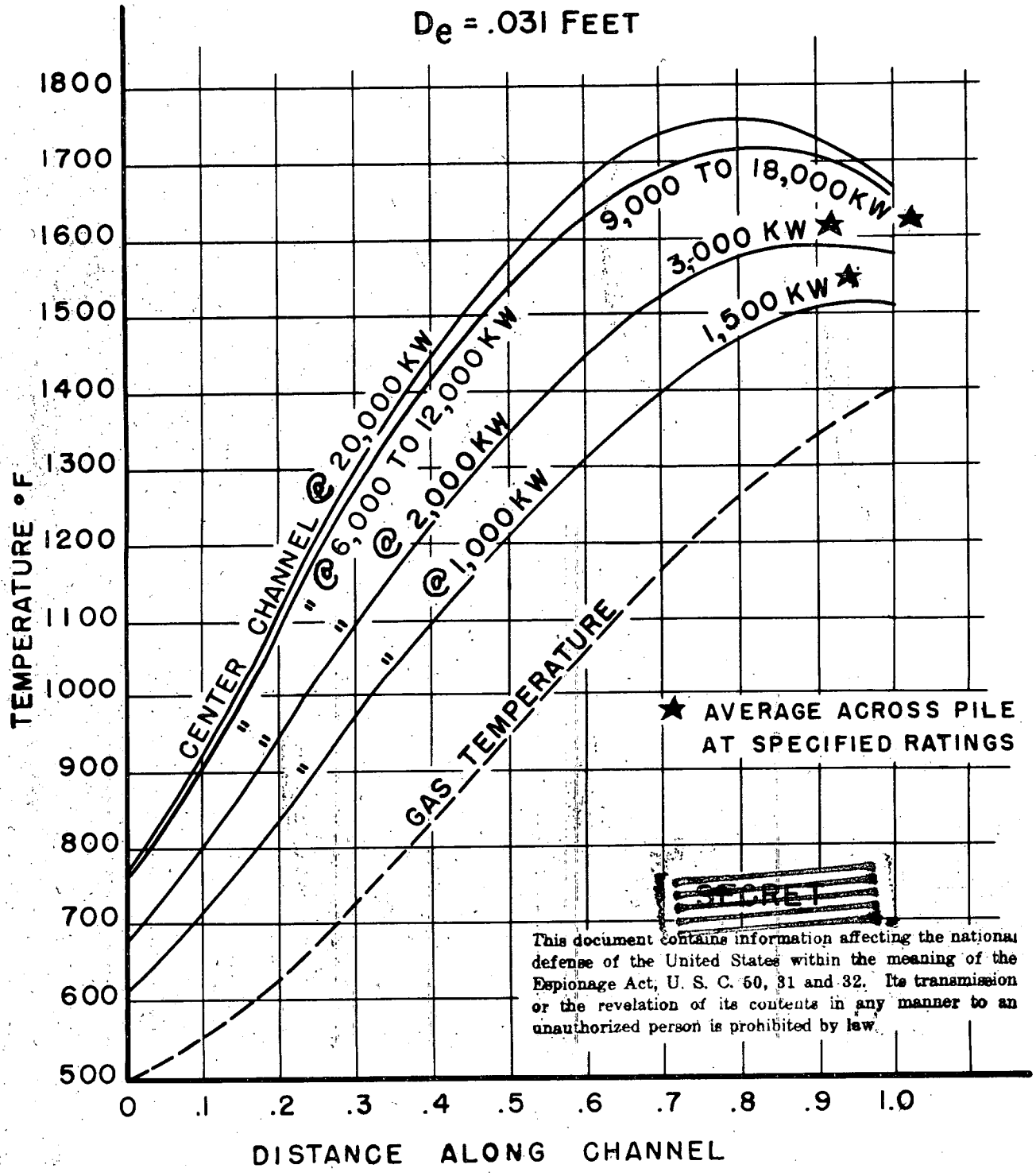
DECLASSIFIED

SECRET

FIG. 65

HIGH TEMPERATURE EXPERIMENTAL POWER PILE

FUEL ELEMENT TEMPERATURES



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

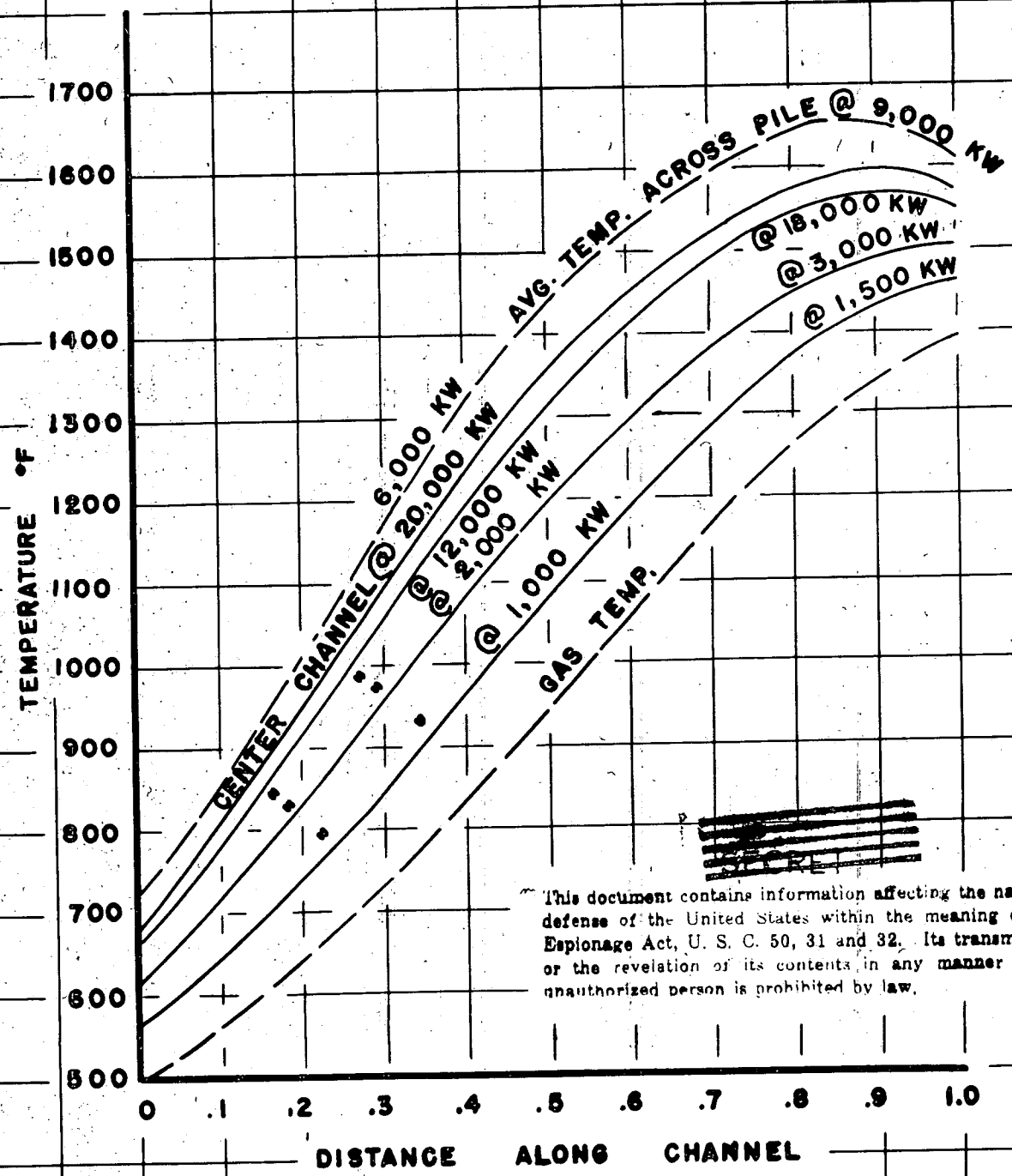
CURVE B

SECRET

FIG. 66

HIGH TEMPERATURE EXPERIMENTAL POWER PILE FUEL ELEMENT TEMPERATURES

D_e = .0227 FEET



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

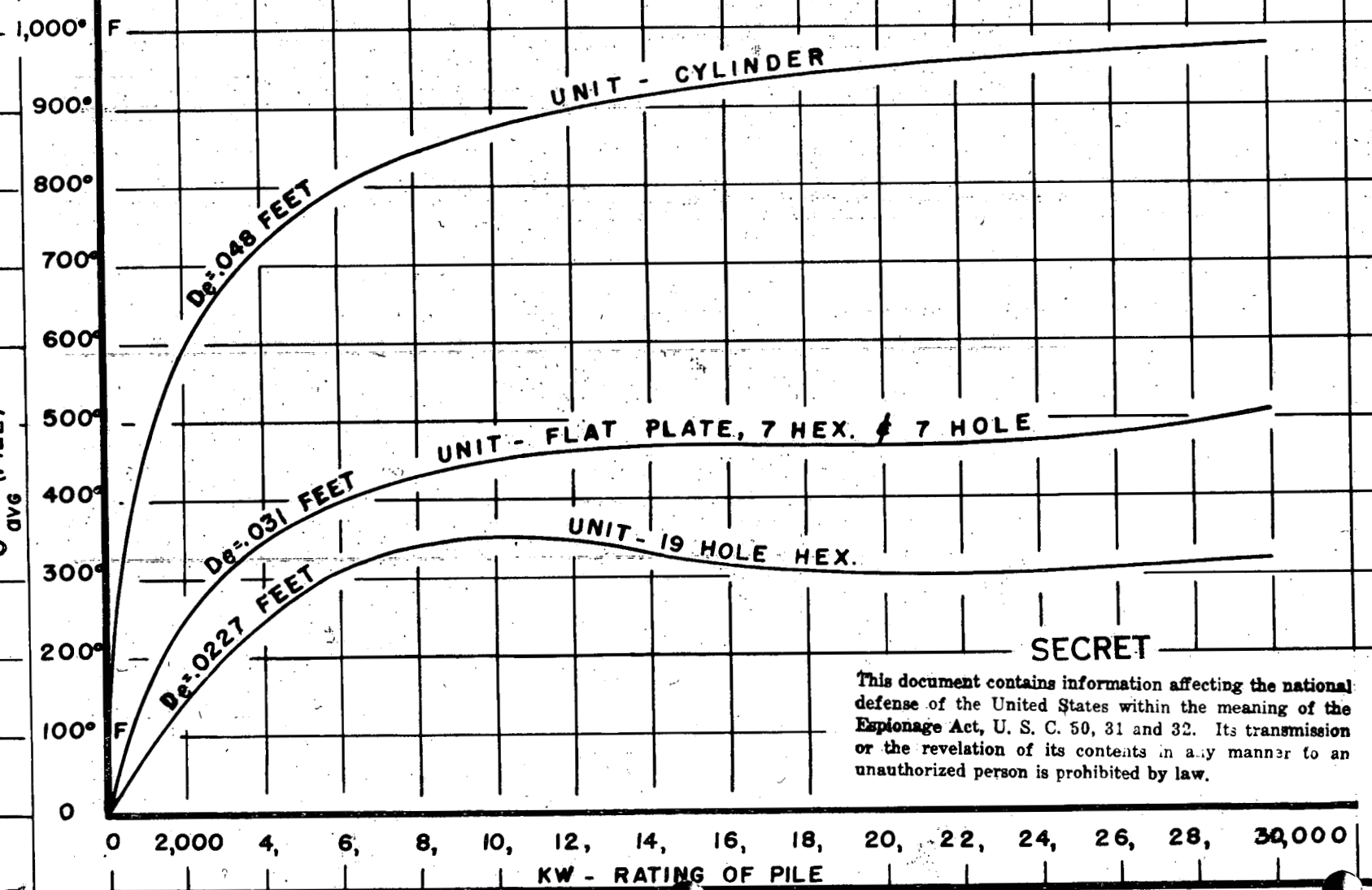
CURVE C

SECRET

FIG. 67

AVERAGE TEMPERATURE DIFFERENCE BETWEEN FUEL ELEMENTS AND GAS IN PILE DESIGN 3A.

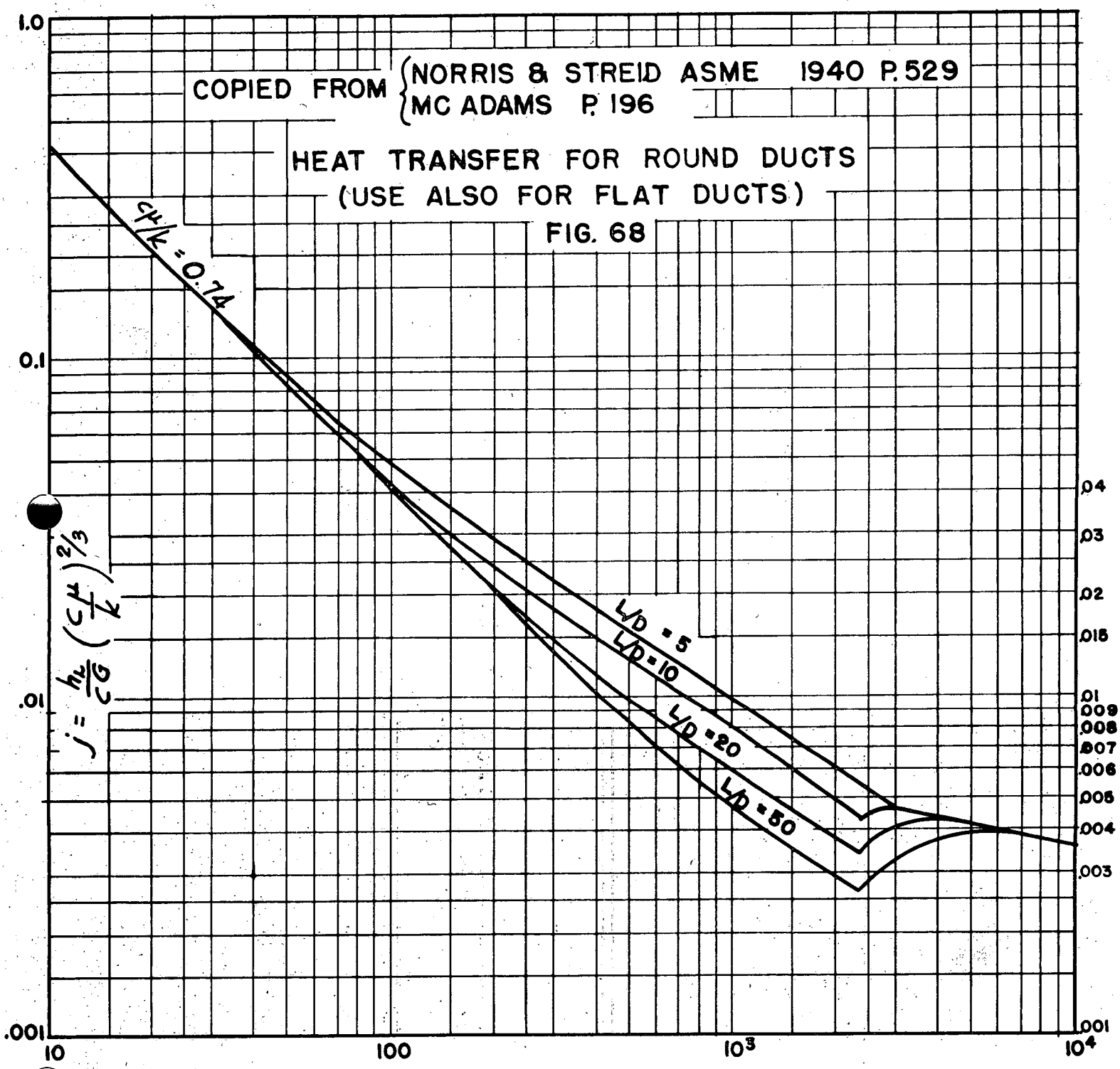
AVERAGE FUEL ELEMENT TEMP. = 950°F + θ_{avg} PILE



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CURVE D



$R_D = \frac{GD}{\mu}$

CHART E

DECLASSIFIED

C. PILE STRUCTURE

The development of the structural features of the pile design described in Section IV has required consideration of and solution of a large number of mechanical problems peculiar to the design of structures operating at high temperatures and high pressures. These problems are further intensified by the close interrelation between many features of the pile design such as the requirements for introducing and removing fuel, the use of neutron absorbing rods for controlling the pile, the use of a ceramic material for the permanent structure, and perhaps most important, the intense radioactivity associated with operation of a pile. The nature of these problems and their influence on the pile structural design is described in the following paragraphs. The primary effects of heat transfer and physics considerations on the structural design, i.e., fixing the cross-sectional dimensions of the beryllium oxide bricks and the length and diameter of the pile, have been described previously and the discussion here is therefore limited to the secondary effects evolving therefrom.

1. Design and Fabrication of Beryllium Oxide Bricks and Reflector Plugs.

In addition to the pile design requirements, the limitations imposed by the present technology of producing beryllium oxide powder and fabricating it into suitable shapes have had considerable influence on the specifications for the BeO bricks and plugs given in Section IV. This is particularly true with regard to the brick length, density, dimensional tolerances, and purity.

Two methods of fabrication of Beryllium Oxide brick have been developed, one by the Norton Co., the other by the A.C. Spark Plug Co. The Norton Co. brick are made by placing BeO powder in a graphite mold, heating to 1600-2100°C. and applying a pressure of 1000-2000 psi. This process produces hexagons 3" across flats with a 2" diameter hole in lengths up to 9 inches with a density averaging about 2.85, and with low dimensional tolerances. These brick are made from Brush Beryllium Co. type G.C. oxide. The A.C. Spark Plug Co. brick have been made by cold pressing of the powdered oxide in steel dies and fired in a continuous kiln at 1750°C. The hexagons made by the Spark Plug Co. are limited to 3" length. The maximum density achieved to date is about 2.6 or 2.7. These bricks are made from Brush Beryllium Co. S. P. oxide. They are much less expensive than the Norton Co. hot pressed brick.

a. Length of Brick. A long brick is desirable for structural stability. However, increasing the brick length increases the axial temperature gradient in the brick. This effect becomes most severe at the center of the pile where the temperature in some bricks will reach a maximum in the center with reduction toward each end of the brick. Thus the optimum brick length, based on conditions at the center of the pile, is a compromise which again is difficult to evaluate in numbers. The cost of fabricating the brick is reduced by using longer brick.

The 6" brick length on which this report is based was chosen because it represents the longest hot-pressed brick obtainable at the time this design was crystallized. Recently the Norton Company has fabricated 9 inch

SECRET

hot-pressed brick, and it now seems likely that some length longer than 6 inches will prove practicable. This question requires further study and test work.

b. Density of Brick and Plugs. The specification of 2.85 density for the brick is considered essential, because of the adverse effect of lower density on critical mass. A reduction from 2.85 to 2.65 average brick density means an increase in critical mass of about one kilogram of fissionable material in the pile, which more than wipes out the cost advantage in using the ceramic brick. In the case of the cylindrical plugs, the effect of density reduction is much less, because these plugs are located in the reflector zone in the 276 outer channels. By reducing the density of these plugs from 2.85 to 2.65 the critical mass of fissionable material required is increased by only 1 or 2 %, which is not major.

c. Dimensional Tolerances. The assembly of the brick in the pile must be accomplished with a high degree of precision, and therefore it is highly desirable that these brick be made with considerably less variation than the values ordinarily accepted for refractory brick and tile. This matter is discussed in detail later in this section under the subject of Pile Alignment. It seems reasonably sure that hot pressed brick can be made to closer dimensional tolerances than ceramic fired brick, unless the ceramic brick are machined. However this subject requires further detailed study in cooperation with the brick manufacturers.

d. Bell and Spigot. The desirability of making the brick with bell and apigot for longitudinal alignment has been given considerable thought. This question is not susceptible to a completely clear cut answer. It is affected materially by the strength of the bell and spigot, and by whether the pile is vertical or horizontal. The longitudinal alignment provided by a bell and spigot seems more necessary in a vertical pile. In a horizontal pile where the channels are overlapped at third points, it seems likely that longitudinal brick alignment can be accomplished by the weight of the brick and the former blocks on top of them. Thus it is not clear that bell and spigot are actually needed. Furthermore, there is some possibility that the weight of the brick above may rupture a bell or spigot in a case where misalignment occurs at a joint.

Rupture tests on two bells and two spigots of the type shown on Fig. 19 indicated a breaking strength in excess of one ton for each bell and each spigot. This high breaking strength plus the length of overlap has led to adoption of the bell and spigot shown on Fig. 19 for use in the vertical pile.

e. Purity. Brush Beryllium Co. type G.C. and S.P. powder and Clifton Products Co. fluorescent grade powder are all of sufficient purity except for boron content. The presence of boron in the beryllium oxide requires an increase in the critical mass of the fissionable material approximately in the amount of 10% for each one part per million of boron.

SECRET
DECLASSIFIED

SECRET

Brush Beryllium Co. type G.C.oxide normally runs 5-15 ppm and type S.P.normally runs 2-10 ppm. By selecting especially pure batches, Brush can supply about 1500 lb. per month of G. C. oxide and probably 1500 lb. per month of S. P. oxide. Presumably somewhat greater quantities can be furnished if 2 ppm material were acceptable. Clifton Products Co. fluorescent powder normally runs somewhat less than 1 ppm boron, and they can supply 2000 to 4000 lbs. per month of powder to 1 ppm specification. The specification of 1 ppm boron represents the lowest boron content which can be met based on material procurement in the quantity required.

f. Summary. The specifications of 2.85 density and at least 6" length for the brick are considered essential in spite of the fact that the only brick which meet them are the Norton Co. hot pressed brick made at Chippewa, Ontario, Canada.

The reflector plug specifications have been deliberately written, to permit them to be made by A. C. Spark Plug by ceramic firing. It was considered desirable to keep a second manufacturer working on the beryllium oxide problem. Furthermore, the A. C. Spark Plug ceramic fired product is made from Bush Beryllium Company S. P. Oxide, which is not used by The Norton Company in making the hot-pressed brick. The use of this different source material for the plugs will speed up powder procurement materially.

2. Pile Arrangement.

In the development of the pile design consideration has been given to both a horizontal and vertical orientation of the pile axis. The vertical pile design described in Section IV was chosen because it simplifies several problems, namely:

1) The problem of retaining the hot end of the bricks has been simplified by depending upon the dead weight of a number of metal blocks at the top of the pile, rather than depending upon the tensile strength of a plate or other structure which would be required with the hot end in any other location. Other approaches to the problem involve either cooling the retaining structure to a uniform temperature, or making the structure in pieces to permit small relative movements, although restraining large movements. The design presented may be regarded as a modification of the latter approach, in which each section is held in place by gravity.

2) Loading and unloading are accomplished from the bottom of the pile, and pile control from the top, which simplifies each of these problems by the fact that neither interferes with the other.

3) Maximum static load on the brick is less, and channel alignment is simplified with this arrangement.

SECRET

DECLASSIFIED

SECRET

The design chosen involves two main limitations, namely:

1) The weight of blocks required at the top to hold the brick in place becomes excessive at differentials not much above 2.5 psi, so that this solution of the hot plate problem is not a practicable one with a pile designed for a gas pressure differential of 10 to 20 psi, which will probably be required if large capacity gas cooled piles are built.

2) With loading and unloading mechanism both at the same end of the fuel channels ("reverse channel loading"), loading is probably restricted to pile shutdown because an entire channel must be completely emptied and reloaded in a loading operation. "Through channel" or "slug" loading are more attractive and may ultimately be feasible. Work done on designs pointing toward this end is discussed in Appendix E.

3. Pressure Shell.

The working pressure in the helium system is 132 psig. This system is protected by a safety valve and rupture disc which are discussed in part F of this section. When these devices function the helium is discharged into a closed tank to avoid atmospheric contamination. The rupture disc is difficult to replace and therefore will be set at a pressure considerably above working pressure to make sure that it blows only in major emergencies, such as a major boiler tube rupture. In order to permit this, the pile and other parts of the helium system are designed for a pressure of 250 psi.

Actually, this design pressure should have some further consideration from two viewpoints:

a. It is advantageous to design the helium system so that the pressure relief devices will never need to blow, even though all the water and steam in the boiler empties into the helium system. Calculations are needed to determine the pressure in the helium system in such a contingency.

b. Since steam in the pile increases reactivity very markedly, careful consideration must be given to the pressure setting of the relief devices. The higher the setting the greater the potential weight of steam which can accumulate in the pile and hence the greater the possible increase in reactivity. Physics calculations must be made to determine whether the desired safety valve pressure setting is acceptable.

The thickness of the pressure shell of the pile is 1 1/2", which corresponds to a circumferential pressure stress of 4200 psi at 132 psi working pressure and 8000 psi at 250 psi design pressure. This is below the stress allowable with low carbon steels at temperatures up to 650 F. The difference is regarded as a reasonable margin of safety to allow for possible radiation damage to the steel. Specific information concerning radiation damage will ultimately be required for all steels used in the pile.

SECRET
DECLASSIFIED

Welding technique requires careful investigation to insure tight joints free from inclusions and blow holes. It is essential that a proven method be used to determine the tightness of the shell.

Calculation of the reinforcement required around shell openings is being left for detail design. Details of welding the manhole to the shell are in the same category.

A fuel unloading tube is mentioned in the description of the pile structure. However, no design work has been done as yet. Provisions will probably have to be made for replacing this tube as there may be considerable wear. Tests now in progress will determine this.

The 6" thickness of the bottom plate was chosen from the viewpoint of the fuel slug latch mechanism. A rough stress check indicates about a 9000 psi maximum stress due to static load, which seems reasonable. At constant power level this plate is also subjected to temperature gradients due to conduction of heat from the brick, and to absorption of gamma and neutrons. It is believed that the resulting temperature stresses will not be excessive, but this item requires careful analysis.

Under changing load conditions, the pile pressure shell and retaining cylinder as well as the bottom plate will have to be checked with respect to the effect of variations in the gas temperature entering the pile. Present boiler specifications involve a gas temperature change from 500 F at 10,000 kw output per boiler to about 350 F. at 500 kw output. The temperature stresses induced in thick metal by a rapid change from 10,000 kw to 500 kw are probably acceptable, but must be checked.

4. Pile Alignment.

The steel forming blocks around the brick structure serve to keep the brick as a close-packed unit and give flexibility for expansion. By tapering top and bottom of individual blocks 45 degrees as shown on Fig. 24, a horizontal component of force of approximately 5 psi is available for centering the brick. Further study and experiment will be required to determine the optimum size and shape of these elements, and to determine whether a taper can be made to center the brick satisfactorily with respect to the pile shell. If not, this introduces only a maximum 3/8" variation at the top of the pile.

The radial clearance between control rod and brick channels is 0.725" with perfect alignment. If the pile shifts the maximum distance of 3/8", a minimum control rod clearance of 0.35" at the top of the brick channel is left for rod distortion and misalignment of rod bearings. The full 3/8" movement is possible only when the pile is cold so that the minimum clearance at design temperature is about 0.45" at the top of the brick.

The control rod thimbles are attached to the pressure shell and to the top plate assembly. There is a differential movement between the 500 F. pressure shell and the 800 F. top assembly plate. Since the plate is centered with respect to the shell, there will be no misalignment for the central thimble, but the outer thimbles will move away from the center

DECLASSIFIED

SECRET

slightly at the bottom as the pile is heated from cold. Since the lower control rod bearing is aligned with the control rod thimbles, misalignment of the thimbles is transmitted to the control rods. For rods on the outer circle calculations indicate 0.04" misalignment at the top plate assembly location and 0.08" at the bottom of the brick channel with the control rod all the way in. Since this rod swing is opposite to the direction of swing of the brick channel, it seems desirable to compensate partially by giving the rod a slight initial angularity, i.e. to incline the control rod thimbles slightly toward the center when cold. The effect of possible differential longitudinal movements of the control rod thimbles must also be studied. Any warping of control rods will seriously affect their alignment.

The problem of control rod alignment and clearances requires careful investigation which should include testing of a full size control rod channel under repeated operation of the rod to simulate actual operation of regulating, shim, and control rods. It is necessary to determine whether the brick will be cracked by contact with the rod, caused by rod vibration or other factors. If so, it will be necessary either

1) to increase clearances by increasing channel size or reducing rod diameter, or

2) to provide a suitable liner for the channel to protect the brick.

Tests are now scheduled to determine the amount of dusting obtained with beryllium oxide brick. Because of the small clearances between brick, retaining blocks, and retaining cylinder, it is essential that there be no appreciable accumulation of dust between brick when cold, since this would cause misalignment or even rupture of the structure upon subsequent heating and expansion. This is a major item which requires complete investigation.

In view of the small diametral clearances between brick and retaining shell (1/4" at bottom and 3/4" at top when cold) it is clear that the assembly of the brick requires a high order of precision. This is also required in order that control channels may be lined up with control rods. Fig. 19 indicates ± 1/64" tolerance across flats on the hexagons. With 25 hexagons across the diameter there is a maximum possible variation of ± 25/64", which is considerably greater than the 1/4" clearance to be provided at the bottom. To make the assembly with bricks of this tolerance will require

1) Selective assembly

2) Drilling bottom plate to average dimensions of actual brick, rather than to nominal 3" dimensions.

3) Machining inside of former blocks to provide proper clearance based on actual brick dimensions.

SECRET
DECLASSIFIED

SECRET

To eliminate these complications it would be necessary to reduce the total variation possible to about 1/16", which would mean limiting the tolerance on each brick to or ± .002", which does not seem feasible.

The maximum variation permissible in the overall height of a column of brick is about 1/16". With ordinary non-selective assembly this would require limiting the variation in brick length to about or ± .005," which seems impracticable. With careful selective assembly the height can be controlled to the required precision provided the average brick length can be held closely. Another possibility is to machine the top brick of each column to give the desired total column height.

The situation as to the reflector plugs in each channel is very much the same, since the total length variation in each channel must be kept to about 1/8" to insure proper operation of the fuel latch mechanism, and the spring which holds the plugs in place. Control of the average plug length plus selective assembly appears to be the best answer in the case of the reflector plugs.

The foregoing indicates that some very careful thought must be given to the problem of brick tolerances. Ultimately the brick tolerance and assembly problems must be discussed in detail with brick manufacturers in order to strike a balance between the difficulty of manufacturing brick to close tolerances and the difficulties of making the brick assembly.

Fig. 23 shows the fuel units held in position by a spring at the bottom of the column and radial lugs in the casting at the top. This drawing shows the spring element carried in a steel tube 5 inches long, which replaces the lowermost beryllium oxide unit in the channel. This reduces the effectiveness of the reflector, which is not acceptable. To avoid the necessity of increasing the reflector length, it is felt that this situation can be remedied by incorporating the spring element into the body of the latch, so that latch and spring can be located in the present latch location, and a beryllium oxide unit will be located in the present spring element location. This change has not been incorporated in Fig. 23 because it will require some study to combine the spring and latch mechanisms satisfactorily in a single body.

5. Temperature Distribution and Gas Flow.

In general the detail composition of all metals in the pile, and the allowable stresses, cannot be determined until a careful temperature analysis of all portions of the pile for all operating conditions has been made.

The temperature level and gradient in the beryllium oxide brick, and the corresponding stresses must be calculated in considerably more detail than has yet been done. Tests are now being run to determine the amount of cracking obtained with various temperature differences across the brick. The results of these tests must be correlated with calculated conditions of the moderator brick for various pile outputs. The effect of load swings, involving rapid changes in the helium temperature entering the pile, must also be studied.

SECRET
DECLASSIFIED

SECRET

This and other problems involve an analysis of heat release and flow distribution in the reactor and reflector channels, also an analysis of the flow diverted from the brick channels to cool the control rod channels and former blocks. It is desirable to have the same gas temperature leaving all brick channels. Reflector plugs are designed to restrict gas flow in reflector channels, since heat release in these channels is much less than in reactor channels. There is also a difference in the heat released in the inner and outer reflector channels. Flow in various channels will be proportioned by orifices at the inlet to each channel. A detailed study of this problem is required.

In order to have a 1400°F. mean gas temperature leaving the outgoing plenum chamber the average gas temperature leaving the brick channels must be somewhat in excess of 1400°F. This actual temperature must be calculated based on estimates of the temperature of the gas leaving control channels and former blocks, and the quantity of gas diverted to these purposes.

Cooling requirements of control rods and details of orifices for the control rod channels must be determined in order to obtain the required flow. The gas temperature leaving control rod channels must be determined for various loads and various control rod positions. Also the stresses in the brick at the top of channels adjacent to control channels must be checked, since the helium leaving the control channels may be much lower in temperature than the helium leaving adjacent channels.

The possible warping of control rods requires careful theoretical study. Tests may prove to be desirable. Heat radiation from adjacent brick, particularly when non-symmetrical around the rod, must be analyzed. The helium flow required to prevent warping must be considered in determining the flow required to cool the control rods.

Cooling passages through the former blocks must keep the temperature of these blocks well below 1400°F. in order that the temperature of the retaining shell may be kept within reasonable limits. Another factor which must be investigated is the desirability and effectiveness of utilizing the former blocks as a thermal shield to absorb gammas leaking from the pile. A complete study of heat transfer in these blocks must be made with due regard to

(a) Temperature of cooling helium.

(b) Heat released in former blocks.

(c) Heat conducted in from beryllium oxide brick.

(d) Heat conducted out into the retaining shell.

(e) Allowable temperature of retaining shell.

SECRET

DECLASSIFIED

SECRET

The helium temperature leaving the former blocks must also be considered, since this helium is used to cool the top plate assembly. It is expected that a temperature of 800 F. maximum on the outer plate be maintained. This thicker, 3/4" thick plate is sufficiently removed from the pile top so that no difficulty is expected due to uneven temperature distribution of gas leaving the pile.

There is no necessity for the light baffle plate at the top of the pile to be gas tight as a leakage there will do no harm. Therefore, this plate is simply bolted to angles fastened to the pressure shell. Clearance around holes is provided so this plate will exert no force on control rod thimbles. The lower plate in the top plate assembly also has clearance around control rod thimbles so that distortion of this plate cannot impair pile operation. A careful temperature analysis is required before metals and thicknesses can be determined for components of the top plate assembly.

Thermal insulation around the outside of the pressure shell has been planned for this design, but no work done. The advisability of such insulation must be thoroughly checked and a satisfactory material determined.

6. Test and Experimental Facilities.

This problem has not yet received detailed consideration. It is evident that materials which can be contained within cylinders five inches long and 1 7/8" diameter could be inserted and removed from either reactor or reflector, by the fuel loader within certain limitations as to the ability of the material to withstand temperature and radiation (i.e. it must not crumble or melt or react chemically or nuclearly) and within limitations as to the effect of the specimen on gas flow in the channel it is in. However, there is not yet apparent any realistic means for gas temperature measurement in connection with materials introduced into the fuel channels.

It seems probable that special test channels would have to be provided. These could be similar to control rod channels, and would be accessible from above. It may be possible to introduce samples with thermocouples attached into channels of this type. This however requires study which as yet has not been undertaken.

7. Shielding.

The design of the various components of the pile does not, in general, depend to any great extent on the type or amount of shielding required.

The composition and extent of the shielding, on the other hand, cannot be closely estimated until several of the more important design considerations of the project are settled, including maximum power operating level, details of pile loading, structure and support, maximum expected fission product diffusion from the various types of fuel to be employed, etc.

SECRET

DECLASSIFIED

On this basis available manpower has been applied to design work which must be completed before final shielding calculations can be made. A preliminary survey of project shielding literature has been made which provides sufficient information for making rough "order of magnitude" shielding calculations when necessary for determination of relative location of various parts of the equipment or components of the plant. Several groups are starting experimental and theoretical work on the general problem of shielding, including experiments now under way at Clinton Laboratories, and use can be made of such developments in connection with shielding studies for this project. Since weight and space are not at a premium in this application, the final selection of the type and arrangement of the shielding would depend largely on economic considerations, but it is anticipated that special shielding material would be required at various points as necessary to provide for optimum arrangement of various adjacent parts or structures and to provide for access through the shielding for repairs to important components.

SECRET
DECLASSIFIED

SECRET

D. FUEL HANDLING

1. General Requirements.

Reliability of the fuel handling equipment is of paramount importance and points toward simplicity of design. This is accentuated in the case of the equipment used for charging and discharging the pile due to induced radioactivity which precludes servicing. Because of this fact, all parts of equipment subject to rapid wear should be external to the helium coolant circuit and remote enough from the pile that induced activity will be negligible. This permits ready replacement of these elements without necessitating extensive shielding of equipment.

Since the possibility of unpredictable failure or unsatisfactory operation must be considered, even that part of the mechanism within the pile pressure chamber must be replaceable. This type of replacement is considered as a major repair and it is anticipated that such an operation would require shut-down of the pile for a period of several days or perhaps weeks. To achieve replacement of such equipment the philosophy has been that this equipment must be capable of removal from the chamber through a reasonably small hole in the pressure shell.

Loading of the pile without reducing the pressure appears at this date to be a reasonable and desirable objective. Consideration of the problem reveals the fact that to achieve a change of fuel within a reasonable length of time requires that the atmosphere within the pile must continue to be helium. Since this is the case, some form of gas lock would be required even for loading at atmospheric pressure. While the construction of the lock might be simplified by loading at atmospheric pressure, this would be achieved at the expense of increased complication in the coolant circuit.

Loading while the pile is in operation has appeared as a desirable objective in the interest of achieving a maximum of flexibility in the pile. There is also merit to the thought that loading under operation would be desirable in a commercial unit. While to date no satisfactory solution has been found for this problem, this objective has not been fully investigated.

The possibility of a channel becoming obstructed has been borne in mind although it is impossible to evaluate the probability without actual experience. Accordingly one of the objectives of the fuel handling device is to provide access to each channel in order that any obstruction within a channel can be removed by means of auxiliary equipment inserted through the access provided.

2. Loading Schedule.

As pointed out in the discussion of the fuel problems the criterion determining a change of fuel is assumed to be the allowable depletion within the fuel elements. A value of 10% depletion in considered a permissible upper limit. While it would be desirable to change each element as it reached 10% in order to reduce to the minimum the reprocessing loss and the number

SECRET

DECLASSIFIED

of elements to be handled in a given period, the mechanics of this problem is as yet unsatisfactorily solved. The next best approach, consistent with reasonably simple mechanisms, is to change an entire channel when the most depleted element has reached the 10% limit.

To obtain an approximate schedule for loading as a basis on which to plan the fuel handling cycle, the consumption of fuel has been calculated for a power level of 12,000 kw of heat, assuming that the flux distribution is that given by the One Group Theory.

Since only an approximate schedule can be formulated at this time the calculations are simplified by assuming the pile divided into 16 concentric zones of uniform radial width and further assuming that the flux within each of these zones is uniform and symmetrical. On these premises the time required to reach 10% depletion of the central element in each zone can be shown to vary in accordance with the curves shown in Fig. 69.

Since it is not practical to discharge each channel as it reaches the 10% limit it becomes necessary to investigate the number of channels to be charged at various time intervals. Assuming that 10% depletion can not be exceeded in any individual fuel element, it becomes essential to replace at any charging period all those channels in which the 10% limit will be reached before the next charging period. Fig. 70 shows the variation in the number of channels to be changed per shut-down with increase in number of days between such shut-downs.

Noted on the curve is the specified number of channels to be changed at 1 week and 2 week intervals. It can be seen that the number of channels changed on a 2 week basis is greater than the number that would be changed in two one week periods. This arises of course, from the need for changing channels in which 10% depletion would be reached prior to the next two week shut-down. This is pointed out more clearly by Fig. 71, which is a plot of the excess fuel elements (per 30 days) consumed on a channel loading basis instead of the replacement of each element at 10% depletion. It can be seen from this curve that even if the pile were shut-down as each channel reached 10% depletion in the central element, 440 elements would be used every 30 days in excess of the 1560 elements that would be used on an individual element changing basis. However, since this at least must be accepted (due to lack of machinery for changing each element) it is worth noting that to increase the period from this absolute minimum to a once-per-week basis causes only about a 10% increase in the material to be reprocessed. Since a once-per-week basis is a more reasonable operating schedule and since the additional cost is moderate it is planned to shut down weekly and change 58 channels.

3. Time Available for Loading.

The excess reactivity in the pile has been estimated as sufficient to overcome the Xenon poisoning for a period of three to four hours after shutdown. (This has been based on the assumption of no diffusion of Xenon from the fuel element and an instantaneous shut-down from full power. While this is the most pessimistic approach to the problem it was used as a basis in order to investigate the possibility of meeting even this short

DECLASSIFIED

SECRET

schedule).

While the change of 58 channels will obviously reduce the amount of Xenon within the pile it is impossible at this point to estimate the quantitative nature of this change. In the interest of conservatism, therefore, it has been decided to neglect this change in estimating the time available for loading. Thus, assuming the lower value of 3 hrs. to be more nearly correct and assuming further that 1 hr. should be made available for start-up of the pile, it can be seen that the fuel change must be made within 2 hrs. Since 58 channels must be changed in this period, the loading apparatus must be capable of changing one channel in two minutes.

4. Gas Locks.

The charging gas lock must serve the dual function of preventing dilution of the pile helium with the surrounding air and to prevent discharge of dangerous amounts of radioactivity in the form of contaminated helium. It must be capable of handling fuel elements at a rate fast enough to meet the loading schedule outlined above; that is, it must permit passage of sufficient fuel and reflector elements to refuel 58 channels within a two hour period. In order to minimize vacuum pump requirements the volume of this lock must be a minimum amount greater than that necessary to accommodate the number of elements being processed at a time. The lock must also provide for operation of a plunger or ram to transport the fuel elements from the lock to the charging machine. It is possible that future investigation will indicate that the fuel elements must be enclosed in a gas tight container under helium pressure, in order to reduce pile helium contamination by various gases which might otherwise be contained within the fuel elements. If this should develop, the gas lock must also contain equipment for opening this container after the contents of the lock surrounding the container have been brought to a satisfactory state of purification. The indications at present, however, are that these precautions are unnecessary.

Due to the rapid loading schedule, it was feared that preheating of fuel elements might be necessary (at least in the case of BeO) in order to avoid thermal cracking upon insertion of cold elements into the hot pile. Such preheating would most logically be incorporated in the gas lock system. The problem was investigated by inserting two cold, ceramic fired BeO fuel elements into an electric furnace, previously heated to 1400°F, and having a 1/2" thick steel plate on the floor of the furnace on which the elements were placed. Although the ceramic fired elements are more resistant to thermal shock than hot pressed elements, the fact that no cracks developed was considered sufficient basis to omit preheating equipment until a more extensive investigation could be carried out.

The purging system must be so designed as to reduce the oxygen content of the gas lock to a value low enough that contamination of the pile helium will not be a serious factor. It must also be capable of reducing the activity within the lock, just before introducing new fuel, to a point where the residual contents may be discharged through the stack without danger to personnel. The first requirement is met by evacuation of the lock to .001

SECRET
DECLASSIFIED

atmosphere prior to pressurizing with helium. The second requirement is more difficult to define due to lack of knowledge about the activity level of the pile helium. It is expected that an activity of 0.1 curies per cubic foot (NPT) will be attained, although if all fission products diffuse into the gas the level will reach something in the order of 1000 curies per cubic foot. (See Coolant System, Part F). The radical difference between these two estimates must, of course, be resolved before final decision on a gas lock can be made; meanwhile, it is necessary to consider two systems to meet the two possibilities of the activity level. The purging system required, if the helium activity approximates the lower limit has been described in Section IV, assuming a safe stack discharge level of 100 curies per day.

Fig. 72 shows the purging system and operating procedure required in the event that the activity level of the pile helium approaches the 1000 curie per cubic foot value. The complications produced are apparent by comparison with Fig. 28 . The high level of activity of the helium dictates the use of a closed helium system in order to prevent discharge of dangerous quantities of radioactivity. To meet the safe stack discharge figure previously noted, the lock must be evacuated to .001 atmosphere before purging with fresh air. The helium removed from the lock must be removed quickly and compressed for reuse at the next pressurizing phase of the cycle. As in the case of the simpler purging system, quick acting valves are employed and these again must be backed up by slower acting valves for repair and replacement of the more frequently used valves. Provision is again made for applying pure helium at a pressure slightly in excess of pile pressure during pile operating periods.

The basic function of the discharge gas lock is identical with that of the charging lock in that it must be provided to prevent mixture of the pile helium and the surrounding atmosphere. It is, however, more complicated than the charging lock since it is necessary to cool the elements during and after discharging. This arises not only from the sensible heat of the elements but also from the heat generation due to the decay of fission products. The heat liberated in the decay coupled with the rapidity of discharge indicate the need for extensive handling equipment within the discharge lock. It is presumably necessary to store and cool all of the elements discharged at one loading operation. The handling equipment is of itself complicated since it must operate within a pressurized system, and in addition, the cooling system which must be provided, will be a closed system of blowers and heat exchangers to prevent escape of activity.

5. Alternate Charging Machine.

In the following paragraphs, an alternate design of charging machine is briefly presented. Since it was proposed considerably later than that described in Section IV, it has not been investigated so thoroughly. The relative merits of the two machines must not be inferred from the design status.

The principle of operation is similar to that of the machine described in Section IV, in that it employs a mono-tube to convey the fuel elements from the entrance passage to the pile, and from the pile to the discharge passage. The difference between the two lies primarily in the

SECRET
DECLASSIFIED

method of indexing the mono-tube with the channels in the pile. In this machine, shown schematically in Fig. 73, the tube has a single 90° bend to form an elongated letter "L", with the horizontal leg serving as the axis of support. The tube is rotatable, within limits, about this axis and is capable of lateral movement along the axis so that the delivery end of the tube generates a cylindrical surface below the pile support plate. The pile support plate is constructed with an integral manifold, consisting of a nest of tubes, one for each channel, curved to transform the flat pile face into a cylindrical surface conforming with that generated by the delivery end of the indexing machine. With this arrangement, the tube can be brought into alignment with a given tube of the manifold by a combination of rotary and axial motion.

As shown in the drawing, the entire mechanism, with the exception of the motors and speed reducers is contained within a pressurized extension on the reactor shell located on the side and below the pile. Rotation of the unit is achieved by an externally splined member, supported by the pressure shell extension and driven by a motor and speed reducer. The splines transmit the required angular motion to the externally splined indexing machine shaft, yet permit independent axial adjustment by allowing relative sliding between the two splines. Axial adjustment is achieved by a balanced rack and pinion drive, and is transmitted to the indexing machine through a pair of thrust bearings which act as a swivel joint to permit independent angular adjustment. The ram drive is provided by a rack and pinion, incorporating a sliding spline in the system between the gear reducer and the pinion.

It will be noted that the three drives are so designed that the motors and gear reducers are mounted in fixed positions on the pressure shell extension and that only rotary gas seals are needed at the points where the drive shafts penetrate the extension. This permits incorporation of the motors in the same fashion as that described in Section IV, so that the motors may be removed from their individual pressure chambers for repair or replacement.

The two-piece construction of the machine within the entrance gas plenum chamber reduces the size of the pressure shell extension to a minimum. The major portion of the unit, including the drives, is inserted through the lateral shell extension, and the remainder (consisting of the delivery end and its supporting structure) is inserted through an opening in the dome which is subsequently sealed. A dovetail, locked by a taper-threaded pipe plug, joins the two sub-assemblies into one integral unit. Removal, due to failure, is accomplished in the reverse order, the inner sub-assembly being equipped with an integral extension (pilot pin) for handling by the external, remote-controlled servicing tool. The extension is capable of taking thrust in either direction to break the joint free, if necessary.

Fuel is introduced into the machine by "muzzle loading" as shown in Fig. 73 . This simplifies the charging and discharging operations, since it permits complete confinement of the ram in the pressure shell extension and requires only the minimum stroke necessary to charge the column of fuel elements into the pile. The charging and discharging locks are located in

SECRET
DECLASSIFIED

SECRET

a single plane to one side of the indexing machine axis; otherwise, the general construction is unaltered from that described in Section IV. Except for these changes in location and method of indexing, the charging and discharging operations are identical with those previously described.

6. Status of Fuel Handling.

a. Charging and Discharging Machine. Both of the machines described in the foregoing paragraphs show promise of satisfactory operation, but require further design work before deciding which one is the more promising. Most of the problems requiring experimental investigation are common to both designs. Of immediate concern are the two problems of tube abrasion and cracking of fuel elements in passing through the curved passage. (This is particularly true of Beryllium Oxide). Bearings which will operate without lubrication and at temperatures up to 500° F must be found or developed; the most likely solution to the problem is the use of anti-friction bearings fabricated from high temperature alloy steel. Rotary gas seals are required for both machines and in the case of the later proposal a sliding seal must be used.

Either of the machines may be adapted for charging a horizontal pile with little or no change in design. It should be pointed out, however, that one of the unsolved problems in the horizontal pile is that of fuel removal. With control rods passing through the plenum chamber at one end of the pile it has so far been impossible to design a discharging machine which will operate in and around the rods.

b. Gas Locks. With the exception of the purging system valves the charging gas lock can scarcely be pursued further at this time. The construction design is partly involved with the location of the lock, which is in turn dependent upon the selection of a charging machine. The choice of a purging system hinges upon knowledge of helium activity. The quick acting valves, on the other hand, are common to both purging systems and can be investigated profitably.

The discharge lock problem has had only sketchy consideration to date, yet it is a problem requiring much thought before a solution can be reached. It must operate on the same time schedule as the charging lock, providing cooling for the spent elements during and for some time after discharge.

c. External Handling and Servicing Equipment. These problems are not of immediate concern since operating conditions are normal and the machines will be readily accessible for repairs and alterations. Both types of equipment are to some extent dependent upon the design selected for the charging machine, and hence must be deferred until that decision is made.

SECRET

DECLASSIFIED

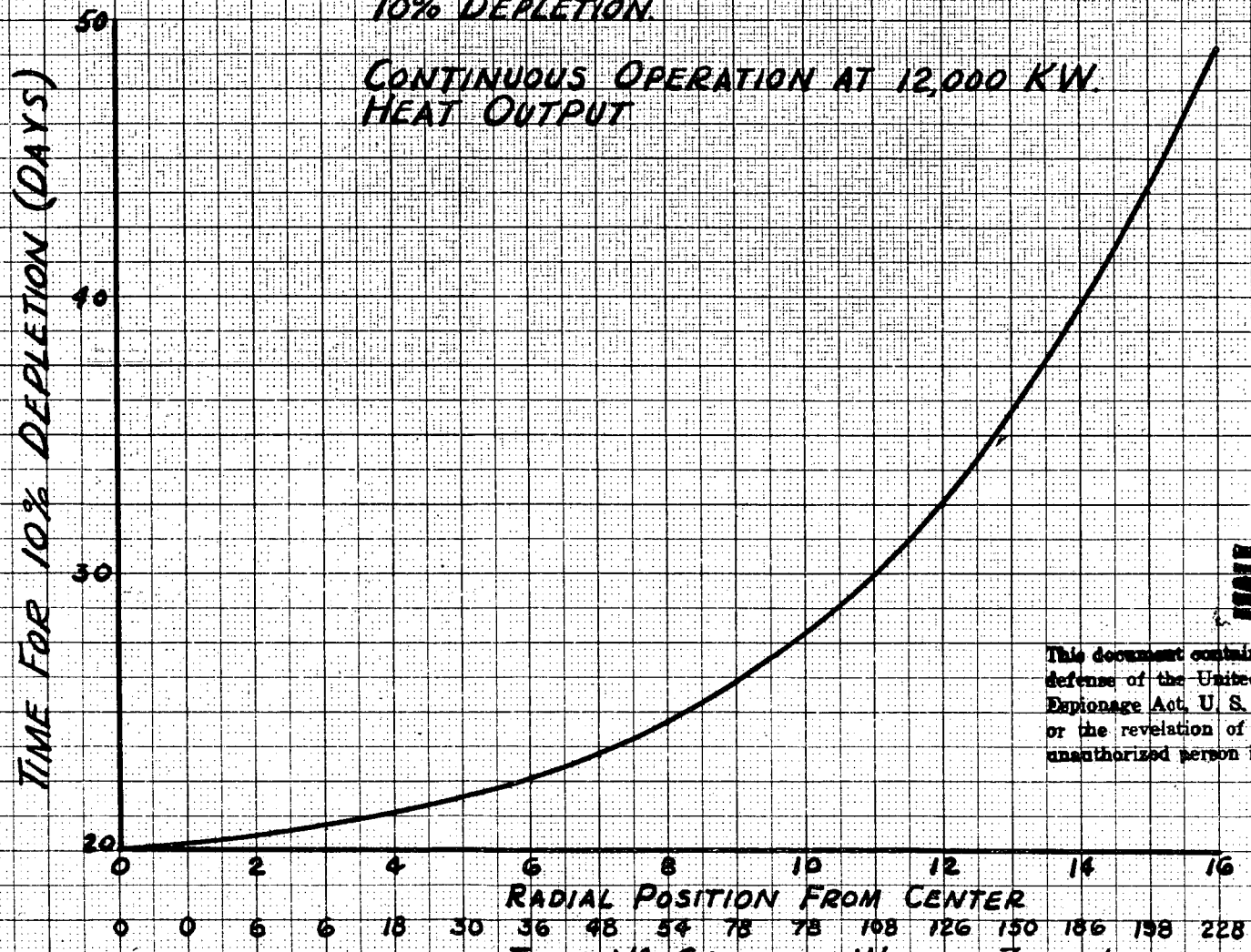
[redacted]

FIGURE: 69

DEPLETION TIME VS. RADIAL POSITION

DEPLETION TIME EQUALS TIME IN DAY FOR CENTRAL ELEMENT IN CHANNEL TO REACH 10% DEPLETION.

CONTINUOUS OPERATION AT 12,000 KW. HEAT OUTPUT



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

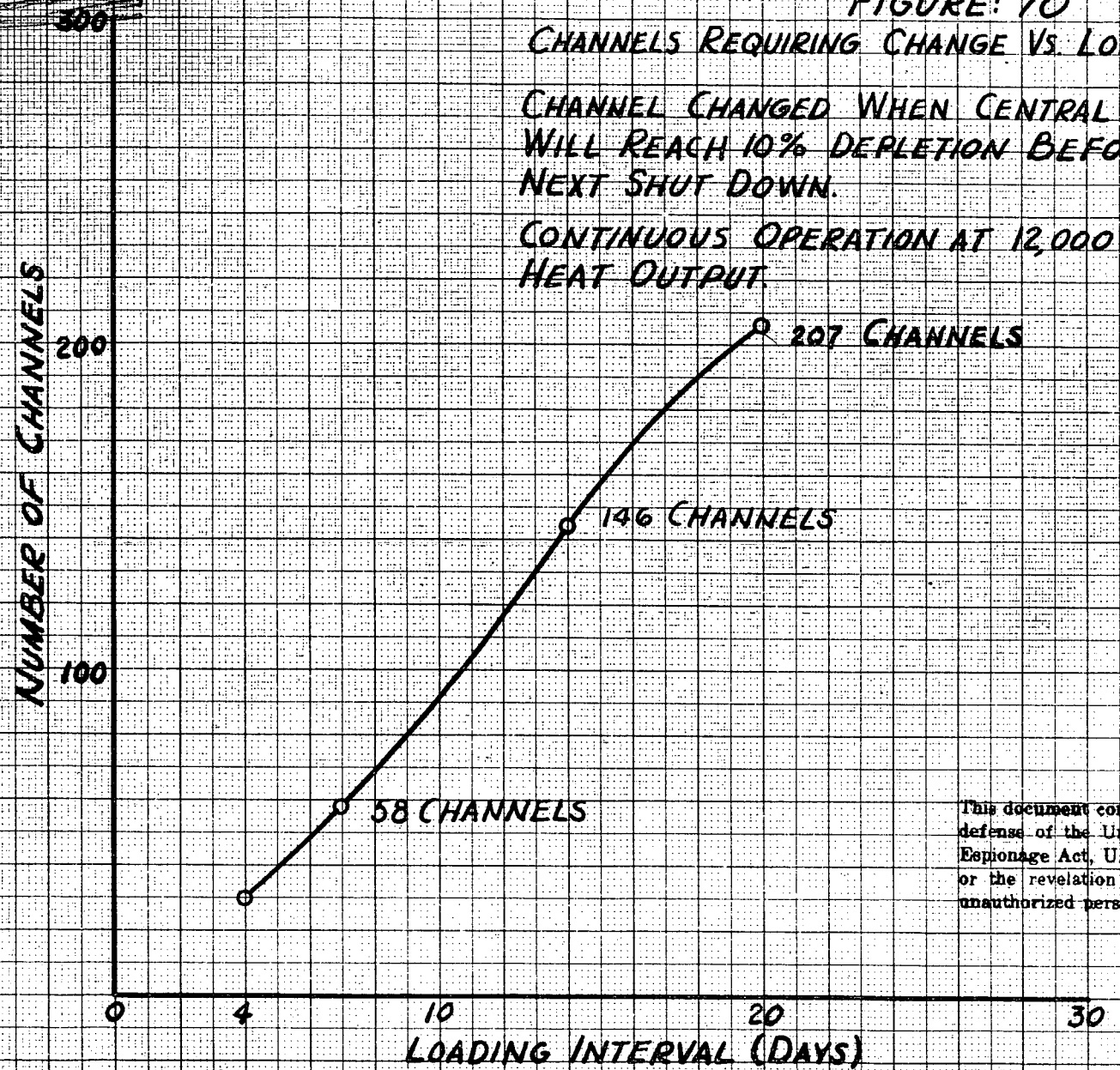
SECRET

FIGURE: 70

CHANNELS REQUIRING CHANGE VS. LOADING INTERVAL.

CHANNEL CHANGED WHEN CENTRAL ELEMENT WILL REACH 10% DEPLETION BEFORE NEXT SHUT DOWN.

CONTINUOUS OPERATION AT 12,000 KW. HEAT OUTPUT.



SECRET

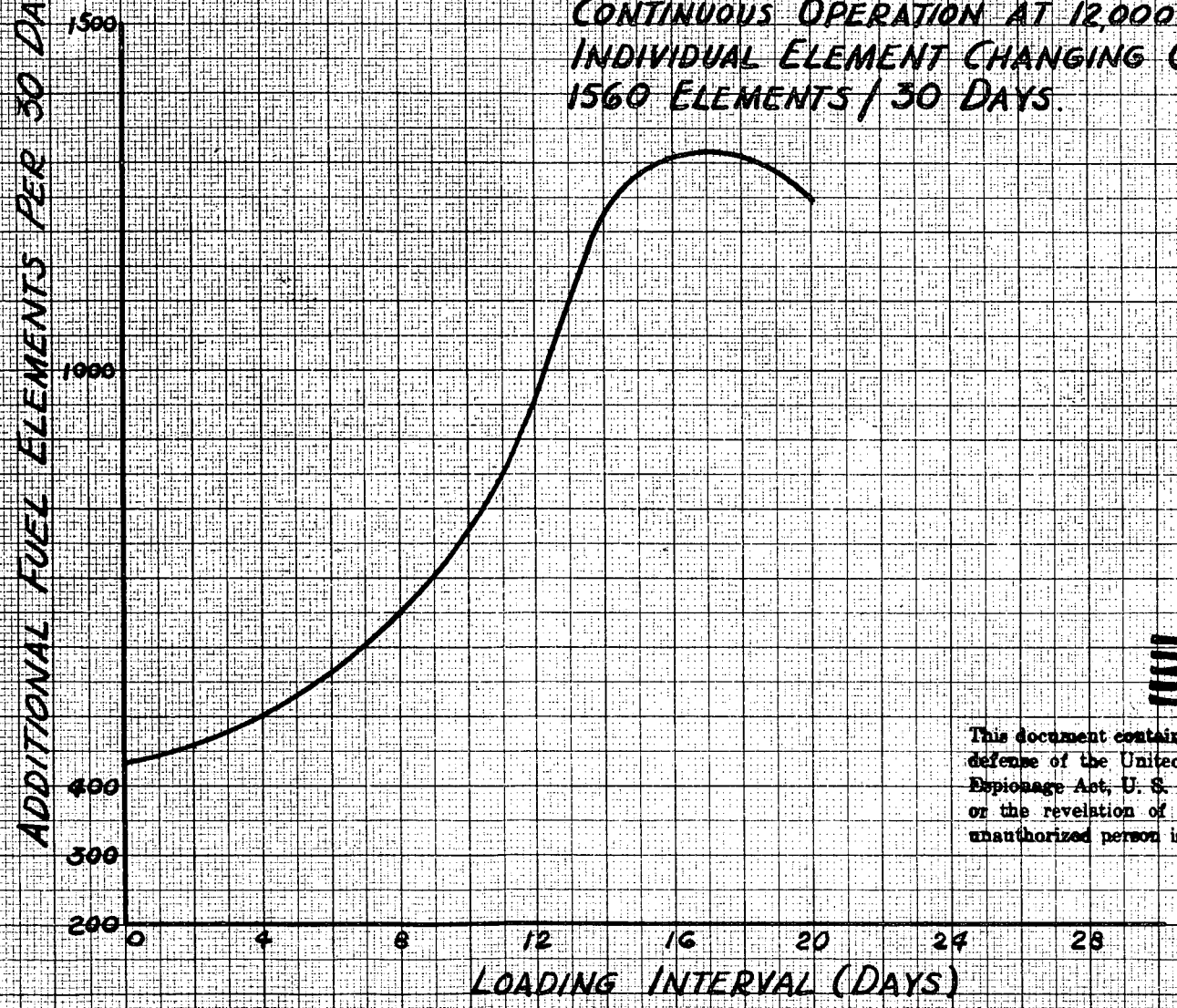
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

FIGURE: 71

MONTHLY EXCESS CONSUMPTION OF FUEL ELEMENTS
CHANNEL LOADING VS. INDIVIDUAL ELEMENTS

CONTINUOUS OPERATION AT 12,000 KW HEAT OUTPUT
INDIVIDUAL ELEMENT CHANGING CONSTANT AT
1560 ELEMENTS / 30 DAYS.

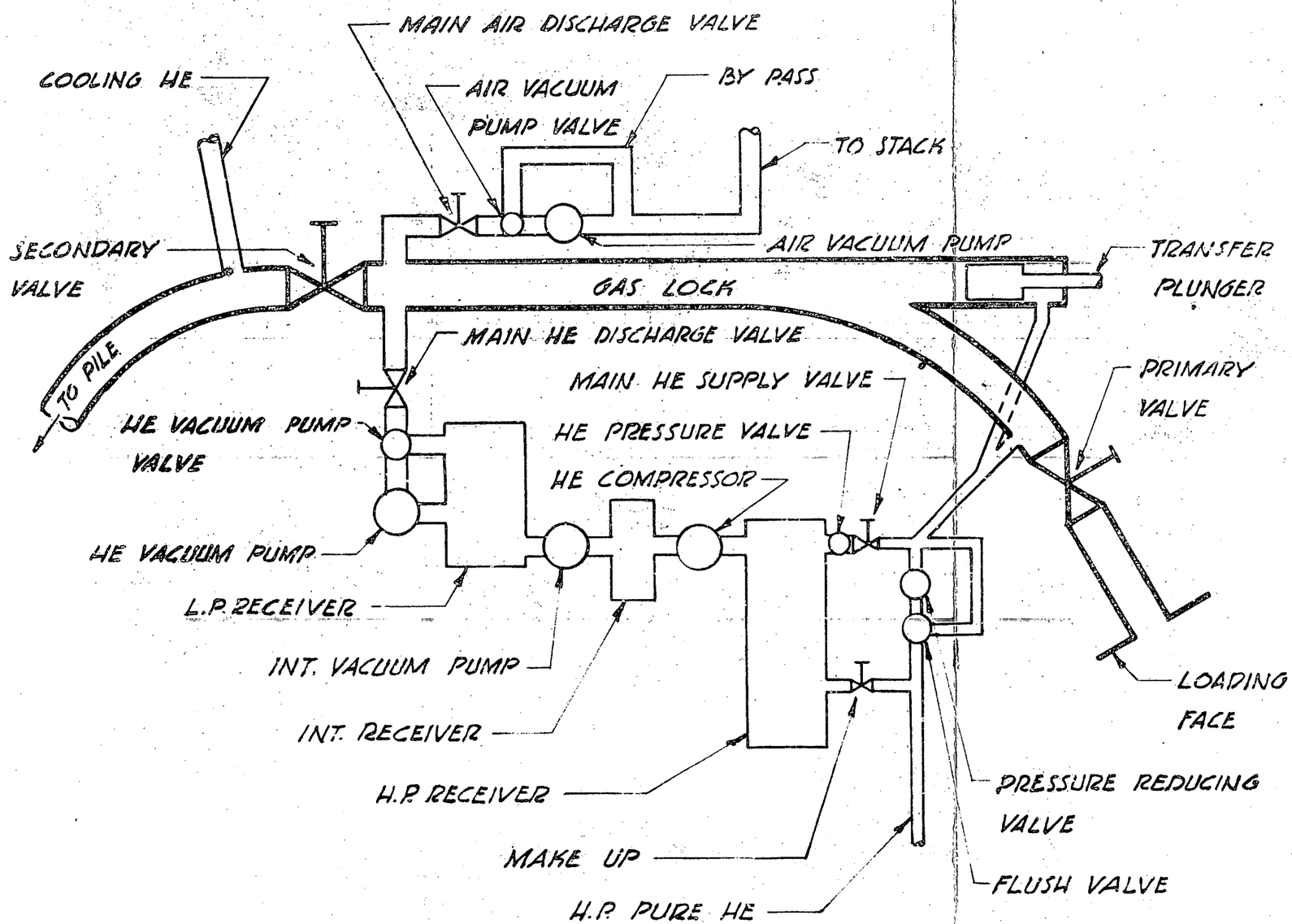


SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET



NOTE: PURGING SYSTEM REQUIRED FOR GAS LOCK IF PILE HE ACTIVITY IS 1000 CURIES PER CU. FT. AT S.T.P.

PREPARATION FOR CHARGING OPERATION

1. OPEN MAIN AIR & HE DISCHARGE VALVES & MAIN HE SUPPLY VALVE.
2. TURN THREE WAY FLUSH VALVE TO "OFF" POSITION.
3. TURN AIR VACUUM PUMP VALVE TO "BY PASS" POSITION.
4. START VACUUM PUMPS & COMPRESSOR.

CHARGING CYCLE

	TIME
1. OPEN PRIMARY VALVE & INSERT FUEL.	10 SEC.
2. CLOSE PRIMARY VALVE & TURN AIR VACUUM PUMP VALVE TO "PUMP" POSITION.	2 "
3. EVACUATE LOCK TO .001 ATMOSPHERE.	15 "
4. TURN AIR VACUUM PUMP VALVE TO "OFF."	1 "
5. OPEN HE PRESSURE VALVE & PRESSURIZE LOCK TO 10 ATM.	2 "
6. OPEN SECONDARY VALVE & CLOSE HE PRESSURE VALVE.	2 "
7. TRANSFER FUEL TO CHARGING MACHINE BY MEANS OF PLUNGER.	8 "
8. WITHDRAW PLUNGER & CLOSE SECONDARY VALVE.	5 "
9. TURN HE VACUUM PUMP VALVE TO "BLOW-DOWN" POSITION & LOWER LOCK TO 1 ATMOSPHERE.	5 "
10. TURN HE VACUUM PUMP VALVE TO "PUMP" POSITION.	1 "
11. EVACUATE LOCK TO .001 ATMOSPHERE.	15 "
12. TURN HE VACUUM PUMP VALVE TO "OFF" POSITION.	1 "
13. TURN AIR VACUUM PUMP VALVE TO "BY-PASS" POSITION.	1 "
14. OPEN PRIMARY VALVE FOR PURGING UNDER STACK DRAFT.	
15. REPEAT FOR EACH CHANNEL.	
TOTAL	68 "

TREATMENT FOR PILE OPERATION

1. AFTER COMPLETING LAST CHARGING CYCLE, REPEAT STEPS 2, 3, & 4.
2. TURN THREE WAY FLUSH VALVE TO "FLUSH" POSITION & RAISE LOCK PRESSURE TO 10 + ATMOSPHERES.
3. TURN THREE WAY FLUSH VALVE TO "PRESSURE REGULATING" TO MAINTAIN LOCK PRESSURE SLIGHTLY ABOVE PILE PRESSURE.
4. CLOSE MAIN AIR & THE DISCHARGE VALVES & MAIN HE SUPPLY VALVE.

FIG. 72

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

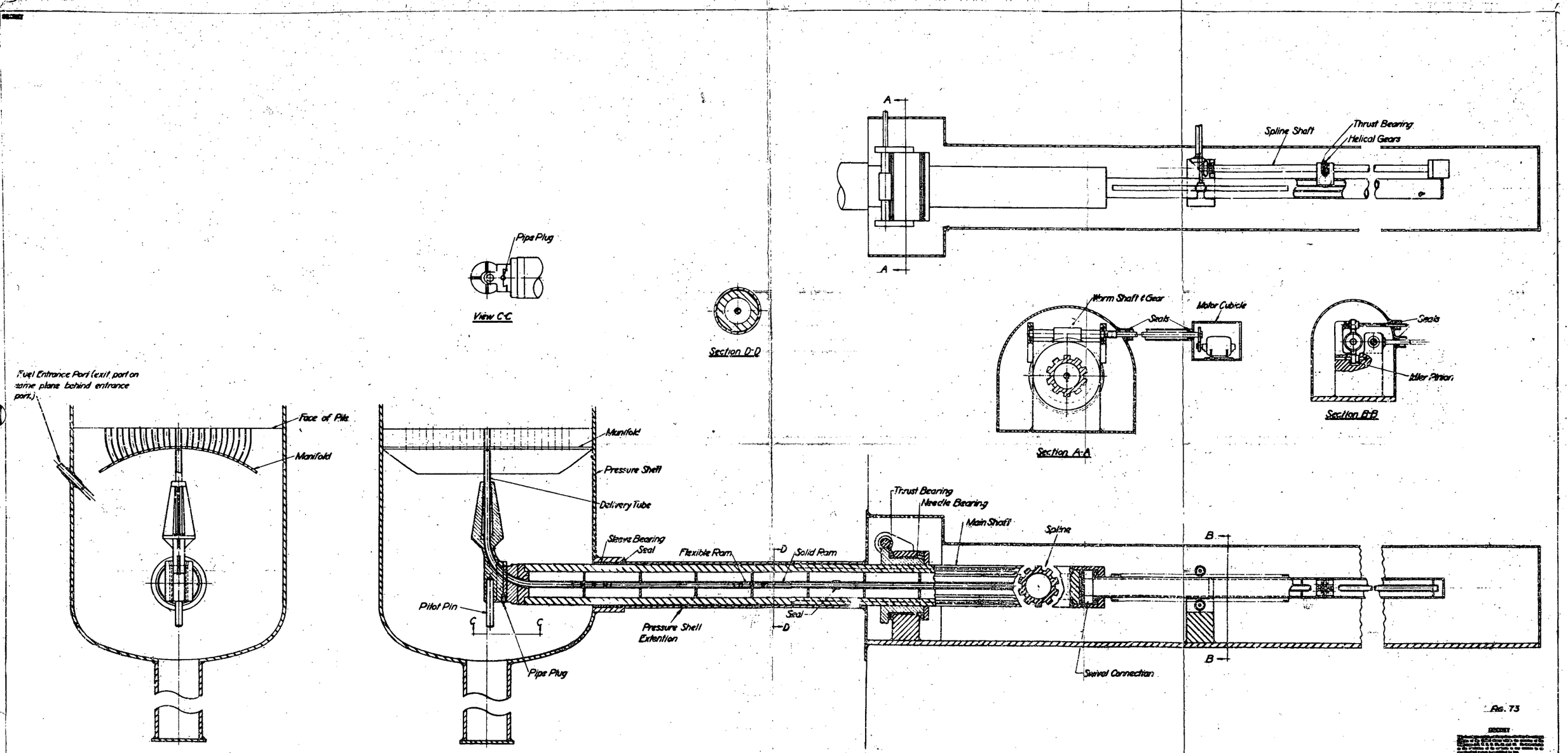
GAS LOCK PURGING SYSTEM II

HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.H.L. 9-12-47	C. R.E.R. 9-12-47	A. NG 9-12-47	RSP 9-16-47	A.L.S. 9-16-47		
PROJ. C-222M						
SCALE:						B-2273

DECLASSIFIED



DECLASSIFIED DECLASSIFIED DECLASSIFIED

SECRET

E. PILE CONTROL.

1. Methods of Controlling a Thermal Pile.

A pile is controlled by changing the percentage of neutrons which cause fissions. When the pile is just critical the neutron flux density is a constant. Under this condition on the average one neutron from each fission causes another fission. If it is desired to raise the power level then the percentage of neutrons which produce fission must be increased. During this period the pile will be supercritical and the power level will be increasing. The rate of rise is a function of the increase in pile reactivity.

The percentage of neutrons which produce fission must be decreased to decrease the neutron flux density. The pile must be brought back to critical to maintain the new flux density level.

These changes can be accomplished in several ways. The fraction of neutrons which leak can be changed or the fraction of neutrons captured by other than fissionable material can be changed. The latter change can be accomplished by changing the amount of fissionable material in the pile, by changing the location of fissionable material in the pile or by introducing a neutron absorber. The fraction of neutrons which leak can be changed by mechanically separating the pile into two or more parts or by removing part of the reflector. These last two are usually very difficult to accomplish.

Most thermal piles have a negative temperature coefficient, that is, the reactivity decreases with increase of temperature. The principal cause of this change is the increased leakage due to the increase in L^2, which is proportional to the square root of the absolute temperature of the pile. In many cases the operating temperature of a high temperature thermal pile is not critical but can be allowed to vary quite a considerable amount. The chief difficulty with this type of control is the long thermal time constant of the pile. This causes a sluggish response of the pile to changes in coolant velocity or coolant inlet temperature.

The normal method of controlling a thermal pile is the use of control rods. These rods are made of a material which is highly neutron absorbent. The control effect is derived, however, not only from changes in the absorption of thermal neutrons but from the attendant changes in the leakage of neutrons out of the pile.

High temperature thermal piles can perhaps be most efficiently controlled by means of a combination of control rods, pile temperature changes, and changes in fuel loading pattern.

2. Control Rod Calculations.

In the application of control rods to thermal piles one of the first things that must be calculated is the change in pile reactivity caused by various numbers of rods of various sizes, shapes, and locations. The theory is well understood and various methods of calculating have been reported.

SECRET
DECLASSIFIED

The most important of these are listed in the bibliography. In general the more straight forward and rigorously correct calculations are extremely difficult and tedious. There are, however, numerous approximations which are relatively simple and give good results under certain conditions. A considerable number of calculations have been made as to the control effect and neutron flux distribution by several different methods. The results have been plotted on curves so that the results can be compared quantitatively for various values of pile constants.

Calculations as to the effect of a central control rod in a pile having the shape of a right circular cylinder have been made. Several methods have been used in making the calculations and the results have been plotted and compared. The methods of making the calculations are fully covered in Appendix F.

The first method is that given by A.M. Weinberg.(1) Changes in k required to keep the pile critical have been plotted against the effective radius of the control rod on Fig. 72. The upper two curves are based on the assumption that the control rod is black to both thermal and fast neutrons. The other two curves are based on the assumption that the control rod is black to thermal neutrons and has no effect on the leakage of fast neutrons. The curves are for $L^2 = 121$ and $L^2 = 212$ with τ held constant at 258. The upper two curves represent an upper limit on the effectiveness of a control rod and the other two curves represent lower limits for the particular values of L^2. The actual effect is somewhere between the two curves and has a tendency to be nearer the lower limit for small rods and nearer the upper limit for large rods. It can also be noted that as L^2 increases with respect to τ the lower limit approaches the upper limit.

The second method is that outlined by J. A. Wheeler(2). This is a two group theory approximation method. It is assumed that the peaks of the thermal and fast flux occur at the same radial distance from the center of the pile. The boundary conditions are as follows: 1. Thermal flux zero at effective radius of control rod. 2. Fast flux regular at center of pile 3. Derivative of thermal flux zero at edge of cylinder of influence and 4. Derivative of fast flux zero at same place. For a given value of k, L^2, and τ and consequently of buckling the radius of the cylinder of influence (distance from center of pile to point of zero derivative of fast and thermal flux) is calculated for control rods with various effective radii. This information is plotted on Fig. 75. Insofar as the rest of the pile is concerned the k within this cylinder of influence is equal to one and the buckling is zero. The local change in k is therefore k - 1. The effect of this equivalent local change in k on the whole pile is then determined by the method of statistical weights with the importance of each point being proportional to the square of the original flux density. The results are given on Fig. 76. The change in k is plotted as a function of the actual radius of the control rod on Fig. 77 for the case of a rod embedded in the moderator.

The change in k for a rod having an effective radius of 1.35 cm. in a pile with a k of 1.78 and a τ of 258 is a linear function of L^2 as shown

(1) Superscripts refer to numbered references at end of section.

SECRET
DECLASSIFIED

SECRET

in Fig. 78.

The change in k for the same rod in a pile having a k of 1.78 and an L^2 of 121 is a linear function of τ for values of τ from 190 to 290. This curve is shown in Fig. 79.

The change in k caused by a single central rod has also been calculated by the more accurate straight forward two group theory method using the following boundary conditions: 1. Thermal flux zero at outside surface of reflector 2. Fast flux zero at outside surface of reflector 3. Continuity of fast and thermal flux and current at interface between reflector and reactor 4. Thermal flux and first derivative of fast flux zero at effective radius of the control rod. When k = 1.78, L^2 = 121, τ = 258, a rod whose effective radius is 15.9 cm gives a k of 0.318.

Control rod effectiveness is also a function of the position of the rod in the pile. The curve in Fig. 80 was obtained by means of the position factor method outlined by J. A. Wheeler[2].

Control rod effectiveness as a function of distance from the center of the pile was also calculated using the Nordheim-Scalettar[3] one group and two group theory approximations. The results are given in Fig. 81 and 82, and the three above methods compared in Fig. 83.

The curve on Fig. 84 shows the change in k for one central and one off-center rod parallel to the pile axis with the off-center rod at various distances from the pile center. In these calculations the position factor method was used and shadowing was not taken into account.

Fig. 85 shows the change in k as a function of the effective radius of an array of seven control rods. One of these rods is located in the center along the axis of the pile and the other six are symmetrically located on a circle around the center. The outer rods are located at such a distance from the center that the cylinders of influence of each are tangent to those of the central rod and of the adjacent rods. As the radius of the rods increases the effect of the control rods as control rods increases but the effect due to their location decreases. The former is more important for small rods, but as the radius of the rod increases the effect due to position decreases rapidly and the overall change in k goes through a maximum and then decreases. The shadowing effect is not taken into account but this effect is probably very small when the cylinders of influence are tangent. Fig. 86 shows the change in k as a function of the actual radius of the rods when embedded in the moderator.

Fig. 87 also shows change in k as a function of the effective radius of seven control rods located as described above. The total effect of these rods is, however, taken as equal to that of a single central rod for which the cross-sectional area of the cylinder of influence is the sum of those for the seven rods individually. For rods with effective radii less than 2 cm. the change in k is approximately the same as that shown on Fig. 85. The approximation by both of the above methods is poor for control rods with large radii.

SECRET
DECLASSIFIED

Fig. 88 and 89 show change in k as a function of distance of an outer ring of rods from the center of the pile. The actual radius of the rods is 2.00 cm. in Fig. 89 and 4 cm. in Fig. 88. The control effect is overestimated for small distances from the center of the pile. This is due to the fact that calculations were made by the method of statistical weights and shadowing effects were neglected.

A two group theory calculation of the effect of an array of seven rods was made by the method outlined by Nordheim and Scalettar[3]. Δk was .458 for six rods located on a circle 26.67 cm. from the central rod. All rods had an effective radius of 1.35 cm.

3. Instrumentation.

The instrumentation of a power plant operating on heat energy obtained from a chain reacting pile consists of those instruments which receive signals from neutron detecting and temperature devices in the pile structure, and conventional power plant instruments in the steam and electric generating apparatus. Neutron flux and temperature measurements are successfully made in existing reactors at temperatures close to ordinary air temperatures. The use of a closed system with helium gas under pressure for pile cooling at high temperature makes it necessary to make new devices for neutron flux and temperature detection, because present devices use materials which would melt or decompose in the pile. The devices should have very long life because it will be practically impossible to replace some of them if failure occurs. The best examples perhaps are the thermocouples which will be located throughout the pile.

a. Neutron Flux Measurement. To control piles to maintain the desired temperatures and power output the neutron flux must be held constant at the required value. Successful control depends on the ability to measure neutron flux continuously and detect changes quickly.

Neutrons are neutral particles which have no property which can be measured directly. They are detected by their effects on materials which produce measurable electric currents. The devices used for neutron flux measurement are metal foils, Geiger counters, neutron thermocouples and ion chambers.

Certain metals, such as iridium, can be placed in a pile and the radioactivity measured after removal. Any scheme depending on this effect would be useless because the effects of the neutrons on foils are cumulative and not suitable for control.

Geiger counters can detect single neutrons. The detecting device yields pulses of electric current as ions produced by alpha particles from the (n,α) reaction of neutrons on boron are swept out of a gas space by an applied direct current voltage. These pulses are counted by electronic circuits which operate a counter or recorder. The Geiger counter is useful for low flux measurements and the circuits can differentiate between pulses due to alpha particles and gamma ionization because the alpha particles produce many more ions per particle than gammas thus yielding larger

DECLASSIFIED

current pulses. It does not have a great enough range; and since it is an integrating type of instrument, it is not useful for measuring rate of change.

The n, α reaction between neutrons and boron releases energy which can be measured by means of a thermocouple if the "hot" junction is coated with boron and the "cold" junction is located close to the hot junction so the effects of temperature are nil. A temperature difference is then due to neutron capture. Neutron thermopiles can be made which give a response large enough to operate indicating meters or relays when the flux is of the order of 10^{12}. The range is limited.

In existing piles the principal neutron flux metering device is the ion chamber. The ion chamber contains a gas space between electrode surfaces which are coated with boron. Alpha particles released by the n, α reaction between neutrons and boron, ionize the gas and a current is obtained by applying a constant voltage to the electrodes. Direct ionization of the gas by gamma radiation is an annoyance which has been combatted in several ways. This can be done by reducing self activation, shielding against gammas with materials having low neutron capture properties, or by balancing out the effect of gammas by use of two ion chambers which are similar except that one has boron coated surfaces and the other does not. These can be connected electrically to balance out current due to gammas leaving a net current due to the neutron flux. The ion chambers in use do not have sufficient range although experimental models have been made to cover the range from 5×10^3 to 5×10^9. Since the ion chamber is generally located in the shield or reflector of a pile such a range of values may be adequate. In present piles the ion chamber is moved in and out of the pile to extend the range. This does not appear to be very practical in a high temperature pile. Iron and steel used in ion chamber construction have been responsible for most of the self activation. The useful range of experimental ion chambers has been extended by use of materials which do not become radioactive and by improvement of the boron coatings. However the high temperature pile will be surrounded by about 20 centimeters of iron and steel so eliminating iron in the chamber will not help much. It appears that the ion chamber must be in the reflector inside of the pile shell. The temperature and radiation in this region will make it necessary to build the chambers of suitable materials which can stand the exposure. Radiation and temperature destroy most insulation. Glass-Kova seals can operate at 350°C. but radiation damages the glass. Other types of insulated seals, such as the silica seals used in the Chalk River ion chambers, use metal seal rings made of metals having low melting temperatures. If the chambers must be placed in the pile it will be necessary to design new ones using suitable materials. On the other hand, the chambers may operate satisfactorily outside of the pressure shell. This may be possible if the chambers are shielded and reflectors used to increase the neutron flux through the ion chambers.

A scheme for separating ion current due to neutron from that due to gammas consists of placing the ion chamber in a closed neutron absorbing shield such as cadmium and a shutter arrangement provided for periodically admitting neutrons. Thus an alternating current component due to neutrons

DECLASSIFIED

SECRET

would be superposed on the background current. This could be separated easily from the background. Such a device would be useful in starting up a pile but a satisfactory shutter has not been devised.

It appears that no one ion chamber can be used to cover the entire range of operating conditions. For safety several duplicate equipments must be used with automatic comparing means for detection of faulty apparatus. The procedure of moving a chamber makes calibration dependent on positions. It therefore would be better to use different equipment for different position to retain calibration independent of position. Transition or movement is undesirable because automatic control during changeover is difficult and manual control is risky if the time constant of the pile is short. Therefore an attempt should be made to make an ion chamber which can cover the entire range of operating conditions.

b. Measurement of Rate of Change of Flux. Rate of change of flux is probably best detected by means of measurement of the rate of change of current from an ion chamber. This can be done electrically in the control circuits.

c. Exit Coolant Temperatures. The temperatures of the coolant leaving the pile will control the rate of coolant flow. The device must therefore respond as quickly as possible to changes in temperatures.

Resistance thermometers and thermocouples are used for temperature measurements in the range expected. Several companies have been developing temperature control instruments which may give more rapid control. These devices control rate of flow of control fluids or gases by means of valves operated by thermal expansion of parts of the devices. Such devices have not been thoroughly tested at temperatures up to 1000°C. hence, it may be necessary to depend on thermocouples and resistance thermometers.

d. Inlet Coolant Temperatures. The temperature of the coolant at the inlet is important and should be as constant as possible to reduce the danger of pile oscillations. The device must be thoroughly reliable. The temperature will be between 375°C. and 500°C. so instruments already developed for process control in this range can be used. The temperature of the coolant in is a function of pile power, rate of flow of coolant and power extracted in the heat exchanger. If the top coolant temperature is controlled by rate of coolant flow the temperature of the coolant in must be controlled by the power output of the pile.

4. Status of Design of Control System.

a. Control Theory. A considerable number of calculations as to the control effect of rods parallel to the axis of the pile have been made. These calculations are sufficient to give a fair first approximation as to the number, size, and location of control rods in a vertical pile.

SECRET
DECLASSIFIED

No good calculations have been made of the effect of partial insertion of control rods parallel to the axis of the pile or of the effect of complete or partial insertion of control rods perpendicular to the axis of the pile. Approximate calculations of the above type should be made in the near future.

More exact calculations of the effect of control rods should be made before the critical experiments are made. Also calculations of the neutron flux distribution with control rods partially inserted should be made. The method of making the more exact calculation of control effect and neutron flux distribution is known, but the actual calculations will take a considerable amount of time. There is no satisfactory method of calculating neutron flux distribution when the control rods are only partially inserted. Very approximate calculations can, however, be made. More exact determination can be obtained from a flux distribution simulator.

It will take one engineer full time, one engineer part time, and one calculator about one year to make all of the necessary calculations.

b. Power Level and Temperature Regulators. The preliminary design of these regulators is well along and can be completed by one engineer in about three months.

After the preliminary design is completed the more detailed design can be started. This will include a detailed investigation of detection means or primary measuring devices, amplifiers, motor characteristics, comparison devices, power supplies, etc. A model regulator and pile simulator should then be built and tested to study speed of response, stability, sensitivity, etc. This detailed design and testing will take an engineer and a laboratory assistant about nine months.

c. Control Rods. The investigation of the general problem and the design of control rods and actuating mechanisms is in a very preliminary stage. The completion of the preliminary design including the building and testing of models will require one engineer for about one year. After this stage has been completed the final detailed design will require about six months.

d. Instrumentation and Safety Relaying. Very little work has been done on this problem. It is not believed that any major difficulties will be encountered. One engineer can complete the preliminary design in somewhat less than one year. The final detailed design will require about six months more.

SECRET
DECLASSIFIED

SECRET

List of Pile Control References

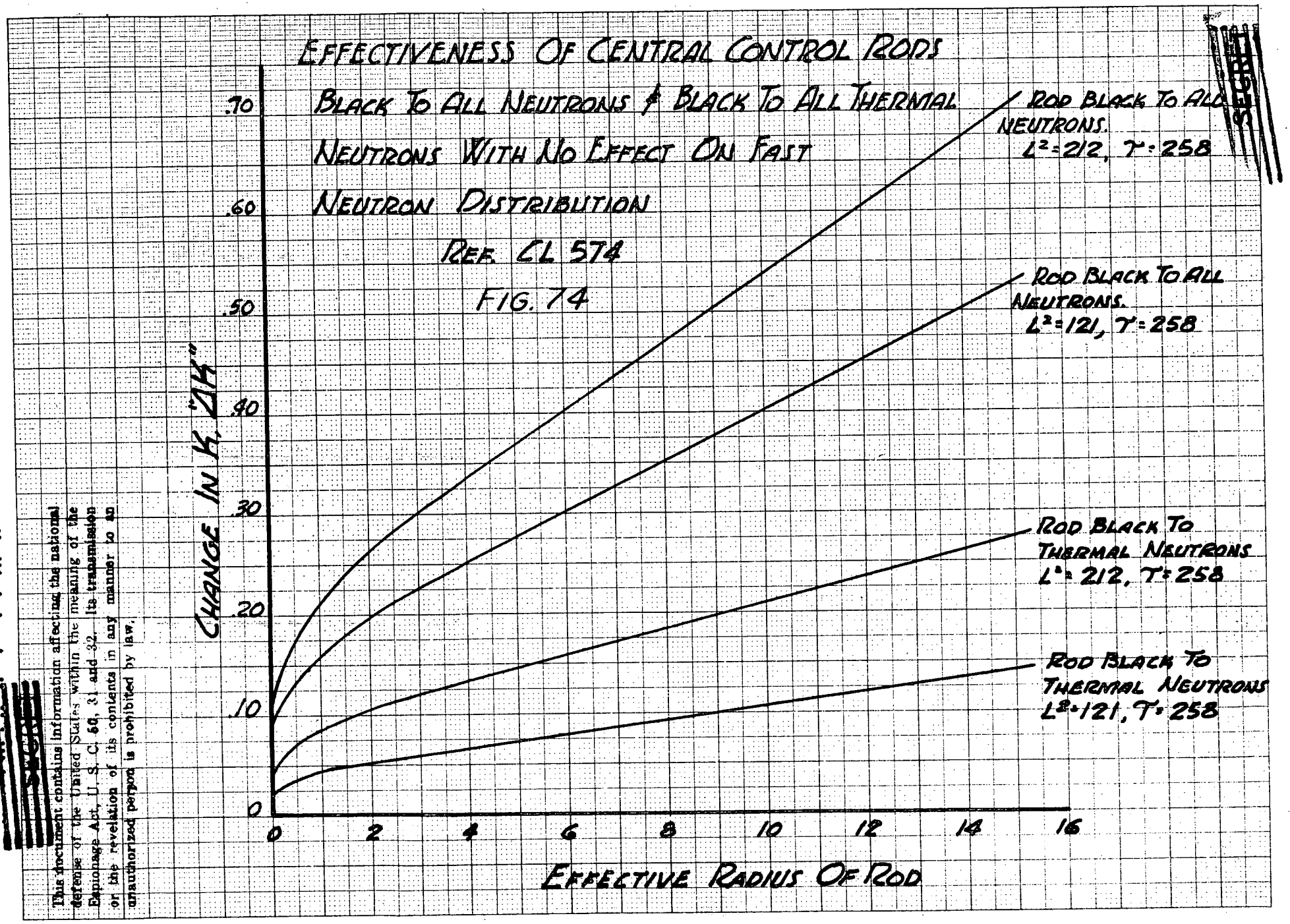
(1) CL-574; Pile Theory Lecture Notes; A. M. Weinberg (June 17, 1943)

(2) N-2292; Principles of Nuclear Power, Chapter 22; J.A. Wheeler (June 28, 1944)

(3) MDDC-42; Theory of Pile Control Rods; R. Scalettar and L. W. Nordheim (June 17, 1946)

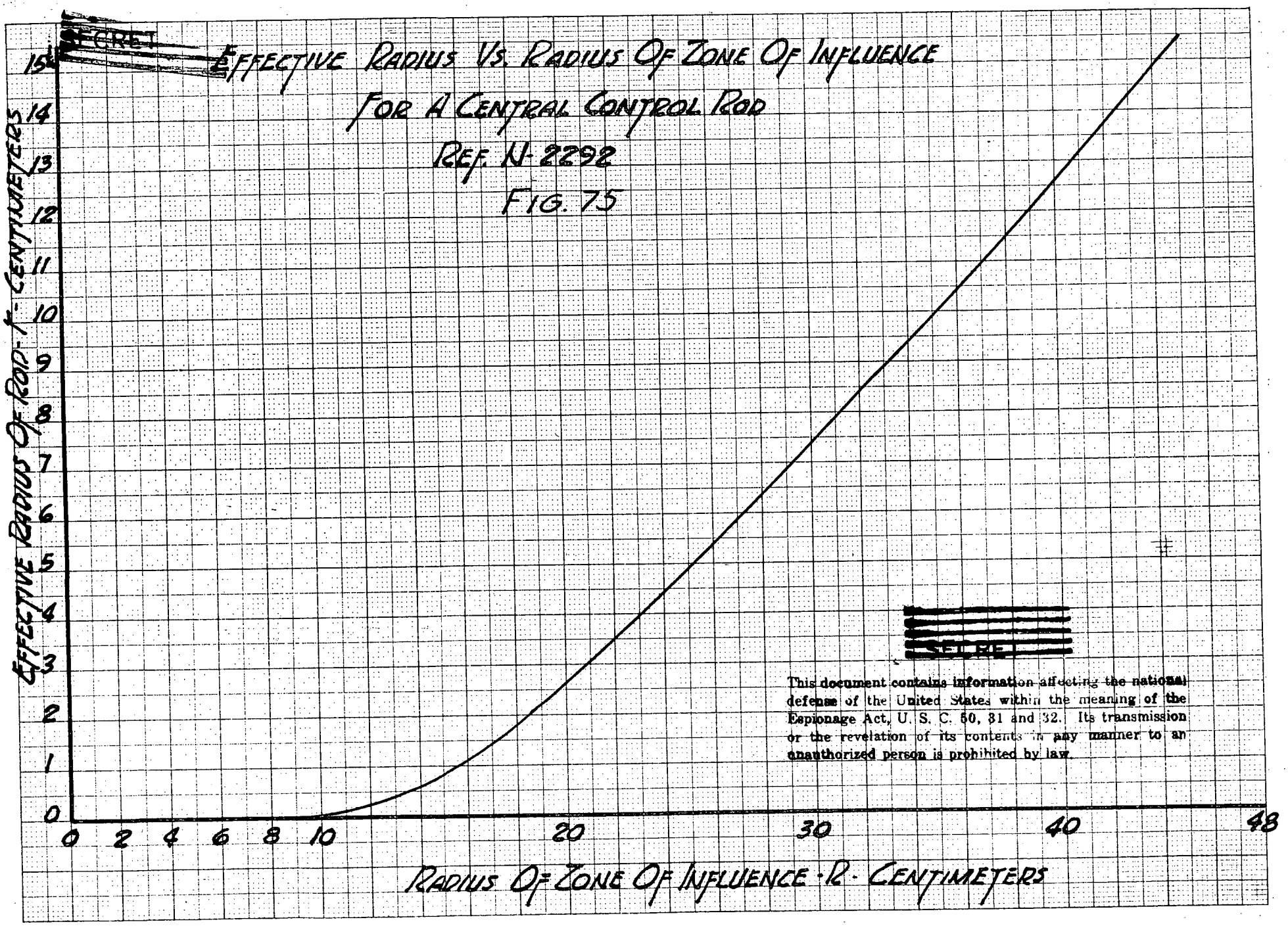
SECRET

DECLASSIFIED



This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

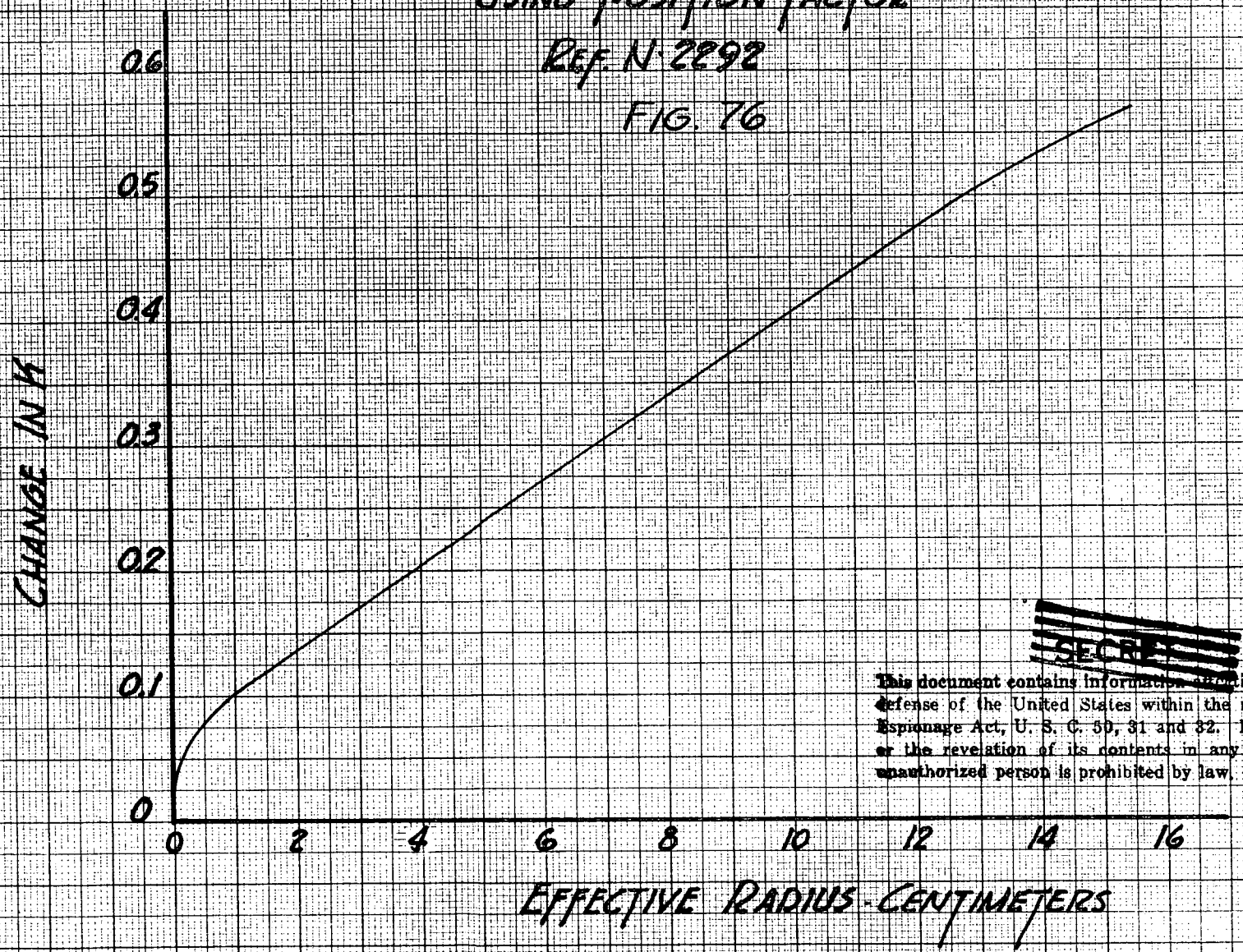

SECRET
EFFECTIVE RADIUS VS. RADIUS OF ZONE OF INFLUENCE
FOR A CENTRAL CONTROL ROD
REF. N-2292
FIG. 75
EFFECTIVE RADIUS OF ROD-r- CENTIMETERS
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
2
4
6
8
10
20
30
40
48
RADIUS OF ZONE OF INFLUENCE -R- CENTIMETERS
SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

[redacted]

CHANGE IN K FOR A CENTRAL CONTROL ROD USING POSITION FACTOR

REF. N-2292

FIG. 76



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

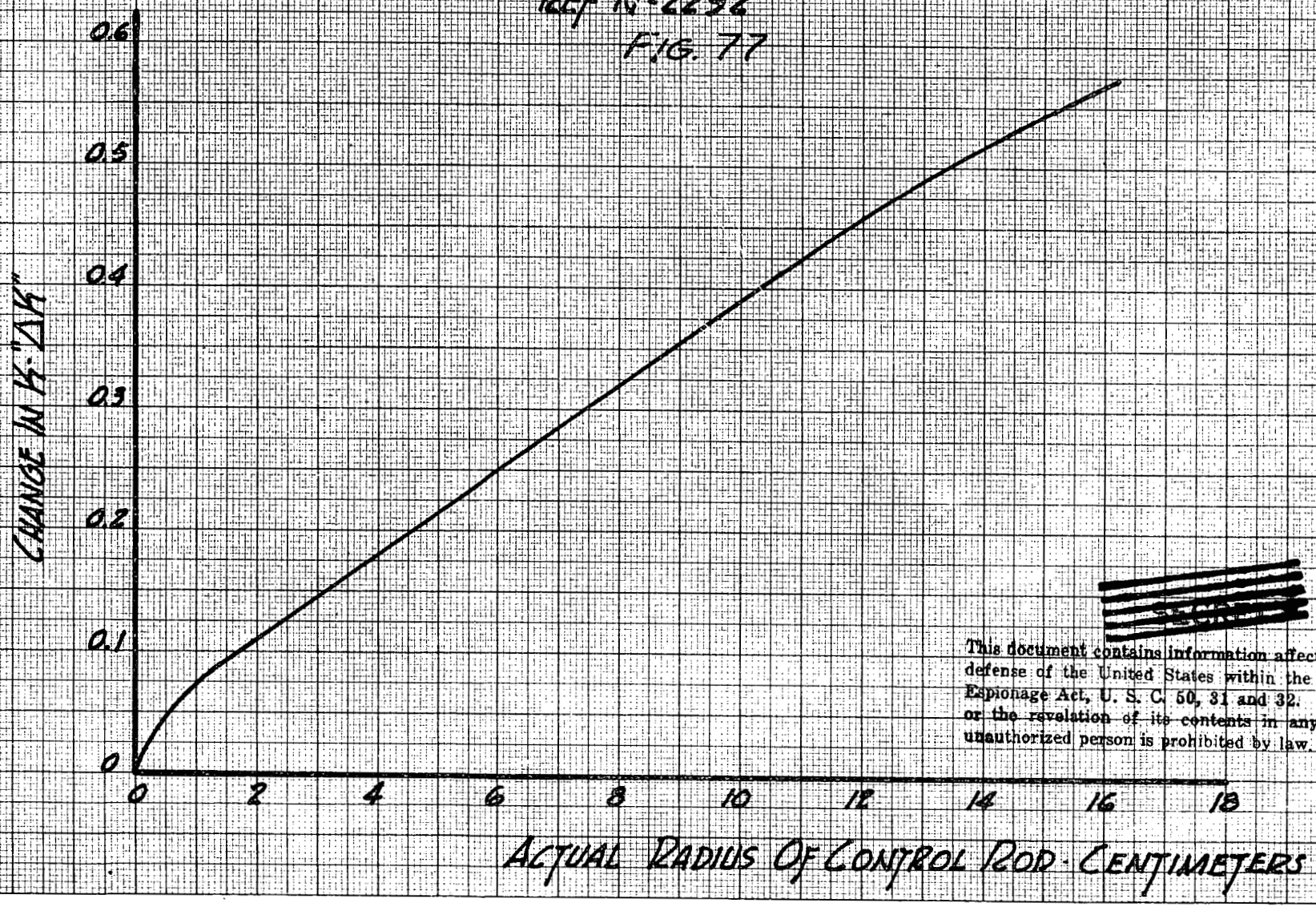
DECLASSIFIED

[redacted]

CHANGE IN K FOR A CENTRAL CONTROL ROD USING POSITION FACTOR

REF N-2292

FIG. 77



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET

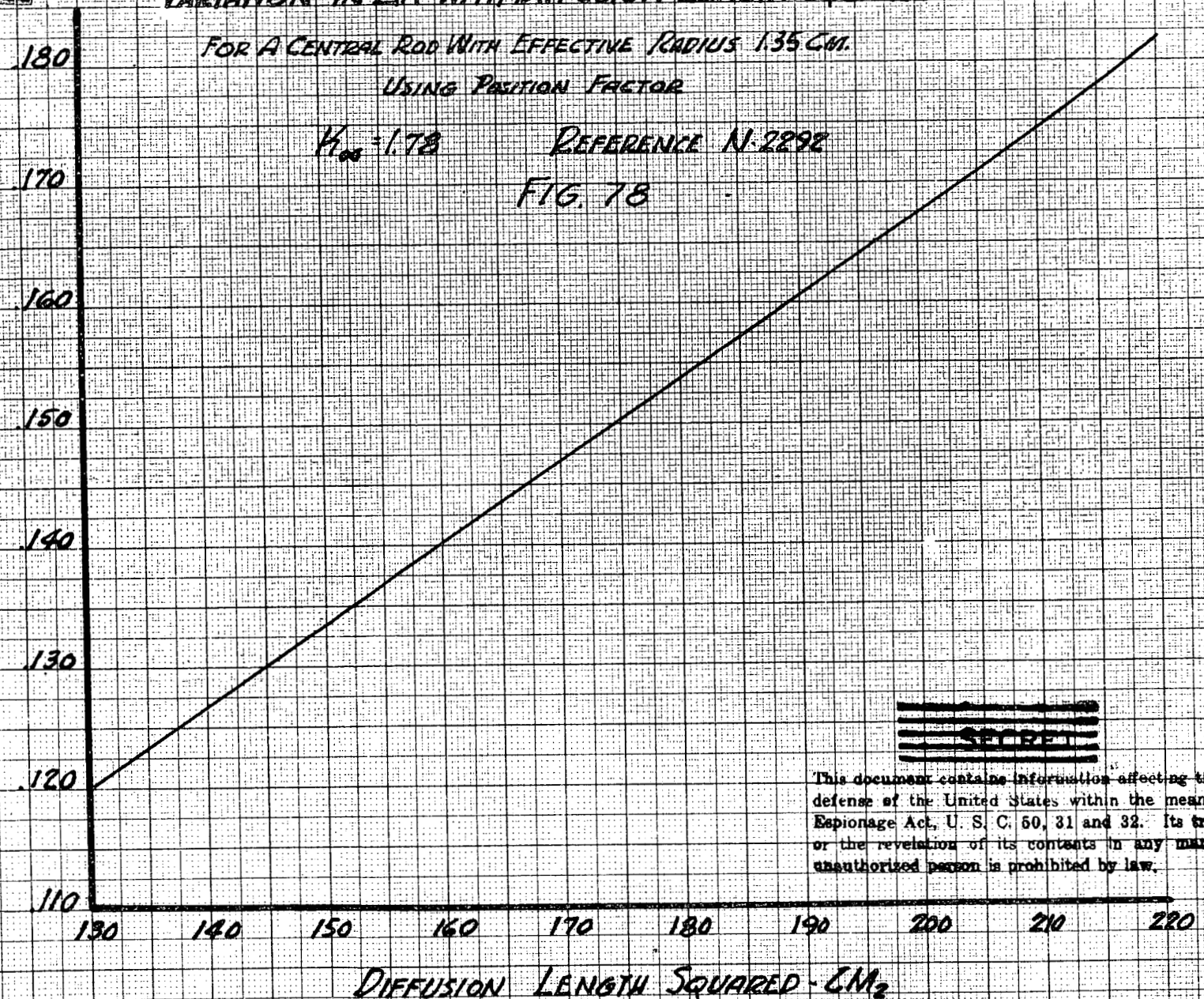
VARIATION IN ΔK WITH DIFFUSION LENGTH SQUARED

FOR A CENTRAL ROD WITH EFFECTIVE RADIUS 1.35 CM.

USING POSITION FACTOR

$K_\infty = 1.78$ REFERENCE N-2292

FIG. 78



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

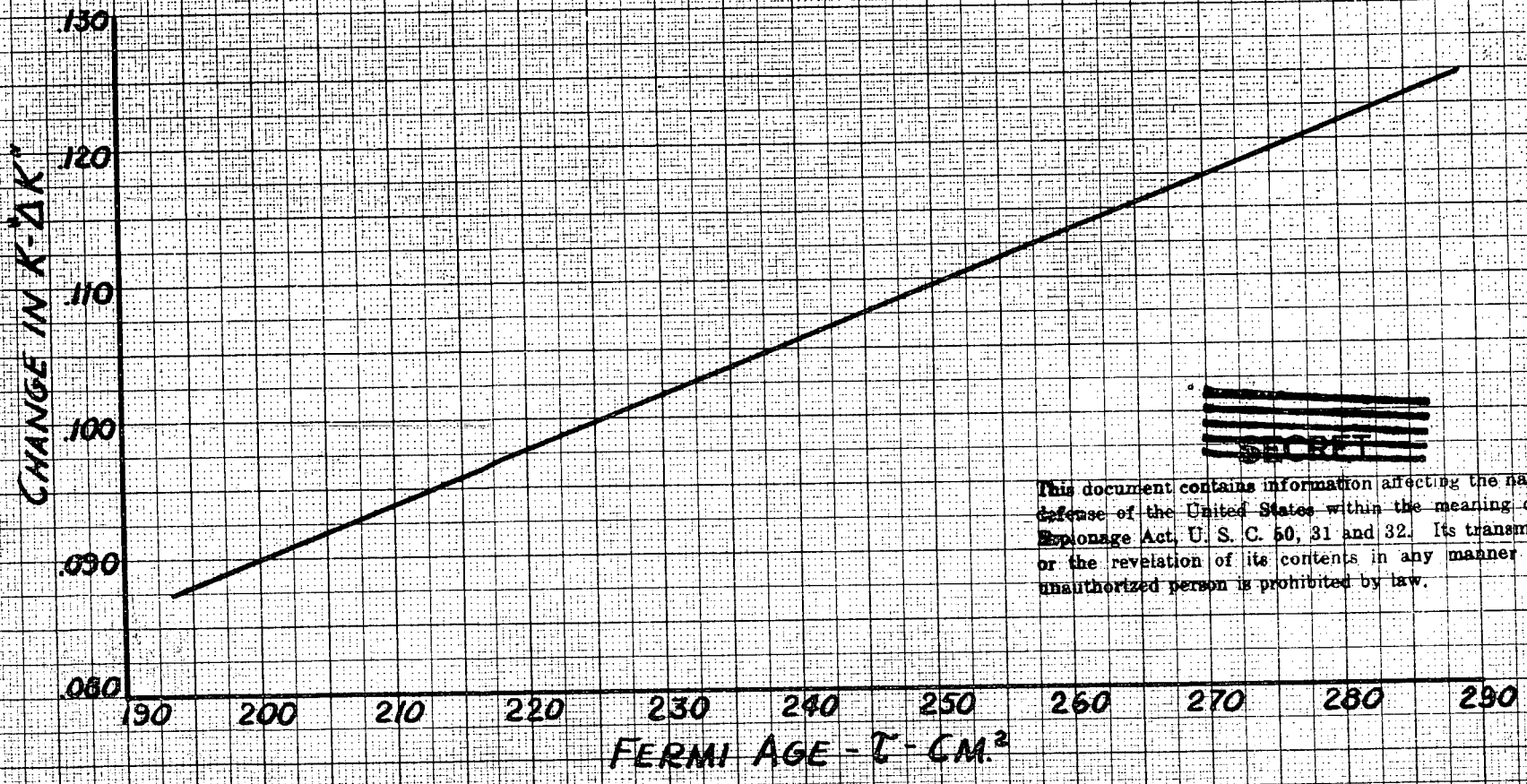
SECRET

VARIATION IN ΔK WITH FERMI AGE - τ - FOR A CENTRAL ROD

K_∞ = 1.78 EFFECTIVE RADIUS ROD - 1.35 CM ; L^2 = 121 CM.^{2}

USING POSITION FACTOR REF - N - 2292

FIG. 79



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

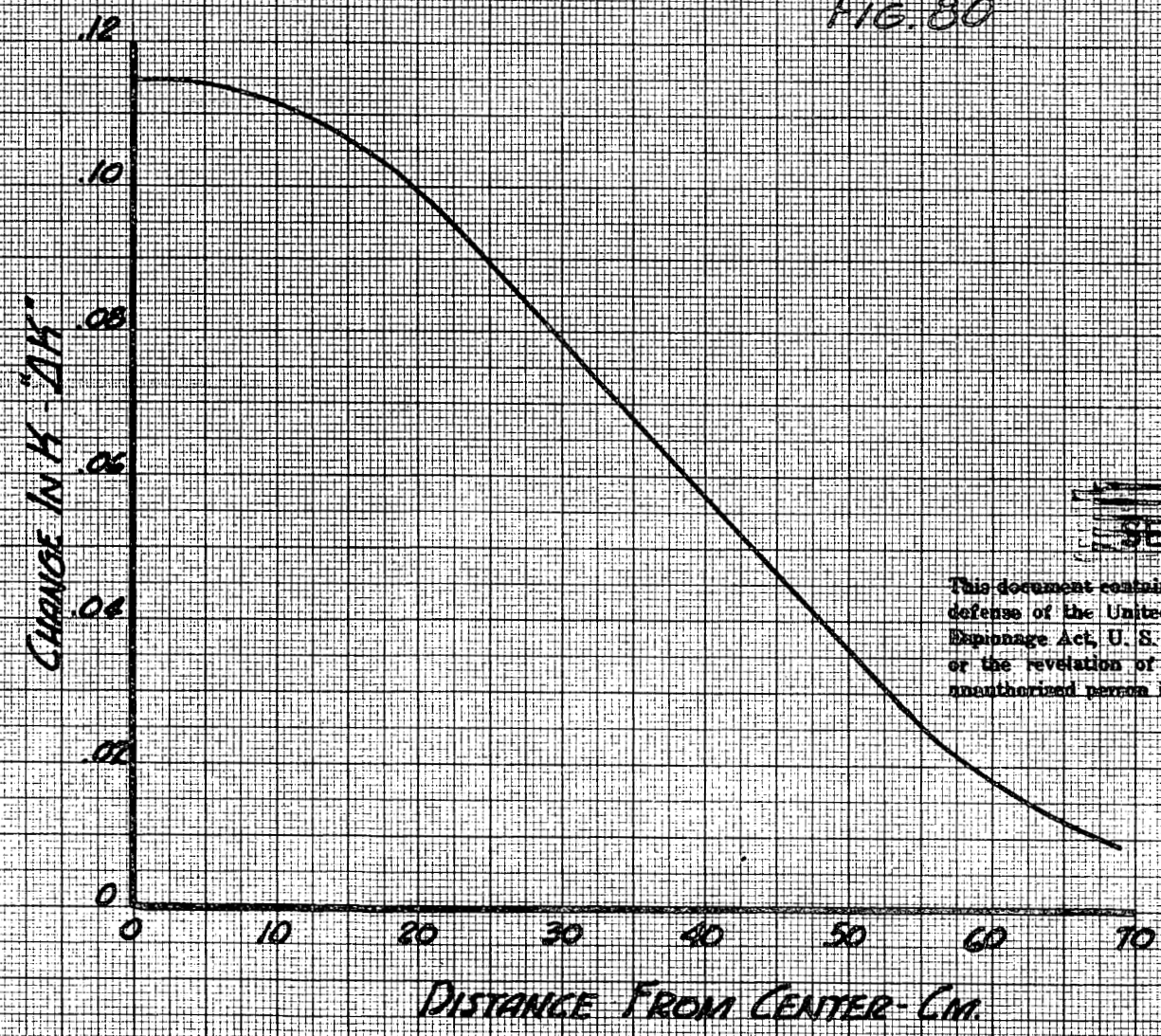
SECRET

CHANGE IN K FOR A SINGLE CONTROL ROD

ACTUAL DIAMETER - 4.00 CM. EFFECTIVE RADIUS 1.35 CM.

USING POSITION FACTOR - REF. N-2292

FIG. 80



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

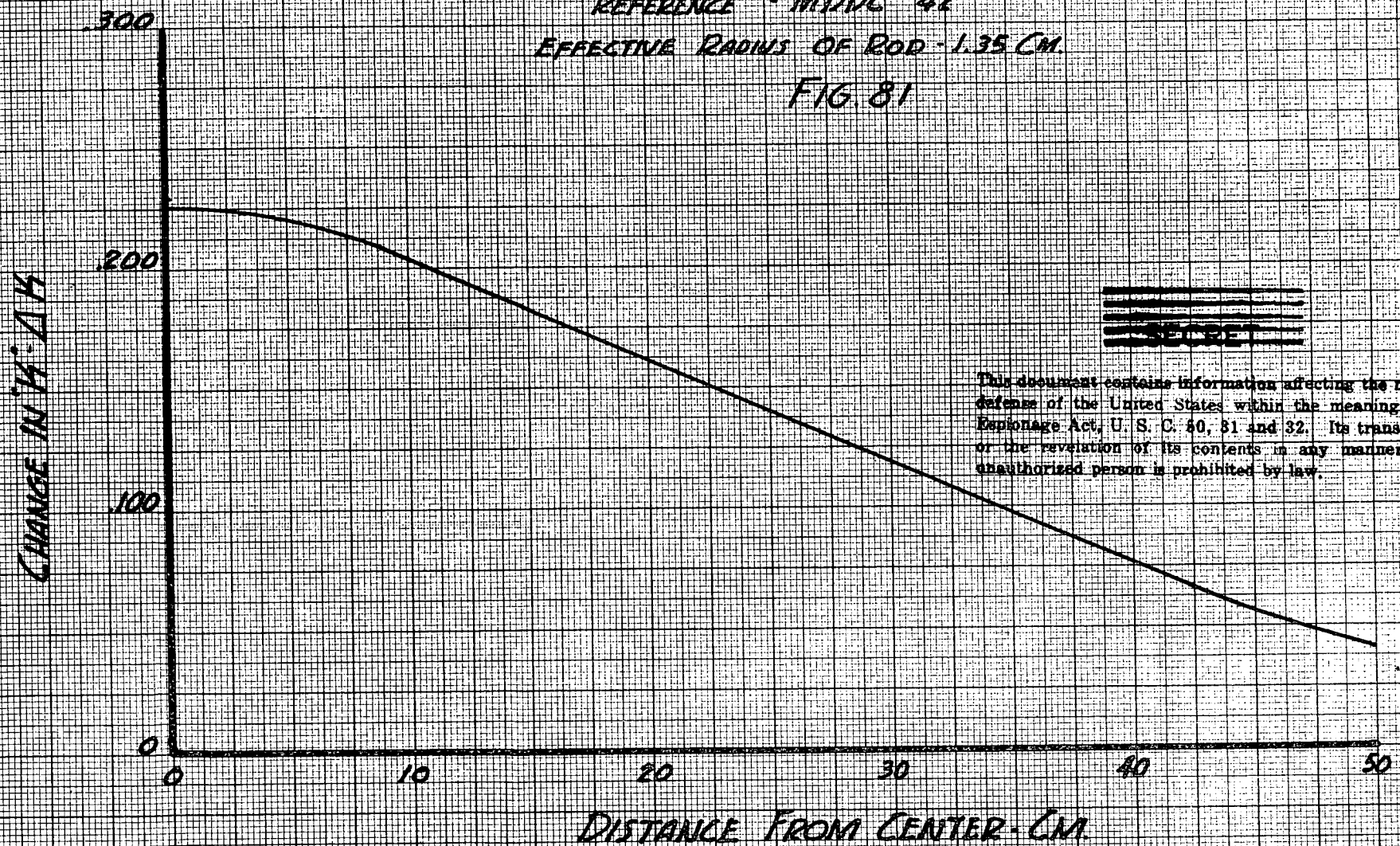
SECRET

EFFECT OF A SINGLE CONTROL ROD ON PILE REACTIVITY USING NORDHEIM-SCALETTAR ONE GROUP THEORY APPROXIMATION

REFERENCE - MDDC 42

EFFECTIVE RADIUS OF ROD - 1.35 CM.

FIG. 81



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

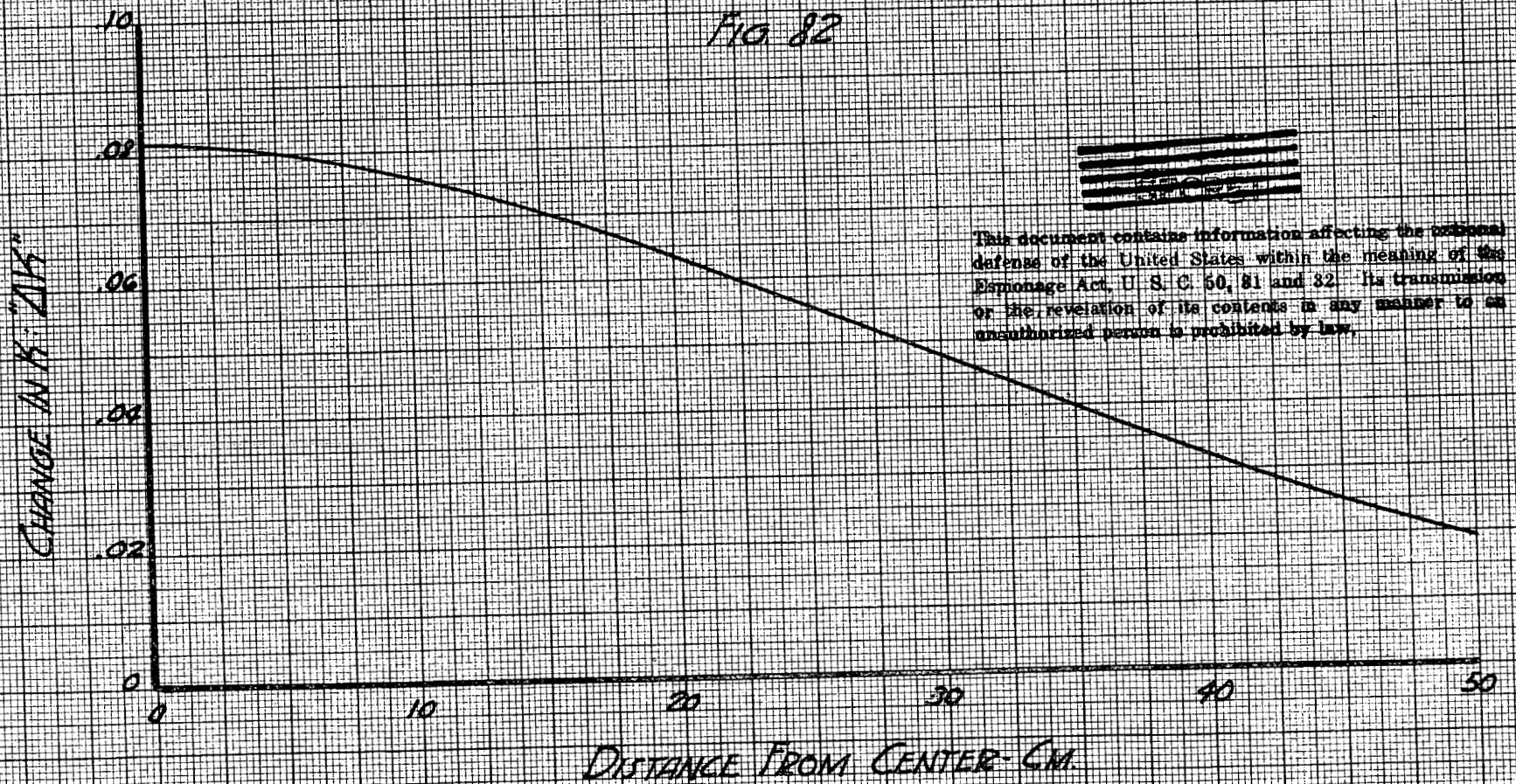
DECLASSIFIED

SECRET

Effect Of A Single Control Rod On Pile Reactivity Using Nordheim-Scalettar Two Group Theory Approximation

Effective Radius Of Rod - 1.35 Cm. Ref MDDC-42

Fig. 82



SECRET

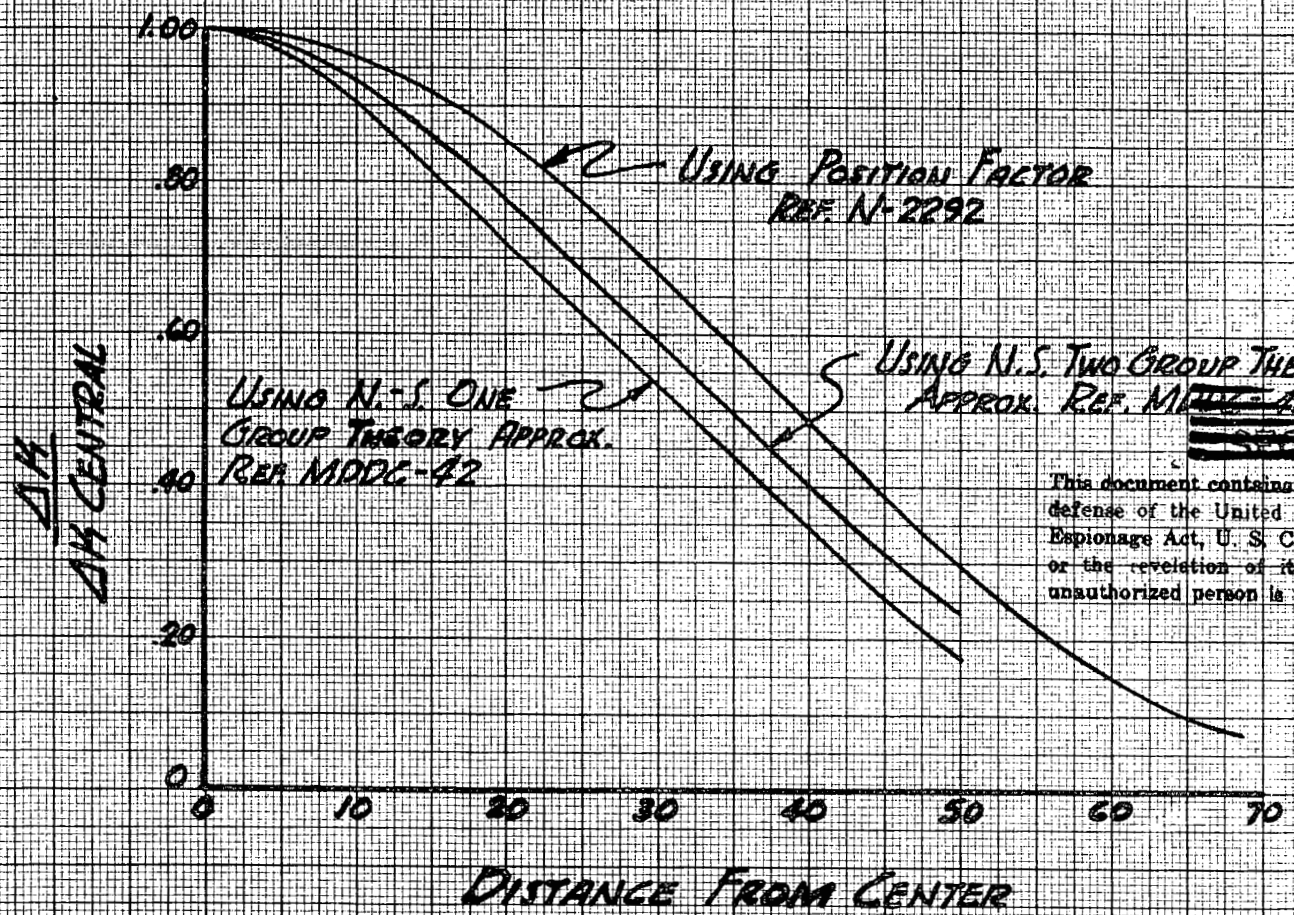
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

[redacted]

COMPARISON OF METHODS FOR CALCULATING CONTROL EFFECTIVENESS FOR ONE ROD - R EFFECTIVE = 1.35 CM.

FIG. 83



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

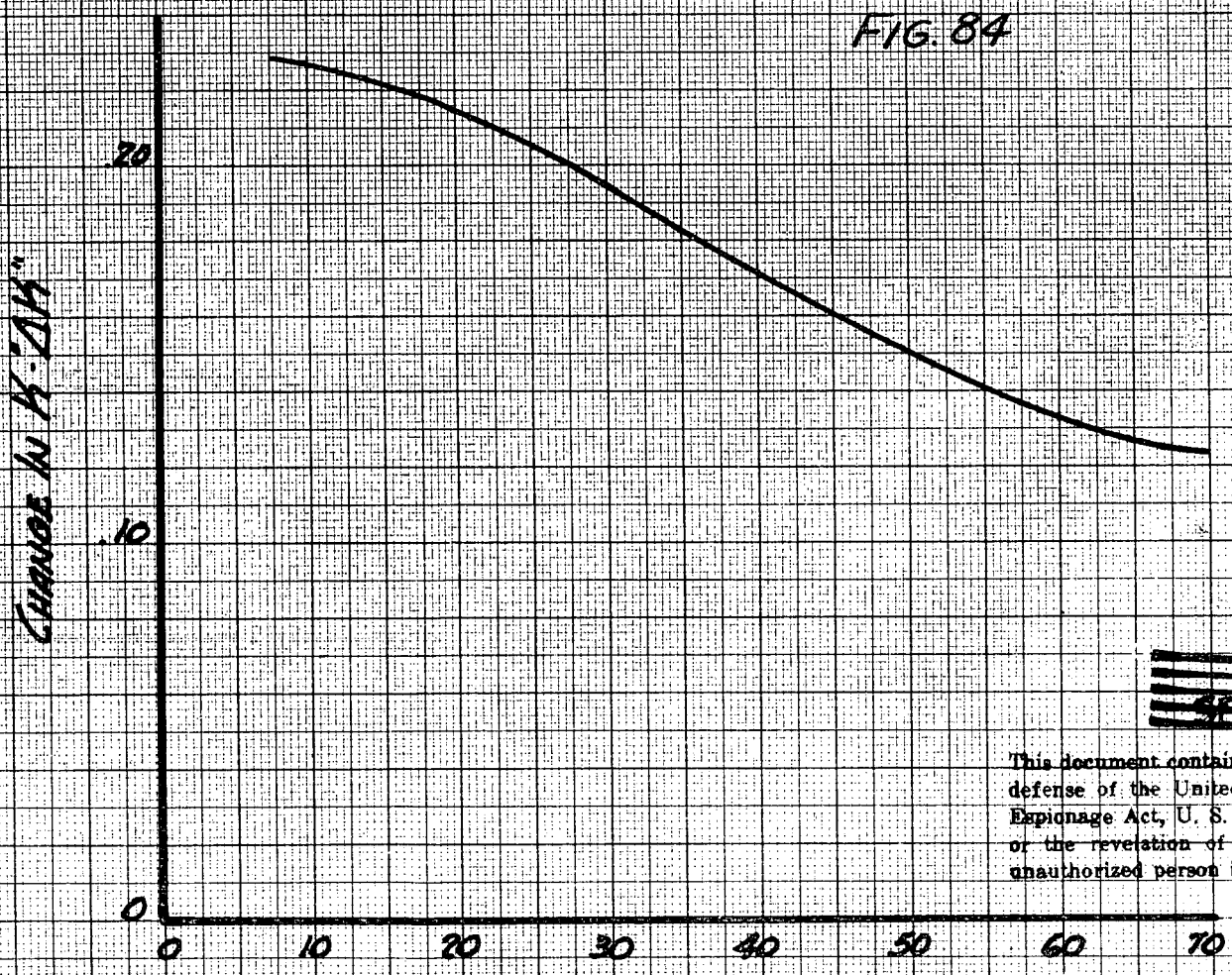
DECLASSIFIED

SECRET

CHANGE IN K FOR ONE CENTRAL AND ONE OFF-CENTER CONTROL ROD

ACTUAL DIA 4 CM. EFFECTIVE RADIUS-1.35 CM. USING POSITION FACTOR- REF. N-2292

FIG. 84

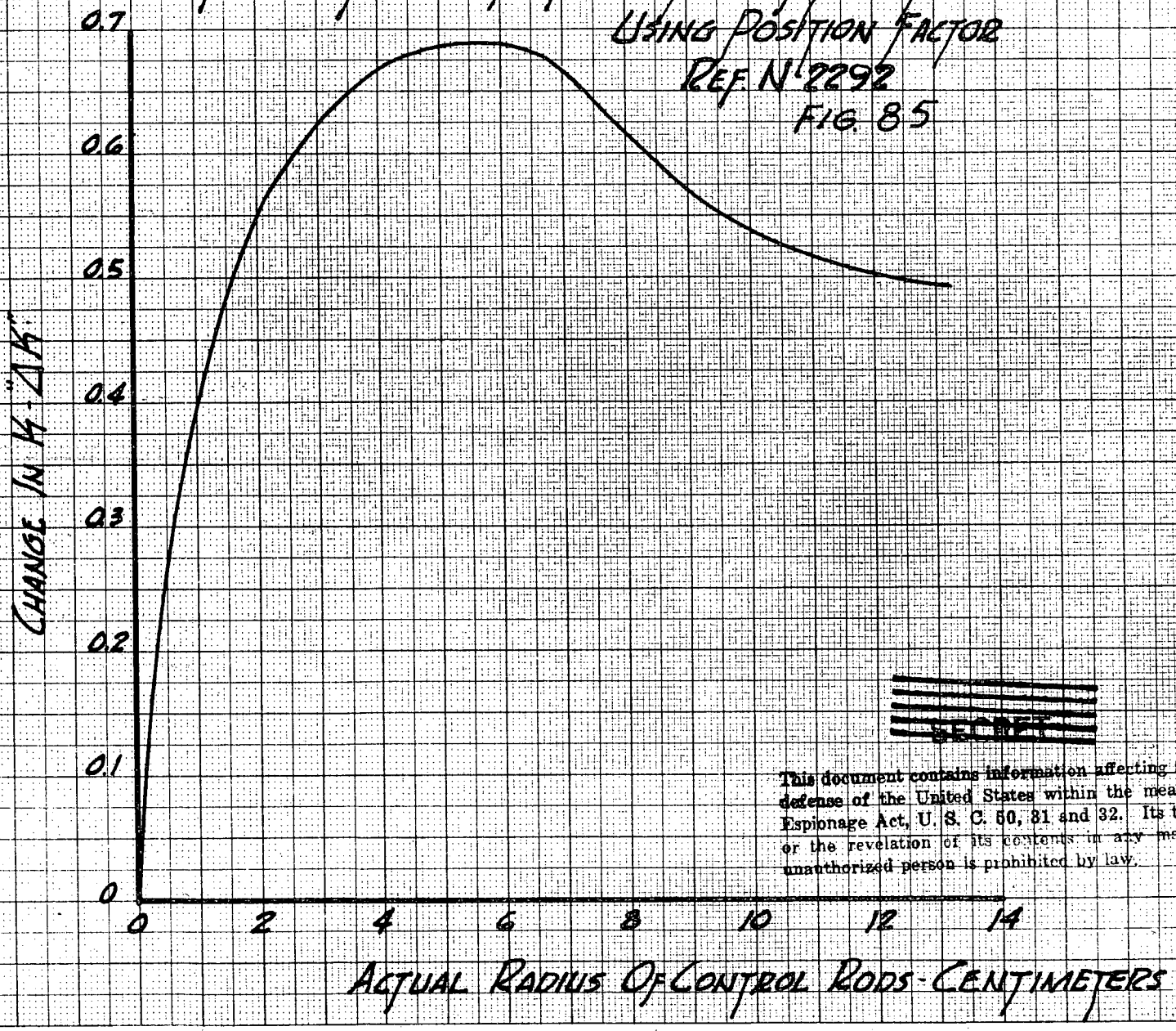


SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

CHANGE IN K FOR AN ARRAY OF SEVEN CONTROL RODS
SIX PLACED WITH ZONE OF INFLUENCE TANGENT TO CENTRAL ZONE
USING POSITION FACTOR
REF. N° 2292
FIG. 85

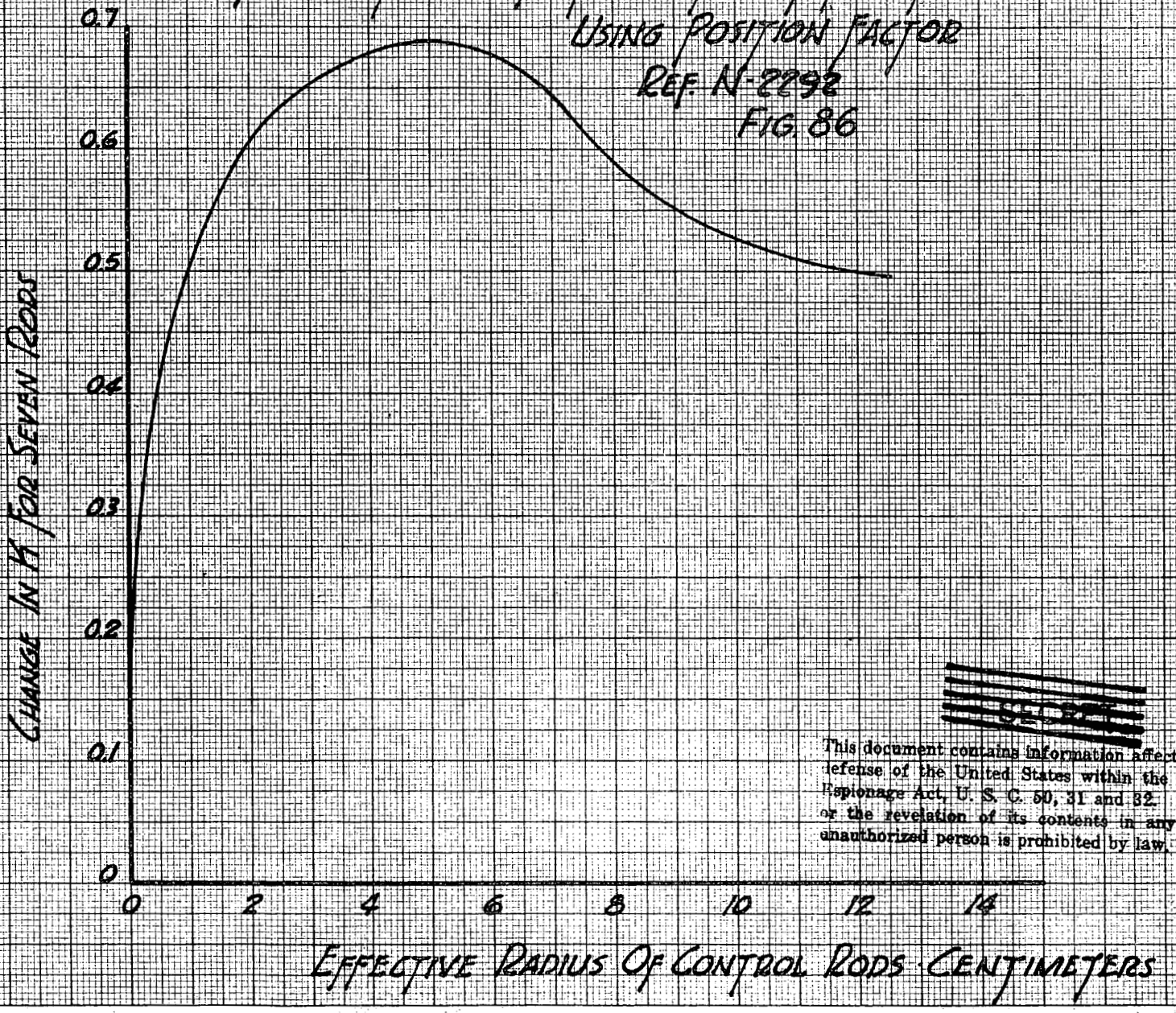


SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

CHANGE IN K FOR AN ARRAY OF SEVEN CONTROL RODS
SIX PLACED WITH ZONE OF INFLUENCE TANGENT TO CENTRAL ZONE
USING POSITION FACTOR
REF. N-2292
FIG. 86



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

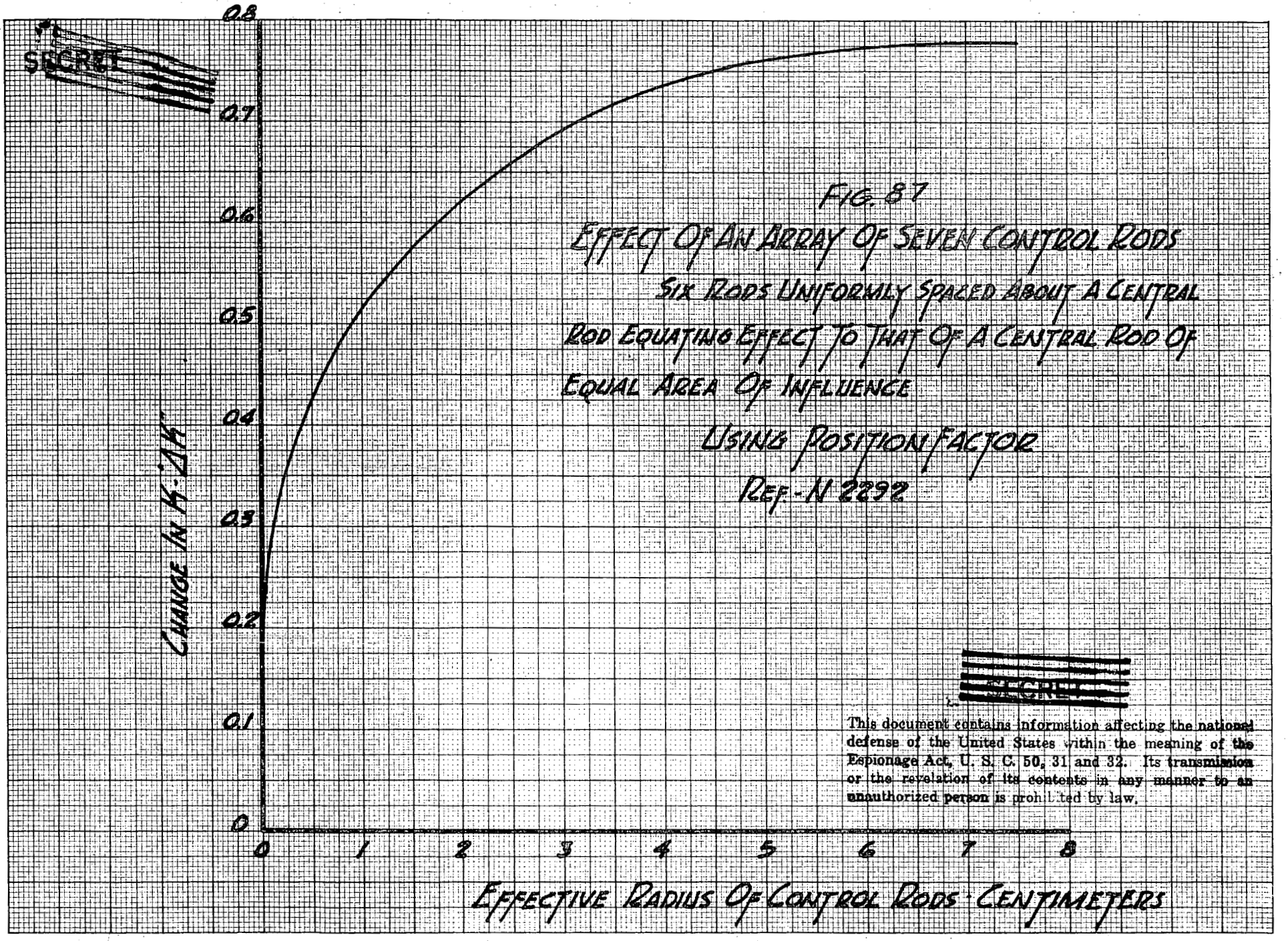


FIG. 87

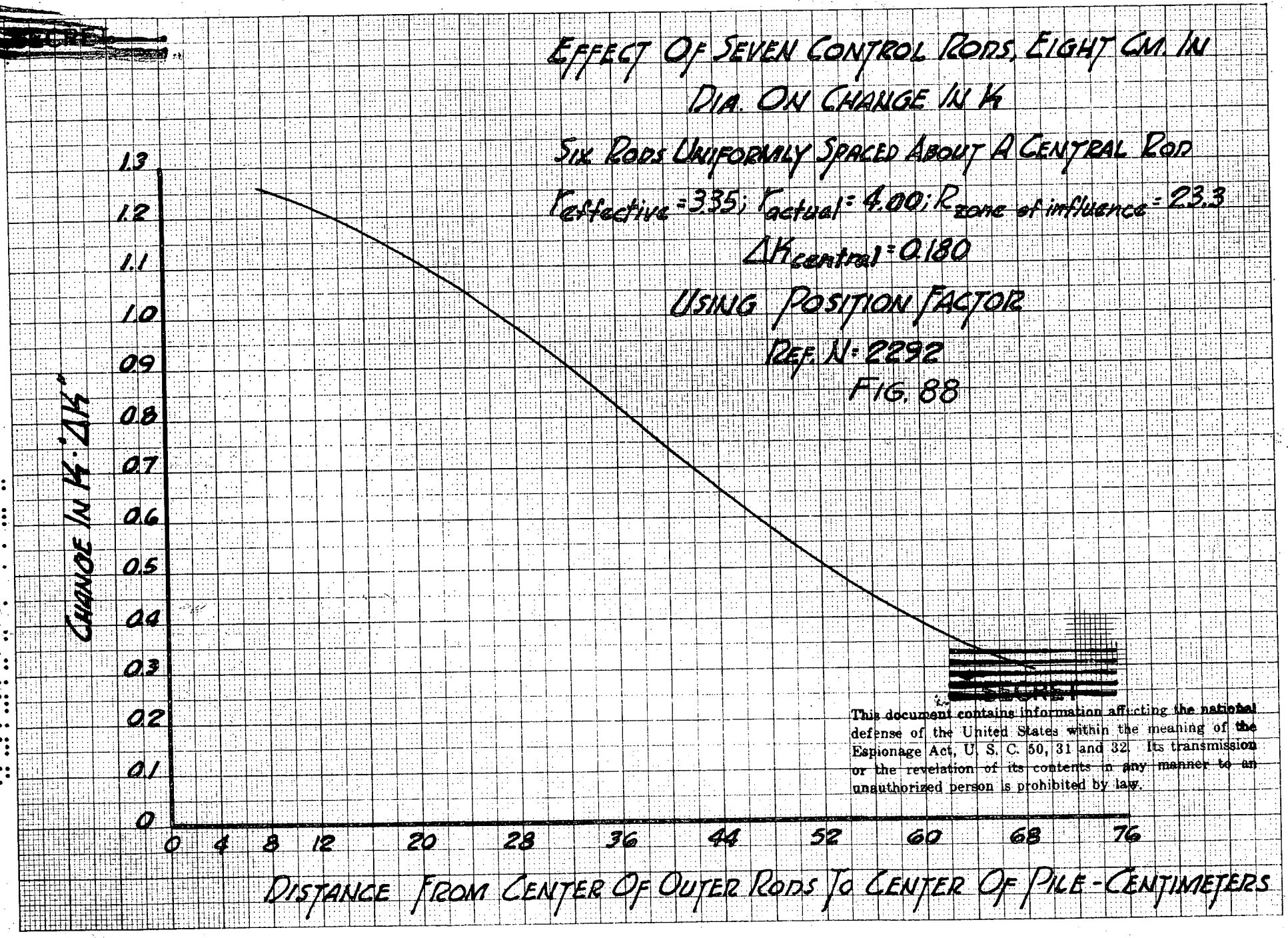
EFFECT OF AN ARRAY OF SEVEN CONTROL RODS SIX RODS UNIFORMLY SPACED ABOUT A CENTRAL ROD EQUATING EFFECT TO THAT OF A CENTRAL ROD OF EQUAL AREA OF INFLUENCE USING POSITION FACTOR

REF.-N 2292

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

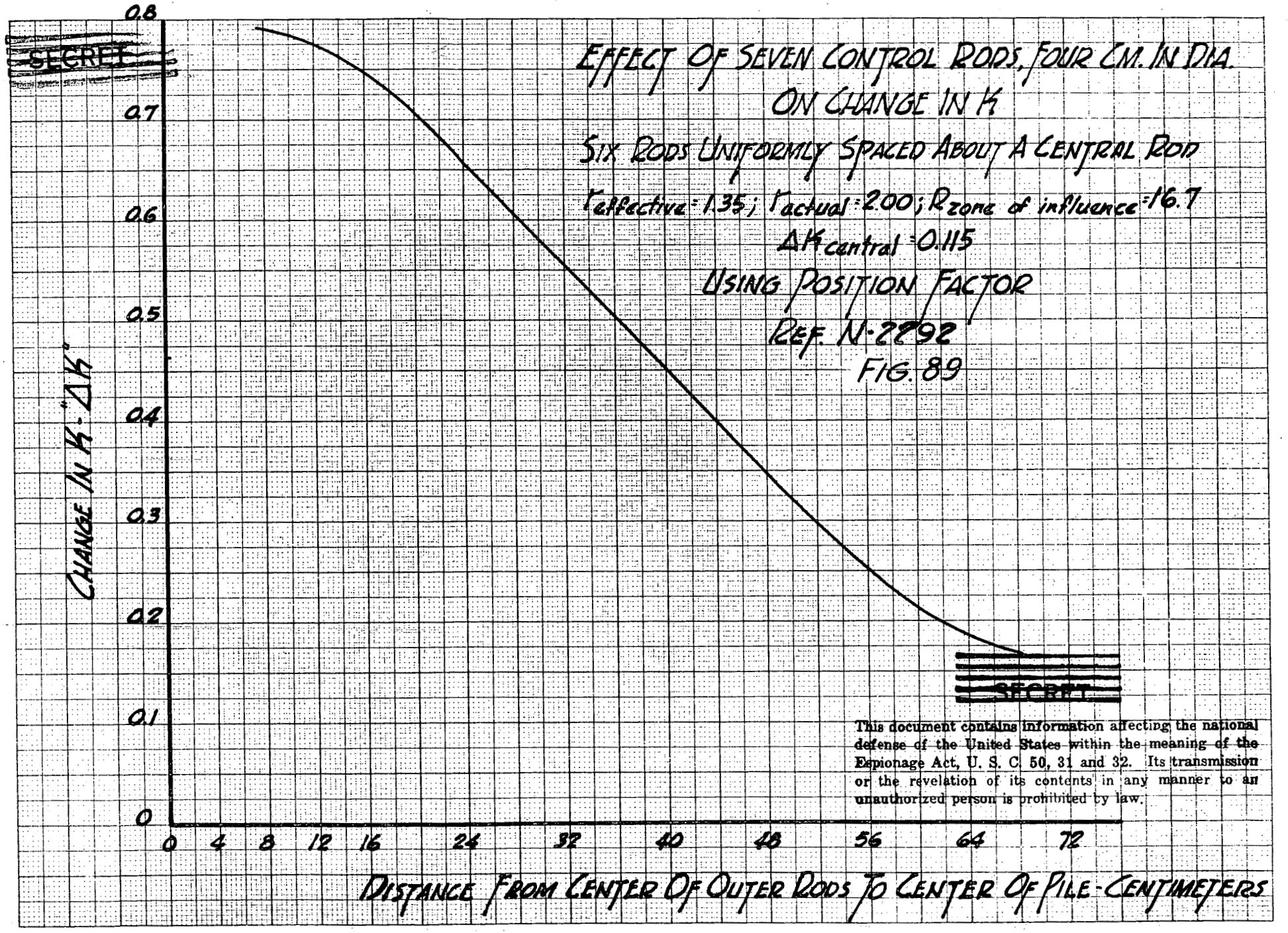
UNCLASSIFIED

[redacted]



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.


SECRET
EFFECT OF SEVEN CONTROL RODS, FOUR CM. IN DIA.
ON CHANGE IN K
SIX RODS UNIFORMLY SPACED ABOUT A CENTRAL ROD
r effective = 1.35; r actual = 2.00; R zone of influence = 16.7
ΔK central = 0.115
USING POSITION FACTOR
REF. N-2292
FIG. 89
CHANGE IN K - "ΔK"
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 4 8 12 16 24 32 40 48 56 64 72
DISTANCE FROM CENTER OF OUTER RODS TO CENTER OF PILE - CENTIMETERS
SECRET
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

F. COOLANT SYSTEM AND POWER CONVERSION EQUIPMENT

A discussion of the status of design and of the development problems of the coolant system and power conversion equipment are presented below for each component.

1. High Temperature Duct

a. General Requirements. The design of a high temperature duct incorporating parallel flow cooling is the result of an extensive study program instituted early in the project to investigate possible ways in which the duct problem might be handled. It was realized that this duct was unique in its design requirements. This duct must handle 1400°F helium at 150 psi absolute, and must be large enough to carry the required gas flow without excessive pressure drop. It must furthermore have means for isolating the pile from the rest of the plant at shutdown to give access for repairs to the boiler. In order to carry out these repairs, the duct must also be capable of decontamination at least up to the point of isolation.

b. Alternate Designs. To meet the foregoing requirements, the following alternate designs were considered. While some of them have considerable merit they were eliminated in favor of the present design because of the reasons set forth. In each case two parallel ducts were planned except where otherwise noted.

(1) Standard Duct with Outside Insulation. This design consisted of two large pipes conveying gas at 1400°F. Each pipe was arranged with a large expansion loop to provide flexibility and expansion. The advantage of this design is simplicity. It does however require alloy piping of thick wall sections because of the low permissible stresses of the material at 1400°F. Also, excessive diameters of expansion loops and lengths of piping are required to provide for the large amount of expansion encountered.

In connection with this design, expansion joints in place of expansion loops were investigated. It was learned, through contact with manufacturers' designers, that satisfactory designs of expansion joints for 1400°F and 150 psi absolute pressure had not been developed.

(2) Duct with Concentric Spaced Metallic Liners with Flow of Gas Confined to Core of Duct Only. In this design, barriers are provided between liners to prevent by-passing of hot gas through spaces between the separate liners. Means is provided for equalizing gas pressure between the core of the duct and spaces between outside liner and the main body of the duct. Three cases were considered: single concentric liner, 2 concentric liners, 2 concentric liners with corrugated metal spacers between. In all cases, air was assumed to circulate along the outside of the pile under forced circulation, in sufficient quantity to reduce the pipe temperature to 900°F. This design provided means for maintaining a satisfactory duct temperature with relatively small amount of expansion. However, in all cases, the high heat loss from the duct and the difficulties of decontaminating with acid are definite disadvantages.

DECLASSIFIED

(3) Multiple Pipes in Parallel. In place of two large ducts, the feasibility of using several smaller pipes was considered. It was proposed to arrange parallel tubes in two groups to facilitate insulation. U-bends would be provided in each tube to take the expansion. This arrangement provided greater flexibility of the connecting piping but connections to the pile and boiler are difficult to arrange as would satisfactory decontamination.

(4) Inside Lined Ducts. A promising design of inside lined ducts is that manufactured by the Baldwin Hill Company. Several ducts have been installed and are in operation at temperatures of 1400°F. With this construction, the insulation surrounding the inner liner is slowly pressurized from the inner duct. Such a construction, of course, is not acceptable where decontamination is necessary. The possibility was considered of providing a tight inner liner and pressurizing the insulation with helium supplied through external jets to the sectionalized inner liner. The duct temperature with this design could be reduced to the low value of 200°F. Means for pressurizing the insulation would, however, complicate the design. Failure of the inner liner would prevent decontamination of the duct.

(5) Counterflow Annular Duct. This design is a variation of the design adopted for the high temperature duct described in the previous sections of this report. The helium coolant enters the annulus of the high temperature duct and flows from the boiler to the pile counter current to the main helium stream in the core of the duct. The chief advantage of the counter flow scheme results from the small temperature difference between the outlet end of the duct and the boiler shell. The advantages of the parallel over the counterflow scheme are the following:

(a) Higher helium temperature entering boiler.

(b) Helium flow maintained in case of failure of concentric liner. Leakage of helium due to liner failure would result in flow of coolant from the annulus into the lower pressure main gas stream. Failure in the counterflow duct would result in reduced gas flow through the pile with danger of overheating.

(c) Small temperature difference between duct and pile outer casing.

(d) Simplified duct piping arrangement.

(6) Mixing of 500°F and 1400°F Helium in Mixing Box at Pile Outlet to Obtain Safe Temperature for Standard Duct. Disadvantages of the scheme are: increased duct diameter, increased boiler heating surface and increased blower power. Furthermore, it would be difficult to design a satisfactory mixing box.

DECLASSIFIED

(7) Use of Heat Exchanger at Pile Outlet to Reduce Helium Temperature to Safe Value for Standard Duct. This scheme introduces several complications since it involves tubing and joints close to the pile which are subject to leakage. Pumps or blowers would be required to circulate the cooling medium. The large amount of heat absorbed by the coolant would be lost. Boiler heating surface and blower power would be increased by the same amount as in case (6).

c. Status of Design. The detailed specifications for the high temperature duct have been prepared. A design layout, Fig. 50, has also been prepared and shows suggested details of construction of the inner and outer ducts. Such things as joints between sections, welding design, etc. are shown on this design layout. Suitability and practicability of the design have been discussed extensively with many consultants. It is not planned to carry out any further work on this duct until final construction plans have been prepared, at which time it is planned to enter into a sub-contract for the final design and construction of this duct along the lines described.

2. Boiler

a. General Requirements of Boiler

(1) Helium circulated through the pile absorbs heat generated therein. Before returning to the pile, the helium is cooled to remove the heat absorbed. It is the function of the boilers to absorb this heat.

(2) The boiler, in addition to absorbing the heat, functions also to make the heat available for the generation of power. In the boiler application herein considered, the boiler unit consists of three sections as follows: economizer section, evaporator section and superheater section.

(a) Economizer Section. Steam condensed in the main turbine condenser is deaerated and pumped to the boiler unit where it first enters the economizer and receives heat from the helium. The temperature of the incoming feedwater (condensate from condenser) is raised to a value close to the saturation temperature corresponding to the pressure in the boiler. Because the economizer handles water at the lowest temperature in the boiler unit, advantage is taken of this fact in arranging the heating surface to obtain counterflow of gas and water. This arrangement makes it possible to obtain low outlet gas temperatures and minimum heating surface.

(b) Evaporator Section. Feedwater, after being heated in the economizer, enters the main steam and water drum of the boiler, where it is mixed with water at saturated temperature. Water is supplied from the steam drum to the evaporator section in this case by means of a pump. (In natural circulation boilers, circulation is produced by U-tube effect caused by difference in density between solid water and mixture of steam and water.) Heat is absorbed by the water in the form of latent heat, resulting in

DECLASSIFIED

SECRET

the generation of steam. Steam thus generated is carried along with the circulating water to the steam and water drum of the boiler where it is separated and piped to the superheater.

(c) Superheater Section. The superheater receives saturated steam from the boiler drum. Heat absorbed in the superheater raises the temperature of the steam by the amount required to give the proper superheat at the inlet of the turbine. Superheaters are generally located in high gas temperature zones to provide sufficient temperature difference between steam and gas and to minimize the amount of surface required. In the case of the power pile boilers, it is desirable, in order to maintain uniform steam temperature with varying load, to locate the superheater following part of the evaporator section.

(3) Maximum reliability is required of the power pile boilers. Experience indicates that with proper design and proper operation, practically 100 percent reliability can be obtained. Improved reliability during the past several years is the result of improved designs, improved operating procedures, the employment of trained operators, and increased knowledge and application of proper feedwater treatment.

(4) The power pile boilers are required to reduce the temperature of helium to a safe value for the helium blowers. In the present application, the feedwater temperature is low enough and the desired helium blower temperature high enough as not to require the boiler unit to reduce the helium temperatures to unreasonable values. Under some conditions such as encountered with high steam pressures and high feedwater temperatures, the helium outlet temperature may be the controlling factor in the design.

(5) Several additional special requirements are encountered on the power pile boilers which are not present on the conventional designs. The familiar conventional boiler includes a furnace in which the fuel is burned and from which the hot gases discharge directly to the boiler heating surface. Many boilers, however, are designed for a variety of special applications. A class of this type are waste heat boilers. The power pile boilers can be considered in this classification. Generally, waste heat boilers are supplied with hot gas at approximately atmospheric pressure. Ducts conducting hot gas to the boiler are refractory lined. Leakage or damage to the duct, because of overheating is not of serious consequence. The boiler enclosure which confines the gas to the boiler heating surface is also constructed of refractory material. Leakage of gas through the walls of enclosure also is generally not serious. Contrasted with the usual waste heat boiler installation, the power pile application presents the following additional design problems:

(a) Boiler enclosure required to confine gas under combination of high gas pressure and high temperature.

(b) Design to provide high heat absorption by arranging heating surface for uniform high gas flow.

SECRET

DECLASSIFIED

(c) Provision for decontamination with acid to remove radioactivity.

(d) All metallic construction required. (refractories or internal insulation not applicable).

(e) Means within the boiler for removing dust carried by the helium.

(f) Means for separating moisture from the helium in event of a leak in the boiler.

(g) Means for providing maximum insurance against boiler leakage.

(h) Means for providing maximum insurance against corrosion of and scale deposits on boiler heating surface.

b. Discussion of Factors Affecting the Design and Selection of Boilers. In Part IV it is pointed out that the design of boilers for the Power Pile application involves problems not met in previous boiler design practice. The major factors involved in the design of these boilers are discussed in this section. The factors are discussed in the order of their importance to the overall design in order to point the way toward proper compromise between conflicting requirements of applicable design factors where necessary.

(1) Steam Leakage. It is important that the boiler design be such that there is the minimum possibility of the occurrence of a steam leak during operation of the boiler. A small steam leak discharging water vapor into the helium system will result in deterioration of the BeO in the pile. A large steam leak of proportions such that steam suddenly replaces most of the helium in the pile cooling passages results in increased pile reactivity. The pile control mechanism must be arranged to function rapidly under these conditions, to avoid overheating of the reactor. Moisture sensitive devices, as described in Part B-6-f, Section IV, will be installed to help protect the pile and the helium system from the effects of a boiler steam leak.

A large steam leak in the boiler may be expected to cause rapid rise in the helium system pressure. The helium system will be constructed for a design pressure of 250 psi gauge, 118 psi higher than the normal maximum helium operating pressure. A pressure sensitive device will be provided to shut down the pile if the pressure rises substantially above the normal operating pressure. If the helium system pressure increases to 250 psi, the designed maximum safe pressure for the system, due to a large steam leak in the boiler or for any other reason, the excess pressure will be relieved to a shielded storage tank as described in Part B-6-g, Section IV.

In order to avoid contamination of the helium system and damage to pile materials, the boiler must be designed to eliminate, insofar as possible, the possibility of a steam leak. A further reason for reli-

DECLASSIFIED

ability is found in the difficulty of making repairs to the boiler once it has been put into operation and thus rendered radioactive. The following points in connection with boiler design, construction and operation appear pertinent.

(a) Minimize the number of welded joints exposed to the helium system.

(b) Minimize the number of tube header joints and locate headers in parts of the boiler not exposed to high temperature helium.

(c) Avoid the location of boiler steam or water drums within the boiler pressure shell.

(d) Design steam and water connections through the pressure shell to eliminate excessive thermal stresses.

(e) Subject all materials of construction to minute inspection, chemical, and physical tests prior to fabrication.

(f) Subject all welded joints to x-ray or equivalent inspection during fabrication.

(g) Subject completed boilers to hydrostatic and temperature tests after fabrication.

(h) Design to eliminate the possibility of non-uniform circulation through parallel tube circuits.

(i) Provide for supply of high purity make-up feedwater.

(j) Minimize the possibility of contamination of feedwater supply through condenser leakage.

(k) Provide for thorough and reliable deaeration of boiler feedwater.

(l) Determine and practice suitable procedure for boiler water treatment to avoid corrosion and scale formation in boilers and to minimize radioactivity of steam generated and boiler blow down (See Part 9 of this section for discussion of radioactivity problems.)

(2) Water Leakage. Avoidance of a water leak or a water-steam leak in the boiler is important for the same reasons as those discussed above in connection with steam leakage, and the means to be relied on for minimizing the possibility of such leakage in service are likewise similar. However, if an appreciable quantity of liquid water is permitted to enter the pile reactor cooling passages, the reactivity increases much more rapidly than is the case for a steam leak; so rapidly, in fact, that it is not feasible to rely on the pile control mechanism to function quickly enough to avoid overheating of the pile.

DECLASSIFIED

To avoid discharge of water into the pile a water separator will be built into the lower end of the boiler shell. This device will be arranged to separate BeO dust from the helium stream during normal operation of the system and be adequate for removal of water in the event of water leakage from the boiler. Dust or water separated from the helium stream passing through the dust and water separator, will be collected at the bottom of the boiler shell, and be blown or flushed out to a decay tank as necessary. Preliminary study indicates that separators of the type normally used in the steam and water drums of conventional steam boilers can be used for these purposes and will be adequate for the degree of water and dust removal necessary to this application. Test of such devices in connection with final boiler design appears desirable. Also, further study of arrangements for disposal of BeO dust collected in the bottom of boiler shell appears necessary.

(3) Helium Leakage. The boiler pressure shell must be designed so as to eliminate the possibility of rupture or leakage of contaminated helium. Rupture of the shell permitting large scale escape of the contaminated helium from the system might subject plant operating personnel to dangerous radiation hazards. Small leaks must be avoided to conserve the helium charge and to minimize radioactivity of the shielding enclosure and ventilation system.

Major factors in providing for sound boiler pressure shell design involve maintenance of reasonably low uniform temperature throughout the shell structure and avoidance of direct exposure of any area to the high temperature incoming helium and minimizing the number of piping connections through the pressure shell. The methods employed for making piping connections to and through the pressure shell must be carefully worked out to avoid excessive thermal stresses, assure free expansion of all parts, and provide suitable shell geometry. All joints and connections should be strength welded or seal welded for permanent tightness.

(4) Decontamination. It is considered important that every reasonable effort be made to design the boiler so that it will be susceptible to decontamination for inspection and repair. It is anticipated that successful decontamination will involve flooding and flushing the boiler with water, steam and acid solutions to dissolve and remove condensed fission products and radioactive dust. Tests are under way for determination of suitable procedures.

Pending further development of suitable decontamination procedures, the following criteria have been set up to provide for design of boilers susceptible to decontamination:

(a) Use of heat insulation within the boiler pressure shell provides the liklihood of absorption of contaminated helium into the pores of the insulation through leaks in the insulation sheathing, making decontamination impossible. Heat insulation within the pressure shell must, therefore, be eliminated, and gas cooling of the pressure shell has been specified.

DECLASSIFIED

(b) Expanded tube joints should not be used as such construction is expected to add to the difficulty of decontamination. Cracks, crevices, and unwelded joints within the boiler pressure shell should be eliminated, insofar as practicable, for the same reason.

(c) Pockets or passages which cannot be readily flooded and flushed with decontaminating solutions should be avoided.

(d) Effort should be made to design the boilers so as to facilitate inspection and repair following decontamination.

(5) Miscellaneous Design Requirements. For more complete discussion of the following boiler design requirements reference may be made to report, "Steam Boilers for Gas Cooled Piles", dated 11 June 1947: Power Pile File No. 405.

(a) The boiler design must be such that it is capable of performing its function as a heat sink for the pile under any desired pile operating condition from atmospheric to 10 atmospheres helium pressure, from 500°F to 1400°F pile outlet helium temperature, and from nominally low helium flow up to rated capacity of the helium blowers.

(b) Since the pile itself is the main experimental feature of the Power Pile project, the boiler design should be based on the best background of experience available and include as little as possible of an experimental or speculative nature.

(c) The boiler design should be such that operation through a wide range of operating conditions can be accomplished reliably and automatically.

(d) The boiler must be capable of dissipating the heat from the pile for a reasonable period of time without damage, regardless of unexpected failure of boiler auxiliaries such as feed or recirculating pumps.

(e) The boiler superheater should be so arranged with respect to the helium flow through the boiler that excessive final steam temperature is avoided throughout the operating range.

(f) The design should be such that maximum advantage is taken of the helium pressure drop allocated to the boiler to secure a high heat transfer rate throughout the heating surface.

(g) The boilers should be of a design which has no fundamental limitations as to higher steaming capacity, helium pressure, steam pressure or steam temperature in order that the operating experience to be gained from this project will be of maximum value in future nuclear power developments.

DECLASSIFIED

SECRET

(6) Applicability of High Pressures and Temperatures. While it is desirable to design the initial power pile installation for conditions which are known to be conservative and with which there has been a background of experience, the advantages of using higher helium pressure and higher steam pressure and total temperature in future studies, should be given consideration.

The advantages of operating steam power plants at high steam pressures and high total steam temperatures to obtain increased efficiency have long been recognized. Steam pressures of 900 psi to 1500 psi and steam temperatures of 900°F to 1000°F are now generally adopted in central stations. The possibilities of applying higher steam pressure and higher steam temperature to the Daniels Pile have been studied. Results of the studies based on 1400°F helium from the pile indicate that the same general design of boiler and superheater adopted for this project is applicable for steam pressures and temperatures now used in Central Stations. Obviously, the amount of heating surface required in superheater and evaporator will be considerably increased. Such is also true in the case of conventional boilers.

Due to increased cost of fuel, several power companies now have steam generating units under erection which incorporate not only high pressures and temperatures, but also reheating of the steam after it has expanded part way through the turbine. While this feature has not been considered in the power pile boilers, it is obvious that the design of the boilers would accommodate a reheater and that the temperature differences between steam and gas would be satisfactory.

It is evident from the various studies that boilers can be designed to operate at steam conditions comparable to those used in Central Stations. Therefore, it is possible to obtain comparable turbine efficiencies in the power pile and central station applications.

The direct heated forced recirculation type boiler as specified and described in Part C-6-b of Section IV was selected after a thorough study of many possible alternate boiler types as the type best suited to the requirements of this application. A discussion of the alternate boiler designs considered for this application is presented below.

c. Discussion of Alternates to the Recirculation Type Boiler. Fig. 91 shows diagrammatically the arrangement of alternate boiler designs. A sketch of the forced recirculation type boiler is included in this drawing for ready comparison.

(1) Once-Through Boiler. In this type boiler, as shown in Fig. 91, the economizer, evaporator, and superheater are arranged in series. No separate recirculating pump is required, as the feed pump provides for the necessary circulation. Only two major piping connections through the boiler pressure shell are required. In the steaming capacity range being considered for this project, it is feasible to construct a once through boiler consisting of a single continuous coil, thus eliminating header joints, minimizing the possibility of steam or water leaks, and providing simplified construction. A single tube handling the entire

SECRET

DECLASSIFIED

flow through the boiler is necessarily of large diameter and comparatively thick wall. The pressure drop through the single tube circuit is high. The effect of higher steam pressure is to increase the thickness of the tube. The increased thermal stress due to the thick wall makes the tube more susceptible to failure than a small thin walled tube. Furthermore, in case of failure, the rate at which steam and water would discharge into the helium might be much greater than in the case of a boiler consisting of many small diameter parallel circuits. For larger capacity than presently contemplated, several parallel tube circuits would be needed, decreasing the simplicity of the design and requiring the use of header joints or extra connections through the boiler pressure shell.

The principle disadvantage of the once-through type boiler is the lack of a background of experience in the design, operation, and control of this type of boiler. Installations in this country to date have been few, of small capacity and of experimental nature. Automatic control of once-through boilers must depend on thermocouples in the tubes near the zone of complete evaporation, as there is no steam-water drum for water level control.

All impurities entering the boiler with the feedwater are either deposited within the boiler tubes with attendant possibility of corrosion or overheating of the tubes, or the impurities are carried out of the boiler in the steam with the possibility of troublesome scale deposits of radioactive material in the steam lines, turbines, condensers, etc. of the power plant. Use of high purity boiler feedwater supply will minimize the possibility of such difficulties with the once-through type boiler. The advantage of the recirculation type boiler in this connection is that there is always water with the steam in the evaporator section of the boiler so that the chance for scale deposit is reduced because there is no zone of complete evaporation and the solids can be removed by blowdown.

(2) Natural Circulation Water Tube Boiler. This type of boiler has the advantage of a wide background of experience in the power generation field. No recirculation pumps are required. The arrangement shown in Fig. 91 provides steam and water drums located within the boiler pressure shell to avoid the complication of the numerous steam and water lines through the boiler shell which are required if external steam and water drums are used. With this arrangement, it is probable that the tube ends must be expanded into the drums as they would be too close to permit of welding in any practical design; thus, decontamination of the boiler would probably prove difficult if not impossible. If alternate construction is used so that a large number of individual tubes are allowed to penetrate the pressure shell to connect to external steam and water drums, the resulting arrangement is complicated, wasteful of materials, and involves difficult thermal stress problems and weakening of the boiler pressure shell. If coils or return bend tube construction is used to reduce the number of steam and water connections through the pressure shell, the steam drum must be located at a considerable elevation above the boiler proper in order to provide sufficient head for adequate natural circulation.

DECLASSIFIED

(3) Natural Circulation Fire Tube Type. This type boiler appears to possess no marked advantage over the other types except, possibly lower cost, and has a fundamental constructional disadvantage in connection with differential expansion of tube sheets and boiler shell. The design which has been considered would require very gradual warming up from room temperature to boiling temperature. The problem of designing the joints between tube sheets and boiler pressure shell to avoid excessive stresses is difficult, particularly at the end of the unit where the hot helium enters, and satisfactory solution is not assured. The situation is complicated by the necessity for enclosing the unit in a pressure tight shell for containing the 150 psi absolute helium at high temperature, particularly since it is desired that no heat insulation be applied to the inside of the shell for reasons explained under consideration of decontamination. Water tube boilers are used almost exclusively for pressures above 400 psi, and the background of experience available indicates that the water tube type is safer.

(4) The Loeffler Type Boiler. This type boiler (See Fig. 91) has been considered for this application because it can be arranged so that no liquid water circuits need be exposed to the helium circuit; thus, should a boiler leak occur in service, only steam can enter the pile and the possibility of a pile explosion due to presence of water in the pile helium passages is avoided. It has been decided that the large parasitic power requirements for the steam circulating pump, which is a vital component of the Loeffler type boiler, outweigh the above advantage. The power required is particularly large in this application because of the necessity for elimination of the usual economizer normally incorporated within the boiler shell of the Loeffler type boiler. Considerations of reliability and maintenance of the large steam pump required also weigh heavily against use of this type of steam generator, as does the lack of any appreciable background of successful experience in its previous use in other fields of power generation.

(5) Dual Systems. At one time in the development of the Power Pile Project it was thought that the sudden discharge of a large quantity of steam into the helium circuit, through a large leak occurring in the boiler, would probably result in explosion of the pile. During this period, serious consideration was given to the use of a dual system, providing an intermediate heat transfer medium. The "Preliminary Power Pile Design Proposal" outlines early studies of helium-liquid mercury; helium-liquid-vapor phase mercury and double helium circuit dual systems to eliminate the possibility of steam or water leakage into the pile by use of intermediate heat exchangers between the boiler and the pile.

All such systems involve additional equipment, complication and expense, as well as increased parasitic power loss for pumping the secondary heat transfer medium. The size of the boilers is considerably increased over that of direct heated boilers. In one study made of a dual helium system, the size of the intermediate heat exchangers alone were several times greater than the size of direct heated boilers of the type selected for this project, and the design of the heat exchangers involves difficult thermal problems.

DECLASSIFIED

SECRET

d. Boiler Characteristics Under Varying Operating Conditions

(1) Operation at Variable Helium Pressure and Temperature. As one of the major functions of the boilers for this project is to act as a heat sink for the power pile, the boiler design must be such that this function can be performed satisfactorily under a wide variety of operating conditions. It is anticipated that there will be an initial operating period of several months duration when the pile is being tested at reduced pressure and temperature before the plant is brought up to designed maximum power output.

Calculations have been made to determine the effects on the performance of a forced recirculation boiler of a type similar to that shown in Figs. 52 and 53, which will obtain under reduced helium pressure and temperature operating conditions. The minor effect of introduction of duct cooling gas into the boiler has been neglected in these calculations. Fig. 92 indicates the results of these calculations in graphical form. The maximum continuous capacity point indicated in the figure is based on use of two boilers at a pile power output of 20,000 KW with the boilers operated at designed steaming conditions, viz 450 psig steam pressure, 775°F steam temperature at superheater outlet and 235°F feedwater inlet temperature.

Heat absorption in the boiler at a given helium mass flow is only slightly affected by the helium pressure in the system. The effect of helium pressure is too small to be considered in an approximate analysis of this type. Helium pressure, however, does affect the pressure loss through the boiler as well as the entire circulating system. Blower capacity also varies widely with varying helium pressure. Superimposed on the curves of Fig. 92 are additional lines indicating maximum helium flow and boiler evaporation corresponding to helium pressures in the system of 5, 10, and 15 atmospheres. The dotted sections of the helium versus evaporation curves are extrapolations. These were extended for the purpose of indicating the approximate capacity of the blower at 15 atmospheres helium pressure.

(2) Boiler Operation at Reduced Steam Pressure and Helium Temperature. In order to operate the pile initially at low helium outlet temperature, the boiler should be capable of absorbing heat when supplied with low temperature helium. Since the saturated steam temperature at the design condition of 450 psi gauge steam pressure is 460°F, the boiler will not absorb heat from helium supplied at temperatures of 460°F or below, when operating at 450 psi gauge steam pressure. However, the boiler can be operated at steam pressures between atmospheric and 450 psi and thus provide means for absorbing heat from the pile when operating at low helium temperatures. The data plotted on Fig. 93 show the effect on the boiler performance of varying helium temperature and steam pressure. All data plotted are for a constant helium flow of 30,600 #/hr, corresponding to the maximum continuous capacity of the current design.

This study indicates that the proposed design of boiler will operate satisfactorily at reduced steam pressures except that steam will be generated in the economizer. With proper provision for discharging

SECRET

steam to the boiler drum, operation would be satisfactory. For short periods of operation, no serious corrosion in the economizer would be encountered. Should it be determined that steaming in the economizer is undersirable, arrangements will be provided, as discussed herein, for avoiding this condition for lengthy operating periods.

Feedwater temperatures leaving the economizer plotted on Fig. 93 are correct only if sufficient pressure is maintained in the economizer to prevent steam generation. If no provision is made to operate with increased pressure in the economizer, as shown by the curves, steam would be generated at steam pressures of 50 psi and 250 psi, regardless of the helium inlet temperature. When operating at a steam pressure of 450 psi, and with helium inlet temperatures below 1025°F, some steam would be generated in the economizer.

For the experimental operating period with reduced steam pressure and reduced helium inlet temperatures, the economizer could be arranged to operate as a third evaporator section of the boiler. This feature could be provided by simple changes to the feedwater lines and piping between gas pressure shell and boiler drum, and the addition of three small valves, as shown in Fig. 51. Normal operation proceeds with valve b open and valves a and c closed. The effect of changing the economizer to an evaporator section of the boiler would be to increase the exit helium temperature, but this would not increase above 500°F. The boiler shown in Fig. 54 does not require these changes for operation at low pressure.

e. Boiler Control Instrumentation. The forced recirculation type boiler to be used will be designed for sufficient inherent stability so that manual control is feasible. Normal operation, however, will proceed automatically through provision of suitable control equipment. Only two control operations are necessary: maintenance of proper steam drum water level and control of steam pressure.

(1) The former can be accomplished by any of several systems which have proved successful and reliable throughout the steam power industry. One of the best of these systems involves metering steam flow from and feedwater to the boiler. Changes in steam demand registered by the steam meter provide corresponding adjustment in the rate of feedwater admission to the boiler. A steam drum water level indicating device is provided, in addition to the steam and water meters, for automatic secondary adjustment of the water level with changes in boiler out put, as necessary to allow for the varying volume of steam contained in the boiler water at different rates of steam generation and evaporation pressure.

(2) The boiler steam pressure can be controlled by adjustment of pile operating level or by adjustment of steam demand at the power generating turbine or other steam consuming equipment in the plant. It is probable that the latter method will be the one employed during early operation of the plant while the pile is being tested. The former method would be preferable for a commercial or military power application and arrangements will probably be made for ultimate test of this type of boiler and pile control.

SECRET

DECLASSIFIED

(3) Safety devices will be provided to shut down the pile automatically in the event of a boiler leak, feed or recirculating pump failure, or excessive helium temperature or pressure. Boiler safety valves discharging to the atmosphere will be provided for the boiler steam drum and superheater outlet to protect the boiler and steam system from excessive steam pressure.

(4) It is planned to provide indicating and recording instruments for guidance in the operation of the boilers, including steam flow, feedwater flow, steam drum water level, steam pressure, steam temperature, feedwater temperature and pressure, water temperature at economizer outlet, helium flow, temperature and pressure, and flow of recirculated water through the evaporator. In addition, simple indicating instruments will be provided for indicating helium temperature and pressure drop at various sections of the boiler for test purposes.

f. Items Requiring Further Consideration

(1) The provision of boiler make-up feedwater of the proper purity, deaeration, and chemical treatment is of great importance to avoid boiler corrosion and scale formation, and to minimize radioactivity of boiler steam and blow down. Ordinary feedwater treatment methods introduce materials into the water which may become highly radioactive and contaminate the entire system. The use of distilled water alone may not be sufficient to inhibit corrosion. Preliminary consideration has been given to this problem, but further study of this matter is necessary. It is planned to carry out this work in consultation with experts in boiler feedwater treatment and control.

(2) Decontamination tests are now underway at Clinton Laboratories to determine effective procedure for boiler decontamination. After determination of general procedure, models of parts of the specific boiler structure to be used should be tested to assure that effective decontamination of the unit can be accomplished in service, and to make possible periodic examination of the boilers and repairs or replacement if necessary.

(3) Results of tests now underway on the erosive properties to be expected in connection with particles of fuel rod and moderator material circulating with the helium stream should be taken account of in the final design of the boilers for this project. These tests should include determination of the possibility of dust film formation in various areas of the boiler heating surface, and thus provide for application of a suitable film resistance factor to boiler design heat transfer rates for proper proportioning of the heating surface to be provided in the superheater, evaporator, and economizer sections of the boiler.

(4) Preliminary study indicates that the design of an effective combination dust and water separator for the lower end of the boiler shell will involve no major problems. Nevertheless, the proper functioning of this structure is of such great importance that careful tests of the structure finally selected appear essential. The effectiveness of the separator in performing its designed function under a wide variety of

DECLASSIFIED

conditions should be determined, as well as the effectiveness of the means devised for discharge from the system the dust or water removed from the helium stream.

(5) Preliminary calculations indicate that the discharge of steam into the helium system in the event of a large leak occuring suddenly in the boiler will not cause increase in pile reactivity at a rate greater than the pile control and safety mechanism can accomodate. It is considered essential that these calculations be repeated with the utmost care when more definite information becomes available as to the construction and characteristics of the boiler, ductwork, pile and control mechanism. These calculations should take into account the change in circulating medium temperature, pressure, water vapor and liquid water content to be expected in the event of a boiler casualty. The design of the helium blowers should take account of the sudden change in the density of the circulating medium under these conditions.

(6) Boilers and ductwork should be tested after installation by use of electric heating coils temporarily installed in the pile pressure shell before the installation of the reactor. Thus, the entire system external to the pile can be operated at full pressure and temperature, though at low power output, and any adjustments or repairs found necessary can be made without the need for prior decontamination.

(7) Consideration is also being given to the effect on the boiler of using higher helium pressures and lower pile inlet helium temperatures. A number of advantages would be gained by these changes, but in the case of reduced pile inlet helium temperature, these advantages could be gained only at the expense of additional heating surface in the boiler.

Increasing the helium pressure results in reduced pressure loss in the system and reduced volume of gas through the blowers. Both of these factors result in reducing the power required for the helium blowers. It follows that with increased helium pressure, the sizes or number of blowers will decrease.

The following are advantages to be gained by reducing the helium outlet temperature:

(a) Reduced helium flow.

(b) Reduced blower power.

(c) Reduced duct diameter.

(d) Higher capacity on single stage blower for same tip speed.

Figs. 92 and 93 show the effect of variable conditions on operating characteristics of a boiler designed to meet existing conditions of helium and steam pressure and temperature. Fig. 94 has been prepared

DECLASSIFIED

to show the effect on the amount of heating surface required in the boiler of varying these design conditions.

The lower curve in Fig. 94 shows that the boiler size does not change greatly with reductions in the helium inlet temperature. The next curve above indicates that there is no great increase in the required size of the boiler if steaming conditions are changed to 1200 psi gauge and 1000°F superheated steam temperature, provided that the helium outlet temperature is allowed to rise to 600°F. If the helium outlet temperature must be kept at 500°F, however, the boiler size is increased several fold as indicated by the curve at the top of Fig. 94.

The curve marked "Steam Press. - 450#, Steam Temperature 775°F, Gas Temperature Out 400°F" shows that the boiler size is increased only 44 percent by designing for 400° F helium outlet temperature instead of 500°F. To provide for this increased surface, the gas pressure shell would be increased in diameter and length; otherwise, no changes would be required to the boiler. The increase in cost of the boiler unit to cover the above changes would be in the order of 10 percent to 20 percent. The reduction in helium flow for the same heat output is approximately 11 percent, and the reduction in blower power approximately 20 percent. The maximum capcity of the blower is approximately 10 percent higher for the same top speed.

The results of this study will have to be correlated with other design factors to see if the specifications should be altered to take advantage of higher operating pressure and lower pile inlet temperature to gain in overall performance at the expense of increasing in boiler size.

3. Low Temperature Duct

a. General Requirements. The design of low temperature ducting is dictated by the following criteria:

(1) Valves must be anchored in horizontal pipe runs for satisfactory operation.

(2) Valves must be installed to be accessible for operation.

(3) Expansion joints must be in vertical pipe runs so that acid used for decontamination can be drained out of them.

(4) Ducting must be so arranged that any equipment which it is intended to isolate is not in direct line with the valves which are doing the isolating.

Arrangements of ducting to fulfill these requirements necessitate a considerable number of expansion joints in the ducting and tend to lengthen the lines. With due consideration for these factors, however, a satisfactory design can be worked out as described in Part B-6 of Section IV.

DECLASSIFIED

b. Status of Design. Status of the low temperature ducting is as follows. Thickness of piping has been calculated. Approximate length of piping required for the venturi meter has been computed so that this length could be provided for in the layout. Expansion of ducts has been computed and the E.B. Badger Company of Boston, Massachusetts has been contacted relative to design of necessary expansion joints. In conjunction with E. B. Badger & Sons, it has been determined that the following tandem expansion joints will be required for the main circulating system:

(1) 10-18" Double 6 corrugation Badger directed flexing, self-equalizing type, stainless steel, expansion joints to take maximum transverse motion of 1.25" and maximum axial expansion of 1.36"; they are fitted with cast steel equalizing rings and carbon steel pipe 1/2" thick and are assembled with limit bias. Price, $1544.00 per unit, totaling $15,440.00.

(2) 8-16" Double 8 corrugation units similar to the above to take maximum transverse motion of 1.69" and maximum axial expansion of .76". Price, $1630.00 per unit, totaling $13,040.00.

(3) 18-16" Double 6 corrugation units to take a maximum transverse motion of .4" and a maximum axial expansion of .6". Price, $1425.00 per unit, totaling $11,400.00.

4. Blowers and Seals

a. General Requirements. Each of the blowers for this application must be capable of supplying helium at a maximum flow of 5340 ft.^{3} per minute with a pressure rise of 3.61 psi; they must be capable of operating at part loads down to approximately one quarter load. The blowers must be tight against radioactive helium out-leakage and air of water vapor in-leakage; they must also operate inside the shielding. The blower drive can either be totally enclosed in the same housing as the blower and, therefore, be tight against leakage or it can be external to the blower and, therefore, require a tight shaft seal to prevent leakage.

b. Development Problems. The use of a totally enclosed electric motor driven blower was chosen for this application because it eliminates the need for an absolutely tight shaft seal. This choice, however, presents another problem in that it subjects the motor windings to intense gamma ray irradiation since they are placed next to the blower inside the shielding. This radiation comes from both the "hot" helium being circulated by the blower and from the radioactive impurities which diffuse past the labyrinth into the motor. This radiation has deletorious effects on certain types of insulating materials as described in Part 9 of this Section. Study of the literature (9) indicates that silicone bonded glass insulation will probably give satisfactory service. Irradiation tests on samples of this type insulation have been undertaken to assure suitability of the particular insulation finally chosen for this design.

(9) A list of numbered references is given at the end of Part F, Section V.

DECLASSIFIED

The effect of the radiation on the oil used to lubricate the bearings in the motor is being investigated. A study of the literature[8] indicates that this effect would cause little trouble if the oil is filtered constantly and changed frequently. The oil will absorb some fission products; hence, this part of the lubrication system will be radioactive.

In order to insure having a suitable blower and drive in the event that insulation breakdown in the canned blower is more serious than anticipated, work has been started on the development of suitable shaft seals so that steam turbines or electric motors outside the shielding can be used for driving the blowers. Commercial seals do not meet the stringent leakage requirements at the operating pressures and speeds needed for this application.

The viscosity plate seal as used at K-25 is being investigated for possible use on this project. A development contract has been let to the Allis Chalmers Manufacturing Company for development of a viscosity plate seal to operate either with 10 atmospheres pressure difference across the seal or with a small pressure difference across the seal, in which case it is planned to back up the viscosity plate seal with a sleeve bearing type seal.

This sub-contract, Number 38, was signed 27 December 1946. The sub-contract estimates that the work called for in it will be completed in about seven months. This period has been extended inasmuch as considerable time was lost in negotiating the sub-contract. The amended sub-contract calls for the submission of a report in triplicate covering all work performed under this sub-contract not later than 1 March 1948. The cost of this work is a lump sum of $36,000 for materials, mobilization, initiation of work and the first 1500 direct engineering man hours, plus $10.00 per hour for each direct engineering man hour in excess of 1500, up to a maximum of 2500 additional direct engineering man hours.

Development of a sleeve bearing seal suitable for use with the viscosity plate seal is being worked on by engineers at the K-25 plant of Carbide & Carbon Chemicals Corporation. Preliminary work on a 2" diameter shaft seal bearing gave promising results[14]. Since then, a full size sleeve bearing seal assembly has been designed which has provision for installing a viscosity plate seal and for testing the combination of the two. This unit also can be tested for the possibility of using the sleeve bearing seal as a primary seal. The construction of this apparatus has been authorized and begun. The sleeve bearing seal will first be tested for use as a backup seal. These tests will be run with SAE 20 oil and with Prestone oil.

This work is being done under account HW-955, and payments are made on monthly billings by transfer of funds. As of 30 June 1947, the billings on this account have totaled $8113.15.

It is estimated that the construction and test of the sleeve bearing seal as a secondary seal will be completed by 1 October 1947. The results of the tests will be made available to Allis-Chalmers as soon as possible so they can benefit from it in their viscosity plate seal development. Upon satisfactory development of both the viscosity plate seal and the sleeve bearing seal, tests will be made of the combination.

DECLASSIFIED

The contact type seal is also being considered for this application. A development sub-contract, Number 89, has been let to the DeLaval Steam Turbine Company for this work. This sub-contract is dated 1 February 1947, and originally called for the development work to be done by 1 September 1947, and a report submitted in triplicate by 1 October 1947. This sub-contract has since been extended for an additional six months. The estimated cost is $25,000 to be paid on monthly billings on the basis of man hours spent on the project.

In connection with this project, irradiation damage tests have been made at Clinton Laboratories on the flatness of carbon nose pieces which are being considered for this application. The distortion obtained was negligible. Radiation tests are also being run on O-rings which DeLaval plans to use in its seals.

If the use of seals on the blowers becomes necessary, a different blower design will be required. To provide for this contingency, proposition designs have been requested and received from Allis-Chalmers Manufacturing Company and DeLaval Steam Turbine Company for blowers to go with their seals.

The Allis-Chalmers proposition for a blower with a seal was submitted on May 21, 1947. This proposition was made to cover the development and test of one blower using the viscosity plate seal backed up by a sleeve bearing seal. The blower is driven by an induction motor located outside the biological shield. The cost of this work was quoted as $87,500 for materials, testing, mobilization, and the first 2500 man hours plus $10.00 per direct engineering man hour for all work in excess of 2500 man hours up to a maximum of 3000 additional man hours. A complete set of reproducible drawings were to be submitted five months after design approval; the complete blower unit, after tests, was to be shipped 20 to 22 months after date of order; a report in triplicate was to be submitted 30 days after shipment of the unit.

The DeLaval proposition for a blower with a seal was submitted on June 25, 1947. This proposition was made to cover the development and test of one experimental unit incorporating the contact type seal. The blower is to be driven by a steam turbine outside the biological shield. The cost of this work was estimated at $83,000. Under this project, reproducible drawings were to be submitted by 1 December 1947, the complete blower by 1 June 1948; a report in triplicate by 30 June 1948.

c. Alternate Designs. A number of alternate blower designs were considered for this application in addition to those whose status was reported in the previous section. These designs fall under two headings: Single stage blower and Multi-stage blower.

(1) Single Stage Blower. The alternate designs considered under this heading involve only the type drive used. In addition to the variable speed induction motor and steam turbine drive described previously, a multi-speed electric drive was considered. This design involves the use of a single stage blower driven by a multi-speed induction motor to handle the required helium flow at all loads. Such a unit would operate at a top speed of 3600 rpm and would be so wired as to permit step-wise operation at 1800 rpm, 1200 rpm and 900 rpm. Loads intermediate to those

DECLASSIFIED

represented by the speeds listed would be carried by by-passing the excess flow.

This design is applicable to both the canned blower and the blower with the seal. It can be operated directly from TVA and requires no turbo-alternator. It also eliminates the need for stand-by steam. Although one blower is all that would be required for maximum capacity, at least two blowers would be necessary so that one would always be available in case of failure of the first unit. This design does not lend itself to the philosophy of parallel operation as adopted for this plant. It requires considerably more power at intermediate loads than the variable speed machines. It is dependent on electricity which, under emergency conditions, may not be available, whereas steam for turbo-alternators is always available as long as heat is being produced in the pile.

The cost of two such units was estimated by Westinghouse engineers to be the order of $300,000.

In conjunction with this approach, another scheme was investigated which involves the use of different size blowers, each running at constant speed to cover the entire load range. For good wheel proportions, each blower would have to run at a different speed or have different diameters at a given speed. If all these units are made to run at 3600 rpm and the diameters chosen for good wheel proportions at the design points, they would not match the pressure drop requirements and excessive power wastage would occur. If both the diameter and speed are varied from blower to blower to meet both the requirements for pressure drop and good wheel proportions, this design reduces to blowers of the same size running at different speeds which is the design described above.

The use of a D.C. motor drive, namely the Ward-Leonard System, was also investigated. This system would require a D.C. source, as well as a D.C. generator and motor. Since this arrangement would necessitate a D.C. source, this system would involve at least an A.C. motor or steam turbine, as well as a constant voltage D.C. generator, a variable voltage D.C. generator and a D.C. motor. It was felt that the variable speed A.C. drive was a better design.

(2) Multi-Stage Blower. Under this heading both the multi-stage centrifugal blower and the multi-stage axial blower were considered.

The multi-stage centrifugal blower would involve the use of two stages to obtain a higher pressure rise at current design conditions. The decision as to whether or not a two stage blower should be used depends on how much of the available heat is to be allocated to the blower for the purpose of an experimental unit. The single stage blower requires about 25 percent of the steam generated in the boilers for this plant, so from a power standpoint alone, it would not be desirable to go to a two stage machine to get an increase in pressure drop. Thought was given, however, to the possible use of two stage blowers despite power considerations, so that various types of fuel units could be tested without exceeding the pressure rise capabilities of the blower. The use of a two stage machine, however, is more complicated; it destroys the nicety of an over-

DECLASSIFIED

hung impeller and, in the case of the canned blower, means utilizing a bearing directly in the helium stream where radiation damage to the oil and vaporization of oil into the system would be greater than with the present design, possibly even prohibitive.

Tests are currently underway to determine the pressure drop charateristics of various type fuel elements which might be used for this application. Certain of these fuel units indicate the need for higher pressure rise output from the blower of the order of 5.5 psi instead of 3.61 psi. The 3.61 psi pressure rise currently being used is the maximum output of a single stage centrifugal compressor operating at 10 atmospheres with maximum permissible tip speed, at 500°F. The current design was chosen as a compromise between this limitation and the maximum expected pressure drop requirements for cooling the pile at 20,000 KW. On this basis, the single stage unit can handle pile operation with all current fuel units at loads up to 16,000 KW pile heat. Higher loads can be obtained with the single stage blower under these conditions by designing for a higher helium system pressure or for reduced blower operating temperature or a combination of both as economics dictate.

The multi-stage axial flow compressor lends itself to use of high rotating speeds and consequently smaller dimensions. Due to its multi-stage character, involving many small elements, it is more complicated and, consequently, more liable to failure. Adherence of radioactive dust particles to the blades would cause more flow disturbance in the axial flow blower than in the radial flow type. Such dust would also tend to disrupt the close clearance necessary in the axial type compressor. Furthermore, due to the high speed, blade failures are more probable and designing a rotor with a critical speed above the maximum operating speed in order to permit speed variation, is more difficult. Since it is possible to use the radial type blower which promises to be more trouble free under current design conditions, it was chosen in preference to the axial flow compressor.

d. Status of Design. Design of the blowers described for this application has been considered by several manufacturers. Propositions for the complete assembly of motor driven blowers with associated turbo-alternators and switchgear have been prepared by the Allis-Chalmers Manufacturing Company and Westinghouse Electric Corporation. A proposition for the motor driven compressor unit is also being prepared by Ingersoll-Rand Company.

Price and delivery quotations submitted for the motor driven blowers, turbo-alternators and switchgear is as follows:

	Price	Delivery
Westinghouse Electric Corp.	$418,000	14 Months
Allis-Chalmers Mfg. Company	233,075	20-22 Months

DECLASSIFIED

5. Large Valves

a. General Requirements. Valves in the main circulating system are required to operate the pile with various pieces of equipment inoperative and to isolate any piece of equipment if it should fail so that it might be repaired or replaced. Due to the large duct sizes, these must be large valves. They must not permit radioactive helium out-leakage from the system and air or water vapor in-leakage to the system. They must not permit interchange of gases on opposite sides of the valves. The double disc buffered, gate valve shown in Fig. 56 was felt to most closely meet these requirements.

Since the valves would be most difficult to replace, reliability is a paramount consideration. Consequently, every effort was made to use known and proven design features. The fact that these valves operate at 500°F and must work through the biological shield, however, introduces design problems which are different from those normally encountered.

b. Development Problems. The chief problems encountered in the valve design for this project are choice of suitable seating materials, selection of a reliable and satisfactory valve stem packing arrangement, and providing for satisfactory operation of the valve through the biological shield. Work has been undertaken at K-25 to determine if a suitable plastic valve seat could be obtained. This test work indicated that valve seats of Silastic-180 (Dow Corning plastic) and 20 percent copper impregnated Teflon (DuPont) had excellent seating properties at 500°F, even after a large number of operations, and at 600°F for short periods. Neither of these materials, however, withstood a two weeks irradiation test in the Clinton pile. They became extremely brittle and lost their resilience so much so as to be unsatisfactory for our use. In order to test distortion and seating problems with a long valve stem, a 4" crane valve from K-25 stock was built up with an extended stem and is currently being tested.

c. Alternate Designs. The following alternate designs were considered for this application: valve with bellows seal, totally enclosed valve, and valve with non-rising stem.

(1) The use of a bellows seal involves the use of a large bellows to withstand 10 atmospheres pressure differential at temperatures approaching 500°F for a travel of 18". It was felt that even with the development of such bellows, a packing gland similar to the one described for the present design would be necessary since the bellows would not be reliable enough for extended operation. While it is possible to use a bellows with pressure balanced on both sides, this arrangement would require a constant changing of balancing pressure with changes in system pressures.

(2) The totally enclosed valve is an attractive possibility but departure from standard design would require an extensive development program to work out the "bugs" and assure reliability of operation. Such a design, furthermore, does not permit hand operation in the event of power failure.

(3) The non-rising stem valve presents sealing problems similar to the present design and, in addition, involves the complication of gear-

DECLASSIFIED

ing within the valve. It was felt that this added complication would offset any advantage that might be gained with a non-rising construction.

d. Status of Design. Propositions for the design, development, manufacture, and test of the valves described for this application have been received from the Chapman Valve Manufacturing Company and the Crane Company. These propositions are based on stainless steel construction, which at one time were considered for the entire system in order to achieve uniform decontamination requirements as dictated by the high temperature duct. Since the current high temperature duct design does not require the use of stainless steel, these valves, along with the rest of the system can be made of carbon steel.

Each of the quotations submitted was for one 16" experimental valve for test; all development costs were to be charged against the first valve. In view of the discrepancy in price, both companies have been asked to prepare cost estimates for the next ten valves. The following quotations were submitted for the first valve, exclusive of special tests:

	Price	Delivery
Chapman Valve Mfg. Company	$27,000	120-150 days after freezing design;
Crane Company	7,108	26 weeks after design and materials are obtained.

6. Moisture Detector

a. General Requirements. The need for the moisture detector arises from the fact that leakage of water from the boiler into the helium system during operation will result in deterioration of the hot BeO moderator as described in Part 9 of this Section. A boiler failure would release large quantities of water and steam into the helium system and might fill the helium passages in the pile almost instantaneously with water vapor and water droplets. This action would cause an increase in reactivity in the pile which must be compensated for by the control rods. If actual drops or a mist of water droplets is carried into the pile, the reactivity may be increased beyond the safe limit of the delayed neutrons, and then the control rods could not move fast enough to limit the power to a safe value. The moisture separator at the bottom of the boiler is installed to prevent any drops of water or vapor from being carried into the pile by the helium so that only dry steam would enter the pile. It is believed from calculations that the control rods could move fast enough to control the pile if only dry steam is introduced into the pile.

Nevertheless, it is considered desirable to have a safety device to start the control or safety rods into the pile before the water vapor enters the pile. This can be done by having a device in the duct from the boiler which will shut down the pile when there is a sudden increase in the moisture content in the helium stream. This instrument will also detect small leaks of steam or water from the boiler into the helium system during operation.

DECLASSIFIED

Both the Infra-red Analyzer and the electric surface conductivity instruments have been used before on other applications. The electric surface conductivity promises to be the simplest instrument for alarm and trip purposes, and presumably, would have a response time of less than one second, which is very desirable. The main questions with this instrument are the effects of corrosion and radiation. Present indications are that corrosion will not be a critical factor, provided a nobel metal is used for the sensitive element. The effect on the reading of this instrument produced by ionization of the gas by radioactivity is a matter which will have to be checked.

Two alternate designs have been considered for this application: an acoustic resonating chamber for gas purity analysis, which has been developed by the General Electric Company and used by K-25 in the control of the process gas systems there, and a line recorder, based on the mass spectrograph principle.

The acoustic analyzer may be applicable, although it has a threshold of 2 to 6 weight percent moisutre in the helium. A mass spectrograph will be used for gas analysis with the purification system, but it is not satisfactory for detection of water vapor inasmuch as its response time is too long to be of value, particularly for automatic pile control purpose.

Other types of instruments have been proposed which should be investigated such as those measuring changes in electrical resistivity and dielectric strength of helium with changes in moisture content.

b. Status of Design. The General Electric Company and the Bailey Meter Company have been contacted relative to the problems of moisture detector design. These problems have also been discussed with engineers at K-25.

While the electric surface conductivity instrument appears to show the most promise for this application at the present time, a more extensive investigation and test program should be undertaken before embarking on a final design. The selection of this instrument is tentative. It has been estimated that suitable moisture detectors can be developed and delivered within about six months from the date of contact.

7. Surge System

a. General Requirements. The surge system is provided as an experimental facility for this plant so that pressure changes can be made at will without dumping the radioactive helium or using undue amounts of fresh helium. The chief problem concerned with design of the surge system is the development of a suitable pump design. Requirements of the pump are being worked out, but no pump development program has yet been instituted.

The helium transfer pump must be of a design which does not leak helium out of the system, nor air into the system. The pump has to operate satisfactorily in intermittent service for long periods without internal inspection or maintenance and without contaminating the helium stream with oil, water, or other lubricant. It must be capable of decontamination for removal and replacement in event of failure.

DECLASSIFIED

A number of alternate tank arrangements for the surge system have been considered, but the general plan of accomplishing the system pressure changes in each is the same. The design described was based on volumes of tanks that can be accommodated on railway flat cars for shipment.

b. Status of Design. The computations on tank sizes and surge system specifications have been worked out. A more refined thermodynamic analysis of the performance of the surge system and calculation of the time required to make pressure changes under abnormal operating conditions has been started.

8. Ventilation of Shielding

Work to be done includes determining the amount of ventilating air required, based on Health Physics considerations, and the determination of the number and location of radioactivity detection apparatus necessary to indicate the approximate location of a leak without the necessity of decontaminating and leak testing the entire helium circulating system.

DECLASSIFIED

9. Radioactivity Problems

a. Outline of Problems. The general problems resulting from pile radiations have been discussed under the topic of pile shielding (Part C of Section V) and properties of materials (Part H of Section V). These problems are the same for any pile regardless of the type of fuel rod used. The diffusion of radioactive fission products from bare fuel units as specified for this pile gives rise to a series of problems peculiar to bare fuel units resulting from the distribution of a high intensity of radiation not only in the pile structure but also in the heat transfer accessories connected to the pile. It is the object of this section to discuss the problems which have been studied in this latter category.

(1) Nature of Radiations Involved. Evaluation of the effects of fission products require specific knowledge of several of the main fission product characteristics. Some of these are fission product distribution, yield, decay energies, and half life distributions. A comprehensive summary of the nuclei formed in fission has been published by the Plutonium Project[1] giving fission product distribution, yields, decay energies, and half-lives.

The most severe effects are to be expected from gamma rays while beta rays and delayed neutrons also require consideration. Generally, the radiation effects from all nuclei can be lumped together. For some studies, however, it is desirable to isolate individual nuclei or groups of nuclei (i.e. - delayed neutron emitters) for separate consideration. A number of important values used in lumped fission product calculations is given in Table VIII.

TABLE VIII

AVERAGE FISSION CHARACTERISTICS [2]

Energy distribution from U^{235}	
Fission fragments	165 Mev
Neutrons	5 Mev
Prompt gammas (~1 Mev. ea.)	5 Mev
Radioactive gamma decay	5 Mev
Radioactive beta decay	7 Mev
Nutrinos	10 Mev

Lumped decay energies from fission products

Gamma Energy: Mev/(Sec.)(fission) = $1.26t^{-1.2}$

Beta Energy: Mev/(Sec.)(fission) = $1.40\ t^{-1.2}$

where t = time, sec.

Delayed Neutron Emitters

Half-life, sec.	Yield, %	Energy, Kev.
55.6	.025	250
22.09	.166	570
4.5	.213	412
1.5	.241	670
0.4	.085	400

(1) A list of numbered references are given at the end of Part F of Section V.

DECLASSIFIED

The distribution of fission product half-lives as shown in Fig. 95 also serves as a basis for interpreting the effects of fission products especially if a purification cycle is connected into the helium system.

(2) Basic Criteria for Evaluating Effects of Radiation. Evaluation of the effects of radiation resulting from fission product diffusion may be made on three distinct bases. For permanent structural materials (example: electrical insulation) the effects of radiation should be within safe limits for the expected life of the pile. For replenishable supplies (lubricants) the effect of radiation on the rate of consumption should be moderate. For biological tolerances, a dose of 0.1 R per day is specified. The first two criteria apply chiefly to machinery which must be installed inside the main biological shield of the pile. The last criterion applies in general to products which are discharged from the pile (steam, helium, etc.).

b. Experimental Data and Calculations Relating to the Diffusion of Fission Products from Bare Fuel Units. The actual diffusion rate of fission products from a bare fuel unit under the conditions encountered in a high temperature power pile is difficult and tedious to determine. Since the diffusion rate of fission products is a statistical problem strongly effected by other statistical variables such as fuel rod history, density, porosity, composition, etc., a great deal of experimental effort would be required to reduce diffusion experiments to a reliable basis for pile design and operation. The state of knowledge on this subject at present is such that the probable rate of diffusion can be established within a factor of about 10. Additional experimental effort would tend to narrow this range of uncertainty but since most of the problems involved are of a non-critical nature and yield satisfactory solutions even for the maximum probable levels of radiation, the undertaking of further experimental work in this field is more a matter of convenience than necessity.

(1) Experimental Work on Fission Product Diffusion. Diffusion rates of Xe from "hot pressed" BeO containing 10% enriched U^{235} produced by the Norton Company were measured by J. E. Wilson at Argonne National Laboratories during 1946 (4). He irradiated samples 1 cm. x 1cm. x 1 cm. in the Argonne pile, then placed them in a high temperature furnace and counted the decay rate of Xe^{133} in a stream of helium passing over the sample. Sufficient time after irradiation was allowed (4 hr.) to allow other Xe isotopes with shorter periods to decay to negligible values. His tests covered both temperature and density of BeO as variables. The values of the diffusion coefficient found are given in Table IX.

DECLASSIFIED

TABLE IX

DIFFUSION CONSTANT OF XENON IN BERYLLIA

Temperature, °C.	Density, gm./cc.	D, cm.^{2}/min.
1000	2.5	9×10^{-9}
1000	2.7	11×10^{-9}
1000	2.9	9×10^{-9}
1000	3.1	1×10^{-9}
1100	3.1	3×10^{-9}
1200	3.1	2×10^{-9}
1325	3.1	3×10^{-9}
1450	3.1	2×10^{-8}

Anomalous variations of the diffusion coefficient both with density and temperature are evident. Wilson estimated that the values given are probably right within a factor of about 2 based on an analysis of experimental errors exclusive of statistical variations of the samples themselves. On the basis of the diffusion constants given, Wilson estimated that 1 to 2 per cent of the Xenon activity would diffuse into the helium for a pile operating at 1000°C. If this same percentage is applied to all volatile fission products with half-lives in excess of $\sim$ 1 hour in order to exclude those nuclei which probably will decay before getting into the helium (J.A.Swarthout[5] estimated that 31% of the fission yield based on 200% could be assumed for this purpose) the percentage of total activity reaching the helium is

$$2\% \times 31/200 = 0.3\%$$

for the upper limit and $\sim$ 0.1% for the lower.

In addition to diffusion, atoms fissioning close to the surface of a fuel rod would recoil directly into the helium. Swarthout[5] estimated that .05% of the total activity would enter the helium by recoil based on a recoil range of 5.5×10^{-4} cm. in BeO

2. Upper Limits Estimates of Activity in Helium. One hundred percent diffusion of the fission products into the helium is assumed for the upper limit activity. This obviously gives a very pessimistic approximation.

c. Experimental Tests on the Effects of Radiation on Pile Components. Extensive tests were conducted in 1943 on the effects of radiation on pile structural materials (graphite, water, lubricants, insulation, etc.) leading up to the design and construction of the Clinton, Hanford and Argonne piles. The results of these tests together with a detailed analysis of subsequent pile operation have established a reliable basis for the effects of radiation on materials[6] and radiation chemistry[7].

DECLASSIFIED

A first order approximation of the effects of radiation on lubricants and other covalent chemical compounds can be made by assuming that the effects from any particular type of radiation is proportional to its ionizing power and that the absorbtion of energy equivalent to 25 ev[7] is sufficient to rupture a chemical bond. Second order effects, chain chemical reactions, and reverse reaction give yields somewhat higher or lower but in the cases of interest here, they are within the same order of magnitude as the first order approximation.

(1) Lubricants[8]. The proposed blower designs require bearings adjacent to the radioactive helium circulated through the pile. The maximum shielding effect which may be expected between the radioactive products in the helium and the lubricant is a reduction of gamma radiation by a factor of 10 ($\sim$ 2 inches iron) and essentially complete shielding against direct beta rays. Secondary radiations (Bremstrahlung) from beta-radiation will however reach the bearing surface but this constitutes only a small fraction of the original energy.

TABLE X

SUMMARY OF EXPERIMENTAL TESTS ON LUBRICANTS

A. Type of lubricants

1. Phillips lubricating oil (paraffin-base) SAE 20
2. Gulfpride motor oils (paraffin base) SAE 10, SAE 20, SAE 30
3. Texaco lubricating greases, Starfak M (straight grease)
4. Texaco Starfak No. 2 Rex 127 (grease with antioxidant)
5. Troco Lubricating grease No. A-07

B. Criterions of Exposure

1. Index of refraction
2. Iodine absorption
3. Viscosity
4. Acidity
5. Decomposition products
6. Physical appearance, odor, etc.

C. Sources of Radiations

1. Cyclotron (6.9 Mev. Duterons)
2. Vande Graff (2-3 Mev beta and X-rays)

The tests were carried out at room temperature and the exposure in some cases was carried sufficiently far to cause the oil to polymerize into a solid (absorption $\sim$10 watt hours/cc.) Correlation of variables enumerated in Table X was most complete for Phillips oil. Other lubricants were tested less exhasutively. Absorption of 1 watt hour/cc. corresponds to the breaking of about 1% of total organic chemical bonds calculated by first order approximation methods[7]. The effects observed on oils irradiated to this extent[8] are summarized in Table XI.

DECLASSIFIED

TABLE XI

RADIATION EFFECTS ON LUBRICANTS

CORRESPONDING TO ABSORPTION OF 1 WATT hr/cc ENERGY

1. Index of refraction: Increased from 1.4943 to 1.4961 (Phillips oil)

2. Iodine absorption: Increased from 5.60 to 12.70 gm. iodine/100 gm. oil (Phillips oil)

3. Viscosity: Increased from 1.955 to 2.775 poise (Phillips oil). Fractional increase for Gulfpride oils was comparable.

4. Acidity: Increased 3-5 mg. NaOH per cc. for greases and about 2 mg. NaOH per cc for oils

5. Decomposition products: Slight gas bubble formation. Oils slightly more odiferous.

6. Physical appearance: Oils still liquid. No marked change in color. Greases bleached slightly.

Most of the experiments summarized above were carried out with gamma rays, and are therefore directly comparable to the effects expected from pile operation. The dosage given also represents a reasonable exposure on the basis of effects observed and therefore serves as a tentative limit of exposure for further engineering calculations.

(2) Electrical Insulation. The conditions of exposure described for lubricants in the helium blower also apply to electrical insulation of the blower motor windings for the "canned motor" blower proposal. Where it is possible to use appreciable shielding between the motor and helium, no radiation problems involving electrical insulation are anticipated.

A summary of experimental work on the effects of radiation on electrical insulation has been prepared (9)(10) in connection with the high temperature experimental power pile design. Data has been reported for over 30 different samples of commercial insulation and plastics tested for exposure to gamma and beta radiations to the extent of 0.1 watt-hour per cc. energy absorbed. Minor variations in resistance of samples were observed before and after gamma radiation tests (actual energy absorbed in gamma radiation tests was not definitely established). For beta-ray tests (energy absorbed $\simeq$ energy emitted from source) actual softening occurred for amphenol and copolene plastics. No highly significant changes in resistance or appearance was observed for the following:

Vinylite 5900 and 5901
Koroseal 1434
Rubber Okonite 313 and 8816 B1

DECLASSIFIED

SECRET

Non-significant variations in resistance were obtained for gamma-ray exposures of Westinghouse Rockbestos, General Electric Deltabestos and silicone bonded glass and mica insulations.

In early tests (1943) the resistance measurements were not carried out simultaneously with the irradiation. A series of tests was reported in 1946[11] in which the resistance measurements were carried out simultaneously with the irradiation but the variations observed were not highly significant and in some cases were quite erratic (within the experimental accuracy of the test instruments).

In actual pile installations, the radiation effects on insulation will result almost exclusively from gamma-rays. Since tests up to 0.1 watt-hr. per cc. exposure have failed to show any marked effects on the resistance or physical properties of the insulations named above a considerable margin of exposure is available beyond this dosage before deterioration may be expected.

d. Calculated Activities in Pile Components. The diffusion of fission products into the helium results in the deposition of a film of radioactive products on the inner surface of the helium system and also gives rise to delayed neutron induced activities in the structural components of the system as well as the water in the steam boiler. It is desireable to be able to reduce the activity of the boiler to a sufficiently low value to permit periodic inspections and maintenance. It is also desireable to keep the activity of the steam to a sufficiently low order not to require shielding on the steam pipes and turbines outside the pile. Anticipated levels of activity for both of these problems have been calculated[12][13].

(1) Acitivity of Structural Parts of Boiler. It is anticipated that the film of fission products which deposits on the helium side of the boiler can be dissolved with suitably inhibited acids in order to make the boiler available for inspection. Exploratory tests using metal samples contaminated in radioactive fission product solutions did not yield any very tenacious films for testing. The films obtained could be washed off with water but acid had a somewhat quicker action. Efforts are being continued to obtain more tenacious films for testing. Since the residual film activity remaining after decontamination depends on the decontamination procedure used, no direct correlation exists between the rate of fission product diffusion from the fuel units and the final film activity in the boiler.

Another contribution to boiler activity results from the absorption of delayed neutrons by certain isotopes to generate radioactive nuclei. This induced activity cannot be decontaminated. The majority of the neutrons absorbed yield either stable nuclei or activities of relatively short decay periods neither of which would seriously interfere with boiler inspection. However, those nuclei which decay with a relatively long periods would either delay or prevent inspections from being made.

SECRET

DECLASSIFIED

From Table VIII the yield of delayed neutrons is 0.7 per cent of the total. Since all delayed neutrons decay with a period of < 1 minute, the loss of delayed neutrons emitters fromaa fuel unit by diffusion is expected to be small. However, it was shown that direct recoil into the helium may amount to 0.05 per cent. The portion of the delayed neutrons in the helium absorbed in any given part of the helium system will be directly proportional to the fraction of the total helium at that location. Since the boiler contains roughly 25% of the total helium in the system, the fraction of delayed neutrons emitted in the boiler is also 25%. The number of radioactive nuclei generated at any particular point will be given by the relation

$$N \times \sum(n-\gamma) / \sum a$$

where

N	=	Total delayed neutrons emitted
$\sum(n-\gamma)$	=	Macroscopic cross-section of parent isotope
$\sum a$	=	Total macroscopic absorption cross - section

The chief long lived (> 2 days) activities affecting inspection of a steel or stainless steel boiler are given in Table XII.

TABLE XII

RADIOACTIVE NUCLEI (> 2 DAY HALF-LIFE)

INDUCED IN STEEL AND STAINLESS STEEL

	Nucleus	Half-life	Parent isotope $\sum(n\,\gamma)/\sum a$
Steel			
	Fe^{55}	4 yr.	6×10^{-2}
	Fe^{59}	47 days	4×10^{-4}
Stainless Steel (18-8)			
	Cr^{51}	26 days	3×10^{-2}
	Fe^{55}	4 yr.	4×10^{-2}
	Fe^{59}	47 days	2×10^{-4}
	Ni^{59}	150 yr.	1×10^{-1}
	Ni^{63}	2.6 yr.	4×10^{-4}

Using the factors given above for delayed neutrons, we have

$$.007 \times .0005 \times .25 = 8 \times 10^{-7} \text{ (say } 10^{-6})$$

of the total neutrons emitted in the boiler. This factor multiplied by the values given in Table XII gives the rate of radioactive nuclei generation. For a pile operating at 4000 Kw. 3×10^{17} neutrons are

DECLASSIFIED

generated per second giving a yield of 3×10^{11}/sec. in the boiler. The growth of various activities and final equilibrium activity are shown in Table XIII.

TABLE XIII

ACTIVITIES INDUCED IN BOILER

Nucleus	Initial rate of growth, curies/day	Equilibrium Activity, curies
Steel		
Fe^{55}	.0003	0.5
Fe^{59}	.00005	0.004
Stainless Steel (18-8)		
Cr^{51}	.01	0.3
Fe^{55}	.0002	0.4
Fe^{59}	.00003	0.002
Ni^{59}	.000006	1
Ni^{63}	.000002	0.005

Since the tolerable induced activity in the boiler without ruling out direct inspection is in the order of 1 to 10 curies of total activity it is apparent that the values of Table XIII are below this limit. For a tenfold error in the delayed neutron yield the steel boiler would still be accessible, for stainless steel the rapid growth of Cr^{51} does not allow a very wide margin of safety for boiler inspection. The induced activity will of course also rise directly proportional to the operating power level. It is concluded from the foregoing discussion that the possibility of direct boiler inspection is dependent on following an operating procedure which will keep induced activities to a minimum. This can be done conveniently only during initial operation at a relatively low power and moderate ($< 1000^{\circ}C$) fuel rod temperature.

(2) Water and Water Impurities. Although the total number of neutrons generated and absorbed in the boiler per second was determined quite simply, the fraction of these which are absorbed in the water is more difficult to determine and would require the solution of diffusion equations applicable to the particular geometry of steel and water found in the boiler. Since the overall accuracy of the steam activity approximation is only sufficient to establish the correct order of magnitude within a factor of 10, exact methods are not warranted and simple approximations are in order.

Due to the relatively high absorption cross-section of steel and the large mass of steel in the boiler tubes and walls, then bulk of the neutrons will diffuse only a few centimeters from their point of generation before being absorbed. This distance is small compared to the overall dimensions of the tube assemblies and the boiler. Since

DECLASSIFIED

the tube assemblies occupy approximately 50% of the boiler volume, the fraction of neutrons absorbed by the assemblies will be 50% as a first order approximation (leakage of neutrons away from assemblies is assumed to be equal to neutrons leaking into them). The macroscopic absorption cross-section for steel and water are 0.23/cm. and 0.02/cm. respectively; however, since the volume of water present in the tube assemblies is roughly twice that of the steel the ratio of water to steel absorption is 0.2 and about 10% (20% to 50%) of the neutrons in the boiler will be taken up by the water.

The chief activities induced in water and its common impurities are shown in Table XIV.

TABLE XIV

ACTIVITIES INDUCED IN WATER AND IMPURITIES

Nuclei	Radiation*	Half-life	No. atoms per curie
O^{19}	4.1 β; 1.6 γ	31 sec.	1.6×10^{12}
Na^{24}	1.4 β; 2.8 γ	14.8 hr.	2.8×10^{15}
Ca^{41}	1.1 γ	8.5 days	3.9×10^{16}
Cu^{45}	0.9 β; 0.7 γ	180 days	8.3×10^{17}
Cl^{36}	0.6 β	>1000 yr.	1.7×10^{21}
Cl^{38}	1.1,2.8,5.0 β;1.6,2.2 γ	37 min	1.2×10^{14}
Mg^{27}	1.8 β;0.6,0.1,1.0 γ	10.2 min.	3.3×10^{13}
S^{35}	0.1 β	87.1 days	4.0×10^{17}
Fe^{55}		~4 yr.	6.7×10^{18}
Fe^{59}	0.3,0.5 β;1.1,1.3 γ	47 days	2.7×10^{17}
P^{32}	1.7 β; no γ	14 days	6.5×10^{16}
Cu^{64}	0.6 β; no γ	12.8 hr	2.5×10^{15}
Cu^{66}	2.9 β	5 min	1.6 c 10^{13}
Si^{31}	1.8 β	170 min	5.6 x 10^{14}

* Strength of radiations given in Mev

DECLASSIFIED

SECRET

Since considerable variation may appear in the concentration of impurities in samples of boiler water, a tabulation of the expected fraction of neutrons absorbed per 100 ppm of impurities will be tabulated to give the relative effects from various sources. This is shown in Table XV.

TABLE XV

FRACTION OF NEUTRONS ABSORBED PER 100 ppm IMPURITIES RELATIVE TO THE TOTAL ABSORBED BY WATER. (BASED ON CROSS-SECTION OF 0.02/cm. FOR WATER)

Isotope	Natural Abundance,%	$\sigma_a(n-\gamma)$ barns	Fraction of neutrons absorbed per 100 ppm impurity
Na^{23}	100	0.45	6×10^{-5}
Mg^{26}	11.1	0.05	7×10^{-7}
Si^{30}	4.2	0.1	3×10^{-7}
P^{31}	100	0.3	3×10^{-5}
S^{34}	4.2	0.26	1×10^{-6}
Cl^{35}	75.4	33.	2×10^{-3}
Cl^{37}	24.6	0.6	1×10^{-5}
Cu^{40}	96.96	< 0.0003	2×10^{-8}
Cu^{44}	2.06	0.6	8×10^{-7}
Fe^{54}	6.04	2.5	8×10^{-6}
Fe^{58}	0.28	0.3	4×10^{-8}
Cu^{63}	70.13	3.1	1×10^{-4}
Cu^{65}	29.87	2.0	3×10^{-5}

The fraction of neutrons absorbed by O^{18} relative to the total for water is 7×10^{-7}. Of all the impurities shown in Table XV, Na, Cl, and Cu are most prevalent in boiler water. Due to the very slow decay rate of Cl^{36} the absorption of the fraction of neutrons shown for Cl^{35} gives only a relatively small degree of activity. Of the remaining activities, Na and Cu are worst. Since the level of activity

SECRET

DECLASSIFIED

will be of a relatively small order anyhow, the effect from any given concentration of minerals in the water will be less than the effect found assuming that the minerals are constituted 100% of Na. The factors giving the number of radioactive O^{19} and Na^{24} nuclei formed relative to the rate of neutron generation in the pile are

$$10^{-6} \times 0.1 \times 7 \times 10^{-7} = 7 \times 10^{-14} \text{ for } O^{19}$$

and

$$10^{-6} \times 0.1 \times 6 \times 10^{-5} = 6 \times 10^{-12} \text{ for } Na^{24}$$

At a pile operating power of 4000 Kw, this corresponds to an O^{19} activity of 10^{-6} curies and Na^{24} activity of 5×10^{-5} curies. Since activities of 0.002 curies per foot of steam pipe are permissable without exceeding a tolerance dose of 0.1 r per 8 hours, 3 feet from a pipe, it is evident that the induced levels of activity estimated are safe by a factor 10^3 to 10^5. This margin of safety is more than adequate to cover possible errors introduced in the various approximations used. The same estimate carried out assuming 100% diffusion of delayed neutron emitters yields 0.2 curies of O^{19} acitivity and 10 curies of Na^{24} acitivity. Since it is desirable to keep radiation dosages to a minimum, it is nevertheless recommended that the mineral concentration in the boiler be kept as low as possible consistent with existing power plant practices and that approach to steam pipes and turbines of the power plant during operation be restricted to necessary maintenance on inspections only.

(e). Evaluation of Radiation Problems Relating to Specific Fuel Rod Proposals. The effects of fission products on the boiler and blower can be approximated directly from the lumped characteristics given in Table VIII and Figure 95. The total beta and gamma radioactive decay energy available is 12 Mev per fission. The variation of the rate of energy emission with time is given by

$$\text{Mev/(sec.)(fission)} = -2.66\ t^{-1.2}$$

Since the nuclei coming from the fuel rod (recoils excepted) are emitted in various stages of decay, the actual average rate of energy emission in the helium per fission is less than that from the relation above. The integrated energy per fission for the first hour amounts to 80% of the total leaving only 20% for emission in the helium if the diffusion process delays the entrance of the fission products into the helium by this amount. Experimental data giving the distribution of fission product age and type in the diffused fission products would be required to determine the average percent of residual decay energy entering the helium but this is hardly justified in view of the minor importance of this factor. Neglect of this factor would introduce a factor of safety of about 2-5 in final estimates.

DECLASSIFIED

The basis used to estimate the activity is that the total decay energy emitted in the helium is roughly proportional to the fraction of fission products diffusing and recoiling into the helium and that the decay rate is in equilibrium with the rate of diffusion.

For a pile power of 4000 Kw, we have 1.2×10^{17} fissions per sec. making available a potential decay energy of 1.4×10^{24} ev. per sec. If 0.3% diffuses into the helium we have 4.5×10^{21} ev. per sec. in the helium or 4.5×10^{13} ev. per sec. per cc. of helium based on 4000 cubic feet of helium. Under discussion of radiation tests on lubricants, it was pointed out that shielding effects of the blower components could be expected to reduce this by another factor of 10 or 4.5×10^{12} ev. per sec. per cc. This is an upper limit of the amount of energy per cc. which the blower components can absorb. Since a radiation dose of 1 watt-hour per cc. corresponds to 2.2×10^{22} ev. per cc. it is evident that over 10^9 sec. would be required to accumulate a maximum dose. For lubricants an exposure period of 10^5 Sec. would still be within reason thereby showing a factor of safety of 10^4. For electrical insulation at least 10^8 sec. (3 yr.) exposure would be desirable before deterioration due to radiation might be expected. This figure is still safe by a factor of 10 over that calculated for the pile operation. Satisfactory service may be expected from both lubricants and insulation used in the helium circulating blower based on BeO fuel rods in the pile.

The substitution of bare graphite units in place of BeO would probably decrease the safety factors given by 10 or so due to the greater porosity of graphite resulting in higher diffusion rates. Satisfactory operation with graphite fuel can be expected at less than 4000 Kw. Radiation surveys made below 4000 Kw. can be used to determine the maximum operating level without causing deterioration of electrical insulation.

The rate of iodine and xenon diffusion may be sufficiently rapid from graphite to eliminate to a large degree the poisoning effect of xenon. A helium purification cycle operating at a rate to purify all the helium once per hour would reduce the poisoning effect to an appreciable degree since the effects of xenon are delayed several hours because of the 6 hr. half-life of the iodine precursor. If this behavior actually turns out to be an advantage in pile operation then it is in the interest of economy and efficiency to operate with the helium at the highest tolerable level of radioactivity which is found experimentally feasible.

10. Purification System.

a. General Requirements. Successful pile operation will be highly dependent on the amount of detrimental impurities contained in the helium system. These impurities are not only introduced by commercial helium used but are formed in the system by volatilization of and by chemical reaction between pile materials.

The design of suitable purification facilities is dependent on knowledge of amount and types of impurities expected and the amounts of each which can be tolerated. Both these questions are difficult to ascertain in themselves and a large part of the work to date on the purification system has been expended in an attempt to answer these questions.

DECLASSIFIED

Table XVI lists the impurity tolerances tentatively established for the design of the purification system. These tolerances are based on limited data and are being revised, as more data becomes available.

Consideration was given to a number of factors in setting these tolerances, the absorption cross section of the impurity and its effect on neutron economy and pile control, induced activity as a result of nuclear reactions, the capacity of the purifier, and particularly the action of the impurity on pile materials.

On this basis a tolerance of 0.1% was established for nitrogen. Removal of nitrogen from the system is not expected to be a serious problem. Helium introduced into the pile system will probably have less than 0.05% nitrogen. There is little likelihood that additional nitrogen will be introduced during pile operation.

The reaction between CO and Fe will be of no consequence providing the concentration of CO is less than 0.1%. At this concentration possible carbon dusting caused by the reaction $2CO \rightarrow CO_2 + C$ will be negligible because of chemical kinetic limitations.

The oxygen concentration must be kept low in order to prevent the loss of Uranium from fuel elements because of the reaction $UO_2 + 1/2\ O_2 \longrightarrow UO_3$ (18)(19). The tolerance of 4×10^{-6}% given for O_2 is based on experimental data. It is not expected that this low tolerance for oxygen will be difficult to maintain. Oxidation of the large areas of metal surfaces (ducts, boilers, etc.) exposed to the hot coolant will tend to remove oxygen. Small concentrations of hydrogen and hydrocarbons will probably be present and assist in the reduction of oxygen content by converting it to H_2O which can be readily removed.

The reaction between BeO and H_2O results in the volatilization of BeO(20). It has been estimated that the quantity of BeO volatilized will certainly be negligible at 10^{-5}% H_2O(15). Maintenance of this concentration of water vapor will not be difficult. It can be done by an electrodryer employing Al_2O_3 and operating at 200 atmospheres. Low temperature charcoal adsorption, the method recommended, may reduce the concentration of water much lower than 10^{-5}%.

Unless a special facility is provided for hydrogen removal, its concentration may approach 0.1%. Actually a slightly reducing tendency in the helium may be advantageous: therefore it is felt that no need exists for specifying a tolerance less than 0.1%.

The tolerance for argon is set at 0.01% because the concentration of argon can very readily be kept below this value. The concentration of Argon should be kept low in order to keep the induced activity low. A value of 0.01% is the tolerance for argon in helium used at the Hanford Engineer Works.

Discussion of impurities which may appear during pile operation is given elsewhere(15). At a conference held with Dr. P.H.Emmett of the Mellon Institute for Industrial Research, Chemical Purity requirements were considered from a thermodynamic point of view(18).

DECLASSIFIED

b. Development Problems. Before a final design can be prepared for the purification system a certain amount of experimental and theoretical work remains to be done. This work falls into six general categories, work on impurity tolerances, purification of chemical impurities, purification of fission and decay products, formation of impurities in the pile during operation, analysis and instrumentation, and degassification.

The following series of experiments are proposed to fill in the gaps in the present information:

(1) Impurity Tolerances

(a) Detailed specifications for additional tests to investigate the reaction $UO_2 + O_2$ and the resultant volatilization of Uranium have been written[21]. The information concerning the volatilization of Uranium from fuel[18] is good but unfortunately is not complete as regards the temperature effect on the rate of reaction. More experimental work should be undertaken to determine the effect of temperature, and also to supply other information such as the effect of BeO density on volatilization of contained Uranium, effect of UO_2 concentration and effect of specimen geometry on loss. Some information esists on the latter but more complete studies should be made.

(b) The results of an investigation of the reaction between steam and BeO have been summarized[20]. At that time work was in progress to determine the effect of H_2O partial pressure on this reaction. Apparently no results of pertinent interest have since been obtained[22]. The loss of BeO expressed in % loss per hour for different temperatures at 2 g of H_2O flow and at 1 atm. pressure are given below:

% Loss/hr	Temperature
10^{-5}%/hr (extrapolated)	700°C
3.6×10^{-3} (extrapolated)	1000°C
2.6×10^{-1} (experimental)	1400°C
9×10^{-1} (experimental)	1540°C

A tolerance of 10^{-5}% has been established for H_2O in the helium coolant for BeO fuel rods at a maximum temperature of 1000°C. It is believed that this tolerance is too conservative and therefore life tests are proposed to determine the effect of H_2O partial pressure on BeO loss at 1000°C.

(c) The tolerances for H_2 and hydrocarbons total 0.2%. This tolerance is somewhat arbitrary. One hesitates to set a higher tolerance, i.e. at 1%, without giving the problem more thorough study. This tolerance is important because at the present time it appears that hydrocarbons will be the chief impurity. Hydrocarbons

DECLASSIFIED

SECRET

will be formed from lubricating oils leaking into the coolant at a possible rate of 2 cc per hour for each blower. Study of the oil leakage should also be made because there is a good possibility that actual leakage may fall far short of the tolerance of 2 cc per hour.

(d) If adoption of less stringent tolerances is permissible, then it may be possible to advise that continuous purification is not necessary, excluding the proposition of fission product removal. A substantial savings can be realized in the final desing, construction, and operation of the pile if the results of studies and experiments permit tolerances which can be met without continuous purification.

(2) Purification - Chemical Impurities. Better cost estimates for helium purification than those made to date should be obtained. Air Reduction Sales Company has made a study of costs for low temperature charcoal adsorption purification[23]. This estimate gives additional information but is not as detailed as is desirable. It merely supplements the previous cost estimate.

Two trips to the Amarillo Helium Plant have been made[17][24] and information concerning facilities and personnel available at the Amarillo Helium Plant was obtained. As a result, a proposition requesting development and preliminary design will be prepared and it is expected that it will receive favorable action by the Bureau of Mines.

By virtue of this proposition, the Bureau of Mines would be authorized to investigate the following problems. To what temperature should the charcoal be refrigerated? A temperature of - 190°C has been estimated but it may not be necessary to go that low to obtain sufficient purity. Better figures for the impurity analysis of helium treated with activated charcoal at different temperatures must be obtained. One cannot say at the present time which is more economical - high or low pressure purification. The physical size of a high pressure plant will be less and therefore require less costly shielding but maintenance and safety facilities will be more costly. More accurate cost data on helium purification as a function of purification rate is also needed.

(3) Purification - Fission and Decay Products. The radioactivity hazard associated with the use of circulating helium coolant in contact with various types of hot fuel elements must be more carefully ascertained that it has been hitherto. The activity has been estimated to range from a minimum of a few tenths of a curie per ft.^{3} to thousands of curies per cubic foot. It is generally believed that such estimates are unduly pessimistic and therefore unrealistic. In one instance in one design of a fuel loading mechanism, this problem was approached by setting a tolerance of 0.1 curie for cubic foot (S.T.P.) for the helium coolant. It is necessary to determine first the magnitude and character of the activity and second the reduction in activity that can be obtained by continuous purification.

SECRET

DECLASSIFIED

The following experiment is one of the proposals for determining the loss of fission products from various types of fuel elements as a function of temperature and helium velocity. Specially designed and constructed equipment will be required and be used in one of the 4" square x 40' long holes running N and S near the bottom of the X pile. A preliminary study of the experiment indicates that two technically trained men full time and the part time of one person qualified to direct the work are required. One Year's time will be required which will include 3 to 4 months to design, construct and test equipment. One month will be needed for assembling equipment and getting it in operation in the pile. Two months will be required to get minimum information on two fuel rod types. Four or five months should be allowed for additional information on other types of fuel rods and also to obtain information of general interest. Authorization for this experiment has not been requested; however, it or a similar experiment is considered an important phase of the current experimental program and should be started as soon as possible.

Detailed study should be given to the possible reduction of activity of the coolant by continuous purification. It is evident that the concentration of fission products can be reduced by purification(25). This fact does not necessarily mean that the radioactivity of the coolant is significantly reduced. Most of the fission products have small half lives and if they enter the helium stream immediately after fission they will decay before the purifier can remove them(25). In the event that the fission products must diffuse through the solid rod material before escaping into the coolant, only the longer half life products will enter the helium stream because the short half life products would have time to decay within the fuel rods; under these conditions the purifier can effectively reduce radioactivity because the purifier can remove the long life products before they decay.

However, this point should be further investigated. Such an investigation will be more useful when the results of the experiment described in the preceding paragraph are available. Although only Te, I, and Xe were determined as volatile constituents of helium which had been passed over hot irradiated BeO containing uranium 235 at Chicago(26), the possibility remains that other volatile constituents are not excluded by these experiments. At the high temperature and at low partial pressures in the power pile coolant, a number of fission and decay products may exist primarily in the vapor phase. The loss of fission products from Uranium metal as a function of temperature has been studied(27).

The radioactivity hazard may become less serious as more progress is made in developing impermeable fuel elements. However, these studies and experiments which are recommended should still be carried out. Design studies and cost estimates from Air Reduction Sales and the Bureau of Mines will have to be modified to include shielding and facilities for handling and disposing of radioactive materials.

DECLASSIFIED

Consultations with other concerns with experience in the field of rare gas purification are also planned. For example, the Linde Air Products Company and the Rare Gas Division of the General Electric Company may be able to give substantial assistance. The General Electric Company is currently operating a shielded helium purification plant at Hanford, Washington, using refrigerated activated charcoal under conditions similar to those expected on this project.

(4) Formation of Impurities in the Pile during Operation. More experiments are required. Quantities and identies of the various gases which may be desorbed from moderator, breeding, and fuel materials must be experimentally determined. Possible formation of O_2 from the decomposition of BeO under radiation and fission product damage conditions should also be investigated. Experimental results which are available concerning the decomposition of BeO by radiation are not conclusive. Other pile materials and proposed and possible fuel materials need be investigated from the standpoint of gas evolution caused by decomposition brought about by radiation.

(5) Analysis & Instrumentation. Although data on the performance of the mass spectrograph has been obtained from the Consolidated Engineering Company, there still is unsolved the problem of adapting their instrument for analysis of gases containing radioactive impurities. The manufacturers, Westinghouse, General Electric Company and Consolidated Engineering Company must be consulted as to the performance that can be expected under ionizing conditions (F. P. decay) and also under the handicap of possible inaccessability of part of the equipment because of radioactivity. Experimental tests, if necessary, should be carried out.

Baird Associates in Cambridge, Massachusetts should be further consulted and recommendations obtained concerning use of infra-red apparatus for analysis of impurities in the power pile coolant. A specially dehumidified infra red analyser should be developed for H_2O analysis. Instruments to monitor the activity of the coolant have not been given sufficient consideration yet.

(6) Degassification. The method for degassification of the pile recommended by Air Reduction Sales Company representatives is outlined in the Description. However, the problem of degassing the pile at the start up should be given more careful consideration. Therefore, it is proposed that negotiations be started with the National Research Corporation, in Boston, Mass. to learn how much assistance they are willing to give. National Research Corporation is pre-eminently qualified by experience with similar problems to make specific recommendations as to procedures, pumps, diffusion pumps, etc.

c. Alternate Designs. Table XVII is a list of other methods of gas purification which might be used to purify helium. The possibility of using a dryer and activated charcoal unit to dehumidify and to deoxygenate the coolant was rejected by representatives of Air Reduction Sales Company because of the inability to remove CO. Use of calcium metal is a possibility;

DECLASSIFIED

however, available experimental data does not warrant its use. Uranium metal turnings have been employed successfully to clean-up inert gases on a laboratory scale. Its use on a larger scale has not been explored. The fact that it forms stable solid products with nearly all the impurities, N_2, H_2, O_2, CO, and H_2O, that may be present suggests that an experimental program to develop its use on a larger scale would be worthwhile. Uranium is not the only metal which might be used. Mo, Cb, Li, Mg, and other metals also should be considered in such an investigation.

Some of the products of reactions of metals with gases are stable. Regeneration of uranium for reuse without removing it from the system (i.e., similar to activation of charcoal) would seem impractical. Therefore, removal of large quantities of impurities may be prohibitive. The small quantities of impurities expected in the coolant may well be best removed by reaction with a metal. This problem should be investigated. Present data is limited to laboratory scale purification and use of these metals as getters in vacuum tubes. There is sufficient need for an inexpensive means of cleaning helium coolant of impurities to warrant some research and development work.

d. Status of Design. The problems connected with helium purification and impurities detection have been discussed with representatives of the Bureau of Mines, Air Reduction Sales Company, Ingersoll Rand Company, General Electric Company and Bailey Meter Company.

Preliminary studies have been made of purification methods, purification rates, impurity tolerances, reduction of coolant radioactivity, and size of plant required.(15)(25)(28)

Although a satisfactory design for helium purification equipment based on available data could be prepared in several months, it would be necessary to conduct the studies and experiments outlined above before a completely adequate and economical design could be assured.

DECLASSIFIED

SECRET

TABLE XVI

CONCENTRATIONS OF IMPURITIES IN HELIUM COOLANT

Impurity	Analysis of Commercial Helium	Tolerances for (10,000 KW)	Mass Spectrometer Limits of Detection Std. Inst.	Mass Spectrometer Limits of Detection Spec. Inst.	Other Instruments Limits of Det.	Analysis of Liquid Air Cooled Charcoal Purified Helium
He	98.0-98.7%	99.6%				99.9%
N_2	1.3-1.8	0.1	4×10^{-2}%	8×10^{-3}%	6% (a)	0.1
O_2	0.02-0.14	4×10^{-5}	2×10^{-2}	4×10^{-3}	10^{-4} (b)	non det.
CO_2	0.00-0.05	0.02	2×10^{-2}	4×10^{-3}		non det.
CO	0.00-0.03	0.08	4×10^{-2}	8×10^{-3}	10^{-5} (c)	0.1
H_2O	0.00-0.10	10^{-5}			2.5×10^{-4} (d)	non det.
H_2	0.03-0.1	0.1	10×10^{-2}	20×10^{-3}	1.0 (e)	0.1
CH_4 + hydrocarbons	0.01	0.1	3×10^{-2}	6×10^{-3}		non det.
A	0.01	0.01	2×10^{-2}	4×10^{-3}	1.0 (f)	non det.

a. "Thermal Gas Analyzer" — General Electric Company

b. "Type C Oxygen Indicator" — American Instrument Company
"Oxygen Indicator" — Mine Safety Appliance Company
"Oxygen Indicator" — Air Reduction Company
"Oxygen Indicator" — Beckman Laboratory

c. "Photoelectric CO Detector" — University of Virginia
"CO Indicator" — National Bureau Standards
"Infra-red analyzer" — Baird Associates, Cambridge, Mass.

d. "Water Vapor Indicator" — American Instrument Company
"Dew Point Recorder" — General Electric Company
"Infra-red Spectrometer — E.I.duPont de Nemours & Co.

e. "Thermal Gas Analyzer" — General Electric Company

f. "X-Ray Photometer" — General Electric Company

SECRET

DECLASSIFIED

SECRET

TABLE XVII

METHODS OF HELIUM PURIFICATION

METHOD	MANUFACTURER	REMARKS	REFERENCE
	GENERAL PURIFICATION		
Activated Charcoal	To be determined	Method recommended	(29)(30)(31)(32)
Dryer & Activated Copper	Air Reduction Sales Company	Does not remove CO	
Uranium Metal	Used for laboratory clean-up of inert gases	Removes nearly all impurities	(33)
Ca,Li,Na,Mg.Metals	Used for laboratory clean-up of inert gases	Removes most impurities	(29)(31)(33)
	REDUCTION OF RADIOACTIVITY		
Activated Charcoal	To be determined	Recommended	(25)(34)
Diffusion Cascade		Proposal of using cascade similar to K-25 type	(35)
Absorption in Fats		Suggested method for cleanup of fission products	(36)
	DEHUMIDIFICATION		
Electrodryer	Pittsburgh Electrodryer Pittsburgh, Pa	-105° dew point	Manufacturers Literature
Activated Alumina	Aluminum Ore Company E.St.Louis, Mo.	-105° dew point	Manufacturers Literature
Florite Dessicant	Floridin Company, Inc Warren, Pa.	-105° dew point	Manufacturers Literature
Silica-gel	Davison Chemical Corp. Baltimore 3, Md.		Manufacturers Literature
Solution 17A	Dow Chemical Company	Soln.of LiBr,CaBr $CaCl_2$ dries to -40°F	Manufacturers Literature
Propionic Anhydrite P_2O_5 Charcoal Resin #1124	DuPont deNemours & Co.	Miscellaneous drying agents suggested by the DuPont Co.	Manufacturers Literature

SECRET

DECLASSIFIED

11. Power Generating System

a. Introduction. In selecting the type of power generating system to be used, the possibilities of using a gas-turbine-cycle system instead of a standard steam-cycle system were considered.

The main consideration which led to the choice of the steam power system for this plant is the reliability of the steam plant over the gas turbine plant in the present state of development. It was felt that since it is the power pile that is to be tested every effort should be made to use for the power generating system, equipment whose reliability can be assured at the present time.

During the summer of 1946, the U.S.Navy offered the propulsion machinery from one of their DE-51 Class Destroyed-Escort Type of Naval vessels to the Power Pile Project for use as power generating equipment contingent on its adaptability to land installation. After inspection of the equipment on board of one of the ships, it was decided that the machinery was suitable for conversion to land installation with comparatively minor modifications to such things as the turbine governing mechansim and the condensing equipment. It was realized also that this equipment would have to be supplemented with additional items for efficient conversion. The necessary installation drawings and specifications for this machinery, together with preliminary inquiries and specifications on other items of power plant equipment necessary for conversion are now on file at Clinton National Laboratories.

b. Pile Load and Energy Dissipation: The heat energy of the pile is converted to useful electrical energy by a standard power generating equipment and hence conducted into the Tennessee Valley Authority power transmission system through appropriate substations. It should be pointed out at this time that insofar as studying the action of the pile under varying load conditions is concerned there is an alternate of simply generating steam and condensing in suitable condensers, rejecting the heat of condensation to the cooling water, and returning the condensate to the boiler for repetition of the cycle. However, while this method would dissipate, satisfactorily, the heat from the pile, it would not satisfactorily prove the feasibility of generating electrical power from nuclear reactors to the public, nor would it show practically how a power pile would react to changes and surges of electrical energy in an actual system.

The final design of the power generating system is a combination of both of the above methods of energy dissipation. Under initial operating conditions, the pile would operate at long periods under low loads and the energy produced would be dissipated to the cooling water. Later, as operating experience is accumulated and higher powers are generated, the energy produced would go to the electrical power system. In addition to the above feature, the presence of extra condensing equipment in the plant furnishes an added safety factor since there is always equipment to absorb surges of power over the design capacity of the installation and should the steam prove dangerously radioactive, to prevent radioactive contamination of the surrounding territory by keeping the steam in a closed system.

DECLASSIFIED

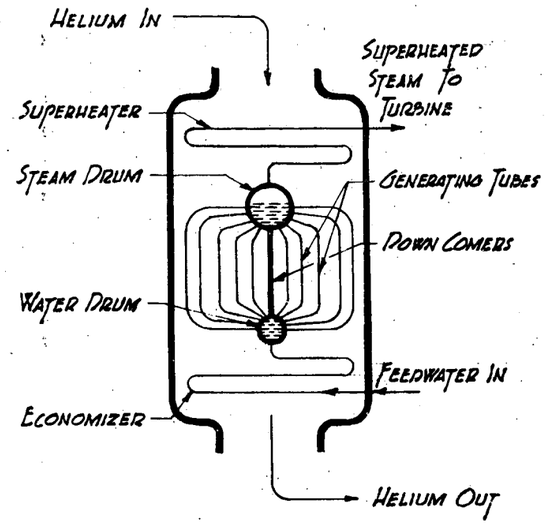
c. Space Requirements for Power Generating Equipment. Aside from building facilities for the pile and control equipment, the boiler, chemical separation, shops, miscellaneous laboratories, change houses, etc. the space requirements for the power generating equipment alone are as follows. The main turbine-generator units, auxiliary turbine generator units including the helium blower excitation sets, motor-generator sets, main switchboard, condensing equipment and pumps, circulating water pumps and auxiliary accessories are to be located in a permanent type of building separated from the pile building in order to reduce the number of personnel who might be exposed to helium leakage in the gas stream to a minimum in case of accident.

This building should consist of two-stories with the upper story containing the generating equipment, switchboards, etc. The minimum floor-space for this equipment has been estimated to be 35'-0" by 70'-0". Directly below, there is a similar size room for condensing equipment and auxiliaries. To one side of the condenser room, a pump-room of about the same dimensions is located and contains the circulating water pumps. The roof of this room would be a suitable location for the emergency condensers and/or other equipment which is to be located outside the building. Adjacent to the pump-room, a space of about 120'-0" by 60'-0" should be allowed for the erection of cooling towers. An outdoor switchyard is located adjacent to the plant and should require a space of about 60'-0" by 100'-0". A space of about 50'-0" square should be reserved for erection of a stack which should extend upward to the inversion layer of the atmosphere to dissipate any radioactive products which are discharged from the plant.

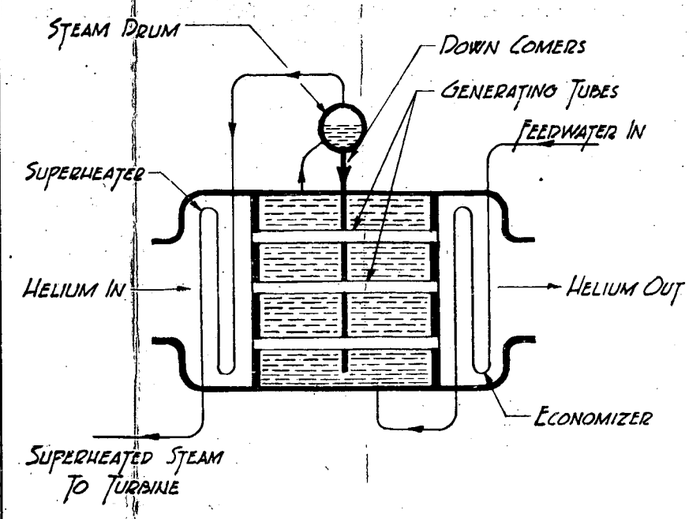
d. Radioactive Contamination of Steam. It has been estimated that the activity of the steam in the system will not be in excess of 1 or 2 duries. (See Part 9 of this Section). This activity can be tolerated in the boiler-turbine system without exceeding the prescribed tolerance (1/10 Roengten per 8 hour day) at a distance of 3 feet from a steam main or turbine provided the boiler helium shell is entirely shielded. This is sufficiently in excess of the anticipated level of activity that no special provisions need be made for shielding the steam mains and turbines. After the plant is in operation, an actual survey of activity can be made to determine radiation levels at points closer than three feet and to prescribe time limit of exposure if such precautions are found to be necessary.

Steam pipings would, therefore, in general be placed such that the prescribed distance from normal contact is at least three feet. Those pipes, valves, turbines and other equipment which cannot be so placed would be guarded by a railing around the turbines or extension stems on the valves. Packing glands or steam joints which cannot be prevented from leakage by normal maintenance should be hooded to conduct the vapors outside of the building. Since the activity of power equipment through which the cooling water from the Clinch River must flow is not excessive, raw water as taken directly from the river would be sufficiently pure for cooling purposes. However, there may be locations(such as water biological shielding)around the plant in which a relatively high activity may exist, and for these locations a closed cycle type of cooling system is recommended. This type of system would use demineralized water, to keep induced activity to a minimum, circulating in a closed cycle with the heat to be dissipated rejected by means of heat exchangers to the raw water from the river. Thus, the tendency to scatter radioactive material around the surrounding territory would be eliminated.

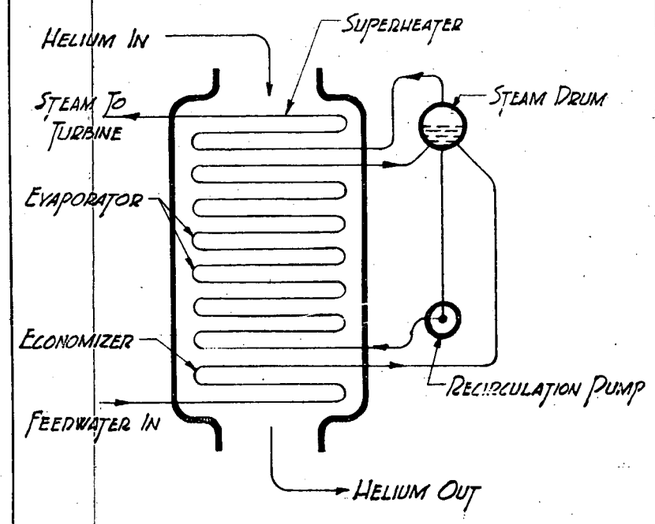
DECLASSIFIED



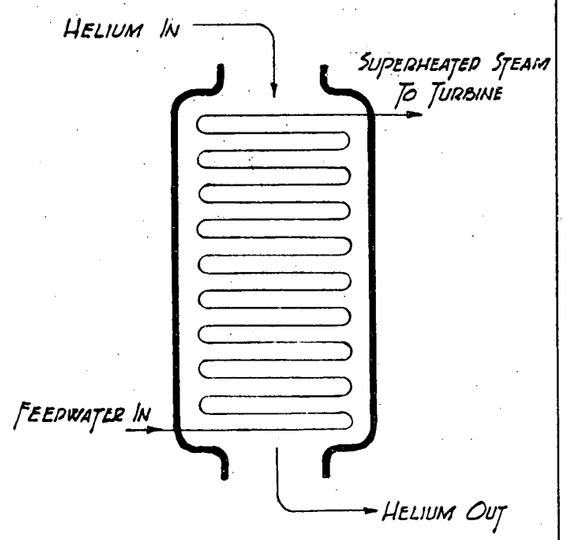
Natural Circulation
Water Tube Type



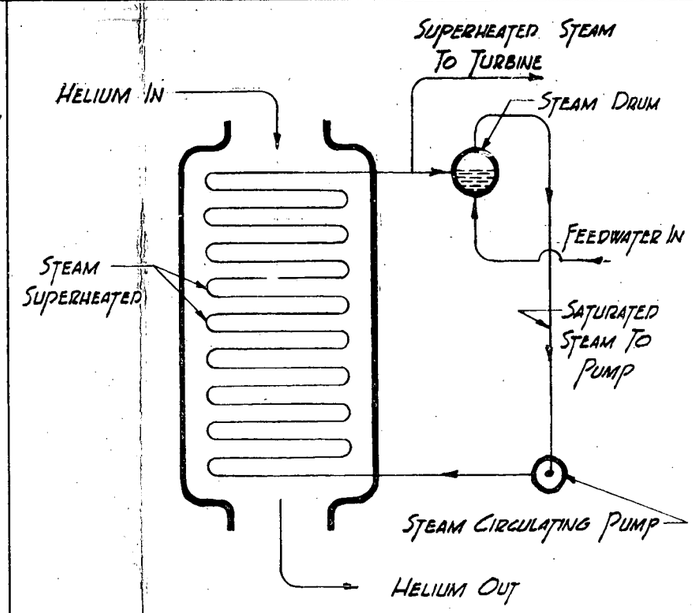
Natural Circulation
Fire Tube Type



Forced Recirculation Type



Once Through Type



Loeffler Type

Fig. 91

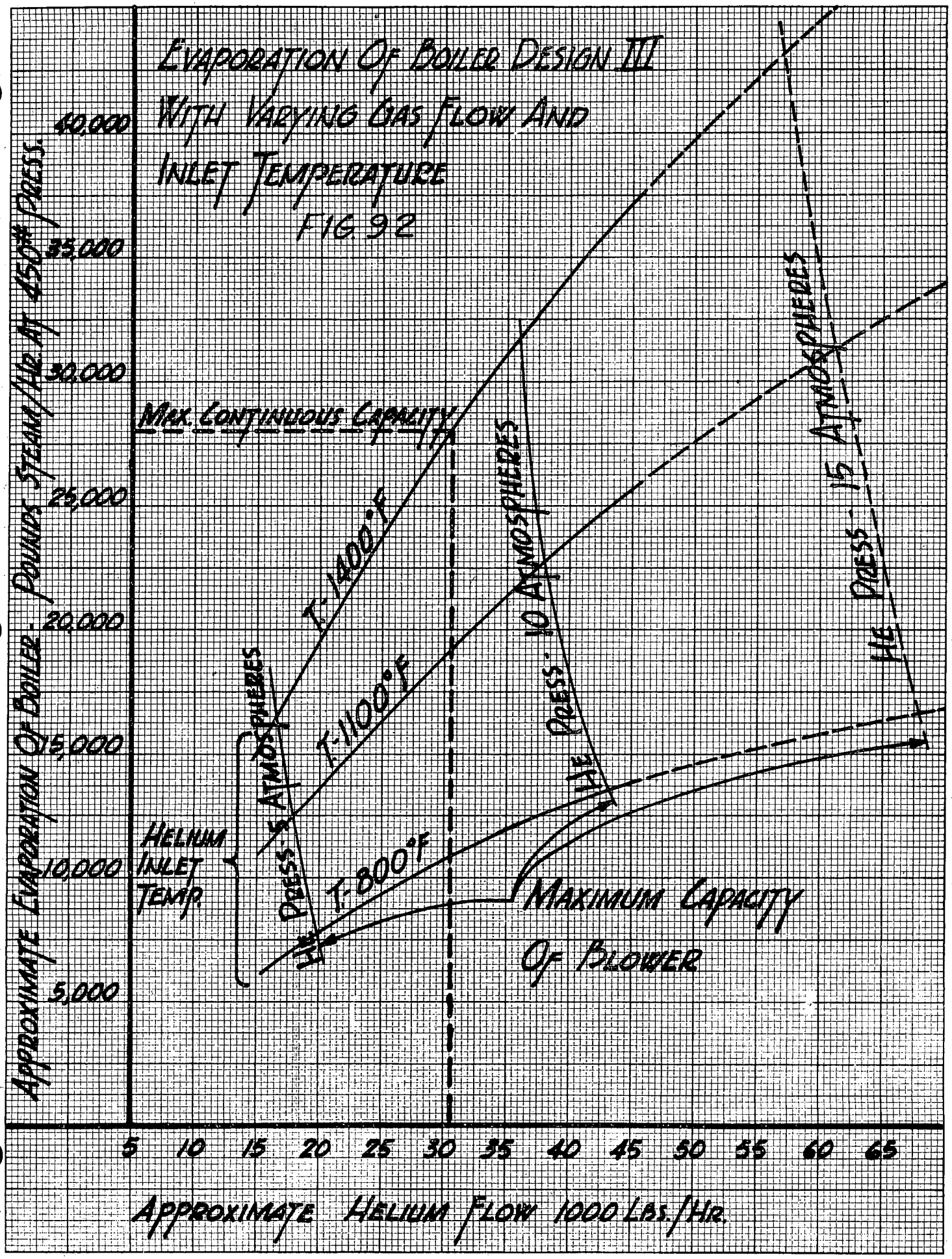
Diagrammatic Arrangement of Type Boilers

High Temperature Gas Cooled Power Pile

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D 8-8-47	C.N.L.	C 9/8/47	A.L.S.	A 9/15/47	R.E.P. 9-15-47	
Prev. C-222M						
SCALE: None						C-2281

DECLASSIFIED
DECLASSIFIED
DECLASSIFIED



DECLASSIFIED

Performance Of Boiler For Design III With Varying Operating Conditions With Helium Flow Constant At 32600 Pounds Per Hour

Fig. 93

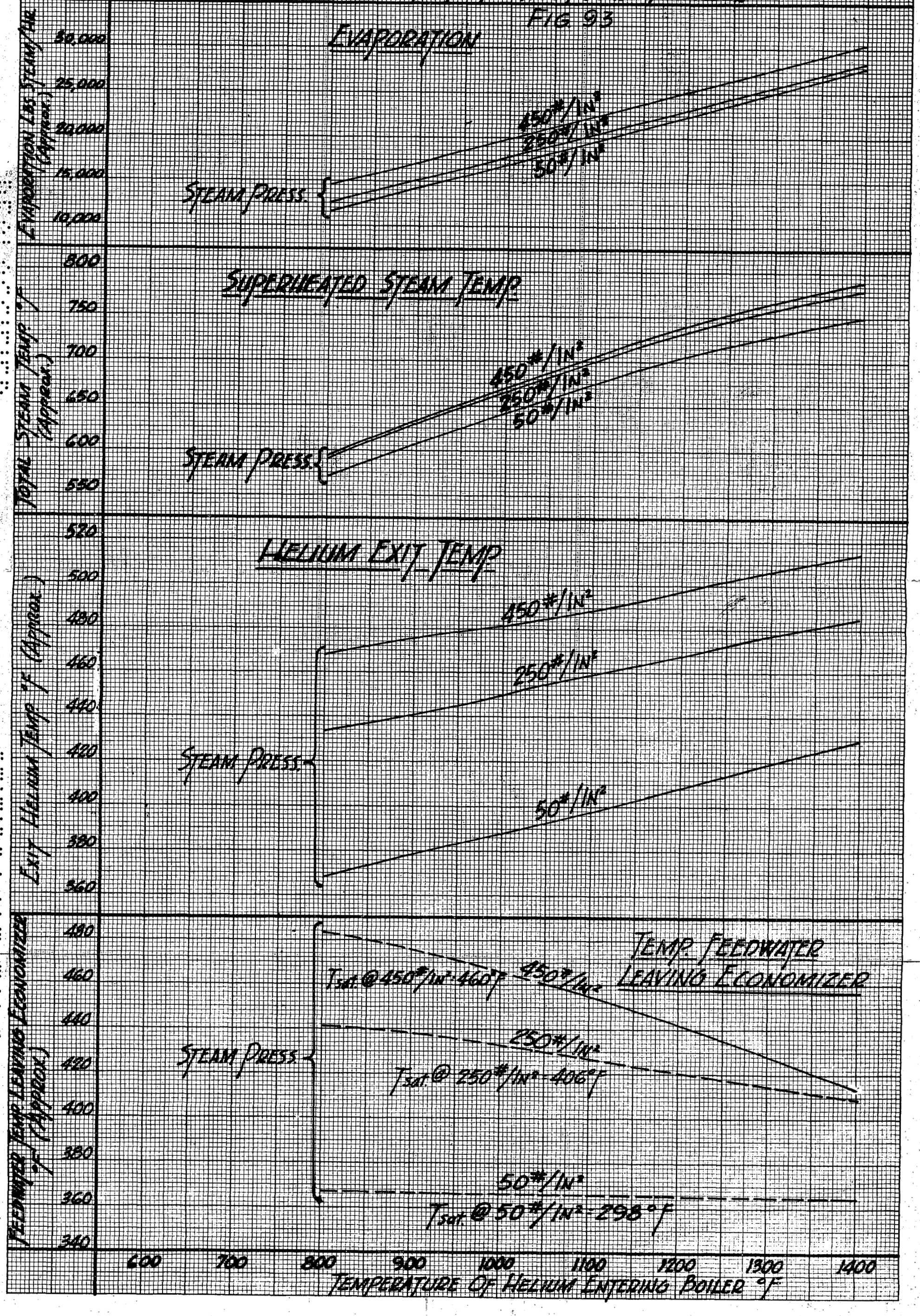
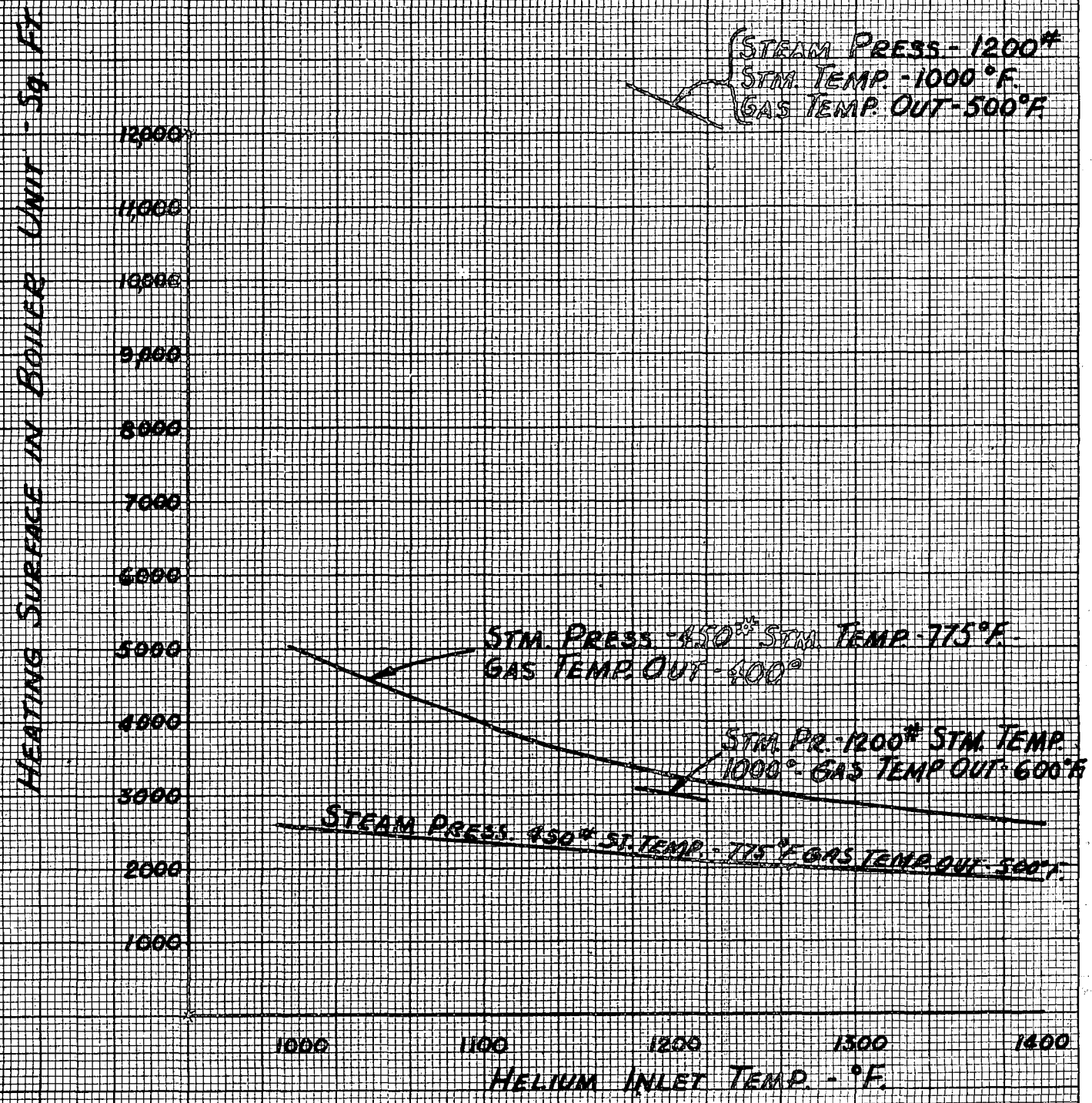


FIG. 94

HEATING SURFACE REQUIRED IN BOILER UNIT VS. VARYING HELIUM INLET TEMPERATURE AND VARYING STEAM CONDITIONS.



DECLASSIFIED

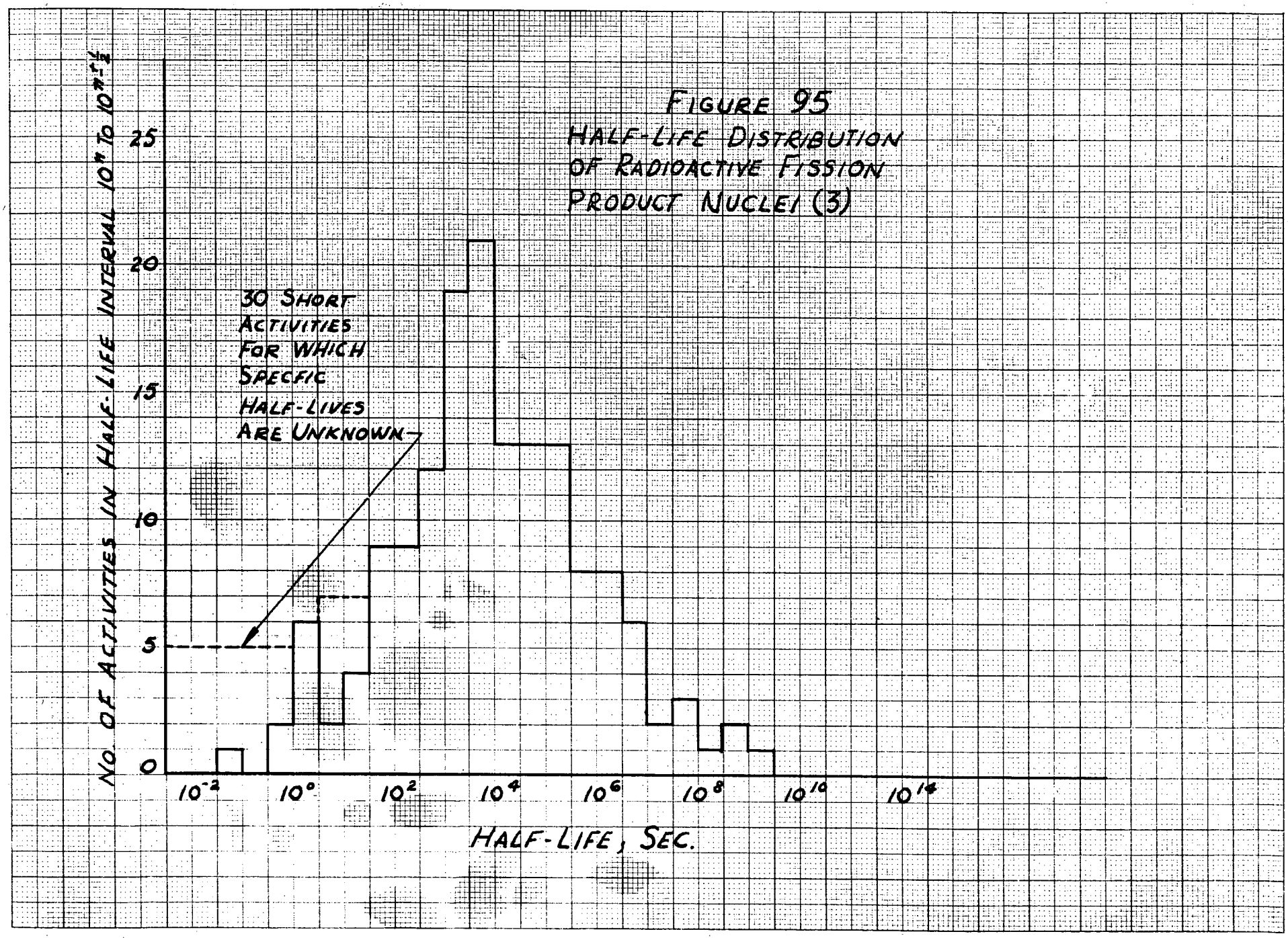


Figure 95
Half-Life Distribution of Radioactive Fission Product Nuclei (3)

SECRET

LIST OF REFERENCES FOR PART F OF SECTION V

1. Nuclei Formed in Fission: Decay Characteristics, Fission Yields and Chain Relationships Issued by Plutonium Project. Journal of American Chemical Society 68 2411-2442 (1946)

2. Description of an "Average Fission". K. Way, MonP-192, Dec. 10, 1946

3. Notes from Seminar in Nuclear Science and Engineering, M.I.T., Cambridge, Mass. 1947. Page 376

4. Diffusion of Fission Products from Beryllia Fuel Rod Material, J. E. Wilson, CT-3765, Jan. 17, 1947

5. Calculation of Levels of Radioactivity to be Expected in Coolant of the Power Pile, M.A.Swarthout to C.R.McCullough, Jan. 15, 1947

6. Effects of Radiation on Solids, S.Siegel, Pile Technology Lecture 33

7. Effects of Radiation on Chemical Compounds, A.O.Allen, Pile Technology Lecture 34

8. Effects of Radiation on Physical Properties of Lubricants in the Daniels Power Pile. W.C.Saeman to C.R.McCullough, Nov. 14, 1946

9. Summary of Tests Showing the Effects of Radiation on Electrical Insulation. W.C.Saeman to C.R.McCullough, Jan. 12, 1947

10. Clinton Laboratories Process Manual, Section 13, Materials of Construction

11. ANL-OCS-75

12. Calculation of Activity Expected in the Steam and Boiler of the Power Pile. W.C.Saeman to C.R.McCullough, Mar. 10, 1947

13. Calculation of Activity Expected in the Boiler Water Impurities Resulting from Absorption of Delayed Neutrons from Fission Products Circulating with the Coolant. W.C.Saeman to C.R.McCullough, May 20, 1947.

14. K-25 Report No. A-3696-3.121.1 dated 2-25-47. "Results of Tests of the Preliminary Bearing Seal Model" by W.F. Boudreau.

15. Memo 3/4/47. J.V.Fitzgerald to C.R.McCullough. File #406

16. Memo 6/23/47. J.V.Fitzgerald to E.B.Ashcraft. File #406

17. Memo 11/12/46. A.L.Preston to D.D.Streid. File #406-1

18. MUC-CAH-46. 6/25/46. Volatilization of Uranium from Fuel Rod Material by C. A. Hutchison, and V.G.Malm

19. ANL-CAH-9. 8/28/46. High Temperature Pile Reactions by C.A.Hutchison

- continued -

SECRET

DECLASSIFIED

LIST OF REFERENCES FOR PART F OF SECTION V (cont'd)

20. ANL-OCS-87. 11/13/46. Pile and General Chemistry for Week ending 11/13/46. C.A.Boyd

21. Memo. 4/14/47. J.V.Fitzgerald to C.R.McCullough. File #406,

22. Memo. 4/14/47. J.V.Fitzgerald to F.Daniels. File #406.

23. Letter. 8/21/47. F.R.Balcar to J.V.Fitzgerald. File #406-2

24. Memo. 7/3/47. J.V.Fitzgerald to E.B.Ashcraft. File #406-1

25. Memo. 5/8/47. J.V.Fitzgerald to C.R.McCullough. File #406

26. CT-3765. 1/17/47. Diffusion of Fission Products from Beryllia Fuel Rod Materials. by J.E.Wilson

27. CC-327, CC-390, CC-594, CC-616. Diffusion of Fission Products from Cast Uranium. by A.L.Voigt.

28. Memo. 6/23/47. J.V.Fitzgerald to E.B.Ashcraft. File #406

29. Memo. 3/27/46. F.C.McCullough to File

30. Hanford Manual

31. "Formal Report on the Purification of Helium Gas" by E. Fields and A.J. Wells. Contract No. NOa(s) 343. E.I.duPont de Nemours & Company

32. "Operating Manual" 150 lb. H.E.P. Unit by W.W.Hurt. Memo Report G-135 E.I. du Pont de Nemours & Company

33. Lecture. 2/10/47. No. 19 S.S.Katz

34. Report MonT-221

35. Memo. A.L.Preston to C.R.McCullough 2/27/47. File #406

36. Memo. C.R.McCullough to E.B.Ashcraft 2/5/47. File #406

SECRET
DECLASSIFIED

G. FUEL ELEMENTS

Heat is generated in the pile as the result of fission of the fuel, i.e., uranium, enriched to 30 percent U^{235}. As shown in Section III, the removal of this heat from the pile requires a relatively large heat transfer surface. The volume of U^{235} in this, as well as in other thermal piles using enriched uranium as fuel, constitutes less than .02 percent of the volume of the entire pile. For this reason, it is necessary to distribute the uranium throughout the pile in such a way as to provide an extended heat transfer surface, maintain sufficient mechanical strength, and provide heat storage capacity to absorb accidental swings of heat output without excessive temperature fluctuations. This can be accomplished by dispersing the fuel uniformly in a relatively bulky matrix material to form a fuel element.

In addition to its function with relation to the heat transfer problem as described above, the fuel elements for the pile design described herein also serve as a means of introducing fissile material into the pile and allow removal (as a unit) of the depleted fissile material, and the fission products when chemical processing becomes necessary.

In the development of fuel elements for the high temperature gas-cooled pile described in this report, matrixes of beryllium oxide, beryllium metal, and graphite have been considered. These materials have been chosen because they possess the following desirable characteristics:

(1) Physical properties suitable to the conditions of operation, including refractoriness and resistance to thermal rupture.

(2) Low capture cross-section for neutrons.

(3) Capacity for slowing down fast neutrons.

(4) Satisfactory fabricating properties.

Other properties desirable for matrix materials and possessed in varying degree by the materials chosen are:

(1) High resistance to deterioration of physical properties under the influence of neutron bombardment and fission product recoil.

(2) Susceptibility to separation from uranium in reprocessing.

(3) Impermeability to fission products or susceptibility to canning.

(4) High mechanical strength and resistance to abrasion.

(5) Chemical stability.

DECLASSIFIED

SECRET

The development of fuel elements has proceeded along general lines as much as possible consistent with the flexibility adopted in the pile design investigations. Early in the program, emphasis was placed on the rapid development of a unit suitable for initial operation of the pile at low power levels as a minimum objective. Thus, the early program was of a short range nature and the fuel element designs described in Section IV represent the results of this work. Later in the project a more extensive and long range program was conceived, and it is that program on which major emphasis is placed in the following discussion.

1. Design Restrictions.

The general interrelation between fuel element design and heat transfer (power removal) and physics considerations has already been discussed briefly in foregoing sections, particularly Section III. Briefly, that discussion showed the following: The heat generated in the fuel unit must be transferred to the gas or coolant and, hence, out of the pile. In order to so transmit this heat, there must be a difference in temperature between the interior and surface of the fuel unit. The gradients in the temperature field thus established will cause differential thermal expansion of the materials. This differential expansion introduces thermal stresses which may cause fracture if not alleviated by plastic flow. Transfer of the heat from the fuel unit wall to the gas requires a certain amount of surface in order to keep the maximum temperature of fuel unit below a maximum permissible value for a given gas temperature. The possibility of going to larger and larger and alrger surface-to-volume ratios to decrease the temperature difference and increase power output is limited by allowable pressure drop. Increasing the surface-to-volume ratio results, in general, in decreasing the hydraulic radius of the gas passage and, therefore, increases the pressure drop. The limiting or allowable pressure drop is determined by the percent of a total power output which can be allocated economically to the blowers.

Additional factors imposin.g restrictions on the design are the chemical processing and fuel handling requirements. As noted in the Materials Section of this report, neutron and gamma ray bombardment and fission product recoils may adversely affect the matrix material. This damage is a function of both radiation intensity and time. Accumulation of the fission products "poisons" the pile as the fuel is depleted. This poisoning, along with depletion of the fissile material and bombardment damage, determines the operational life of the fuel element and the time at which chemical processing becomes necessary. Both chemical processing and the associated problem of introducing and removing the fuel influence the selection of the shape and matrix material of the fuel element.

The pertinent restrictions imposed by the reactor design and the coolant conditions described in Section IV are as follows:

(1) Channels are to be 2" diameter round hole.

(2) The minimum diametral clearance between concentrically located fuel units and channel walls is to be 1/16".

SECRET

DECLASSIFIED

SECRET

(3) The channel is to be a smooth hole and any guides or fins or spacers must be an integral part of the fuel unit.

(4) The peak nominal pressure of the coolant is to be 10 atmospheres and may be as low as 1 atmosphere.

(5) The pile inlet gas temperature is to be 500°F.

(6) The pile outlet gas temperature is to be 1400°F.

(7) The pressure drop through the pile is to be 2.5 psi.

In the following discussion of the problems associated with the development and design of fuel elements conforming to the requirements enumerated and described above, each of the matrix materials, beryllium metal, beryllium oxide, and graphite are considered.

2. Beryllium Oxide

a. Fabrication. Methods of fabrication which have been considered and explored for BeO are as follows:

(1) Hot Pressing

(a) $BeO-U_3O_8$ mixture yielding $BeO-UO_2$ unit by reduction, a one step process.

(b) Pre-pressing of mixture followed by hot-pressing, devised to reduce space and ram travel and insure more uniform density.

(c) Hot-pressing of pre-formed inert segments together with the powder mix to obtain controlled fuel deposition.

(2) Extrusion

(a) $BeO-U_3O_8$ mixture with organic plasticizer and water added is vacuum extruded under high pressure, then fired for the length of time and at the temperature required to yield the desired density and composition, $BeO-UO_2$.

(b) BeO powder with organic plasticizer and water added is extruded and fired in reducing atmosphere, then fuel is introduced by impregnation with uranyl nitrate and fired to UO_2.

(3) Dust Pressing

(a) $BeO-U_3O_8$ is dry pressed in molds, then fired to required density, resulting in a $BeO-UO_2$ body.

SECRET

DECLASSIFIED

(b) $BeO-U_3O_8$ is slip cast in plaster paris, dried, removed from mold, then ceramically fired.

The principle effort has been concentrated on hot-pressing and extrusion methods. A considerable amount of experimental work to expand the limitations and perfect techniques has been carried out by Battelle Memorial Institute on the extrusion process and by the Norton Company on hot-pressing. Because of liaison difficulties, arrangements are being made to have future hot-pressing experimental work done at Y-12 area.

Manufacturing limitations are complexity of cross-section and thinness of walls. Multiple cell structures having seven circular cells with wall thickness of the order of 0.10 inches are the most complex cross-section units of BeO yet produced by hot-pressing. Tolerances of ±.01 inches can be held. Feasibility of hot-press fabrication of units with inert ribs is being determined by attempts to join inert ribs and a tube in the hot-press operation. Hot-pressed units of densities varying from 67% to 98% of theoretical can be fabricated. Multiple cell structures having seven hexagonal cells with wall thicknesses of the order of 0.10 inches represent the most complex cross-section units manufactured by extrusion. Shrinkage on firing can be held to a predetermined value within 1% so that a tolerance of ± .01 inches on cross-sectional dimensions can be held. Ribs can be separately attached, following extrusion, by a "welding" operation using BeO or Beryl powder and a plasticizer.

Experiments are now in progress pointed at fabrication of units of a higher order of complexity. Units having a grid cross-section composed of unit cells 1/8 inch square and walls 1/32 inch thick are being attempted. Extruded units are being attempted at BMI, while hot-pressing of such units is being carried out at Y-12. Chief problem appears to be that as walls become thinner, particle sizes approach the same order of magnitude.

Residual stresses are inherent in hot-pressed units, with some elimination believed obtained by annealing. No residual stresses are encountered in units fabricated by the extrusion process. Effects of annealing on residual stresses in BeO bodies are not known.

Microscopic examination indicates preferred crystal orientation in both hot-pressed and extruded samples, the latter more pronounced. Preferred or orientation in hot-pressed sample is radial, while in the extruded sample it is axial. Additional information on properties of fabricated units is given in the Materials Section of this report.

b. Incorporation of Uranium in Fuel Elements. Two general methods of introducing the fuel have been considered: Impregnation of the ceramic body and homogeneous mixing of the fuel in powdered form with the BeO powder, followed by fabrication of the unit. Impregnation was attempted several years ago at ANL. A more elaborate program is being conducted here incidental to high temperature thermal conductivity measurements during irradiation in the X pile (See Materials). Impregnation is possible, but uniform disposition and firing to a stable form is uncertain. Units have been prepared from mixture of BeO and U_3O_8 powders by hot-pressing. Microscopic inspection indicates non-uniform disposition of agglomerated UO_2 particles. A thorough exploration of the problem is necessary.

DECLASSIFIED

c. Operational Criteria. The three criteria in the discussion to follow (physical stability, strength, and optimum power output) have been grouped together as operational criteria because of the interdependence of factors involved. Operational failure of BeO bodies as fuel elements occur by thermal stress rupture. The maximum possible power output of units of this material is determined by the relation of thermal stresses developed to ultimate strength. The stresses developed and the allowable stresses are a function of the shape of the element and the properties of the material.

(1) Stress Analysis. Development of shape and material for BeO fuel elements has proceeded along the lines of minimizing the applied stress and maximizing the allowable stress. The stresses developed in the fuel unit may be classified as:

(a) Stresses Attributed to Externally Applied Loads (such as weight of other elements, restriction of expansion, or supporting catches). Stresses in this class are unimportant when considering BeO elements because of their very high crushing strength (80,000 psi).

(b) Residual Stresses Imposed by Manufacturing Techniques These stresses are identified with the hot-pressing method, but not with the extrusion method. The magnitudes of residual stresses can conceivably be 100% of the ultimate stress. Attempts have been made to eliminate residual stresses by annealing, and some success has been attained. Complete elimination is improbable.

(c) Thermal Stresses Resulting from Differential Thermal Expansion. The principal work on BeO fuel units during the year has centered around this third class. The thermal stresses are a function of the physical properties of the material, the shape of the element, and the heat generation. Analysis of thermal stresses in fuel elements to enable comparison of such stresses with ultimate strengths involves determining: First, the spatial distribution of heat generation: Second, the associated temperature field: Third, the attendant deformations: Finally, the stress distribution.

Distribution of Heat Generation

The heat generation is a result of fission and, hence, a function of neutron flux. Although homogenity has been generally assumed to date in flux distribution studies for the development of the power pile, heterogeneity exists if elemental portions are studied. The fast flux varies from minimum at lattice center to a maximum at the fuel element where generated, while the slow flux distribution is reversed, being a minimum at the fuel element where maximum absorption occurs. A study giving these distributions is not necessary in the early design stages. Without appreciable error, flux density and, hence, the radial heat generation rate has been assumed uniform across the fuel element for preliminary work.

Associated Temperature Field

The temperature field is defined by a rate equation having two component terms which indicate temperature changes brought about

DECLASSIFIED

SECRET

by heat transmission and temperature changes arising from heat generation. Solution of this rate equation will yield the spatial variation of the temperature. Analysis of the temperature distribution in the fuel units of simple corss-section can be obtained if the problem is somewhat idealized. In the case of more complex cross-sections, a unique solution for steady state is impossible, and approximate analyses of any value are extremely time consuming. Within limitations, special computing machines will facilitate simple transient studies. Large variations in physical properties with time and temperature (characteristic of pile materials) along with asymmetry introduced by eccentric location of fuel elements in the channel occur to complicate the problem. For use in preliminary design work, simple logarithmic and parabolic temperature distributions have been assumed.

Deformation and Stress Distributions

Deformations in the fuel elements which give rise to stresses exist when the temperature field is not uniform and can be determined if the boundary conditions are simple. In the case of complex cross-sections approximate solutions of the deformation equations can be obtained with large expenditures of time. Knowledge of the relationship between stress and strain, even when Hooke's laws are inapplicable will allow conversion of deformation to stress.

It is evident that the purely analytical approach to the problem of evaluating resistance of fuel elements to thermal rupture is inadvisable because of the time, cost, and manpower tie-up and the unreliability of results. Some detailed analytical comparative work such as studies of fillet types might be profitably carried out to obtain qualitative results. Simple analysis for preliminary design has been based on the relation $E\alpha\Delta t f$ where E is Young's Modulus, α the coefficient of expansion, Δt a temperature difference, and f a form factor.

(2) Evaluation of Merit of Fuel Element. Two examinations of fuel elements must be made to arrive at a merit evaluation. The first examination determines the maximum allowable power output of the rod, while the second examination discloses the allowable power absorption of the coolant. The power at which output equals absorption is the rated power of the unit, and hence of the pile.

(a) Maximum Power Output of Element. The limiting power output of a BeO fuel element is that at which the element ruptures under thermal stress (or combination of the three classes of stress indicated earlier). This limiting, or maximum allowable, power output is a function of the physical properties of the material and the geometry of the cross-section (not considering axial variation). In effect, then, it may be expressed by the product of a material factor (F_m) and a shape (F_f). Because test facilities are not available for its direct determination, the material factor is separated into two components; one being

SECRET
DECLASSIFIED

SECRET

a factor indicating resistance of unirradiated material to thermal rupture (F_r), the other being a factor indicating reduction in resistance to thermal rupture brought about by irradiation damage (F_i).

Thermal Rupture Resistance Factor (F_r)

To determine F_r for unirradiated material, a standard specimen which is a radially symmetrical tube having thick walls (1 1/2" O.D. x 1" I.D.) is used. The heat is put thru the material instead of being generated in the material. Conversion to absolute values of allowable heat output of the element for the case where heat is generated in the material can be made by calculating the form factor for the two cases and multiplying test results by the ratio. A figure of merit is obtained by calculating the ratio of F_r for the material chosen as standard (e.g., hot-pressed BeO of a given density), both at a chosen temperature. Three of the standard specimens of the material to be investigated are strung on a carbon tube heating element. Power is supplied electrically and converted to heat by electrical resistance. The voltage drop in the heating element between the ends of the center tube is measured and the surface temperature is obtained by means of an optical pyrometer. It is assumed that all heat developed along the heating element between ends of the center specimen must pass through the specimen radially because of the masking effect of the end specimens. The voltage drop across the cylinder, for a known current will then quite accurately indicate the heat flow thru the specimen. Because some materials to be tested may react with air, a controlled inert atmosphere has been adopted. To control surface temperatures within limits, the inert gas has a metered flow. Thus the test is not dependent on the vagaries of natural convection cooling. Radial symmetry of test conditions is established so that consistent results can be obtained. Additional shielding is available to facilitate tests at very high temperatures if desired. "Pilot plant" apparatus has been arranged to demonstrate the general feasibility of this type test and several runs have been made. An integrated design of the apparatus is being worked out.

Irradiation Damage Factor (F_i)

Lack of test facilities prohibits testing which will give the overall material factor directly and makes necessary separation into two factors. For complete results it is desirable to have tests in which sufficient data is obtained to develop a family of three dimensional surfaces. The three dimensions constitute one class of variables (material factor, irradiation time and flux, temperature). The family parameter is a material function of another class of variables (structure, method of fabrication, density, composition). It is necessary

SECRET

DECLASSIFIED

to take measurements while the sample is actually under irradiation at the desired temperature if quantitative data is desired. In practice this is not possible at present, for it would require a high temperature, high flux pile as an experimental facility or hot facilities in other piles. The next best alternative to actually conducting the material factor test under simultaneous irradiation and temperature conditions is to irradiate the sample, at the desired temperature, conducting the thermal rupture resistance factor test after removal from the pile (temperature is obtained in the pile by self-heating due to presence of fissionable material). This type of test is discussed in the following section on Materials. Even an overall test of this kind is likewise impossible with existing facilities. The best that can be done is to examine changes due to irradiation of the fundamental physical properties pertinent to thermal rupture resistance.

As stated above, investigation of materials for use in piles differs from other material applications in that an additional primary variable must be introduced, namely irradiation. So to completely investigate fundamental physical properties, the number of tests required is tremendously increased. However, before irradiation tests are made every attempt should be made to cut down on the number of such tests which are required by trying to obtain material which is satisfactory from all standpoints before checking irradiated properties. All the known data from tests of BeO is recorded in the following section on Materials. The dearth of information evident on inspection strongly emphasizes the fact that additional information is required. To obtain the required fundamental data for proper engineering of fuel units for a power pile, a long range, long time program is in order. The investigation procedure followed is to obtain data completely defining each of the unirradiated properties which make up the factor F_r. Next, irradiated samples are tested. The test temperatures of the unirradiated samples is kept the same as the temperatures reached by the irradiated sample. Values of a theoretical form of F_r are calculated from both sets of data, and the value of F_i is obtained by ratio.

The question of value and accuracy of F_i so obtained can be discussed qualitatively: The effect of healing of irradiation damage by temperature is not included, so that results may be pessimestic. For accuracy, the equilibrium damage factor should be obtained. For certain properties, there is some chance of attaining this by incorporating self-heating and temperatures measurements within the pile. None of the experiments allow distinction between the damage suffered under fast neutron bombardment and that incurred by fission product recoil. Such separation is essential if it is desired to extrapolate results for use on a pile design different from that in which the tests are being run. The thermal flux is not proportional to the fast flux in a given pile, nor are the neutron energy

DECLASSIFIED

SECRET

spectrums the same for different piles. This then denies an accurate simple relationship of exposure time of samples and thermal flux densities for the test pile and the pile being desired.

Shape Factor (F_f)

Using the standard specimen devised for material factor tests, the material factor is obtained for a standard material (which is a semi-conductor, having a low or zero temperature coefficient of resistance, a low resistance to thermal rupture, and good machineability or formeability). Specimens are then prepared from such a material in the image of any cross-sectional shape to be evaluated. An electric current is passed through the specimen which heats up, simulting uniform heat generation of the type expected in an actual element. The heat input can be accurately measured. The test is run to obtain the power output at the instant of thermal rupture. By proper shielding, use of a metering orifice in the chemically inert coolant stream, and provision for eccentric location of the specimen in the channel, operating conditions may be closely simulated.

Because of the nature of the standard material, results are obtained on a statistical basis, using 15 samples per test. Preliminary tests are run on the standard shape chosen for the material factor tests in order to have a standard for comparison. Ratios between the standard test results and those of the specimens being studied will provide a shape figure of merit. Absolute values of F_f are obtained by multiplying the shape figure of merit by the F_f for the standard shape.

Studies of a number of materials are made to determine the one most suitable for such tests. The value of F_r is used as a criteria for comparing the resistances of the proposed standard materials to thermal rupture. Considerable data on BeO-graphite mixtures as semi-conductors indicates a value of F_r of the order of 500 Btu/hr.ft. The specific resistance indicates that if this material is used, the power and voltage requirements are undesirably high for laboratory work and would require expensive apparatus taking a considerable time to design and construct. The order of magnitude of F_r sought is 10 Btu/hr.ft.. Techniques of preparation of sample and high negative temperature coefficients of electrical resistance make choice of the standard material difficult.

To enhance the value of such shape factors tests and aid in pointing the way to design of more propitious shapes by comparison, an augmenting program of analytical and experimental stress analysis has been planned. Contract proposals have been submitted by Westinghouse, but have been held up pending classification of the Power Pile Division program.

SECRET

DECLASSIFIED

(b) Maximum Power Absorption of Coolant If the shape of the element and temperature-pressure-velocity conditions of the coolant are unfavorable, the maximum permissable output of the element cannot be utilized. After determining the material and shape factors, the relation of maximum permissable power output of the element to the temperature of the element is known. Some value of this relation corresponds to the maximum allowable heat transfer ability of the coolant. The power rating of the element is thus given by the intersection of the curves. One curve is a plot of maximum fuel element power output versus temperature. The other is a curve of maximum coolant power absorption versus temperature. Relations for obtaining power absorption vs. maximum fuel element temperature are given in Report Mon 299. Essentially, the maximum temperature of the fuel element for a given power absorption is obtained by:

1. Calculating pile output for various value of heat transfer from element at pile center.

2. Calculating the temperature difference between pile material and gas at the center of the pile.

d. Impermeability Because of the nature of the piles considered during the year, no "canning" requirement was imposed on fuel unit development. "Canning" of the units to render the surface impervious to fission products is considered desirable but not essential. Only ceramic coatings have been given consideration thus far. A program is being planned in conjunction with the ceramists at Battelle Memorial Institute but has not yet materialized.

e. Neutron economy In considering materials and processing of fuel elements, neutron economy is a predominant factor. Beryllium, oxygen, and carbon (when pure), have exceedingly low cross-sections for capture of thermal neutrons. This makes them valuable as materials for fuel element matrices. The inclusion of any adulterant or admixture markedly raises this capture cross-section. Thus any intended or natural inclusions must be carefully considered. The improvement in adherance to other criterion realized must be balanced against the penalty paid in non-productive capture of thermal neutrons. As an example, 3%. addition of Al_2O_3 to BeO will increase the volume absorption by 28%. Such increase may seriously curtail conversion characteristics.

f. Development of materials As noted briefly before, work on developing materials has been pointed specifically at increasing resistance to thermal rupture. The means by which this increase is to be realized are considered to be the following:

1. Increase the thermal conductivity so that heat flow may be realized with smaller temperature gradients.

2. Increase the plastic flow characteristics to give maximum reduction in $d\sigma/d\epsilon$ with an attendant minimum reduction or possible increase in ultimate strength.

DECLASSIFIED

3. Reduce the coefficient of thermal expansion, i.e., $d\epsilon/d\Delta T$ so that deformations and hence thermal stresses will be less for given temperature gradients.

4. Evolve structures which will suffer minimum irradiation damage. At present, indications are that for BeO bodies, investigation of porous bodies rather than high density bodies, aggregates of large and small particle sizes rather than uniformly small particle sizes, impregnated bodies rather than homogeneous mixtures, and admixtures rather than the pure phase material will prove most fruitful. The trend toward lower density bodies conflicts with the desirability of high density from the standpoint of desirable nuclear physics characteristics of a moderator material, and it remains to be seen which will be the dominating factor for a given application. Background for investigation of porous bodies is of a statistical nature, and the guides provided by theories of solids cannot be used. Behavior of porous bodies seems unpredictable when one tries to correlate existing postulation with experimental results.

Recent work in the field of cerametallics indicates promising aspects of investigation of mixed BeO-Be bodies. Higher thermal conductivity and diffusivity as well as increased possibility of plastic flow can be expected from such oxide-metal mixes.

The facilities of Battelle Memorial Institute and of the Bureau of Mines Station at Norris are being utilized in carrying out the material investigations on the BeO phase. Work at the Bureau of Mines Station has just recently been started, while Battelle has had a large program going for over a year. Briefly, work at Battelle is devoted primarily to studies of all aspects of extruded beryllium bodies. Extensive experiments are being carried out on such bodies to determine physical properties in the temperature range 0-1000°C. The type of work being done at Norris consists of attempts to improve properties of BeO by varying particle sizes, types of powder, and porosity along with use of admixtures such as beryl, MgO, etc. Details of work at Battelle and at the Bureau are contained in formal progress reports and memoranda.

DECLASSIFIED

3. Graphite

a. General. Problems encountered in development of graphite fuel elements do not lend themselves to the same type of discussion employed in examination of BeO. Instead, discussion will be based on incorporation of fuel, operation, processing, and miscellaneous problems.

Graphite elements are considered to have one of the following structures:

Type 1. - homogeneous, having a solid mixture of fuel and matrix materials.

Type 2. - impregnated, having porous matrix with interspersed fuel;

Type 3. - heterogeneous, having a solid matrix with solid or powdered fuel regularly arranged in cells.

Experimental manufacture of the graphite bodies of structural type one indicates that any cross-sectional shape not too fragile for handling can be produced. Manufacture of the matrices for structural types two and three offers no difficulty. Past experiences on manufacture of articles having complex shape cross-sections for other fields indicate that limitations are outside of the requirements of fuel element design.

b. Incorporation of Uranium. Some trouble has been encountered in preparing specimens of type one in that conversion of the U_3O_3 to UC or UC_2 has not been regularly attained. The work on this is being done at Clinton Laboratories. A graphite unit in which the fuel is partially a carbide and partially an oxide is chemically unstable. Reaction might continue during operation with attendant gas evolution and possible destruction of integrity evidenced by crumbling. Such a condition could not be tolerated in a pile, and complete conversion to a chemically stable form is required before operation. The problem of developing techniques for impregnation of porous graphite to produce elements of type two has been solved. Experiments at Clinton Laboratories have succeeded in consistently obtaining uniform distribution of fuel in 2 cm. diameter samples with a concentration of 20% by weight. Work on the prepartion of an heterogeneous type three element has been carried out, but has been confined to a survey of data on properties of uranium carbide. The principal problem involved in preparation of this type three element is that of determining physical and chemical interrelations between the matrix and full inserts.

c. Operation. Failures of graphite elements in operation have been studied principally from the standpoint of thermal stress rupture, which would lead to the conclusion that the operational problems are the same as those for BeO. There are two factors which may alleviate the stress rupture problem, forcing consideration of the possibility of failure by change of state (vaporization) becoming dominant.

(1) In the normal state, graphite has an extremely high resistance to thermal rupture, of the order of 100 times that of BeO. When irradiated at low temperatures, however, the graphite appears to

DECLASSIFIED

suffer great damage. The physical properties are adversely affected so that pessimistic interpretation of meagre data indicates lowering of the resistance to thermal rupture to that of BeO after irradiation. Even less conclusive data indicate that this irradiation damage may be "annealed out" under high temperature. In fact, it is hoped that for high temperature operation the equilibrium value rate of dosage to rate of "healing" will be not greatly different from unirradiated values.

(2) The other alleviating factor is an indication that the stress strain curve for graphite does not have a constant value of slope from zero strains to failure, but that the slope is materially decreased at higher strains. This phenomenon, if indicative of plastic flow characteristics, should be progressively more pronnunced as temperature is increased. If this is the case, and a considerable amount of plastic flow is possible, strains arising from temperature differences would not be accompanied by high stress and failure by thermal stress rupture would not occur. In more detail, the following is of interest:

Past design applications of graphite have all been of such nature that stress-strain relations did not have to be considered. As a result, engineering design data of this type has not been sought by the companies working with graphite. The ultimate strength in tension quoted in project data was obtained from a tensile test in which intermediate stress and strain measurements were not taken. Similarly, the modulus of elasticity (E) valve used, i.e. the slope was obtained as a constant for low values of E. If one were to use this data indiscriminately, a straight line stress-strain diagram would be drawn having the equation $\sigma = E\epsilon$, and ending at intersection with the line σ = constant = ultimate strength. The strain corresponding to failure would be calculated by dividing the ultimate stress by E, and the temperature difference which produces such a strain would be simply obtained by dividing this strain by the thermal expansion coefficient.

One incomplete stress-strain diagram for graphite at room temperature has recently been prepared. Although it does not extend through the complete range to failure, the test represented by it was carried far enough to show reduction in $d\sigma/d\epsilon$ with increasing ϵ. If $d\sigma/d\epsilon$ is not actually constant but decreases with increasing strain, the temperature difference required to produce the strain corresponding to failure is greater. If these temperature differences are small compared to the mean temperature of the body, the $\sigma - \epsilon$ relation need only be obtained for a single temperature value. If not, a composite curve must be obtained by a series of tests covering the temperature range.

Reduction or localization of fission product recoil damage to isolated regions can be accomplished by use of the type three structure previously described. Not only would the damage be localized but it would occur in an extremely high temperature region where the greatest annealing and healing can be expected.

DECLASSIFIED

SECRET

As noted under the section on BeO, detailed discussion of properties of graphite and graphite mixes can be found under the section on material properties. Some additional work is in progress. Preliminary arrangements have been made for securing pieces of graphite which have experienced various irradiation times at Hanford. Such pieces are required for establishment of stress-strain relationship for study of plastic flow before and after irradiation and after annealing. Some specimens can be prepared for heat thru-put tests, which cannot be run on unirradiated graphite. Such data can be only qualitative, and connot include results of fission product damage.

Work is being done in developing a new field of testing by attempting measurements of thermal conductivity variation with irradiation at high temperatures on samples in a pile. All of the difficulties of the techniques involved have not been resolved as yet. Initial work is on impregnated graphite samples and hot-pressed BeO samples. Other types of samples include impregnated BeO and Be-U alloys. As mentioned previously, impregnation studies on graphite were successfully carried out incidental to this program. Details of this work are to be found in Materials section of this report.

Attempts to obtain material figures of merit for graphite force consideration of the fact that heat thru-put apparatus is incapable of causing rupture of unirradiated graphite specimens. The highresistance to thermal rupture requires power above the capacity of the heating element. To evaluate resistance to thermal rupture then, fundamental physical property tests must be resorted to. Data from these tests before and after irradiation will allow calcualation of reduction in power rating. This maybe correlated with heat thru-put tests on irradiated bodies if great damage is realized.

d. Processing. Chemical processing of graphite fuel elements is discussed in detail in Section IV. It might be pointed out here, however, that consideration of the use of a graphite matrix with UC-graphite powder or solid mix inserts will greatly alleviate the chemical processing problem. Not only will smaller amounts of material and shorter cooling off periods be involved, but the matrix can be reused after a short waiting period.

e. Miscellaneous Problems

(1) Canning. The problem of retaining fission products and fuel in graphite has been explored in view of the desirability of cutting down activity on the system outside the reaction and loss of fuel. In addition, control problems indicate undesirability of release of fission fragments which are delayed neutron emitters.

Systems for obtaining the desired degree of impermeability can be classified as follows:

(a) metal coating

(b) ceramic coating

SECRET

DECLASSIFIED

(c) repeated impregnation and graphitization with pitch

(d) metal jacketing

(e) discrete disposition of fuel

The generalized notes on canning investigations given in discussions of BeO bodies apply in this case also. Work on impregnation and graphitization has been carried out at Clinton Laboratories. Results show that any desired degree of impermeable surface can be obtained. The type of permeability tests used here do not prove resistance to diffusion and penetration of solid and volatile fission products. Metal jacketing involves the possibility of placing the graphite-UC mix in a tight fitting steel jacket. This scheme requires consideration of relative thermal expansions, pressure build-up, and stresses. A tight fit is required to allow heat transfer at reasonable temperatures. The use of a graphite matrix with solid or powdered fuel inserts is a very promising possibility for canning. The graphite matrix can be rendered impermeable by impregnation and graphitization. Even without this, fission fragments which are delayed neutron emitters can be retained until the neutrons are released because of the relatively great distance from point of fission to the surface of the rod.

4. Beryllium.

Fuel elements using beryllium metal as the matrix material fail at high temperature by change of state, i.e., melting or volatilization with the additional possibility of failure under thermally induced strains, i.e., creep failure. The latter type of failure is improbable because of plastic flow of material and the short operational life of the fuel elements. The principle problems involved in application of Be metal derive from the low state of development of the technology of Be and its alloys.

Because of the temperature limitations, shape is the more important design consideration. Paper work indicates that the rate of transfer of Be to other parts of the system is not severe at temperatures below 1700°F. This temperature has been selected as the feasible upper operation limit of Be fuel elements. The only apparent way of improving the power output of these units is to utilize greater surface-to-volume ratios. Limitations on this approach derive from pressure drop restrictions, dimensional stability requirements (exhibition of warping of this section) and manufacturing techniques. The first limitation requires utilization of as thin a wall as possible, which the last two (primarily the last one) determine the lower limits.

Almost none of the work done on beryllium and its alloys has been or is pointed specifically at fuel element design application. It was realized quite early that a mountain of work on technology of Be must be accomplished prior to design application of any type. Work on metallurgy and manufacture of basic forms has been in progress for some time. Practically nothing has been done on high temperature properties. Principal contributors to the field at present are MIT, Battelle Memorial Institute and Los Alamos. Some work on creep has been recently completed at Westinghouse Electric Company.

DECLASSIFIED

SECRET

Several miscellaneous problems have been considered. Chief of these is the problem of retaining fission products, i.e. "canning". Outside of steel jacketing, the only promising possibility lies in cladding the Be-U alloy with Be. Preliminary work on such Be--Be-U--Be sandwiches has been carried out. Cladding has been accomplished in the case of round bar extrusions and flat plates, and good bonding has been obtained. Cladding of joints, welds, and loose ends poses an additional problem.

A second problem is that of the possibility of self-welding of units stacked in a channel. Only experimental work can resolve the question. Undoubtedly, if the danger of welding proves eminent, the ends can be prepared in such a way as to eliminate the trouble.

SECRET

DECLASSIFIED

SECRET

H. MATERIALS

In the development of the power pile design, considerable work has been done in the determination of the properties of several materials having potential significance in the development of atomic power. In particular, a critical evaluation has been made of the available data on the properties of beryllium oxide, beryllium metal, graphite, thoria, and thorium. The results are tabulated and discussed in the following paragraphs.

1. Beryllium Oxide.

Beryllium oxide possesses a number of the physical properties which are required of a moderating material in high temperature gas-cooled piles. The desired properties are:

(1) Low atomic weight.

(2) A combination of high scattering cross section and extremely low overall absorption cross section.

(3) High density.

(4) Freedom from impurities such that the total absorption is small.

(5) Adequate supply at a reasonable cost.

(6) Relatively high chemical and physical stability under operating conditions.

(7) Low vapor pressure.

(8) Feasible chemical processing, fabrication and reprocessing operations.

a. Sources of Beryllia.[1,2] At present, the chief commercial source of beryllium is the ore Beryl ($3BeO\text{-}Al_2O_3.6SiO_2$)(14%BeO, 5.4%Be). Other ores such as Chrysoberyl ($BeO.Al_2O_3$), and Helvite (complex silicate) have also been considered. Only Beryl sources have been exploited, since they have proved to be economically more feasible.

Beryl is found in Colorado, in the Black Hills of South Dakota, in Maine and New Hampshire, and in many of the Atlantic states. However, most of the beryl consumed has been imported.

(1) Resources in Reserve (Measured and Estimated)[1].

In the United States, workable reserves of Beryl are estimated to be 8000 tons, with an additional 2000 tons which might conceivably be worked in the future. The reserves of low-grade Helvite ores are believed to be 4500 tons of a grade containing 2 percent BeO and 184,000 tons of a grade containing 1/2 percent BeO. Thus, about 2400 tons of BeO is maximum that the United States reserves can yield in the future.

SECRET

DECLASSIFIED

Most foreign resources, excepting those of Brazil and India, are believed to have been exhausted during the war. Data are meager. However, some German notes indicate reserves in Norway, Finland, France and Rumania. Expected production from United States and Brazil sources will be at the rate of about 2000 tons per for the next 5 to 10 years.

(2) U. S. Stockpiles.

In the fall of 1946, the United States had on hand, in government controlled stockpiles, about 4100 tons of Beryl ore. The graded averages indicate a potential yield of 10% BeO or 410 tons from this stockpile. No large private stockpiles are believed to exist in this country.

(3) Prices of Beryl Ore.

Markets are uncertain and depend on large orders to stimulate production and bring unit costs down. The purchase unit used is defined as 20 pounds of BeO per ton. For large orders, a price of $13 per unit can be reasonably expected. At present, for small orders, the market prices run close to twice that figure.

b. Chemical Processing of Ores (1,3). Beryl ore is very resistant to acid attack - except for hydrofluoric acid. Nevertheless, acid methods are used for decomposing the ore and recovering its beryllium oxide content. These processes are based on the fact that, after suitable heat-treatment, beryl reacts with sulfuric acid. The speed of reaction, moreover, increases with increasing temperature of heat treatment so that the ore becomes very reactive if it is melted and quenched by pouring into water. The quenched beryl has had its original lattice structure destroyed. More than 90% of the beryllia can then be removed by treatment with 56% sulfuric acid. In one process the sulfate liquor is concentrated and beryllium sulfate recovered by fractional crystallization. The purified sulfate is then roasted to oxide, w ith sulfates of aluminum, lithium, caesium, and rubidium obtained as by-products. In the alternate process, the beryllium is precipitated from the solution as the hydroxide, which is then heated to 1000° C. to yield the oxide.

c. Producers of BeO Powder and Their Products (1). Principal producers in this country are Brush Beryllium Company, Clifton Products Company and Beryllium Corporation of America. Brush and Clifton have been working on BeO for some time, while BCA has just recently entered the field.

Three basic types of powder are produced by Brush and Clifton companies. The various grades which have been used in fabricating shapes are designated as follows:

	Brush	Clifton
Low fired at about 1200°C - high purity	GC grade	Fluorescent grade
Low fired at about 1200°C - low purity	SP grade	Metal grade
High fired (fused and ground)	High fired grade	Refractory grade

DECLASSIFIED

Analogous grades are not identical but are quite similar. The low fired grades sell at about $4.00 per pound, while the high-fired grades sell at about $8.00 per pound.

Brush and Clifton can produce BeO at a rate of about 15 tons per month each, so that an adequate source of supply is available.

Characteristics of the three commercial powders have been studied after fabrication with the results as shown:

Material	Surface Area M^2/gm	Diameter (calcd)	Diameter from electron Micrograph	Shape
Brush G.C.	2.9	0.68 μ	ca. 0.5 μ	irregular
Clifton Fluorescent grade	17	0.12 μ	0.05 to 0.10 μ	plate like
Clifton Metal grade	20	0.10 μ	0.05 μ	

d. Physical Properties.

(1) Properties of a Single Crystal.

The physical properties of a single crystal of BeO are as follows:

Beryllium Oxide, BeO

Melting Point, 2820° K = 4616° F

Boiling Point, 4170° K = 7046° F

Zero Magnetic Susceptibility

Hexagonal with C = 1.63; crystals prismatic with distinct $10\overline{10}$ cleavage;

H = 9, g = 3; insoluble in acid; uniaxial positive with No = 1.719,

Ne = 1.7333, Ne - No = 0.014, color, white; hardness of 9.

(2) Melting Point.

The melting point is rapidly lowered by the presence of impurities such as alkali and alkali earth metals as well as acidic radicals such as silica. To avoid excessive sintering and fluxing, it is necessary to produce an oxide of high purity.

DECLASSIFIED

(3) Thermal Capacity [1].

Values of the instantaneous thermal capacity given in I.C.T. are as follows:

Temperature °F	Thermal Capacity Cp $\frac{Btu}{lb\ °F}$
212	0.299
392	0.351
752	0.421
1112	0.461
1472	0.487
1652	0.497

(4) Density[1,3].

The theoretical density of beryllium oxide is 3.025 g/cc. Hot pressed commercial size specimens have been produced with bulk density, ρ, greater than 2.80. (Small samples have been prepared with ρ = ca. 2.96). Ceramically fired commercial size specimens have been produced with a bulk density of 2.6. However, the first bodies produced by slip casting and ceramic firing had a bulk density of about 2.2.

Density of BeO Powder

Low fired	0.1 to 0.2
High fired	ca. to 0.5

(5) Hardness [4].

The hot-pressed, high density product will easily scratch glass; the low density, ceramically-fired bodies may be made as soft as chalk. The hardness of pure BeO has been reported as 9.

Norton Company reported the following hardness values:

Material	Average Knoop No(K100)
Beryllium carbide	2410
Beryllium nitride	2040
Beryllium oxide (fused)	1250
Chromium plate	880
Agate	640

SECRET
DECLASSIFIED

(6) Vapor Pressure.[1,12]

Experimental Values of The Vapor Pressure.

Temperature °C	Vapor Pressure in mm. Hg.
1999	3.57×10^{-4}
2140	2.35×10^{-3}

(7) Emmissivity [1].

The emmissivity has been measured as a function of temperature. The term "black" designates hot pressed units, while "white" indicates that the "black" unit has been annealed in a gas-fired kiln.

Temperature °F	Emmissivity (total) "black"	"white"
1000	0.50	0.20
2000	0.70	0.35
3000	0.80	0.50

(8) Electrical Resistivity [1].

Beryllium oxide is an excellent electrical insulator even at temperatures above 2000° C. As an electrical insulator it surpasses all other metallic oxides having refractory value. Experimental data are shown in the following table:

Electrical Resistivity as a Function of Temperature

Temperature °C	Resistivity Megohms/cu. cm.
800	125
1100	15

(9) Thermal Conductivity [1].

The thermal conductivity of high density beryllium oxide is approximately the same as that of pure iron.

Temperature °F	Density	Thermal Conductivity (Estimated) (Btu/hr.ft. °F)
500	2.0	29.5
1000	2.0	17.0
1500	2.0	11.8

DECLASSIFIED

SECRET

Temperature	Density	Thermal Conductivity (Btu/hr.ft. °F)
2000	2.0	8.8
500	3.025	49.0
1000	3.025	29.0
1500	3.025	19.6
2000	3.025	14.5

(10) Thermal Expansion (1).

The coefficient of thermal expansion has been measured for hot pressed, kiln fired and electrically fused material. The electrically fused and hot pressed BeO apparently showed some preferred orientation.

Linear Thermal Expansion of Beryllium Oxide

Temperature °F	Material	$K \times 10^{-6}$ °F^{-1}
500	density = 2.8	4.5
1000	(hot-pressed)	5.4
2000		7.0
500	density = 2.015	3.6
1000	(fired)	4.2
2000		5.1
500	density = 1.753	3.55
1000	(electrically fused)	4.15
2000		5.05

(11) Elastic Modulus (1).

The elastic modulus of hot-pressed beryllium oxide samples has been measured by the quartz crystal vibration method and found to be of the order of 315×10^{10} dynes/cm^2 (ca. 45.8×10^6 psi) for a density of 2.85 g/cc.

The study of elastic modulus vs. density for pure BeO has given a definite linear relationship:

$$E = (320\rho - 595) \times 10^{10} \text{ dynes/cm}^2$$

ρ = density g/cc

SECRET

DECLASSIFIED

Experiments indicate that the value of the elastic modulus decreases by only about 10% in going from room temperature to 1000° C (acoustic experimental technique).

(12) Tensile Strength (1).

The tensile strength of hot-pressed 90% BeO-10% UO_2 cylinders of density = 3.1 has been found to be approximately 16,000 psi (1.1 x 10^9 dynes/cm^2) by the bursting strength method. This agrees well with the tensile strength predicted from the compressive strength measurements on the basis of analogy with other materials. Norton Company reported a strength of pure BeO hot pressed (ρ = 2.8) of 10^9 dynes/cm^2.

The tensile strength decreased only a small amount over the temperature range from 20°C to 1460°C (according to a German report). Tests at Battelle at 2500° F. on pure BeO gave a modulus of rupture strength of 15,000 psi. This indicates there was little change of tensile strength with temperature. The perfect elasticity of BeO and the transverse nature of the fracture justifies and supports the validity of tensile stress calculated from rupture strength.

(13) Crushing Strength (1).

The compressive strength of sintered beryllium oxide bodies is a sensitive function of the density and to a slightly lesser extent of the method of fabrication of the beryllium oxide.

Cold Compressive Strength of Beryllia Shapes

Sample	Density gm/cc	Compressive Strength Psi	Compressive Strength Dynes/cm^2
Ceramically fired from Brush high fired BeO	2.22	14,560	1.00 x 10^9
Ceramically fired from Brush S.P. powder	2.0	17,000	1.18 x 10^9
Hot pressed from high fired powder (fused)	2.89	117,000	8.07 x 10^9
Hot pressed from Brush S.P. powder	2.95	193,000	13.3 x 10^9
Ceramically fired from low fired powder	2.6	99,300	6.85 x 10^9

Battelle reported the following data for compressive strength:

Temperature °F	Compressive Strength Psi
2500	68,000
2700	66,000
2800	53,000

SECRET
DECLASSIFIED

SECRET

A specimen heated to above 2960° F. in six hours and held above 2960° F. for over an hour gave no measurable deformation under a load of 170 psi.

The relationship between the crushing strength and the elastic modulus has been evaluated as follows:(4)

Crushing Strength	Elastic Modulus
psi	(10^{10} dynes/cm^2)
20×10^3	120
40	160
80	220
100	245
140	290
180	335
200	355

(14) Poisson's Ratio.

Poisson's ratio was measured on a hot pressed specimen and it was found to be ca. 0.19.

e. Thermal Stability of BeO (1,5). BeO sinters as low as 1200° C, and when BeO pieces of high porosity ($\rho < 2.3$) are heated for periods of several hours at 1500° C or above, it is known that they slowly decrease in size and increase in density. The change in size of hot-pressed, dense bodies during similar heating periods is very small; they usually expand very slightly. The beryllia bodies appear to be dimensionally stable when they have been fired or annealed (for hot-pressed shapes) above 1700° C and then used at somewhat lower temperature. Such changes as do occur do not appear to be an appreciable structural limitation.

Beryllia shows good resistance to thermal spalling, particularly after annealing at a temperature greater than 1750° C. A mixture of grain sizes in the BeO powder improves resistance to thermal spalling over that of uniform, fine grain powder. Experimental investigations have been made of the resistance to thermal stresses due to temperature differences in the beryllia, and also of the effect of cyclic temperature variations.

f. Plasticity (1,9). Beryllium oxide is a perfectly elastic material over most of the temperature range of interest. Since rapid annealing takes place at temperatures greater than 1750° C some plastic flow might occur in that region. However, the occurrence of plastic flow in pure BeO has never been definitely observed. Mixtures of oxides and other refractories (high BeO content) undergo creep at high temperatures.

SECRET

DECLASSIFIED

g. Effect of Method of Fabrication. Preferred orientation is shown in units made by hot-pressing and extrusion methods. Consequently, the products show anisotropic properties.

The hot-pressing technique produces high density products. Cold-pressing followed by ceramic firing produces units of medium density. Extruded products are low or medium density. Slip-cast beryllia ware is usually a low density material.

The grain size in the hot-pressed material is of the order of 5 microns while in the annealed samples it is of the order of 20 to 50 microns. Therefore, there is some crystal growth in both the hot-pressing and annealing operations. The grains are approximately isodimensional. Fluorescent powder showed a larger grain than the G.C. powder. Permeability of the material is small and irregular.

The crystal size in the ceramic fired material is similar to that of hot-pressed bricks. For the most part the crystals are isodimensional but some areas show columnar crystals. The permeability of the material is small but somewhat erratic since the holes are not well connected.

The particle size of the original powder and the chemical impurities in it markedly effect the properties of extruded units. Units made from fluorescent grade of BeO show only slight crystal growth up to 3100° F. Units made from high-fire grade of powder showed marked orientation after extrusion due to the particle shape. Uniform crystal growth occurred at temperatures above 3100° F. The units made from S.F. powder began to show crystal growth at temperatures above 2800° F.; at 3100° F. large columnar crystals were formed. The permeability of the extruded units tend to be rather great -- partly due to flaws in the finished product.

h. Effect of Annealing. Residual stresses may be removed by annealing at temperatures around 1750° C. Noticeable grain growth begins to occur in the region from 1150 to 1200° C but the rate of growth is very slow.

i. Nuclear Physics Data [1,6,7,8]. Experimental measurements of cross sections of BeO are not at present very consistent. (See Section XI for values used in the analysis).

$$\sigma \text{ (absorption)} = 0.011 \text{ barns}$$

$$\sigma \text{ (transport)} = 10.3 \text{ barns}$$

$$\sigma \text{ (scattering)} = 10.1 \text{ barns}$$

$$L\ (\rho = 2.7) = 26.8$$

j. Resistance to Chemical Attack. At 1400° C., beryllium oxide is unaffected by exposure for long periods of time to oxygen, hydrogen, air, nitrogen, or helium. Water vapor, however, attacks beryllium oxide under these conditions, causing it to volatize, the reaction between the BeO and

DECLASSIFIED

water vapor resulting in a transport of the BeO to cooler zones of the gas or vapor volume. The reaction has been studied as a function of rate of flow and of the pressure of the water vapor, with results as follows:

BeO Loss for 2 1/2 Hour Test Run (1400° C.)

Rate of Steam Condensation (ml/min)	Water Vapor Pressure mm HG.	Weight of BeO Lost %
1	90	0.55
3	90	0.70
2	760	0.70
5	760	0.91

The following thermodynamic properties are of interest in a study of the chemical reactions of beryllia:

Thermodynamic Properties of BeO

Melting Point	2820°K
Boiling Point	4170°K

$\Delta H_{298.1}$	= -147	k cal/mol.	$Be + \frac{1}{2} O_2 \rightarrow BeO_{(s)}$
$\Delta S_{298.1}$	= -0.02342	k cal/mol. deg	
$\Delta F_{298.1}$	= -140	k cal/mol.	
ΔF_{1000}	= -124.7	k cal/mol.	
ΔF_{1500}	= -111.5	k cal/mol.	
ΔF_{2000}	= -101.0	k cal/mol.	

	ΔF_{1500} k cal/mol.	The equilibrium gas pressure in atm. at 1500°K
$BeO \rightarrow Be + \frac{1}{2} O_2$	111.5	$(O_2) 3.98 \times 10^{-33}$
$BeO + C \rightarrow Be + CO$ (g)	52.58	$(CO)\ 2.1 \times 10^{-8}$

The inertness of BeO to carbon at elevated temperatures and its ability to withstand attack by fused alkali are remarkable properties.

k. Porosity and Permeability (1). As previously mentioned, variations in density and porosity are produced by the various methods of manufacture of beryllium oxide bodies. Experiments indicate that the high density bodies are not gas permeable. The Germans, Degussa, had developed a sintered beryllium oxide which was gas tight; also a slip-cast beryllia which was gas-tight at 2200° C.

DECLASSIFIED

SECRET

Experimental Data on Porosity and Permeability

Density g/cc	Pore Volume In %	Vacuum Tight 1/2" Thickness	Pore Radius
2.918	3.3	Apparently	
2.2	27.2	Not (18.6% of pore volume was readily available)	4×10^{-4} cm
(AGOT Graphite)	26	Not (20% of pore volume readily available)	2×10^{-4} cm

1. Functional Uses. The industrial uses of beryllia may be summarized as follows:

1. The "high-fired" oxide is used for crucibles and molds in processes where common materials could react chemically or physically with the material being heated or cast.

2. The low-fired high purity oxide has been utilized for some time in the manufacture of fluorescent lamps.

3. The low-fired, low purity oxide is used principally as the basic material to be processed in production of beryllium metal.

4. In rare instances, BeO is used as a refractory brick. Here the high cost has restricted its adoption.

Beryllia is more refractive and less reactive than calcium oxide or magnesium oxide. Thus, thorium can be melted at 1900° C. and beryllium at 1290° C. in beryllia ware without attack. Consequently, beryllia has been used not only in crucibles but also in thermocouple shields, casting mold spill-ways and funnels. Beryllia, in general, has been more satisfactory than thoria and zirconia during die pressing and firing operations. This might not continue to be true for slip-casting operations.

m. Beryllium Oxide Mixtures (1). Mixtures of BeO and uranium oxide up to 10% by weight of UO_2 have been made both by ceramic firing and by the hot-pressing method. There is much evidence that the effect of UO_2 is slight. The 10% UO_2 (by weight) is approximately one atomic percent, and the UO_2 is present as a mechanical mixture of two phases (not even a eutectic). The melting point is the same as pure BeO and no compound is known. Direct comparison has been made of the heat conductivity of pure beryllium oxide with hot pressed bodies containing 10% UO_2, and they have been found, within the limits of error, to be the same. In general, the density of mixed oxide pieces is greater than that of pure beryllium oxide pieces made under the same conditions by an amount approximately equal to the added weight of the uranium oxide. Although all the other physical properties of pure oxide and the mixed oxide have not been directly compared, it is believed that the addition of 10% UO_2 does not significantly alter these physical properties. However, the presence of the UO_2 apparently produces an acceleration in the rate of crystal growth.

SECRET

DECLASSIFIED

SECRET

The fabrication of BeO-uranium oxide mixtures has, in general, been carried out starting with the uranium as U_3O_8. During the process of hot pressing in graphite molds this is essentially all converted to UO_2. In the temperature range between about 500° C. and 1000° C., and in the presence of air, the UO_2 is readily converted to U_3O_8 and intermediate compounds. This conversion involves an expansion and, consequently, when it occurs in a sintered BeO-UO_2 body, crumbling is apt to occur. This crumbling is observed even in the case of high density, low porosity, hot-pressed shapes when they are heated in air at about 700° C.

It has been found that at 1500° C., U_3O_8 is quite volatile in the presence of oxygen. This is probably due to a dissociation to form the more volatile higher oxide, UO_3. If a BeO-UO_2 body is heated above 1000° C in a gas stream containing oxygen, volatilization also occurs.

Experimental data indicate the following:

The crushing strength of mixed oxides (10% UO_2, 30% U^{235} enrichment) is essentially the same as that of pure BeO of comparable density. Additives of lime, silica, alumina or uranium oxides produced no appreciable effect upon the elastic modulus. However, the addition of 20% graphite reduced the modulus by a factor of three (105×10^{10} dynes/cm^2). It is of interest that for a UO_2-U_3O_8 prism of density 8.5 g/cc, $E = 429 \times 10^{10}$ dynes/cm^2.

Material	Temp. Range °C	Thermal Conductivity in cal/ cm sec °C	Melting Point
BeO (powder)	50 to 500	ca. 0.0024	2820°K
UO_2 (powder)	20-225 270-610	0.00034 0.00019	2500°K
U_3O_8 (powder)	25-150	0.00067	
	310-600	0.00061	
Lampblack	15-120	0.00003	

n. Effect of Irradiation (1,10,11). The two important types of radiation in this regard are neutrons and fission fragments.

(1) Neutron Bombardment.

An "average" fission neutron having an energy of 2 Mev, on making an elastic collision with another atom, will produce a primary knocked-on ion or atom. The energy of these primary recoil atoms is dissipated in part by electronic excitation, in part by elastic collisions. Thus, each primary recoil atom may produce a large number of displaced atoms by elastic collisions. These displaced atoms, which disrupt the lattice, have a pronounced effect on physical properties. Neutrons with thermal energies also make elastic collisions with the atoms of the material but these collisions have no effect on the properties (identical with elastic vibrations of the lattice).

SECRET
DECLASSIFIED

The unit of exposure -- one megawatt day per central ton (mwd/ct) is approximately equivalent to a thermal flux of 10^{13}. Measurements were made on the irradiated specimens to determine changes in:

1. Linear dimensions.
2. Crushing strength.
3. Elastic modulus.
4. Thermal conductivity.
5. Lattice constants.

A partial study of the effects of annealing was also made.

The effect of neutron bombardment (exposed at alightly above room temperature) has been examined in some detail for pure hot-pressed beryllium oxide. The maximum exposure was about 200 mwd/ct.

(a) Linear Dimensions. The expansion of pure BeO due to neutron irradiation was very slight. It appeared rapidly to approach a saturation value which did not exceed 0.1% after 200 mwd/ct exposure.

(b) Crushing Strength. The crushing strength of pure BeO increased from 5 to 10% in 200 mwd/ct. It did not tend to approach a saturation value.

(c) Elastic Modulus. The elastic modulus did not change by as much as the precision of the experiment (of the order of 0.3%).

(d) Thermal Conductivity. The thermal resistivity of BeO rises to 1.5 x its original value. Apparently it approaches a saturation value.

(e) Lattice Constants. X-ray pictures indicated that there was no change in lattice dimensions (within an accuracy of 1 part in 6000) nor was there any difference in the intensity of the lines.

(f) Effect of Annealing. Annealing of pure BeO at 900° C for 1 1/2 hours gave indications of complete return normal of the linear expansion and the thermal conductivity.

(2) Fission Recoil [11].

The heavy particles produced by fission have such high energies that the result is a large number of displaced atoms. In addition to the displacement, the fission fragment loses energy by electronic excitation, causing local melting in the immediate vicinity of the fission track. After equilibrium has been attained the fission

DECLASSIFIED

fragments act as foreign atoms in the lattice. As an example, the number of displaced uranium atoms produced by a pair of fission fragments has been estimated as 130,000. Obviously, the effects of fission recoil cannot be separated from the effects of neutron bombardment.

To determine the effects of irradiation, a large number of samples of BeO plus UO_2 were prepared by the hot-pressing technique and subjected to bombardment in the H.E.W. pile at a flux ca. 10^{13} neutrons/cm^2/sec. for periods of 24 days, 63 days, and 133 days. All samples of mixed oxide (both 2 and 10% UO_2) contained 30% enrichment of U^{235}. About 6% of the U^{235} atoms present in the samples had undergone fission during 200 mwd/ct of bombardment. That was equivalent to about 2% of the total number of uranium atoms. The maximum temperature of the samples during irradiation was estimated to be approximately 700° C.

(a) Linear Dimensions. For both low and high density mixed oxides of 2 and 10% UO_2, the average expansion was less than 1% for 200 mwd/ct. It appears that the rate of expansion decreases as irradiation time continues. The 10% UO_2 samples, which show somewhat higher densities, expanded very slightly more on the average than did the 2% samples (on the average of lower density).

(b) Crushing Strength. Data on both the 2 and 10% mixed oxides indicated that the crushing strength very quickly decreased as much as 25% and thereafter remained approximately constant.

(c) Elastic Modulus. The mixed oxide bodies showed a reduction in the value of the elastic modulus of ca. 30% in 200 mwd/ct irradiation.

(d) Thermal Conductivity. The thermal resistivity of the mixed oxides was increased (6.5 times for 2%, 6.0 times for 10%) by 200 mwd/ct of irradiation. The major effect was apparently realized after a very short exposure; however, the resistance continued to increase slowly. The damage suffered was greater for the 2% mixture, evidently, because the temperature was considerably lower during the irradiation.

(e) Effect of Annealing. Annealing the mixed oxides for 64 hours at 200° C and 88 hours at 400° C failed to indicate any significant annealing of the linear dimension changes. Annealing for 1 1/2 hours at 900° C $\cong$ 1652° F. produced a decrease in length of the order of 0.1%.

DECLASSIFIED

SECRET

Effect of Annealing in Vacuum at 900°C for 3 hours
For Samples Irradiated 23 Days at H.E.W.

Sample	% Change Due to Irradiation	% Linear Dimension Change Annealed Out
#26, pellet high density 2% UO_2	0.66	94
#27, pellet high density 2% UO_2	0.64	76
C-25 prism high density 2% UO_2	0.46	56

(Standard unirradiated samples showed no changes for this annealing cycle).

Annealing at 200°C = 392°F and 400°C = 752°F did not change the conductivity or linear dimensions of the irradiated samples. Annealing at 900°C = 1652°F for 1 1/2 hours did change the conductivity as shown.

Effect of Annealing on Thermal Conductivity
(1 1/2 Hours at 900°C = 1652°F)

Sample 24 Day Bombardment	Estimated % Change Annealed Out
10% UO_2	42.5
2% UO_2	60.5
BeO pure	(Approx.) 100

The measurements of the changes in thermal conductivity were made at an average specimen temperature of 73° C. The use of the ratio of the decrease in thermal conductivity at 73°C may be very misleading as an index of the damage caused by irradiation to a material which is to be used at operating temperatures above 500° C., since the ratio changes with temperature.

SECRET

DECLASSIFIED

SECRET

2. Beryllium.

Beryllium metal possesses many of the properties considered desirable for moderator materials, although, the operating range of the pile would be restricted by certain physical properties of the metal.

a. Sources of Beryllium [2,20,22]. Since the present method of producing beryllium involves the reduction of BeO to beryllium, the sources of beryllium are the same as those of beryllia.

b. Chemical Processing [20,22]. The reduction of Be from its oxide is difficult because of the high degree of stability and inertness of the oxide. Aluminum is not suitable for this purpose and even Ca and Mg, although potentially suitable, cannot be used because of their low melting points or dissociation temperatures.

Since the reduction of beryllium chloride by Na, Mg or Ca is feasible; it is in general, obtained by reduction of one of the halides. The usual reaction is as follows:

$$BeF_2 + Mg \rightarrow Be + MgF_2$$

The reduction is performed in a graphite retort at a temperature slightly above the melting point of beryllium (1280°C = 2340°F). The crude beryllium metal, as removed from the top of the cooled melt, contains considerable amounts of entrapped MgF_2.

Metallic beryllium flakes are produced by electrolyzing a fused bath containing $BeCl_2$ in a stainless steel cell at a temperature below the melting point of the metal.

Experimental work has also been done on other methods, such as thermal decomposition of the iodide.

c. Producers of Beryllium. The principal producers of beryllium in U.S.A. are as follows:

1. Brush Beryllium Company.

2. Beryllium Corporation of America.

3. Clifton Products.

The Brush Beryllium Company and B.C.A. use the reduction of BeF_2 method. Clifton Products uses the electrolytic method -- similar to the German developments.

d. Physical Properties. The following table gives physical properties of beryllium as compared with three of the more common metals, magnesium, aluminum and iron.

SECRET

DECLASSIFIED

Property	Units	Be	Mg	Al	Fe
Density	gm/cc	1.86	1.74	2.7	7.8
Melting point	°C	1280 - 2336°F	691	660	1530
Boiling point	°C	2900	1125	2500	2800
Crystal structure		H.C.P.	H.C.P.	F.C.C.	B.C.C.
Tensile strength	psi	20,000 to 50,000	35,000 to 40,000	7,000 to 15,000	30,000
Tensile elongation	% on 2"	0 - 2	5 - 15	50	50
Thermal expansion	c.g.s.	19×10^{-6}	14×10^{-6}	23×10^{-6}	12×10^{-6}
Thermal conductivity	c.g.s.	0.2	0.37	0.5	0.2
Electrical Resistivity	Ohm/cm.	4×10^{-6}	4.5×10^{-6}	2.655×10^{-6}	8×10^{-6}

In many respects beryllium is a remarkable element. Its position in the periodic table at the head of group II, indicates that it has the typical properties of a transition element possessing metallic as well as metalloid properties. This position in the table between the metal lithium and the metalloid boron also explains the relatively high melting point.

(1) Structure [23,25].

Crystal structure--hexagonal close-packed, 2 atoms in an elementary cell. Lattice constants have been reported over the following ranges:

a_1 2.2680 to 2.283 °A

a_3 3.5735 to 3.64 °A

a_3/a_1 1.562 to 1.5847

These rather wide deviations could hardly be attributed to impurities since their effect on the lattice dimensions is normally very small.

The ratio a_3/a_1 is somewhat smaller than for ideal hexagonal closest packing of spheres. Consequently, each atom has six nearest neighbors above and below it (2.20 °A), and six somewhat further removed neighbors (2.28 °A) in its own plane (1 to the a_3 axis).

(a) Atomic constants.

Atomic number, 4; atomic weight, 9.02; stable isotope, Be^9.

SECRET
DECLASSIFIED

SECRET

(a) Atomic constants. (continued)

Electron distribution and ground term -- $1S^2 \; 2S^2 \; 1_{S_0}$

Atomic radius = 1.12 °A, one-half the average distance between a Be atom and its twelve neighbors in Be metal.

Ionization potentials:

1st.	9.50 volts
2nd.	18.14
3rd.	153.10

Atomic volume is 4.90 cc/gm (if density is 1.84 g/cc).

(b) Density and hardness.

Density	Condition
1.862 g/cc	calculated from crystal structure
1.85	99 % plus Be
1.844	99.5 % plus Be
1.816	99.96 % plus Be

The hardness of Be decreases with increasing purity.

Brinell Hardness	% Be
153	98.9
97 → 114	99.5
98	99.962

The hardness of beryllium also decreases with increasing temperature.

Temperature	Brinell Hardness	Load, kg.
300	86.9	2,000
600	61.9	1,500
900	11.2	500
1000	9.7	500

SECRET

DECLASSIFIED

SECRET

The effect of cold working and annealing is shown by the following data.

Material	Rockwell B Number
Cast (vacuum melt	60 → >70
Deformed before annealing	95 → 100
Annealed at 600° C	93
Annealed at 800° C	86
Annealed at 1000° C	72

(c) Transformations. Indications of allotropic modifications have been reported at -45°C, + 450°C, and 735°C. However, these experimental results have not yet been verified.

(2) Thermal Properties [25].

(a) Thermal expansion. The average values of the coefficient of linear expansion has been measured for polycrystalline material with the following results:

Temperature °F	Coefficient x 10^{-6} $°F^{-1}$
400	6.8
800	8.0
1200	9.2
1600	10.3

99.96% Be

The coefficient of expansion is somewhat greater in the direction normal to the hexagonal (a_3) axis than parallel to that axis.

The coefficient of cubic expansion has been reported at room temperature as 6.66 x 10^{-6} $°F^{-1}$.

(b) Thermal capacity.

Temperature °F	Thermal Capacity Btu/lb °F
86	0.508
212	0.524
752	0.589
1112	0.638
1472	0.679

SECRET

DECLASSIFIED

[redacted]

(c) Thermal conductivity [24,1].

Temperature °F	Conductivity Btu/hr.ft. °F R_1	X_1
392	76.9	73.4
752	67.5	63
1112	58.4	52.5

(R_1 was extruded vacuum cast, X_1 was extruded flake metal)

(3) Melting and Evaporation.

(a) Melting point 1278 ± 5°C

(b) Heat of fusion has been reported as 341, 345.5, and 250 - 275 cal/g. Beryllium has the highest heat of fusion of all metals.

(c) Vapor pressure [21]

Temperature °F	Pressure in atmo.
915	7.5×10^{-17}
1120	4.4×10^{-14}
1540	6.2×10^{-10}
1975	3.4×10^{-7}

(d) Boiling point = 2967° C.

(e) Heat of vaporization = 52 k cal/g.

(f) Entropy of vaporization = 16 E.U.

(4) Electrical, Magnetic and Optical Properties.

(a) Electrical resistivity. The electrical resistivity depends on the purity, of the metal, and in impure samples it is strongly affected by thermal treatment if the latter changes the distribution of the impurities. The resistivity increases with temperature and pressure.

(b) Thermoelectric power. Beryllium is slightly less positive than copper. A value of 0.16 volt for EMF of 99.96% Be against Pt at 100° C has been reported.

[redacted]

DECLASSIFIED

(c) Magnetic susceptibility. Beryllium is diamagnetic; with atomic susceptibility of 82×10^{-7}.

(d) Reflectivity. Average value for white light reported as 0.5 to 0.55. Declines to a minimum at 1640°A.

(e) Emissivity.

Solid - 0.61 at 6500 to 5500°A.
Liquid - 0.61 at 6500°A up to 3620°F.
Liquid - 0.81 at 5500°A up to 3620°F.

(5) Mechanical Constants.

(a) Elastic deformation.

Material	Young's Modulus 10^6 psi	Proportional Limit (%)
Chill cast, 99.5% Be	42.6	
Forged (77% red.) 99.5% Be	40	9.4
Annealed in H_2 (1000°C)	36.8	8.7
Extruded tube (longitudinal)	36	18.9

(b) Inelastic deformation. At room temperature, the inelastic deformation of several samples of beryllium is as follows:

Material	Yield Strength 10^3 psi	Offset %
99.5% forged, anneal in H_2 at 1000°C	26.4	0.2
Forged (77% red.)	35.3	0.2
Extruded (Area red. 4/1)	26.7	2.0
Extruded (Area red. 16/1)	37.4	2.0

The effect of temperature on yield strength of a sample of pure Be extruded with an area reduction of 4:1:

°F	Yield Point	Compression Tests Load, 10^3 psi	
		10% Reduction	20% Reduction
1292	11.5	18.0	20.0
1472	7.0	7.15	7.5
1652	3.25	3.6	4.0

(c) Shearing strength. The shearing strength of a 99.5% pure Be, forged rod is 38.6×10^3 psi.

DECLASSIFIED

(d) Ultimate strength.

Material	Tensile Strength psi	Elongation %
As cast	20,000	0
Reduction 1/16	40,000	
Reduction 1/64	60,000	
Extruded	50,000	0 to 2
Recrystallized - heated) 24 hours at 725°C)	50,000	3
Brush "Q"	20,000 to 50,000	0.1
Brush "Q" unchanged by heat treatment		
Brush "QT"		1.5
Clifton flake extruded		0.5
Heat treated Clifton flake	50,000 to 70,000	5 to 7

(6) Elevated Temperature Tensile, Creep and Stress Rupture Properties (21,24,27).

Tensile strength remains constant up to 752°F. and then decreases rapidly with increasing temperature. Tensile elongation increases rapidly up to about 25% at 572° F.

Temperature °F	Stress psi to produce Rupture in 1000 hours	1% Creep in 1000 hours
930	4200	4200
1300	700	520
1700	56	26
2000	7	4

The agreement between the results reported by various investigators on stress - rupture data is not very good, due probably to the difficulty of maintaining an inert atmosphere.

Short-time compressive tests on chill-cast beryllium rod showed that the apparent proportional limit dropped steadily from 20,000 psi at room temperature to 1,200 psi at about 1800° F.

e. Fabrication of Beryllium. The greatest fabrication difficulties are associated with the lack of ductility of the metal. The cause of brittleness in the beryllium is unknown; so far, it has not been attributed to any one specific impurity. Attempts have been made to alleviate this brittle condition by alloying with an element which will produce a solid solution. No improvements in ductility were obtained; although, some higher tensile strengths were obtained but they were usually associated with a decrease in ductility.

(1) Vacuum melting.

A vacuum furnace has been used for melting Be in a BeO crucible. Be reacts with C to form Be_2C so graphite crucibles cannot be used. Be does not react with H_2 thus it could be used as a protec-

DECLASSIFIED

tive atmosphere. The vacuum melting virtually eliminates all Mg and fluorides present in the crude metal. No data exists on the effect of melting time and temperatures on the amount of refinement of the metal.

(2) Casting.

Castings are made in graphite molds fitted with an alundum hot-top. Melts as large as 60 pounds have been made. Argon is flowed into the vacuum furnace just before casting.

Beryllium is generally cast at temperatures in the range of 1400 to 1450° C. Mold temperatures must be carefully regulated as low temperatures result in poor surfaces and cracks while excessive temperatures initiate reaction with the melt giving large quantities of Be_2C. Low thermal conductivity molds prolong the freezing time such that extremely large grains grow in the Be ingot. Sharp corners in the mold result in cracks in the casting.

Casting defects in Be ingots are usually in some form of pipes and internal cracks. Be is also subject to coarse, dendritic crystal growth. The ingots have planes of weakness where the crystals intersect as they grow out from the walls of the mold.

(3) Extrusion.

In general, the beryllium billet is encased in an iron jacket (1/16" thick) to permit extrusion which is usually carried out at 1000° C, although it can be done as low as 700° C. In order to produce the maximum refinement of grain structure which results from cold working it is desirable to extrude at the lowest possible temperature.

(4) Forging.

Forging is facilitated if the cast billet is first extruded, again employing an iron jacket in both the extrusion and forging processes. Recrystallization does not occur during the forging operation, hence, forging does not significantly improve the properties of beryllium.

(5) Rolling.

Rolling can be carried out on an extruded flat plate which has been fitted with a new iron jacket. Temperature ranges from 1200° -- 2000° F.

(6) Welding.

Satisfactory welds have been obtained by means of the heliarc in materials less than 1/8" thick.

DECLASSIFIED

Experiments have shown that fusion occurs when finished beryllium surfaces are held in contact at about 2000° C. in an inert atmosphere. Aluminum braze and copper braze methods also show promise.

(7) Recrystallization.

The minimum recrystallization temperature is 700°C., but this temperature must be maintained for a long time. At 800°C., complete recrystallization takes place in about one hour. When Be is deformed at temperatures around 1000°C., it does not recrystallize.

(8) Preferred Orientations.

Beryllium (close packed hexagonal structure) is anisotropic and exhibits preferred orientations after deformation. The basal planes tend to line up parallel to the axis of extrusion, and the prism faces tend to be perpendicular to the extrusion axis.

Preferred orientation results in anistropy of mechanical properties; thus, tensile strength is about three times as great when measured perpendicular to extrusion direction as it is when measured parallel to this direction.

f. Production, Costs and Losses.

(1) Production.

At the present time about 500 to 1000 lbs/month of beryllium metal is being produced in this country, although total production capacity is estimated to be over 2000 lbs/month.

(2) Costs.

The present price of beryllium metal varies considerable depending upon the grade, purity and manufacturing process.

These various prices have been quoted:

1.	Cast ingots of unspecified size B.C.A.	$75.00/lb
2.	Technical grade lumps (ca. 85% Be)	$44.00/lb
3.	Selected grade lumps (ca. 98% Be)	$60.00/lb
4.	Technical grade extruded	$95.00/lb
5.	"Q" Process blocks	$114.00/lb

Welding costs tend to be higher than normal because of the increased time required and the inert gas used for control of atmosphere.

Extrusion of small and simple shapes (rods and bars of not greater than 3" dia.) will give a product at about $100 per pound.

DECLASSIFIED

Beryllium can be rolled into 1/4" thick plates from previously extruded stock for about $120 per pound.

(3) Losses in fabrication.

Casting - 20% scrap-usable for melting stock.
Extrusion - 15% scrap - usable for melting stock.
Rolling - 20% scrap - if not too thin it can be used for melting stock.
Machining - 8 to 12% for each operation; the scrap can not be remelted.

g. Beryllium - Uranium Alloys. It is not likely that a small atomic percent uranium will have much effect on fabrication and physical properties of the metal. A thorough investigation of the beryllium - rich alloys has not been made. However, the volatility of UBe_{10} and UBe_{13} systems has been studied up to 1500° C. These compounds showed no particular merit.

h. Nuclear Physics Data.

$$\sigma_{tr} = 3.5 \text{ barns}$$

$$\sigma_{a} = 0.01 \text{ barns}$$

i. Resistance to Chemical Attack. Beryllium has a great affinity for oxygen, particularly at high temperatures. In a manner similar to aluminum, solid beryllium is covered with a film of oxide which protects it from further oxidation and corrosion. Consequently, water or water vapor has no effect even at a red heat. Nitrogen combines with beryllium to form the nitride at temperatures above 900° F. Beryllium burns in an iodine atmosphere to give BeI_2 (with bromine it gives $BeBr_2$). The beryllium halides can be decomposed at high temperatures. Beryllium reacts with carbon to give Be_2C, this tendency is very great in the vicinity of the melting point.

j. Resistance to Irradiation (11).

(1) Neutron bombardment.

Annealed and unannealed, cast and extruded beryllium samples have been exposed at H.E.W. between metal slugs for 50 mwd/ct. No significant changes were found in elastic modulus, damping properties, electrical resistivity, hardness, or physical dimensions.

No data are available for exposures at high temperatures or even of the effect of fission recoil at moderate temperatures.

DECLASSIFIED

3. Graphite.

The primary use of graphite is as a moderator. Its combination of properties of low atomic weight, low neutron absorption and ready availability strongly favored its use. In competition with other moderator materials, it has advantages of cheapness, inertness and ability to withstand high temperatures.

a. Sources of Graphite(14)(15). Essentially pure carbon is known in widely varied forms, from the diamond, white, transparent and extremely hard, to graphite, black, opaque and unctuous. As a constituent of all organic materials, carbon is found in abundance in all parts of the world. The carbon used as a raw material in the manufacture of carbon products may be obtained either in the natural free form, such as, anthracite coal and natural graphite; as a by-product, petroleum coke; or by direct manufacturing processes, such as lampblack.

The natural graphite was not considered during the war because of its scarcity. However, it is a possible raw material for special items (i.e. where high density is desirable). Since the ash of carbon seems to be located within the structure, inaccessible to acids and alkalies, as pure a raw material as possible is needed for the graphitization process. Petroleum coke, formed from asphalt, is low in ash (ca. 0.5%) and crystallizes readily. Lamp-black, another high purity form of carbon, is very difficult to crystallize satisfactorily and it is somewhat deficient in its resistance to thermal shock.

b. Chemical Processing. The commercial preparation of very pure graphite is a long and difficult process. Since the special requirements are high purity and high density, special petroleum cokes are selected to provide a low vanadium impurity and a high density; special pitch with a low boron content is used; also, the furnace resistor elements are high purity granular petroleum coke. Carbon does not sinter at temperatures as high as 2500°C, and so cannot be cast; however, it can be mixed with a binder such as pitch for extrusion. The binder is then carbonized by slow heating "gas-bake" requiring some 4 to 6 weeks. The operating temperatures during the gas-bake are around 800 to 1000°C. The rather porous gas baked products are then treated with pitch in vacuo and regraphitized in a special furnace (2800 to 3000°C). The heating cycle is of 3 to 4 days duration; however, the entire operation requires over two weeks. The final product is AGOT graphite with a density of 1.64. The object of the pitch impregnation is to increase the density and strength of the final product.

Graphitization can be visualized as a condensation of a more or less chaotic structure toward the ordered crystalline structure of graphite, and the specific gravity gives a measure of this condensation. The deviation of the specific gravity from 2.26 on 3000°C baked material is a measure of the imperfection in crystal structure. Changes in other physical properties on graphitization are as follows:

(1) A decrease of specific resistance by a factor of 5.

(2) An increase in thermal conductivity by a factor of 25 to 30.

DECLASSIFIED

SECRET

(3) A 50% decrease in thermal expansion coefficient.

(4) A 20% decrease in elastic modulus.

(5) A 20% decrease in strength.

(6) A 2-1/2" decrease in the heat of combustion.

c. Producers of Graphite. The graphite produced for the project was made by National Carbon Company, Inc., a unit of Union Carbide and Carbon Corporation.

d. Physcial Properties. All of the AGOT graphite was not made of the same kind of coke; in addition, the material acquired directional properties during the extrusion, therefore, considerable variations in physical properties are to be expected. In the following compilation parallel refers to cuts taken parallel to the direction of extrusion, and perpendicular to cuts taken perpendicular to the direction of extrusion.

(1) Structure and Properties of a Single Crystal. Structurally, AGOT graphite consists of a granular material bonded together to form a porous mass. The bonding agent is carbon which is deposited by the thermal decomposition of pitch.

The distinction between carbon and graphite is one of dggree. It is possible to go continuously, by heat alone, from a material described as carbon to one described as graphite. Low temperature carbon contains a spacing which is equivalent to the distance between the layer planes of a true graphite. In graphite crystals, carbon atoms form identical planes consisting of regular hexagons, the planes being parallel and equidistant, with alternate planes being identically placed. The hexagons of the intermediate planes are displaced in the direction of a vertex of the hexagon by a distance equivalent to one side of the hexagon. The crystal structure as determined by an X-ray analysis is as follows:

Atoms arranged in nearly plane sheets, 1.42° A apart in hexagonal honeycomb.

Distance of adjacent planes, 3.35° A

Space lattice constants at room temperature:

$\underline{a}$ = 2.4563 °A

$\underline{c}$ = 6.6956 °A

SECRET

DECLASSIFIED

SECRET

(2) Thermo-Chemical Properties (14).

Sublimation temperature 3,650 ± 50°C

Oxidation	1% per day at 450 to 550°C
Critical temperature	3730°C = (6740°F)
Critical pressure	170 kg/cm^2 = 2420 psi
Heat of Sublimation*	
(evaporation in vacuo)	177 k cal/mole
(spectroscopic data)	124.8 cal/mole
Heat of Combustion	7.835 k cal/gm
Heat of Fusion	8 to 11 k cal/mole

* ANL(18) - reported 202 ± 4 kcal/mole at 2000°C

(3) Thermal Capacity(15).

Temperature °C	Thermal Capacity cal/g°C
0	0.15
200	0.28
400	0.37
600	0.44
900	0.46

(4) Density(15). True density in g/cc

Natural graphite	2.25
Artificial graphite	2.08 to 2.12

Apparent density (stacking density)

Natural graphite	1.85 to 2.0
Artificial graphite	1.45 to 1.80
AGOT	1.61 to 1.71

Bulk density of powdered graphite

100 mesh	0.48
40 mesh	0.42
20 mesh on 40 mesh	0.70

SECRET

DECLASSIFIED

SECRET

(5) Vapor Pressure [18].

Temperature in °C	Vapor Pressure in mm Hg
2000	8.35×10^{-7}
2500	2.34×10^{-3}
3000	5.8×10^{-1}

(6) Emissivity[18]. The reflectivity has been measured and reported as 0.25 for light of 0.655 μ. The emissivity for a transmissivity of zero, would be 0.75. This probably corresponds to a smooth polished graphite surface. Experimental values have been reported in the range from 0.75 to 0.92 (mostly in the higher range).

(7) Electrical Resistivity[14,15,17].

(a) Specific Resistance of AGOT Graphite.

	Parallel	Perpendicular
Specific resistance at room temperature (ohm cm)	0.0005 to 0.0008	0.0010 to 0.0013

(b) Variation of Specific Resistance with Temperature.

Temperature	(% of room temperature value)
20°C	100%
400	82%
800	85%
1200	90%
2000	100%

(8) Thermal Conductivity [14,15,17].

(a) Thermal Conductivity of AGOT Graphite in Btu/hr ft °F (Values at 80.6°F)

Type of AGOT	Parallel	Perpendicular
Whiting	96.5	75
Gulf Clenes	106	77.4
Kendall	135	70

DECLASSIFIED

SECRET

(b) Variation of Thermal Conductivity with Temperature.

Temperature	% of value at 0°C
θ °C	100%
200	75
400	60
600	55

(9) Thermal Expansion. Coefficient of Thermal Expansion of AGOT - Graphite in °F (values at 140°F)

Type of AGOT	Parallel	Perpendicular
Whiting	1.3×10^{-6}	2.1×10^{-6}
Gulf Clenes	0.83×10^{-6}	2.0×10^{-6}
Kendall	0.61×10^{-6}	1.5×10^{-6}

The thermal coefficient of expansion as a function of temperature may be expressed as follows:

$$b = b_o + 1.055 \times 10^{-9}\, t$$

b = mean coefficient from room temperature to t°F

(10) Elastic Modulus[14]. Modulus of Elasticity in psi

Type of AGOT	Parallel	Perpendicular
Whiting	14.6×10^5	9.3×10^5
Gulf Clenes	14.9×10^5	------
Kendall	19.4×10^5	8.9×10^5

(11) Tensile Strength[14,15,17]. Since only Van der Waals forces act between planes of the graphite crystal, slip or cleavage would be expected to readily occur. Consequently, tensile strengths have been reported in the low range of 1200 to 1500 psi; for example

Parallel to axis	1490 psi
Perpendicular to axis	1335 psi

SECRET

DECLASSIFIED

(12) Crushing Strength. Crushing strengths have been reported in the range of 2700 to 5100 psi; for example:

Parallel to axis	4766 psi
Perpendicular to axis	5130 psi

(13) Poisson's Ratio. No experimental data are available for study. A value of 0.2 has been assumed as a conservative estimate for purposes of calculation.

(14) Thermal Stability. Graphite remains stable at extremely high temperatures, that is, below 2000°C. It will not sinter at temperatures as high as 2500°C even under pressure (4000 psi).

Because of the fortuitous combination of low thermal expansion, high thermal conductivity and moderate plasticity, graphite exhibits a very high resistance to thermal shock.

A very serious limitation on the use of graphite is the rather moderate oxidation temperatures in the presence of air, 1100 to 1300° F. Long exposure at temperatures above 700°F. will produce appreciable damage from oxidation.

(15) Plasticity[14,15]. Graphite has moderate plasticity at temperatures above 2000°C. Tests indicated that graphite would readily flow at 2400°C but only very little at 2200°C. Petroleum cokes become plastic at temperatures as low as 1650 to 1700°C.

(16) Effect of Extrusion. During extrusion there is a tendency for the particles to line up with their long axis parallel to the axis of extrusion. This results in directional effects on the following properties; thermal expansion, thermal conductivity, electrical resistivity, elastic modulus, the various strengths, etc.

(17) Coefficients of Friction[15]. The low coefficient of friction of graphite has made it useful for its antifrictional characteristics in combination with its thermal and chemical stability. Values for the coefficient of friction are listed below.

Condition	Coefficient of Friction
Static	0.31
Sliding	0.22

(18) Nuclear Physics Data [14,19]

σ_{tr} = 4.8 barns

σ_{a} = 0.0045 barns

DECLASSIFIED

The effect of neutron absorption of impurities in AGOT graphite is shown in the following table:

Type of Graphite	Whiting	Gulf Clenes	Kendall
Boron	0.00056 barns	0.00048 barns	0.00041 barns
Vanadium	0.00023 barns	0.00004 barns	0.00001 barns
Calcium	0.00004 barns	0.00002 barns	0.00002 barns
Titanium	0.00001 barns	0.00001 barns	0.00001 barns
Iron	0.00001 barns	0.00001 barns	0.00001 barns
TOTAL	0.0085 barns	0.00052 barns	0.00046 barns

Value for AGOT graphite 0.0045 barns

Value for pure graphite (calcd.) 0.0040 barns

(19) Resistance to Chemical Attack. From the chemical standpoint, graphite is inactive, resisting the action of most acids, notably hydrofluoric, alkalies and other chemicals, which are not highly oxidizing in their behavior. The fact that graphite burns on exposure to air at high temperatures seriously restricts its application in many fields. Graphite is subject to wet oxidation by strong oxidizing agents, which apparently penetrate the planes and exfoliate the graphite. Typical oxidizing agents are potassium chromate in phosphoric acid and liquid bromine.

It is considered possible that extraneous atoms, of H,N,O, etc., depending on the atmosphere present during manufacture, attach to the edges of crystals. Graphite after heating in H_2 in not wettable by water; however, graphite which has been heated in air takes up water readily -- a property which it loses after standing for some time.

(20) Porosity and Permeability. Standard AGOT graphite has an approximate value of porosity of 18 per cent. Special porous graphite (ca. 50%) has been made for high gas or liquid permeability. On the other hand, high density, low porosity graphite which is nearly impermeable to gases can be produced by special techniques.

(21) Resistance to Irradiation[11,14]. Each fission neutron will produce about 2000 displaced carbon atoms, chiefly through intermediary recoil carbon atoms. The resulting disturbances are then of two kinds: holes in the lattice and intersticial atoms lying between hexagonal planes.

DECLASSIFIED

It was expected that displacement of carbon atoms would produce pronounced changes in physical properties. A considerable amount of data has been obtained on the exposure of graphite at low temperatures but none for high temperatures. There is also a great paucity of data on the effect of annealing graphite which has previously been irradiated for relatively long times.

(a) Neutron Bombardment. Exposure for approximately 600 mwd/ct at about 50°C produced a 30 to 35 fold decrease in thermal conductivity, a 5 to 6 fold increase in electrical resistance, a 3 to 4 fold increase in elastic modulus and about a 2 to 3 fold increase in breaking and crushing strengths.

All of the properties would appear to be approaching saturation values. The degree of saturation was most complete for the elastic modulus, breaking and crushing strengths but least for the thermal resistance.

Graphite expands or grows on exposure to fast neutrons. The growth is confined to the direction perpendicular to the axis and is ca. 0.5% expansion for 1000 mwd/ct. in a Hanford test hole. An expansion as high as 2.5% has been observed for longer expsoure in a region of high fast flux.

Neutron irradiation also produces increases in hardness, difficulty of machining, abrasiveness, and stored energy (considered as heat of combustion); however, it causes decrease in the coefficient of thermal expansion.

The effect of short periods of irradiation varies with the type of graphite. It appears to cause increased damage directly with the degree of graphitization; thus lampblack suffers only 1/10 the damage as a special high fired (3000°C) AGOT graphite.

All of the changes can be healed to some extent by annealing, but with increasing exposure the residual changes become greater. Data are too scarce to allow a reliable estimate of the improvements to be expected from various annealing cycles.

Since the most important fundamental experiments on graphite are probably those of energy storage, the following data are reported:

Exposure	Energy Stored After Irradiation	Energy Stored After 1000°C Anneal
45 mwd/ct	57 cal/gm	1 cal/gm
120	105	7.7
212	163	17.6
616	307	90.4

DECLASSIFIED

(b) Fission Recoil. The damage caused by fission recoil is much more extensive than that due to fast neutrons alone. The data available for analysis are very meager. However, the following preliminary results have been obtained at Argonne National Laboratory showing the comparison between pure graphite and an impregnated graphite containing 7 weight per cent U_3O_8 of 30% enrichment. For an exposure of 8 hours the impregnated graphite showed increases of the following magnitudes:

Property	Value after radiation / Value before radiation
Specific Electrical Resistance	1.75
Thermal Resistance	1.50
Modulus of Elasticity	1.55

For comparison purposes pure graphite under the same conditions gave an increase factor of 1.03 for the three physical properties. Relative changes in electrical resistivity for graphite bodies are as shown (7 day exposure in Argonne Pile).

Material	Relative Change
Pure Graphite	1
Impregnated with 7 wt % of natural U	2 to 3
Impregnated with 7 wt % of 30% enriched U	72

The effect of annealing on impregnated graphite which has been irradiated is not known.

DECLASSIFIED

SECRET

4. Thorium Oxide.

Thorium is of importance as a "fertile" material for capturing excess pile neutrons. The process may be represented briefly as follows:

$$1 \text{ neutron} + 1 \text{ atom } Th^{232} \xrightarrow{40 \text{ days}} 1 \text{ atom } U^{233}$$

Consequently, the thorium is eventually transformed into a fissionable atom.

a. Sources of Thorium Oxide[2]. The chief source of thorium has been from monazite sands (thorium and rare-earth phosphates). Black monazite sands are found along the coast of Brazil, New South Wales, on the southwest coast of India, and elsewhere. India has recently held most of the market because of low labor costs.

Thorium occurs in many other forms. As an average, acidic igneous rocks contain ca. 3 to 4 x 10^{-4} per cent of thorium. Sometimes thorium is found in the form of fairly pure crystals: $Th\ O_2$ in Thorite and Thorianite.

b. Chemical Processing of Ores.[25]. Since it is essential that the impurities in Th be as low as possible, it is necessary to purify the thorium compounds. Hexone is used to extract the Th from an aqueous solution which also contains $Ca\ (NO_3)_2$ and HNO_3. The Th is extracted back from the hexone with pure water. It is then precipitated as the oxalate, and calcined at 550°C to give the oxide.

c. Physical Properties.

(1) Crystal Properties.

Thorium oxide, di- (thoria) ThO_2

Molecular wt. 264.12

Cubic crystal, white

Density 9.69

Melting Point 3050°C

Boiling point 4400°C

(2) Thermal Capacity.

Temperature °F	Cp in Btu/lb °F
32	0.0571
162	0.0589

SECRET

DECLASSIFIED

[redacted]

(3) Thermal Conductivity.

Temperature °F	Conductivity in Btu/hr.ft °F
212	7.23
392	4.34
572	3.18
752	2.89

(ρ = 9 gm/cc)

(4) Thermal Stability. Little information is now available on thoria. However, the test samples used to measure the thermal conductivity fractured while under test. If this failure were due to thermal stresses the bodies could be improved by decreasing the density, that is, increasing the porosity.

Apparently, thoria is very inert at high temperatures but its use may be limited by unfavorable physical properties.

5. Thorium.

Thorium, like its oxide, is useful as a fertile material

a. Sources of thorium. The use of thorium and the occurrence of its various ores were discussed in the section on throium dioxide.

b. Chemical Processing of Ores.[25] Fairly pure workable thorium has been produced by three different processes.

(1) Bomb process: The thorium oxide is treated with H_2F_2 under atmospheric pressure at 550°C to give Th F_4. The Th F_4 is reduced by Ca with Zn Cl_2 as a "booster" or auxiliary oxidant to supply additional heat to melt the product and produce massive metal. The dry charge is packed in a steel bomb then heated in a gas furnace at 625°C for 20 minutes when ignition occurs.

The metal separates as a solid ingot of Th-Zn alloy (6% Zn). The Zn is completely distilled away on remelting and casting.

(2) Reduction by calcium metal. Thorium dioxide is mixed with Ca metal and $CaCl_2$ and heated to red heat in a sealed bomb. The resulting oxychlorides of Th and Ca is leached with water and the Th obtained in granular form. The granular metal is pressed into rods and then sintered at about 1300°C. The metal can then be extruded, rolled or otherwise worked.

[redacted]

DECLASSIFIED

(3) Other methods. Powdered thorium has been produced by the electrolysis of K_2ThF_6 fused with a mixture of equal parts of NaCl and KCl. The powdered metal can be pressed, sintered and then worked.

Some thorium has been produced by the decomposition of ThI_4 on a thorium filament.

c. Producers of Thorium. Project metal came primarily from two sources: Ames (reduction of ThF_4 by Ca) and Westinghouse (reduction of ThO_2 by Ca). Representative costs are as follows:

Cast billets	$ 30.00/lb
Powdered compacts	100.00/lb
Extruded rods	60.00/lb

d. Physical Properties[25].

(1) Structure.

(a) Atomic constants.

Crystal lattice: F.C.C.

Atomic number: 90

Atomic weight: 232.12

Stable isotopes: Th^{232} (100%)

Radiation: α- rays 4.20 MEV

half-life 1.39×10^{10} years

Atomic radius: 1.76A

Atomic volume: 20 cc/g atom

(b) Density and hardness.

Material	Density g/cc
Ames cast	11.46
Ames extruded	11.61
Electrolytic	11.1 to 11.49

Material	Hardness (Rockwell E)
Annealed 400-500°C	80 - 92
Annealed 600°C	58 - 80

DECLASSIFIED

(c) Transformation. Thorium is free of phase transitions and is more isotropic than uranium. In general, its properties are somewhat better than those of uranium.

(2) Thermal Properties.

(a) Thermal Expansion.

Temperature Range (°C)	Linear Expansion Coefficient (10^{-6} °C^{-1})
20 - 60	11.1
60 - 100	11.4
100 - 200	11.9
200 - 300	13.1

(b) Thermal Capacity.

Temperature Range °C	Thermal Capacity (cal/g°C)
-253 to -196	0.0197
0 to 1000	0.0276

(3) Melting and Vaporization.

(a) Melting point. 1800 to 1850°C

(b) Boiling point. ca 3800°C

(c) Heat of vaporization. 145 to 177 kcal/g. atom

(4) Electrical Properties

Electrical resistivity. 13 to 25 x 10^{-6} ohms/cm

(5) Mechanical Constants. For extruded stock at 1500°F.

(a) Tensile strength. 42,000 psi

(b) Elongation. 40%

(c) P. L. 25,300 psi

(d) Reduction of area. 38%

DECLASSIFIED

SECRET

(6). Fabrication of Thorium.

(a) Casting. Thorium has been cast in beryllia molds by melting at 1900°C in beryllia crucibles under a pressure of 5 x 10^{-5} mm of Hg. It is very difficult to obtain pure cast metal, since the ThO_2 is soluble in the metal and the melt reacts with the beryllia crucible. The beryllium produced can be boiled out of the melt.

(b) Extrusion. Both cast and sintered thorium have been extruded at about 600° C.

(c) Rolling. Successive cold rolls have been made (15 to 20% reduction) with brief intermediate anneals. One sample (annealed, 69 Rockwell E) after cold rolling to 60% reduction showed a hardness of 83 Rockwell E. The metal has also been hot rolled.

(d) Machining. Thorium can be readily machined, cutting somewhat like mild steel. It can be machined without a coolant; however, the turnings may ignite. The wear on cutting tools is high. Although thorium drills readily, it is very abrasive on drills. The surface of the metal produced by grinding is satisfactory.

(e) Recrystallization. Complete recrystallization can be obtained at 575 to 585°C or higher for a period of 10 hours or less. Very little or only incomplete recrystallization can be obtained at lower temperatures.

(7) Resistance to Chemical Attack. Thorium is quite active chemically.(2) It is attacked slowly at room temperature by air (changes from silver - white to dark gray) and reacts rapidly at higher temperatures with hydrogen, oxygen, nitrogen and halogens. It is only very slowly attacked by boiling water, but at higher temperatures corrosion by water vapor is appreciable. The molten metal (above 1600°C) reacts with beryllia, graphite, lime, magnesia and zirconia.

SECRET

DECLASSIFIED

[redacted]

6. Thermal Stress Figure of Merit.

This is a combination of material properties which have been found convenient and significant for the evaluation of various materials with respect to resistance to thermal stress. It is defined as follows:

$$\text{Thermal stress figure of merit} = \frac{S_t k (1 - \sigma)}{Eb}$$

where,

E = Young's Modulus

b = Thermal Coefficient of Expansion

k = Thermal Conductivity

σ = Poisson's Ratio

S_t = Tensile Strength

The values of the figure of merit for unirradiated graphite, BeO, and Be, calculated on the basis of the material properties given previously, are as follows:

Material	Operating Temperature, °F.	Thermal Stress Figure of Merit
Graphite	500	25,000
	1000	14,000
	1500	8,000
BeO	500	2,500
	1000	1,300
	1500	700
Be	500	5,000
	1000	3,000

[redacted]

DECLASSIFIED

7. High Temperature Thermal Conductivity Experiment.

Very little information exists concerning the simultaneous effect of irradiation damage and annealing at high temperatures. The meager data that have been obtained suggest that the net damage resulting from simultaneous irradiation and annealing may not be as serious as that indicated by irradiation at moderate temperatures followed by annealing. In addition, the conductivity as measured at room temperature may not be a valid criterion of damage at high temperatures. Accordingly, an experimental program has been initiated to determine the simultaneous effect of irradiation damage and annealing by measuring the thermal conductivities of samples, which contain fissionable material, during the time that they are exposed within the X-pile at Clinton Laboratories.

a. Method. The test specimens are cylinders, 2 c.m. in diameter and 5 c.m. in length containing a known weight of U^{235}. When exposed in a region of a known thermal flux the amount of heat generated is fixed and calculable. Thermocouples are used to measure the actual temperatures and temperature differences across the specimens. The samples are mounted in special units such that the desired operating temperatures are reached. The thermal conductivities are calculated from the experimental data, the physical properties, and the dimensions of the test specimens.

b. Materials Tested. Samples of the following materials were obtained for tests:

1. Impregnated graphite
2. Molded graphite
3. Impregnated BeO
4. Molded BeO

c. Status. Initial tests are now under way, but insufficient time has elapsed to secure results.

DECLASSIFIED

SECRET

List of References on Materials

1. Pile Technology, Lecture #19, "Beryllium Oxide" presented by C. R. McCullough Feb. 14, 1947

2. Pile Technology, Lecture #26, "Distribution of Uranium, Thorium and Beryllium Ores and Estimated Cost" by Clark Goodman

3. The Production of Beryllium Oxide and Beryllium Copper by B. R. F. Kjellgren - Trans. of Electrochemical Society Vol. 89, 1946, 247-261

4. CF-3807 March 4, 1947

5. Technical Information from Clifton Products, Inc. Reference A, Sept. 25, 1945

6. MUC-KW-60 April 12, 1946

7. MON-P-304 April 1, 1947

8 R. G. Sachs Lecture in Theoretical Nuclear Physics

9. Progress Report of Strength and Creep of Special Ceramic Bodies in Tension at Elevated Temperatures by R. F. Geller and M. D. Burdick N.B.S., ARR, No. 6D24, Washington June 1946

10. ANL-CAB-13 Irradiation History of BeO, BeO-UO_2 Samples 6-197 by J. R. Gilbreath 6-6-47

11. Pile Technology, Lecture #33 Effects of Radiation on Materials - Solids by S. Siegel

12. ANL-CAB-7 Feb. 5, 1947 J. R. Gilbreath

13. Preliminary Report on Microscopy of BeO Powders and Bricks by L. T. Newman 7-8-47

14. Pile Technology, Lecture #21 and 22 Production and Properties of Graphite by H. G. MacPherson

15. CL-696 Vol. I, II E, 1 Project Handbook

16. Handbook of Chem. & Physics

17. Carbon, Graphite & Karbate Products - National Carbon Co., Inc. 1946

18. ANL-OCS-93, 97 and 103

19. MON-P-289 April 28, 1947

20. Pile Technology, Lecture 10 and 11 - Metallurgy of Beryllium by A. R. Kaufmann

SECRET

DECLASSIFIED

SECRET

21. Memo from C. R. McCullough to Memo 2-3-47 Design Study for a Beryllium Metal Power Pile

22. Beryllium - Its Production and Application Reinhold Pub. Corp. 1929

23. Reine Metalle by A. E. van Arkel 1939 Edwards Brothers, Inc. 1943

24. BMI-HRN Memo No. 1,2,3,4,5,6,7,8

25. Metals Handbook 39Ed.

27. Westinghouse Research Laboratories, East Pittsburgh Research Memo SM-583, Creep-Rupture Tests of Beryllium June 2, 1947

SECRET

DECLASSIFIED

SECRET

VI. DESIGNS FOR HIGH OUTPUT GAS-COOLED POWER PILES

This section presents the results of a preliminary evaluation of the use of high temperature gas-cooled piles for the production of relatively large amounts of power (60,000 and 250,000 kw of heat). The studies were made in accordance with the general principles presented in Section III, using the methods of calculation described in Section V. In making these studies the work has been carried only far enough to establish the general features of the design, namely, the nature and dimensions of the pile structure, the critical mass of fissionable material, the nature of the fuel elements, the possibilities of high conversion, etc.

A. 250,000 KW DESIGN

The studies of a gas-cooled pile rated at 250,000 kw included consideration of beryllium oxide, beryllium metal, and graphite as the permanent structure and moderating material.

1. Design Conditions

The following design conditions were assumed:

Pile Thermal Rating, KW	250,000
Coolant	Helium
Operating Pressure, Atmos.	40
(a similar performance could be achieved with Hydrogen gas operating at 18 atmos.)	
Ratio Thermal Power to Blower to Pile Thermal Output, R	0.15
Efficiency of Conversion of Thermal Input to Blower to Blower Pressure - Power	0.15
Radial Heat Release Ratio, Fx	1.5
Axial Heat Release Ratio, Fy	1.28
Heat Generated in Structure, based on local Rate in Fuel Elements	$\frac{\text{Mass structure}}{\text{total mass}} \times 8\%$
Ratio Pressure Drop in Gas System to Pressure Drop in Pile	1.4

SECRET

UNCLASSIFIED

SECRET

Design Conditions (continued)

Ratio Pressure Drop in Pile to that Used for Heat Transfer	4.0
Length of Reactor	.9D
Length Reactor + Reflector	1.5 Reactor
Fuel	U^{235}
Enrichment	30%
Temperature at which nuclear constants were calculated	650°C

	BeO	Be	Graphite
Maximum Allowable Fuel Element Temperature	2,000°F	1,500°F	2,000°F
Maximum Allowable Permanent Structure Temperature	1,500°F	1,100°F	1,500°F
Pile Inlet Temperature	500°F	450°F	500°F
Pile Outlet Temperature	1,400°F	1,100°F	1,400°F

The performance of these piles was calculated based on the following thermal stress limitations,

BeO (density, ρ = 2.87):

$$\text{Fuel elements} = \frac{14,500}{5.5 \times 2 \times 1.5} = 900 \text{ psi}$$

where 5.5 is a radiation damage factor
2.0 is a factor of safety to take care of transient conditions
1.5 is a factor to take care of the eccentric loading of the fuel elements

$$\text{Moderator bricks} = \frac{14,500}{1.5 \times 3.0} = 3,200 \text{ psi}$$

where 1.5 is a radiation damage factor
3.0 is a factor of safety to take care of transient conditions

Graphite

$$\text{Fuel Elements} = \frac{1,400}{80 \times 2 \times 2.0} = 4.37 \text{ psi}$$

where 80 is a radiation damage factor

SECRET

DECLASSIFIED

SECRET

Moderator bricks $= \frac{1,400}{20 \times 4.0} = 17.5$ psi

where 20 is a radiation damage factor

Beryllium

Fuel Elements - no thermal stress limitations

Permanent structure = 2,000 psi total stress limitation

The thermal stresses were calculated using the idealized stress equations for elastic deformation with the values for conductivity, Young's modulus and expansion coefficients for the actual operating temperatures as given in the properties of materials section of this report. The values without radiation damage were used and the above stress factors were applied to take care of radiation damage. The conditions at the center of the pile were considered to be the most severe and a heat generation of 1.89 times average was assumed for both the fuel elements and moderator bricks.

2. Performance

The locus of pile designs is plotted on Figures 96, 97, and 98 for BeO, Be, and graphite moderated piles, respectively. Curve I of Figure 96 shows the locus of pile designs for an allowable fuel element stress of 900 psi and with a BeO fuel element material density of $\rho = 2.1$. Thus this curve gives critical mass, pile voids, and excess neutrons produced per neutron absorbed in U^{235}, X,* as a function of the radius of the reactor for 250,000 KW output helium-cooled piles designed as specified above. It can be seen from this curve that if a minimum critical mass is desired the pile would be designed with a reactor radius of 90 cm and 6.1 kg critical mass. However, this has an excess neutron per neutron absorbed in U^{235} of X = 0.87 for U^{235} fuel. If a higher X is desired, a pile with 75 cm radius requiring 10 kg ciritical mass of U^{235} could be chosen. This pile has an X of 1.045.

---

*X, the excess neutrons produced per neutron absorbed is defined as the neutrons which leave the reactor plus those absorbed by the U^{238} plus those absorbed by poisons such as Xenon per neutron absorbed in U^{235}. It is a measure of the neutrons available for conversion.

SECRET

DECLASSIFIED

Curve II shows the operating line for a stress limit of 900 psi but using a fuel element density of $\rho = 2.87$. This curve does not extend beyond $\alpha = .5$ because above this point the web thickness of the fuel elements becomes less than 1/32". This thickness is now considered a practical limit in manufacture. Tests of BeO fuel elements of $\rho = 2.87$ and $\rho = 2.1$ indicate that the less dense material has about twice the thermal stress resistance of the 2.87 density material. Advantage of this higher thermal stress resistance was taken in calculating Curve I of Fig. 96.

Curve III is the locus of possible piles if the allowable fuel element stress is 3,500 instead of 900 psi. Curve IV is the line if there is no stress limitation, that is, for piles which are designed to meet the heat transfer and pressure drop requirements only.

It can be seen that a cylindrical gas-cooled pile with BeO moderator designed for 250,000 KW thermal output would lie somewhere between Curve II and Curve IV. Based on presently available BeO materials and their physical properties, Curve I appears to be a reasonable design line. However, it is possible that annealing out of radiation damage at high temperatures, alloying of BeO, or modification of its granular structures to increase its thermal stress resistance would reduce the operating line toward Curve IV as a limit.

Figure 97 shows the performance of a Be moderated, 250,000 KW gas-cooled pile designed for the specifications given above. Only one operating line is shown since there is assumed to be no thermal stress limitation in the fuel elements. This is a reasonable assumption since plastic flow, of a very small magnitude, will take place relieving any large thermal stresses which may tend to form. The particular design point will, of course, be dependent upon the emphasis on conversion as compared to the emphasis on minimizing critical mass.

The performance of a graphite moderated 250,000 KW gas-cooled pile is shown in Figure 98. Curve I shows the locus of possible design points for a fuel element design stress of 4.37 psi, while Curve II is the locus for a design stress of 350 psi. Curve III is the locus if there were no thermal stress limitation. The stress limitation of 4.37 psi for graphite arises from the choice of a conservative value of 80 for the radiation damage factor.

The values of X (excess neutrons) for U^{235} is shown for the three moderator materials. Since η for U^{235} is only 2.1, it is apparent that it will be extremely difficult to achieve breeding with this fuel. However, if U^{233} is used as a fuel, with its $\eta = 2.3$ to 2.4, the values of X can be expected to be between 1.2 to 1.25, and the possibility of attaining breeding becomes more promising.

The use of a high efficiency conversion blanket, may lead to an abnormally high value for the maximum to average heat release ratio. However, the ratio (1.91) which has been used for the designs considered herein, is itself considerably higher than would be expected in a pile with a good reflector.

The pile sizes, critical mass of fissionable material and excess neutrons of all three of these moderators are sufficiently favorable that no one of these can be considered sufficiently good or another sufficiently bad to exclude the other two. Therefore, the details for representative designs of all three moderators is presented in Table XVIII. Only the conservative designs with radiation damage are presented.

DECLASSIFIED

SECRET

TABLE XVIII

PERFORMANCE OF 250,000 KW GAS-COOLED PILES

Moderator	BeO		Be		Graphite
Design point on Figures 96, 97 and 98	A	B	C	D	E
Critical Mass U^{235}	6.2	10.2	6	8.7	15.8
X (excess neutrons per absorption) if fuel is U^{235}	0.915	1.045	0.88	1.016	1.040
Diameter of reactor, ft.	5.64	4.9	5.05	4.52	6.87
Length of reactor, ft.	5.1	4.4	4.6	4.1	6.19
% Voids, α (in the case of BeO is physics voids with ρ = 2.87)	46%	53%	40%	50%	40%
Gas Passage Area, A_g, sq. ft.	10	9.14	8.0	8.0	14.6
Temp. diff. between Gas and Fuel Element at center of pile, θ_o	250	300	645	645	85
Maximum Fuel Element Temp., ^oF	1580	1600	1500	1500	1450
Structure					
Brick Hole or Permanent Structure Size	2"hex	2"dia	4"i.d. sq.	4"i.d. sq.	2"dia
Brick Wall Thickness	5/16"	1/4"	9/32"	1/4"	1/4"
Fuel Elements					
Equivalent Dia. D_e(")	.182"	.1895"	.35"	.336"	.082"
Fuel Element Wall Thickness, inches	.055"	.038"	1/16"	1/16"	1/32"
Stresses					
Fuel Elements	900	900	----	----	4.37
Permanent Structure	2,600	3,000	2,000	2,300	17.5
Estimated Average Flux	$5x10^{14}$	$4x10^{14}$	$5x10^{14}$	$4x10^{14}$	$3x10^{14}$

SECRET

DECLASSIFIED

SECRET

The fuel element and structure shapes of the various designs is shown in the following figures:

BeO Unit A	-	Figure 99
BeO Unit B	-	Figure 100
Be Unit D	-	Figure 101
Graphite Unit E	-	Figure 102

The fuel elements of all these units are relatively small, i.e., 2" to 4" dimensions. This results from the fact that the thermal stresses due to the heat generated in the structure limits the structure thickness to approximately 1/4". With this thickness of only 1/4" a small brick size (or Be frame spacing) must be used to assure a mechanically strong structure. Furthermore, to minimize fissionable material requirements it is desirable to place as much material in the permanent structure as possible. This is accomplished by using small fuel elements as pointed out in Section III. The BeO Unit A is shown as a hexagonal brick with a circular hole. This difference in design is shown because the best brick shape from a thermal stress standpoint is not known. Present information indicates that the shape shown for the B Unit is twice as good as that for Unit A because of the elimination of corner stress, but a thicker section is required. The fuel element wall thickness for the BeO and graphite units range from 1/32" to 1/16" thick. These thin walls again result from the low values of allowable fuel element thermal stresses which were assumed in the study. Such thin wall structures have been extruded in Germany of natural clay; a full size picture of such a structure is shown in Fig. 103.

B. 60,000 KW DESIGN

1. Design Conditions

In making this study of a gas-cooled pile rated at 60,000 KW thermal output consideration was given to its possible application to naval ship propulsion. Accordingly, in addition to the design conditions assumed previously for the 250,000 KW unit, the following special conditions peculiar to this type of service were assumed:

Rating	15,000 shaft horsepower
Pile space allowed	Minimum possible
Critical Mass of Fissionable Material	" "
Conversion	As much as possible, but at no sacrifice of above requirements
Fuel Loading	Pile to run 6 months at 20% load without reloading

SECRET

DECLASSIFIED

The pile heat exchange fluid was assumed to be helium and the study limited to a BeO moderator.

The pile chosen to meet these specifications is as follows:

Thermal Rating	60,000 KW
Reactor dimensions	
Reactor diameter	3.8 ft.
Reactor length	3.4 ft.
Critical Mass U^{235} (at op. temp. = 650°C)	3.5 Kg
X (excess neutrons per absorption in U^{233})	1.0
U^{235} consumed in 6 months	2.0
Cross-section area of pile devoted to control rods	11%
Fuel plate thickness	.042"
Gas passage equiv. diameter	.087"
Fuel element thermal stress	900 psi
Operating Press	40 Atmos
Inlet temperature	500°F
Outlet temperature	1400°F
Temperature difference between gas and fuel element at center of pile, θ_0	140°F
Maximum pile temperature	1520°F
% Pumping power	20%
Gas duct sizes	
entering pile	2 - 10"
leaving pile	2 - 14"

DECLASSIFIED

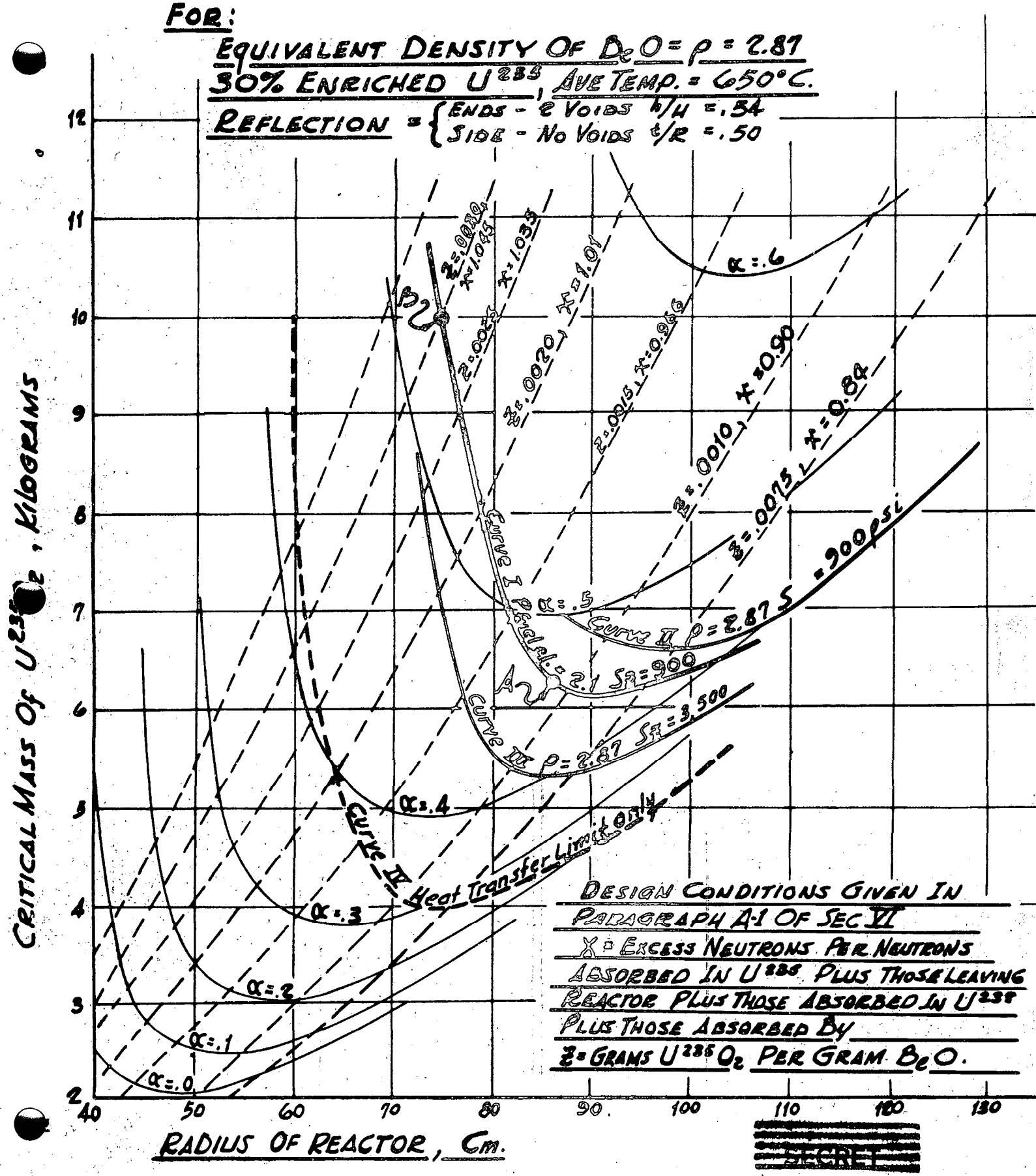
LOCUS OF POSSIBLE PILE DESIGNS FOR 250,000 THERMAL K.W. OUTPUT FOR A B_eO MODERATED AND REFLECTED CYLINDRICAL PILE

FOR:

EQUIVALENT DENSITY OF $B_eO = \rho = 2.87$

30% ENRICHED U^{235}, AVE TEMP. = 650°C.

REFLECTION = { ENDS - 2 VOIDS h/H = .54; SIDE - NO VOIDS t/R = .50 }



DESIGN CONDITIONS GIVEN IN PARAGRAPH A-1 OF SEC VI

X = EXCESS NEUTRONS PER NEUTRONS ABSORBED IN U^{235} PLUS THOSE LEAVING REACTOR PLUS THOSE ABSORBED IN U^{238} PLUS THOSE ABSORBED BY

Z = GRAMS $U^{235}O_2$ PER GRAM B_eO.

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

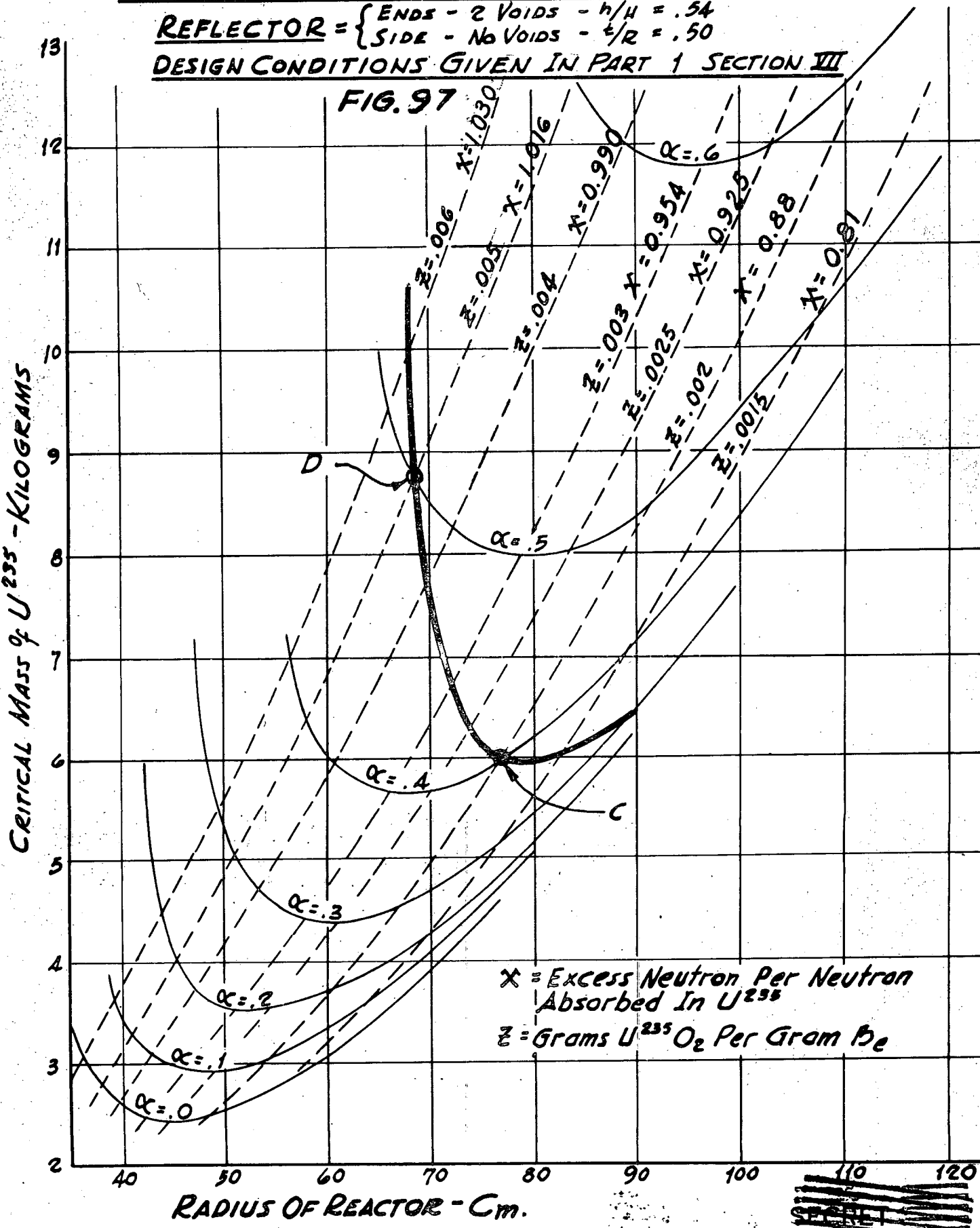
SECRET

LOCUS OF POSSIBLE PILE DESIGNS FOR 670,000 THERMAL K.W. OUTPUT FOR A B_e MODERATED and REFLECTED CYLINDRICAL PILE FOR 30% ENRICHED U^{235} AVE. TEMP. 650°C

REFLECTOR = { ENDS - 2 VOIDS - h/H = .54
SIDE - NO VOIDS - t/R = .50 }

DESIGN CONDITIONS GIVEN IN PART 1 SECTION VII

FIG. 97



SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

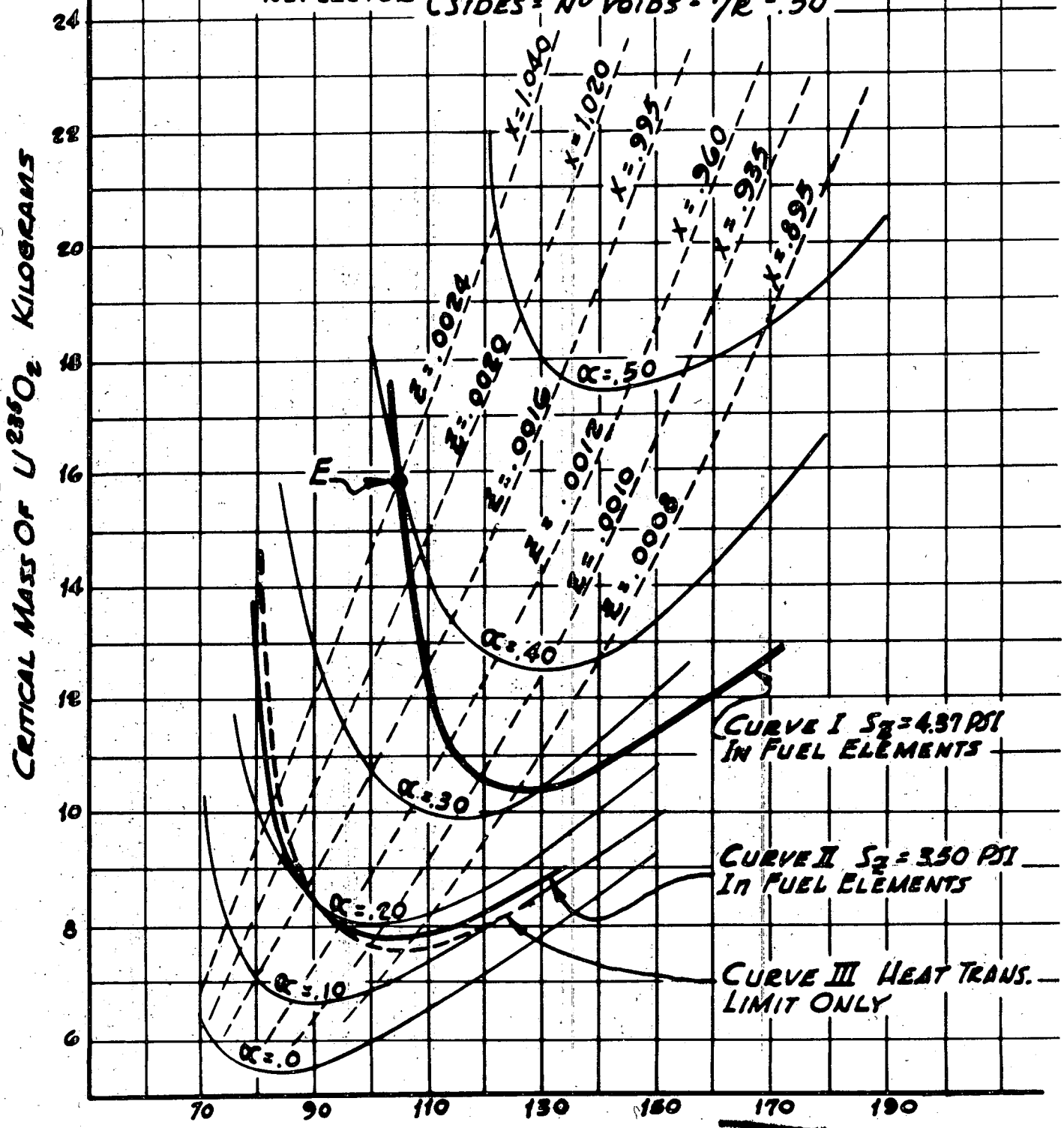
UNCLASSIFIED

[redacted]

FIG. 98

LOCUS OF POSSIBLE PILE DESIGN FOR 250,000 K.W. OUTPUT OF A GRAPHITE MODERATED and REFLECTED CYLINDRICAL PILE

GRAPHITE DENSITY = 1.60
U^{235} = 30% ENRICHMENT
AVERAGE TEMP. = 650° C.
REFLECTOR { ENDS = α VOIDS - h/H = .54
SIDES = No VOIDS - T/R = .50



[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

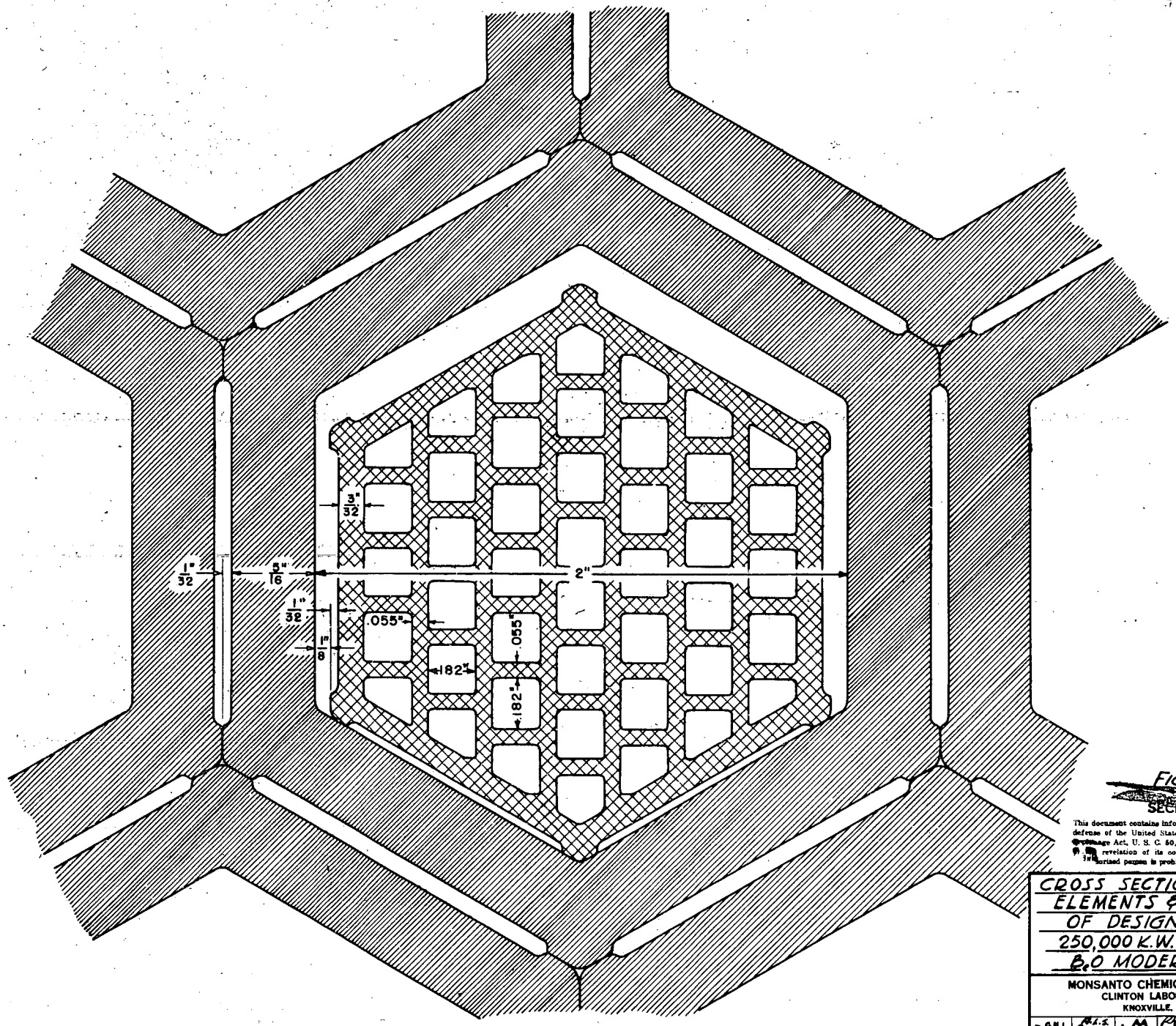


FIG. 99

~~SECRET~~

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or revelation of its contents in any manner to an unauthorized person is prohibited by law.

CROSS SECTION OF FUEL ELEMENTS & BRICKS OF DESIGN "A" 250,000 K.W. UNIT B_2O MODERATOR

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. G.N.L. 7-18-47	C. 7-18-47	A. 7/18/47	7-17-47			
PROJ. C-222 M						
SCALE: 4" = 1"						C-2249

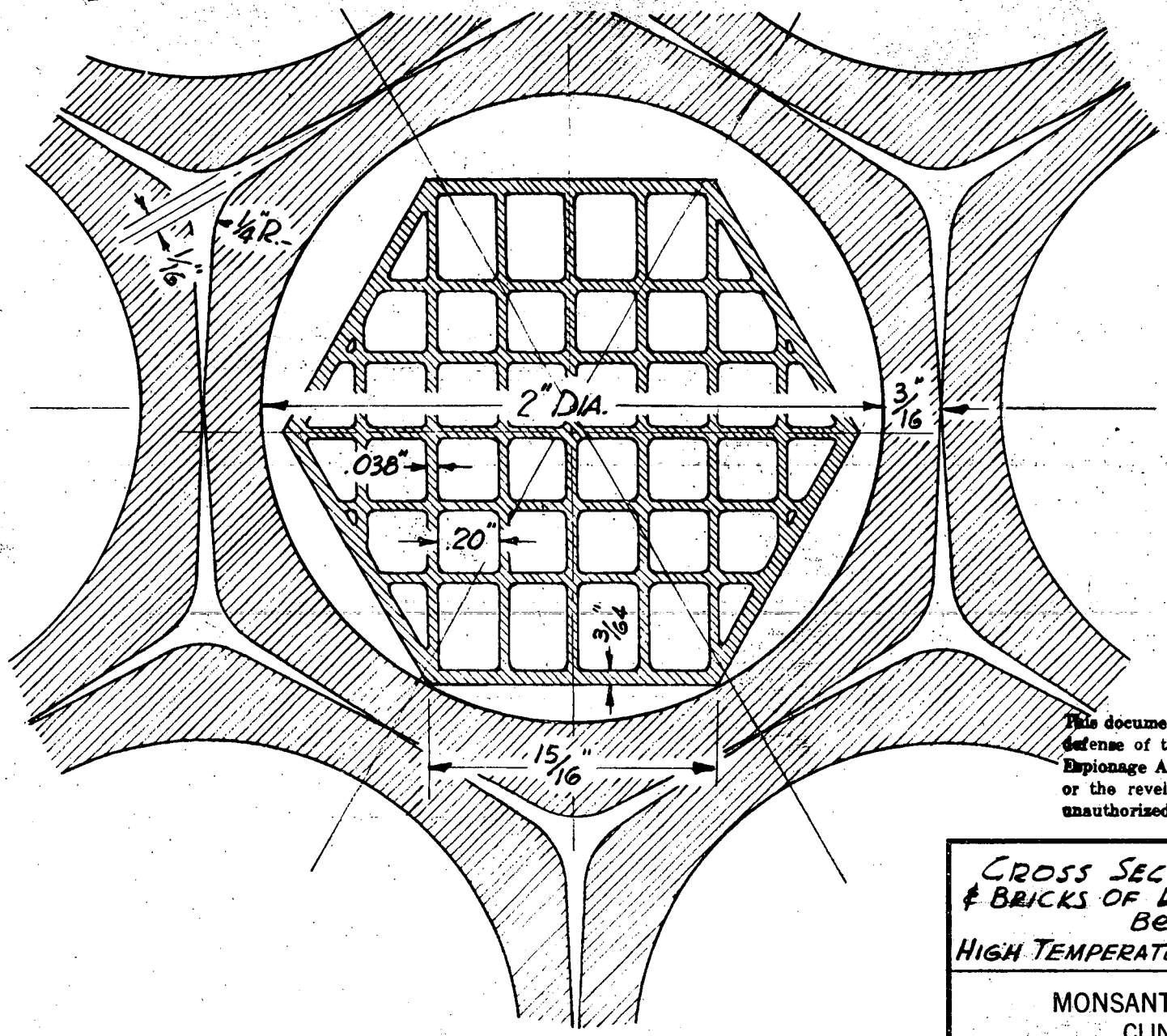


FIG. 100

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CROSS SECTION OF FUEL ELEMENT & BRICKS OF DESIGN B 250,000 KW BeO MODERATOR
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.N.L. 8-22-47	C. H.L.S. 8-22-47	A. R&P 9-16-47				
PROJ. C-222M			A-2297			
SCALE: 2"=1"						

~~SECRET~~

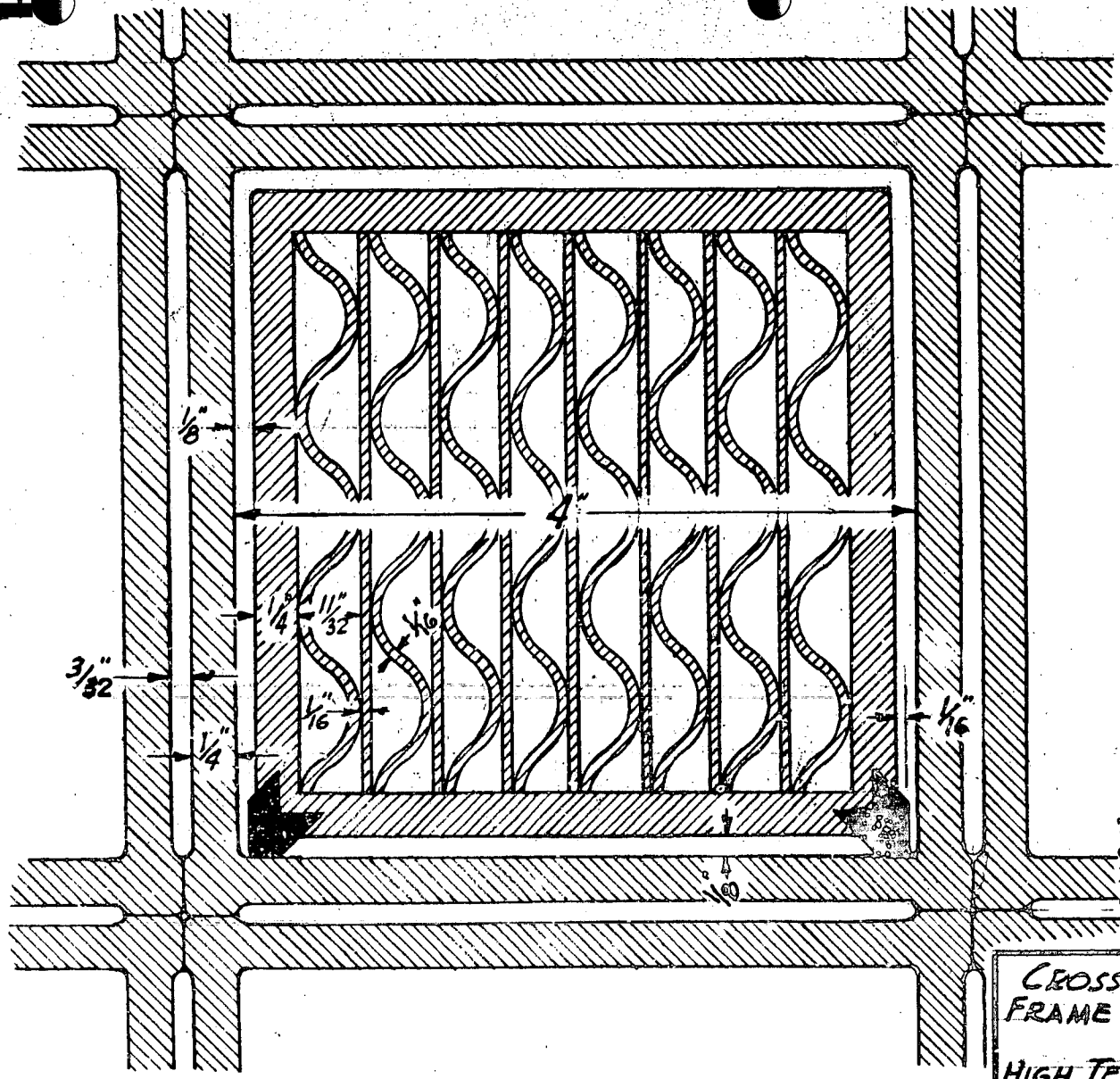


FIG. 101

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CROSS SECTION OF FUEL ELEMENT & FRAME OF DESIGN D 250,000 KW UNIT
Be MODERATOR
HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.N.L 8-22-47	C. R.L.S. 8-22-47	A. AA 8/22/47	RSP 9-16-47			
PROJ. C-222 M				A-2296		
SCALE: FULL						

~~SECRET~~

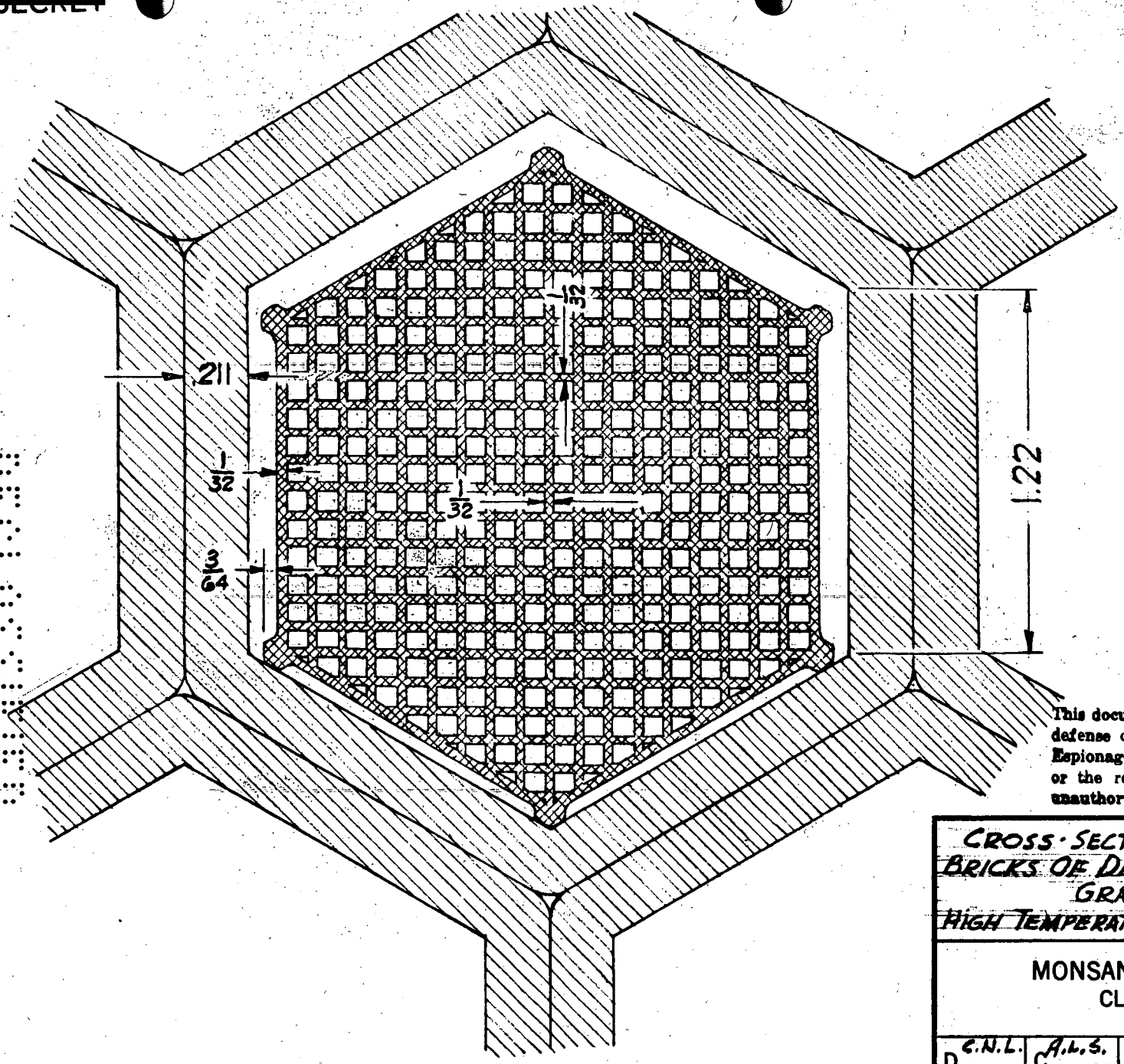


FIG. 102

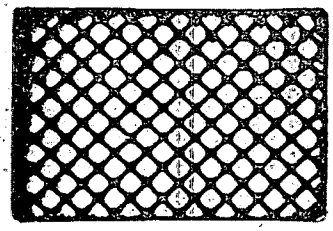
~~SECRET~~

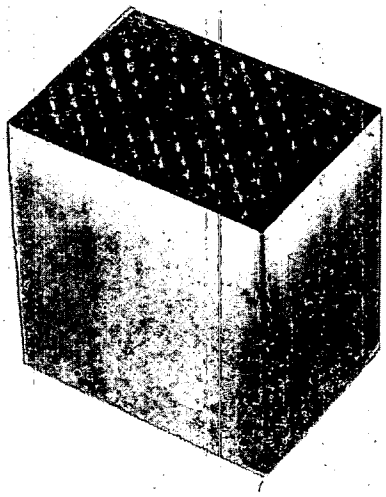
This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

CROSS-SECTION OF FUEL ELEMENT & BRICKS OF DESIGN "E" 250,000 KW UNIT GRAPHITE MODERATOR HIGH TEMPERATURE GAS COOLED POWER PILE

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

D. C.N.L. 8-19-47	C. A.L.S. 8-19-47	A. NGP. 8-19-47	RSP 9-16-47			
Proj. C-222M				A-2293		
SCALE: 2"=1"						





FULL SIZE

FIG. 103

GERMAN THIN WALL STRUCTURE

EXTRUDED OF NATURAL CLAY

DECLASSIFIED

SECRET

VII. RECOMMENDATIONS

It is the opinion of the Division that the pile described in this report can be built and operated successfully for the purposes described. A current directive by the Atomic Energy Commission provides for continued study of power reactors; but on the other hand, does not provide for early construction of a power reactor of any type. The Division has, therefore, submitted a program intended to further the development of power reactors within the scope of the Commission's directive. This program was submitted to the Administration of Clinton Laboratories as part of a letter dated September 12, 1947. The program is as follows:

"POWER PILE DIVISION PROGRAM

Fiscal Years, 1948, 1949, and 1950"

"I. Broad Evaluation of Power Reactors
(A preliminary engineering study of general designs of power reactors).

A. Survey and classification of reactors proposed or conceived for high temperature operation and production of power.

B. A preliminary appraisal of more promising power reactors as determined by Item A from the standpoints of nuclear physics, heat transfer, control, materials, chemistry, thermodynamic cycles, economics, mechanics, etc.

It is considered that the broad evaluation of power reactors is a continuing function of the Power Pile Division of Clinton Laboratories. The attainment of its objectives will be the recommendation for detailed evaluation of one or more reactors each year so that the Atomic Energy Commission can be continuously kept up to date as to the aspects of power from atomic energy."

"II. Detailed Evaluation of Power Reactors
(Preliminary design of reactors selected by broad evaluation studies)

A. Nuclear and conversion studies associated with the particular design

B. Specific selection of heat transfer medium, moderator, fuel and fertile material.

C. Determination of preliminary dimensions of the pile

D. Evaluation of engineering problems and establishment of test programs peculiar to particular designs.

E. Study of materials adapted for use in high temperature reactors, tabulation of properties, and recommendations for test and experimental evaluation programs.

SECRET

DECLASSIFIED

F. Preliminary design of over-all nuclear power plants and also of basic components, such as structure of reactor, shielding, fuel handling equipment, fuel elements, coolant system auxiliaries, heat exchangers, etc."

"III. Design of High Temperature Experimental Reactor

A. Preparation of design specifications.

B. Layout design.

C. Detailed design and construction of components required for preliminary test work.

This activity would begin in the fiscal year 1949 upon the approval of the Atomic Energy Commission for the construction of an experimental high temperature reactor. It would be expected to start approximately May 1, 1949, and would consist of a substantial part of the group from the detailed evaluation of a power reactor. Since the manpower figures are given as averages for the year, the number of persons shown is far less than those who will be actively engaged as of July 1, 1949. It is expected that the need for, and desirability of, constructing such an experimental high temperature reactor would evolve from the broad and detailed evaluation studies described under Items I and II, and the work on development and testing of materials and processes described under Item V. Thus, it is visualized that the evaluation studies would lead to the general specifications for a pilot plant utilizing that type of power reactor which would be of particular significance in the development of atomic power and its associated technology. Similarly, the work on materials and testing is expected to lead to the determination of the type of tests and test facilities which are required for adequate development of materials, processes, and mechanisms for nuclear power plants. The construction of a suitable experimental high temperature power reactor will represent an integration of these over-all objectives."

"IV. Cooperation in the design of the Hetrogeneous High Flux Reactor

A. This will consist of recommendations and preliminary designs of such features of the high flux reactor of particular interest to the Power Pile Division. For example, the facilities to be provided for the simultaneous high flux and high temperature testing of materials is at present under active consideration by members of the Power Pile Division.

B. Cooperation as requested by the Technical Division in the design of certain features of the high flux pile by members of the Power Pile Division who are particularly expert and experienced in these fields.

C. Cooperation with the Technical Division and the Pile Review Committee, as requested, in the review and evaluation of designs as prepared because of the large general engineering experience of certain members of the Power Pile Division.

DECLASSIFIED

It is expected that this feature of the Power Pile Division program will be mainly covered in the fiscal year 1948, since the construction schedule of the high flux reactor presupposes that all designs will be frozen before July 1, 1948."

"V. Development and Testing of Materials and Processes

A. Investigation and development of materials for use in the construction of power reactors. This includes beryllium metal, beryllium oxide, graphite, and related substances.

B. Study and design of processes necessary to the construction and operation of power reactors. For example, recovery of uranium from fuel elements, purification of coolant, fabrication of fuel elements.

C. Design and performance of tests as required; such as, mechanical and thermal testing of moderator and fuel materials; effects of radiation; life and functional testing of valves, gaskets, fuel handling devices, etc.; diffusion of fission products; exponential experiments. For a more detailed breakdown of this program, see letter and attachments of August 7, 1947 to J. C. Stewart.

This program is a continuing one with a large number of detailed objectives which will be reached as suitable new materials are developed, the properties of materials determined, processes are devised and proven, and mechanisms are found to be satisfactory and durable. It is expected that a considerable portion of the effort on this program will be dedevoted to the development of adequate tests and adequate experimental facilities for determination of radiation effects on materials."

"VI. Construction and operation of a Reactor Simulator Laboratory

It is proposed to construct a simulator, which is in reality a nuclear flux calculator for the study of the physics problems of reactors, which includes the determination of critical size, flux distribution for any geometry, multiple region problems and many other problems where the physical constants are a function of space. The equipment will consist of electrical networks, electronic circuits, and instrumentation. Work has already started on this simulator, as it was a necessary approach to the solution of the manpower shortage for the design of the high temperature gas-cooled power pile. It is realized that this simulator is of much more general use to the project than the problems of the Power Pile Division; and it is therefore, proposed as a service to the project as a whole."

DECLASSIFIED

SECRET

APPENDIX A

CONSULTANT SUBCONTRACTORS
to
POWER PILE DIVISION

Air Reduction Company
Babcock & Wilcox Company
Combustion Engineering Company
DeLaval Steam Turbine Company
Foster-Wheeler Company
Fredric Flader, Incorporated
General Electric Company
National Carbon Company
Purdue University
Westinghouse Electric Corporation
Colvin, Fred H.
Daniels, Farrington
Randolph, Donald W.
Willard, John E.
Yellott, J. I.
Wright Aeronautical Corporation

SECRET

DECLASSIFIED

SECRET

APPENDIX B

LIST OF PERSONNEL ON POWER PILE DEVELOPMENT

C. ROGERS McCULLOUGH, DIRECTOR

Dr. Farrington Daniels - Special Consultant

Allis-Chalmers Mfg. Co.

Anderson, G. A.	Mech. Engr.	Design and development
Etherington, H.	Mech. Engr.	Engineering development

Babcock & Wilcox Co.

Moore, W. T.	Mech. Engr.	Boilers and refractories

Combustion Engineering Co.

Marshall, L. J.	Mech. Engr.	Boilers and power plants

Fredric Flader, Inc.

Corey, V. B.	Physicist	Control design (terminated)
Downing, G. G.	Mech. Engr.	Gas turbine and rocket motors
Preston, A. L.	Mech. Engr.	Gas handling equipment

General Electric Company

Powell, F. K.	Mech. Engr.	Research & development (terminated.)
Stevens, H. E.	Elect. Engr.	Research & development
Streid, D. D.	Mech. Engr.	Gas turbine development (terminated.)
Wade, E. J.	Elect. Engr.	Electronic controls (terminated.)

Monsanto Chemical Company

Amerine, H. G.	Elect. Engr.
Butler, J. W.	Assoc. Engr.
Collett, W. K.	Draftsman
Daume, W. B.	Adm. Ass't.
Early, B. F.	Design Draftsman
Fairchild, H. B.	Mech. Engr.
Fitzgerald, J. V.	Physical Chemist
Franklin, E. B.	Jr. Engr. (term.)
Fromm, L. W.	Chem. Engr.
Galbreath, W. W.	Ceramist
Garrison, G. M.	Sr. Clk. (term.)
Haberstro, L. W.	Design Draftsman
Harrer, J. M.	Elect. Engr.
Hurst, R. V.	Jr. Physicist
Hutto, E. L.	Design Draftsman
Jackson, H. K.	Chem. Engr.
Kelso, E. L.	Chem. Engr.
Humphries, J. R.	Chem. Engr.
Ledgerwood, Jr. C. H.	Draftsman
Livesey, L. C.	Mech. Engr.
McArdle, M.	Civil Engr. (term.)
Pate, Jr. W. A.	Mech. Engr.
Phillips, R. W.	Assoc. Engr. (term.)
Rice, Jr. R. E.	Mech. Engr.
Schlanger, A. L.	Mech. Engr.
Segaser, C. L.	Mech. Engr.
Solbrig, A. W.	Assoc. Engr.
Strauchman, A. E.	Draftsman
Thalgott, F. W.	Mech. Engr.
Thomas, T. H.	Mech. Engr.
Tinney, I. C.	Jr. Chemist
Tyson, M. H.	Chem. Engr. (deceased
Willson, E. M.	Research Ass't.
Wilson, M.	Jr. Engr.
Kaskie, J. C.	Chem. Engr. (term.)
Weger, L. C.	Chem. Engr. (term.)

SECRET

DECLASSIFIED

SECRET

National Advisory Committee for Aeronautics

Dietrich, J. R.	Physicist	Research & development
Simon, S. L.	Physical Chem.	Research & development (term.)

National Carbon Co.

MacPherson, H. G.	Physicist	Research & development

Navy Bureau of Ships

Amorosi, A.	Mech. Engr.	Gas turbines & heat transfer
Emerson, G. B.	Mech. Engr.	Heat transfer equipment

Northrop Aircraft, Inc.

Brittan, R. O.	Mech. Engr.	Stress analysis

Purdue University

Sibbitt, W. L.	Chem. Engr.	Research in heat transfer

Tennessee Valley Authority

Dean, W. E.	Elect. Engr.	Electrical power engineering (term.)
Saeman, W. C.	Chem. Engr.	Chemical process de elopment (term.)

Westinghouse Electric Corporation

Ashcraft, E. B.	Physical Chem.	Chemical research & development
Hunter, L. P.	Physicist	Physics research
Miller, E. F.	Mech. Engr.	Mechanical development (term.)
Palladino, N. J.	Mech. Engr.	Steam turbine design
Ross, P. N.	Elect. Engr.	Electric power transmission
Simpson, J. W.	Elect. Engr.	Electrical equipment design
Toepfer, A. H.	Elect. Engr.	Electronics research

Wright Aeronautical Corporation

Kasschau, K.	Mech. Engr.	Aircraft engine development

SECRET

DECLASSIFIED

SECRET

APPENDIX C

METHODS OF PILE-PHYSICS CALCULATIONS.

A. SYMBOLS AND DEFINITIONS

B	Buckling	$B = -\frac{\Delta(nv)}{nv}$
k	Multiplication Constant	Number of neutrons produced per neutron absorbed assuming no leakage (infinite pile)
L	Diffusion length	$L^2 = 1/6\,\overline{r^2} = \frac{1}{3\,\Sigma_a\,\Sigma_{tr}}$

where $\overline{r^2}$ = mean square distance from birth to death of a thermal neutron.

$\mathcal{L}$	Leakage	Number of neutrons leaking from reactor of pile per neutron absorbed by fissionable material.
nv	Neutron flux	Number of neutrons crossing a surface of 1 Cm^2 area per second
nv_{th}	Flux of thermal neutrons	
nv_f	Flux of neutrons of energy above thermal (epithermal)	
p	Resonance escape probability	Fraction of total number of neutrons born that reach thermal energy, assuming no leakage (infinite pile)
H	Axial length of pile	
h	Twice thickness of axial reflector	
N	Number of atoms per cm^3	
R	Radius of reactor	
t	Thickness of radial reflector	
	Volume of pile	
δk	Change in Multiplication constant	

SECRET

DECLASSIFIED

SECRET

Δ	Laplacian operator	
$\nabla(nv)$	Gradient of neutron flux	
η	Number of fission neutrons produced per neutron absorbed by fissionable material.	
λ_{tr}	Transport mean free path	The average distance in the direction of its original motion that a neutron would travel after an infinite number of collisions. $\lambda_{tr} = \frac{1}{\Sigma_{tr}}$
$\lambda_{tr}\nabla(nv)$	Neutron current	
ξ	Logarithmic energy loss	Average loss of logarithm of neutron energy per collision
ρ	Density	
σ	Microscopic cross section	Effective target area presented by one nucleus to a given type of event
σ_a	Absorption cross section	
σ_s	Scatter cross section	
σ_{tr}	Transport cross section	$\sigma_{tr} = \sigma_s(1 - \overline{\cos\theta})$ where $\overline{\cos\theta}$ is average value of cosine of scattering angle.
Σ	Macroscopic cross section	$\Sigma = N\sigma$
τ	Neutron "age"	$\tau = 1/6\ \overline{r^2}$ where $\overline{r^2}$ = mean square distance from point of birth of fast neutron to point where it becomes thermal.

Subscripts:

m	moderator
25	U^{235}
28	U^{238}

B. PHYSICAL CONSTANTS USED.

1. Room temperature properties of moderator:

	BeO	Be	Graphite
ρ	2.90	1.85	1.64

SECRET

DECLASSIFIED

	BeO	Be	Graphite
τ	134 cm^2	93 cm^2	366 cm^2
σ_a (1)	.0118 x 10^{-24} cm^2	.0108 x $10^{-24} cm^2$	.0045 x 10^{-24} cm^2
σ_{tr}	10.3 x $10^{-24} cm^2$	3.5 x $10^{-24} cm^2$	4.8 x 10^{-24} cm^2
ξ	.172	.206	.158

2. Room temperature properties of Uranium.

$$\sigma_a = 645 \times 10^{-24} cm^2 \text{ for } U^{235}$$

$$\eta = 2.1 \text{ for } U^{235}$$

$$\sigma_a = 2.6 \times 10^{-24} cm^2 \text{ for } U^{238}$$

C. CALCULATIONS AND FORMULAE

General Assumptions: In all the pile computations the moderator, fuel, and voids are considered uniformly distributed throughout the reactor. The entire pile is assumed to be at the same average temperature.

1. Thermal utilization, f_{25}.

$$f_{25} = \frac{1}{1 + \frac{N_m \quad \sigma_{am} + N_{28} \quad \sigma_{a28}}{N_{25} \quad \sigma_{a25}}}$$

2. Resonance escape probability, p

$$p = e^{-A/\mu\xi}$$

where

$$\mu = 10^{24} \sigma_{sm} \frac{N_m}{N_{28}}$$

and A is obtained from curve in MUC-RGS-AVM-5, giving A as function of . The curve is an extensive extrapolation of experimental data.

3. Multiplication Constant, k

$$k = \eta \; p \; f_{25}$$

4. Diffusion length, L

---

(1) σ_a for Be and BeO has been increased to the values shown to allow for approximately 1/2 part per million of Boron as impurity.

SECRET

DECLASSIFIED

$$L^2 = \frac{1}{3(\Sigma_a)\text{ total }(\Sigma_{tr})\text{ total}}$$

$$L_1^2 = L_o^2 \sqrt{\frac{T1}{T_o}}$$ where L_o^2 is at room temperature (T_o) and L_1^2 at any other temperature, (T_1)

5. Buckling of reactor, B.

$$L^2 B + 1 = k e^{-\tau B}$$

6. Effect of voids ($\alpha = \frac{\text{volume of voids}}{\text{volume of assembly including voids}}$)

$$B = B_o (1 - \alpha)^2$$ where B_o is buckling with zero voids.

7. Critical size of bare cylindrical pile with $\frac{\text{height}}{\text{radius}} = 1.85$ (Figs. 1, 4, 5).

$$R = \frac{2.94}{\sqrt{B}} \qquad H = \frac{5.44}{\sqrt{B}}$$

8. Criticality condition for cylindrical piles with reflectors; one-group theory. (Figs. 1, 8, 9, 10, 11, 12)

a. The pile radius (R), height (H), radial reflector thickness (t) and axial reflector thickness (h) are set at the desired values. The ratio of fuel to moderator (Z) in the reactor is left undetermined, and its determination constitutes the solution of the problem.

b. The neutron flux (nv) is assumed to satisfy the following equations in the reactor and reflector:

$$\Delta (nv)_1 = -B_\alpha (nv)_1 \qquad \text{in reactor}$$

$$\Delta (nv)_2 = \frac{1}{L_2^2} (nv)_2 \qquad \text{in reflector}$$

The solutions of these equations can be expressed in terms of trigonometric functions of the arguments $\beta_1 x$ and $\beta_2 x$ in the axial direction, and Bessel functions of the arguments $\alpha_1 r$ and $\alpha_2 r$ in the radial direction, where

$$\alpha_1^2 + \beta_1^2 = B_\alpha$$
$$\alpha_2^2 + \beta_2^2 = -\frac{1}{L_2^2}$$

the subscript 1 referring to the reactor and 2 to the reflector.

c. The following boundary conditions are applied:

$nv = 0$ at outer edge of reflector.

nv and $\lambda_{tr} \nabla (nv)$ continuous at reflector-reactor interface. These boundary conditions yield a set of two simultaneous transcendental equations in α_1 and β_1 which, with the above relation, determine a B_α

d. The Z necessary to give a B_α equal to that obtained above can be read from a curve of B vs Z, computed from the buckling equation.

DECLASSIFIED

SECRET

9. Two-group calculations of flux distribution (figs. 6 and 7.)

The two-group calculation was made on computation sheets prepared by Mr. B. I. Spinrad, based on the theory outlined in report MonP-246.

10. Effect of poisons on pile reactivity. (figs. d, e, f, g)

If the unpoisoned pile has a multiplication constant k_o, a thermal utilization f_o, and buckling B_o, and if a neutron absorber is distributed uniformly through the pile in small amount to the extent of producing an additional macroscopic absorption cross section Σ_p, the buckling of the poisoned pile can be maintained at the value B_o if the multiplication constant is increased by an increment δk, such that

$$\frac{\delta k}{k_o} = \frac{\beta}{(1+\beta) k_o e^{-\tau B_o}}$$

where

$$\beta = f_o \frac{\Sigma_p}{\Sigma_{a25}}$$

11. Neutron Economy. (Figs. 2 and 5)

Per neutron absorbed by U^{235}:

$\frac{1}{f_{25}} - 1$ = number neutrons absorbed by moderator.

$\eta - \frac{1}{f_{25}}$ = number leaking from reactor plus number absorbed by U^{238} = $\mathcal{L} + A_{28}$ = total neutrons available for conversion

$\eta(1-\beta)e^{-\tau B}$ = number absorbed by U^{238}

SECRET

DECLASSIFIED

SECRET

APPENDIX D

SUPPLEMENTARY NEUTRON PRODUCTION DURING PILE OPERATION

The use of beryllium as a pile moderator presents the possibility of realizing an appreciable neutron yield from a Be (γ,n) reaction or a Be (n, 2n) reaction.

1. Delayed Neutrons from Be (γ,n)

The threshold for the Be (γ,n) reaction is reported at 1.627 Mev (Project Handbook, IV C). The neutron yield may be approximated from that specified for a RaC-Be photo-neutron source (γ-ray energy - 1.761 Mev). The standard yield is reported to be 2.9×10^4 neutrons per second per curie for 1 gm. Be at a distance of 1 cm. from a point source (Project Handbook, IV C). The yield of photo-neutrons from a solid sphere of BeO can be calculated as follows:

2. Weight of Be in spherical shell around source

$$W = 4\pi r^2 \rho \, dr$$

where W = weight of Be, gm.

r = radius, cm.

ρ = 0.9 gm. Be/cm^3. based on BeO with density of 2.5

Since the intensity of the source varies inversely as the square of the radius and since it may be assumed that attenuation of the γ-rays due to photo-neutron production is negligibly small over the distance considered, the integrated yield from a source of 1 curie RaC is given by:

$$N = 2.9 \times 10^4 \int_0^r \frac{4\pi \rho \, r^2 \, dr}{r^2}$$

$$\text{or } N = 3.28 \times 10^5 \, r \quad \frac{\text{(neutrons)}}{\text{(sec.)(curie)}}$$

Since this function is linear in r the total neutron yield is relatively insensitive to variations of the position of the source over the central half of the mass and hence the total yield from a distributed source over the central portion of the volume is simply the product of the yield per curie times the number of curies.

SECRET

DECLASSIFIED

The total curies of γ- photons having an energy in excess of the Be (γ,n) threshold from fission products has not been determined with sufficient completeness to permit a very good approximation of the total yield. A review of the fission product decay chains giving emitters which may have energies in excess of the threshold are listed below. (ref. JACS, 68, 2411-2442 - 1946)

Mass	Chain	Yield, %
72	Zn $\xrightarrow[49\ hr.]{}$ Ga $\xrightarrow[14\ hr.]{>1.63\ \gamma}$	1.5×10^{-5}
75	Ge $\xrightarrow[89\ m.]{\gamma}$	-----
77	Ge $\xrightarrow[12\ hr.]{\gamma}$	0.0091
84	Se $\xrightarrow[2\ m.]{}$ Br $\xrightarrow[30\ m]{\gamma}$	9.65
86	Rb $\xrightarrow[19.5\ d]{\gamma}$	2×10^{-5}
94	Kr $\xrightarrow[1.4\ s.]{}$ Rb $\xrightarrow[Short]{}$ Sr $\xrightarrow[2\ M.]{}$ Y $\xrightarrow[20\ m.]{\gamma}$	5
134	Sb $\xrightarrow[<10\ m.]{}$ Te $\xrightarrow[43\ m.]{}$ I $\xrightarrow[54\ m]{>1\ \gamma}$	~5.7
135	Te $\xrightarrow[<2\ m]{}$ I $\xrightarrow[2.7\ hr]{1.6\ \gamma}$	5.9
140	Xe $\xrightarrow[16\ s]{}$ Cs $\xrightarrow[short]{}$ Ba $\xrightarrow[12.8\ d.]{}$ La $\xrightarrow[40.0\ hr.]{>1.63\ \gamma}$	6.1
141	Xe $\xrightarrow[3\ s]{}$ Cs $\xrightarrow[short]{}$ Ba $\xrightarrow[18\ m]{\gamma}$ La $\xrightarrow[3.7\ hr.]{\gamma}$	5.7
142	Cs $\xrightarrow[1-2\ m.]{}$ Ba $\xrightarrow[6\ m]{}$ La $\xrightarrow[74\ m]{\gamma}$	-----
156	61 $\xrightarrow[<5\ m.]{}$ Sm $\xrightarrow[10\ hr.]{}$ Eu $\xrightarrow[15.4\ d]{>1.63\ \gamma}$	0.013

DECLASSIFIED

SECRET

The only chains with γ - photons in excess of the Be (γ ,n) threshold specifically given are 72, 140, and 156, all with a half-life considerably in excess of 1 day. The photon energy for chain 135 is just under the threshold and is listed as a possible source since statistical variations and experimental errors may permit some over-lapping in this case. For all others no specific energy is given and they are listed only to complete the survey. However, since Spatz and Cahn (See below) actually determine 5 photo-neutron periods of a day or less from U^{235} fission products it appears reasonable to select 5 representative chains from the remaining group in order to arrive at a reasonable source strength of γ - photons. On this basis the fission yield of chains yielding γ - photons sufficiently energetic to produce photo-neutrons may be 10 to 30%. A value of 20% will be used to complete this estimate.

The neutron yield from the fission product γ's will be assumed to be the same as that from a RaC - Be source (Actually it may be higher). One curie of fission product γ's at equilibrium would result from 1.8×10^{11} fissions/sec. (assuming 20% yield) from which 4.5×10^{11} fission neutrons/sec. would result. A BeO pile having a 100 cm. radius would produce $3.28 \times 10^5 \times 100$ or 3.28×10^7 photo-neutrons/sec. from the Be (γ ,n) reaction or roughly .01% of the total.

A. W. Spatz and A. Cahn (Report MonS-29, Sept. 17-18, 1945) measured photo-neutrons produced in D_2O (threshold for D - 2.183 Mev. Project Handbook, IV C) by delayed γ's produced by fission of U^{235}. They found photo-neutrons with half-lives of 1 day, 2 hr., 32 min., 5.2 min., and 1.5 min. The total intensity from these sources amounted to about 5% of the total delayed neutrons or 0.037% (5% of 0.75%) of the total fission neutrons. Photo-neutrons with periods less than 1.5 min. will increase this percentage somewhat. The fact that the threshold for Be is considerably less than for D would also indicate an increased percentage yield of photo-neutrons from a be moderated pile.

H. W. Newson (Clinton Laboratory Pile Technology Lectures 42 & 43) indicates that the expected photo-neutrons produced in the proposed Clinton High Flux Pile several hours after shut-down will be smaller than the full power level of generation by a factor of 10^5 or 10^6. It is therefore evident that the independent estimates presented here establish the order of magnitude of the delayed photo-neutrons as 0.01 to 0.1 per cent of the total neutrons.

3. Prompt Neutrons from Be (γ ,n)

Since essentially 60% of all neutrons generated disappear in N, γ -reactions (the other 40% cause further fissions) from which γ -photons of the order of 5-7 Mev may be expected, prompt photo-neutrons are also of interest. The RaC-Be yield factor applied in this case gives a yield of 0.05% prompt photo-neutrons. Correction for γ - photons higher in energy than RaC would tend to increase this value while correction for the widely distributed origin of the γ - photons outside the BeO mass will tend to reduce it. The correct order of magnitude is probably around 0.1%.

SECRET

DECLASSIFIED

The cross-section for the Be (n, 2n) reaction using fission neutrons was measured by Montgomery and Staebler (CP 781, July 10, 1943), and was given as 7.2×10^{-26} cm^2. They replaced a slab of graphite with Be in one of the cells of the Argonne pile and noted the change in reactivity. The following equation was used to calculate the n, 2n - cross-section:

$$\delta k/k = q/Q = N \sigma (n,2n)/4 \pi \bar{r}^2$$

where

q/Q = fractional increase of fast neutrons per cell per sec.

N = Number of Be atoms

$\bar{r}$ = Average radius of Be atoms from uranium lump

A value of .0033 was reported for $\delta k/k$ or q/Q as defined above. In other words the expected yield of neutrons from a Be (n, 2n) reaction is only 0.33% of the total fission neutron yield. Williamson and Weinberg (CP 1231, Dec. 27, 1943) gave a corrected yield of 0.25%. For BeO the effect will be somewhat less.

4. Summary:

The delayed neutrons resulting from Be (γ,n) reactions in the pile appear to be of the order of .01 to 0.1 percent. This is roughly 1 to 10% of the total delayed neutrons and would therefore have a small but significant contribution towards pile control. The major benefit from this source of neutrons comes in starting the pile, since the photo-neutrons generation remains at a level 10^5 to 10^6 less than the generation at full power and therefore provides a powerful source of neutrons for start-up.

Prompt neutrons from Be (γ,n) and Be (n, 2n) reactions appear to be about 0.1 to 1% and will therefore have a small but significant effect on the pile reactivity.

SECRET

APPENDIX E

DESCRIPTION OF AN ALTERNATE PILE STRUCTURE DESIGN

The ability to load and unload fuel in an operating pile is desirable when considering a commercial application of atomic power. Several proposals designed to accomplish this have been given considerable thought and study. While the objective is considered attainable, a number of the problems encountered have not yet been solved with a degree of assurance comparable to the pile described in the main body of this report. As the present state of knowledge is advanced it may very well be that one of these alternates will appear more favorable than the current design.

The most promising alternate proposal consists of an assembly of horizontal channels with provision for continuous channel loading; i.e., loading into the 1400°F. pile face and ejecting fuel slugs, against the gas flow, at the 500°F. face.

The arrangement of pile elements is illustrated in Fig. 104. Beryllium oxide brick of the type shown in Fig. 105 are arranged to form a horizontal cylinder 75" long and approximately 72" diameter with 517 horizontal channels. Metal segments, "A", in Fig. 104 curved on one side and shaped to fit the contour of the bricks on the other side, surround the brick structure and are, in turn, confined in a steel retaining shell, "B". This shell rests on four sliding supports anchored to the pressure shell, and is guided by the keys shown. The shell is supported on the foundation. Thermal insulation "E" outside minimizes heat loss from the pile.

Referring to Fig. 106 the two ends of the pile will be identified as the fuel entry end and fuel exit end respectively. At the fuel exit end, a plate "A", extending across the retaining shell, restrains the brick from moving toward the fuel exit end. It is drilled to match the channels and is supported and centered by radial pins. There is no necessity for restraining fuel slugs at this end as gas force is sufficient to prevent them from falling out of the pile. They are positively ejected as new slugs are inserted at the fuel entry end. The fuel entry end is divided into two sections by a tube sheet structure. This is necessary to separate the 1400°F. section from the pressure shell, and to provide a 500°F. section for a fuel loading mechanism that can be similar to that described in Section IV of this report.

Brick structure is restrained by ported bridge tubes, "B", which go from pile face to loading face. A transverse gas baffle structure, "C", across the tube assembly, provides for part of the 500°F. entering gas to pass over the unported length of these tubes and thus provide a relatively cool loading zone. Each tube functions as a strut, restraining end movement of its corresponding brick channel, yet having sufficient lateral flexibility to follow the radial expansion movements of the brick. The tubes also function as a passage for fuel elements from loading to pile faces.

SECRET

DECLASSIFIED

SECRET

Referring to Fig. 107, which is an enlarged illustration of the bridge tubes, gravity operated latches "A", one for each tube, retain fuel elements against gas flow. Check valves "B" are placed at the tube ends in order to prevent recirculation of hot gas through the tubes due to pressure gradients from center to edge of the ported tube nest. These valves are designed to close by gravity and to permit entry and withdrawal of the fuel ram. Since the loading zone is essentially isolated from gas flow, the opening of one valve during fueling does not permit flow, except momentarily to equalize any difference in pressure that may exist.

The brick structure is portioned into reactor, reflector, and conversion zones, as shown in Fig. 108. The central zone, consisting of the mid 45" of 241 channels, is the reactor. Control rods require 13 of these channels; the remaining 228 channels within the length of the reactor zone will be charged with fuel elements, with reflector elements at each end. The 276 channels surrounding the reactor form the side reflector blanket, any portion of which may be used for conversion. The reflector channels will be filled with loose fitting solid BeO plugs.

An unloading device, which must operate at the same end as the control rods presents a somewhat difficult problem which has not yet been solved. A possible alternative may be to have control rods enter from the sides, or perpendicular to gas flow. Assuming this to be permissable from a physics viewpoint, the problem of forming holes in this plane with the present 3" hexagonal bricks introduces complication possibly as severe as that of an unloading mechanism.

The ported bridge tubes are somewhat questionable. The possibility of a channel overheating may cause damage to a tube, which introduces the problem of replaceability of this part. Further work on heat transfer and instrumentation may prove this fear to be unfounded.

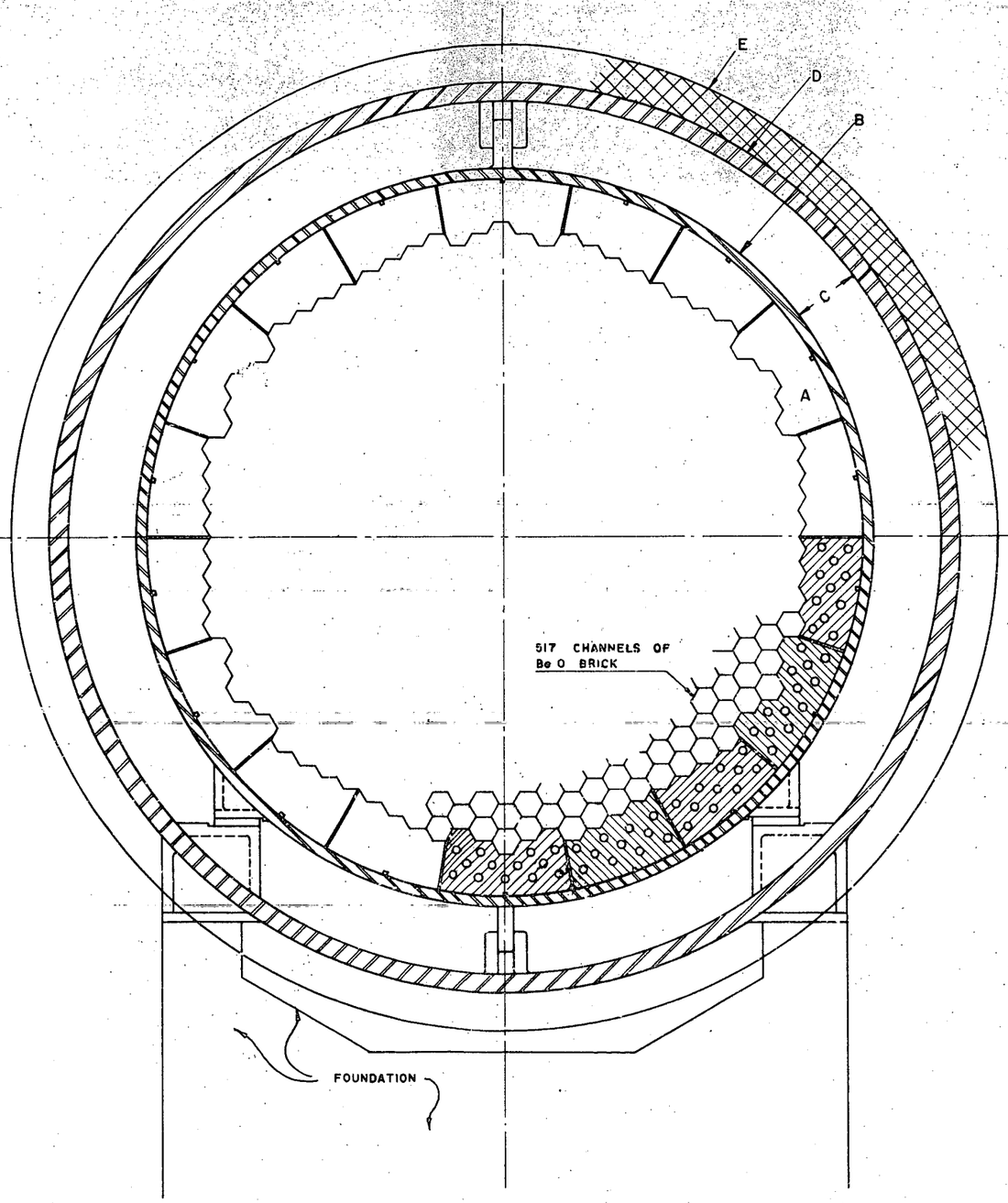
The effectiveness of the check valve proposed to prevent by-passing of gas is questionable. Considerable work on this problem will probably evolve a more satisfactory solution.

Several other schemes were proposed which attempted to load under pile operation. These were based on means for retaining the hot end of the pile in direct contact with the pile face. For the most part, these retaining means were based on a flat plate that contained slightly oversized holes to match the brick channels. They consisted of arrangements of segmented plates, flexible beams, grids, etc. They appeared unfavorable because of the likelihood of distortion from local overheating adjacent to an overheated channel or group of channels. A better understanding of temperature distribution might make this approach seem more promising.

SECRET

DECLASSIFIED

SECRET



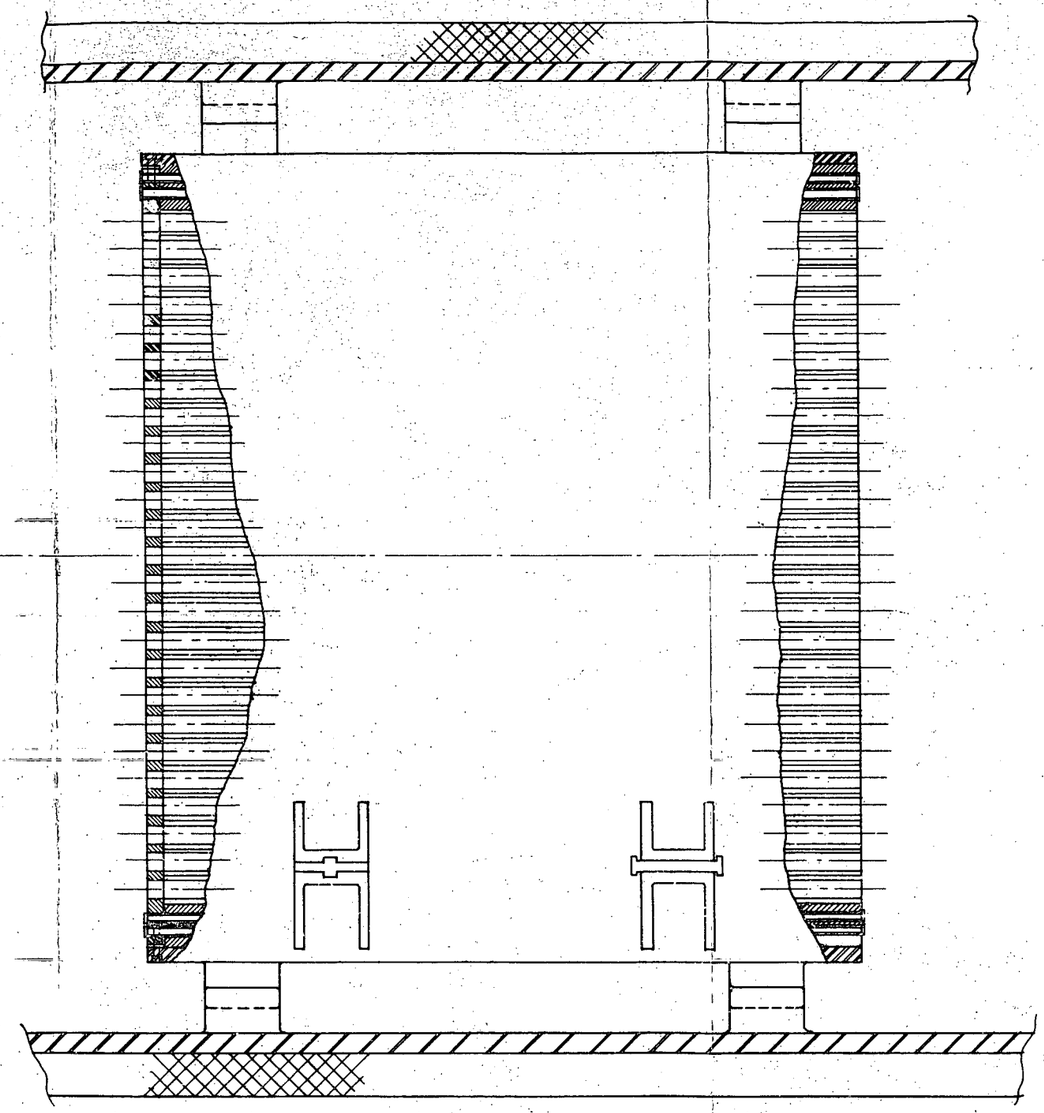


FIG. 104

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

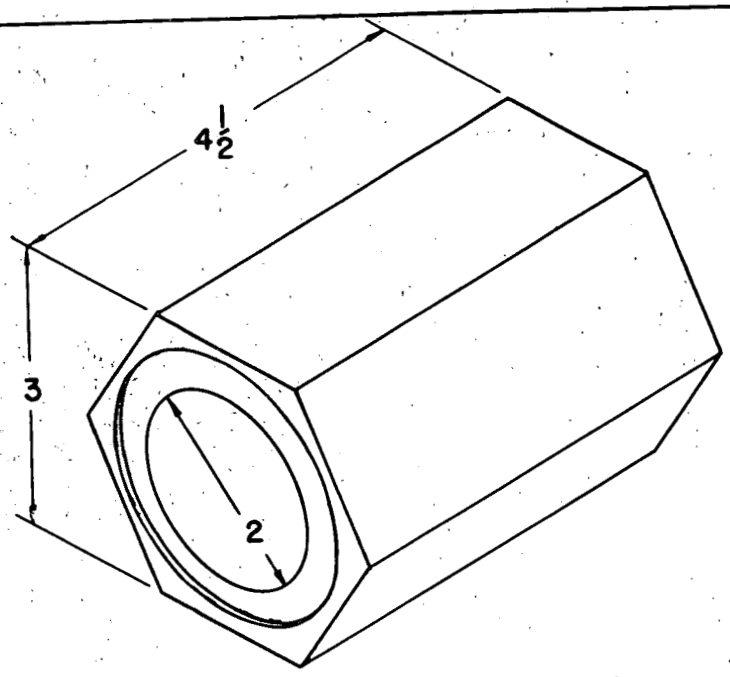
PILE SUPPORT ARRANGMENT

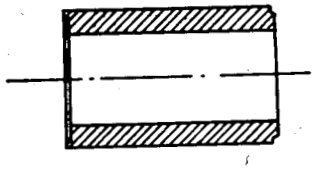
MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

COLLETT D. 7/2/47	C. A.L.S. 7-11-47	A. E.D.M. 7-14-47	R.E.P. 7-14-47			
PROJ. C-222M						D - 2223

DECLASSIFIED DECLASSIFIED DECLASSIFIED

SECRET





SECTION

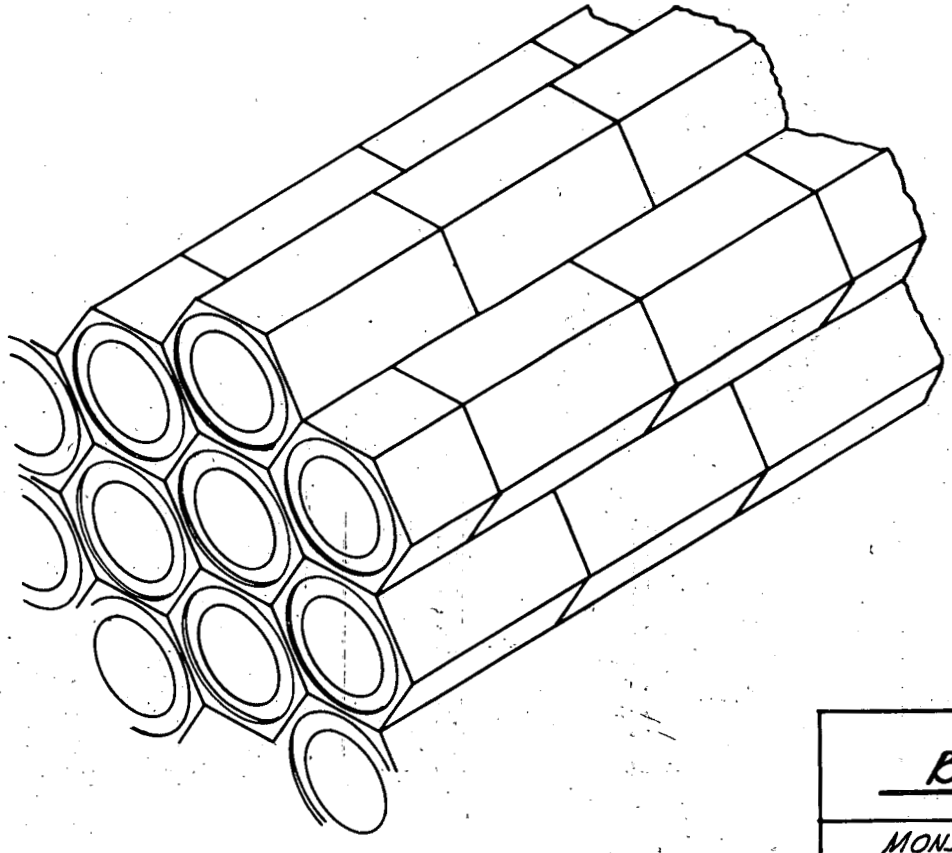


FIG. 105

BeO BRICK

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Structural D. 6-30-47	A.L.S. C. 7-11-47	E. Fm. A. 7-14-47	R. E.P. 7-14-47			
Proj. E 222 M				C-2222		

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

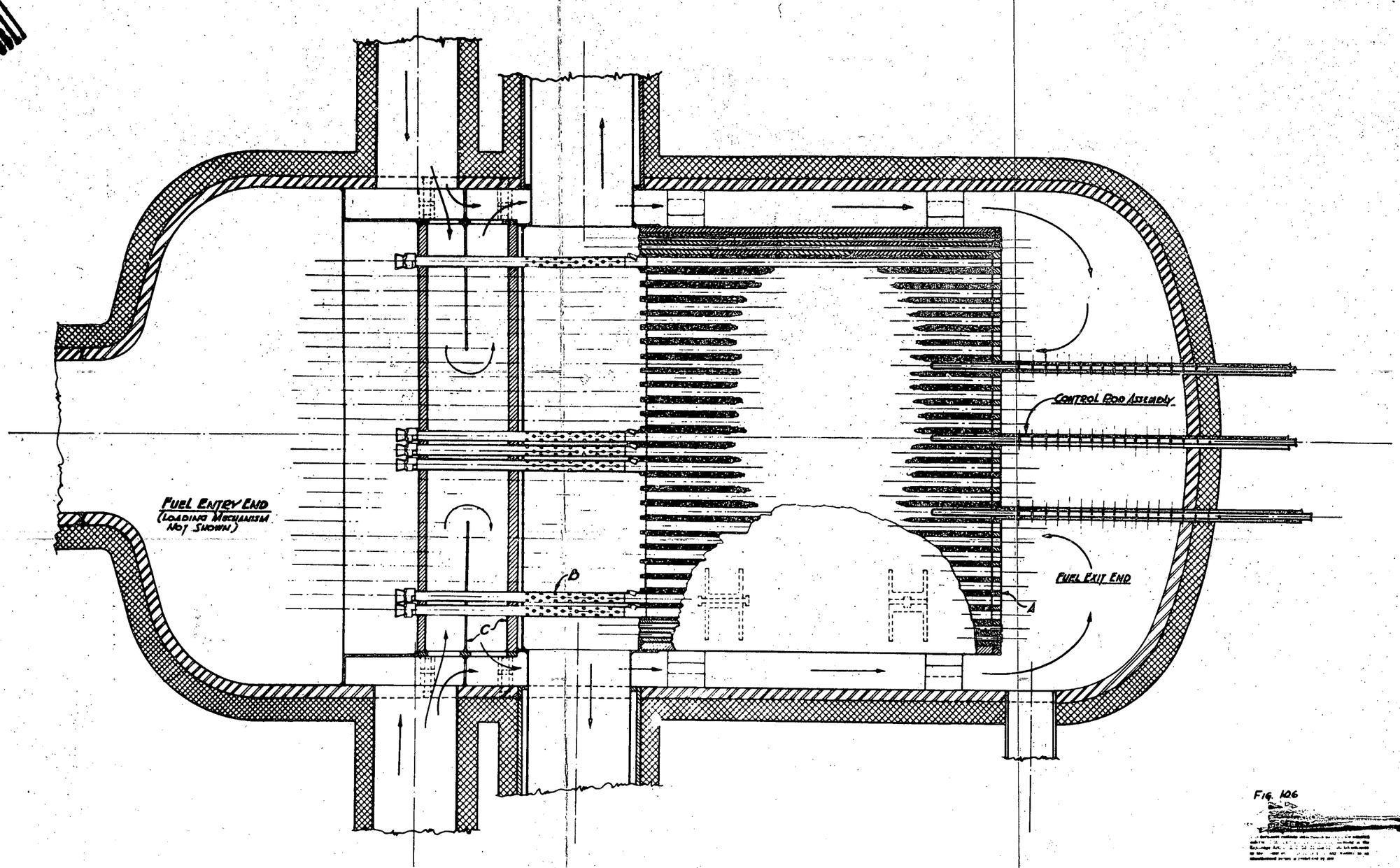


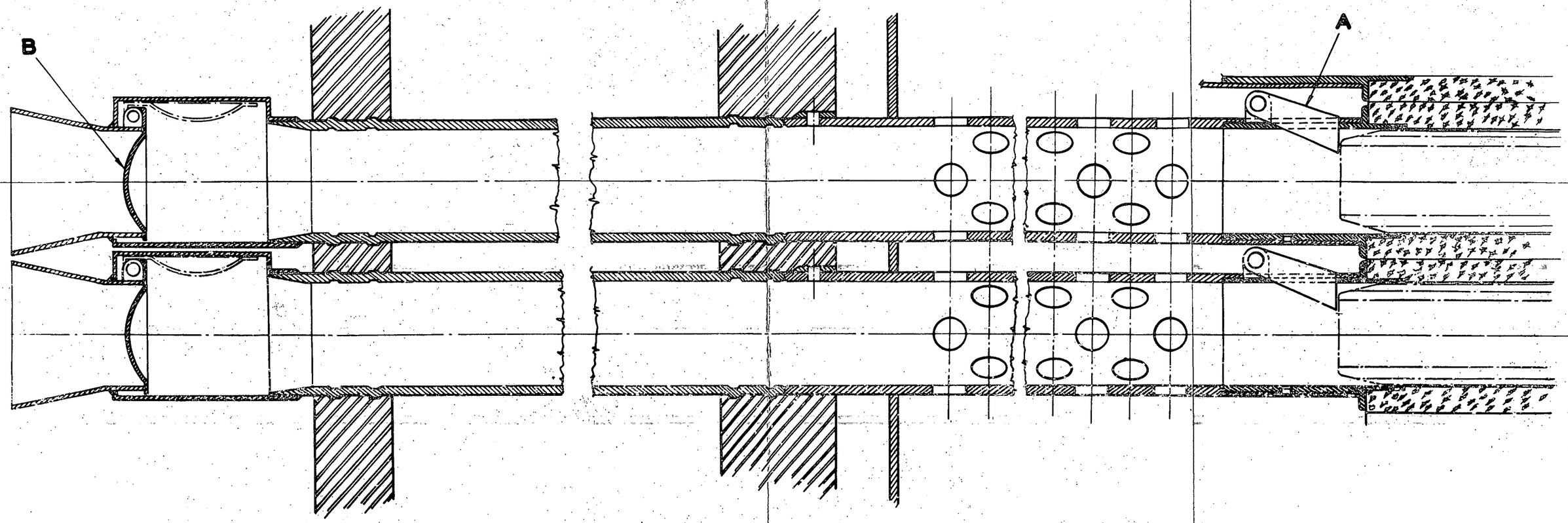
FIG. 106

PILE CROSS SECTION ASSEMBLY

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Draughtsman	H.L.S. 6-24-47	6-26-47	R.E.P. 6-27-47			
D 6-26-47 C		A				
PROJ: C-222M						
SCALE:						E-2609

DECLASSIFIED



SECTION THROUGH BRIDGE TUBES

FIG. 107

SECRET

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

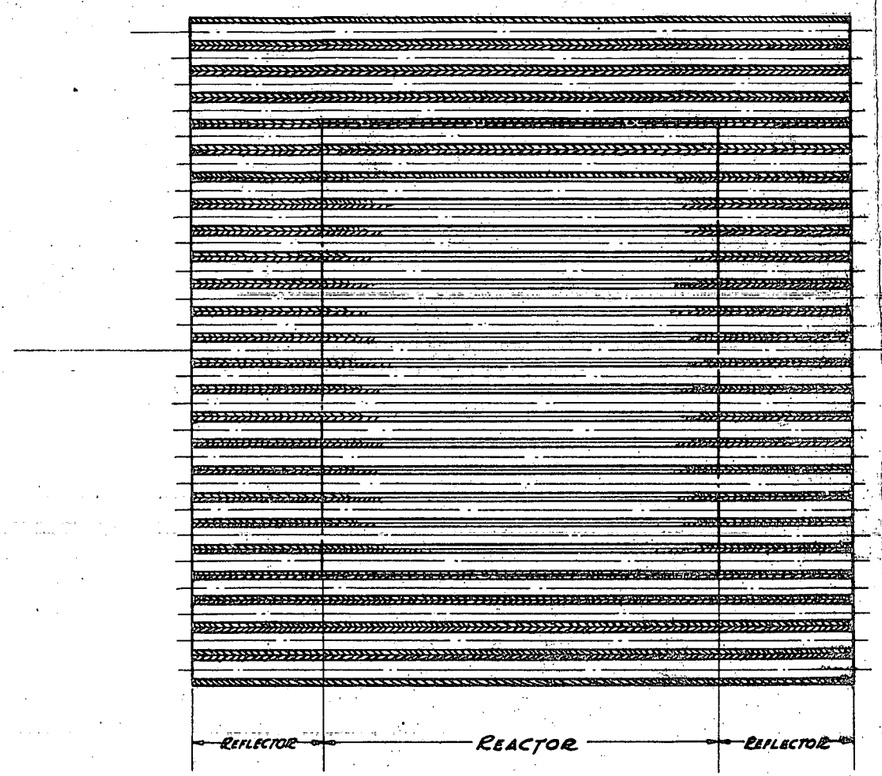
BRIDGE TUBES
SECTION

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

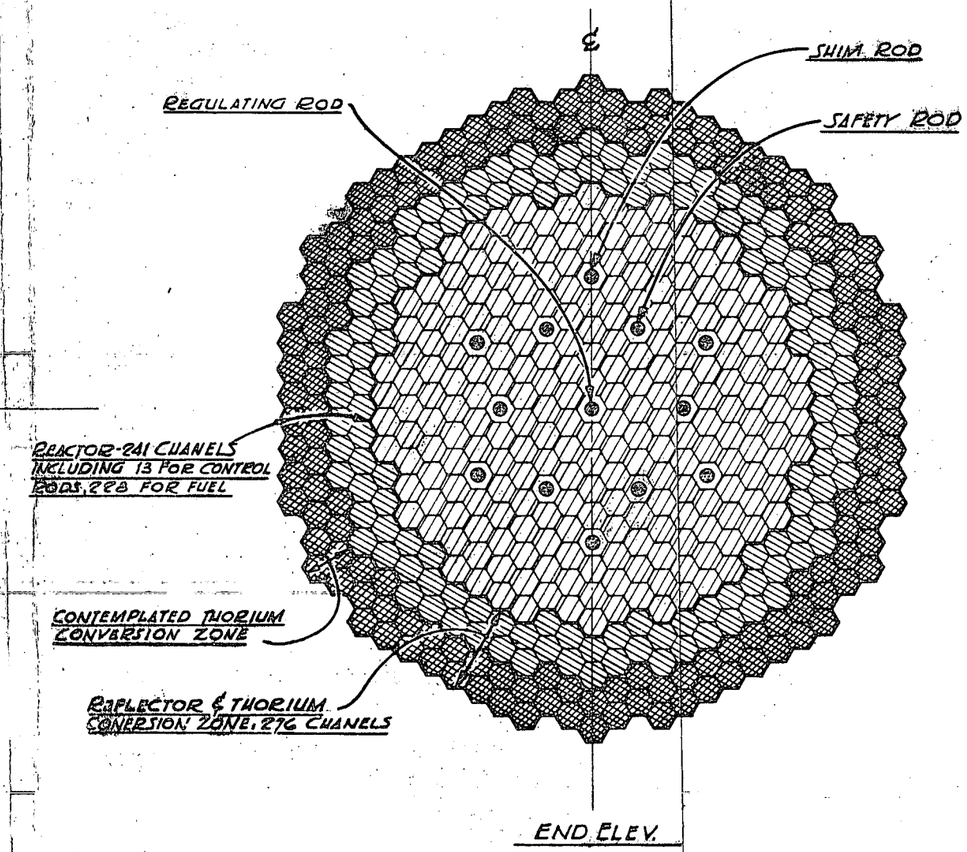
Drawn D.L.30-41	H.L.G. C. 7-11-41	E.J.M. A. 7-14-41	R.L.P. 7-17-41			
Proj. E.R.E.H.						D-2221

DECLASSIFIED
DECLASSIFIED

SECRET



SECTION ⅝ ℄



END ELEV.

FIG. 108

[redacted]

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U. S. C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

BRICK ASSEMBLY

MONSANTO CHEMICAL COMPANY
CLINTON LABORATORIES
KNOXVILLE, TENN.

Drawn	F.L.S.	E.J.M.	REP		
D. 6-27-47	C. 7-11-47	A. 7-14-47	7-19-47		
Proj. C-222M				D-2960	

DECLASSIFIED

APPENDIX F
PILE CONTROL – METHODS OF CALCULATION

1. EFFECTIVENESS OF CONTROL RODS AS GIVEN BY WEINBERG IN CL-574

The neutron distribution for an infinitely long pile of radius R without a control rod is

$$(nU)_0 = J_0\left(\sqrt{\frac{k_0-1}{M^2}}\, r\right)$$

while with a control rod of radius r_0 it is

$$(nU)_1 = Y_0\left(\sqrt{\frac{k-1}{M^2}}\, r_0\right) J_0\left(\sqrt{\frac{k-1}{M^2}}\, r\right) - Y_0\left(\sqrt{\frac{k-1}{M^2}}\, r\right) J_0\left(\sqrt{\frac{k-1}{M^2}}\, r_0\right)$$

and

$(nU)_1 = 0$ at $r = R$, from which

$$\frac{Y_0\left(\sqrt{\frac{k-1}{M^2}}\, r_0\right)}{J_0\left(\sqrt{\frac{k-1}{M^2}}\, r_0\right)} = \frac{Y_0\left(\sqrt{\frac{k-1}{M^2}}\, R\right)}{J_0\left(\sqrt{\frac{k-1}{M^2}}\, R\right)}$$

If $\sqrt{\frac{k-1}{M^2}}\, r_0 = x$ and $\sqrt{\frac{k-1}{M^2}}\, R = \frac{R}{r_0} x \equiv \xi$

and the equation becomes

$$\frac{Y_0(x)}{J_0(x)} = \frac{Y_0(\xi)}{J_0(\xi)}$$

This equation was solved by plotting the functions on the left and right hand side on the same coordinate system and reading off values of (x) and (ξ) which make the two functions equal.

Each pair of values of x and ξ correspond to a value of $\frac{R}{r_0}$, or ξ is a function of $\frac{R}{r_0}$

DECLASSIFIED [redacted]

The value of $k-1$ with the control rod is given by

$$\sqrt{\frac{k-1}{M^2}} = \frac{\xi\left(\frac{R}{r_0}\right)}{R}$$

and

$$\frac{k-1}{k_0-1} = \frac{\xi^2\left(\frac{R}{r_0}\right)}{(2.405)^2} = 1 + 2\,\frac{\xi\left(\frac{R}{r_0}\right) - 2.405}{2.405}$$

if the rod is all black, or

$$\frac{k-1}{k_0-1} = 1 + 2\frac{L^2}{M^2}\,\frac{\xi\left(\frac{R}{r_0}\right) - 2.405}{2.405}$$

if the rod effects only thermal neutrons.

In considering piles of finite length, the ratio of bucklings

$$\frac{B_r^2}{B_{r_0}^2} = 1 + 2\,\frac{\xi\left(\frac{R}{r_0}\right) - 2.405}{2.405} \quad \text{and} \quad \frac{B_r^2}{B_{r_0}^2} = 1 + 2\frac{L^2}{L^2+\tau'}\,\frac{\xi\left(\frac{R}{r_0}\right) - 2.405}{2.405}$$

where τ' is adjusted to make two group theory agree with Fermi theory

$$1 + \tau' B_0 = e^{\tau B_0}$$

B_0 = total buckling without rod $= \frac{2.405}{R}$ where $R = 81.8$ cm

$B_{r_0}^2 = B_0 - B_z^2$ where B_z^2 = longitudinal buckling $= \left(\frac{\pi}{h}\right)^2$

where $h = 151.3$ cm.

$B = B_r^2 + B_z^2$

and

$\Delta k = k - k_0$ where $k = (1 + L^2 B)(1 + \tau' B)$ and

$k_0 = (1 + L^2 B_0)(1 + \tau' B_0)$

Curves were plotted for $L^2 = 212$, $\tau = 258$ and $L^2 = 121$, $\tau = 258$

Bessel functions in British Association Tables. [redacted]

[redacted]

2. EFFECTIVENESS OF CONTROL RODS AS APPROXIMATED BY WHEELER - N2292

If a control rod is inserted in a pile the local effect of the rod in a cylinder of influence may be calculated by choosing the radius of the cylinder of influence such that the derivative of the flux equals zero at that radius, assuming that the derivatives of slow and fast fluxes goto zero at the same radius

The equations:

$$\Delta(nv)_f - K_f^2 nv_f + k\frac{\Sigma_{ath}}{\Sigma_{af}}(nv)_s = 0$$

$$\Delta(nv)_s - K_{th}^2(nv)_s + \frac{\Sigma_{af}}{\Sigma_{ath}}(nv)_f = 0$$

where $K_f^2 = \frac{1}{\tau}$; $K_{th}^2 = \frac{1}{L^2}$; Σ_{ath} = thermal absorbtion cross section and Σ_{af} = effective slowing down cross section,

have solutions of the form

$$(nv)_f = (gZ - h\tilde{Z})\cos\frac{\pi}{150}z$$

$$(nv)_s = (S_1 gZ - S_2 h\tilde{Z})\cos\frac{\pi}{150}z$$

where $S_1 = \frac{\lambda_f}{\lambda_{th}}\frac{B_1 + K_f^2}{kK_{th}^2}$; $S_2 = \frac{\lambda_f}{\lambda_{th}}\frac{B_2 + K_f^2}{kK_{th}^2}$ with a cosine distribution of the flux in the axial or z direction.

B_1 & B_2 are the negatives of the fundamental and transient pile Laplacians. Equivalent length of pile = 150 cm.

DECLASSIFIED [redacted]

$Z = A J_0(b_1 r) + N_0(b_1 r)$

and

$\tilde{Z} = C J_0(i b_2 r) + i H_0^{(1)}(i b_2 r)$

where r is the effective radius of the control rod

and $b_1^2 = B_1 - \left(\frac{\pi}{150}\right)^2$; $-b_2^2 = B_2 - \left(\frac{\pi}{150}\right)^2$

The boundary condition $\frac{d\,nu}{dr} = 0$ at $r = R$, R = radius of the cylinder of influence, implies that

$$\left.\frac{dZ}{dr}\right]_{r=R} = 0 \quad \text{and} \quad \left.\frac{d\tilde{Z}}{dr}\right]_{r=R} = 0$$

$$-A b_1 J_1(b_1 R) - b_1 N_1(b_1 R) = 0$$

$$A = -\frac{N_1(b_1 R)}{J_1(b_1 R)}$$

and

$$-C i b_2 J_1(i b_2 R) + b_2 H_1^{(1)}(i b_2 R) = 0$$

$$C = \frac{H_1^{(1)}(i b_2 R)}{i J_1(i b_2 R)}$$

$$Z = -\frac{N_1(b_1 R)}{J_1(b_1 R)} J_0(b_1 r) + N_0(b_1 r)$$

$$\tilde{Z} = \frac{H_1^{(1)}(i b_2 R)}{i J_1(i b_2 R)} J_0(i b_2 r) + i H_0^{(1)}(i b_2 r)$$

A further boundary condition is that $(nu)_4$ be regular at $r = 0$

$$\underset{r\to 0}{Z} = \text{const} - \frac{2}{\pi} \ln \frac{2}{\gamma b_1 r} = \text{const} - \frac{2}{\pi} \ln \frac{1.22}{b_1 r}$$

$$\underset{r\to 0}{\tilde{Z}} = \text{const} + \frac{2}{\pi} \ln \frac{2}{\gamma b_2 r} = \text{const} + \frac{2}{\pi} \ln \frac{1.22}{b_2 r}$$

The singularities are of the same order hence for $(nu)_4$ to be regular:

$$g = h$$

DECLASSIF[redacted]

A third boundary condition is that $(nv)_s = 0$ at $r = r_0$ = effective radius of the control rod.

in $(nv)_s = (S_1 g z + S_2 h \tilde{z}) \cos \frac{\pi}{150} z = 0$ at $r = r_0$

substituting values of $S_1, S_2, g = h, z, \& \tilde{z}$

$$(B_1 + K_f^2)\left[-\frac{N_1(b_1 R)}{J_1(b_1 R)} J_0(b_1 r_0) + N_0(b_1 r_0)\right] = -(B_2 + K_f^2)$$

$$\left[\frac{H_1^{(1)}(i b_2 R)}{i J_1(i b_2 R)} J_0(i b_2 r_0) + i H_0^{(1)}(i b_2 r_0)\right]$$

Using $k = 1.78$, $L^2 = 121$, $\tau = 258$ values of B_1 and B_2 and hence values of b_1 & b_2 were determined The value of R necessary with given values of r_0 may be found.

The effective change in local multiplication factor $\delta k_{local} = k - 1$

The overall loss in k due to a control which does not greatly distort the general distribution of the neutron density of the pile

if Radius of zone of equivalence = R_i

Radius of Pile = R_p

Value of square of virtual neutron density over zone of equivalence without control rod = $\overline{n^2}_i$

Value of square of virtual neutron density over whole pile without control rod = $\overline{n^2}_p$

DECLASSIFIED

is

$$\Delta k = \delta k_{local} \times \frac{R_i^2}{R_p^2} \times \frac{\overline{n^2_i}}{\overline{n^2_p}}$$

Assuming a $J_0(x)$ distribution of the flux before a control rod is inserted; $x = \frac{2.4048}{R_p} r$; r = distance from center of pile

$$\overline{n^2_i} = \frac{\int n^2 \, dA}{A} = \frac{2\pi R_p^2}{\pi R_i^2 \, 2.4048^2} \int_0^x x J_0^2(x) \, dx \; ; \; x = \frac{2.4048}{R_p} R_i$$

and

$$\overline{n^2_p} = \frac{2}{2.4048^2} \int_0^{2.4048} x J_0^2(x) \, dx$$

with $\int_0^x x J_0^2(x) \, dx = \frac{x^2}{2}\left(J_0^2(x) + J_1^2(x)\right)\Big]_0^x$

Using $R_p = 81.2$ cm

$$\overline{n^2_p} = \frac{2}{2.4048^2}(.7793) = .271$$

for off-center rods an approximation gives

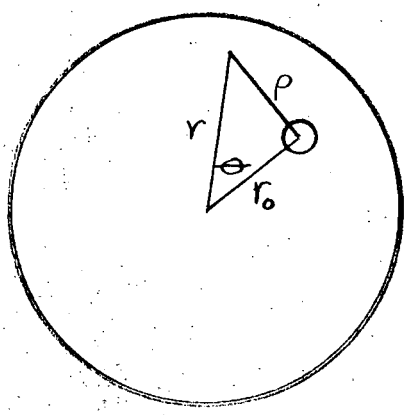
$$\overline{n^2_i} = \frac{2 R_p^2}{2.4048^2 R_i^2} \frac{\int_{x_1}^{x_2} x J_0^2 x \, dx}{x_2 - x_1} \quad \text{where } x_2 = \frac{2.4048 \, r_2}{R_p}$$

and $x_1 = \frac{2.4048 \, r_1}{R_p}$; r_1 & r_2 = distance of inner and outer bounds of zone of influence from center of pile

J, N, and $H^{(1)}$ are Bessel functions in the notation of Jahnke and Emde

[redacted]

3. NORDHEIM SCALETTAR APPROXIMATION APPLIED TO ONE CONTROL ROD – ONE GROUP THEORY



LET ρ = dislance from control rod
r = distance from pile center
r_0 = distance from pile to control rod center
θ = angle measured with respect to a line joining pile and control rod centers
R = radius of pile + extrapolation distance

The pile equation,

$$\Delta(nu) + b\,(nu) = 0$$

where b is the negative of the pile Laplacian, $\mu^2 = b - B_z^2$, B_z^2 = longitudinal buckling, has a solution of the form

$$(nu) = \sum_{n=0}^{\infty} J_n(\mu r)\{A_n \cos n\theta + B_n \sin n\theta\} + Y_0(\mu\rho)$$

based on the assumption that the regular solution is essentially constant over the surface of the rod

Applying the addition theorem for Bessel functions

$$Y_0(\mu\rho) = Y_0(\mu r) J_0(\mu r_0) + 2\sum_{n=1}^{\infty} Y_n(\mu r) J_n(\mu r_0) \cos n\theta \quad (r > r_0)$$

and the boundary condition $(nu) = 0$ at $r = R$

$$(nu) = 0 = \sum_{n=0}^{\infty} J_n(\mu R)\{A_n \cos n\theta + B_n \sin n\theta\} + Y_0(\mu R) J_0(\mu r_0) + 2\sum_{n=1}^{\infty} Y_n(\mu R) J_n(\mu r_0) \cos n\theta$$

since (nu) must be an even function $B_n = 0$ and setting the Fourier coefficient, for $f(\theta) = 0$, of $\cos n\theta = 0$

$$J_n(\mu R) A_n + \varepsilon Y_n(\mu R) J_n(\mu r_0) = 0$$

where $\varepsilon = 1$ when $n = 0$, $\varepsilon = 2$ when $n = 1, 2, 3, \cdots \infty$

[redacted]

This gives

$$A_n = -\varepsilon \frac{Y_n(\mu R)}{J_n(\mu R)} J_n(\mu r_0) \qquad n = 0, 1, 2, 3 \cdots \infty$$

Substituting in the original equation and applying the boundary condition $nu = 0$ at the control rod surface $r = r_0$, $\rho = x$ = effective radius of control rod, $\theta = 0$

$$nu = 0 = -\frac{Y_0(\mu R)}{J_0(\mu R)} J_0^2(\mu r_0) + Y_0(\mu x) - 2\sum_{n=1}^{\infty} \frac{Y_n(\mu R)}{J_n(\mu R)} J_n^2(\mu r_0)$$

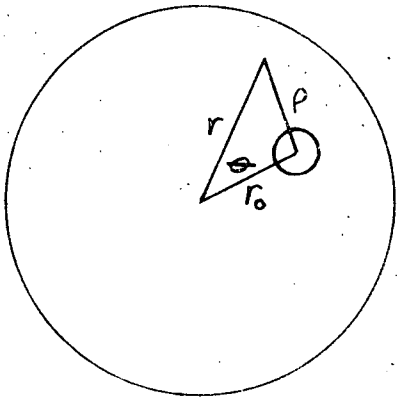
The values of μ which satisfied this equation, for values of r_0 from 0 to 50 cm, $R = 81.2$ cm $x = 1.35$ cm were found, and values of k for a critical pile, as found from $k = (1 + L^2 B) e^{\tau B}$, where $L^2 = 121$, $\tau = 258$ and $B = \mu^2 + \left(\frac{\pi}{150}\right)^2$, were compared with the k for a critical pile and no rod, using $\mu = \frac{2.4048}{R}$ in the same critical equation.

I, K, Y, and J are Bessel functions in the British Association tables notation.

[redacted]

4. NORDHEIM SCALETTAR APPROXIMATION APPLIED TO ONE CONTROL ROD

TWO GROUP THEORY



LET ρ = distance from control rod
r = distance from pile center
r_0 = distance from pile center to control rod
θ = angle measured with respect to line between pile and control rod centers.
R = pile radius + extrapolation distance

Neutrons are divided into two classes, fast and slow, $(nu)_f$ and $(nu)_s$, coupled by the equations

$$\Delta(nu)_s - K_s^2(nu)_s + K_s^2 a\,(nu)_f = 0$$
$$\Delta(nu)_f - K_f^2(nu)_f + K_f^2 \frac{k}{a}(nu)_s = 0$$

with notation as given in the discussion for seven rods

These equations have solutions of the form:*

$$(nu)_s = \sum_{n=0}^{\infty} J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1\rho) + \sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + D\,K_0(\mu_2\rho)$$

$$(nu)_f = \alpha\left[\sum_{n=0}^{\infty} J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1\rho)\right] + \beta\left[\sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + D\,K_0(\mu_2\rho)\right]$$

Applying the condition $(nu)_f$ is regular at $r=0$, the singularities will be of the same order and will subtract if $D = \frac{\alpha}{\beta}\cdot\frac{2}{\pi}$

Applying the condition $(nu)=0$ at $r=R$, and using

[redacted]

the addition theorem for Bessel functions

$$Y_0(\mu\rho) = Y_0(\mu_1 r) J_0(\mu_1 r_0) + 2\sum_{m=0}^{\infty} Y_n(\mu_1 r) J_n(\mu_1 r_0) \cos n\theta \quad (r > r_0)$$

we get

$$(nv)_s = 0 = \sum_{n=0}^{\infty} J_n(\mu_1 R)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1 R) J_0(\mu_1 r_0)$$
$$+ 2\sum_{n=1}^{\infty} Y_n(\mu_1 R) J_n(\mu_1 r_0)\cos n\theta + \sum_{n=0}^{\infty} I_n(\mu_2 R)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\}$$
$$+ \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\left[K_0(\mu_2 R) I_0(\mu_2 r_0) + 2\sum_{n=1}^{\infty} K_n(\mu_2 R) I_n(\mu_2 r_0)\cos n\theta\right]$$

with a similar expression for $(nv)_f$

The function must be even, hence $B_n = 0$

and

$$(nv)_s = 0 = \sum_{n=0}^{\infty}\{J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_0) + I_n(\mu_2 R) A_{2n}$$
$$+ \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\varepsilon K_n(\mu_2 R) I_n(\mu_2 r_0)\}\cos n\theta$$

$$(nv)_f = 0 = \sum_{n=0}^{\infty}\left[\alpha\{J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_0) + \frac{\beta}{\alpha} I_n(\mu_2 R) A_{2n}\right.$$
$$\left. + \frac{2}{\pi}\varepsilon K_n(\mu_2 R) I_n(\mu_2 r_0)\}\right]\cos n\theta$$

where $\varepsilon = 1$ when $n = 0$ and $\varepsilon = 2$ when $n = 1, 2, 3 \cdots \infty$

These equations are Fourier series for $f(\theta) = 0$, hence

$$J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_0) + I_n(\mu_2 R) A_{2n} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\varepsilon K_n(\mu_2 R)$$
$$I_n(\mu_2 r_0) = 0 \qquad (n = 0, 1, 2, 3, \cdots \infty)$$

and

$$J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_0) + \frac{\beta}{\alpha} I_n(\mu_2 R) A_{2n} + \frac{2}{\pi}\varepsilon K_n(\mu_2 R)$$
$$I_n(\mu_2 r_0) = 0 \qquad (n = 0, 1, 2, 3, \cdots \infty)$$

from which

$$A_{10} = \frac{-Y_0(\mu_1 R) J_0(\mu_1 r_0)}{J_0(\mu_1 R)} \qquad A_{20} = -\frac{\alpha}{\beta}\cdot\frac{2}{\pi}\frac{K_0(\mu_2 R) I_0(\mu_2 r_0)}{I_0(\mu_2 R)}$$

$$A_{1n} = -\frac{2 Y_n(\mu_1 R) J_n(\mu_1 r_0)}{J_n(\mu_1 R)} \qquad A_{2n} = -\frac{\alpha}{\beta}\cdot\frac{2}{\pi}\cdot\frac{2 K_n(\mu_2 R) I_n(\mu_2 r_0)}{I_n(\mu_2 R)}$$

$n = (1, 2, 3 \cdots \infty)$

substituting in the original flux equations and applying the boundary condition $(nu)_s = 0$ at the rod, $r = r_0$, $\rho = x$ = effective radius of the rod, $\theta = 0$

$$(nu)_s = 0 = -\frac{Y_0(\mu_1 R)\, J_0^2(\mu_1 r_0)}{J_0(\mu_1 R)} + Y_0(\mu_1 x) - 2\sum_{n=1}^{\infty} \frac{Y_n(\mu_1 R)\, J_n^2(\mu_1 r_0)}{J_n(\mu_1 R)}$$

$$-\frac{2}{\pi}\frac{\alpha}{B}\frac{K_0(\mu_2 R)\, I_0^2(\mu_2 r_0)}{I_0(\mu_2 R)} + \frac{2}{\pi}\cdot\frac{\alpha}{\beta}\, K_0(\mu_2 x) - 2\sum_{n=1}^{\infty}\frac{2}{\pi}\cdot\frac{\alpha}{\beta}$$

$$\frac{K_n(\mu_2 R)\, I_n^2(\mu_2 r_0)}{I_n(\mu_2 R)} .$$

The values of k in the critical pile equation, with $L^2 = 121$, $\tau = 258$, and with longitudinal buckling $= \left(\frac{\pi}{150}\right)^2$, which gave a μ_1 and μ_2 satisfying the above equation were determined using values of r_0 from 0 to 50 cm, $R = 81.2$ cm, $x = 1.35$ cm

Comparison of these values of k with the value of k for no rod - ref. seven rod calculations - gave Δk for various rod positions

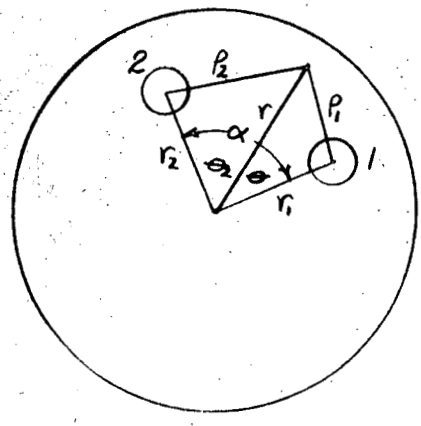
* Based on the assumption that all terms are essentially constant over control rod surface except those which have singularities there.

I, K, Y, and J are Bessel functions in the British Association Tables notation.

DECLASSIFIED

5. NORDHEIM SCALETTAR APPROXIMATION APPLIED TO TWO CONTROL RODS

ONE GROUP THEORY



LET ρ_1, ρ_2 = distance from control rods 1 and 2
r = distance from center of pile
θ = angle measured with respect to a line passing through pile and control rod centers
α = angle between lines passing through pile and control rod centers
r_1, r_2 = distance of rods 1 & 2 from pile center

The pile equation,

$$\Delta(nu) + b\,(nu) = 0$$

where b is the negative of the pile Laplacian, $\mu^2 = b - B_z^2$, B_z^2 = longitudinal buckling, has a solution of the form:

$$nu = \sum_{n=0}^{\infty} J_n(\mu r)\{A_n \cos n\theta + B_n \sin n\theta\} + Y_0(\mu\rho_1) + C\,Y_0(\mu\rho_2)$$

based on the assumption that the regular solution is essentially constant over the control rod surface and that the irregular solution due to one rod is essentially constant over the surface of the other rod

Using addition theorem for Bessel functions; $r > r_1$, $r > r_2$

$$Y_0(\mu\rho_1) = Y_0(\mu r)\,J_0(\mu r_1) + 2\sum_{n=1}^{\infty} Y_n(\mu r)\,J_n(\mu r_1)\cos n\theta,$$

etc.

and applying boundary condition $nu = 0$ at $r = R$

R = radius of pile $+ 0.71\,\lambda_t$

[redacted]

$$(nv) = 0 = \sum_{n=0}^{\infty} J_n(\mu R)\{A_n \cos n\theta + B_n \sin n\theta\} + Y_0(\mu R) J_0(\mu r_1)$$
$$+ 2\sum_{n=1}^{\infty} Y_n(\mu R) J_n(\mu r_1) \cos n\theta + C\{Y_0(\mu R) J_0(\mu r_2)$$
$$+ 2\sum_{n=1}^{\infty} Y_n(\mu R) J_n(\mu r_2) \cos n\theta_2\}$$

and $\cos n\theta_2 = \cos n\alpha \cos n\theta + \sin n\alpha \sin n\theta$

$$(nv) = 0 = \sum_{n=0}^{\infty}\Big[\{J_n(\mu R) A_n + \varepsilon Y_n(\mu R) J_n(\mu r_1) + C\varepsilon Y_n(\mu R) J_n(\mu r_2) \cos n\alpha\}$$
$$\cos n\theta + \{J_n(\mu R) B_n + C\varepsilon Y_n(\mu R) J_n(\mu r_2) \sin n\alpha\} \sin n\theta\Big]$$

where $\varepsilon = 1$ when $n = 0$ and $\varepsilon = 2$ when $n = 1, 2, \cdots \infty$

This is a Fourier series for $f(\theta) = 0$ hence

$$A_0 = \frac{-Y_0(\mu R) J_0(\mu r_1) - C \quad Y_0(\mu R) J_0(\mu r_2)}{J_0(\mu R)}$$

$$A_n = \frac{-2 Y_n(\mu R) J_n(\mu r_1) - 2C Y_n(\mu R) J_n(\mu r_2) \cos n\alpha}{J_n(\mu R)} \qquad (n = 1, 2, \cdots \infty)$$

$$B_n = \frac{-2C Y_n(\mu R) J_n(\mu r_2) \sin n\alpha}{J_n(\mu R)} \qquad n = 1, 2 \cdots \infty$$

Using boundary condition that $(nv)_s = 0$ at rod 1, using $\rho_2 = r_{21}$ = distance from rod 2 to rod 1 and $\rho_1 = x_1$ = effective radius of rod 1.

$$0 = \sum_{n=0}^{\infty} J_n(\mu r_1)\{A_n \cos n\theta + B_n \sin n\theta\} + C Y_0(\mu r_{21}) + Y_0(\mu x_1)$$

But $\theta = 0$

$$0 = \sum_{n=0}^{\infty} J_n(\mu r_1) A_n + C Y(\mu r_{21}) + Y_0(\mu x_1)$$

[redacted]

Substituting the value of A_n

$$0 = \sum_{n=0}^{\infty} J_n(\mu r_1)\left\{\frac{-\varepsilon Y_n(\mu R) J_n(\mu r_1) - C\,\varepsilon Y_n(\mu R) J_n(\mu r_2)\cos n\alpha}{J_n(\mu R)}\right\}$$

$$+ C Y_0(\mu r_{21}) + Y_0(\mu x_1)$$

$$C = \left[\frac{-Y_0(\mu x_1) + \sum_{n=0}^{\infty} \varepsilon J_n^2(\mu r_1)\dfrac{Y_n(\mu R)}{J_n(\mu R)}}{Y_0(\mu r_{21}) - \sum_{n=0}^{\infty} \varepsilon J_n(\mu r_1) J_n(\mu r_2)\dfrac{Y_n(\mu R)}{J_n(\mu R)}\cos n\alpha}\right]$$

If control rod 2 is at pile center $r_{21} = r_1$, $r_2 = 0$, and $n=0$ is the only order which has meaning in the denominator

$$C = \frac{-Y_0(\mu x_1) + \sum_{n=0}^{\infty} \varepsilon J_n^2(\mu r_1)\dfrac{Y_n(\mu R)}{J_n(\mu R)}}{Y_0(\mu r_1) - J_0(\mu r_1)\dfrac{Y_n(\mu R)}{J_n(\mu R)}}$$

Using the boundary condition $(nu)_s = 0$ at rod 2, using $r_2 = 0$ $\rho_2 = x_2$ $\rho_1 = r_{21} = r_1$, the original flux equation gives.

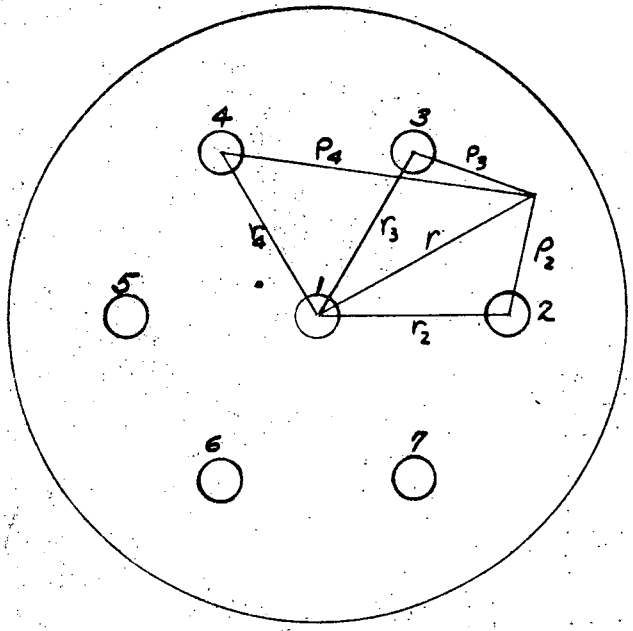
$$0 = A_0 + Y_0(\mu r_1) + C\,Y_0(\mu x_2)$$

This equation was solved for μ using $r_1 = 26.67$ cm; $x_2 = x_1 = 1.35$ cm, $R = 81.2$ cm. and the value of k for a critical pile, as determined from $k = (1 + L^2 B)\,e^{\tau B}$ where $L^2 = 121$ $\tau = 258$ and $B = \mu_1^2 + \left(\frac{\pi}{150}\right)^2$, was compared with the k for a critical pile with no rod, using $\mu = \frac{2.404\,8}{R} = \frac{2.404\,8}{81.2}$ in the same critical equation

Y and J are Bessel Functions in the British Association Tables notation.

[redacted]

6. NORDHEIM SCALETTAR APPROXIMATION APPLIED TO SEVEN CONTROL RODS
TWO GROUP THEORY



LET $\rho_1, \rho_2, \rho_3 \cdots \rho_m$ = distance from control rod 1, 2, 3 --- m

θ = angle measured with respect to line passing through pile and control rod centers

$r_1, r_2 \cdots r_m$ = distance of control rod 1, 2 --- m from pile center

$\alpha_2 \cdots \alpha_m$ = angular spacing of control rods 2 --- m measured from line joining pile and rod 1 centers

r = distance from pile center

Neutrons are divided into two classes, fast & slow - $(nv)_s$ and $(nv)_f$ - coupled by the equations

$$\Delta (nv)_s - K_s^2 (nv)_s + K_s^2 a (nv)_f = 0$$
$$\Delta (nv)_f - K_f^2 (nv)_f + K_f^2 \cdot \frac{k}{a} (nv)_s = 0$$

where K_s^2 and K_f^2 are reciprical diffusion length squared and age respectively, and $a = p \frac{\sigma_{af}}{\sigma_{as}}$ where p is the resonance escape probability, σ_{af} is an effective slowing down cross-section for fast neutrons, and σ_{as} the slow neutron absorbtion cross-section

These equations have solutions of the form

$$(nv)_s = \sum_{n=0}^{\infty} I_n(\mu_1 r)\{A_{1n} \cos n\theta + B_{1n} \sin n\theta\} + Y_0(\mu_1 \rho) + \sum_{m=2}^{7} C_m Y_0(\mu_1 \rho_m) + \sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n} \cos n\theta + B_{2n} \sin n\theta\} + D K_0(\mu_2 \rho_1) + \sum_{m=2}^{7} C_m D K_0(\mu_2 \rho_m)$$

UNCLASSIFIED

$$(nU)_f = \alpha\Big[\sum_{n=0}^{\infty} J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1\rho_1) + \sum_{m=2}^{7} C_m Y_0(\mu_1\rho_m)\Big] + \beta\Big[\sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + D K_0(\mu_2\rho_1) + \sum_{m=2}^{7} C_m D K_0(\mu_1\rho_m)\Big]$$

where $-B_1$ and $-B_2$ are the fundamental and transient Laplacians obtained from the characteristic equation of the above pile equations, α and β are the ratio of fast to slow fluxes for these two Laplacians respectively.

$$\alpha = \frac{K_f^2 \frac{k}{a}}{K_f^2 + B_1} \qquad \beta = \frac{K_f^2 \frac{k}{a}}{K_f^2 + B_2}$$

where $\mu_1^2 = B_1 - B_z^2$; $-\mu_2^2 = B_2 - B_z^2$ $\quad B_z^2$ = longitudinal buckling

Bessel functions are in the notation of British Assoc. Tables.

Applying the condition that $(nU)_f$ have no singularity at $\rho = 0$

$$D = \frac{\alpha}{\beta}\cdot\frac{2}{\pi}$$

$$(nU)_s = \sum_{n=0}^{\infty} J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1\rho_1) + \sum_{m=2}^{7} C_m Y_0(\mu_1\rho_m) + \sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\Big[K_0(\mu_2\rho_1) + \sum_{m=2}^{7} C_m K_0(\mu_2\rho_m)$$

$$(nU)_f = \alpha\Big[\sum_{n=0}^{\infty} J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta + Y_0(\mu_1\rho_1) + \sum_{m=2}^{\infty} C_m Y_0(\mu_1\rho_m) + \frac{\beta}{\alpha}\sum I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta + \frac{2}{\pi}K_0(\mu_2\rho_1) + \frac{2}{\pi}\sum_{m=2}^{7} C_m K_0(\mu_2\rho_m)\Big]$$

Using addition theorem for Bessel functions; $r > r_1; r_2 \cdots$

$$Y_0(\mu_1\rho_1) = Y_0(\mu_1 r) J_0(\mu_1 r_1) + 2\sum_{1}^{\infty} Y_n(\mu_1 r) J_n(\mu_1 r_1)\cos n\theta,$$

$$K_0(\mu_2\rho_1) = K_0(\mu_2 r) I_0(\mu_2 r_1) + 2\sum_{1}^{\infty} K_n(\mu_2 r) I_n(\mu_2 r_1)\cos n\theta,$$

and with $\cos n\theta_m = \cos n\alpha_m \cos n\theta + \sin n\alpha_m \sin n\theta$

$\varepsilon = 1$ where $n = 0$; $\varepsilon = 2$ where $n = 1, 2, \cdots \infty$

$$(nU)_s = \sum_{n=0}^{\infty} \Big\{ J_n(\mu_1 r)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + \varepsilon Y_n(\mu_1 r) J_n(\mu_1 r_1)\cos n\theta$$
$$+ \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 r) J_n(\mu_1 r_m)\{\cos n\alpha_m \cos n\theta + \sin n\alpha_m \sin n\theta\}$$
$$+ I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\Big[\varepsilon K_n(\mu_2 r) I_n(\mu_2 r_1)\cos n\theta$$
$$+ \sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 r) I_n(\mu_2 r_m)\{\cos n\alpha_m \cos n\theta + \sin n\alpha_m \sin n\theta\}\Big]\Big\}$$

with a similar expression for $(nU)_f$

Applying the boundary condition $nU = 0$ at $r = R$

R = radius of the pile + extrapolation distance

$$(nU)_s = 0 = \sum_{n=0}^{\infty}\Big\{\Big[J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_1)$$
$$+ \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m)\cos n\alpha_m + I_n(\mu_2 R) A_{2n}$$
$$+ \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\varepsilon\Big(K_n(\mu_2 R) I_n(\mu_2 r_1) + \sum_{m=2}^{7} C_m K_n(\mu_2 R) I_n(\mu_2 r_m)\cos n\alpha_m\Big)\Big]$$
$$\cos n\theta + \Big[J_n(\mu_1 R) B_{1n} + \sum_{m=2}^{7}\varepsilon C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m)\sin n\alpha_m$$
$$+ I_n(\mu_2 R) B_{2n} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m)\sin n\alpha_m\Big]\sin n\theta\Big\}$$

$$(nU)_f = 0 = \alpha\sum_{n=0}^{\infty}\Big\{\Big[J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_1)$$
$$+ \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m)\cos n\alpha_m + \frac{\beta}{\alpha} I_n(\mu_2 R) A_{2n}$$
$$+ \frac{2}{\pi}\varepsilon\Big(K_n(\mu_2 R) I_n(\mu_2 r_1) + \sum_{m=2}^{7} C_m K_n(\mu_2 R) I_n(\mu_2 r_m)\cos n\alpha_m\Big)\Big]$$
$$\cos n\theta + \Big[J_n(\mu_1 R) B_{1n} + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m)\sin n\alpha_m$$
$$+ \frac{\beta}{\alpha} I_n(\mu_2 R) B_{2n} + \frac{2}{\pi}\sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m)\sin n\alpha_m\Big]\sin n\theta\Big\}$$

These are Fourier series for $f(\theta) = 0$ hence:

$$\Big[J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_1) + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \cos n\alpha_m$$

$$+ I_n(\mu_2 R) A_{2n} + \frac{\alpha}{\beta} \cdot \frac{2}{\pi} \varepsilon \Big(K_n(\mu_2 R) I_n(\mu_2 r_1) + \sum_{m=2}^{7} C_m K_n(\mu_2 R) I_n(\mu_2 r_m)$$

$$\cos n\alpha_m \Big) \Big] = 0$$

$$\Big[J_n(\mu_1 R) A_{1n} + \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_1) + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \cos n\alpha_m$$

$$+ \frac{\beta}{\alpha} I_n(\mu_2 R) A_{2n} + \frac{2}{\pi} \varepsilon \Big(K_n(\mu_2 R) I_n(\mu_2 r_1) + \sum_{m=2}^{7} C_m K_n(\mu_2 R) I_n(\mu_2 r_m)$$

$$\cos n\alpha_m \Big) \Big] = 0$$

Solving for A_{1n} & A_{2n}

$$A_{1n} = - \frac{\varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_1) + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \cos n\alpha_m}{J_n(\mu_1 R)}$$

$$A_{2n} = -\frac{\alpha}{\beta} \frac{\frac{2}{\pi} \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_1) + \sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m) \cos n\alpha_m}{I_n(\mu_2 R)}$$

$n = 0, 1, 2 \cdots \infty$

$$J_n(\mu_1 R) B_{1n} + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \sin n\alpha_m + I_n(\mu_2 R) B_{2n}$$

$$+ \frac{\alpha}{\beta} \cdot \frac{2}{\pi} \sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m) \sin n\alpha_m = 0$$

$$J_n(\mu_1 R) B_{1n} + \sum_{m=2}^{7} C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \sin n\alpha_m + \frac{\beta}{\alpha} I_n(\mu_2 R) B_{2n}$$

$$+ \frac{2}{\pi} \sum_{m=2}^{7} C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m) \sin n\alpha_m = 0$$

$$B_{1n} = - \sum_{m=2}^{7} \frac{C_m \varepsilon Y_n(\mu_1 R) J_n(\mu_1 r_m) \sin n\alpha_m}{J_n(\mu_1 R)}$$

$$B_{2n} = -\frac{\alpha}{\beta} \cdot \frac{2}{\pi} \sum_{m=2}^{7} \frac{C_m \varepsilon K_n(\mu_2 R) I_n(\mu_2 r_m) \sin n\alpha_m}{I_n(\mu_2 R)}$$

$n = 1, 2, 3 \cdots \infty$

Applying boundary condition that $(nu)_s = 0$ at effective radius of rod 2, and considering all terms essentially constant over surface of rod 2 except those which have singularities there X_m = effective radius of rod m r_{12} = distance from rod 1 to rod 2, r_{32} = dist from rod 3 to rod 2 etc.

$$0 = \sum_{n=0}^{\infty} J_n(\mu_1 r_2)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1 r_{12}) + C_2 Y_0(\mu_1 x_2)$$
$$+ C_3 Y_0(\mu_1 r_{32}) + C_4 Y_0(\mu_1 r_{42}) + C_5 Y_0(\mu_1 r_{52}) + C_6 Y_0(\mu_1 r_{62})$$
$$+ C_7 Y_0(\mu_1 r_{72}) + \sum_{n=0}^{\infty} I_n(\mu_2 r_2)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\}$$
$$+ \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\Big[K_0(\mu_2 r_{12}) + C_2 K_0(\mu_2 x_2) + C_3 K_0(\mu_2 r_{32}) + C_4 K_0(\mu_2 r_{42})$$
$$+ C_5 K_0(\mu_2 r_{52}) + C_6 K_0(\mu_2 r_{62}) + C_7 K_0(\mu_2 r_{72})$$

If rod 1 is in the center of the pile and the other rods are spaced uniformly around rod 1, the C_m will all be equal (from symmetry)

Substituting values of $A_{1n}, A_{2n}, B_{1n}, \& B_{2n}$ with $\theta = 0$

$$C\Big[Y_0(\mu_1 x_2) + Y_0(\mu_1 r_{32}) + \cdots Y_0(\mu_1 r_{72}) + \frac{\alpha}{\beta}\frac{2}{\pi}\{K_0(\mu_2 x_2) + K_0(\mu_2 r_{32}) + \cdots$$
$$+ K_0(\mu_2 r_{72})\}\Big] = -Y_0(\mu_1 r_{12}) + \sum_{n=0}^{\infty} J_n(\mu_1 r_2)\,\varepsilon\,\frac{Y_n(\mu_1 R)}{J_n(\mu_1 R)} J_n(\mu_1 r_1)$$
$$+ C\sum_{n=0}^{\infty}\varepsilon\, J_n(\mu_1 r_2)\frac{Y_n(\mu_1 R)}{J_n(\mu_1 R)}\left(J_n(\mu_1 r_2)\cos n\alpha_2 + \cdots + J_n(\mu_1 r_7)\cos n\alpha_7\right)$$
$$- \frac{\alpha}{\beta}\cdot\frac{2}{\pi} K_0(\mu_2 r_{12}) + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\sum_{n=0}^{\infty}\frac{K_n(\mu_2 R)}{I_n(\mu_2 R)} I_n(\mu_2 r_1) I_n(\mu_2 r_2) +$$
$$+ C\frac{\alpha}{\beta}\sum_{n=0}^{\infty}\varepsilon\, I_n(\mu_2 r_2)\frac{K_n(\mu_2 R)}{I_n(\mu_2 R)}\left(I_n(\mu_2 r_2)\cos n\alpha_2 + \cdots + I_n(\mu_2 r_7)\cos n\alpha_7\right)$$

Solving for C:

$$C = \left[\frac{-Y_0(\mu_1 r_{12}) + \sum_{n=0}^{\infty} J_n(\mu_1 r_2)\, \varepsilon \frac{Y_n(\mu_1 R)}{J_n(\mu_1 R)} J_n(\mu_1 r_1) - \frac{\alpha}{\beta}\cdot\frac{2}{\pi} K_0(\mu_2 r_{12})}{Y_0(\mu_1 x_2) + Y_0(\mu_1 r_{32}) + \cdots + Y_0(\mu_1 r_{72}) + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}\left\{ K_0(\mu_2 x_2) + \right.} \right.$$

$$\frac{+\frac{\alpha}{\beta}\cdot\frac{2}{\pi}\sum_{n=0}^{\infty} I_n(\mu_2 r_2)\frac{K_n(\mu_2 R)}{I_n(\mu_2 R)} I_n(\mu_2 r_1)}{\left. + K_0(\mu_2 r_{32}) + \cdots + K_0(\mu_2 r_{72}) \right\} - \sum_{n=0}^{\infty} \varepsilon J_n(\mu_1 r_2)\frac{Y_n(\mu_1 R)}{J_n(\mu_1 R)}\left(J_n(\mu_1 r_2) \right.}$$

$$\frac{\left. \cos n\alpha_2 + \cdots + J_n(\mu_1 r_7)\cos n\alpha_7 \right) - \frac{\alpha}{\beta}\cdot \sum_{n=0}^{\infty} \varepsilon I_n(\mu_2 r_2)}{\frac{K_n(\mu_2 R)}{I_n(\mu_2 R)}\left(I_n(\mu_2 r_2)\cos n\alpha_2 + \cdots + I_n(\mu_2 r_7)\cos n\alpha_7 \right)} \Bigg]$$

Substituting back in original equation and setting $(nv)_s = 0$ at control rod 1, $(r = r_1)$, making $n = 0$

$$0 = \sum_{n=0}^{\infty} J_n(\mu_1 r_1)\{A_{1n}\cos n\theta + B_{1n}\sin n\theta\} + Y_0(\mu_1 x_1) + C\sum_{m=2}^{7} Y_0(\mu_1 r_m) + \sum_{n=0}^{\infty} I_n(\mu_2 r)\{A_{2n}\cos n\theta + B_{2n}\sin n\theta\} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi} K_0(\mu_1 x_1) + \frac{\alpha}{\beta}\cdot\frac{2}{\pi} C\sum_{m=2}^{7} K_0(\mu_2 r_m)$$

where:

$x_1 = 1.35$ cm; $r_m = 26.67$ cm; $r_{12} = 26.67$ cm; $r_{32} = r_{72} = 26.67$ cm

$r_{42} = r_{62} = 46.19$ cm; $r_{52} = 53.33$ cm; $R = 81.2$ cm; $r_1 = 0$;

$x_2 = 1.35$ cm $\alpha_2 = 0$, $\alpha_3 = 60°$; $\alpha_4 = 120°$ $\alpha_5 = 180°$; $\alpha_6 = 240°$; $\alpha_7 = 300°$

$p = .98$, $L^2 = 121$, $\tau = 258$

$$A_{10} = -\frac{Y_0(\mu_1 R)}{J_0(\mu_1 R}\left\{1 + 6C\,J_0(\mu_1 r_2)\right\}$$

$$A_{20} = -\frac{\alpha}{\beta}\cdot\frac{2}{\pi}\,\frac{K_0(\mu_2 R)}{I_0(\mu_2 R)}\left\{1 + 6C\,I_0(\mu_2 r_2)\right\}$$

since $r_2 = r_3 = \cdots = r_7$; $r_1 = 0$; and $\cos n\alpha_2 + \cos n\alpha_3 + \cdots + \cos n\alpha_7$ equals 6 when $n=0$ and equals 0 when $n = 1,2,3,4$

$$C = \left[\frac{-Y_0(\mu_1 r_2 + J_0(\mu_1 r_2)\frac{Y_0(\mu_1 R)}{J_0\,\mu_1 R} - \frac{\alpha}{\beta}\cdot\frac{2}{\pi}K_0(\mu_2 r_2) + \frac{\alpha}{\beta}\,\frac{2}{\pi}I_0(\mu_2 r_2)\frac{K_0(\mu_2 R)}{I_0(\mu_2 R)}}{Y_0(\mu_1 x_1) + Y_0(\mu_1 r_{32}) + Y_0(\mu_1 r_{42}) + Y_0(\mu_1 r_{52}) + Y_0(\mu_1 r_{62}) + Y_0(\mu_1 r_{72})}\right.$$

$$\frac{+\frac{\alpha}{\beta}\cdot\frac{2}{\pi}\left\{K_0(\mu_2 x) + K_0(\mu_2 r_{32}) + K_0(\mu_2 r_{42}) + K_0(\mu_2 r_{52}) + K_0(\mu_2 r_{62}) + K_0(\mu_2 r_{72})\right\}}{\left. -6J_0^2(\mu_1 r_2)\frac{Y_0(\mu_1 R)}{J_0(\mu_1 R)} - 6\frac{\alpha}{\beta}\cdot\frac{2}{\pi}I_0^2(\mu_2 r)\frac{K_0(\mu_2 R)}{I_0(\mu_2 R)}\right]}$$

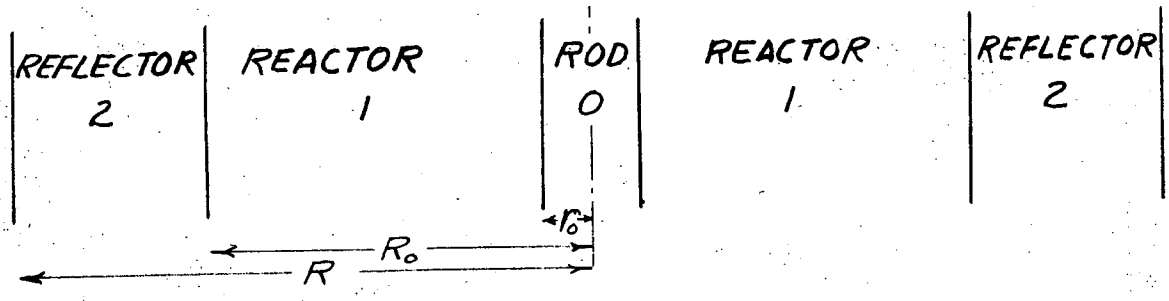
and the original equation becomes

$$A_{10} + Y_0(\mu_1 x_1) + 6C\,Y_0(\mu_1 r_2) + A_{20} + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}K_0(\mu_2 x_1) + \frac{\alpha}{\beta}\cdot\frac{2}{\pi}(6)C\,K_0(\mu_2 r_2) = 0$$

The value of k in the critical pile equation, with $L^2 = 121$ and $\tau = 258$, and with longitudinal buckling $= \left(\frac{\pi}{150}\right)^2$, which gave a μ_1 and a μ_2 satisfying the above equation was found to be $k = 1.978$

Comparison of this value with the value of k satisfying the critical equation with no rods in the pile — $\mu_1 = \frac{2.4048}{R} = \frac{2.4048}{81.2} = .029615$ with the same L^2, τ, and longitudinal buckling, $k = 1.552$ — gave a $\Delta k = .426$ for the array of rods.

7. Analysis of Control Rod Effect on a Pile with Reflector



The pile equations are

$$\Delta nu_f - K_f^2 (nu)_f + k \frac{\Sigma_{as}}{\Sigma_{af}} (NV)_s = 0$$

$$\Delta (NV)_s - K_s^2 (NV)_s + \frac{\Sigma_{af}}{\Sigma_{as}} (nu)_f = 0$$

where $(nu)_f$ or (nu) and $(NV)_s$ or (NV) denote fast and thermal flux respectively in region 1-0

and

$$\Delta (nu)_f - K_{fr}^2 (nu)_f = 0$$

$$\Delta (NV)_s - K_{sr}^2 (NV)_s + \frac{\Sigma_{afr}}{\Sigma_{asr}} (nu)_f = 0$$

where $(nu)_f$ or (nu) and $(NV)_s$ or (NV) denote fast and thermal flux respectively in region 2, where Σ_{as} and Σ_{asr} are thermal absorbtion cross sections for reactor and reflector, respectively, and Σ_{af} and Σ_{afr} are effective slowing down cross sections in the reactor and reflector, respectively, and where other notation is as defined below.

These equations have solutions of the form:

in region 10:

$$(nv)_{10} = a J_0(B_{r_1} r) + b N_0(B_{r_1} r) + c\, J_0(i B_{r_2} r) + d\, i H_0^{(1)}(i B_{r_2} r)$$

$$(NV)_{10} = S_1\{a J_0(B_{r_1} r) + b N_0(B_{r_2} r)\} + S_2\{c J_0(i B_{r_2} r) + d\, i H_0^{(1)}(i B_{r_2} r)\}$$

and in region 2

$$(nv)_2 = e J_0(i K_{r_1} r) + f\, i H_0^{(1)}(i K_{r_1} r)$$

$$(NV)_2 = S_3\{e J_0(i K_{r_1} r) + f\, i H_0^{(1)}(i K_{r_2} r)\} + g J_0(i K_{r_2} r) + h\, i H_0^{(1)}(i K_{r_2} r)$$

where $S_1 = \frac{\lambda_{10}}{\Lambda_{10}} \frac{K_f^2 + B_1}{k K_s^2}$; $S_2 = \frac{\lambda_{10}}{\Lambda_{10}} \frac{K_f^2 + B_2}{k K_s^2}$; $S_3 = \frac{\lambda_2}{\Lambda_2} \frac{K_{fr}^2}{K_{sr}^2 - K_{fr}^2}$

$K_f^2 = \frac{1}{\tau}$; $K_s^2 = \frac{1}{L^2}$; $K_{fr}^2 = \frac{1}{\tau_r}$; $K_{sr}^2 = \frac{1}{L_r^2}$ $\quad B_z = \left(\frac{\pi}{150}\right)^2$

τ and L^2 are age and diffusion length squared in reactor

τ_r and L_r^2 are age and diffusion length squared in reflector

$B_{r_1}^2 = B_1 - B_z^2$; $-B_{r_2}^2 = B_2 - B_z^2$ $\quad -K_{r_1}^2 = -K_{fr}^2 - B_z^2$; $-K_{r_2}^2 = -K_{sr}^2 - B_z^2$

$$B_1 = \frac{-(\tau + L^2) + \sqrt{(\tau + L^2)^2 + 4(k-1)\tau L^2}}{2\tau L^2} \qquad B_2 = \frac{-(\tau + L^2) - \sqrt{(\tau + L^2)^2 + 4(k-1)\tau L^2}}{2\tau L^2}$$

The boundary condition $(nv)_2 = 0$ at $r = R$ and $(NV)_2 = 0$ at $r = R$ implies that

$$e = -\frac{i H_0^{(1)}(i K_{r_1} R)}{J_0(i K_{r_1} R)} f \quad \text{and} \quad g = -\frac{i H_0^{(1)}(i K_{r_2} R)}{J_0(i K_{r_2} R)} h$$

Substituting these values and applying the condition that $(nv)_{10} = (nv)_2$ and $(NV)_{10} = (NV)_2$ at $r = R_0$

① $$a J_0(B_{r_1} R_0) + b N_0(B_{r_1} R_0) + c J_0(i B_{r_2} R_0) + d\, i H_0^{(1)}(i B_{r_2} R_0) - f\left[i H_0^{(1)}(i K_{r_1} R_0) - \frac{i H_0^{(1)}(i K_{r_1} R)}{J_0(i K_{r_1} R)} J_0(i K_{r_1} R_0)\right] = 0$$

② $$S_1 a J_0(B_{r_1} R_0) + S_1 b N_0(B_{r_1} R_0) + S_2 c J_0(i B_{r_2} R_0) + S_2 d\, i H_0^{(1)}(i B_{r_2} R_0) - S_3 f\left[i H_0^{(1)}(i K_{r_1} R_0) - \frac{i H_0^{(1)}(i K_{r_1} R)}{J_0(i K_{r_1} R)} J_0(i K_{r_1} R_0)\right] = h\left[i H_0^{(1)}(i K_{r_2} R_0) - \frac{i H_0^{(1)}(i K_{r_2} R)}{J_0(i K_{r_2} R)} J_0(i K_{r_2} R_0)\right]$$

The boundary condition of continuity of current at R_0 leads to:

$$③\ \lambda_{10}\Big\{-a\,B_{r_1}J_1(B_{r_1}R_0) - b\,B_{r_1}N_1(B_{r_1}R_0) - c\,B_{r_2}\,i\,J_1(iB_{r_2}R_0) + d\,B_{r_2}H_1^{(1)}(iB_{r_2}R_0)\Big\} - \lambda_2 f\,K_{r_1}\Big\{H_1^{(1)}(iK_{r_1}R_0) + \frac{iH_0^{(1)}(iK_{r_1}R)}{J_0(iK_{r_1}R)}\,i\,J_1(iK_{r_1}R_0)\Big\} = 0$$

and.

$$④\ \Lambda_{10}\Big\{-S_1B_{r_1}a\,J_1(B_{r_1}R_0) - S_1B_{r_1}b\,N_1(B_{r_1}R_0) - S_2c\,B_{r_2}\,i\,J_1(iB_{r_2}R_0) + S_2B_{r_2}d\,H_1^{(1)}(iB_{r_2}R_0)\Big\} - \Lambda_2S_3f\,K_{r_1}\Big\{H_1^{(1)}(iK_{r_1}R_0) + \frac{iH_0^{(1)}(iK_{r_1}R)}{J_0(iK_{r_1}R)}\,i\,J_1(iK_{r_1}R_0)\Big\} = \Lambda_2h\,K_{r_2}\Big\{H_1^{(1)}(iK_{r_2}R_0) + \frac{iH_0^{(1)}(iK_{r_2}R)}{J_0(iK_{r_2}R)}\,i\,J_1(iK_{r_2}R_0)\Big\}$$

Further conditions are $(nu)'_{10} = 0$ at $r = r_0$ and $(NV)_{10} = 0$ at $r = r_0$

$$⑤\ -a\,B_{r_1}J_1(B_{r_1}r_0) - b\,B_{r_1}N_1(B_{r_1}r_0) - c\,B_{r_2}\,i\,J_1(iB_{r_2}r_0) + d\,B_{r_2}H_1^{(1)}(iB_{r_2}r_0) = 0$$

$$⑥\ S_1\{a\,J_0(B_{r_1}r_0) + b\,N_0(B_{r_1}r_0) + S_2\{J_0(iB_{r_2}r_0) + d\,i\,H_0^{(1)}(iB_{r_2}r_0) = 0$$

The solution of these equations with $L^2 = 121$, $\tau = 258$; $L_r^2 = 1092$; $\tau_r = 149$; $R = 91$ cm; $R_0 = 61$ cm; $\frac{\lambda_2}{\lambda_{10}} = \frac{\Lambda_2}{\Lambda_{10}} = .258$

$\frac{\lambda_{10}}{\Lambda_{10}} = \frac{\lambda_2}{\Lambda_2} = 1$ gives the radius of control rod necessary to make a critical pile with any given k.

To find the k for a critical pile with no control rod instead of equations 5 & 6 use $(nU)'_{10} = 0$ at $r=0$ and $(NV)'_{10} = 0$ at $r=0$

thus

5-a $\quad -b\,B_{r_1} N_1(0) + d\,B_{r_2} H_1^{(1)}(0) = 0$

6-a $\quad -S_1 b\,B_{r_1} N_1(0) + S_2 d\,B_{r_2} H_1^{(1)}(0) = 0$

$N_1(0)$ and $H_1^{(1)}(0)$ are singularities of the same order, and

$B_{r_1} \neq B_{r_2}$, $S_1 \neq S_2$

hence

$b = d = 0$

Substituting these values in equations 1 to 4 gives a system which may be solved for k.

Bessel functions are in the notation of Jahnke and Emde.

[redacted]

APPENDIX G

PRELIMINARY BOILER SPECIFICATIONS

Heat will be supplied to two boilers from a single power pile in the form of helium gas at 1400 F and 132#/in.^{2}g. pressure at the pile.

Output of Each Boiler

Maximum continuous load	34.15×10^6 Btu/hr.
Normal " "	20.49×10^6 " "
Minimum " "	1.71×10^6 " "

Steam Conditions

Press. at Superheater Outlet	- 450 #/in.^{2}g.
Design pressure of boiler	- 550 "
Total steam temperature	- 735 F
Feedwater temperature to boiler unit	- 235 F

Proposals are requested on two boiler units of the forced recirculation type. Each boiler unit shall consist of cylindrical gas pressure casing designed to withstand the high temperature and pressure of the helium. The design shall be such that the gas pressure casing is subjected to the lowest possible internal temperature consistent with good design practice. No insulation will be permitted within the gas pressure shell or the inlet or outlet ducts connected to it.

Each boiler unit shall consist of superheater, boiler or evaporative surface, and economizer. It is desired that the gas pressure shell be designed with a minimum of openings for conveying water and steam to and from the boiler unit. The components of boiler unit within the gas pressure shell should be designed with a minimum number of welded connections. All joints however will be welded.

Each boiler shall be equipped with separate steam and water drum to which the steam and water from the evaporative section of the boiler shall be discharged. Each boiler unit shall be equipped with two independent motor driven forced circulation pumps to be furnished by bidder, each with sufficient capacity to supply the required quantity of water to operate the boiler satisfactorily at maximum continuous output.

Superheater will be designed to maintain approximately constant steam temperature over the full output range of the boiler when supplied with helium gas at a pressure 132#/in.^{2}g and temperatures entering the boiler as given in performance tabulation of these specifications. If anything lower superheated steam temperatures are preferred at the lower loads. A minimum temperature of 685°F at the minimum continuous load is considered satisfactory.

Feedwater will be supplied to the economizer at a temperature of 235°F.

[redacted]

DECLASSIFIED

Water temperature leaving the economizer should preferably be limited to 420°F.

Arrangement of Equipment

It is proposed to rigidly connect the pile to the boiler by single large pipe. The horizontal expansion in the pipe amounts to 1.1". A method of supporting the gas pressure shell of the boiler which will provide for this amount of expansion is desired. It is furthermore desired that the steam and water drum be rigidly supported and that the connecting tubes between the recirculation pumps and gas pressure shell and between gas pressure shell and steam and water drum be designed with sufficient flexibility to provide for expansion without excessive thrust on these members.

In operation the gas pressure shell will be inaccessible. It will be surrounded by enclosure 6 ft. in thickness. Steam and water drum and recirculation pumps will be located outside of this enclosure and will be accessible. Figure 51 indicates the desired general arrangement of the equipment.

Materials.

Materials used in boiler drums, boiler superheater and economizer tubing, all steam and water headers and all tubes used in the boiler assembly shall conform to the material specifications of the ASME code for power boilers. The gas pressure shell in which all of the heat transfer surface is located should also be designed in accordance with the ASME Boiler Code using the allowable stresses for steam boilers for the temperatures encountered, assuming a design pressure within the shell of 250#/in.^{2}g. In addition to the internal pressure, this shell should be also designed to support all elements of the heating surface and any other loads or thrusts which might be encountered resulting from the particular design proposed.

In addition to the above considerations it is desired to provide insurance against loss of metal caused by acids used in removal of contaminants. For this reason it is desired that thickness of gas pressure shell, and all tubes and headers in contact with the helium be increased by 1/10" over the values determined from the ASME code allowable stresses.

Inspection of Material

Because of the serious consequences resulting from failure of materials or as a result of inadequate fabricating procedures it will be necessary to provide rigid means of inspecting materials and their manufacture for all elements of the boiler unit.

Low Load Operation

On shutdown the pile will continue to supply heat to the boiler at a reducing rate. In case of mechanical failure or interruption to the power

DECLASSIFIED

SECRET

supply of the circulating pumps it is desired that the boiler be designed to operate satisfactorily under natural circulation with the pile supplying helium to the boiler at 1250 F corresponding to an absorption rate in the boiler of 1.71×10^6 Btu/hr. This minimum continuous load is the lowest load at which the boiler will be required to operate continuously at a helium temperature of 1260 F and a pressure of 132#/in.^{2}g. At lower loads helium temperature and pressure may be gradually reduced if required by operation of the boiler.

Dust and Moisture Separator in Gas Stream.

It is desired that a combination dust and moisture separator, located in the gas pressure shell be provided by the bidder. This separator will function normally to remove a small amount of dust which will be picked up by the helium.

In the case of serious leak or tube rupture in the boiler a large amount of water and steam will be discharged into the gas stream. It is expected that the bulk of the liquid water will be discharged into the lower section of the gas pressure shell where means will be provided for its removal. Some water however will be carried along with the helium in the form of droplets or slugs. It is a secondary purpose of the combination separator to remove this portion of the boiler leakage. It is desired that the moisture in the helium leaving the separator be reduced to less than 5% weight.

It is contemplated that the separator will be located at the gas outlet from the boiler surface at or in the outside annulus forming the passage through which the exit gases travel upward to the outlet connection of the boiler. When operating at the maximum continuous load the pressure loss through the collector should not exceed 5" H_2O.

The quantity and sizing of the dust particles in the gas stream are not definitely determined. Bidders are therefore requested to specify the expected collection efficiency of the collector based on various percentages of material under 10 microns and under 50 microns entering, assuming a density of 2.9 compared to water.

Helium Cooled Duct

The arrangement of the high temperature duct between pile and boiler is indicated on Fig. 50. Helium discharged from the pile at 1400 F flows through the inner core. Cooler helium from the discharge of the helium blowers at approximately boiler outlet temperature, is supplied to the high temperature duct annulus at the pile. This helium coolant flows through the annulus to the boiler thence through an inner annulus in the upper section of the boiler. The position of the outlet of the inner annulus through which the coolant helium is discharged into the boiler is dependent on the temperature of the coolant. It is intended that the annulus outlet be located at a position where the temperature of the main gas stream

SECRET

DECLASSIFIED

corresponds approximately to that of the coolant helium discharging from the annulus. The estimated quantities and temperatures of the helium coolant entering the boiler are given below. Consideration should be given to these factors in determining the design and performance of the boiler.

Boiler Output Btu/hr	1.71×10^6	20.49×10^6	34.15×10^6
Temp. Helium entering Boiler °F.	1250	1330	1345
Helium Flow through Annulus#/hr.	400	3700	4600
Temp. Helium coolant at inner annulus discharge °F	885	885	885

Accessibility

Maximum reliability from standpoint of materials, design and operation is imperative. It is the intention to provide designs which with proper operation will operate indefinitely without requiring adjustment or replacement of any part of the unit with-in the gas pressure shell. It would be desirable however to provide a manhole in the shell if, by its use, satisfactory inspection of the interior can be accomplished. On the other hand simplicity and reliability are paramount. It is not desired that the design be complicated to any extent to provide accessibility for inspection.

Replacement

It is expected that the gas pressure shell and enclosed heating surface assembly will be completely assembled in the shop. Erection at the site will involve connections of inlet and outlet ducts to the gas inlet and outlet connections of the boiler. The joints between the ducts and the boiler shell shall be so welded or flanged and seal welded as to facilitate removal and replacement of the entire shell assembly in event of failure.

Baffles.

A design of boiler without baffles is desirable. If baffles are required they should be arranged approximately vertical to avoid shelves or pockets where dust circulated with the helium might lodge.

Provision for Acid Cleaning

Boiler shall be designed to permit acid cleaning of the interior of the heating surface. The design should also provide for acid cleaning of the exterior of the heating surfaces and all other parts in contact with the helium gas. Care should be taken to avoid all cracks and crevices where acid might enter and not be removed when the gas pressure shell is drained. Pockets which are not self draining should also be avoided.

Fittings

Each boiler shall be equipped with the following fittings to be supplied by the bidder. Bidder shall specify manufacturer designation and size.

DECLASSIFIED

Boiler

2 - Safety Valves
1 - Feed Valve
1 - Feed check valve
2 - Blowoff valves
1 - 12" steam gauge
2 - 12½" water gauges and valves
2 - Illuminators for gauges

Superheater

1 - Safety valve
2 - Vent valves

Circulating Pumps

2 - Stop check valves on pump discharge
2 - Gate valves on pump suction

Feedwater Control Equipment and Instrumentation

It is requested that the bidder supply a list of feedwater control equipment required to operate the boiler, also a list of instruments which they would recommend for an installation of this type.

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U.S.C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

DECLASSIFIED

SECRET

Performance

Predicted performance to be inserted in blank spaces by Bidder.

Heat absorption by Boiler - Btu/hr.	1.71×10^6	20.49×10^6	34.15×10^6
Helium			
Helium flow - #/hr/boiler	-	-	-
Helium temp. entering boiler unit °F	-1250	-1330	-1345
" " leaving " " "	-		500
" press. entering " #/in.^{2}g.	132.	132.	132.
" press. drop thru boiler unit in H_2O	-	-	14.00
Steam and Water			
~~Total steam temperature~~ at superheater outlet °F	-	-	735
Steam press. at superheater outlet #/in.^{2}g	450	450	450
Evaporation- #/stm/hr.	-	-	-
Temp. feedwater to unit °F	235	235	235
Superheater			
Helium temperature entering °F	-	-	-
" " leaving °F	-	-	-
Draft loss thru superheater, in H_2O	-	-	-
Steam press. drop (boiler drum to superheater outlet) #/in.^{2}	-	-	-
Boiler			
Solids carryover in steam ppm	-	-	1.0Max.
Helium temp. entering °F	-	-	-
Helium temp. leaving °F	-	-	-
Draft loss thru boiler in H_2O	-	-	-
Economizer			
Helium temp. entering °F	-	-	-
Helium temp. leaving °F	-	-	-
Draft loss thru economizer in H_2O	-	-	-
Water temp. entering °F	235	235	235
" " leaving °F	-	-	-
Water press. loss thru economizer #/in.^{2}	-	-	-
Circulating Pumps			
Quantity of water circulated, GPM	-	-	-
Power Input to pumps, KWH	-	-	-
Number of pumps operating	-	-	-
Dust Collector			
Pressure drop H_2O	-	-	-

This document contains information affecting the national defense of the United States within the meaning of the Espionage Act, U.S.C. 50, 31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

SECRET

DECLASSIFIED

SECRET

* It has been determined that it is not necessary to design to maintain this temperature uniform over the load range.

Proposition Drawing

Complete proposals are not desired at this time. This preliminary specification is intended to outline the essential features of the design to enable the bidders to prepare proposition drawings. At this time, it is desired that the bidder supply only proposition drawings with necessary description of equipment and the performance data requested.

AUTHORITY

DECLASSIFIED