REFERENCE 26

F. E. KRUESI, J. O. ERKMAN, AND D. D. LANNING, "CRITICAL MASS STUDIES OF PLUTONIUM SOLUTIONS," HANFORD ATOMIC PRODUCTS OPERATION REPORT HW-24514 (DEL.) (MAY 1952).

HW-24514 DEL

AEC RESEARCH AND DEVELOPMENT REPORT

CRITICAL MASS STUDIES OF PLUTONIUM SOLUTIONS

F. E. KRUESI, J. O. ERKMAN and D. D. LANNING

MAY 19, 1952

HANFORD LABORATORIES

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

GENERAL ELECTRIC

HW-24514 DEL
UC-46, Criticality Studies
(TID-4500, 15th Ed.)

CRITICAL MASS STUDIES OF PLUTONIUM SOLUTIONS

By

F. E. Kruesi, J. O. Erkman and D. D. Lanning
Physics Sub-Unit
Applied Research Unit

May 19, 1952

Reissued in Declassified Form, February 15, 1960

By

Nuclear Physics Research
Physics and Instrument Research and Development Operation

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

Work performed under Contract No. W-31-109-Eng-52 between the Atomic Energy Commission and General Electric Company

Printed by/for the U. S. Atomic Energy Commission

Printed in USA. Price $2. 25. Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

HW-24514 DEL
UC-46, Criticality Studies
(TID-4500, 15th Ed.)

CRITICAL MASS STUDIES OF PLUTONIUM SOLUTIONS

By

F. E. Kruesi, J. O. Erkman and D. D. Lanning
Physics Sub-Unit
Applied Research Unit

May 19, 1952

Reissued in Declassified Form, February 15, 1960

By

Nuclear Physics Research
Physics and Instrument Research and Development Operation

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

Work performed under Contract No. W-31-109-Eng-52 between the Atomic Energy Commission and General Electric Company

Printed by/for the U. S. Atomic Energy Commission

Printed in USA. Price $2. 25. Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

The chain reacting conditions for plutonium nitrate in water solution have been examined experimentally for a variety of sizes of spheres and cylinders. The effects on the critical mass of the displacement of hydrogen and the addition of poisons to the fuel were measured in water tamped and bare reactors.

In this report the data obtained in the investigation is presented graphically and in tables. Some preliminary analysis has been made yielding the results:

i) the absorption cross-section of Pu^{240} is 925 ± 200 barns and
ii) the minimum critical mass of Pu^{239} in water is 510 grams at a concentration of about 33 grams per liter.

CRITICAL MASS STUDIES OF PLUTONIUM SOLUTIONS

INTRODUCTION

The criticality experiments reported here were undertaken to provide data for nuclear safety. Experimentation was directed toward the determination of the minimum critical mass of a light water tamped and moderated, homogeneous plutonium solution. The effects on critical mass of geometry, concentration, foreign atoms, isotopic content, tamping, and temperature were investigated. This information together with a study of the effects of various perturbations such as control rods, shafts, voids, etc. was required to evaluate the degree of safety afforded in the processing of these solutions. Some work has been directed toward the interpretation of data in terms of existing reactor theory. The intent of this report is to make available the critical mass data obtained during the course of the Hanford program and to describe the experimental facilities and procedures employed for this work.

EXPERIMENTAL FACILITIES AND PROCEDURES

Site Layout

These criticality studies were conducted in an isolated area, three miles from other project installations. The reactor assembly was remotely operated as it was felt that the greatest hazard to personnel in the event of the worst possible disaster would be that of high radiation levels and air-borne plutonium contamination. The control and laboratory buildings were separated by a distance of 175 feet and so oriented that neither the generally prevailing nor force winds would carry air-borne contamination towards the control building. This distance was acceptable from both radiation and contamination considerations and was not so great as to cause instrumentation difficulties.

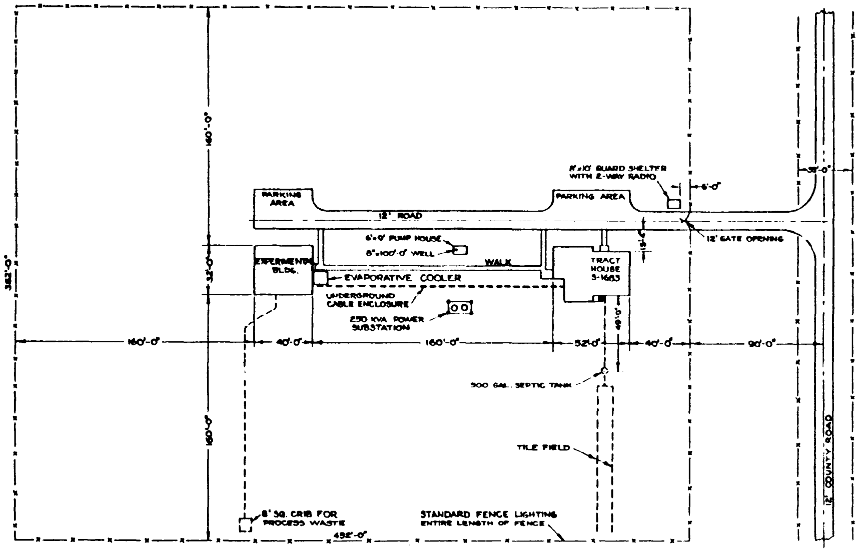
The control building housed the control equipment for the operation of the reactor assembly and provided facilities for instrument repair, air sample monitoring and office purposes.

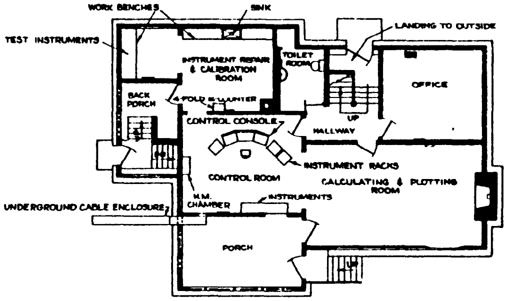
The laboratory building was designed specifically for these studies. It contained two thermally insulated reactor assembly rooms, a chemical laboratory for the handling and storage of plutonium solutions, a room for the storage of radioactive material and wastes, a personnel change room, and work areas. Air exhaust and filtering equipment was provided to service the chemical laboratory and exhaust hood, reactor rooms, and work areas. Figures 1 and 2 show the P-11 Area plot plan and building arrangement.

Fluid System

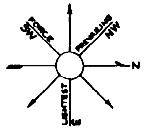
In the design of the plutonium fluid handling system special consideration was given to problems of nuclear safety, plutonium contamination, and corrosion resistance. Gravity flow was selected for the transfer of solution through the system as it was felt that plutonium contamination problems precluded the use of pneumatic pressure in this type of experimental apparatus. Solution flow rates were limited by pipe size and fluid head restrictions to about two liters per minute. Calculations had shown that inadvertent additions of fuel at this rate after criticality had been attained would not give rise to an explosive reaction. As the conditions of criticality for plutonium solutions were not known at the outset of these studies, vessel sizes and spacings were deliberately made overly conservative. All vessels except the reactors were made with diameters not exceeding five inches and were wrapped with 0.020 inch cadmium to reduce the effectiveness of possible tamping. All vessels, including the reactors, were vented to a common manifold which was in turn filtered to the atmosphere to compensate changes in barometric pressure.

Plutonium solutions were prepared and introduced into the fluid system in an exhaust hood located in the chemical laboratory. One hundred fifty linear feet/minute of air were provided across the open face of the hood. The output of the hood was filtered through six parallel CWS Type 197-54-303C filters. The air sample activity of the filtered exhaust air varied directly with the activity of chemical processing. General levels in the chemical laboratory were about 10^{-11} microgram Pu/cc while individual samples ran as high as 10^{-9} microgram Pu/cc.



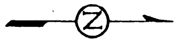


TRACT HOUSE
FIRST FLOOR PLAN
SCALE: 1/8" = 1'-0"



WIND DIRECTION

PLOT PLAN
SCALE: 1" = 40'-0"



NONE

2nd Issue Ⓜ
8-7-51

FIGURE 1

NO.	DESCRIPTION	REV. BY DATE	APP'D BY	DIV.	DATE
	REVISIONS				

SCALE: AS SHOWN

DRAWN DATE 7-24-51

CHECKED A.J.B. DATE 8-2-51

ISSUED DATE

DES. ENG. W.L.G. DIV. R & D.

ENGINEER REQUEST NO.

PROJECT NO. C-340

APPROVALS		
BY	DIV.	DATE

U. S. ATOMIC ENERGY COMMISSION
HANFORD WORKS
GENERAL ELECTRIC

0110
0800

BUILDING ARRANGEMENTS

PROJECT TITLE P-11 PROJECT

BLDG. NO. 122

DWG. NO. H-7-901

SHEET NO.

SHEETS

DWG. NO.	DRAWING TITLE
H-7-621	DRAWING LIST

REFERENCE DRAWINGS

NEXT USED ON

CLASSIFICATION

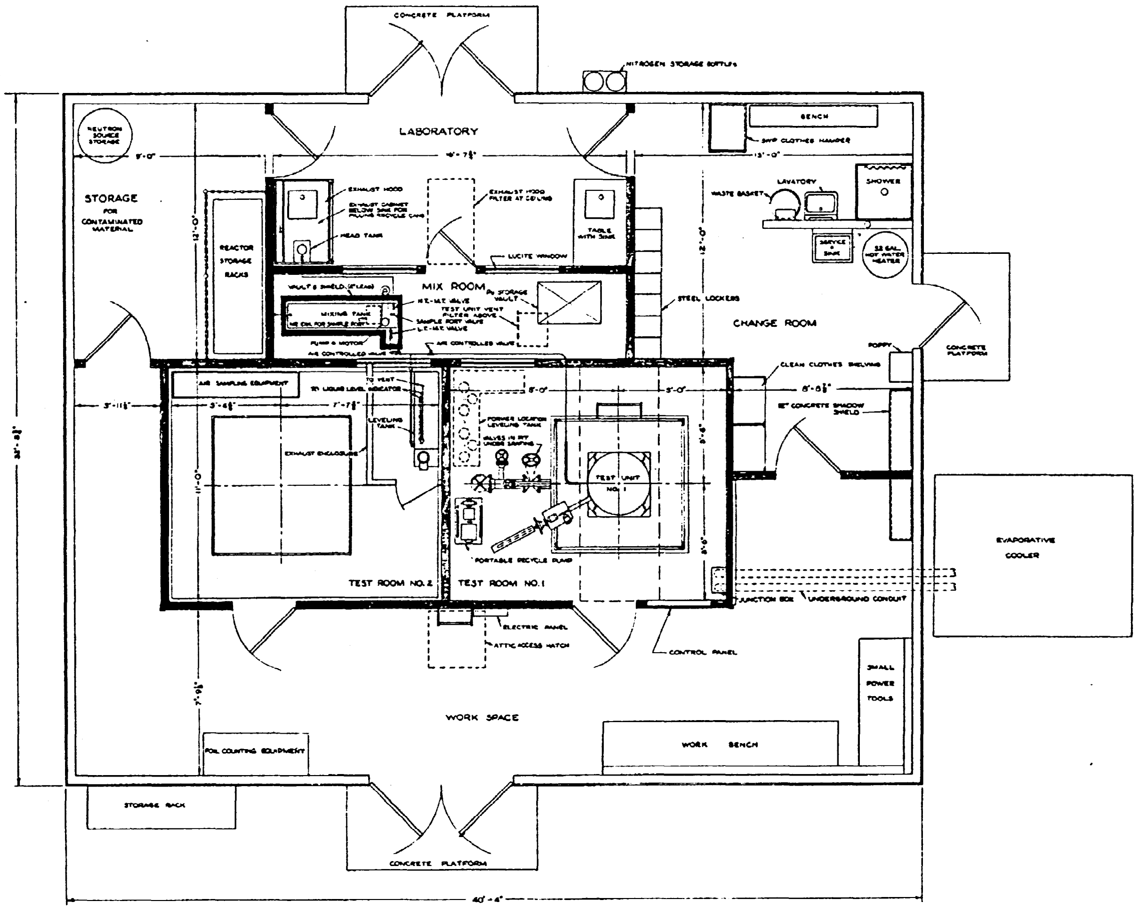


FIGURE 2

REVISIONS

SCALE: ½" = 1'-0"

DATE 7-25-54

PROJECT NO. C-340

APPROVALS

U. S. ATOMIC ENERGY COMMISSION
HANFORD WORKS
GENERAL ELECTRIC

0804

H-7-898 ARCHITECTURAL FLOOR PLAN & DETAILS
H-7-413 BUILDING ARRANGEMENTS

REFERENCE DRAWINGS

NEXT USED ON

NONE
CLASSIFICATION

FLOOR PLAN

PROJECT TITLE
P-11 PROJECT

BLDG. NO. 120
DWG. NO. H-7-900

The chief components of the fluid system were the head tank, mixing tanks and agitator, leveling tanks and reactors. Solution was cycled through the system after passing through appropriate valves in the following manner:

a) A vacuum pump isolated from gross contamination by a CWS gas mask filter evacuated the head tank.

b) A quantity of solution not exceeding 2.5 liters was drawn through the decant tube into the tangential head tank opening and the vacuum released. (A sight glass of polythene tubing paralleled the head tank for volumetric measurement purposes.)

c) This solution was released to the mix tanks and agitated with previous fuel additions to attain homogeniety. The mix tanks with a 35 liter capacity consisted of two paralleled cylinders five inches in diameter and five feet in length, spaced 23 inches between centers. An agitator or recirculating pump drew solution from the outlet of both tanks and exhausted to the inlet of the tanks. A sampling port was provided at the outlet of the recycling pump.

d) This homogeneous fuel mixture drained to the leveling tanks as they were lowered. The leveling tanks (35 liter capacity) consisted of a single vertical bank of six paralleled cylinders which were raised or lowered with respect to the reactor and mix tanks to provide the required fluid heads. Each tank was five inches in diameter, 18 inches in height, and separated from adjacent tanks by a minimum of ten inches between centers. Fluid level within the tanks was indicated by a Republic liquid level bubbler to within ± 1/16 inch after correcting for specific gravity.

e) The reactor vessel was filled as outlined in the procedures section of this report by raising the leveling tanks from the control room to provide the desired flow rate. A remotely operated valve (solenoid operated air cylinder actuating diaphram type valve) controlled fluid flow.

f) Fluid was returned to the mix tanks or head tank for further processing or withdrawal by reversing this process.

All piping and fluid tanks were fabricated from type 347 stainless steel. Flexible portions of the system were fabricated from 3/8 inch OD polythene tubing which was protected by a one inch ID tygon tubing. A compression type squeeze clamp was used with excellent results to join the plastic and stainless portions of the fuel lines. Polythene diaphram type valves were used throughout the system to eliminate valve stem contamination or the need for bellows. Air seals prevented contamination spread where removable components were introduced into the fluid system.

Upon completion of the greater part of the experimental program discussed in this report modifications were made to the fluid system because of fluid capacity limitations and corrosion failure at welded joints. Sufficient criticality data on plutonium had been gained to allow a relaxation in vessel geometry limitations. The mix tanks described above were replaced by a single tank having 6 x 14 x 60-inch dimensions with three internal equally spaced cadmium absorbing curtains paralleling the long dimension of the tank. The leveling tanks were replaced with a single 10 x 15 x 30-inch tank containing cadmium absorbing curtains spaced 2-1/2 inches apart. The capacity of the system was raised to 80 liters in this manner.

Figure 3 shows a schematic (diagram) of the fluid handling system.

Fuel

Plutonium nitrate was utilized as the basic fuel material in view of its 1) availability, 2) chemical stability, 3) solubility at required concentrations, and 4) ease of reconcentration and recovery in the Hanford process. Subsequent alterations in chemical form and solution constituents were made by the critical mass experimental group as necessary. Fuel was prepared for critical mass experimentation in the following manner.

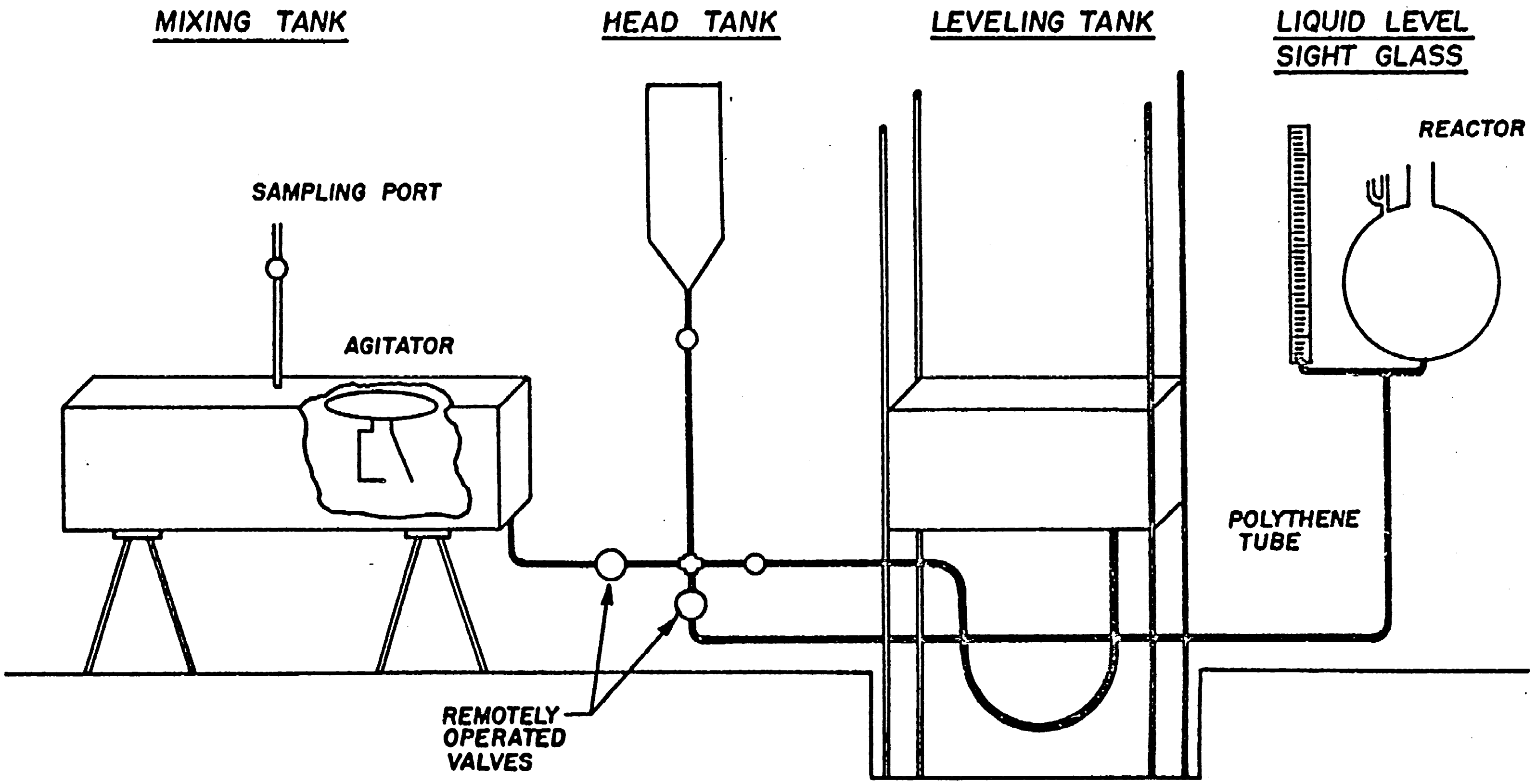


FIGURE 3

Fluid Transfer System

a) Plutonium was received in 160 gram batches either as a 1000 gram Pu/liter, viscous concentrate or as a 350 gram Pu/liter solution. The viscous concentrate was converted to 320 gram Pu/liter solution by the addition of weak nitric acid with about two hours of continuous agitation.

b) This solution was introduced to the fluid system either by decanting into the head tank when bulk additions were required or by pipetting measured volumes directly to the mix tank through the sample port for small concentration adjustments.

c) Distilled water and 70 per cent nitric acid were added as in (b) to produce the required fuel concentrations. Precautions were taken to maintain a fuel acidity of at least 1 $\underline{M}$ HNO_3 to prevent hydrolysis and subsequent precipitation of basic plutonium compounds.

d) This fuel mixture was thoroughly agitated after each concentration adjustment for a period of about 15 minutes to insure complete homogeneity. The entire fluid content of the system was drained to the mix tanks prior to agitation.

e) Analytical samples representative of fuels reaching criticality were taken through the sampling port by lowering a clean dry glass pipette into contact with the solution and withdrawing the required sample (usually 10 ml).

Fuel analyses were obtained as outlined in the analytical section of this report. Concentration estimates based on known fuel additions were not better than ± 5.0 per cent owing to volume changes through displacement, assay inaccuracies (± 2.0 per cent) in arriving plutonium material, and small solution holdups in various parts of the system.

Criticality considerations required an investigation of the effects of various fuel impurities. These studies included bismuth, phosphate, lithium, sulfate, and the isotopic content of the fuel.

Bismuth

$Bi(NO_3)_3 \cdot 5 H_2O$ crystals were dissolved in plutonium nitrate solution in concentrations ranging up to 300 grams Bismuth ion/liter. It was necessary to maintain an acidity of 1.5 $\underline{M}$ HNO_3 to prevent hydrolysis and subsequent precipitation of basic bismuth nitrate compounds.

Phosphate

Eighty-five per cent phosphoric acid was added to plutonium nitrate in the plus six oxidation state with resulting concentrations ranging up to 280 grams of PO_4 ion per liter. Potassium permanganate was used as an oxidant to prevent the formation of insoluble Pu(IV) phosphate. Difficulties were encountered in preventing precipitation and in removal of the MnO_2 reduction product.

Lithium

Weighed quantities of lithium nitrate were dissolved in distilled water and added step wise to the fuel in concentrations ranging up to 1.5 grams lithium ion/liter.

Plutonium Isotopic Content

Effects of the relative isotopic contents of Pu^{239} and Pu^{240} on criticality were studied by experimenting with fuels of 0.52, 1.65, 3.12, 4.05, and 4.3 weight % Pu^{240}. The entire fuel content was removed and the system flushed with 2.0 $\underline{M}$ HNO_3 prior to the introduction of each new fuel.

An inventory of about three kilograms of plutonium was required for experimental purposes. An accountability loss of less than one per cent was apparent upon completion of the experimental program.

REACTOR ASSEMBLY

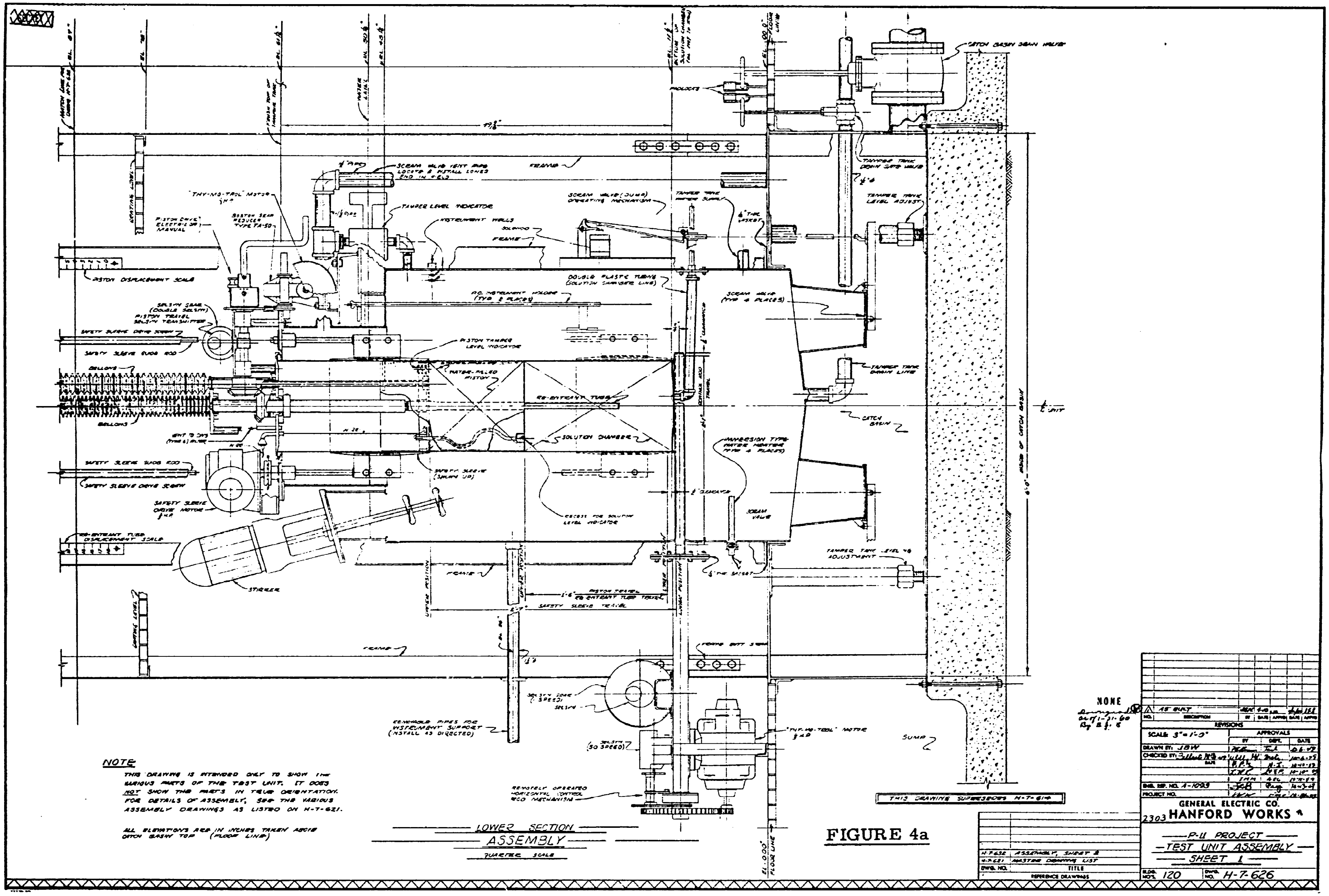
The reactor assembly used in these experiments was designed for criticality measurements in shperical and cylindrical geometries under conditions of effectively infinite water tamping. Principles of nuclear safety, experimental parameters, precision requirements, and the elimination or reduction of perturbing effects were given primary consideration in determining equipment specifications.

Fundamentally, the reactor assembly consisted of a reactor, immersed in a water tamper, fed from the leveling tanks, and controlled by cadmium absorbers. The reactor was driven by an artifical neutron source inserted through a reentrant tube until such time as background multiplication met instrument sensitivity requirements. Auxiliary apparatus was provided for nuclear safety requirements and the control of experimental parameters. Figures 4a and 4b are assembly drawings for a tamped cylindrical reactor. Figures 5a and 5b are assembly drawings for a tamped spherical reactor. The following is a detailed description of the different components of the reactor assembly.

Reactors

Spherical reactors were fabricated by the pressing and spinning of 0.050 inch, type 347, stainless steel sheet with the exception of one reactor fabricated from 20 gauge 2S aluminum. Volumes of tamped spheres ranged from 11.37 to 29.00 liters corresponding to nominal diameters of 11 and 15 inches. Radial sphericity aberation did not exceed 1/8 inch. A fuel feed pipe of 3/8 inch OD stainless tubing was attached to the base of each sphere. A supporting neck, 2-1/8 inch OD, 1/8 inch wall, suspended the reactor in the water tamper. The coaxial safety, reentrant, and source tubes passed through the supporting neck into the reactor. Two electrical fluid contactor housings of one inch pipe projected from the supporting neck.

Cylindrical reactor units with a twelve inch water filled piston tamper were fabricated from 0.062 inch stainless steel sheet. The reactor volume was determined by the piston height which was adjustable to a maximum of 19 inches either by manual or remote operation to a precision of ± 0.010 inches. The cylinder wall-piston annulus did not exceed 0.050 inches. Four cylindrical reactors ranged from 8.0 to 12.0 inches inside diameter. Two electrodes insulated by a one inch diameter polythene body recessed into the piston tamper served as fluid contactors. The

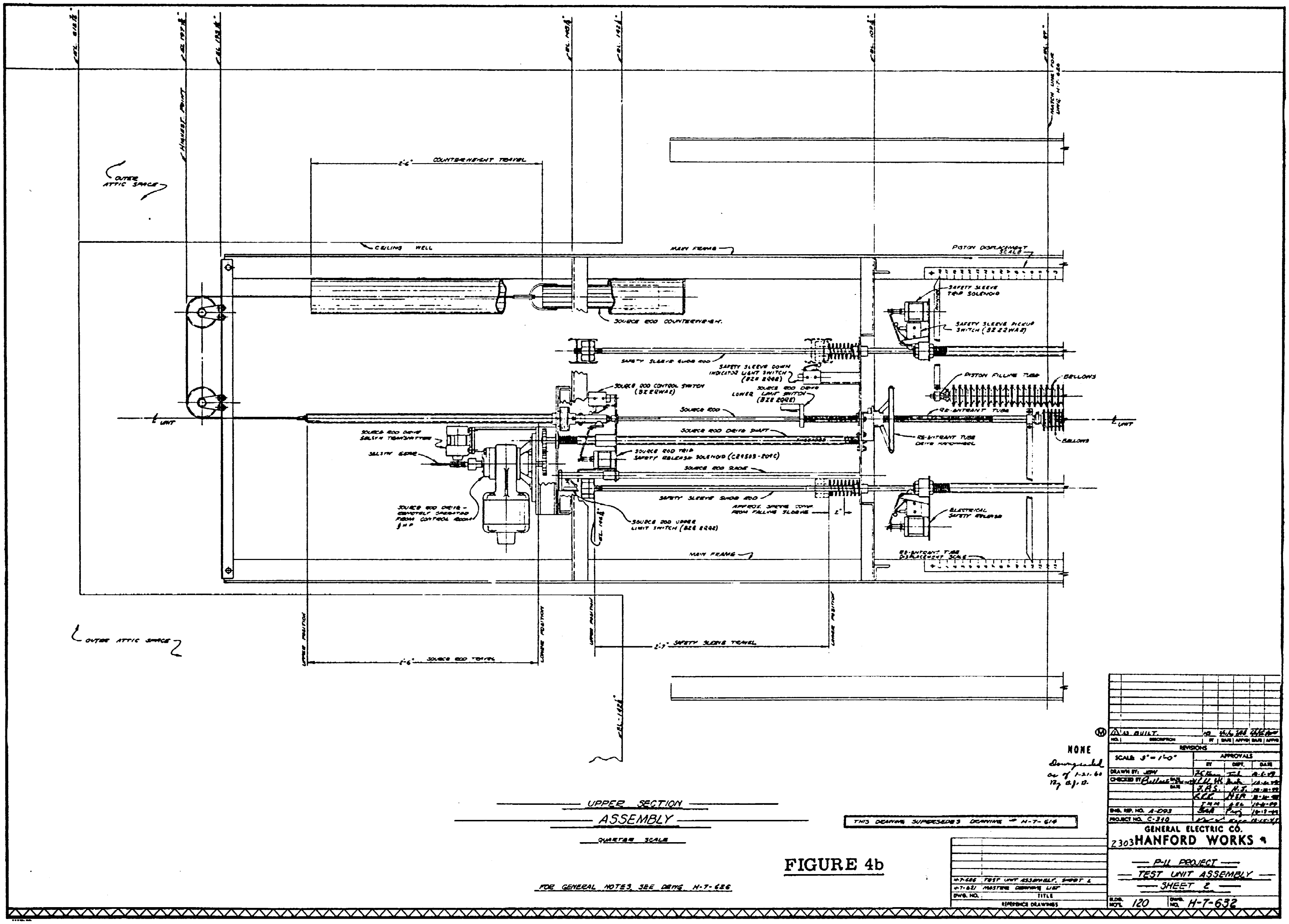


NOTE

THIS DRAWING IS INTENDED ONLY TO SHOW THE VARIOUS PARTS OF THE TEST UNIT. IT DOES NOT SHOW THE PARTS IN TRUE ORIENTATION. FOR DETAILS OF ASSEMBLY, SEE THE VARIOUS ASSEMBLY DRAWINGS AS LISTED ON H-7-621.

ALL ELEVATIONS ARE IN INCHES TAKEN ABOVE CATCH BASIN TOP (FLOOR LINE)

FIGURE 4a



℄ EL. 212⅞"
℄ EL. 197⅞"
℄ EL. 193⅛"
℄ EL. 160⅝"
℄ EL. 152⅛"
℄ EL. 109⅞"
℄ EL. 87"
MATCH LINE FOR DWG. H-7-626
℄ HIGHEST POINT
OUTER ATTIC SPACE
2'-6" COUNTERWEIGHT TRAVEL
CEILING WELL
MAIN FRAME
PISTON DISPLACEMENT SCALE
SAFETY SLEEVE TRIP SOLENOID
SAFETY SLEEVE PICKUP SWITCH (9Z22WA2)
SOURCE ROD COUNTERWEIGHT
SAFETY SLEEVE GUIDE ROD
SAFETY SLEEVE DOWN INDICATOR LIGHT SWITCH (8ZE 2QQ2)
SOURCE ROD CONTROL SWITCH (9Z22WA2)
LOWER SOURCE ROD DRIVE LIMIT SWITCH (8ZE 2QQ2)
PISTON FILLING TUBE
BELLOWS
℄ UNIT
SOURCE ROD
RE-ENTRANT TUBE
SOURCE ROD DRIVE SHAFT
THREADED
RE-ENTRANT TUBE DRIVE HANDWHEEL
BELLOWS
SOURCE ROD DRIVE SELSYN TRANSMITTER
SELSYN GEAR
SOURCE ROD TRIP SAFETY RELEASE SOLENOID (CR9503-209C)
SOURCE ROD GUIDE
SAFETY SLEEVE GUIDE ROD
APPROX. SPRING COMP. FROM FALLING SLEEVE
2"
ELECTRICAL SAFETY RELEASE
SOURCE ROD DRIVE - REMOTELY OPERATED FROM CONTROL ROOM ¼ HP
SOURCE ROD UPPER LIMIT SWITCH (8ZE 2QQ2)
EL. 164⅞"
MAIN FRAME
RE-ENTRANT TUBE DISPLACEMENT SCALE
OUTER ATTIC SPACE
UPPER POSITION
LOWER POSITION
2'-6" SOURCE ROD TRAVEL
UPPER POSITION
LOWER POSITION
2'-7" SAFETY SLEEVE TRAVEL
℄ EL. 142⅛"
UPPER SECTION
ASSEMBLY
QUARTER SCALE
FOR GENERAL NOTES SEE DWG. H-7-626
THIS DRAWING SUPERSEDES DRAWING # H-7-614
NONE
Downgraded as of 1-21-60 By A.J.B.
Ⓜ
1 AS BUILT.
NO. DESCRIPTION BY DATE APPR'D DATE APPR'D
REVISIONS
SCALE: 3" = 1'-0"
APPROVALS
BY DEPT. DATE
DRAWN BY: JEW
CHECKED BY
ENG. REP. NO. A-1093
PROJECT NO. C-310
H-7-626 TEST UNIT ASSEMBLY, SHEET 1
H-7-621 MASTER DRAWING LIST
DWG. NO. TITLE
REFERENCE DRAWINGS
GENERAL ELECTRIC CO.
Z303 HANFORD WORKS
P-11 PROJECT
TEST UNIT ASSEMBLY
SHEET 2
BLDG. NO. 120
DWG. NO. H-7-632

FIGURE 4b

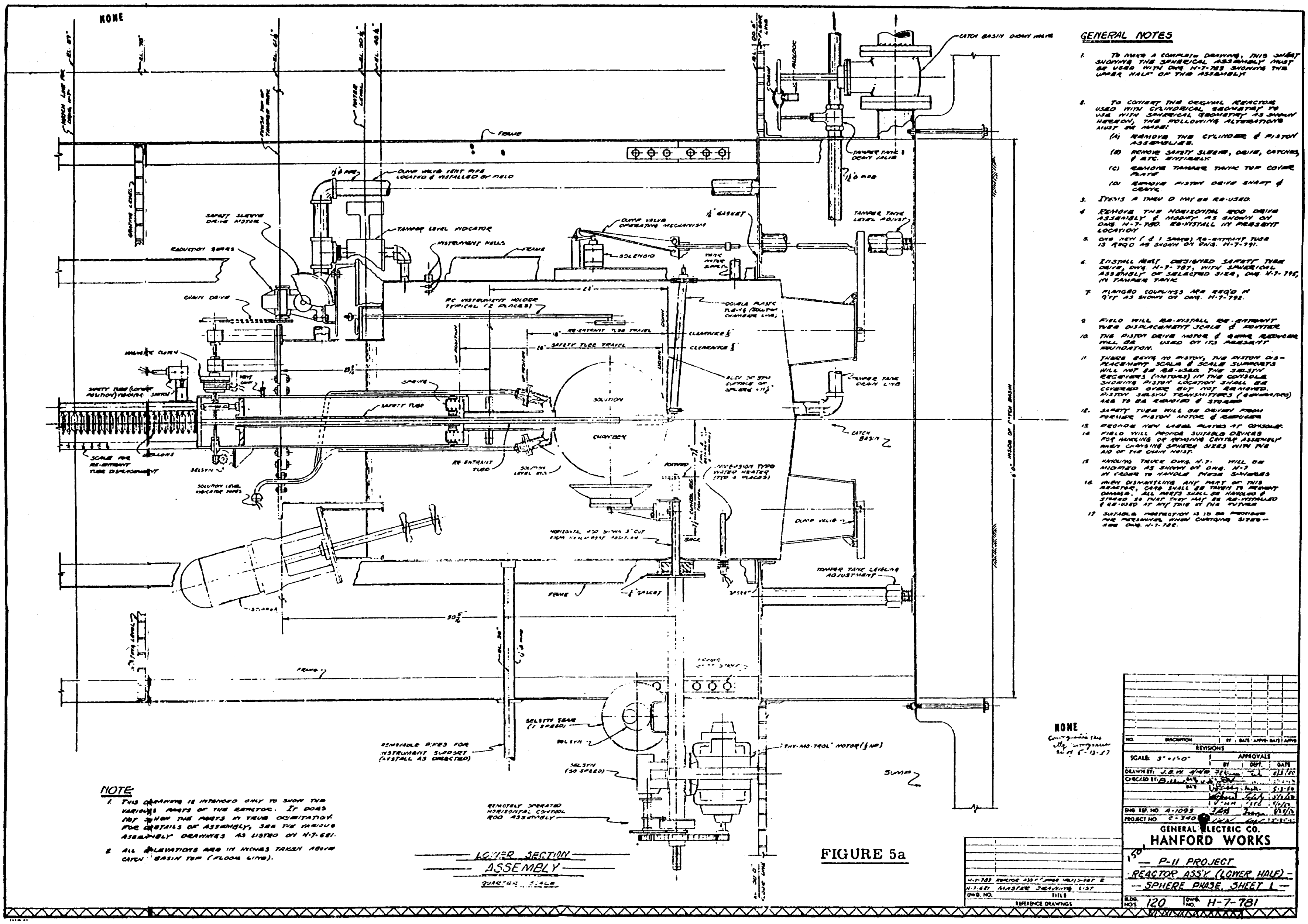

GENERAL NOTES
1. TO MAKE A COMPLETE DRAWING, THIS SHEET SHOWING THE SPHERICAL ASSEMBLY MUST BE USED WITH DWG. H-7-783 SHOWING THE UPPER HALF OF THE ASSEMBLY.
2. TO CONVERT THE ORIGINAL REACTOR USED WITH CYLINDRICAL GEOMETRY TO USE WITH SPHERICAL GEOMETRY AS SHOWN HEREON, THE FOLLOWING ALTERATIONS MUST BE MADE:
(A) REMOVE THE CYLINDER & PISTON ASSEMBLIES.
(B) REMOVE SAFETY SLEEVE, DRIVE, CATCHES & ETC. ENTIRELY.
(C) REMOVE TAMPER TANK TOP COVER PLATE
(D) REMOVE PISTON DRIVE SHAFT & CRANK.
3. ITEMS A THRU D MAY BE RE-USED.
4. REMOVE THE HORIZONTAL ROD DRIVE ASSEMBLY & MODIFY AS SHOWN ON DWG. H-7-780. RE-INSTALL IN PRESENT LOCATION
5. ONE NEW (& 1 SPARE) RE-ENTRANT TUBE IS REQ'D AS SHOWN ON DWG. H-7-791.
6. INSTALL NEWLY DESIGNED SAFETY TUBE DRIVE, DWG. H-7-787, WITH SPHERICAL ASSEMBLY OF SELECTED SIZE, DWG. H-7-795, IN TAMPER TANK
7. FLANGED COUPLINGS ARE REQ'D IN Q'TY AS SHOWN ON DWG. H-7-792.
9. FIELD WILL RE-INSTALL RE-ENTRANT TUBE DISPLACEMENT SCALE & POINTER
10. THE PISTON DRIVE MOTOR & GEAR REDUCER WILL BE USED ON ITS PRESENT FOUNDATION.
11. THERE BEING NO PISTON, THE PISTON DISPLACEMENT SCALE & SCALE SUPPORTS WILL NOT BE RE-USED. THE SELSYN RECEIVERS (MOTORS) IN THE CONSOLE SHOWING PISTON LOCATION SHALL BE COVERED OVER BUT NOT REMOVED. PISTON SELSYN TRANSMITTERS (GENERATORS) ARE TO BE REMOVED & STORED
12. SAFETY TUBE WILL BE DRIVEN FROM FORMER PISTON MOTOR & REDUCER
13. PROVIDE NEW LABEL PLATES AT CONSOLE.
14. FIELD WILL PROVIDE SUITABLE DEVICES FOR HANDLING OR REMOVING CENTER ASSEMBLY WHEN CHANGING SPHERE SIZES WITH THE AID OF THE CHAIN HOIST.
15. HANDLING TRUCK DWG. H-7- WILL BE MODIFIED AS SHOWN ON DWG. H-7 IN ORDER TO HANDLE THESE SPHERES
16. WHEN DISMANTLING ANY PART OF THIS REACTOR, CARE SHALL BE TAKEN TO PREVENT DAMAGE. ALL PARTS SHALL BE HANDLED & STORED SO THAT THEY MAY BE RE-INSTALLED & RE-USED AT ANY TIME IN THE FUTURE
17. SUITABLE PROTECTION IS TO BE PROVIDED FOR PERSONNEL WHEN CHANGING SIZES - SEE DWG. H-7-782.
NOTE
1. THIS DRAWING IS INTENDED ONLY TO SHOW THE VARIOUS PARTS OF THE REACTOR. IT DOES NOT SHOW THE PARTS IN TRUE ORIENTATION. FOR DETAILS OF ASSEMBLY, SEE THE VARIOUS ASSEMBLY DRAWINGS AS LISTED ON H-7-681.
2. ALL ELEVATIONS ARE IN INCHES TAKEN ABOVE CATCH BASIN TOP (FLOOR LINE).
LOWER SECTION
ASSEMBLY
QUARTER SCALE
NONE
NONE
CATCH BASIN DRAIN VALVE
PADLOCK
TAMPER TANK DRAIN VALVE
1 1/2" Ø PIPE
TAMPER TANK LEVEL ADJUST
1/4" GASKET
DUMP VALVE OPERATING MECHANISM
SOLENOID
TANK WATER SUPPLY
DUMP VALVE VENT PIPE LOCATED & INSTALLED BY FIELD
1 1/2" Ø PIPE
TAMPER LEVEL INDICATOR
INSTRUMENT WELLS
FRAME
SAFETY SLEEVE DRIVE MOTOR
REDUCTION GEARS
CHAIN DRIVE
MAGNETIC CLUTCH
SAFETY TUBE (LOWER POSITION) RECORDING SWITCH
SCALE FOR RE-ENTRANT TUBE DISPLACEMENT
BELLOWS
SELSYN
SOLUTION LEVEL INDICATOR WIRES
RC INSTRUMENT HOLDER TYPICAL (2 PLACES)
24"
18" RE-ENTRANT TUBE TRAVEL
26" SAFETY TUBE TRAVEL
UP POSITION
DOWN
CLEARANCE
8 1/4"
SPRING
SAFETY TUBE
RE ENTRANT TUBE
SOLUTION LEVEL IND.
SOLUTION
CHAMBER
DOUBLE PLASTIC TUBING (SOLUTION CHAMBER LINE)
ELEV. OF TOP SURFACE OF SPHERE +11 1/2
TAMPER TANK DRAIN LINE
CATCH BASIN
IMMERSION TYPE WATER HEATER (TYP 4 PLACES)
FORWARD
BACK
DUMP VALVE
HORIZONTAL ROD SHOWN 3" OUT FROM HOME POSITION
TAMPER TANK LEVELING ADJUSTMENT
1/4" GASKET
FRAME
50 5/16"
EL. 30"
1 1/2" Ø PIPE
6'-0" INSIDE OF PIT BASIN
GRATING LEVEL
NOTCH LINE FOR DWG. H-7
FINISH TOP OF TAMPER TANK
WATER LEVEL
EL. 0'-0" FLOOR LINE
SELSYN GEAR (1 SPEED)
SELSYN
SELSYN (30 SPEED)
REMOVABLE PIPES FOR INSTRUMENT SUPPORT (INSTALL AS DIRECTED)
REMOTELY OPERATED HORIZONTAL CONTROL ROD ASSEMBLY
"THY-MO-TROL" MOTOR (1/4 HP)
SUMP
NO. | DESCRIPTION | BY | DATE | APPD | DATE | APPD
REVISIONS
SCALE: 3" = 1'-0"
APPROVALS
BY | DEPT. | DATE
DRAWN BY: J.B.W. 4/14/50
CHECKED BY:
ENG. REF. NO. A-1093
PROJECT NO. C-340
GENERAL ELECTRIC CO.
HANFORD WORKS
P-11 PROJECT
REACTOR ASS'Y (LOWER HALF)
SPHERE PHASE, SHEET 1
BLDG. NO'S 120
DWG. NO. H-7-781
H-7-783 REACTOR ASS'Y (UPPER HALF) SHEET 2
H-7-681 MASTER DRAWING LIST
DWG. NO.
TITLE
REFERENCE DRAWINGS

FIGURE 5a

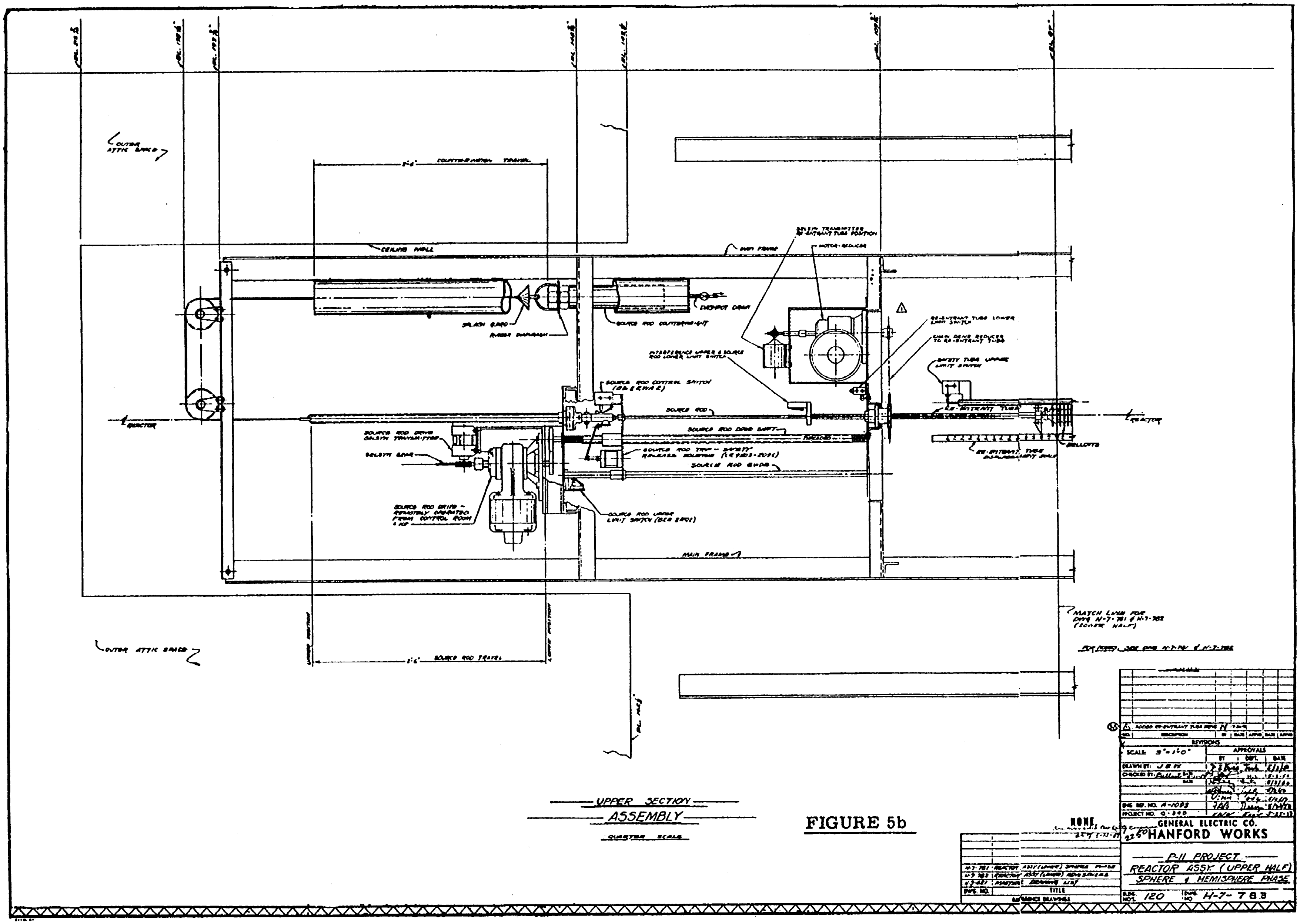

OUTER ATTIC BRACE
COUNTERWEIGHT TRAVEL
CEILING WALL
MAIN FRAME
SPLASH GUARD
RUBBER DIAPHRAGM
SOURCE ROD COUNTERWEIGHT
DASHPOT DRAIN
SELSYN TRANSMITTER RE-ENTRANT TUBE POSITION
MOTOR-REDUCER
RE-ENTRANT TUBE LOWER LIMIT SWITCH
CHAIN DRIVE REDUCER TO RE-ENTRANT TUBE
SAFETY TUBE UPPER LIMIT SWITCH
INTERFERENCE UPPER & SOURCE ROD LOWER LIMIT SWITCH
SOURCE ROD CONTROL SWITCH (BZ-2RW2)
SOURCE ROD
SOURCE ROD DRIVE SHAFT
THREADED
RE-ENTRANT TUBE
REACTOR
BELLOWS
RE-ENTRANT TUBE DISPLACEMENT SCALE
SOURCE ROD DRIVE SELSYN TRANSMITTER
SELSYN GEAR
SOURCE ROD TRIP - SAFETY RELEASE SOLENOID (CR9503-209C)
SOURCE ROD GUIDE
SOURCE ROD DRIVE - REMOTELY OPERATED FROM CONTROL ROOM 1/4 HP
SOURCE ROD UPPER LIMIT SWITCH (BZE 2RQ1)
MAIN FRAME
UPPER POSITION
LOWER POSITION
SOURCE ROD TRAVEL
OUTER ATTIC BRACE
MATCH LINE FOR DWG H-7-781 & H-7-782 (LOWER HALF)
FOR LOWER SEE DWG H-7-781 & H-7-782
UPPER SECTION
ASSEMBLY
QUARTER SCALE
ADDED RE-ENTRANT TUBE DRIVE
NO. DESCRIPTION BY DATE APPD DATE APPD
REVISIONS
SCALE: 3" = 1'-0"
APPROVALS
BY DEPT. DATE
DRAWN BY: J E H
CHECKED BY:
ENG. REF. NO. A-1093
PROJECT NO. C-340
NONE
GENERAL ELECTRIC CO.
HANFORD WORKS
P-11 PROJECT
REACTOR ASSY. (UPPER HALF)
SPHERE & HEMISPHERE PHASE
BLDG. NO. 120
DWG. NO. H-7-783
H-7-781 REACTOR ASSY (LOWER) SPHERE PHASE
H-7-782 REACTOR ASSY (LOWER) HEMISPHERE
H-3-421 MASTER DRAWING LIST
DWG. NO.
TITLE
REFERENCE DRAWINGS

FIGURE 5b

re-entrant tube and source rod were inserted into the reactor through a 3/4 inch column centered in the piston tamper. A 1/4 inch spiral vent tube passed displaced air through the tamper piston. Grease seals and air bellows prevented the escape of contamination where adjustable mechanisms passed through the top of the cylinders.

Three untamped spherical reactors were fabricated from 0.050 inch stainless steel with capacities of 34.15, 49.00, and 67.61 liters corresponding to nominal diameters of 16, 18, and 20 inches. A control rod was introduced into the reactor core parallel to the vertical axis of the sphere and displaced four inches from it.

Tamper

Reactor units were surrounded by a minimum of 12 inches of water tamper contained in a 300 gallon cylindrical tamper tank, the main body of which was three feet in diameter and four feet in height. The work of Beck, et al(1) demonstrates that this is an effectively infinite tamper. The temperature of the tamper and subsequently that of the reactor was normally held to 80 F which was 5.0 F above ambient room temperature and was controlled to within ± 0.5 F by electrical immersion heaters, agitator, and thermostatic regulators. The bottom of the tamper tank was dished to improve water circulation. Four quick opening dump valves (4 inch diameter) in the tank bottom released the tamper to a catch tank in about four seconds upon interruption of the secondary safety circuit. The catch tank had sufficient capacity for two tamper scrams and could be either drained to the crib or recycled to the tamper tank to reduce the time required to obtain temperature equilibrium.

Control Rod

The reactivity of tamped spherical reactor assemblies was controlled by a cadmium cup in the tamper with a surface area approximately ten per cent of the reactor surface area. Bare spheres were controlled by a two inch wide cadmium blade sandwiched by stainless steel that was introduced

---

(1) Beck, C. K., A. D. Callihan, J. W. Morfitt, and R. L. Murray, K-343, April 19, 1949.

into the reactor core. A 36 square inch cadmium sheet passed horizontally 7/8 inch below the bottom of the cylindrical reactors affording the necessary control. The control cup or blade approached or receded from the reactor with a variable speed between the limits of 1.5 and .25 inches per minute and could be positioned to a precision within ± 0.003 inches as indicated by a coarse and vernier selsyn combination.

Figure 6 shows experimental control rod calibrations in terms of equivalent grams of plutonium.

Safety Control

The safety control used in conjunction with the spherical reactors consisted of a 1.75 inch diameter cadmium tube, sandwiched by stainless steel, suspended 12 inches above the top of the reactor by a magnetically held rack and pinion. Upon release, the 18 inch length of active absorber passed through the supporting neck and came to rest along a sphere diameter. The time lapse between release of the magnetic clutch and completion of the rod motion was about one second. The safety tube was controlled remotely, its position being indicated by a selsyn receiver. Graphite filled fluorthene was used for bearing surfaces in the corrosive atmosphere above the reactor.

The safety control used in conjunction with the cylindrical reactor was a cadmium sheath external to and coaxial with the reactor. This sheath was 12 inches in height and of such diameter as to clear the reactor wall by 1/4 inch on a diameter. The sheath dropped to a position surrounding the reactor in about one second after being released.

Source Rod and Re-entrant Tube

A Polonium-Beryllium neutron source of approximately 10^6 neutrons/second attached to a 3/8 inch diameter aluminum rod was remotely positioned within the reactor or removed from it as required. The rate of travel of the source was about 30 inches per minute when motor driven. A release and counter-weight mechanism permitted a rapid source withdrawal for

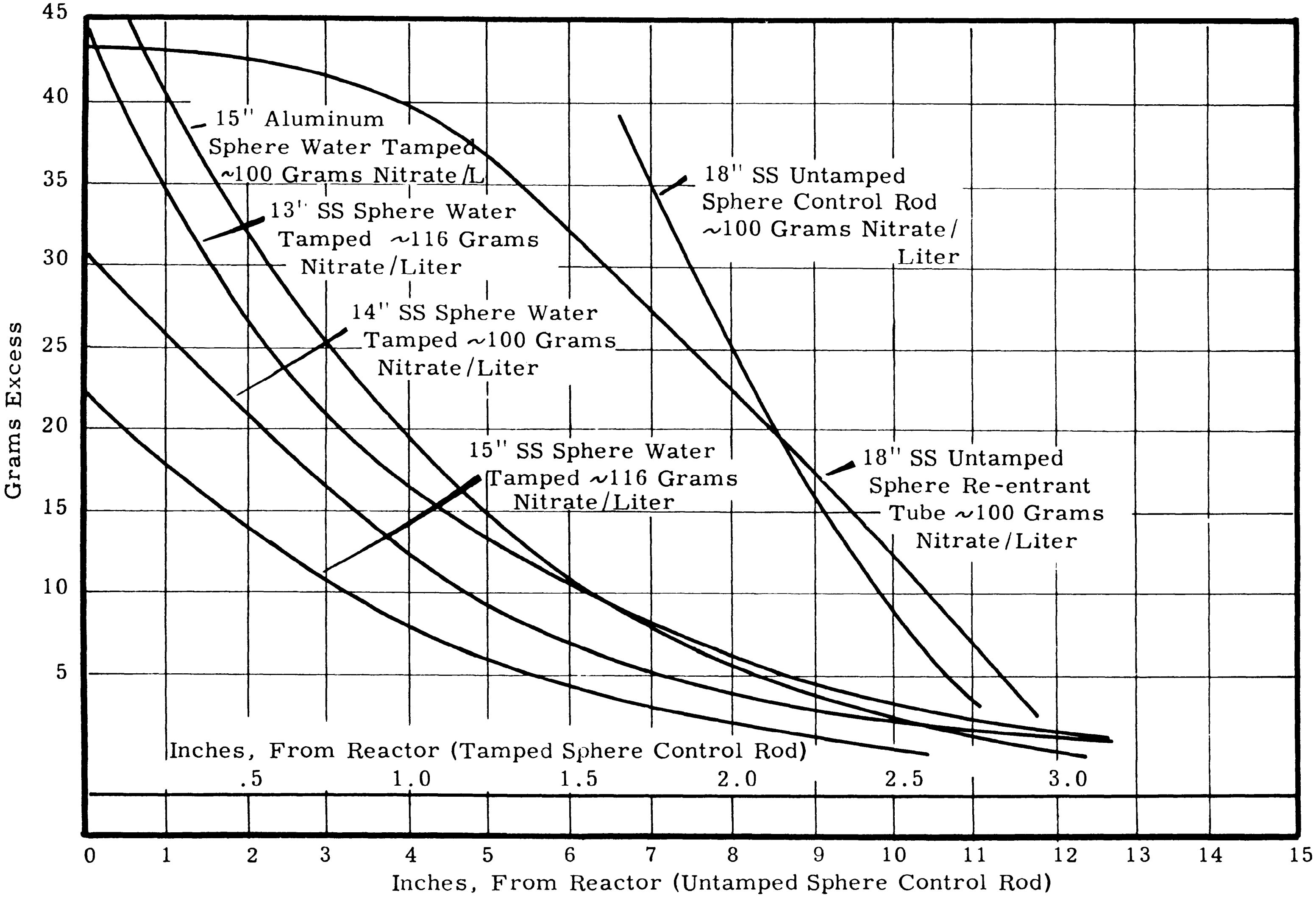


FIGURE 6

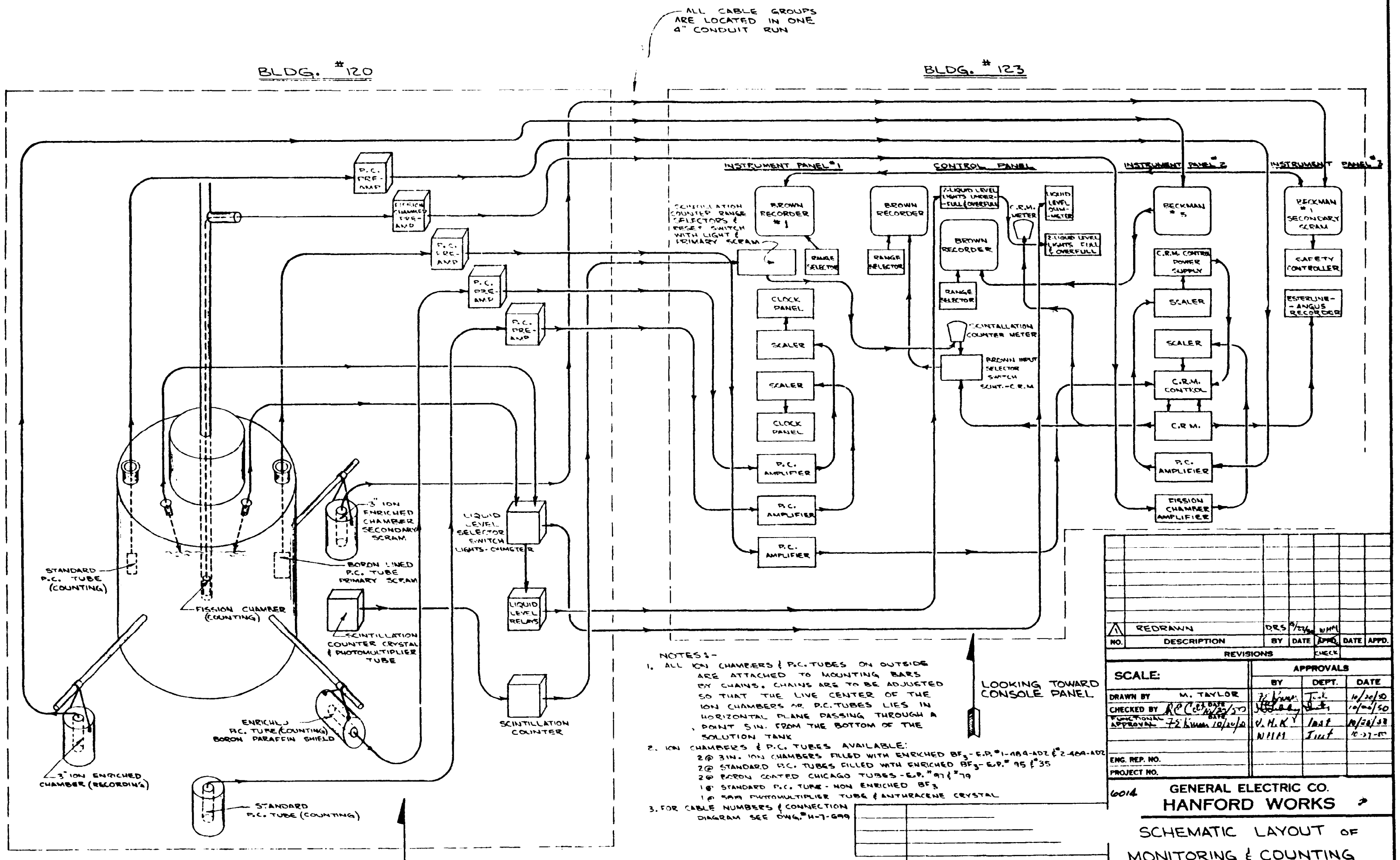
Grams Excess in Reactor vs. Control Rod and Re-entrant Tube Position at Critical "source jerk" criticality tests. The total source travel was 30 inches as measured from the reactor base and indicated on a selsyn receiver.

A 5/16 inch ID stainless steel re-entrant tube isolated the source from the reactor fuel for contamination reasons. This tube was either manually or remotely positioned over its 20 inches of travel.

INSTRUMENTATION AND SAFETY CONTROL CIRCUITS

The instrumentation required for monitoring and recording the reactivity variations of the critical assemblies consisted of neutron detectors driving scalers, a counting rate meter, and recording potentiometers. Boron trifluoride and boron lined proportional counters and boron trifluoride filled ionization chambers monitored the neutron flux external to the reactor. A uranium-235 cylindrical fission counter of 3/8 inch OD measured the neutron flux within the reactor depending upon the position of the source rod to which it was attached. Neutron detectors external to the tamper tank were filled with enriched BF_3 and were surrounded by paraffin moderators to increase sensitivity. Gamma activity was followed by a scintillation counter with an anthracene phosphor (3 x 3 x 1 cm) and 5819 photomultiplier. A logarithmic amplifier and period meter having a range of six decades and capable of measuring periods as short as three seconds was provided. A standard five inch gamma chamber was located in the control room for personnel monitoring. The placement and use of these detectors is discussed in the Operating Procedures section of this report and shown schematically in Figure 7.

The signals from the proportional counters and fission counter were fed into preamplifiers located in the reactor assembly room and were further amplified after transmission (200 feet) to the control room before being fed into scalers (usually four including the fission counter) and a General Radio counting rate meter. Scale of 256 scalers were used. The current from the enriched BF_3 ionization chambers was amplified by Beckman micro-micro ammeters which in turn actuated Brown strip



NOTES:-

1. ALL ION CHAMBERS & P.C. TUBES ON OUTSIDE ARE ATTACHED TO MOUNTING BARS BY CHAINS. CHAINS ARE TO BE ADJUSTED SO THAT THE LIVE CENTER OF THE ION CHAMBERS OR P.C. TUBES LIES IN HORIZONTAL PLANE PASSING THROUGH A POINT 5 IN. FROM THE BOTTOM OF THE SOLUTION TANK
2. ION CHAMBERS & P.C. TUBES AVAILABLE:
   - 2@ 3IN. ION CHAMBERS FILLED WITH ENRICHED BF_3 - E.P. #1-484-ADZ & #2-484-ADZ
   - 2@ STANDARD P.C. TUBES FILLED WITH ENRICHED BF_3 - E.P. # 95 & #35
   - 2@ BORON COATED CHICAGO TUBES - E.P. #97 & #79
   - 1@ STANDARD P.C. TUBE - NON ENRICHED BF_3
   - 1@ 5819 PHOTOMULTIPLIER TUBE & ANTHRACENE CRYSTAL
3. FOR CABLE NUMBERS & CONNECTION DIAGRAM SEE DWG. #H-7-699

DWG. NO.	TITLE
H-7-699	CABLE SCHEMATIC

REFERENCE DRAWINGS

NO.	DESCRIPTION	BY	DATE	APPD.	DATE	APPD.
1	REDRAWN	D.R.S.	3/27/52	WHM		

REVISIONS

CHECK

SCALE:

		APPROVALS BY	DEPT.	DATE
DRAWN BY	M. TAYLOR			10/20/50
CHECKED BY	RCC DATE 10/23/50			10/20/50
FUNCTIONAL APPROVAL	DATE 10/20/50	V. H. K.	Inst	10/28/50
		WHM	Inst	10-27-50
ENG. REP. NO.				
PROJECT NO.				

6014

GENERAL ELECTRIC CO.
HANFORD WORKS

SCHEMATIC LAYOUT OF MONITORING & COUNTING EQUIPT. P-11 PROJECT

BLDG. NO'S 120
DWG. NO. H-4-1042

FIGURE 7

recorders. The output from the scintillation counter amplifier also actuated a Brown recorder. A modification to this recorder circuit permitted either 3 x or 10 x normal sensitivity for observation of small reactivity changes.

Primary and secondary scram circuits were provided to rapidly deactivate the reactor assembly. These scram circuits were activated by a rise of neutron or gamma flux above a predetermined level, a period of the system shorter than a predetermined value, an electrical power or circuit failure, or manual operation of a push button.

A primary scram occurred if the neutron or gamma levels exceeded nine tenths of full scale on the counting rate meter or scintillation counter meter on any sensitivity range, or by a period shorter than one second as recorded by the counting rate meter. The primary scram circuit was designed to allow a reasonably rapid reactivation upon clearance of trouble without requiring personnel to leave the control room except to correct circuit or equipment failure.

The secondary scram circuit was provided to more completely deactivate the unit in the event the primary scram circuits failed. A trip level exceeding nine tenths full scale of a Beckman amplifier and controller driven by a BF_3 ionization chamber automatically activated this scram circuit.

In the case of the tamped spheres and cylinders, the primary scram caused the safety tube (or sleeve) to drop to the all-in position. This also prevented the raising of the fuel leveling tanks, however, the leveling tanks could be lowered at any time. The secondary scram initiated the events of a primary scram and in addition opened the dump valves in the tamper tank releasing the water from the tank.

For the bare spheres, a primary scram dropped the control rod to an all-in position while a secondary scram dropped both the control rod and the safety tube into the reactor.

PLUTONIUM CONTAMINATION PROBLEMS

A significant part of the total effort required to accomplish these experiments was spent on special problems associated with the handling of plutonium contamination. Experience with plutonium nitrate solutions showed that all sources of contamination on open lines or equipment had to be eliminated upon detection as it was very difficult to prevent the spread of contamination once the material became dry. A loose contamination source of the order of 10^{-7} grams of plutonium was found to produce a significant rise in air sample activity in the reactor room. Routine exposure without respiratory protection was permissible where air levels were known to be less than 4×10^{-12} micrograms plutonium per cubic centimeter. Assault masks were required with CWS red cannisters for all work in zones exceeding this level. No equipment was released from the laboratory building unless a negative "poppy" survey or smear resulted. Potentially contaminated equipment not lending itself to surveying was not released except under controlled conditions. Equipment and tools probing less than 500 d/m were released from contaminated work zones for general use within the building. Routine "poppy" surveys and air and tamper water sampling were required throughout the experimental program.

The laboratory building designed for these experiments was divided into a number of small rooms, previously described, in order to localize potential contamination hazards. Normal activity was possible in most parts of the laboratory even though one or more rooms were contaminated. Various techniques were used in removing contamination from working areas and equipment. Floors, walls, and some large equipment in rooms containing plutonium were covered with G. E. cocoon, a strippable coating. In addition, 10 ply absorbent paper or heavy sisal paper was taped to the floor in these rooms. Grossly contaminated areas where decontamination was not feasible were covered over with cloth backed industrial adhesive tape and coated over with G. E. cocoon. Polished metallic or glass surfaces were easily cleaned with dilute nitric acid liberally applied with glass wool followed by paper tissue wipes to absorb the acid and plutonium. Dry contamination could be removed by contact with tacky masking tape or by wiping down a surface with a damp rag.

Plutonium solution leaks through valve castings, flanged joints, and particularly at welded joints and seams, were experienced during the course of the experiments. Several techniques of prevention and repair that proved reliable for this type of application are discussed below:

a) Flange leaks were avoided by turning flange facings to leave a slightly raised ring to cut into the gasket material. Rings on opposing flanges were made of slightly different radii. Polythene and teflon were used as gasket material.

b) Piping leaks frequently occurred where connections were directly welded. These failures were eliminated by welding an overlapping sleeve with an inside diameter slightly greater than the outside diameter of the tubing to one tube slipping the sleeve over the second tube, and welding. No attempts were made in repairing a leak by direct welding on exposed lines as contamination considerations prohibited this procedure. Piping leaks were successfully arrested by tightly wrapping the faulty joint with # 33 Scotch Electrician Tape. This tape adhered well to a clean dry surface was found to be resistant to all solutions used in these studies and gave no signs of deterioration after a year of service.

c) No successful techniques were found to repair leaks that would not lend themselves to the above treatment. Temporary repair was effected by the use of industrial adhesive or absorbent dressings other than glass wool. A number of acid resisting cements were tried with poor results.

d) A highly successful preventative technique for tubing and equipment not previously contaminated was that of flame spraying polythene on stainless steel and other surfaces. This plastic coating is impervious to most chemical reagents, is flexible and tough, and is strongly bonded to the sprayed surface when applied correctly.

e) Faulty equipment components could be removed with a minimum of contamination difficulty by first wrapping the tube section to be cut with masking tape and then cutting through the tape with a hack saw. The replacement equipment was welded onto the existing line using the sleeve technique outlined above.

PROCEDURES AND TECHNIQUES

Approach to Critical Height

Establishment of the critical height in the various cylinders at different fuel concentrations was accomplished by the inverse multiplication extrapolation method. Stepwise addition of fuel to the reactor in increments limited in magnitude by the observed source multiplication at preceding cylinder heights is the basis of this method. The initial height to which the vessels were filled was arbitrarily chosen in the early experiments as one-third the predicted critical height. Accurate extrapolation from multiplication measurements taken at less than one-half critical height, however, was difficult to achieve since the neutron distribution undergoes marked changes as the cylinder height increases. After several experiments had been completed and due confidence gained in both the equipment and accuracy of predictions all initial counting was done at one-half predicted critical height. This alteration of procedure allowed larger increments of fuel to be added to the cylinder as a result of the more accurate extrapolations.

The inverse multiplcation curves are most frequently found to extrapolate to a premature critical height if the detectors from which they arise are located outside the reactor and some distance from the background neutron source. The foregoing conditions were both necessary in these experiments in order to avoid perturbation effects. There was determined only one detector location that consistently yielded a near straight line on the reciprocal multiplication versus height plot. All other locations, both inside and outside the tamper, produced concave curves. This most useful position was eight to ten inches directly below the center of the reactor with the longitudinal axis of the counter in a horizontal plane. All monitors, however, produced extremely accurate predictions, i. e. , ± 0. 05 inch, of the critical height after the fuel height had been increased to within about two inches of criticality.

The actual operating procedure followed in a routine criticality determination was as follows:

(1) A thorough checklist was completed to insure that all the equipment was functioning properly.

(2) All personnel were removed to the control building and the area was put on an operating basis which prohibited the entry of visiting personnel.

(3) The neutron source was positioned in the reactor.

(4) Safety devices were made ready and automatic trip levels set.

(5) The height of the cylinder was adjusted remotely to one-half the predicted critical height.

(6) Fuel was introduced continuously into the reactor until its level reached the moveable piston in the cylinder, at which time flow was interrupted by the closing of the remotely operated feed line valve.

(7) A negative hydrostatic head was placed on the remote valve line by repositioning the leveling tanks.

(8) The neutron activity, as detected by four individual monitors, was recorded and assigned the value of unity for the multiplication plot.

(9) The control rod was returned to the "all in" position.

(10) The cylinder height was then adjusted to allow sufficient fuel to enter the reactor to give approximately twice the initial source multiplication as based on the predicated critical height.

(11) Steps six through ten were repeated in the order given and a second multiplication measurement taken which, along with the previously acquired data determined the third piston height setting. This process was repeated until at some final height the system was determined to be critical, as indicated by a linear rise of flux, with the control rod mostly withdrawn.

(12) The fuel level in the reactor was lowered approximately one-half inch and the source and re-entrant tube withdrawn from the reactor.

(13) Steps six through ten were again repeated, this time without the re-entrant tube present and with the source at the top of the reactor.

(14) After two new multiplication measurements were taken the cylinder was made critical at the height indicated by the extrapolation of these two measurements.

The increment of cylinder height used in the final repositioning of the piston was dictated by the extrapolated prediction of control rod strength. Because the control rod was beneath the cylinder its effectiveness was quite sensitive to changes in cylinder height. In the initial experiments the final multiplication measurements were taken in duplicate, one set with the rod "all-in", the other with it "all-out". The height difference between these two infinite multiplication extrapolations was assigned to the strength of the control rod. This procedure was dispensed with as soon as it was evident that the control rod had been evaluated under all significantly different conditions.

A range of values for the poisoning effect of the re-entrant tube has resulted from habitually determining two critical heights, one with the tube in place, the other with it withdrawn. This range indicates that the fuel must be over concentrated so as to add 15 to 35 grams in cylindrical reactors 18 inches tall and 12 to 9 inches in diameter, respectively, in order to compensate for the poisoning effect of such a tube.

Approach to Critical Concentration

The data taken during the investigation of criticality conditions for cylinders contributed significantly to the accuracy of predictions of critical concentration for the range of spherical reactors used. In those cases where comparatively unpredictable poisons were introduced in the fuel, criticality was reached by successive concentrations of the fuel. A plot involving reciprocal multiplication and concentration normally led to a reliable estimate of the critical concentration if the full reactor was twenty-five to fifty grams subcritical. The one exception to be noted here is the case involving very concentrated fuel, as illustrated by the attempt to make the eleven inch sphere critical. The fuel additions to this sphere eventually resulted in such extensive leakage because of poor moderation that the ineffectiveness of further concentration was clearly reflected in strongly concave reciprocal multiplication plots. The control cups used with the spheres facilitated large stepwise fuel concentrations by merit of their large control strength. This is in view of the fact that the fuel was never concentrated in any one operation by an amount which resulted in the addition of more grams of plutonium to the reactor than the control cup was able to compensate. The nominal range of poisoning by these cadmium coated cups was of the order of twenty-five to fifty grams, with the largest sphere having the weakest control cup.

After the initial sphere experiments the operating procedure was revised to exclude the necessity of the preliminary critical concentration determination with the re-entrant tube in place. For each sphere, however, two fuel concentrations were sampled and analyzed, one of which had resulted in a slightly supercritical sphere without control rod, the other just subcritical.

The spontaneous fission source of neutrons within the fuel itself accompanied by the artificial source at the edge of the reactor was deemed sufficient neutron background to meet the sensitivity requirements of the monitoring and safety instruments. This precluded the preliminary determination with the re-entrant tube down and all later tests were made with it withdrawn into the neck of the sphere. Criticality determinations were frequently conducted with fuels of greater than 3% Pu^{240} by weight in the absence of an artificial source since the number of spontaneous fission neutrons is of a magnitude suitable for detection through several inches of water.

Periods

Period measurements were taken in several spheres to establish the amount of excess plutonium required to produce periods between five and 90 seconds. A typical plot of the data taken appears in Figure 8.

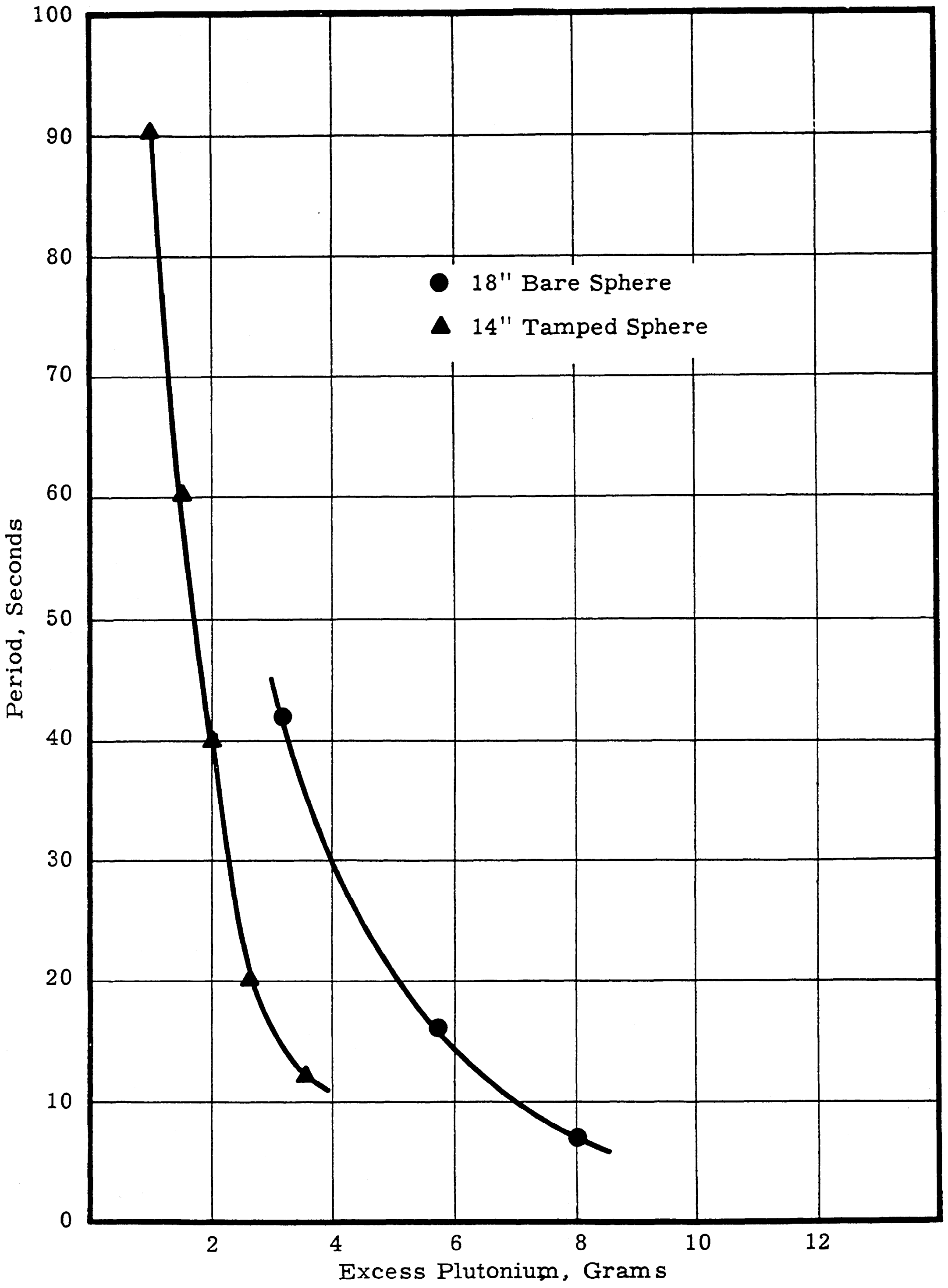


FIGURE 8

Period vs. Excess Plutonium in Grams

This type of plot indicated reliably, in the case of a slightly overconcentrated sphere, the amount of plutonium to be removed from the reactor in order to make it just subcritical without control rod.

Power Levels

Nominal power levels at critical were of the order of twenty milliwatts. The highest exposure experienced by personnel in the control room was approximately 25 milliroentgens per hour, this being an unusually high level experiment. Personnel exposure seldom exceeded one-quarter mr/hr during normal runs. Operating power levels were purposely limited to as low values as possible to avoid overexposure of personnel from residual fuel activity during fuel alterations.

Correction for Sphere Neck

A mockup of the supporting neck assembly for the sphere was installed on the lower half of the reactor. It was mounted against the side of the sphere which opposed the control rod. The critical position of the rod was noted, the mockup removed, and a new critical rod position determined. The difference, in grams, represented by the two rod positions was attributed to the mockup and subsequently assigned to the sphere neck. This value is a maximum of five grams for all spheres made critical.

Cross Section Measurements

Estimates of the thermal neutron absorption cross section for two isotopes were arrived at from criticality studies. A comparison of the neutron absorption by a known amount of boron with that of the isotopes studied is the basis of these estimates.

Gas samples of these isotopes were placed in the re-entrant tube inserted in a spherical reactor which was several grams supercritical with the control rod completely withdrawn. The unknown samples were introduced into the reactor alternately with born (BF_3) standards in identical containers. Comparison of the relative periods resulting from the same control rod setting produced the unknown cross-section values. The sensitivity of the system to internal poisoning of the reactor was set at 10^{19} atoms of boron as a result of these experiments.

Analytical Procedures

Consistent biases in the analyses of P-11 samples were detected by analyzing standard samples, and gross discrepancies were checked by the use of multiple analyses. The precisions reported indicate the magnitude of the variation from the true value which should be exceeded only about once in one hundred analyses.

Plutonium

Plutonium is reduced to the +3 state with titanous chloride and then titrated (reoxidation to the +4 state) with standard ceric sulfate. The titration is carried out in 3 N sulfuric acid under an innert atmosphere of nitrogen and is followed potentiometrically. Nitrates are removed by evaporation with sulfuric acid and iron corrections are applied, if iron is present. The precision of this method is ± 1.0 per cent.

Hydrogen Ion

Total acid or hydrogen ion concentration in plutonium solutions is obtained by oxalate complexing of plutonium and direct titration of the acid with standard base. Methyl red is used to indicate the end point. The precision of this method is ± 1.4 per cent.

Iron

Iron is reduced to the ferrous state with hydroxylamine hydrochloride and reacted with ortho-phenanthroline in slightly acid solutions to form an intense reddish-purple complex which is measured spectrophotometrically. The acidity of the solution is maintained between 3.5 - 4.5 pH by using a buffer. The precision of this method is ± 1.4 per cent.

Density

This method is based on weighing a known volume of the liquid at 25 C. The value reported is density in grams per cubic centimeter. The precision of the method is ± 0.03 per cent.

Phosphate

Phosphate ion is precipitated as ammonium phosphomolybdate. The precipitate is collected on a suitable filter, washed, and dissolved in an excess of standard sodium hydroxide. The excess sodium hydroxide is titrated with standard acid using phenol red-bromothymol blue as the indicator. The precision of this method is ± 2 per cent.

Nitrate

Nitric acid formed from the action of sulfuric acid on a nitrate compound is distilled under vacuum and collected in a condenser coil which is immersed in a dry ice-isopropyl alcohol mixture. The acid distillate is titrated with standard sodium hydroxide. The precision of the method is ± 0. 6 per cent.

Water

The Carl Fisher method for determination of water was used. In this application, the sample is added to a known amount of Carl Fisher reagent and the excess reagent back titrated with a methanol-water mixture to a dead stop end point. A tungsten electrode is used. The precision of the method is ± 0. 9 per cent.

Bismuth

Bismuth is titrated (reduced to metallic state) with standard chromous sulfate. The titration is carried out in a 0. 5 $\underline{M}$ H_2SO_4 - 2. 5 per cent NaCl solution buffed with tartaric acid. The titration is done under an inner atmosphere of CO_2 and followed potentiometrically. Ferric iron is added to obtain the first potentiometric end point since the small amounts of plutonium present did not reveal this end point. Nitrates are removed by heating with formic acid. The precision of the method is ± 1. 7 per cent.

Manganese

Permanganate formed by periodate oxidation of manganese in an acid solution is determined spectrophotometrically. A one cm light path length is used and the optical density determined at wave lengths of 525 and 545 millimicrons. The precision of this method is ± 1 - 2 per cent.

Lithium

Lithium is determined spectrochemically by the copper spark method using barium as an internal standard. Lithium line 6707 and barium line 6694 are photometered and intensity ratios are determined by means of a Hurter-Driffield curve. The precision of the method is ± 3.0 per cent.

Per Cent Plutonium-240 by Weight

The precision of these determination is ± 7 per cent.

DESIGN AND DISCUSSION OF EXPERIMENTS

A review of the critical mass problems pertaining to the Hanford separations processing had indicated the desirability of determining the minimum critical mass of a plutonium solution. Such a measurement cannot be accomplished in practice because of features of plutonium chemistry, the presence of the Pu^{240} isotope, the necessity of providing a reactor shell, and the dependence of critical mass on temperature. In these experiments, it was necessary to provide as favorable a condition for criticality as was feasible and to evaluate the magnitude of each of the above factors by additional experimentation.

Nitrate Ion Effect

The basic fuel selected was plutonium nitrate dissolved in dilute nitric acid. The presence of the nitrate ion associated with the plutonium and nitric acid has an important influence on the critical mass due to its ability to displace moderating media and its parasitic absorption of thermal neutrons. The nuclear properties of the fuel are determined essentially by the plutonium, nitrate, and hydrogen concentration. The effect of an increase in nitrate concentration is to cause a displacement of hydrogen and an increase in parasitic macroscopic absorption and therefore an increase in critical mass. Figures 9 and 10 show the dependence of critical mass on nitrate concentration for tamped and bare spherical reactors, respectively. Within the range of data taken and experimental error imposed it is found that a linear relationship exists between the logarithm of the critical mass and the nitrate concentration, as is shown in Figures 11 and 12.

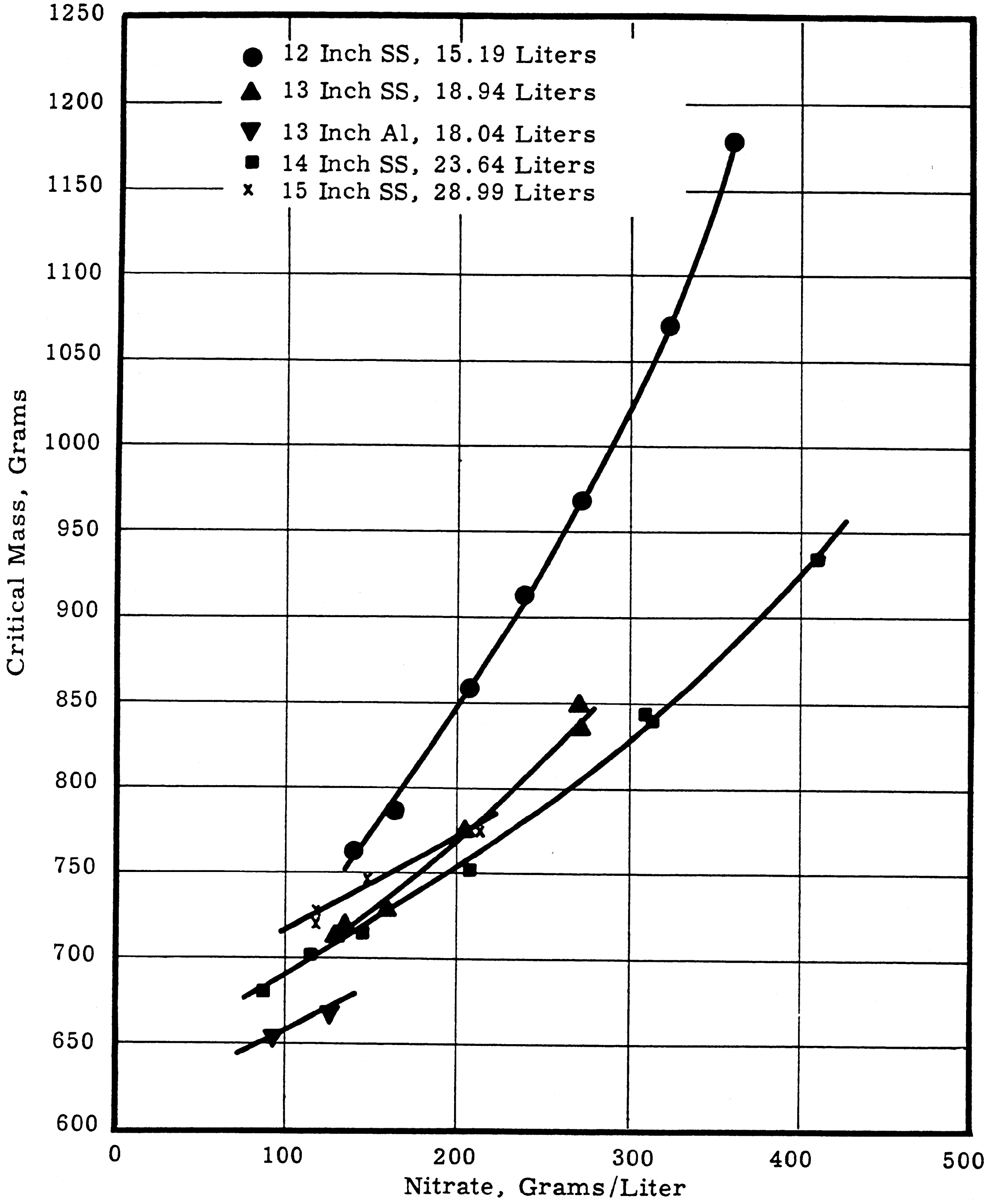


FIGURE 9

Critical Mass vs. Nitrate
Water Tamped Spheres
3.12% Pu^{240}, 27 C

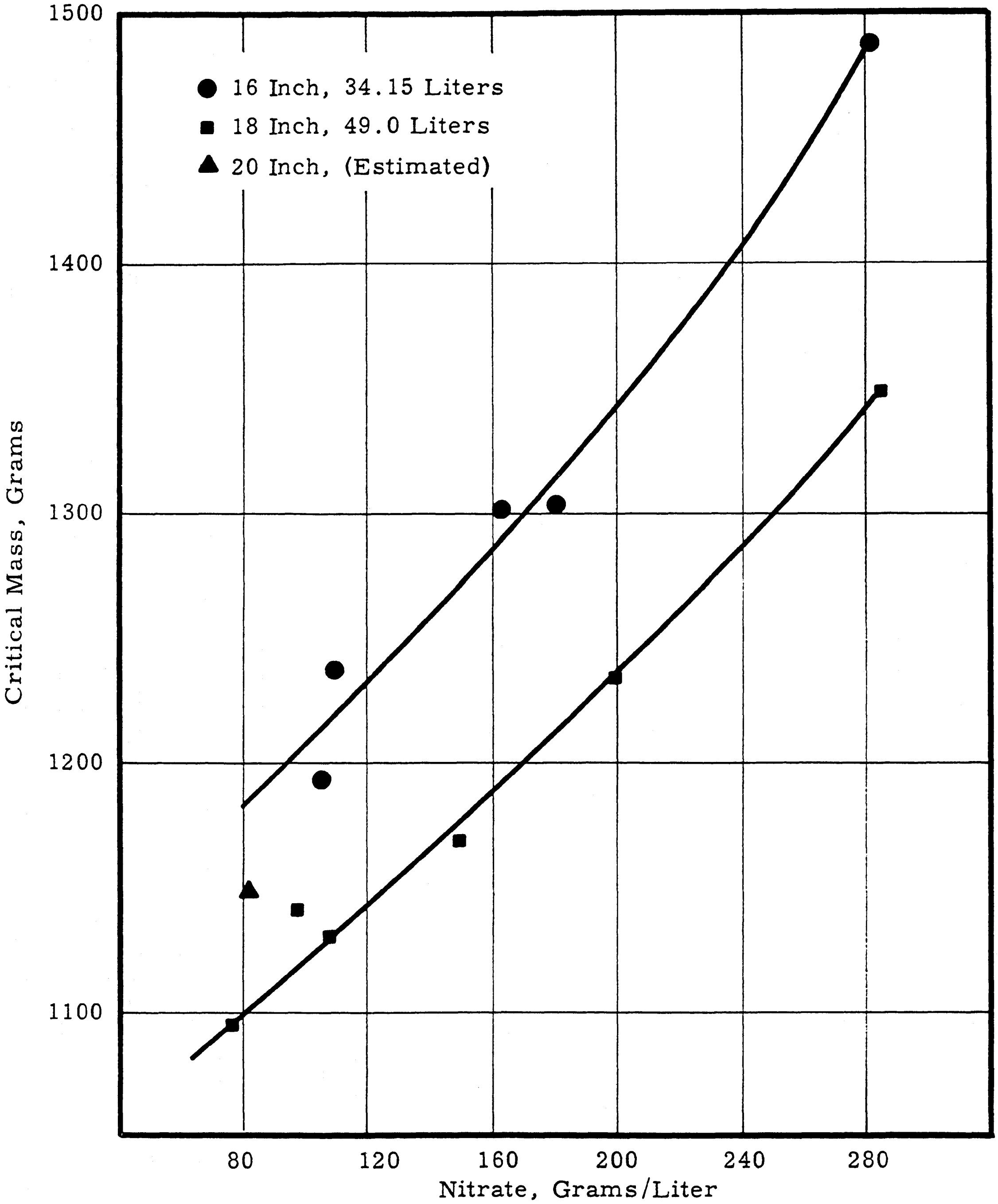


FIGURE 10

Critical Mass vs. Nitrate
Bare SS Spheres
~ 4.2% Pu^{240}

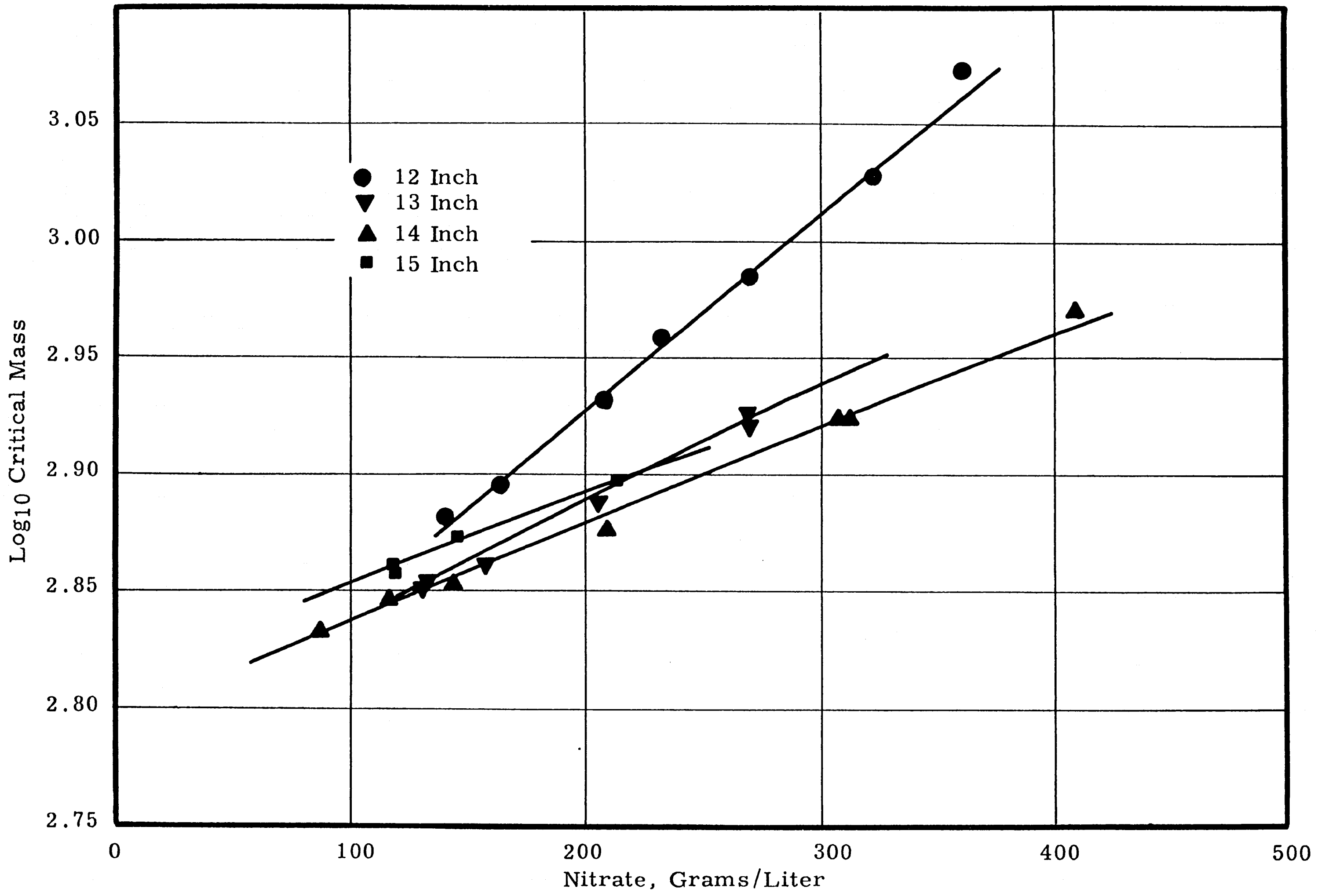


FIGURE 11

Log$_{10}$ Critical Mass vs. Nitrate
Water Tamped SS Spheres
3.12% Pu^{240}, 27 C

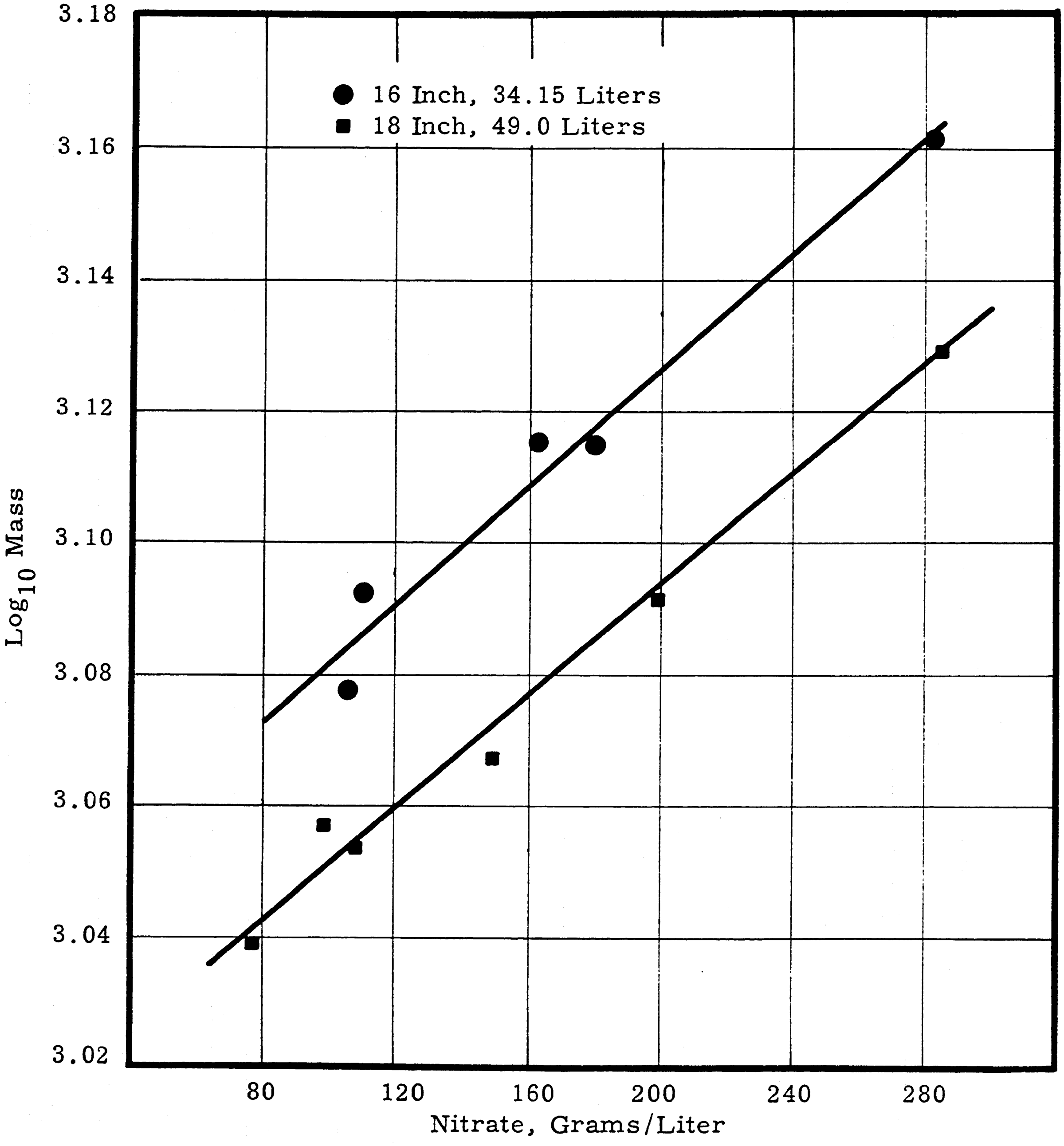


FIGURE 12

Log_{10} Mass vs. Nitrate
Nitrate Bare SS Spheres
~ 4. 2 Pu^{240}

Isotopic Content of Plutonium

Plutonium produced by reactor conversion is principally a mixture of the Pu^{239} and Pu^{240} isotopes. As the nuclear properties of these isotopes are quite different, it is necessary to specify the isotopic content of a fuel under consideration. Figure 13 shows the effect of isotopic concentration on critical mass in the tamped 14-inch diameter sphere for fuels ranging between 0.55 and 4.4 per cent Pu^{240}, and Figure 14 shows the effect for those ranging between 1.65 and 3.12 per cent Pu^{240} in the 13-inch sphere. Such data indicate a large total absorption cross section for Pu^{240} of 925 ± 200 barns. Figure 15 expresses the variation in critical mass with change in per cent Pu^{240} in the 14-inch sphere at a nitrate concentration of 110 grams/liter.

Optimum Concentration

It is necessary to establish experimentally the optimum concentration of plutonium in order to find a minimum critical mass. Experiments were made in a series of four spheres of sufficient volume range to bracket the experimentally determined minimum mass. Figure 16 shows the dependence of critical mass on reactor volume for fuels having identical nitrate and isotopic content. These curves show that the optimum concentration of plutonium in aqueous solution lies at about 33 grams of plutonium per liter.

These curves also show the dependence of critical mass on volume for the range studied.

The Effect of Other Non-fissionable Elements

The effect of the addition of compounds of non-fissionable elements other than those of the original fuel on criticality was investigated. These impurities were introduced in order to predict their behavior when used as reagents in separation processes. These tests were directed toward an independent evaluation of effect of poisoning and displacement in the reactor core.

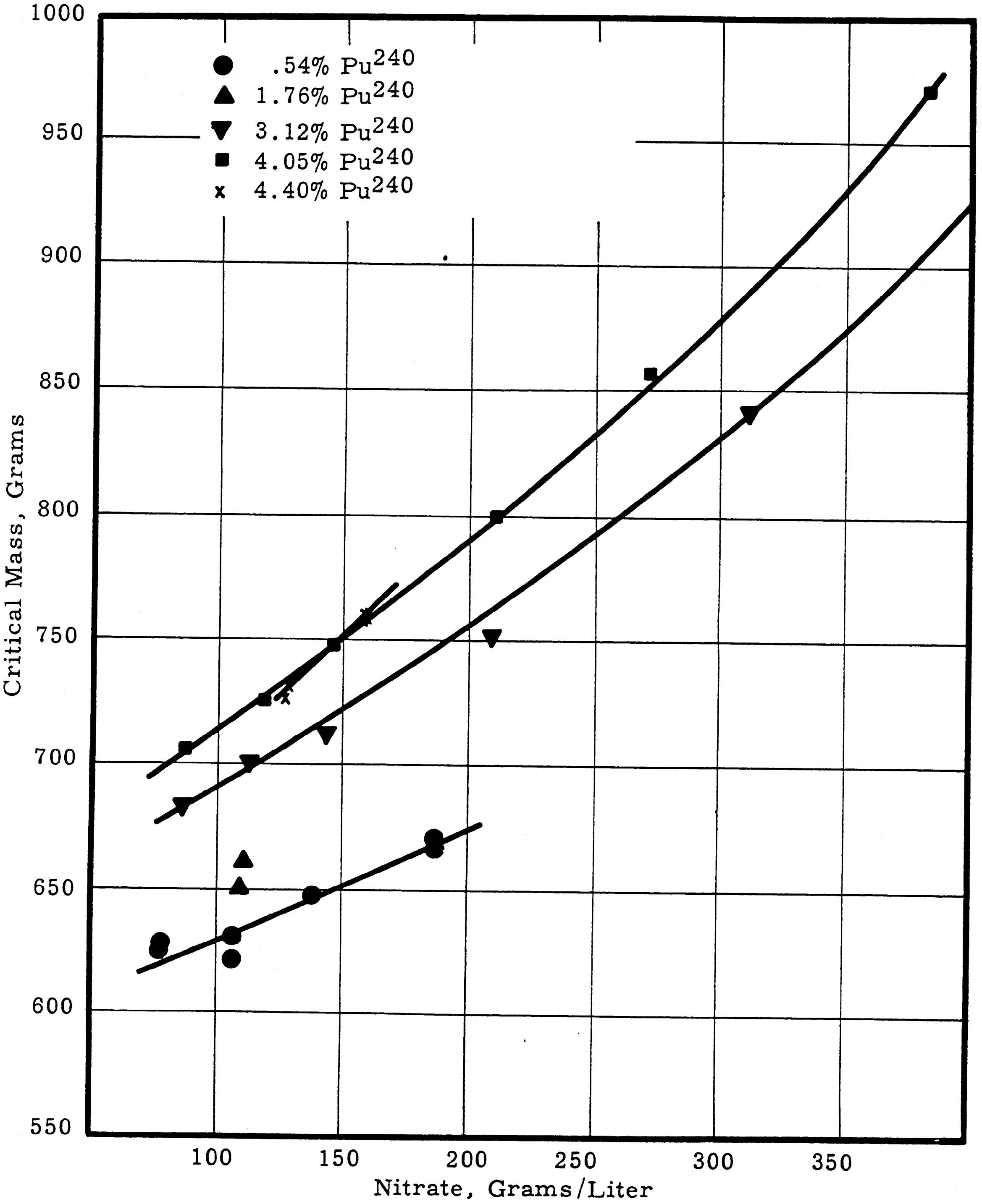


FIGURE 13

Critical Mass vs. Nitrate
Water Tamped 14" SS Sphere
23.64 Liters, 27 C

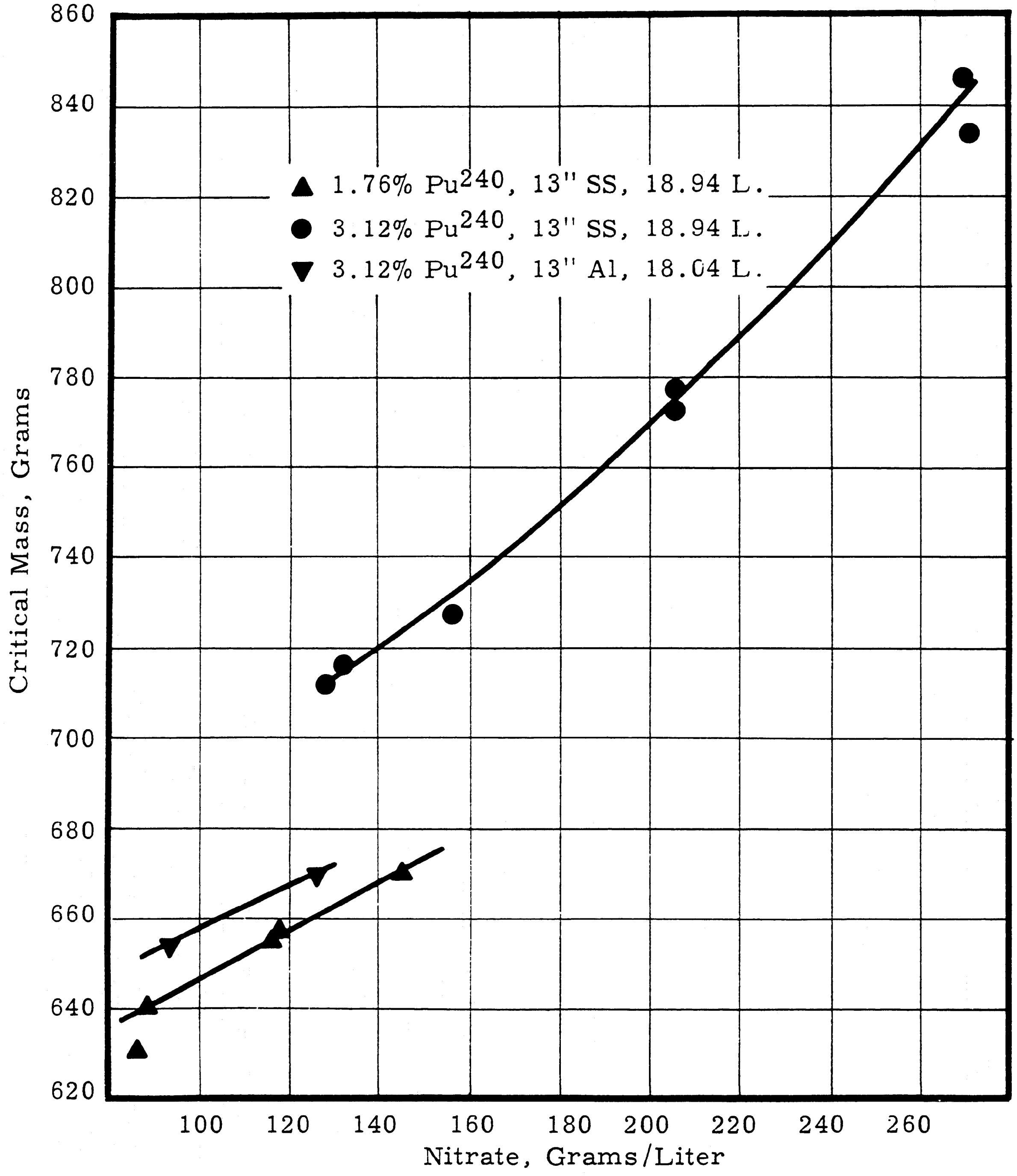


FIGURE 14

Critical Mass vs. Nitrate
Water Tamped 13" Spheres

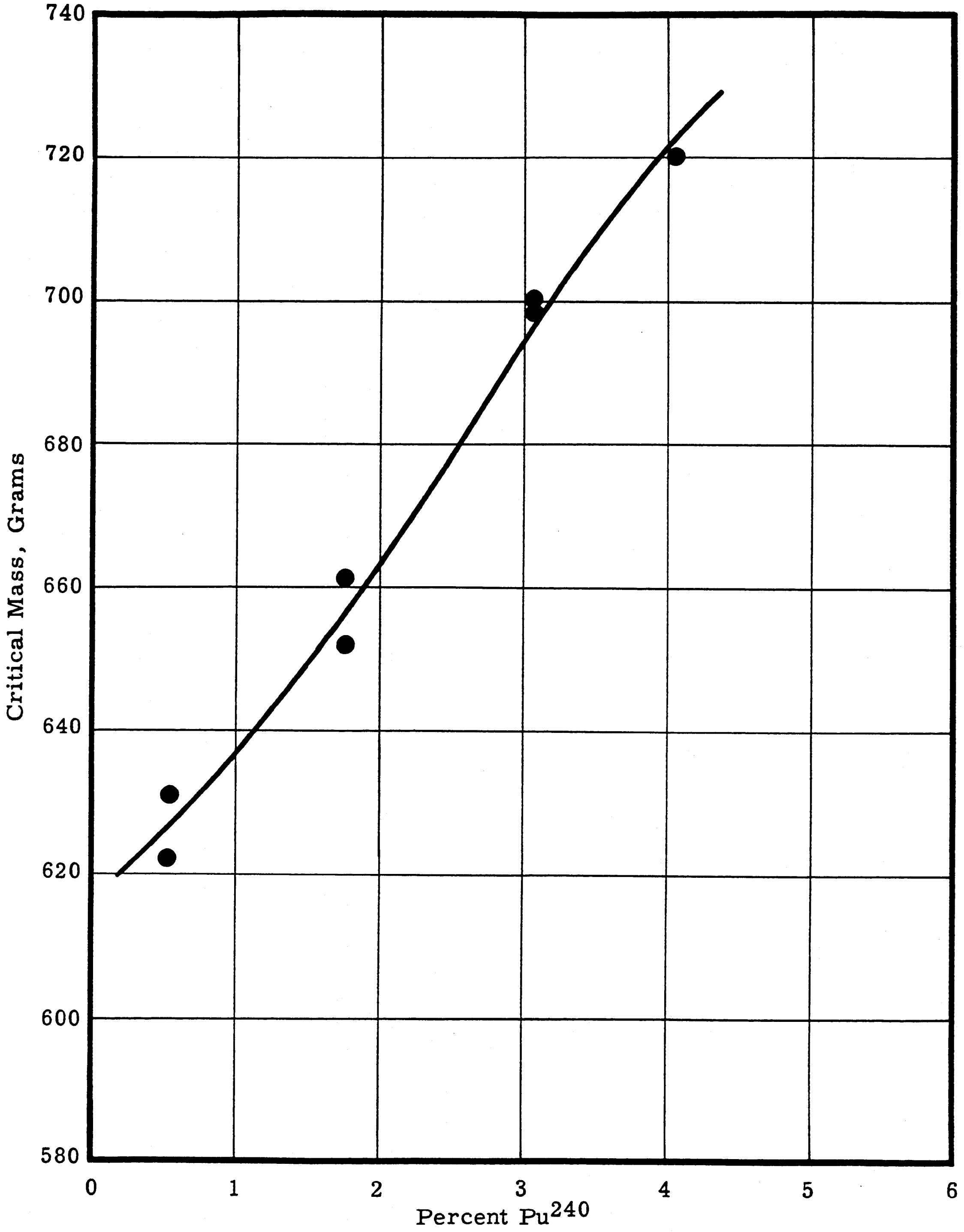


FIGURE 15

Critical Mass vs. Per Cent Pu^{240}
14" Water Tamped Sphere
~ 110 Grams Nitrate/Liter

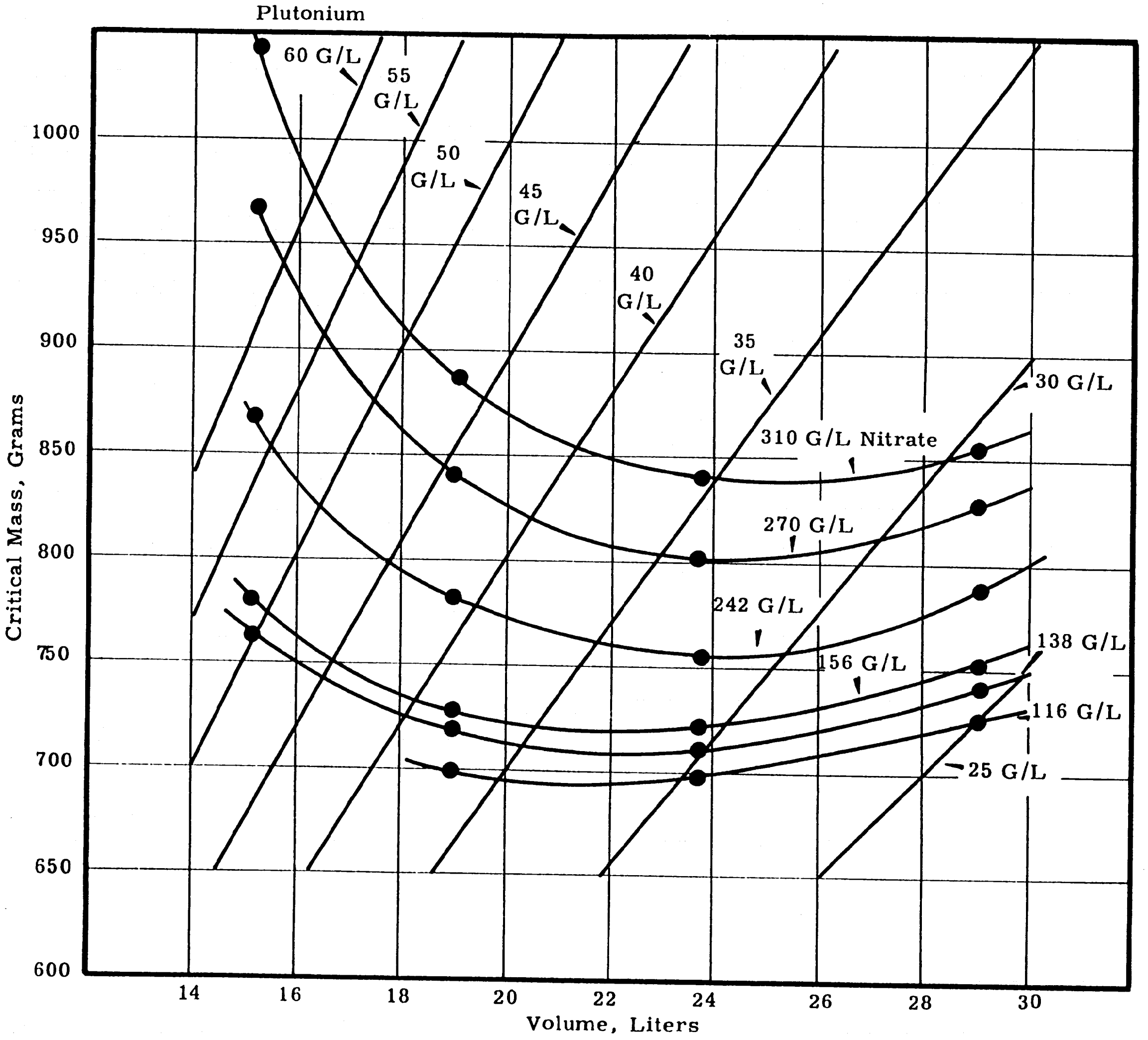


FIGURE 16

Critical Mass vs. Volume
Water Tamped SS Spheres
3.12% Pu^{240}, 27 C

Lithium nitrate was added in increments to obtain a poison calibration in a tamped and bare reactor. It was selected for this purpose because of its large absorption cross section with a $1/\sqrt{E}$ energy dependence. At the concentrations required here, about one gram of lithium per liter, displacement effects are negligible. The change in critical mass with lithium for the tamped 14-inch reactor is shown in Figure 17. The rather wide variation in experimental points is attributed to difficulties encountered in the analytical determination of fuel constituents. The short section of graph represents the variation of mass with lithium at a nitrate concentration of about 207 grams NO_3/liter. The effect of the progressive increase in nitrate concentration associated with the lithium and fuel additions, was corrected by the adjustment of the data to a nitrate concentration of 110 grams per liter.

A similar calibration, Figure 18, was made in the 18-inch bare sphere at a nitrate concentration ranging from 116 to 132 grams NO_3/liter.

Two attempts were made to investigate the effect of displacement by impurities. Additions of phosphoric acid were made after first oxidizing the fuel to the Pu(VI) oxidation state. Difficulties were encountered because of the fuel precipitation and because of the relatively large quantities of potassium permanganate required. A second attempt was made using sulfuric acid for displacement purposes. The absorption cross section of phosphorous and sulfur are sufficiently low that either acid could have produced the desired effect. Unfortunately, difficulties encountered in the analytical determination of the fuel constituents prevent a quantitative measurement of the increase in mass with displacement. It is readily apparent however, that a decrease in core hydrogen density as the result of the addition of impurities causes an increase in critical mass even though the total parasitic absorption in the core is reduced by this process. Figure 19 shows the effect of displacement of hydrogen in the case of additions of nitrate as compared with lithium additions.

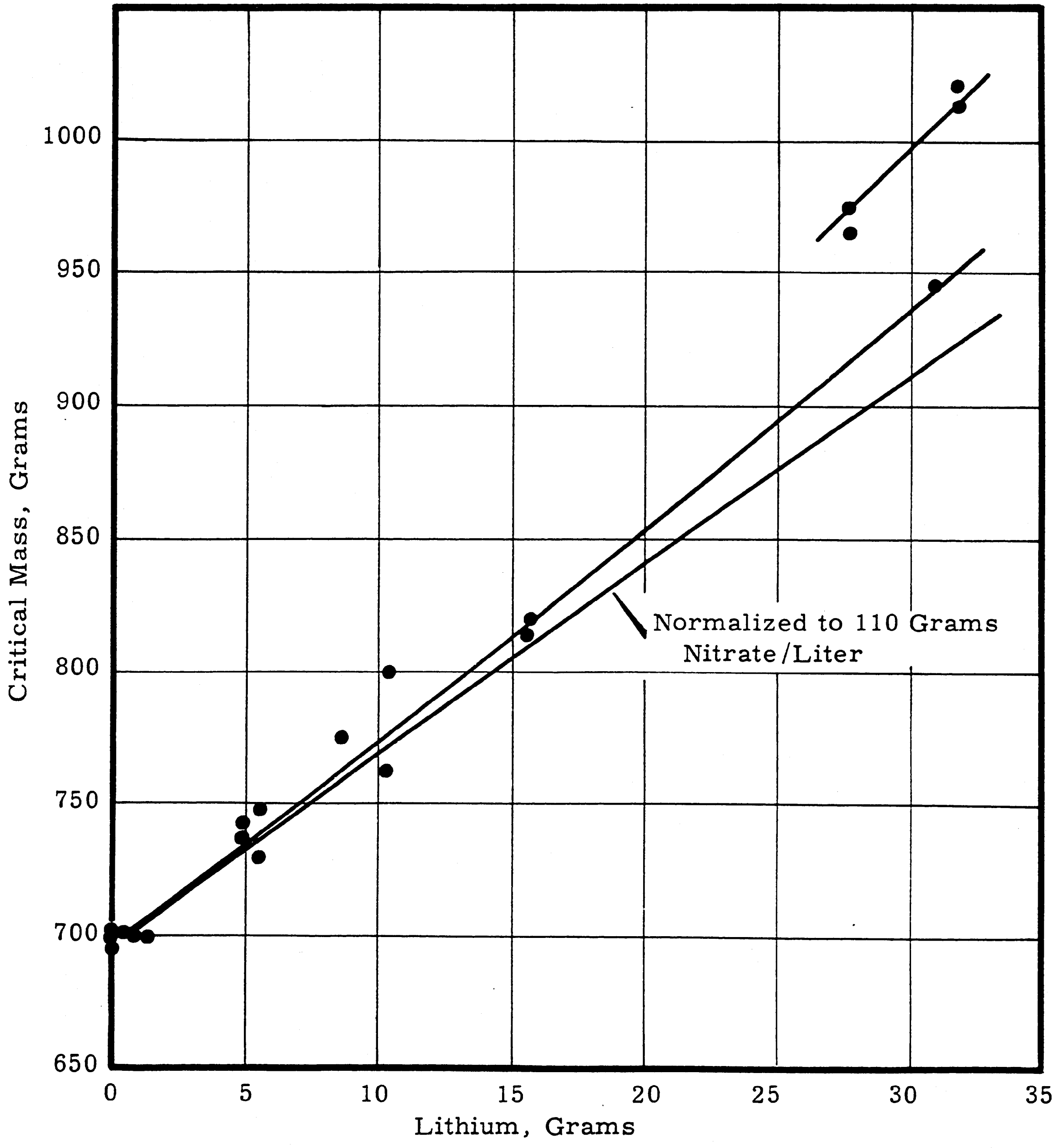


FIGURE 17

Critical Mass vs. Lithium
Water Tamped 14" SS Sphere
3.43% Pu^{240}

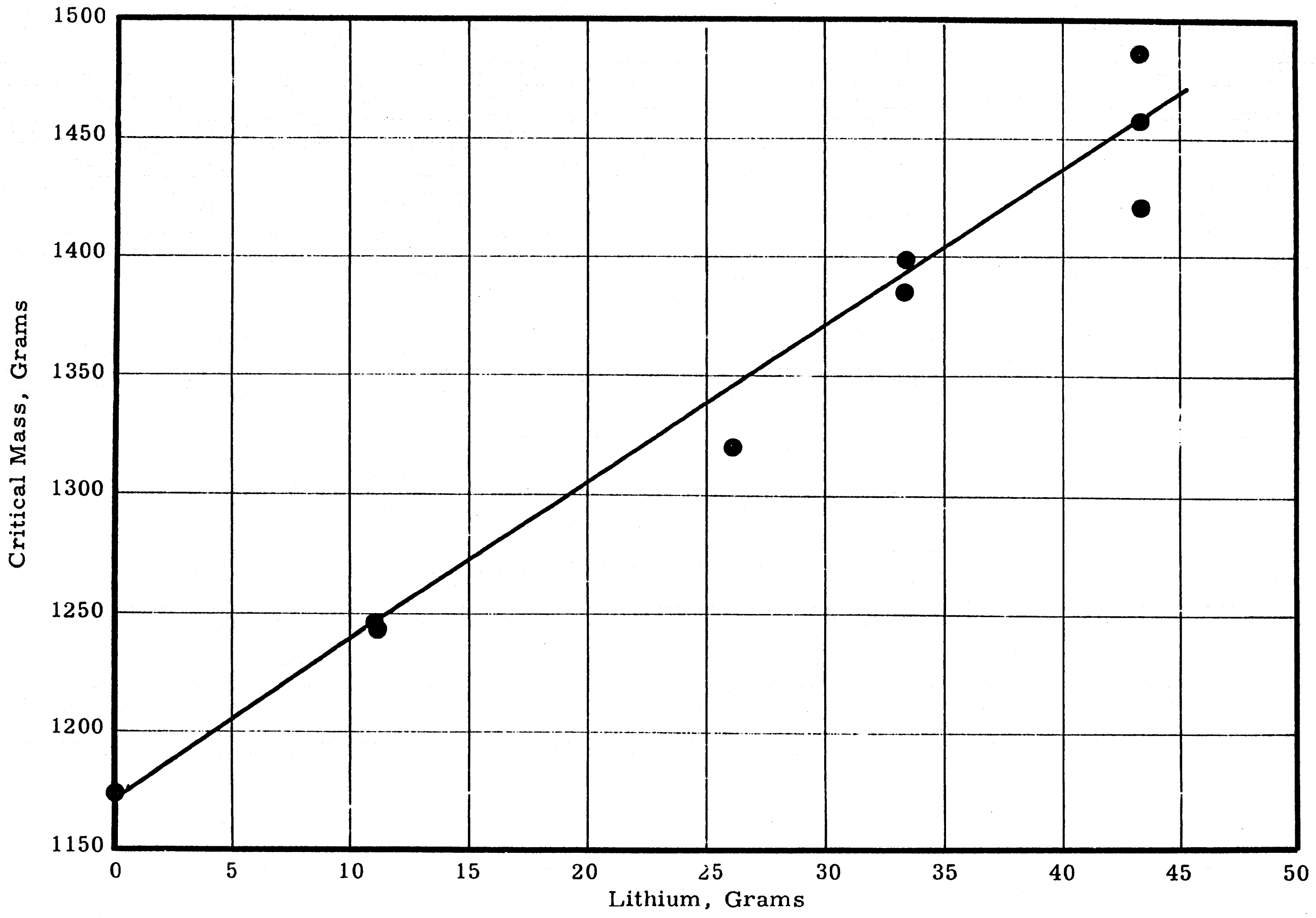


FIGURE 18

Critical Mass vs. Lithium
Bare SS 18" Sphere
4.2% Pu^{240}, 25 C

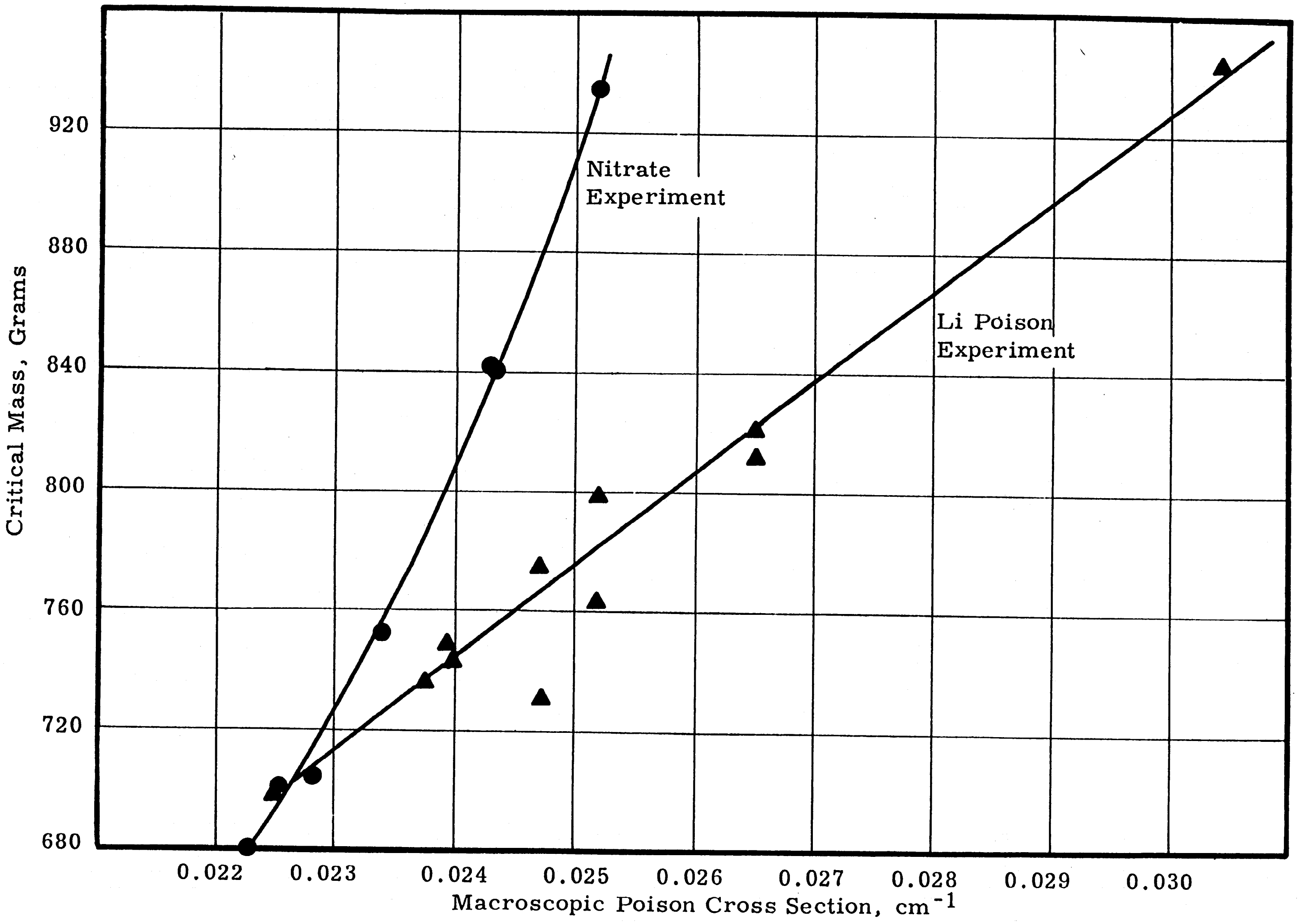


FIGURE 19

Critical Mass vs. Macroscopic Poison Cross Section
14" Water Tamped Sphere - 3. 12% Pu^{240}

Bismuth was added to a fuel solution to determine whether its inelastic scattering properties would have an appreciable effect on criticality. Figure 20 shows the increase in mass with bismuth concentrations. However, this curve must be corrected for the nitrate which was added with the $Bi(NO_3)_3 \cdot 5\ H_2O$ crystals and fuel. The necessary correction is not fully understood. If the increase in nitrate is corrected for by subtracting the incremental change in mass for the equivalent nitrate increase, the resulting curve indicates an increase in critical mass with increasing bismuth concentration, followed by a decrease to just less than the original bismuth free mass at the highest bismuth concentration reached. It does not seem reasonable that this should be the case as inelastic properties should manifest themselves on an atomic concentration basis.

Reactor Shell Effect

An attempt was made to correct the measured critical mass values for the perturbation caused by the thin stainless steel reactor shells. The presence of such a wall between the fuel and reflector increases the necessary critical concentration, or for a given concentration, the critical volume. This effect is due to the large capture cross section of iron for thermal neutrons reflected back into the core. An evaluation of the magnitude of this effect was made by comparing the critical radius of a tamped aluminum sphere with negligible wall absorption, and a tamped sphere with a thin stainless steel wall using the same fuel. A single reactor made of 20 gauge 2S aluminum was used for this measurement. A second test was made by surrounding a cylindrical reactor with an additional thickness of stainless steel and noting the increase in critical height required to attain criticality.

It was apparent from these limited experiments that the effect of the wall increased as the hydrogen content or moderation in the core was decreased. This observation was qualitatively made by noting an increase in the control cup strength under these conditions.

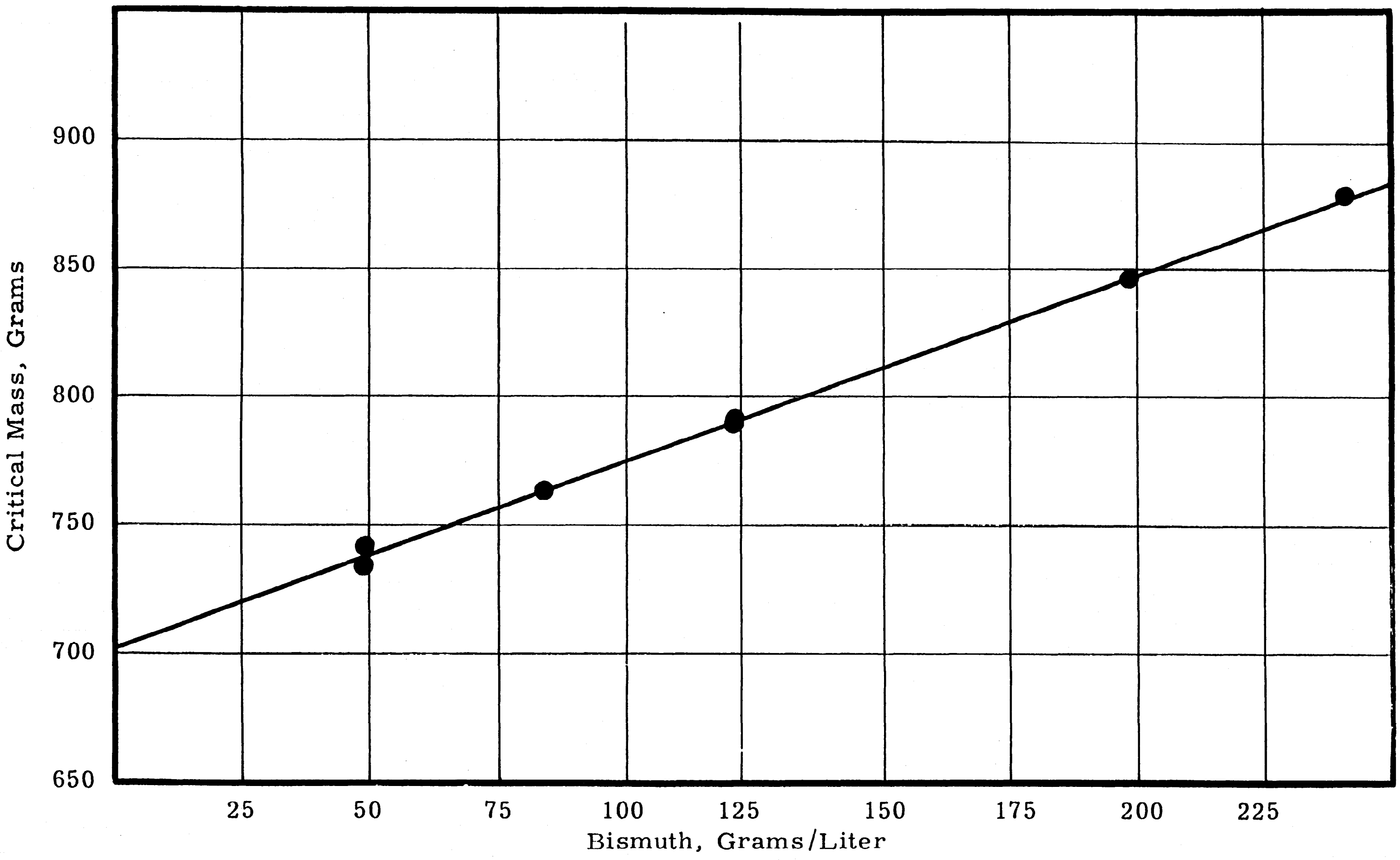


FIGURE 20

Critical Mass vs. Bismuth
Water Tamped 14" SS Sphere
23.64 Liters 3.12% Pu^{240}

It was found that the addition of a 0.020-inch layer of cadmium to a bare spherical reactor effected a reduction in critical mass by reflection of neutrons, of 20 grams at low nitrate concentrations. This indicated that a correction must also be made for the reflection of the 0.050-inch wall of the bare reactors.

The extent and reliability of the data is not sufficient to correct for the effect of the reactor shell under all conditions. Comparison of the bare and tamped stainless steel spheres gives an extrapolation length of about 3.2 cm at a hydrogen concentration of about 108 grams/liter, which may be increased to about 5 cm after correcting for reflection and absorption. Only the absorption effect of the steel shell was measured. It was found that the presence of the steel shell required an increase in the critical radius of about 0.22 cm or about 30 grams in the critical mass.

Temperature Effect

The temperature dependence of critical mass as measured in a reactor is due to the change in density of the moderator with temperature and to a change in the average neutron energy. Measurements were made in a range of 60 to 120 F. It is not possible on the basis of the data to fix the values of these effects. A rise in temperature in tamped reactors produced a negative reactivity coefficient of not more than -1.0 gram Pu/° C over the range of these experiments. The temperature at criticality was held at 27 C for the greater part of this work.

PREDICTION FORMULA

Derivation of Formula

It has not been possible on the basis of simple diffusion theory to predict the critical mass of plutonium solutions quantitatively. The data obtained in the course of these studies has been analyzed in an attempt to arrive at an expression which will predict the critical mass over the entire range of the work done with plutonium nitrate solutions.

The thermal utilization, f, of the fuel is found to vary linearly with hydrogen concentration as shown in Figure 21 using cross-section values as given below. Since the change in thermal utilization is relatively insensitive

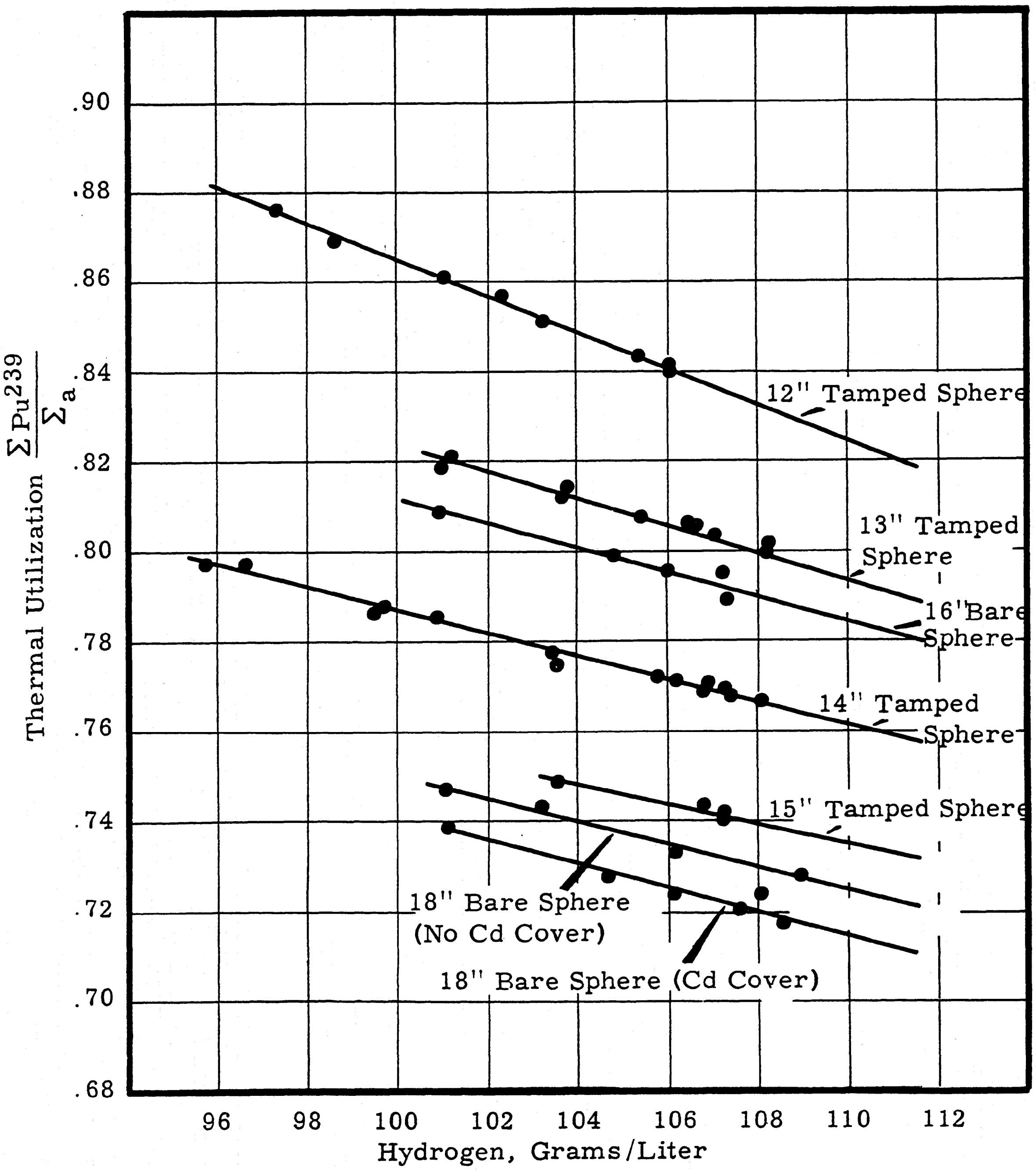


FIGURE 21

Thermal Utilization versus Hydrogen

to small poison changes, the increase in thermal utilization with decreasing hydrogen concentration must be due to a change in moderation. The change in f is also a function of the sphere volume, or the buckling (B), as given by $B = \frac{\pi^2}{(R+1)^2}$ in diffusion theory where R and 1 are the reactor radius and extrapolation length, respectively. Using an extrapolation length of 4 cm for tamped steel spheres as approximately indicated by Figure 22, the thermal utilization for plutonium nitrate fuels is given by:

$$f = (38.90 - 0.2494\ H)B + 2.743 \times 10^{-3}\ H + 0.221$$

where H is the hydrogen concentration in grams/liter.

The critical mass is then given by:

$$M = \frac{V\ 239 \times 10^4}{\sigma_{239}\ (6.02)(1-w)} \left[\frac{\sum \text{poison}}{1/f - 1 - \left(\frac{w}{1-w}\right) \frac{239}{240}\ \frac{\sigma_{240}}{\sigma_{239}}} \right]$$

where V = volume in liters
σ = cross section in barns
w = Pu^{240} fuel fraction
σ_{240} = 1000
σ_{239} = 1150
σ_H = 0.32
σ_N = 1.7

This formula predicts the critical mass over the range of these experiments of tamped spheres within experimental error and tamped cylinders to within ± 3 per cent.

Minimum Critical Mass

This formula enables us to predict the hypothetical minimum critical mass of plutonium-239 and water. A mass of 509 grams is predicted on this basis at a concentration of about 32.6 grams/liter in a 12.2 inch diameter thin steel sphere at a temperature of 27 C. A somewhat smaller mass would result in the absence of the spherical shell.

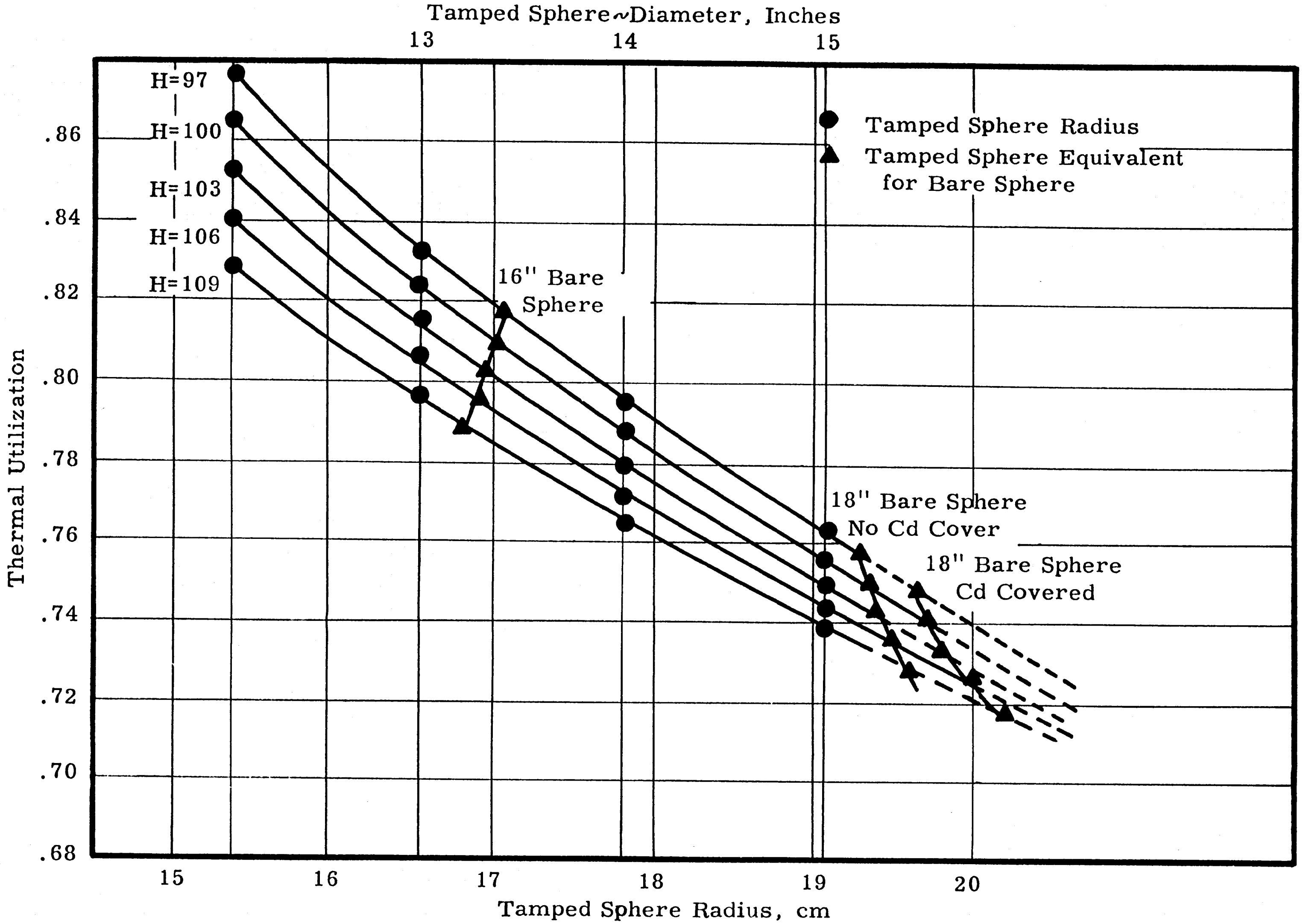


FIGURE 22

Thermal Utilization versus Tamped Sphere Radius

The predictions arrived at by this formula are in good agreement with values obtained from other data analyses and graph extrapolation.

A maximum safe tamped cylindrical diameter of six inches is indicated. The maximum safe thickness of 2. 8 inches is found for an infinite tamped slab. The maximum safe volume of a moderated fuel solution is 5. 8 liters, containable in a 8. 8-inch diameter thin steel sphere.

CYLINDRICAL REACTORS

The initial critical mass studies at Hanford were undertaken in cylindrical reactors due to: 1) the relative ease of changing reactor volume as compared with concentration, 2) the desire to make early comparisons with similar data on U^{235} reported by Beck, et al,(1) and 3) the large uncertainty in theoretical prediction of the range of concentration required to obtain a minimum mass. These experiments provided a means of scoping the work requiring investigation. It was not recognized until the completion of a number of these experiments that the nitrate concentration of the fuel would have such a significant bearing on critical mass. Unfortunately, no attempt was made to hold nitrate concentration constant, although the freeacid content was held between 1. 5 and 2. 0 N HNO_3. These data should be corrected for nitrate variation which is difficult to accomplish in the geometries encountered. Figure 23 shows the relationship between critical concentration and height in each of four cylinders made critical. Figure 24 gives the critical mass in terms of plutonium concentration.

An estimate of the nitrogen and hydrogen concentrations in each of the reactors is given in Figure 25 as a function of reactor height. This information is provided to indicate that the shape of the above curves will be altered somewhat after the nitrate correction is applied due to an increase in nitrate concentrations as the fuel is concentrated.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of G. M. Muller and J. W. Flora to the P-11 Project.

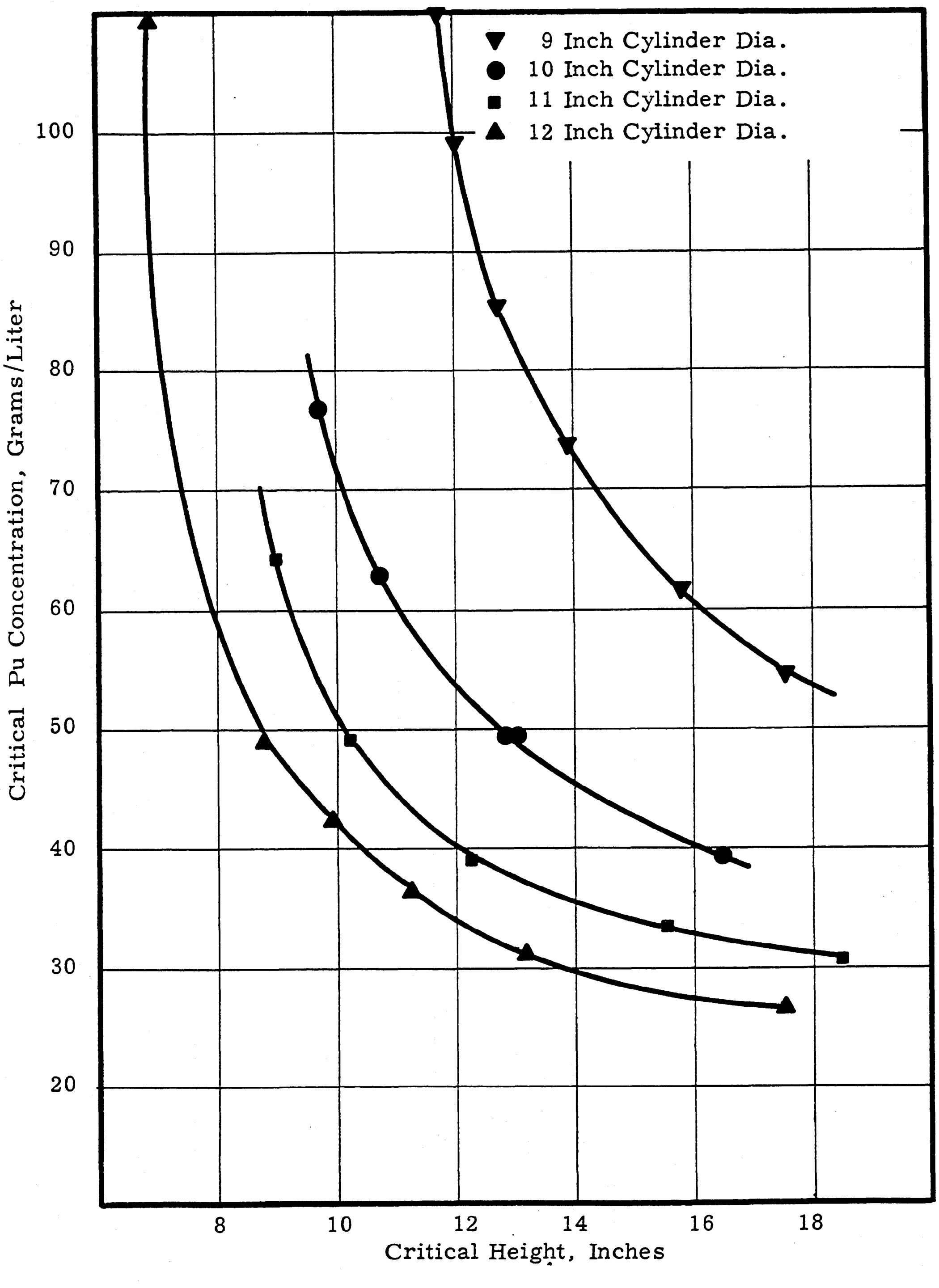


FIGURE 23

Critical Pu Concentration versus Critical Height
Water Tamped SS Cylinders
2.4% Pu^{240}, 27 C

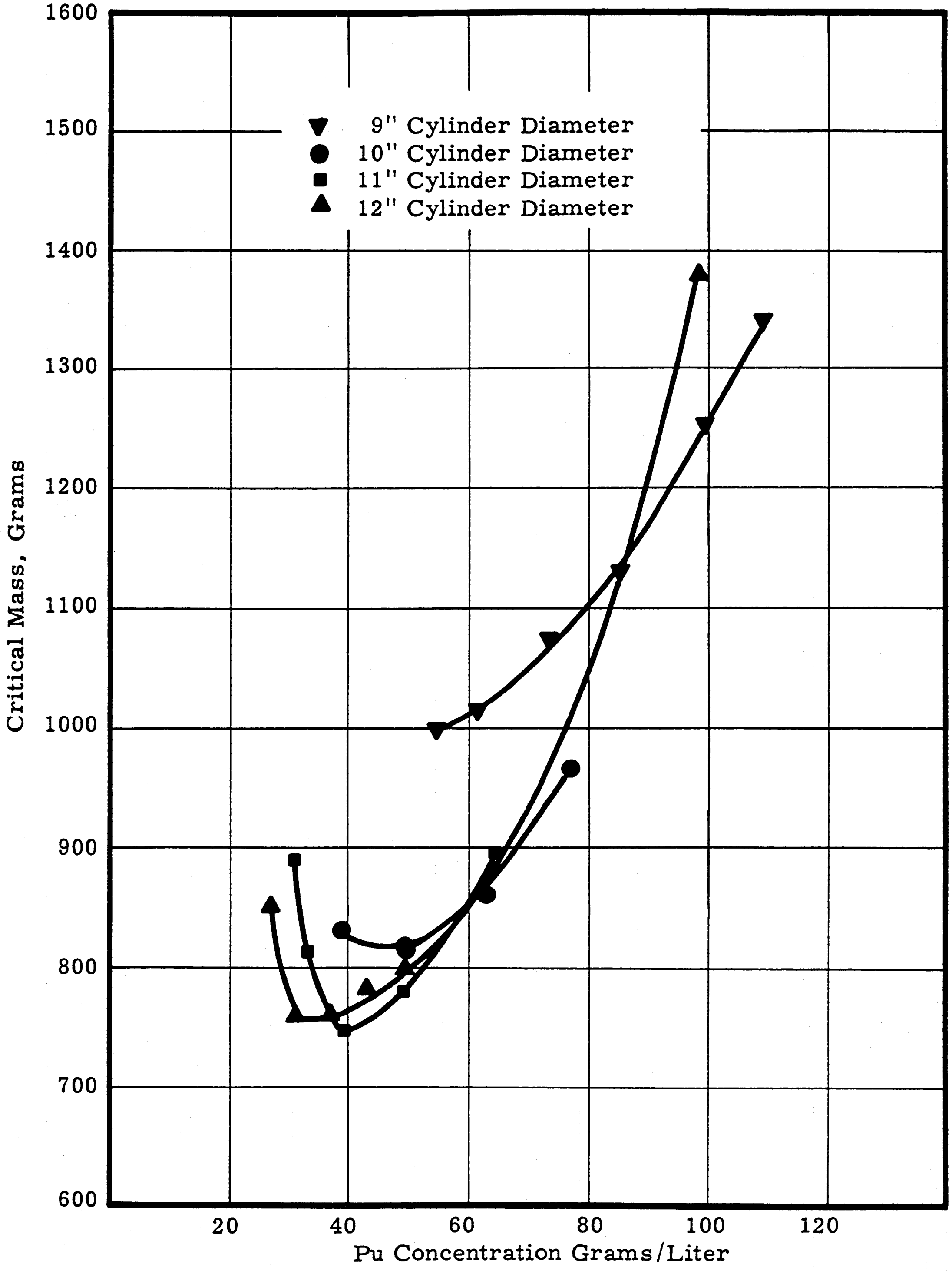


FIGURE 24

Critical Mass versus Pu Concentration

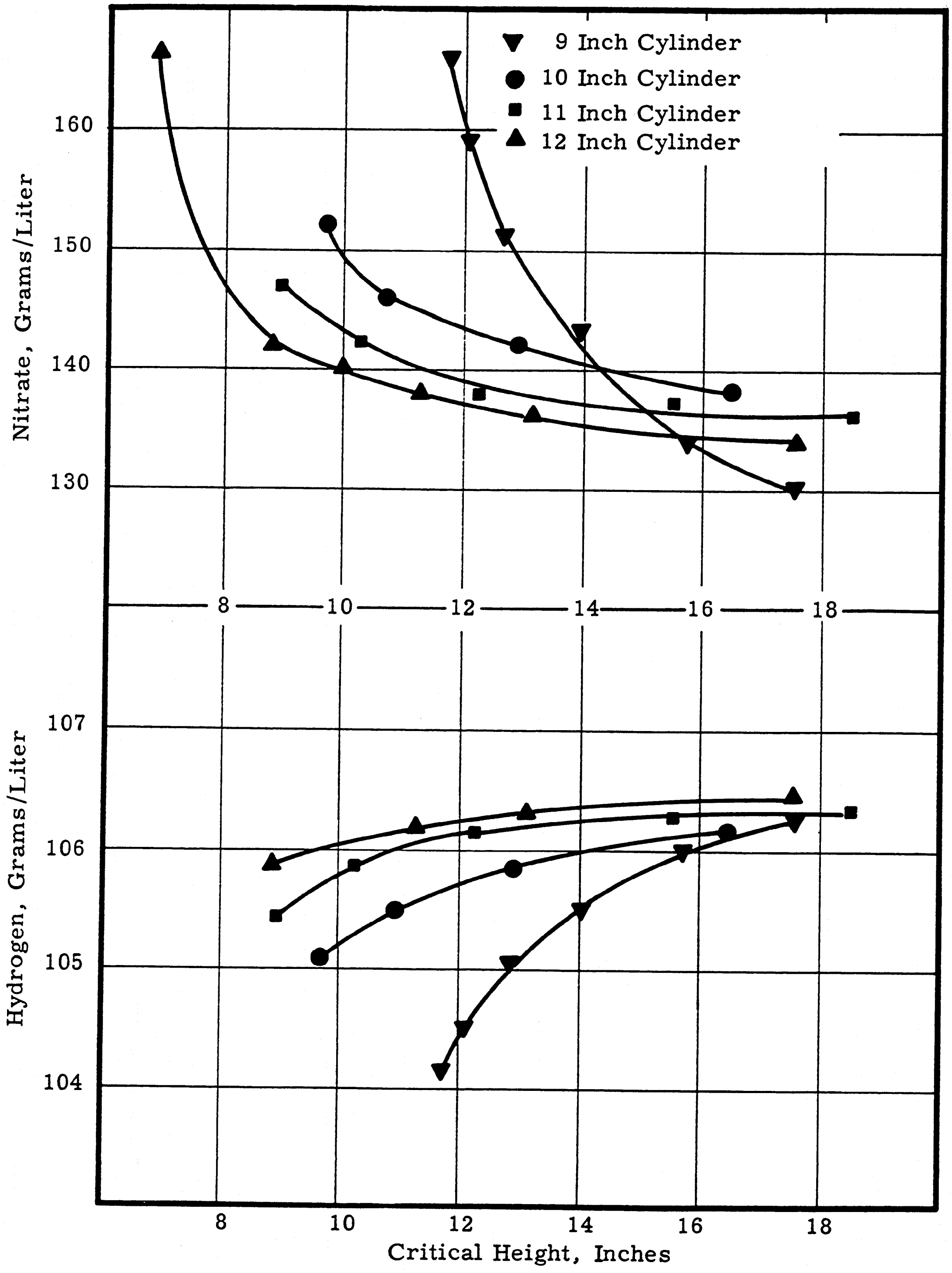


FIGURE 25

Estimated Nitrate and Hydrogen versus Critical Height

APPENDIX

DATA

Explanation of Data Tables

In the tables which follow, the results of the P-11 Criticality Experiments are summarized. A description of the chemical analysis of the fuels, and an indication of the accuracy of the results was given on page 33. A blank space in these tables indicates that no analysis was made in that particular case, as when a duplicate sample was submitted for plutonium and iron assays only. In some cases where analytical results were not obtained, estimated values have been used which are based on recorded fuel additions. These values may be in error as much as ± 5 per cent, as indicated on page 12.

Entries in the data tables not covered by the reference above are described below.

Reactor Diameter. For cylinders, the reactor diameter is reported to within ± 0.02 inches. The nominal diameter is given for the spheres.

Reactor Height. The height of the cylinders was measured to ± 0.01 inches.

Reactor Volume. Cylinder volume was calculated to be uncertain to the extent of ± 0.6 per cent. The volume of the spheres was measured to ± 0.3 per cent.

Temperature. The temperature of the tamper was controlled to within ± 0.25 F. The temperature of the fuel used in the untamped reactors is reported to within ± 1.0 F.

Total Hydrogen. This quantity may be calculated in one of three ways for most of the experiments reported.

1. By calculations based on the chemical analysis for water described under analytical procedure.

2. The water content may be calculated by subtracting the plutonium, iron, nitrate, hydrogen ion and any other fuel constituent from the density. Total hydrogen is then found as in (1).

3. An equation, based on nitric acid tables, was developed giving total hydrogen in terms of nitrate and hydrogen ion concentrations only, i. e., hydrogen = 111. 8 + hydrogen ion concentration - 0. 0535 x nitrate ion concentration.

Analyses for water were not made for the cylinder and bare sphere experiments, so that the first method is not generally applicable. The second method was considered to be reliable, and was used for experiments other than nitrate experiments and lithium experiments. The cumulative error is a disadvantage of this method. The third method was used for the nitrate and lithium experiments. Over the range of these experiments (up to 80 grams plutonium per liter), this method gives good results when compared to method number two, even though the displacement of the plutonium has been neglected. The smaller cumulative error and the ease of computation are the advantages of this method when used for the fuels mentioned above. The error in this quantity is estimated to be less than 1. 0 per cent.

Critical Mass. The critical mass, as reported, is the product of the volume of the reactor and the plutonium concentration, with a correction being made for the control rod, if necessary. These critical masses are estimated to have an uncertainty of 1. 5 per cent.

Spectrographic Analysis. Samples of the fuel were subjected to spectrographic analysis to determine if any impurities were present in significant amounts. The tamper water was also analyzed, and was found to contain no significant amount of impurities. Results of the tamper water analysis are not included in this report.

WATER TAMPED CYLINDER DATA

Reactor Diameter (inches)	8.0[a]	9.0	9.0	9.0	9.0	9.0	9.0	10.0	10.0	10.0
Plutonium Assay (grams/liter)	77.40[a]	109.16	99.09	85.14	73.92	61.49	54.53	77.40	76.93	62.47
Acid Normality	1.41[b]	1.68	1.37	1.29[b]	1.78	1.34[b]	1.36	1.41[b]	1.41[b]	1.52[b]
Per Cent Pu^{240} by weight	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85
Tamper Temperature (F)	81.0	81.5	80.0	80.5	81.0	81.0	79.5	83.5	83.0	83.0
Density (grams/cc)	1.175	1.2110	1.1997	1.1859	1.1592	1.1441	1.1329	1.175	1.165	1.146
Total Nitrate (grams/liter)	152[b]	166[b]	136.5	151[b]	125.6	134[b]	119.8	152[b]	152[b]	146[b]
Iron Assay (grams/liter)	0.644	0.395	0.378	0.321	0.231	0.303	0.257	0.644	0.327	0.269
Total Hydrogen (grams/liter)	105.1[b]	104.6[b]	105.9	105[b]	106.8	106.0[b]	106.7	105.1[b]	105.1[b]	105.5[b]
Critical Height (inches)	(19.01)	11.76	12.09	12.73	13.94	15.78	17.55	9.93	9.74	10.73
Critical Volume (liters)	(15.66)	12.25	12.60	13.26	14.52	16.44	18.29	12.78	12.53	13.79
Critical Mass (grams)	(1212)	1337	1249	1128	1073	1011	997	989	964	860

a. This cylinder was subcritical by an unknown amount.

b. These numbers are estimates based on log book entries.

WATER TAMPED CYLINDER DATA (contd.)

Reactor Diameter (inches)	10.0	10.0	10.0	10.0	10.0	11.0	11.0[d]	11.0[d]	11.0	11.0
Plutonium Assay (grams/liter)	49.26	49.26	39.10	39.10[c]	39.10[c]	39.10	54.43	47.21	47.21	41.73
Acid Normality	1.63[b]	1.63[b]	1.70[b]	1.70[b]	1.70[b]	1.70[b]	1.36	1.38	1.38	2.77
Per Cent Pu^{240} by weight	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85	2.85
Tamper Temperature (F)	84.0	84.0	83.0	64.0	122	85.4	80.5	80.5	80.5	81.5
Density (grams/cc)	1.130	1.130	1.110	1.110	1.110	1.110	1.1329	1.1202	1.1202	1.1604
Total Nitrate (grams/liter)	142[b]	142[b]	138[b]	138[b]	138[b]	138[b]	120	117	117	215
Iron Assay (grams/liter)	0.260	0.260	0.172	0.172	0.172	0.172	0.257	0.275	0.275	0.255
Total Hydrogen (grams/liter)	105.8[b]	105.8[b]	106.1[b]	106.1[b]	106.1[b]	106.1[b]	106.7	106.9	106.9	103
Critical Height (inches)	12.87	12.82	16.44	16.24	17.49	12.28	10.08	11.09	10.66	12.85
Critical Volume (liters)	16.56	16.50	21.16	20.90	22.51	19.12	15.69	17.27	16.60	20.01
Critical Mass	816	813	827	817	879	747	856	815	784	835

c. Assays for fuel used in temperature coefficient experiments have not been corrected to the temperature at which the experiment was made.

d. In this experiment, a 0.065 inch layer of stainless steel was placed around the cylinder. The ends of the cylinder were not changed.

WATER TAMPED CYLINDER DATA (contd.)

Reactor Diameter (inches)	11.0	11.0	11.0[e]	11.0	11.0	11.0	11.0	12.0	12.0	12.0
Plutonium Assay (grams/liter)	36.90	33.54	30.81	63.99	48.98	48.75[c]	48.75[c]	48.75	42.29	36.52
Acid Normality	4.28	1.76[b]	1.78[b]	1.17	1.38	1.27	1.27	1.27	1.36	1.39
Per Cent Pu^{240} by weight	2.85	2.85	2.85	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Tamper Temperature (F)	81.5	86.0	83.5	80.5	80.5	69.5	114.0	84.5	84.0	81.0
Density (grams/cc)	1.2022	1.099	1.098	1.1483	1.1360	1.1260	1.1260	1.1260	1.1152	1.1077
Total Nitrate (grams/liter)	300.0	137[b]	136[b]	121.1	139.0	116.3	116.3	116.3	126.6	107.1
Iron Assay (grams/liter)	0.263	0.193	0.173	0.298	0.238	0.223	0.223	0.223	0.174	0.161
Total Hydrogen (grams/liter)	100.6	106.2[b]	106.3[b]	106.5	105.7	106.8	106.8	106.8	106.4	107.4
Critical Height (inches)	16.93	15.57	18.55	8.98	10.22	10.18	10.52	8.80	9.94	11.21
Critical Volume (liters)	26.36	24.24	28.88	13.98	15.91	15.85	16.38	16.31	18.42	20.77
Critical Mass (grams)	973	813	889	895	780	773	799	799	779	758

e. This experiment was subcritical. A reliable extrapolation to the critical height was made.

WATER TAMPED CYLINDER DATA (contd.)

Reactor Diameter (inches)	12.0	12.0	12.0	12.0	12.0
Plutonium Assay (grams/liter)	31.14	31.14[c]	31.14[c]	26.45	109.16
Acid Normality	1.44	1.44	1.44	1.09	1.68
Per Cent Pu^{240} by weight	2.9	2.9	2.9	2.9	2.85
Tamper Temperature (F)	82.5	67.0	116.6	78.5	82.0
Density (grams/cc)	1.1028	1.1028	1.1028	--	1.2110
Total Nitrate (grams/liter)	114.0	114.0	114.0	134[b]	166[b]
Iron Assay (grams/liter)	0.153	0.153	0.153	0.154	0.395
Total Hydrogen (grams/liter)	107.1	107.1	107.1	105.7[b]	104.6[b]
Critical Height (inches)	13.16	13.03	13.59	17.50	6.82
Critical Volume (liters)	24.39	24.14	25.18	32.43	12.64
Critical Mass (grams)	759	752	784	858	1380

NITRATE EXPERIMENTS, TAMPED SPHERES

Nominal Reactor Diameter (inches)	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Reactor Volume (liters)	15.19	15.19	15.19	15.19	15.19	15.19	15.19	15.19	15.19	15.19
Per Cent Pu^{240} by weight	3.12	3.12	3.12	3.12	3.12	3.12	3.12	3.12	3.12	3.12
Plutonium Assay (grams/liter)	50.39	50.25	51.80	56.20	56.75[f]	59.93	60.35[f]	63.75	64.16	70.22
Total Nitrate (grams/liter)	138	139	163	207	--	237	--	270	--	322
Density (grams/cc)	1.1318	1.1306	1.1482	1.1682	--	1.1898	--	1.2152	--	1.2412
Iron Assay (grams/liter)	0.178	0.199	0.272	0.203	0.286	0.199	0.184	0.204	0.190	0.218
Acid Normality	1.57	1.61	2.20	2.49	--	3.20	--	3.62	--	4.07
Water Assay (grams/liter)	922.8	941.3	920.0	899.2	--	879.8	--	860.9	--	843.6
Total Hydrogen (grams/liter)	106.0	106.0	105.3	103.2	--	102.3	--	101.0	--	98.6
Temperature (F)	80.5	81.0	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	763	761	786	854	860	911	911	961	973	1070

[f] The sample represented by data in this column was taken from the same fuel as the sample represented by the immediately preceding column.

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches)	12.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
Reactor Volume (liters)	15.19	18.94	18.94	18.94	18.94	18.94	18.94	18.94	18.94	18.94
Per Cent Pu^{240} by weight	3.12	1.76	1.76	1.76	1.76	1.76	3.12	3.12	3.12	3.12
Plutonium Assays (grams/liter)	77.22	34.06	33.17	34.59	34.81	35.65[b]	38.11	37.99	38.83	40.69
Total Nitrate (grams/liter)	359	87.1	86.2	117.0	116.0	145.0	128	132	156	205
Density (grams/cc)	1.2695	1.0858	1.0848	1.1012	1.1006	1.1161	1.1107	1.1106	1.1279	1.1547
Iron Assay (grams/liter)	0.237	0.123	0.124	0.113	0.121	0.124	0.110	0.095	0.141	0.248
Acid Normality	4.72	1.04	1.02	1.44	1.46	1.88	1.67	1.64	2.01	2.90
Water Assay (grams/liter)	822.7	955.6	962.4	939.8	940.1	929.2	--	--	926.7	906.2
Total Hydrogen (grams/liter)	97.3	108.2	108.2	107.0	107.0	105.9	106.6	106.4	105.5	103.7
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	81.0	80.5	77.0	80.5
Critical Mass (grams)	1176	640	631	656	654	670	712	716	727	773

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches)	13.0	13.0	13.0	13.0[g]	13.0[g]	14.0	14.0	14.0	14.0	14.0
Reactor Volume (liters)	18.94	18.94	18.94	18.04	18.04	23.64	23.64	23.64	23.64	23.64
Per Cent Pu^{240} by weight	3.12	3.12	3.12	3.12	3.12	0.54	0.54	0.54	0.54	0.54
Plutonium Assays (grams/liter)	41.10	44.64	44.12	36.27	37.11	26.33	26.69	26.77	26.23	27.91
Total Nitrate (grams/liter)	205	269	270	93.1	125	77.3	78.3	107	107	138
Density (grams/cc)	1.1548	1.1905	1.1910	1.0910	1.1106	1.0692	1.0695	1.0869	1.0858	1.1030
Iron Assay (grams/liter)	0.266	0.269	0.262	0.114	0.128	0.143	0.146	0.147	0.150	0.160
Acid Normality	2.90	3.71	3.63	1.15	1.66	0.99	0.97	1.42	1.41	1.85
Water Assay (grams/liter)	908.6	865.2	868.3	955.1	942.5	967.6	967.2	955.5	954.9	936.6
Total Hydrogen (grams/liter)	103.7	101.1	101.0	108.0	106.8	108.6	108.6	107.5	107.5	106.3
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	777	846	834	654	669	625	627	631	622	648

g. Aluminum sphere.

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches)	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
Reactor Volume (liters)	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64
Per Cent Pu^{240} by weight	0.54	0.54	0.54	1.76	1.76	3.12	3.12	3.12	3.12	3.12
Plutonium Assays (grams/liter)	27.39	28.63	28.50	27.95	27.92	28.78	30.15	29.61	29.74	30.33
Total Nitrate (grams/liter)	137	188	187	109	110	87.4	109	110	115	143
Density (grams/cc)	1.1040	1.1321	1.1300	1.0885	1.0885	1.0769	1.0918	1.0914	1.0931	1.1087
Iron Assay (grams/liter)	0.152	0.165	0.163	0.092	0.096	0.110	0.129	0.127	0.113	0.113
Acid Normality	1.90	2.72	2.70	1.44	1.42	1.02	1.39	1.40	1.51	1.92
Water Assay (grams/liter)	945.0	915.0	914.8	939.4	938.6	957.7	951.8	948.2	941.4	925.4
Total Hydrogen (grams/liter)	106.4	104.5	104.5	107.4	107.3	108.1	107.3	107.3	107.1	106.1
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	647	666	671	652	661	681	708	699	701	713

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches)	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
Reactor Volume (liters)	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64
Per Cent Pu^{240} by weight	3.12	31.2	3.12	3.12	4.05	4.05	4.05	4.05	4.05	4.05
Plutonium Assay (grams/liter)	31.79	35.82	35.53	39.62	29.82	29.94	30.79	30.75[f]	31.72	34.07
Total Nitrate (grams/liter)	208	308	311	408	--	87.49	--	119.3	146.8	210.7
Density (grams/cc)	1.1460	1.1993	1.2001	1.2508	--	1.0777	--	1.0967	1.1117	1.1496
Iron Assay (grams/liter	0.120	0.144	0.146	0.147	0.104	0.128	0.083	0.074	0.086	0.093
Acid Normality	2.90	4.39	4.32	5.75	--	1.01	--	1.44	1.88	2.92
Water Assay (grams/liter)	898.6	844.7	852.4	799.7	--	959.8	--	940.3	--	890.1
Total Hydrogen (grams/liter)	103.6	99.7	99.5	95.7	--	108.1	--	106.8	105.8	103.4
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	752	841	840	935	706	706	727	726	748	801

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches)	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	15.0
Reactor Volume (liters)	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	23.64	28.99
Per Cent Pu^{240} by weight	4.05	4.05	4.05	4.05	4.05	4.05	4.40	4.40	4.40	3.12
Plutonium Assay (grams/liter)	33.81[f]	36.38	37.84	38.72	41.12	41.19[f]	31.04	30.79	32.41	25.02
Total Nitrate (grams/liter)	--	272.4	334[b]	335.2	384.9	--	127	126	158	116
Density (grams/cc)	--	1.1826	--	1.2172	1.2405	--	1.1021	1.1016	1.1205	1.0899
Iron Assay (grams/liter)	0.100	0.104	0.115	0.126	0.126	0.126	0.110	0,105	0.102	0.084
Acid Normality	--	3.69	--	5.46	5.40	--	1.71	1.63	2.22	1.60
Water Assay (grams/liter)	--	865.7	--	833.4	811.9	--	930.8	944.0	926.3	947.0
Total Hydrogen (grams/liter)	--	100.9	--	--	96.6	--	106.7	106.7	105.6	107.2
Temperature (F)	--	80.5	--	80.5	80.5	--	80.5	80.5	80.5	80.5
Critical Mass	795	857	892	915	971	973	727	729	758	726

NITRATE EXPERIMENTS, TAMPED SPHERES (contd.)

Nominal Reactor Diameter (inches	15.0	15.0	15.0	11.0[h]
Reactor Volume (liters)	28.99	28.99	28.99	11.37
Per Cent Pu^{240} by weight	3.12	3.12	3.12	3.12
Plutonium Assays (grams/liter)	25.10	25.83	27.05	135.8
Total Nitrate (grams/liter)	116	147	212	229
Density (grams/cc)	1.0899	1.1068	1.1409	1.2733
Iron Assay (grams/liter)	0.092	0.094	0.096	0.464
Acid Normality	1.60	2.08	3.07	1.81
Water Assay (grams/liter)	946.5	927.1	900.7	901.7
Total Hydrogen (grams/liter)	107.2	106.0	103.5	101.3
Temperature (F)	80.5	80.5	80.5	80.5
Critical Mass (grams)	722	746	787	--

h. This reactor was subcritical by an unknown amount.

PHOSPHATE AND BISMUTH EXPERIMENTS

Reactor: 14-inch nominal diameter (23.64 liters), water tamped stainless steel sphere.

Fuel: 3.12 Per Cent Pu^{240}

Plutonium Assay (grams/liter)	30.15	29.61	31.21	31.05[f]	32.22	33.46	33.36[f]	35.75	37.37	32.14
Total Nitrate (grams/liter)	109	110	153	154	187	220	227	315	260	114.8
Density (grams/cc)	1.0918	1.0914	1.1698	1.1753	1.2245	1.2854	1.2957	1.4103	1.4795	1.0999
Iron Assay (grams/liter)	0.129	0.127	0.139	0.159	0.141	0.142	0.160	0.169	0.230	0.130
Acid Normality	1.39	1.40	1.36	1.42	1.54	2.37	2.35	2.2[b]	2.3[b]	1.85[b]
Water Assay (grams/liter)	951.8	948.2	932.1	924.7	899.7	894.6	894.4	856.7[i]	838.9[i]	925.7
Total Hydrogen (grams/liter)	107.8	107.7	105.9	106.4	104.5	103.9	104.3	98.1	96.2	104.6
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Bismuth (grams/liter)	0.0	0.0	49.8	49.8	83.65	121.6	121.6	196.7	241.0	0.0
Phosphate (grams/liter)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Manganese (grams/liter)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.66
Critical Mass (grams)	708	699	739	735	763	792	790	846	880	760

i. The results on these two water analyses are questionable due to interference of bismuth in the samples.

PHOSPHATE AND BISMUTH EXPERIMENTS (contd.)

Plutonium Assay (grams/liter)	32.67	32.95	35.85	35.62
Total Nitrate (grams/liter)	112.4	117.3	128.6	113.2
Density (grams/cc.)	1.1339	1.1654	1.2268	1.2603
Iron Assay (grams/liter)	0.149	0.178	--	-
Acid Normality	1.81[b]	1.89[b]	2.07[b]	1.83[b]
Water Assay (grams/liter)	899.1	861.4	804.3	764.4
Total Hydrogen (grams/liter)	103.3	100.5	99.19	95.57
Temperature (°F)	80.5	80.5	80.5	80.5
Bismuth (grams/liter)	0.0	0.0	0.0	0.0
Phosphate (grams/liter)	50.61	92.92	244.4	280.0
Manganese (grams/liter)	3.0	2.02	0.59	0.303
Critical Mass (grams)	775	781	844	845

LITHIUM EXPERIMENT

Reactor: 14-inch nominal diameter (23.64 liter volume), water tamped stainless steel sphere.

Fuel: 3.43 Per Cent Pu^{240} by weight.

Plutonium Assay (grams/liter)	29.60	29.75	29.55^{f}	31.19	31.42^{f}	31.66	30.84^{f}	32.82	33.92	32.40^{f}
Total Nitrate (grams/liter)	111	111	112	118	117.6	119	--	122	125	--
Density (grams/cc)	1.0925	1.0923	1.0916	1.0968	1.0966	1.0984	--	1.1008	1.1030	--
Iron Assay (grams/liter)	0.142	0.129	0.148	0.157	0.187	0.151	0.165	0.147	0.154	0.165
Acid Normality	1.51	1.46	1.46	1.49	1.50	1.54	--	1.53	1.54	--
Water Assay (grams/liter)	948.3	944.7	947.4	946.1	943.5	944.2	--	943.9	943.8	--
Lithium Assay (grams/liter)	0.0	0.0	0.0	0.206	0.206	0.235	--	0.362	0.441	--
Total Hydrogen (grams/liter)	107.3	107.3	107.2	107.0	--	107.0	--	106.8	106.6	--
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	695	698	699	736	742	749	730	775	799	763

LITHIUM EXPERIMENT (contd.)

Plutonium Assay (grams/liter)	34.70	34.39[f]	39.94	41.34	40.99[f]	42.98	43.31[f]
Total Nitrate (grams/liter)	131	-	147	206	-	210	-
Density (grams/cc)	1.1086	-	1.1243	1.1566	-	1.1599	-
Iron Assay (grams/liter)	0.168	0.161	0.162	0.192	0.259	0.188	0.171
Acid Normality	1.38	-	1.84	2.77	-	2.75	-
Water Assay (grams/liter)	927.4	-	921.5	900.7	-	895.2	-
Lithium Assay (grams/liter)	0.661	-	1.31[b]	1.17	-	1.34	-
Total Hydrogen (grams/liter)	106.4	-	105.7	103.5	-	103.3	-
Temperature (F)	80.5	80.5	80.5	80.5	80.5	80.5	80.5
Critical Mass (grams)	820	813	944	973	964	1012	1020

NITRATE EXPERIMENTS, UNTAMPED STAINLESS STEEL SPHERES[j]

Nominal Reactor Diameter (inches)	18	18	18	18	18	18	16	16	16	16	16
Reactor Volume (liter)	49.0	49.0	49.0	49.0	49.0	49.0	34.15	34.15	34.15	34.15	34.15
Per Cent Pu^{240} by weight	4.2	4.2	4.2	4.2	4.2	4.2	4.17	4.17	4.17	4.17	4.17
Plutonium Assay (grams/liter)	22.35	23.40	23.14	23.85	25.18	27.48	34.80	36.22	38.31	38.15	43.20
Total Nitrate (grams/liter)	76.12	97.77	107.78	148.41	199.16	285.75	104.4	109.4	163.0	180.0	281.8
Density (grams/cc)	1.0662	1.0788	1.0860	1.1020	1.1472	1.1816	1.0961	1.0991	1.1374	1.1396	1.1958
Iron Assay (grams/liter)	0.120	0.126	0.135	0.123	0.137	0.141	0.104	0.120	0.124	0.178	0.179
Acid Normality	0.935	1.431	1.560	2.27	3.49	4.63	1.12	1.31	2.79	2.58	4.18
Total Hydrogen (grams/liter)	108.70	108.0	107.6	106.1	104.6	101.1	107.3	107.2	106.9	104.7	100.9
Temperature (F)	72	71	68	70	73	69	73	75	75	73	72
Critical Mass (grams)	1095	1140	1132	1167	1235	1347	1194	1237	1302	1303	1483

[j] Eighteen-inch Reactor was covered with 0.020 inch cadmium.

LITHIUM EXPERIMENT

Reactor: 18-inch nominal diameter, (49.0 liters volume), untamped stainless steel sphere (covered with 0.020-inch cadmium)

Fuel: 4.2 Per Cent Pu^{240}

Plutonium Assay (grams/liter)	23.94	25.43	25.47[f]	25.98	27.00[f]	28.28	28.54[f]	29.83	30.43[f]	29.06[f]
Total Nitrate (grams/liter)	125.6	123.3	116.5	132.6	103.0	132.7	132.2	141.4	134.2	131.8
Density (grams/cc)	1.0894	1.0917	1.0914	1.0964	1.0985	1.1001	1.1006	1.1043	1.1059	1.1050
Iron Assay[k] (grams/liter)	0.0389	0.0407	0.165	0.0361	0.154	0.0392	0.133	0.0435	0.092	0.208
Acid Normality	1.66	1.64	1.45	1.74	1.74	1.64	1.37	1.69	1.49	1.47
Lithium Assay (grams/liter)	0.0	0.223	0.223	0.528	0.528	0.680	0.680	0.88	0.88	0.88
Total Hydrogen (grams/liter)	106.7	106.8	107.0	106.4	108.0	106.3	106.1	105.9	106.1	106.2
Temperature (F)	75	77	77	73	73	78	78	81	81	81
Critical Mass (grams)	1173	1242	1244	1270	1320	1386	1399	1459	1488	1421

[k] Where duplicate samples occur, the high iron assay is more reliable.

SULFATE EXPERIMENT

Reactor: 18-inch nominal diameter (49.0 liters volume), untamped stainless steel sphere

Fuel: 4.2 Per Cent Pu^{240}

Plutonium Assay (grams/liter)	23.87	24.94[f]	24.76	25.20	24.48[f]	26.07	25.82	26.88[b]
Total Nitrate (grams/liter)	84.3		80.2	84.38	87.3	82.54	89.9	93.36
Density (grams/cc)	1.0730	1.0725	1.1247	1.1716	1.1725	1.2242	1.2252	1.2567
Iron Assay (grams/liter)	0.099	0.082	0.117	0.136	0.181	0.103	0.121	0.110
Hydrogen Ion (grams/liter)	1.24	1.02	2.79	4.05	4.40	6.05	7.28	7.09
Sulfate Assay (grams/liter)	0.0	0.0	76.3	149.0	--	231.0	--	279.0
Total Hydrogen (grams/liter)	109	108.6	108.0	105.7	105.9	104.3	104.7	102.2
Temperature (F)	72.5	--	73.0	76.0	--	73.0	--	74.5
Critical Mass (grams)	1166	1227	1219	1231	1206	1282	1270	1317

FUEL IMPURITIES

By Spectrochemical Analysis in Parts Per Million

Element	10" Cylinder Experiment	11" Cylinder Experiment	13" Sphere Experiment	18" Sphere Li Experiment	
Ag	50	10	L1	--	--
Al	20	100	L10	50	8
As	L50	L50	L50	--	--
B	--	10	5	--	--
Ba	L20	L200	L20	L30	L50
Be	L0.02	L2	L0.02	L0.1	L0.1
Bi	500	500	500	--	--
Ca	1000	200	20	200	130
Cd	L20	200	10	80	80
Ce	L200	--	L200	L500	L800
Co	20	L20	L20	--	--
Cr	1000	1000	2000	30	20
Cu	10	100	20	--	--
Fe	G1000	--	2000	--	--
Hg	L200	--	L200	L1000	L1000
In	5	5	L2	L130	L200
K	500	1000	100	--	--
La	G2000	--	G2000	5000	5000
Li	L1	L5	L2	L5	32000
Mg	50	20	200	30	20
Mn	200	200	200	50	30
Na	500	1000	50	500	500
Ni	1000	400	1000	500	320
P	1000	G1000	100	--	--
Pb	50	500	20	L200	L320
Sb	100	500	L50	--	--
Si	50	50	L50	--	--
Sn	5	50	5	--	--
Sr	L4	--	L4	L8	L10
V	L200	L200	L200	--	--
Zn	L100	200	L100	L500	L800
Tl	L100	--	L100	L300	L500

L Less than G More than

BIBLIOGRAPHY

I. Hanford Reports

A. Facilities and Operating Procedures

"Outline of Proposed Experiments - P-11 Project", by F. E. Kruesi
HW-14049, August 2, 1949.

"Outline of Proposed Experiments - P-11 Project Supplement A", by F. E. Kruesi
HW-17291, March 22, 1950.

"Improvements in P-11 Facilities and Experimental Data Following Initial Experiments", by F. E. Kruesi
HW-18305, July 12, 1950.

B. Monthly Progress Reports

"100 Areas Technical Activities Report - Physics"
July 1949 through April 1952

C. Chemical Assistance

"The Separation of Lithium from Plutonium by Plutonium(IV) Peroxide Precipitations", by W. A. Reas
HW-20649, March 28, 1951.

"P-11 Analytical Work", by W. N. Carson, Jr.
HW-17984, June 2, 1950.

"Chemical Assistance for P-11", by P. F. Gast
HW-19567, November 24, 1950.

"Chemical Assistance Work for P-11", by W. A. Reas
HW-20224, February 7, 1951.

D. Radiation Hazards and Nuclear Safety

"Radiation and Explosion Hazards in Critical Mass Experiments", by W. J. Ozeroff
HW-15279, December 2, 1949.

"Comments on Nuclear Safety of the Proposed P-11 Project", Beck, et al.

GEH-16,427.

"Summary of Discussion between H. Hurwitz and T. M. Snyder on the Hanford Critical Experiment", by H. Hurwitz.

GEH-16,396

E. Experimental Results

"Summary of P-11 Results", by P. F. Gast

HW-18791, Septembet 11, 1950.

F. Calculations

"P-11 Calculations for the Million, Part I", by G. M. Muller

HW-13881, July 11, 1949.

II. K-25 Critical Mass Studies for Hanford

"Feasibility Study of Uranium Studies for Obtaining Data Needed in Hanford Operations", by Beck, et al.

K-320, April 19, 1949.

"Critical Mass Studies, Part V", by Callihan, et al.

K-643, June 30, 1950.

"Contamination of Uranium-235 with Boron", by P. F. Gast

HW-17079, March 3, 1950.

"Results of Critical Mass Studies for Hanford at K-25", by P. F. Gast

HW-19112, October 11, 1950.

"HW Criticality Experiments", by F. E. Kruesi

HW-14734, October 13, 1949.

"Hanford Criticality Experiments", by F. E. Kruesi

HW-17188, March 13, 1950.

III. Off-Site Reports

A. Uranium

"Critical Mass Studies - Part III", Beck, et al.
K-343, April 19, 1949.

B. Plutonium

"Critical Mass of a Water Tamped 49 Solution", by Feld and Slotin
LA-272, May 14, 1945.

IV. P-11 Master Drawing List H-7-621.