CRITICALITY HANDBOOK

Volume I

June 30, 1968

R. D. Carter
G. R. Kiel
K. R. Ridgway

Advance Process Development Section
Research and Development Department
Chemical Processing Division

Atlantic Richfield Hanford Company
Richland, Washington 99352

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GENERAL CONTENTS

PREFACE

This Handbook was produced primarily to aid Atlantic Richfield Hanford Company employees whose work involves criticality safety considerations. Use of this book is not intended to replace final analysis of problems by a qualified criticality safety specialist, but it should permit greater freedom in preliminary studies.

The mere existence of a fissile material in quantities greater than a minimum critical mass creates some finite risk that criticality will occur. This risk of criticality can be held to an acceptably low probability by imposing restrictions on the manner in which the fissile material is processed, transported, and stored. This Handbook provides guidance in such areas for the process engineer or designer in the initial steps of equipment and process design or modification prior to review by a criticality safety specialist. In addition, the Handbook combines a number of fissile material handling requirements into a single reference manual and supplements more widely recognized reference works.

Because the increasing amount of experimental data permits (and sometimes demands) periodic revision of criticality parameters and because those of us in criticality safety work sometimes have peculiar ideas about what constitutes an applicable, useful or safe set of data for our own peculiar problems, we have designed the Handbook in a loose-leaf form. Thus, pages can be updated, new material added or sections rearranged to the desire of the user.

Some of the data included here is less conservative than material from TID-7016 and TID-7028, the normally accepted general references on criticality parameters. This is primarily due to a greater amount of available experimental data and to greater confidence in the computer programs presently used in criticality calculations. The computer codes used are generally indicated with each set of data. Those used within the Atlantic Richfield Hanford Company are currently:

For cross section generation and reactivity calculations	GAMTEC II HAMMER
For critical size and reactivity calculations, one and two dimensions	HFN HAMMER DTF-IV EXTERMINATOR-2 DOT ANISN
For reactivity calculations of single units and arrays in three dimensions	GEM 4 KENO

No attempt has been made initially to generate "safe" parameters. Wherever generated parameters are considered to have a potential for being nonconservative, comparisons with existing experimental data (if any) are shown or referenced, and an attempt is made to indicate the degree to which the data is nonconservative.

The proper use of the enclosed information requires a basic understanding of criticality. Improper use of this information can result in a criticality incident with the possible loss of life and many lost man-hours during recovery.

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I. ADMINISTRATION

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A. INTRODUCTION

The administrative portion of this book is specific for the Atlantic Richfield Hanford Company (ARHCO), but others may find it useful and instructive. The policies and procedures for imposing restrictions on the processing, transporting, and storage of fissile materials within ARHCO are summarized here. This material covers lines of responsibility, criticality prevention criteria and emergency conditions much of which has been extracted from ARHCO Policy Guides, Operating Instructions, and Technical Criteria.

B. POLICY

The management policy of the Atlantic Richfield Hanford Company (ARHCO) regarding criticality prevention in facilities designed to process,transport,and store fissile materials is defined in a series of policy guides and operating instructions that delineates policy, responsible personnel and the appropriate authority necessary to assure compliance with the policy. The policy for criticality prevention is that, in all of its activities involving fissionable materials, ARHCO shall exercise control such that the probability of a criticality incident is held at the lowest practical level. Where practicable, the design of manufacturing and laboratory facilities and equipment handling fissionable materials will include geometric limitations to minimize the probability of a criticality incident. In addition, there will be a criticality prevention system based on written specifications and implemented by written administrative procedures. The specifications will establish limits so that no single credible equipment failure or human error can cause a criticality incident. The written specifications will define limits in practical and administratively controllable terms. Appropriate personnel training and enforcement assure understanding of the specifications and appropriate use of the administrative procedures. Table B.1 shows the responsibilities and relationships for criticality control and Figure B.1 shows the path for criticality prevention specification development approval and auditing within ARHCO.

TABLE B.1

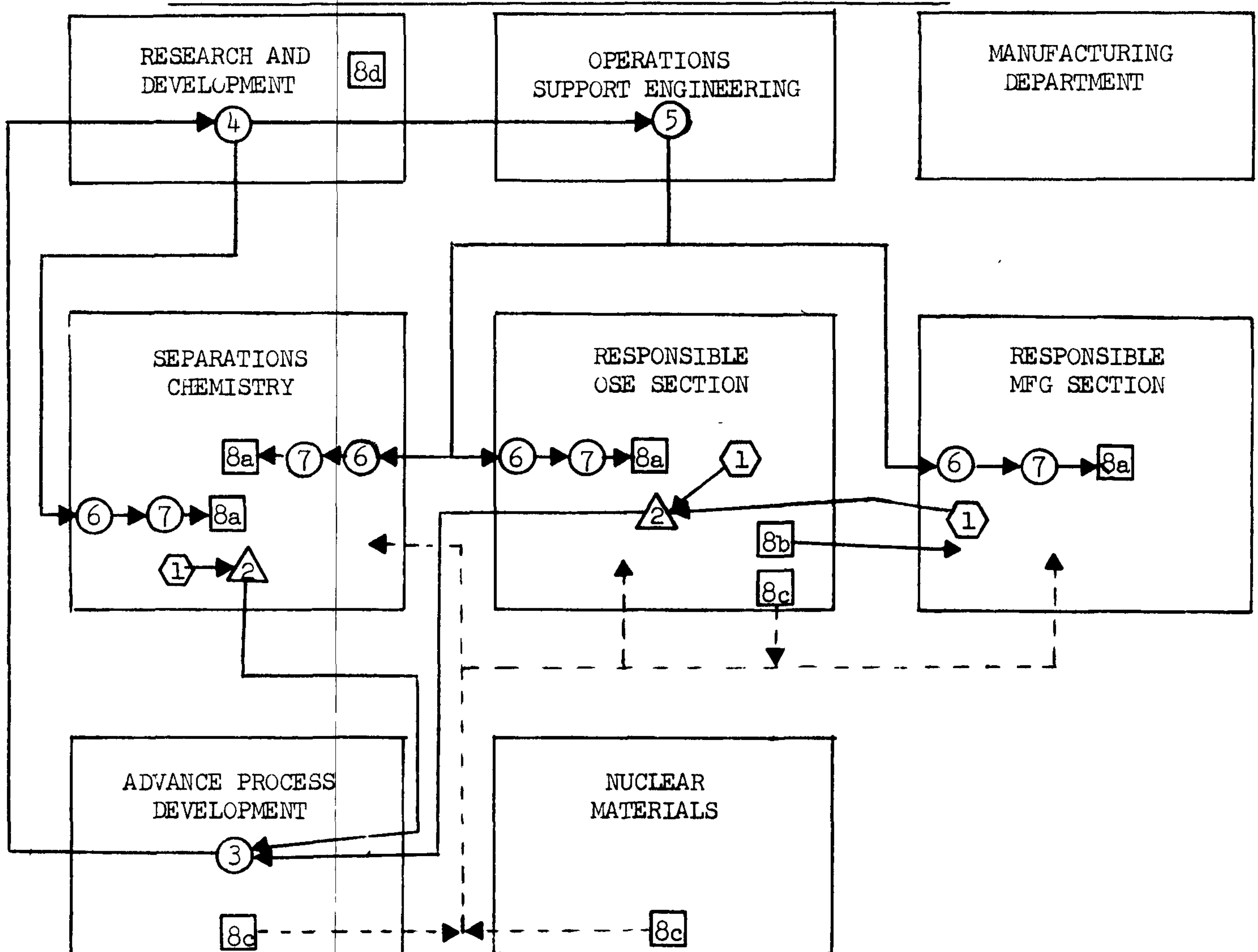
CRITICALITY CONTROL RESPONSIBILITIES

Control Mechanisms	Initiate[1]	Approve	Implement	Advise
Technical Criteria	R&D	Vice President-Operations		External Experts
Design Review	FE	R&D	Plant	R&D
Hazards Review	Plant, OSE FE, R&D		Plant, FE, OSE	R&D, FE
Operating Specifications	R&D, OSE, FE	R&D, OSE	Plant	External Experts
Quarterly Audits	OSE		OSE, R&D	
Annual Review and Audit	R&D		External Experts	
Personnel Training	Each Component	Each Component	Each Component	R&D, FE, OSE
Emergency Plans	Plant	Plant	Plant	R&D, FE, OSE
Facility Changes	Plant, OSE, R&D, FE	OSE, FE	Plant	R&D, OSE

[1] R&D = Research and Development Department
OSE = Operations Support Engineering Department
FE = Facilities Engineering Department
Plant = Any of the operating facilities.

FIGURE B.1

PATH FOR CRITICALITY PREVENTION SPECIFICATIONS



1 - Need for Criticality Prevention Specifications (CPS) is identified.
2 - CPS is formulated, drafted, reviewed, and signed by issuer.
3 - Reviewed for technical content by Senior Engineer Criticality Prevention.
4 - Approved by Manager of Research and Development.
5 - Approved by Manager of Operations Support Engineering.
6 - Accepted by Manufacturing Section, Separations Chemistry Laboratory, or Pu Process Engineering.
7 - Administered by the responsible Section or Laboratory.
8 - (a) Continual self audit by responsible Section or Laboratory.
(b) Continual audit by responsible OSE Section.
(c) Quarterly formal audit by representatives from Nuclear Materials, APD and OSE.
(d) Annual audit of Chemical Processing Division by external experts.

NOTE: Criticality Prevention Specifications applicable to the Facilities Engineering activities follow a route analogous to that outlined for the Separations Chemistry Laboratory. Operations Support Engineering is involved only in the quarterly audit function.

C. TECHNICAL CRITERIA FOR THE PREVENTION OF CRITICALITY [1]

1. INTRODUCTION

Atlantic Richfield Hanford Company (ARHCO) Policy Guide 1.6.6, "Criticality Prevention," and Operating Instruction 1.6.6.2, "Criticality Prevention in Process Facilities," present the policy of the Chemical Processing Division with respect to the control of criticality hazards, and delegate the responsibility for specifying safe limits for the design and operation of process facilities to the Manager, Research and Development Department. The purpose of this document is to define the technical criteria to be used in developing the limits within which CPD facilities are to be designed and operated. These criteria are based on the operating experience accumulated from the processing of fissile materials since the year 1944.

The mere existence of a fissile material in quantities greater than a minimum critical mass creates some finite risk that criticality will occur. This risk of criticality can be held to a very low value by imposing restrictions on the manner in which the fissile material is stored or handled. Such controls are to be imposed as needed.

2. POLICY

In all of its activities involving fissile materials, ARHCO shall exercise control such that the probability of a criticality incident is held at the lowest practical level.

3. SPECIFICATIONS

ARHCO Policy Guide 1.6.6 and Operating Instruction 1.6.6.2 require that criticality prevention specifications define the limits within which operating or experimental work may be performed; before issuance, these specifications must be reviewed for technical adequacy by a specialist in criticality calculations and approved by the Manager, Research and Development.

(1) R. E. Tomlinson, "Technical Criteria for the Prevention of Criticality, Chemical Processing Division, ARH-468 REV, April 1971.

3.1 Materials to be Covered

All fissile materials shall be controlled by specifications unless specifically exempted below. Fissile materials are those nuclides capable of sustaining a nuclear chain reaction. Known fissile nuclides are: ^{233}U, ^{235}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Am, ^{243}Am, ^{244}Cm, ^{247}Cm, ^{244}Cf, and ^{251}Cf.

The following materials are exempt from need for specifications:

- Natural and depleted uranium.
- Fifteen grams of ^{241}Am or any fissile nuclide with atomic number <95.
- Two grams of any fissile nuclide with atomic number ≥ 95.
- Uranium solutions, compounds and metal, if not latticed, enriched to ≤ 1.0 percent ^{235}U or its nuclear equivalent.
- ^{237}Np, ^{238}Pu, ^{241}Am, and ^{244}Cm with H/X ≥ 5 in any amounts.

3.2 Assumptions

In formulating design and operating limits, the responsible process engineer shall consider all pertinent process conditions and failure possibilities. The worst foreseeable combination of fissile material density, diluent composition and distribution, reflection, interaction, and measurement uncertainty must be assumed. Some conditions may be assumed to be incredible if specifically excluded by technical or design considerations. For example, allowances may be made for neutron absorbers, i.e., nitrogen, boron, uranium-238, etc., that will be associated with the fissile material, provided the presence of the absorber can be satisfactorily assured by technical factors or operational control. The use of the assumed conditions by the criticality specialist in reviewing the problem implies his consideration and acceptance of them.

3.3 Technical Review

For specifications that are clearly referable to nationally recognized criticality prevention data, the technical review may be based on agreement between the specification and the data. For specifications based on calculations that cannot be checked by simple reference to recognized data, the review shall be made using two independent calculational methods or a specialist other than the one making the original review will check the calculations.

3.4 Experimental Basis

The specified limits shall be derived from experimental data whenever possible. In the absence of directly applicable experimental measurements, the limits may be based on theoretical calculations, provided the validity of the calculational method has been proven by correlation with experimental data. Attempts shall be made to assign limits of error to both experimental and calculational results.

3.5 Safety Factors

Safety factors must be included in all limits and shall be appropriate for the degree of risk involved. Minimum safety factors may be used when the specified limits are directly referable to experimentally verified values, when operations and design limits can be held within the specified limits with a high degree of confidence, and when an accidental nuclear reaction would produce a minimum of risk to operating personnel or production continuity and no hazard to the public.

The k_{eff} to be used as permissible upper limits for the worst foreseeable conditions is defined below for three levels of confidence in the accuracy of the calculated k_{eff} value:

a. If reliable experimental data exist for closely similar systems and adequate calculational techniques exist for relatively small extrapolation of the data, the k_{eff} of spheres and cylinders shall not exceed 0.98 and the k_{eff} of slabs shall not exceed 0.97.

b. If limited experimental data exist for a similar system and relatively large but reasonable extrapolations are necessary, the calculated k_{eff} of the system shall not exceed 0.95.

c. If no applicable experimental data are available such that calculations must be based on theory derived from experimental data, the calculated k_{eff} of the system shall not exceed 0.90.

Increased safety factors should be used in some conditions as noted below.

3.5.1 Probability of Error

Safety factors shall be proportionate to the probability that the specified criticality prevention limits will be exceeded. For example, it is possible to specify the exclusion of water or equipment dimensions with a high degree of confidence. On the other hand, a possible operating error has a finite probability of being committed at some time in the future.

3.5.2 Risk to Personnel

Sizable and multiple safety factors are desirable when personnel are to be located in the proximity of fissile materials; conversely, when a massive shield is interposed between the fissile material and personnel, a somewhat higher risk of criticality can be tolerated. In this context, a massive shield is defined as at least two feet of ordinary concrete or its attenuation equivalent for the neutrons and gamma rays emitted during a nuclear excursion; the shield and other containment barriers should have sufficient mechanical strength to confine any materials dispersed by the potential reaction.

3.6 Allowance for Emergencies

Recognizing that gross contamination of the environment would create a greater cumulative hazard than would be created by nuclear criticality, the specifications may permit actions involving an increased risk of criticality if necessary to protect a facility from incipient loss of confinement barriers by fire or explosion.[1]

4. SAFETY MECHANISM LIMITS

The several mechanisms whereby criticality may be prevented are listed below in decreasing order of safety assurance. The decision as to which mechanism, or combination of mechanisms, is to be used in a given situation shall represent a balanced judgment, considering the possibility for failure of each mechanism, the degree of risk to personnel or production continuity, and the cost of implementation.

In specifying limits on dimensions, concentrations, or masses, all credible conditions must be considered.

4.1 Geometrically Safe Equipment

Geometrically safe equipment is subcritical by virtue of neutron leakage under all possible conditions of inventory and reflection. To be "geometrically safe" the diameter of a cylinder shall be specified as no more than 2.8 inches, 1.8 inches, or 1.7 inches for handling uranium-235, uranium-233, or plutonium, respectively; similarly, the thickness of a slab shall be

[1]ARHCO Operating Instruction 1.6.6.3, "Criticality Prevention in Fire Fighting," 1971.

specified as no more than 0.5 inch, 0.2 inch, or 0.25 inch, respectively.

These limits are so restrictive that large-scale processing of fissile materials in "safe" equipment would be prohibitively expensive.

4.2 Geometrically Favorable Equipment

Geometrically favorable equipment is subcritical, by virtue of neutron leakage, under the worst foreseeable process conditions. The absence of water flooding or sufficient inventory to sustain a fast neutron reaction may be assumed if these conditions can be maintained with minimal administrative control; such assumptions, if made, must be recorded as a precluded condition in the criticality prevention specification applicable to that facility. The reliance on one dimension of a vessel controlling the reactivity parameters requires that all other dimensions of the vessels either be physically limited by available space or be included in the calculations as infinite dimensions.

The following values are permissible upper limits under the worst foreseeable process conditions, assuming directly applicable criticality data or standards and normal failure potential. If greater uncertainty exists in either the technical basis for the specification or the assurance of control, proportionately greater safety factors as specified in section 3.5 b and c shall be used.

4.2.1 Cylinders

To be "geometrically favorable" the diameter of a cylinder is limited to a maximum value which corresponds to a k_{eff} no greater than 0.98 or to 95 percent of the critical diameter.

4.2.2 Slabs

To be "geometrically favorable" the thickness (the smallest dimension) of a slab is limited to a value which corresponds to a k_{eff} no greater than

0.97 or to 90 percent of the critical slab thickness.

4.2.3 Irregular Shapes

For vessels of unspecified or irregular shape, the permitted volume is no more than 75 percent of the minimum volume that would be critical at optimum concentration.

4.3 Fixed Poisons

When "fixed poisons" are used to prevent nuclear criticality, the equipment must be so constructed that neutron absorbers in the structure prevent criticality under all foreseeable process conditions. Fixed poisons are normally used in a vessel in such a manner as to permit an increase in the size of a critically favorable vessel, the allowable fissile mass, the allowable fissile concentration, or some combination of the three. Periodic inspections shall be specified, as required by the "fixed-poison removal potential of the system," to verify the quantity and location of the poison in the structure. In no case shall inspection intervals exceed one year.

4.4 Nuclear Blanks

A nuclear blank consists of a physically removed section of a process line. Nuclear blanks are used in lines from flushing or utility chemical headers to process equipment when the inadvertent addition of a chemical could cause criticality, such as by precipitation.

4.5 Administrative Controls

When it is not practical to prevent criticality by using favorable geometries or fixed poisons, reliance must be placed either on limitations of mass or concentration, or on the presence of soluble poisons. The process conditions so controlled by operating personnel shall be limited to insure that neutron loss by leakage or absorption will prevent criticality even though any single credible error or omission has been committed. Instruments and/or mechanical devices are provided to assist operating personnel to measure and control the process conditions within prescribed limits.

The following values are permissible upper limits for each mechanism of control, assuming directly applicable criticality data or standards and normal failure potentials. If greater uncertainty exists in either the technical basis for the specification or the assurance of control, proportionately larger safety factors shall be used.

4.5.1 Control by Mass Limits

The quantity of fissile material in a given location is to be limited to an amount less than half that required to sustain a nuclear reaction under any credible conditions of geometry, moderation, and reflection. A double batched condition shall not result in a k_{eff} higher than the applicable limit in Section 3.5 under the worst foreseeable conditions.

In continuous processing systems located behind massive shielding, the quantity of fissile material in a vessel is limited to a maximum of 75 percent of the mass required to cause a criticality in that vessel under the worst credible condition; the k_{eff} of the system under this condition must be within the appropriate limits of 3.5 above. If the continuous processing system is located in an area normally occupied by personnel, the mass in a vessel is limited to less than 50 percent of the mass required for criticality under the worst credible conditions in that vessel.

4.5.2 Control by Concentration Limits - Solutions

The concentration of fissile material dissolved or dispersed in another medium is to be limited such that neutron absorption in the diluent prevents criticality.

The permitted concentration of fissile materials in solution shall not be greater than 50 percent of the minimum critical concentration in that vessel; if the vessel is behind a massive shield, the permitted concentration may be 75 percent of the minimum critical concentration. In neither case shall the k_{eff} at the allowable concentration exceed the applicable value listed in 3.5. In addition, there shall be specified for the vessel a mass limit such that the k_{eff} of the system shall not exceed the applicable value listed in 3.5 under the worst conditions attainable by the inadvertent concentration of the fissile material, as by precipitation, evaporation, etc.

4.5.3 Control by Concentration Limits - Arrays

The dispersal in space of discrete accumulations of fissile materials is controlled with respect to geometry and distance such that the nuclear reactivity of any single subcritical unit is not significantly increased by the mutual exchange of neutrons (interaction) with adjacent units. For a planar or three-dimensional array, the permitted array shall either have a k_{eff} no greater than the applicable value listed in 3.5 for the worst foreseeable conditions or shall be limited in number of units to one-half that calculated to be a critical reflected array. Double batching of a single unit in the array must not exceed the designated k_{eff}.

4.5.4 Control by Soluble Poisons

Neutron absorbing materials are to be in solution with the fissile materials in sufficient concentration to prevent criticality under all foreseeable process conditions. If reliance is placed on the presence of a soluble nonprocess neutron absorber to avoid criticality, the minimum poison concentration shall be specified such that the k_{eff} of the system shall not exceed the applicable value listed in 3.5 for the worst foreseeable conditions. The term "worst foreseeable conditions" must include consideration of mechanisms that might change the poison (absorber) concentration, as well as potential changes in fissile atom concentrations.

Soluble poisons shall not be used as the primary means of precluding criticality unless the system is behind a massive shield. Soluble poisons may be used in unshielded systems as a secondary control to be operative in the event that the primary control mechanism is voided.

5. FIRE FIGHTING

In areas containing fissile materials, the requirements of ARHCO Operating Instruction, 1.6.6.3, "Criticality Prevention in Fire Fighting," shall be considered in all criticality prevention requirements. For example, when specific fire fighting systems (such as automatic sprinkler systems or fire fog) are allowed, the system shall be limited by design such that the addition of the fire fighting media will not permit criticality via increased moderation, reflection, dilution, etc.

D. AUDITS

One of the most important aspects of safety is the auditing function which determines the compliance of the equipment designs and administrative procedures with established criticality prevention criteria. Experience has shown that the auditing function should be started near the beginning of a design project and be carried on during subsequent normal operation as a routine event.

1. Design Review

A criticality review of the scope design of each piece of equipment and of the overall facility is necessary at the very beginning of a new project to establish the safety parameters and guidelines for future detailed design. Using the scope design review as a guide, the detailed design should be reviewed as often as necessary to assure that each individual piece of equipment is subcritical in the worst foreseeable process condition. At the completion of the design phase, a hazards review (including all elements of safety, as well as criticality) should be conducted. The depth of the review depends on the complexity of the piece of equipment or new facility. A final hazards review in depth should be made just prior to the start-up of a new facility and may form the basis for a safety analysis report.

2. Criticality Prevention Specification

Coincidental with the final hazards review (or slightly before) the criticality prevention specifications are prepared by the responsible department using the technical criteria as a basis. The acceptance of these specifications by the plant operations manager implies that adequate administrative procedures can be formulated and enforced and that these procedures are auditable. These specifications may be modified at any time, but the modification requires the same signatory approval as the original specification.

Subsequent day-to-day audits by the operational personnel, quarterly audits by Operational Support Engineering and Research and Development personnel, and annual audits by external criticality specialists form a sound basis for criticality control. The reports of these audit groups give a measurement of the adequacy of criticality prevention throughout Atlantic Richfield Hanford Company (ARHCO).

3. Facilities Change Notice

The operation of any plant requires modification and/or equipment replacements on a day-to-day basis. Hazards control in major projects is handled via scope reviews, criticality prevention specifications, etc., as defined above. A small equipment modification or a series of small modifications, however, could result in a loss of control and could end in a criticality incident. To assure adequate and continuous control of criticality, a facilities change notice is employed to describe any planned physical changes to plant or equipment. The notice once initiated by a responsible person is submitted to the Operations Support Engineering group for review for potential chemical or criticality hazards. When appropriate, nuclear safety experts are requested to review the change. All changes involving equipment handling fissile materials must be reviewed prior to making the physical change.

If the facility change is considered to affect criticality safety adversely, a hazards review is made.

E. TRAINING AND EMERGENCY

1. Training and Alarm Systems

At Atlantic Richfield Hanford Company (ARHCO), each section manager is responsible for providing training programs for his employees as required to effectively discharge his criticality safety responsibilities. The overall training program consists of a series of general lectures and familiarization with the type and use of plant equipment, nuclear physics, criticality prevention, and emergency procedures. Chemical Processing Division employees concerned with the manipulation of fissile materials are trained by their supervisors. Two chapters of the Chemical Operator Training Manual, ARH-35, are concerned with emergency procedures and nuclear safety. All chemical operators are required to complete a formal training program and checklists are maintained to show individual progress.

Each plant manager is responsible for the maintenance of a criticality alarm system and building personnel evacuation procedures. The safety of building visitors is specifically included in the procedures. Part of the employee training program includes the testing of these evacuation alarms and procedures at sufficient intervals to be sure that all building personnel are trained to respond satisfactorily to the criticality alarm.

F. CRITICALITY PREVENTION IN FIRE FIGHTING

The first three minutes of a fire's existence is the most effective time to fight it. Prompt action should be taken to apply an extinguishing agent or to isolate the burning material. Since water is the most efficient general purpose agent for fighting fires, its early use in an approved manner is encouraged. Automatic detection and extinguishing systems are generally recommended to facilitate early and effective control of fires.

In areas containing fissile materials, the use of water is limited as outlined below to keep the risk of nuclear criticality at an acceptably low level. However, the consequences of releasing alpha-radioactive materials to the environment would probably exceed the consequences of a nuclear criticality. The senior fire officer is therefore authorized to use whatever methods he judges to be necessary to preserve the integrity of building structures.

Chemical processing facilities (or areas within facilities) are categorized and posted to denote the fire fighting agents that can be used safely. The classification and posting methods used by Atlantic Richfield Hanford Company (ARHCO) are consistent with those currently in use by other Hanford contractors.

1. Definitions

The risk that a criticality could be caused by adding water to chemical processing facilities varies from zero to high, depending on the quantity, form and packaging of the fissile materials present. For fire fighting purposes, chemical processing facilities have been divided into four categories, depending upon the criticality risks involved, as follows:

Category	Probability of Criticality if Water is Added
A	Zero. The addition of water to the facility cannot cause criticality because the quantities of fissile materials present are too small.

B Minimal. The likelihood of criticality resulting from fighting a fire with water is very small. While fissile materials are normally present in quantities exceeding a minimum critical mass, the fissile materials are in a form, in packaging, or so stored that criticality is practically impossible.

C Finite. Under some foreseeable conditions, the addition of water could cause criticality. This category embraces two types of areas:

1. Those process areas in which fissile materials are normally present in quantities exceeding a minimum critical mass; the fissile materials are normally held in such a manner that the addition of water would not cause criticality.

2. The personnel working areas immediately surrounding Category D facilities.

D High. Fissile materials are normally present in a configuration that could be made critical by the addition of water, or the configuration is very likely to be changed by fire such that the addition of water could cause criticality.

2. Designation of Areas

Each Criticality Prevention Specification has a Fire Fighting Section in which the fire fighting categories assigned to the facilities covered will be specified along with any special fire fighting restrictions or precautions. The assigned categories are subject to change with changing process or equipment. All plant areas not specifically mentioned in Criticality Prevention Specifications are in Category A.

To provide immediate fire fighting guidance, all areas (except Category A) are posted with an appropriate noncombustible sign denoting the fire fighting category for that area. The signs should be mounted 1/8 inch from the surface to which they are attached and positioned in the center of and immediately above the entrance to each categorized area. Usually this will be on the face of the door frame. Where the height of the door exceeds seven feet, the sign will be posted at a height of six feet on the frame opposite the door hinges. Each sign will be lettered in black, in the shapes and colors indicated below. "Scotch Lite" reflective colors are recommended.

CATEGORY A: No posting.

CATEGORY B: Diamond shape with a fluorescent green background showing the letter "B". Areas excluded from posting requirements are B Plant process cells, underground waste tanks, vaults, and cribs.

CATEGORY C: An equilateral triangle with a fluorescent red background showing the letter "C" is used to denote rooms or areas. A square sign with the notation "C HOODS" on a fluorescent orange background is used to denote glove boxes or other enclosures within a room.

CATEGORY D: A round sign with a fluorescent blue background showing the letter "D" is used to denote rooms or areas. A rectangular sign with the notation "D HOODS" on a fluorescent yellow background is used to denote glove boxes, refrigerators or other enclosures within a room.

3. Fire Fighting Precautions

The approved methods of fire fighting in each category are listed below. There are no restrictions in any of the categories for the use of dry chemicals, CO_2, Freon-1301, high expansion foam, and inert gases providing the methods do not displace or rearrange the fissile materials. Restrictions on the use of water as defined below and in Table F.1 are observed unless authorization from the attendant building management is obtained at the time of emergency. However, every effort is made to prevent a breach of the building confinement. When in the opinion of the senior fire officer, there is imminent danger of loss of control, he is allowed to fight the fire at his discretion after considering all circumstances.

Category A Areas

No special criticality precautions are taken in fighting fires in Category A areas. Automatic fire fighting systems of any approved type may be installed, and water may be used in any quantity or form.

Category B Areas

No special criticality precautions are taken by fire fighters in Category B areas. Automatic fire fighting systems of any approved type may be installed. While water may be used in any quantity or form, the use of high expansion foam or water fog is preferred over a stream of water to minimize the probability of relocating fissile materials into a critical array. Operating personnel are to be alert to the possibility that fissile materials could be pushed together as a result of the fire or fire fighting efforts (e.g., collapsing structures, gushing water, etc.) thereby significantly increasing the risk of criticality.

Category C Areas

Plans for the use of water to fight fires in Category C areas are incorporated into the Criticality Prevention Specifications applicable to the facility involved and may include dry chemicals, water fog, high expansion foam or automatic sprinkler systems. Automatic fire fighting systems which use limited amounts of water may be recommended. Fire fighters should not direct a solid stream of water at process equipment or floor areas in the vicinity without prior clearance from the attendant building management or in his absence, the senior fire officer.

Fire fighters should be alerted to the possibility that fissile materials in the hoods may have been or may be rearranged from their normal position into a more reactive configuration. If possible, an assessment of the additional risk of criticality should be made, preferably by operational personnel before the fire fighting methods other than those permitted above are used.

Situations which potentially present a hazard include the following:

a. The widespread accumulation of process solution or solids on the floor or in a sump to a depth of two inches or greater;

b. An accumulation of resin or other process solids in a mound more than four inches high;

c. Burning plutonium metal; or

d. Metallic plutonium if it has been deformed or displaced from its normal position.

Category D Areas

Directions for the use of water to fight fires in Category D areas is incorporated into the Criticality Prevention Specifications applicable to the area. Automatic fire fighting systems which use water are not permitted, and the inadvertent drainage of water into these areas is precluded by design. The use of water fog will be acceptable under conditions listed in the Criticality Prevention Specifications. Fire fighters should not use water in any other forms without prior clearance from the attendant building management or, in their absence, the senior fire officer. If the confinement barriers enclosing a Category D area are destroyed during a fire, a prudent decision must be made, after considering the immediate facts, as to what means of fire fighting will be required to minimize injury to personnel, uncontrolled contamination spread and damage to facilities.

4. Responsibilities

The processing, storing or transporting of fissile materials within chemical processing facilities is controlled by Criticality Prevention Specifications. All chemical processing areas containing fissile material are categorized for fire fighting and the category listed in the Criticality Prevention Specification.

In addition, the following specific responsibilities are assigned to each Operations Division Department Manager with respect to those areas under his functional control:

a. Implementing the fire fighting restrictions covered in this Operating Instruction.

b. Posting the facilities under his jurisdiction and keeping the posting current.

c. Providing procedures and training for fire fighting.

d. Keeping the Fire Protection Section informed as to the categories currently assigned to the various work areas.

TABLE F.1

RECOMMENDED FIRE-FIGHTING CONTROLS DEFINED BY CATEGORIES

	Category A	Category B	Category C	Category D
I. Nuclear Considerations				
Fissile material present, relative to minimum critical mass	Less than	More than	More than	More than
Normal basis for avoiding criticality	Limited total mass	Dilution, or limited mass per ft^3	Specified geometry and/or limited mass per ft^3	Specified geometry and/or limited mass per ft^3, plus absence of H_2O
II. Installed Fire-Fighting Systems				
Deluge Type	Permitted	Discouraged	Excluded	Excluded
Sprinkler or Water Fog				
Automatic operation	Permitted	Permitted	Permitted	Excluded
Manual operation	Permitted	Permitted	Permitted	Selective(1)
High-Expansion Foam				
Automatic operation	Permitted	Permitted	Permitted	Permitted
Manual operation	Permitted	Permitted	Permitted	Permitted
III. Recommended Controls on Activities of Firemen				
Advice needed from operations on use of water	None	May be volunteered	Selective(1)	Recommended
Use of Aqueous Fire-Fighting Agents				
Solid stream of water	Permitted	Discouraged	Excluded	Excluded
Water fog	Permitted	Permitted	Permitted	Selective(1)
High-expansion foam	Permitted	Permitted	Permitted	Permitted

(1) As permitted in Criticality Prevention Specifications.

UNCLASSIFIED

G. PACKAGING OF FISSILE MATERIALS AND ON-SITE TRANSPORTATION

Atlantic Richfield Hanford Company (ARHCO) complies with all applicable Department of Transportation and Atomic Energy Commission (AEC) Regulations for packaging radioactive materials for off-site transportation. International shipments will also comply with all applicable IAEA Regulations. Responsibility and accountability for the package and its contents transfers to the AEC at the Company's dock. For on-site shipments the package and method of transportation must also comply with AEC Regulations. Only approved off-site and on-site shipping and storage containers are used. See Sections II.F.3, 4, 5, and 6 for approved containers and allowed array sizes.

1. Fissile materials are those nuclides capable of sustaining a nuclear chain reaction. However, for criticality safety it is not necessary to consider as fissile those fissile nuclides which, under any conceivable conditions, could not possibly be accumulated in sufficient amount, or in the proper form, to exceed a safe mass. Nuclides currently considered fissile are: ^{233}U, ^{235}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Am, ^{243}Am, ^{244}Cm, ^{247}Cm, ^{244}Cf, and ^{251}Cf. Natural and depleted uranium are not considered fissile materials. See DOT Regulations for other exemptions.

2. Fissile radioactive material packages are classified according to the controls needed to provide nuclear criticality safety during transportation as follows:

   a. Fissile Class I packages may be transported in unlimited numbers, in any arrangement, and require no nuclear criticality safety array controls during transportation. A transport index is not assigned to Fissile Class I packages for purposes of nuclear criticality safety control. However, the external radiation levels may require assignment of a transport index.

   b. Fissile Class II packages may be transported together in any arrangement, but in numbers which do not exceed an aggregate transport index of 50. For purposes of nuclear criticality prevention, the transport index of an individual package shall not be less than 0.1 nor more than 10 and shall be the higher of the two values required by either external radiation levels or criticality prevention. Such shipment requires no nuclear criticality safety control by the shipper or carrier during transportation.

c. Fissile Class III shipments contain packages which do not qualify as Fissile Class I or II packages. Nuclear criticality prevention and radiation control during transportation are provided by special arrangement between the shipper and the carrier.

3. Miminum Critical Mass (MCM) is the smallest amount of fissile material of a specific type, physical form, and enrichment which is capable of sustaining a nuclear chain reaction under optimum conditions.

4. Criticality Safety and criticality prevention are used synonymously; the terms refer to the limits established to prevent nuclear chain reactions in a nonreactor environment.

5. Off-site Shipment is the movement of material from ARHCO facilities to any receiver other than the on-site Hanford contractors listed below:

   Atlantic Richfield Hanford Company

   Battelle Memorial Institute - Pacific Northwest Laboratory

   Douglas United Nuclear

   Hanford Environmental Health Foundation

   J. A. Jones Construction Company

   WADCO

6. International Shipment is the movement of material outside the continental boundaries of the United States.

7. Packager is the manager of the section which prepares or directs the preparation of a package for off-site shipment and transfers the package to AEC-RL for transport.

8. Shipper is the manager of the section which prepares or directs the preparation of a package and delivers it to an on-site Hanford contractor. Off-site shipments are made by the Richland Operations Office of the Atomic Energy Commission.

9. Transport Index means the number placed on a package to designate the degree of control to be exercised by the carrier during transport. The transport index for a package of radioactive material shall be determined by: (1) the highest radiation dose rate, in millirem per hour at three feet from any accessible

external surface of the package; or (2) for Fissile Class II Packages only, the number calculated by dividing the number "50" by the number of similar packages which may be transported together.

10. Packaging, Posting, and Transporting Procedures are prepared for the first shipment of a series of shipments, or for a one-of-a-kind type shipment. Ensuing packaging routinely follows this established procedure until it is modified. The manager of the responsible section must determine, with the aid of supporting engineering groups, that the package posting and transportation meets all the applicable Federal Regulations as well as ARHCO Criticality Prevention Specifications.

II. ENGINEERING DATA

A. USEFUL TABLES AND CONSTANTS

B. BUCKLING AND OTHER NUCLEAR PARAMETERS

C. PLUTONIUM PHYSICAL PROPERTIES

D. URANIUM PHYSICAL PROPERTIES

E. REFLECTOR SAVINGS AND EXTRAPOLATION DISTANCES

F. MISCELLANEOUS

FUNDAMENTAL CONSTANTS

Name			Value
Avogadro's Number (Physical Scale)	N_o	=	6.0249×10^{23} molecules/gm mole (physical scale)
Base of Natural Logarithms	e	=	2.7183 . . .
Curie	c	=	3.7×10^{10} dis/sec
Gravitational Acceleration	g	=	980.7 cm/sec^2
Mass Unit, Atomic	amu	=	1.65979×10^{-24} gms = 1.0000 amu
Planck's Constant	h	=	6.625×10^{-27} erg-sec
Pi	π	=	3.1416 . . .
Stefan-Boltzmann Constant	k	=	5.67×10^{-5} erg/cm^2-deg^4-sec
		=	1.380×10^{-16} erg/degree
Universal Gas Constant	R	=	0.08206 liter-atm/gm-mole/^{o}K
Velocity of Light	c	=	2.998×10^{10} or 3×10^{10} cm/sec
Wave-Length Associated with 1 ev	λ_o	=	12397.67 Angstroms
First Zero of the Zero Order Bessel Function of the First Kind	J_o	=	2.40482 . . .

USEFUL VARIATIONS ON FUNDAMENTAL CONSTANTS

π^2	=	9.8696
π^3	=	31.006
J_o^2	=	5.7831
e^2	=	7.3890
e^3	=	20.085

LENGTH

Length	m	yd.	ft.	in.	cm	mm
1 meter	1	1.0936	3.28	39.37	100	1000
1 yard	0.9144	1	3	36	91.44	914.4
1 foot	0.3048	0.3333	1	12	30.48	304.8
1 inch	.0254	.0278	.0833	1	2.54	25.4
1 centimeter	.01	.0109	.0328	0.3937	1	10
1 milimeter	.001	.00109	.00328	.03937	0.1	1

AREA

Area	ft^2	in^2	cm^2
square foot	1	144	929.03
square inches	.00694	1	6.4516
square centimeters	.001076	0.155	1

VOLUME

Volume	ft^3	gal.	l	in^3	cm^3
cubic foot	1	7.481	28.32	1,728.	28,317.
gallons	0.1337	1	3.7853	231.	3785.4
liters	.0353	0.2642	1	61.025	1000
cubic inches	.00058	.00433	.0164	1	16.387
cubic centimeters	.0000353	.000264	.001	.061	1

MASS

Mass	kg	lb.	g
kilograms	1	2.204	1000
pounds	0.4536	1	453.59
grams	.001	.0022	1

DENSITY

Density	lbs/ft^3	lbs/gal	g/l	g/cm^3
pounds per cubic foot	1	0.1337	16.02	.01602
pounds per gallon	7.481	1	119.83	0.11983
grams per liter	.05805	.00776	1	.001
grams per cubic centimeter	62.43	8.3452	1000	1

ENERGY

Energy	Kw hr	Btu	ft lb	cal	Mev
1 Kw hr	1	3412	2.66×10^6	8.60×10^5	2.24×10^{19}
1 Btu	2.93×10^{-4}	1	778.1	252	6.58×10^{15}
1 ft lb	3.77×10^7	1.29×10^{-3}	1	0.324	8.46×10^{12}
1 cal	1.16×10^{-6}	3.97×10^{-3}	3.088	1	2.61×10^{13}
1 Mev	4.45×10^{-20}	1.52×10^{-16}	1.18×10^{-13}	3.83×10^{-14}	1

MASS ENERGY

Mass Energy	Mass Unit	Mev	Erg	Calorie
1 Mass Unit (mu)	1	931	1.49×10^{-3}	3.56×10^{-11}
1 Mev	1.07×10^{-3}	1	1.60×10^{-6}	3.82×10^{-14}
1 Erg	670	6.24×10^5	1	2.39×10^{-8}
1 Calorie	2.81×10^{10}	2.62×10^{13}	4.186×10^7	1

POWER

Power	Hp	Kw	Btu/hr	cal/sec	Mev/sec
1 Hp	1	0.7457	2544	178.1	4.65×10^{15}
1 Kw	1.341	1	3412	239	6.24×10^{15}
1 Btu/hr	3.93×10^{-4}	2.93×10^{-4}	1	0.070	1.82×10^{12}
1 cal/sec	5.61×10^{-3}	4.18×10^{-3}	14.29	1	2.61×10^{13}
1 Mev/sec	2.15×10^{-16}	1.60×10^{-16}	5.47×10^{-13}	3.83×10^{-14}	1

INCHES v. CENTIMETERS

Inches	cm	Inches	cm
1	2.54	21	53.34
2	5.08	22	55.88
3	7.62	23	58.42
4	10.16	24	60.96
5	12.70	25	63.50
6	15.24	26	66.04
7	17.78	27	68.58
8	20.32	28	71.12
9	22.86	29	73.66
10	25.40	30	76.20
11	27.94	31	78.74
12	30.48	32	81.28
13	33.02	33	83.82
14	35.56	34	86.36
15	38.10	35	88.90
16	40.64	36	91.44
17	43.18	37	93.98
18	45.72	38	96.52
19	48.26	39	99.06
20	50.80	40	101.60

FRACTIONS TO DECIMALS

To 4th Decimal

1/2	0.5	1/9	0.1111+	1/15	0.06667−
1/3	0.3333+	1/10	0.1	1/16	0.0625
1/4	0.25	1/11	0.09091−	1/17	0.05882+
1/5	0.2	1/12	0.08333+	1/18	0.05556−
1/6	0.1667−	1/13	0.07692+	1/19	0.05263+
1/8	0.125	1/14	0.07143−	1/20	0.05

Exact Values

1/64	.015625	11/32	.34375	21/32	.65625
1/32	.03125	23/64	.359375	43/64	.671875
3/64	.046875			11/16	.6875
1/16	.0625	3/8	.375	45/64	.703125
5/64	.078125	25/64	.390625	23/32	.71875
3/32	.09375	13/32	.40625	47/64	.734375
7/64	.109375	27/64	.421875	3/4	.75
		7/16	.4375	49/64	.765625
1/8	.125	29/64	.453125	25/32	.78125
9/64	.140625	15/32	.46875	51/64	.796875
5/32	.15625	31/64	.484375	13/16	.8125
11/64	.171875			53/64	.828125
3/16	.1875	1/2	.50	27/32	.84375
13/64	.203125	33/64	.515625	55/64	.859375
7/32	.21875	17/32	.53125		
15/64	.234375	35/64	.546875	7/8	.875
		9/16	.5625	57/64	.890625
1/4	.25	37/64	.578125	29/32	.90625
17/64	.265625	19/32	.59375	59/64	.921875
9/32	.28125	39/64	.609375	15/16	.9375
19/64	.296875			61/64	.953125
5/16	.3125	5/8	.625	31/32	.96875
21/64	.328125	41/64	.640625	63/64	.984375

UNITS

Factor by Which Unit is Multiplied	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

DIMENSIONS of Seamless and Welded STEEL PIPE

ASA-B36.10 and B36.19

NOMINAL PIPE SIZE	OUT-SIDE DIAM.	NOMINAL WALL THICKNESS FOR													
		SCHED. 5*	SCHED. 10*	SCHED. 20	SCHED. 30	STAND-ARD†	SCHED. 40	SCHED. 60	EXTRA STRONG§	SCHED. 80	SCHED. 100	SCHED. 120	SCHED. 140	SCHED. 160	XX STRONG
⅛	0.405	.....	*0.049*	.....	.....	*0.068*	0.068	.....	*0.095*	0.095	.....	.....	.....	.....	.....
¼	0.540	.....	*0.065*	.....	.....	*0.088*	0.088	.....	*0.119*	0.119	.....	.....	.....	.....	.....
⅜	0.675	.....	*0.065*	.....	.....	*0.091*	0.091	.....	*0.126*	0.126	.....	.....	.....	.....	.....
½	0.840	.....	*0.083*	.....	.....	*0.109*	0.109	.....	*0.147*	0.147	.....	.....	.....	0.187	0.294
¾	1.050	*0.065*	*0.083*	.....	.....	*0.113*	0.113	.....	*0.154*	0.154	.....	.....	.....	0.218	0.308
1	1.315	*0.065*	*0.109*	.....	.....	*0.133*	0.133	.....	*0.179*	0.179	.....	.....	.....	0.250	0.358
1¼	1.660	*0.065*	*0.109*	.....	.....	*0.140*	0.140	.....	*0.191*	0.191	.....	.....	.....	0.250	0.382
1½	1.900	*0.065*	*0.109*	.....	.....	*0.145*	0.145	.....	*0.200*	0.200	.....	.....	.....	0.281	0.400
2	2.375	*0.065*	*0.109*	.....	.....	*0.154*	0.154	.....	*0.218*	0.218	.....	.....	.....	0.343	0.436
2½	2.875	*0.083*	*0.120*	.....	.....	*0.203*	0.203	.....	*0.276*	0.276	.....	.....	.....	0.375	0.552
3	3.5	*0.083*	*0.120*	.....	.....	*0.216*	0.216	.....	*0.300*	0.300	.....	.....	.....	0.438	0.600
3½	4.0	*0.083*	*0.120*	.....	.....	*0.226*	0.226	.....	*0.318*	0.318	.....	.....	.....	.....	.....
4	4.5	*0.083*	*0.120*	.....	.....	*0.237*	0.237	.....	*0.337*	0.337	.....	0.438	.....	0.531	0.674
5	5.563	*0.109*	*0.134*	.....	.....	*0.258*	0.258	.....	*0.375*	0.375	.....	0.500	.....	0.625	0.750
6	6.625	*0.109*	*0.134*	.....	.....	*0.280*	0.280	.....	*0.432*	0.432	.....	0.562	.....	0.718	0.864
8	8.625	*0.109*	*0.148*	0.250	0.277	*0.322*	0.322	0.406	*0.500*	0.500	0.593	0.718	0.812	0.906	0.875
10	10.75	*0.134*	*0.165*	0.250	0.307	*0.365*	0.365	0.500	*0.500*	0.593	0.718	0.843	1.000	1.125	.....
12	12.75	*0.165*	*0.180*	0.250	0.330	*0.375*	0.406	0.562	*0.500*	0.687	0.843	1.000	1.125	1.312	.....
14 O.D.	14.0	.....	0.250	0.312	0.375	0.375	0.438	0.593	0.500	0.750	0.937	1.093	1.250	1.406	.....
16 O.D.	16.0	.....	0.250	0.312	0.375	0.375	0.500	0.656	0.500	0.843	1.031	1.218	1.438	1.593	.....
18 O.D.	18.0	.....	0.250	0.312	0.438	0.375	0.562	0.750	0.500	0.937	1.156	1.375	1.562	1.781	.....
20 O.D.	20.0	.....	0.250	0.375	0.500	0.375	0.593	0.812	0.500	1.031	1.281	1.500	1.750	1.968	.....
22 O.D.	22.0	.....	0.250	.....	.....	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....
24 O.D.	24.0	.....	0.250	0.375	0.562	0.375	0.687	0.968	0.500	1.218	1.531	1.812	2.062	2.343	.....
26 O.D.	26.0	.....	.....	.....	.....	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....
30 O.D.	30.0	.....	0.312	0.500	0.625	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....
34 O.D.	34.0	.....	.....	.....	.....	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....
36 O.D.	36.0	.....	.....	.....	.....	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....
42 O.D.	42.0	.....	.....	.....	.....	0.375	.....	.....	0.500	.....	.....	.....	.....	.....	.....

All dimensions are given in inches.

The decimal thicknesses listed for the respective pipe sizes represent their nominal or average wall dimensions. The actual thicknesses may be as much as 12.5% under the nominal thickness because of mill tolerance. Thicknesses shown in light face for Schedule 60 and heavier pipe are not currently supplied by the mills, unless a certain minimum tonnage is ordered.

*Thicknesses shown in *italics* are for Schedules 5S and 10S, which are available in stainless steel only.

†Thicknesses shown in *italics* are available also in stainless steel, under the designation Schedule 40S.

§Thicknesses shown in *italics* are available also in stainless steel, under the designation Schedule 80S.

VOLUME PER UNIT LENGTH OF
CYLINDRICAL CONTAINERS

Diameter	Liters	Liters	US Gallons	
(inches)	(per in)	(per ft)	(per in)	(per ft)
1.0	0.0129	0.154	0.0033	0.040
1.5	0.0290	0.347	0.0076	0.091
2.0	0.0515	0.618	0.0135	0.163
2.5	0.0804	0.965	0.0212	0.254
3.0	0.1158	1.390	0.0305	0.367
3.5	0.1577	1.892	0.0416	0.499
4.0	0.2059	2.471	0.0543	0.652
4.5	0.2606	3.127	0.0688	0.826
5.0	0.3218	3.861	0.0849	1.019
5.5	0.3893	4.672	0.1028	1.234
6.0	0.4633	5.560	0.1223	1.468
6.5	0.5438	6.525	0.1436	1.723
7.0	0.6306	7.568	0.1665	1.999
7.5	0.7239	8.687	0.1912	2.294
8.0	0.8237	9.884	0.2175	2.611
8.5	0.9299	11.158	0.2456	2.947
9.0	1.0425	12.510	0.2753	3.304
9.5	1.1615	13.938	0.3068	3.682
10.0	1.287	15.44	0.3399	4.079
10.5	1.419	17.03	0.3748	4.498
11.0	1.557	18.69	0.4113	4.936
11.5	1.702	20.42	0.4496	5.395
12.0	1.853	22.24	0.4895	5.875
12.5	2.011	24.13	0.5312	6.374
13.0	2.175	26.10	0.5745	6.895
13.5	2.346	28.15	0.6196	7.435
14.0	2.523	30.27	0.6663	7.996
14.5	2.706	32.47	0.7148	8.578
15.0	2.896	34.75	0.7649	9.179
15.5	3.092	37.11	0.8168	9.802
16.0	3.295	39.54	0.8703	10.444
16.5	3.504	42.05	0.9256	11.107
17.0	3.720	44.64	0.9825	11.791
17.5	3.942	47.30	1.0412	12.494
18.0	4.170	50.04	1.1015	13.219
18.5	4.405	52.86	1.1636	13.963
19.0	4.647	55.76	1.2273	14.728
19.5	4.894	58.73	1.2928	15.514
20.0	5.149	61.78	1.3599	16.319
20.5	5.409	64.91	1.4288	17.146
21.0	5.676	68.12	1.4993	17.992
21.5	5.950	71.40	1.5716	18.859
22.0	6.230.	74.76	1.6455	19.747
22.5	6.516	78.20	1.7212	20.654
23.0	6.809	81.71	1.7985	21.583
23.5	7.108	85.30	1.8776	22.531
24.0	7.414	88.97	1.9583	23.500
24.5	7.726	92.72	2.0408	24.490
25.0	8.045	96.54	2.1249	25.499
25.5	8.370	100.44	2.2108	26.530
26.0	8.701	104.42	2.2983	27.580
26.5	9.039	108.47	2.3876	28.651
27.0	9.384	112.61	2.4785	29.743
27.5	9.734	116.81	2.5712	30.854
28.0	10.092	121.10	2.6655	31.987
28.5	10.455	125.47	2.7616	33.139
29.0	10.825	129.91	2.8593	34.312
29.5	11.202	134.42	2.9588	35.506
30.0	11.585	139.02	3:0599	36.719
(30 gal drum)				
18.4	4.356	52.27	1.151	13.81
(55 gal drum)				
22.5	6.516	78.20	1.7212	20.654

(Taken from Y-1272, Y-12 Plant Nuclear Safety Handbook.)

ADDITIONAL CONVERSION FACTORS

Multiply	by	To Obtain
atmospheres	14.70	lbs/sq in
atmospheres	76.0	cm Hg
barns	10^{-24}	cm^2
cm Hg	0.1934	lbs/sq in
"	1.316×10^{-2}	atm
"	0.4465	ft of water
chemical scale	1.000272	physical scale
curie	2.22×10^{12}	disintegrations/min
"	3.7×10^{10}	dis/sec
"	10^{3}	millicuries
"	10^{6}	microcuries
"	10^{-3}	kilocuries
dynes	1.02×10^{-3}	gms
dynes	2.248×10^{-6}	lbs
electron volt (ev)	10^{-6}	Mev
" "	1.6×10^{-12}	ergs
" "	1.6×10^{-19}	joules
radians	57.3	degrees
temperature deg C + 273	1.0	abs deg Kelvin
temperature deg C	1.8	temp deg F -32
temp deg F + 459	1.0	abs deg Rankine
temp deg F-32	0.5555	temp deg C.
watts	10^{7}	ergs/sec
"	0.7376	ft-lb/sec

DENSITY OF MIXED METALS

$$\rho_t = \frac{\rho_1}{1 + \left(\frac{1}{w_1} - 1\right)\frac{a_1}{a_2}} + \frac{\rho_2}{1 + \frac{1}{\left(\frac{1}{w_1} - 1\right)\frac{a_1}{a_2}}}$$

where

ρ_t = density of mixture

ρ_1 = density of metal #1

ρ_2 = density of metal #2

w_1 = Wt. fraction of metal #1

a_1 = Atomic Wt. metal #1

a_2 = Atomic Wt. metal #2

$$(a/o)_1 = \frac{100}{1 + \frac{a_1}{a_2}\left[\frac{100}{w/o_1} - 1\right]}$$

$$(w/o)_1 = \frac{100}{1 + \frac{a_2}{a_1}\left[\frac{100}{a/o_1} - 1\right]}$$

AREAS OF COMMON PLANE FIGURES

circle --- $\pi r^2 = 1/4\ \pi d^2 = .785\ d^2$ = 78.5% of enclosing square

sphere --- $4\pi r^2 = 12.57\ r^2 = \pi d^2$

triangle --- 1/2 bh

ellipse --- 78.54% of enclosing rectangle

hexagon --- 0.866 (distance between flats)^2

octagon --- 0.822 (distance between flats)^2

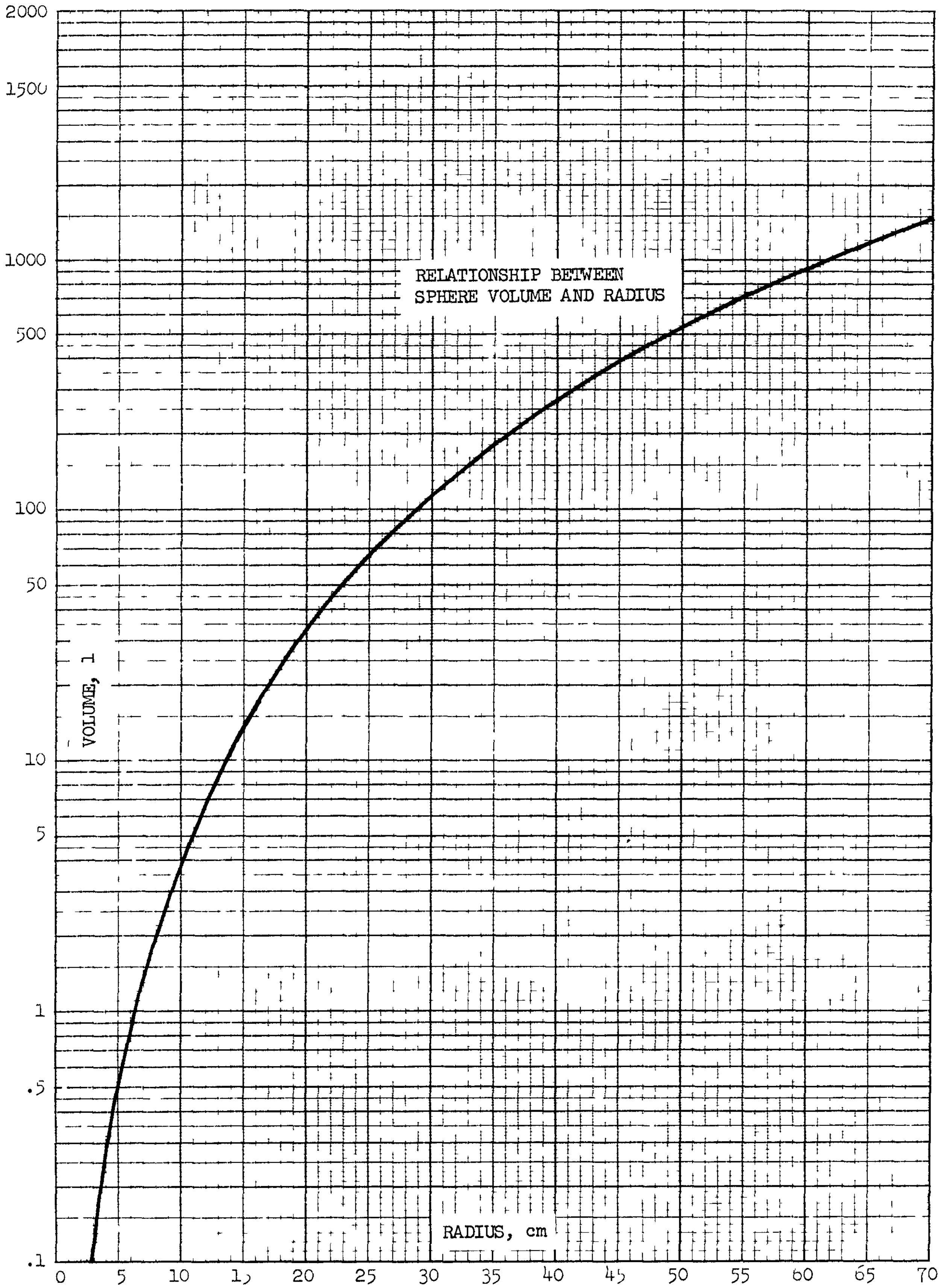
annulus --- 0.7854 (O.D.^{2} - I.D.^{2})

VOLUME OF COMMON SOLID SHAPES

sphere --- $4/3\pi r^3 = 4.189\ r^3 = 1/6\pi d^3$ = 52.36% of enclosing cube

cylinder --- $\pi r^2 h$ or 78.54% of enclosing box

cone --- $\frac{\pi}{3} r^2 h$ or $\frac{h}{3}$ (area of base)


RELATIONSHIP BETWEEN
SPHERE VOLUME AND RADIUS
VOLUME, l
RADIUS, cm
2000
1500
1000
500
100
50
10
5
1
.5
.1
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70

USEFUL RELATIONSHIPS

Liters in an Annular Tank = $\frac{(2r_o + \Delta r)\Delta r h}{318.3}$ where r_o = inner radius, cm

Δr = annulus thickness, cm

h = height, cm

Lattice Spacing - Hexagonal Lattices

simple rod, L.S. = $1.9046 \; r\sqrt{W/U+1}$, $(W/U \geqq .10268)$

clad rod, L.S. = $1.9046\sqrt{r_u^2(W/U)+r_c^2}$, $(W/U \geqq .10268 r_c^2/r_u^2)$

clad tube, L.S. = $1.9046\sqrt{(r_{2u}^2-r_{1u}^2)(W/U)+(r_{2c}^2-r_{1c}^2)}$, $\left(W/U \geqq \frac{.10268 r_{2c}^2 + r_{1c}^2}{r_{2u}^2 - r_{1u}^2}\right)$

where W/U = water-to-uranium volume ratio

r_u = uranium radius

r_c = cladding radius

subscripts 1 and 2 denote inner and outer radius, respectively

W/U - Hexagonal Lattices

simple rod, W/U = $\left[1.1027 \; (L.S.)^2/d^2\right]-1$, $(L.S. \geqq d)$

clad rod, W/U = $\left[1.1027 \; (L.S.)^2/d_u^2\right]-d_c^2/d_u^2$, $(L.S. \geqq d_c)$

clad tube, W/U = $\left[1.1027(L.S.)^2-(d_{2c}^2-d_{1c}^2)\right]/(d_{2u}^2-d_{1u}^2)$, $(L.S. \geqq d_{2c})$

where d = diameter

Equivalent relationships - hexagon and circle of equal area

radius of circle = .52504 x (lattice spacing)

Neutron Velocity - Energy Relationships

$v = 13.8 \times 10^5 \sqrt{E}$ cm per sec

where E = energy in electron volts

SIMPLE ROD LATTICE SPACINGS IN HEXAGONAL ARRAYS

W/U Vol. Ratio	ROD DIAMETERS, INCHES 0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
.6	.2409	.3614	.4818	.6023	.7227	.8432	.9637	1.0841	1.2046
.7	.2483	.3725	.4967	.6208	.7450	.8692	.9933	1.1175	1.2416
.8	.2555	.3833	.5111	.6389	.7666	.8944	1.0221	1.1499	1.2770
.9	.2625	.3938	.5251	.6563	.7876	.9189	1.0501	1.1814	1.3127
1.0	.2694	.4040	.5387	.6734	.8081	.9427	1.0774	1.2121	1.3468
1.1	.2760	.4140	.5520	.6900	.8280	.9660	1.1040	1.2420	1.3800
1.2	.2825	.4238	.5650	.7062	.8475	.9887	1.1300	1.2712	1.4125
1.3	.2889	.4333	.5777	.7221	.8665	1.0110	1.1554	1.2998	1.4442
1.5	.3011	.4517	.6023	.7529	.9034	1.0540	1.2046	1.3552	1.5057
1.7	.3130	.4694	.6259	.7824	.9389	1.0954	1.2518	1.4083	1.5648
2.0	.3299	.4948	.6598	.8247	.9897	1.1546	1.3196	1.4845	1.6494
2.5	.3563	.5345	.7126	.8908	1.0690	1.2471	1.4253	1.6034	1.7816
3.0	.3809	.5714	.7618	.9523	1.1428	1.3332	1.5237	1.7141	1.9046
3.5	.4040	.6060	.8081	1.0101	1.2121	1.4141	1.6161	1.8181	2.0201
4.0	.4259	.6388	.8518	1.0647	1.2776	1.4906	1.7035	1.9165	2.1294

WHAT IS BUCKLING ?

by

Gerhard Dessauer
Director of Savannah River Laboratory's Physics Section

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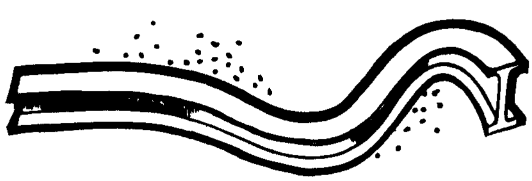
INTRODUCTION

The frequent use of the term "buckling" baffles some of our friends in the engineering, metallurgical, and chemical branches of our technology, just as we reactor physicists are often perplexed by metallographic slides or by process stream terminology

The barrier against the understanding of buckling is partly semantic and partly mathematical. The first difficulty arises from our careless use of the same word for two fundamentally different concepts: geometric buckling and material buckling. The second arises from the fact that a concise and elegant treatment of the subject involves the use of differential equations. At the risk of being somewhat long-winded, I am taking an "operational" approach to make the two kinds of buckling plausible without higher mathematics



The reader is presumed to know that the neutrons we are concerned with are set free as a result of nuclear fission inside a reactor, but perish after an erratic journey by being caught in a nucleus, fissionable or not, inside or outside the reactor.

1. The Multiplication Constant

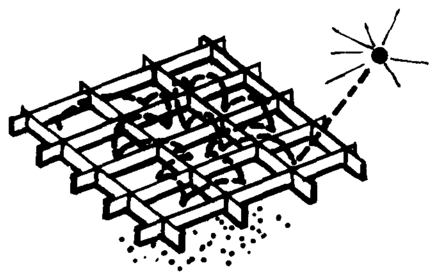
When a neutron chain reaction continues at a constant rate it is because enough of the neutrons born in a given number of unrelated fissions* survive competing hazards to give rise to the same number of new fissions. This survival is threatened by two kinds of accidents that may terminate the useful life of a neutron prematurely. One is leakage from the reactor, the other is non-productive absorption within the reactor.

The ratio of fissions in two successive related generations is called k, the multiplication constant. If k is less than one, the offspring are less numerous than the progenitors and the fission rate declines with time. If k is greater than one, fissions become more frequent in time and the reactor power increases. Whether a given type of lattice proposed by an engineer will support a chain reaction within an enclosure of his choice (i.e., whether or not k can be ≥ 1) is a crucial question that must be answered by the physicist before the engineer gets involved in detailed design.

2. Leakage from the Reactor, Geometric Buckling

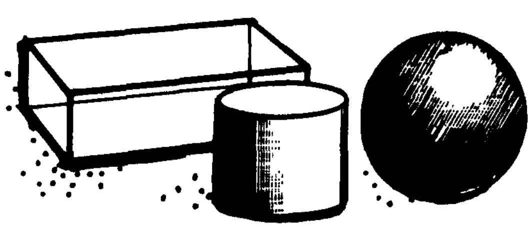
The answer depends, in part, on the amount of leakage of neutrons from the reactor. If the lattice were infinite, there would be no leakage. Thus, it is convenient to write k as a product of two terms, the multiplication constant of an infinite lattice of the proposed composition, k_{∞}, and the fraction of the neutron offspring that *does not* leak from the finite lattice. The latter term depends on properties of the lattice and also on the size and shape of the reactor. These dependencies can, in fact, again be split into two separate factors, one of which relates to the lattice only and the other to the geometric shape only. The first has to do with the average distance traveled by a neutron in the lattice from its place of birth to its place of death. Only neutrons that are born near the surface can escape from the reactor. Conversely, neutrons that are born at a distance inside the surface of the reactor that is substantially greater than the average traveling, or "migration" distance within the lattice will not get to the surface and, hence, will not leak out. Actually, the first factor in the leakage term turns out to be the average square of the distance traveled by the neutrons during their life within the lattice, and is called the migration area, M^2. The greater M^2, the greater is the depth from which neutrons can leak and therefore the greater is the total leakage from the reactor.

*For example, in all fissions occurring within a given time interval that is short compared to the lifetime of a neutron in the reactor.



The second factor entering into the non-leakage term is related to the size and shape of the reactor, only. It is possible to combine all pertinent information on size and shape in a single expression. This turns out to vary inversely as the second power of the characteristic dimensions of the reactor. It is called the geometric buckling, B_g^2. Formulae for the geometric buckling of the simplest shapes are as follows:

Shape	B_g^2	Definition of Symbols
Parallelepiped	$\pi^2\left(\frac{1}{a^2}+\frac{1}{b^2}+\frac{1}{c^2}\right)$	a, b, c = edges
Cylinder	$\pi^2/h^2 + 2.405^2/r^2$	h = height; r = radius
Sphere	π^2/R^2	R = radius



In principle, a B_g^2 can be determined for any size or shape. It is a purely geometric procedure. The geometric buckling may be expressed in units of cm^{-2}. In practice, this unit is too large, and smaller units are used. Some people use m^{-2} (= 10^{-4} cm^{-2}), others use 10^{-6} cm^{-2}, the *microbuck*.

It can be shown that the product of the two factors, M^2 and B_g^2, represents the number of neutrons that leak from the reactor for each neutron that dies within the reactor. Hence, the fraction of all lost neutrons that are lost through leakage is

$$\frac{M^2 B_g^2}{1 + M^2 B_g^2}$$

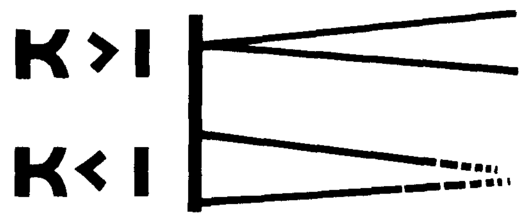
and the fraction of neutrons that *do not* leak is

$$\frac{1}{1 + M^2 B_g^2} \quad .$$

The multiplication constant can now be written in the form

$$k = \frac{k_\infty}{1 + M^2 B_g^2} \quad . \qquad (1)$$

Once the lattice and reactor size and shape are chosen, the crucial question, whether or not k can be ≥ 1, is thus reduced to the determination of M^2 and k_∞, both of which are properties of the (infinite) lattice. M^2 can be calculated or measured, more or less directly. However, the evaluation of k_∞ involves a number of separate steps. These steps will be discussed in the following section. After reading that section, the reader may wish that the determination of M^2 and of all the quantities entering k_∞ be simplified and replaced by a single concept and measurement. This wish will be fulfilled when we get to the section on *Material Buckling*.



3. Survival Inside the Reactor

Not all of the neutrons that escape leakage from the reactor contribute to the chain reaction by causing fission. Many are captured in the non-fissionable nuclei that make up the structural material, the moderator and other substances present. Even when a neutron is captured in a fissionable nucleus, there is a fair chance that this nucleus will not undergo fission. In that case, a neutron is withdrawn from the chain reaction by the fuel itself.

The average number of neutrons created in a fission event is designated by ν, (= 2.43 for U^{235}). To arrive at a value of k_∞ for a proposed lattice, this number ν must be multiplied by the probability that a neutron will escape capture by a non-fissionable nucleus and by the probability that a fissionable nucleus, having captured the neutron, will undergo fission. The latter probability is usually written as

$$\frac{1}{1 + \alpha}$$

where α is the probability ratio, capture to fission, in the fissionable nucleus.

Thus, $k_\infty = \nu x$ (capture escape probability) $\times \frac{1}{1+\alpha}$.
Since both ν and α are nuclear properties of the fuel and not directly properties of the lattice, they are often represented by a common symbol, *the neutron reproduction factor*:

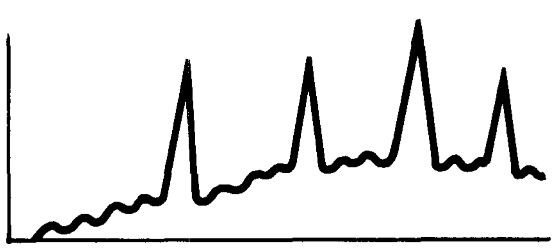
$$\eta = \frac{\nu}{1 + \alpha} \quad .$$

In lattices that contain no U^{238} or other resonance absorbers, and in which the fuel is fully enriched uranium, there is, in general, no appreciable capture until the neutrons have been slowed down from their initial kinetic energy of some MeV to the "thermal" kinetic energies of the lattice nuclei, the average of which is about 0.025 eV. In this case, the capture-escape probability is therefore simply the fraction of thermal neutrons that become available to the fuel or the "*thermal utilization*" f. For each thermal neutron, $(1-f)$ neutron is absorbed by nuclei other than the fuel, and f is absorbed by the fuel. Thus, in fully enriched lattices, $k_\infty = \eta f$.

The reactor physicist looks up η in a book supplied by the "pure" nuclear physicist and calculates or measures f, by considering the concentrations and the appetites for neutrons (cross sections) of the various nuclei in the proposed lattice.

If the lattice contains appreciable amounts of U^{238}, the story of neutron survival becomes complicated by two effects. A fast virgin neutron can produce a fission in the "non-fissionable" U^{238}.† This results in a dividend of extra neutrons. The calculation of this dividend is complex and depends on the proximity of the nucleus that undergoes fission to the U^{238} target and to the moderator. To avoid writing a complicated formula, this "fast fission effect" is usually accounted for by a factor ϵ introduced into the expression for k_∞.‡

Even more involved is the other complication introduced by U^{238}. This nucleus captures appreciable numbers of neutrons having a kinetic energy intermediate between that possessed by a neutron in the fleeting moment of its virginity and that shared by the neutron with the surrounding matter during its "thermal" life. If the neutrons have a reasonable chance of interacting with U^{238} before they are fully slowed down through collisions with the moderator, there is a substantial chance of their capture in the "resonances" of U^{238}. This chance is designated by $(1-p)$; and p is called "*resonance escape probability*".



A total description of the neutron life cycle in an infinite lattice containing U^{238} can now be given as follows: A fission produces ν neutrons, these are increased by the factor ϵ via fast fissions in U^{238}, reduced before thermalization by the factor p through resonance capture in U^{238}, reduced after thermalization by the factor f through competing thermal capture in non-fissionable nuclei, and reduced by competing thermal capture in the fuel by the factor $1/(1+\alpha)$.

†To cause fission in U^{238} a neutron must have kinetic energies above 1 MeV. The term "fissionable" is commonly applied only to nuclides that can be made to undergo fission with thermal neutrons.

‡$(\epsilon - 1)$ is the dividend rate accruing from fast fission.

Thus, $$k_\infty = \nu \epsilon p f \frac{1}{1+\alpha}$$

or, $$k_\infty = \eta \epsilon p f . \qquad (2)$$

This is the famous "four-factor" formula for k_∞. The thermal capture in the non-fissionable U^{238} is sometimes included in η rather than in f. Thus, the η used for natural uranium metal is usually not that of U^{235} but a synthetic quantity that involves, besides the ratio of capture to fission in U^{235}, the ratio of capture in 99.3% U^{238} to fission in 0.7% U^{235}.

By inserting (2) into (1) we obtain

$$k = \frac{\eta \epsilon p f}{1 + M^2 B_g^2} . \qquad (3)$$

To answer our crucial question, the reactor physicist must evaluate, calculate or measure the geometric buckling, the migration area M^2, the neutron reproduction factor η, the fast fission factor ϵ, the thermal utilization f, and the resonance escape probability p. Actually, things are even more involved than described here. For example, the distribution in energy of the neutrons, the neutron spectrum, affects the nuclear parameters that enter into η.

It appears that each new lattice requires a considerable number of calculations and/or measurements. However, if there existed a single quantity that combined M^2, η, ϵ, p and f, in such a way that the crucial question could be answered quickly and directly, only a single measurement might be needed. Fortunately, there is such a quantity. It is the "*material buckling*".

4. Material Buckling

Let us consider the case in which a reactor is precisely critical. In that case, the pile dimensions (B_g^2) are such that the particular combination of B_g^2 and of the lattice parameters η, ϵ, p, f, and M^2, that is shown in equation (3) makes $k = 1$. In that case, and only then

$$1 + M^2 B_g^2 = \eta \epsilon p f.$$

We may generalize this relation by introducing a new concept, the "material buckling" B_m^2 such that the equation

$$1 + M^2 B_m^2 = \eta \epsilon p f$$

holds, no matter what k is. Thus, B_m^2 is merely shorthand for

$$B_m{}^2 = \frac{\eta\epsilon pf - 1}{M^2} \qquad (4)$$

$B_m{}^2$ happens to be equal to $B_g{}^2$ when $k = 1$, but, in general, it need not be.

By introducing this shorthand into equation (3) we may now write the generally valid equation

$$k = \frac{1 + M^2 B_m{}^2}{1 + M^2 B_g{}^2}$$

Our crucial question whether k is greater or equal to 1 can now be replaced by the equivalent question whether $B_m{}^2$ is greater or equal to $B_g{}^2$. If $B_m{}^2$ is greater than $B_g{}^2$, k is greater than 1; if $B_m{}^2 = B_g{}^2$, $k = 1$, if $B_m{}^2$ is less than $B_g{}^2$, k is less than 1.

This problem may be compared with the problem of fitting a lady customer If the dress (geometric buckling) fits the lady (material buckling) the situation is critical for the husband's pocketbook. If the lady is too small for the dress, the matter is inconsequential. If she is too big, the experiment may result in an accident.

5. Material Buckling

5. The Measurement of Material Buckling

We have seen that $B_m{}^2$, the material buckling, is a certain combination of properties of the infinite lattice, while $B_g{}^2$, the geometric buckling, is a property of the surface enclosing the finite lattice The concept of the material buckling is attractive because it reduces the criticality question to a simple comparison of $B_m{}^2$ and $B_g{}^2$, quantities that are different in concept but are similar in their physical dimensions (length^{-2}) and can be expressed in the same units.

Material buckling is directly measurable, thereby obviating separate determinations of M^2 and of the factors entering k_∞. Of course, a more detailed knowledge of reactor performance requires a variety of information beyond the question of initial criticality. Problems of reactor stability, reactivity lifetime, and productivity depend on other combinations of the lattice parameters discussed above, and on still other parameters. The reactor physicist measures, or calculates, many things besides buckling.

Buckling measurements are made according to two principal methods, in critical or in exponential facilities.

In the "critical" experiments, k is very precisely made equal to unity, by equating the unknown material buckling and the geometric buckling In critical experiments with liquid moderator it is possible to achieve this equality by varying the geometric buckling through adjustment of the liquid level. In situations where the geometric buckling is fixed, the equality is achieved by modifications of the material buckling of the unknown lattice. This can be done by changing, by known amounts, some or several of the reactor parameters that enter into $B_m{}^2$ (see equation 4). For example, f (and M^2) may be adjusted by the addition to the reactor, or removal from the reactor, of poisons that compete for neutrons with the fuel, e.g., by means of control rods In more sophisticated experiments, a sample of the unknown lattice is inserted into a host lattice of known material buckling, and the reactor is adjusted to criticality The material buckling of the unknown can then be found by solving a set of equations.

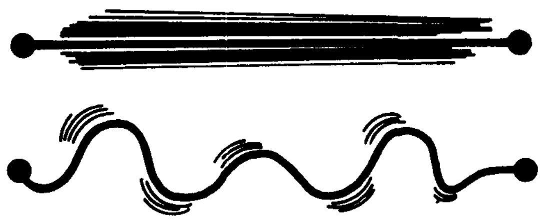
In the "exponential" experiments, it is possible to determine material buckling in a subcritical sample of the lattice and therefore without recourse to geometric buckling Since this sample cannot maintain a chain reaction, neutrons must be fed into the lattice. The most common arrangement is a cylindrical sample supplied by neutron sources arranged across the bottom surface. (However, Fermi's original exponentials were parallelepipeds.) In such an arrangement, one measures the distribution of neutrons throughout the lattice. The rates at which the neutron population decreases as one proceeds away from the source, and as one approaches the surfaces of the lattice, determine a unique value of $B_m{}^2$. In the conventional vertical tank, it is usually sufficient to measure the radial neutron distribution at one or two levels and the vertical neutron distribution at one or two radii. A plot of neutron density along a vertical axis may be fitted by exponential functions, hence the term "exponential" facility.

Once the material buckling is known, the critical size of the lattice can be derived for any desired shape. This is particularly helpful in problems of nuclear safety in connection with the storage and handling of many fuel pieces. For example, cylindrical fuel slugs could be arranged in many different ways: like bamboo sticks, like soldiers on the drilling ground, or in pyramids like the cans in some grocery stores. From a single material-buckling measurement in an exponential, the critical sizes of any of these configurations can be evaluated, whereas the corresponding critical measurements would require assemblies in each of these configurations.

6. Semantics of Buckling

My dictionary defines the noun "buckle" as "a distortion, as a bulge, bend, kink, or twist in a beam. . .", all of which sounds akin to the problem of fitting the lady customer.

Actually, buckling is related to an eigenvalue problem. The second-order differential equation that maps out the shape of a string or of a membrane in an operating musical instrument involves the local inertia (mass density) and tension of the string or membrane. Solutions are subject to the condition that the ends of the string or the edge of the membrane are in a fixed



position. A similar differential equation describes the neutron density distribution in an operating reactor and involves local lattice properties in a combination called "buckling", as exemplified by our equation (4) defining $B_m{}^2$. The solutions are subject to the condition that the flux must approach zero along the boundary of the reactor. This is true only if the average buckling assumes certain values (the eigenvalues) which involve the information entering into our $B_g{}^2$.

If the buckling is zero somewhere in an operating reactor, the flux distribution is "flat" in this region, that is, the flux changes with constant slope, for example with zero slope. Where the buckling is positive, the flux shape displays curvature and may have a peak, where the buckling is negative there may be a flux depression. So here is some analogy with the "distortions or bulges" in the vibrating string or membrane.

To some of our colleagues, the word buckling is repulsive. They prefer to talk about "the Laplacian", which is not a fortunate choice as it confuses the concepts of differential operator and of eigenvalue.

It was Professor J. A. Wheeler who introduced the term "buckling" into reactor physics. In geometrodynamics, a branch of physics, in which Wheeler is a leading pioneer, the *material* world is reduced to *geometry*.

USEFUL RELATIONSHIPS BETWEEN K_{eff}, B_m^2 and B_g^2

The reactivity of a fissile system can be described by

$$k_{eff} = \frac{k_\infty}{1 + M^2 B_g^2}$$

where

k_{eff} = effective multiplication constant

k_∞ = multiplication constant for an infinite amount of the fissile material

B^2 = geometrical buckling of the system

M^2 = migration area of the neutrons (about 25 to 30 cm for H/fissile atom ≥ 20)

at critical $k_{eff} = 1.0$ and $B_m^2 = B_g^2$, where

B_m^2 = material buckling of the fissile material, or

$$1 = \frac{k_\infty}{1 + M^2 B_m^2}$$

Substituting, we have:

$$k_{eff} = \frac{1 + M^2 B_m^2}{1 + M^2 B_g^2}$$

and we can determine the reactivity of a given system with a known geometry and material, or

$$B_m^2 = \frac{k_{eff}(1 + M^2 B_g^2) - 1}{M^2}$$

where the geometry and the limiting k_{eff} is known and the material buckling is desired, or

$$B_g^2 = \frac{1}{M^2}\left[\frac{1 + M^2 B_m^2}{k_{eff}} - 1\right]$$

where the limiting k_{eff} and the material is known and the limiting geometry is desired.

These equations may be used for rough determinations of the desired parameters for simple geometrical shapes with no interaction.

Safety Factors

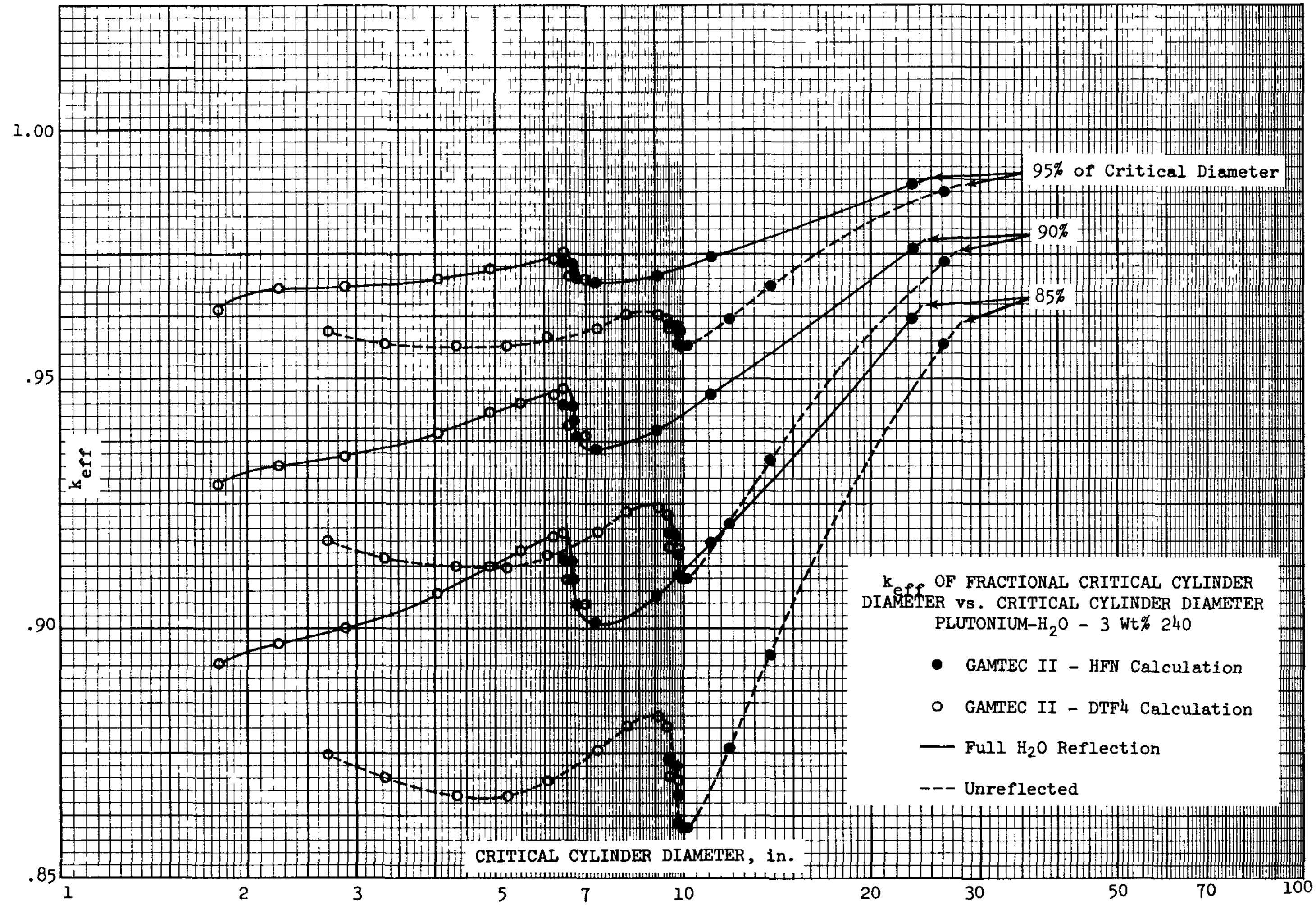
As stated in the ARHCO Technical Criteria for the Prevention of Criticality, page I.C-3.5, safety factors must be included in all limits and the three degrees of safety factor specified are based upon the confidence in calculations and the risks involved. A common method of applying safety factors is the use of fractional critical dimensions, volumes or masses. The advantage of using fractional critical dimensions is the ease of application using readily available critical dimension data. While these values are satisfactory in most cases, large systems thus specified may have an effective multiplication constant (k_{eff}) very close to one, the critical condition. In these cases effective protection will not be attained. On the other hand, the fraction of critical dimension method may be overly restrictive for smaller systems.

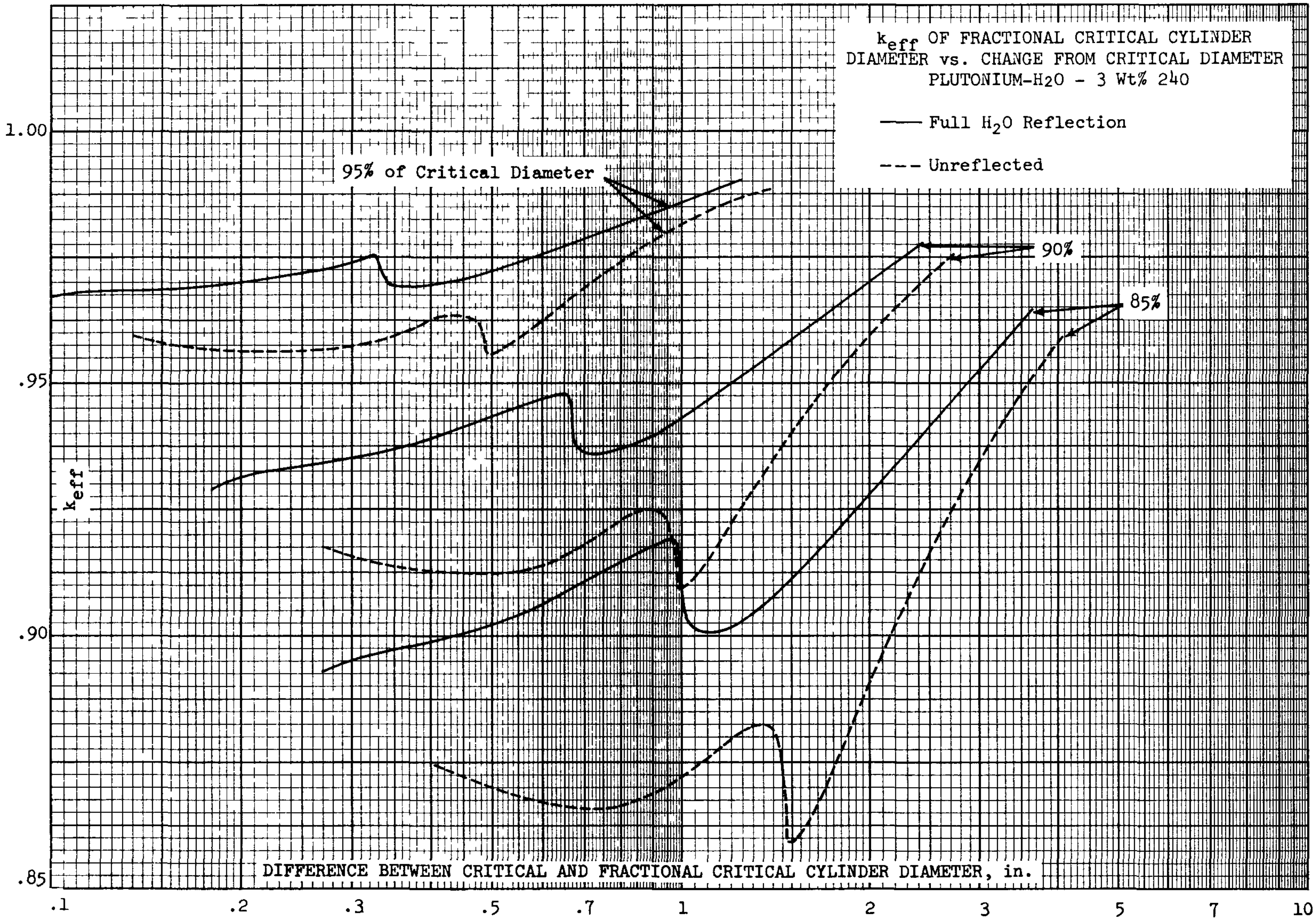
A safety factor based on the k_{eff} of a system provides a more consistent overall protection. However, this method of applying the safety factor must be used with caution when dealing with small critical systems where small changes in critical dimensions may result in large changes in k_{eff}. Unless the k_{eff} safety factor is less than that normally required for larger systems, the resulting minute dimensional safety factor may be beyond the control of equipment fabricators.

The criticality prevention specialist must consider the limitations on the use of either method in applying safety factors to critical limits. Both k_{eff} limits and dimension limits are specified in the ARHCO criteria, page I.C-6.4.2.

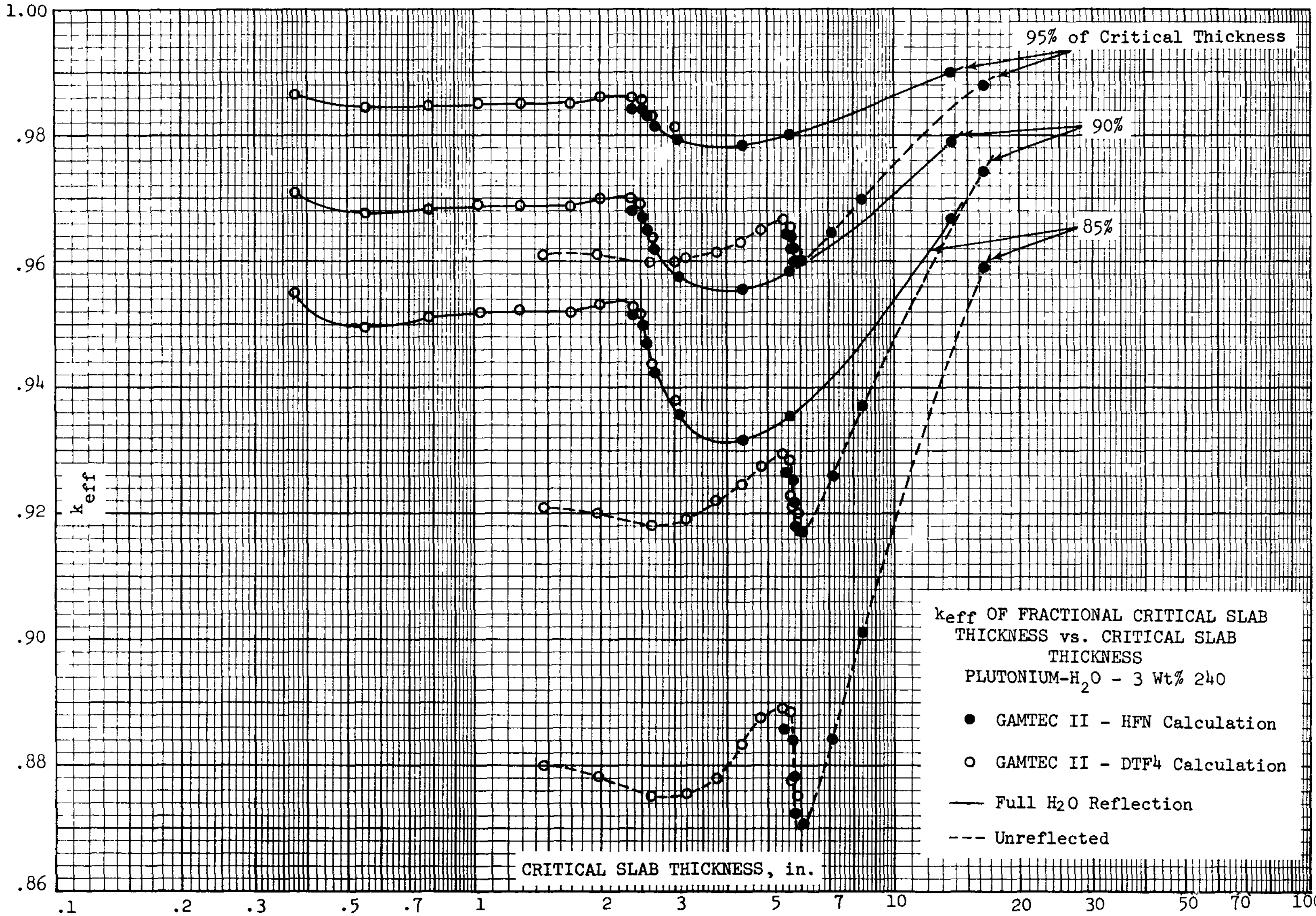
In the following figures the k_{eff} of fractional critical slabs, cylinders, masses and volumes are indicated for both reflected and bare systems using plutonium-water solution densities. These figures are used only to illustrate the variation one can find. Other fissile systems could be more restrictive.

The first part of the calculations for the figure was done with the HFN diffusion theory code at .01, .02, .03, .07, .15, .3, .6, and 1.0 grams of plutonium per cubic centimeter. Although this code is known to be accurate for thermal systems it becomes non-conservative at high concentrations. Therefore, the DTF4 transport theory code was used to obtain k-effective values for the faster systems over a range (including sufficient overlap to permit a smooth curve to be drawn) of .07, .15, .6, 1, 2, 5, 7, 10, 15 and 19.6 grams of plutonium per cubic centimeter. The indicated critical reflected slab thickness for plutonium metal may be somewhat large as a result of poor flux matching between core and reflector. However, for our purposes the indicated change in k-effective should be satisfactory.

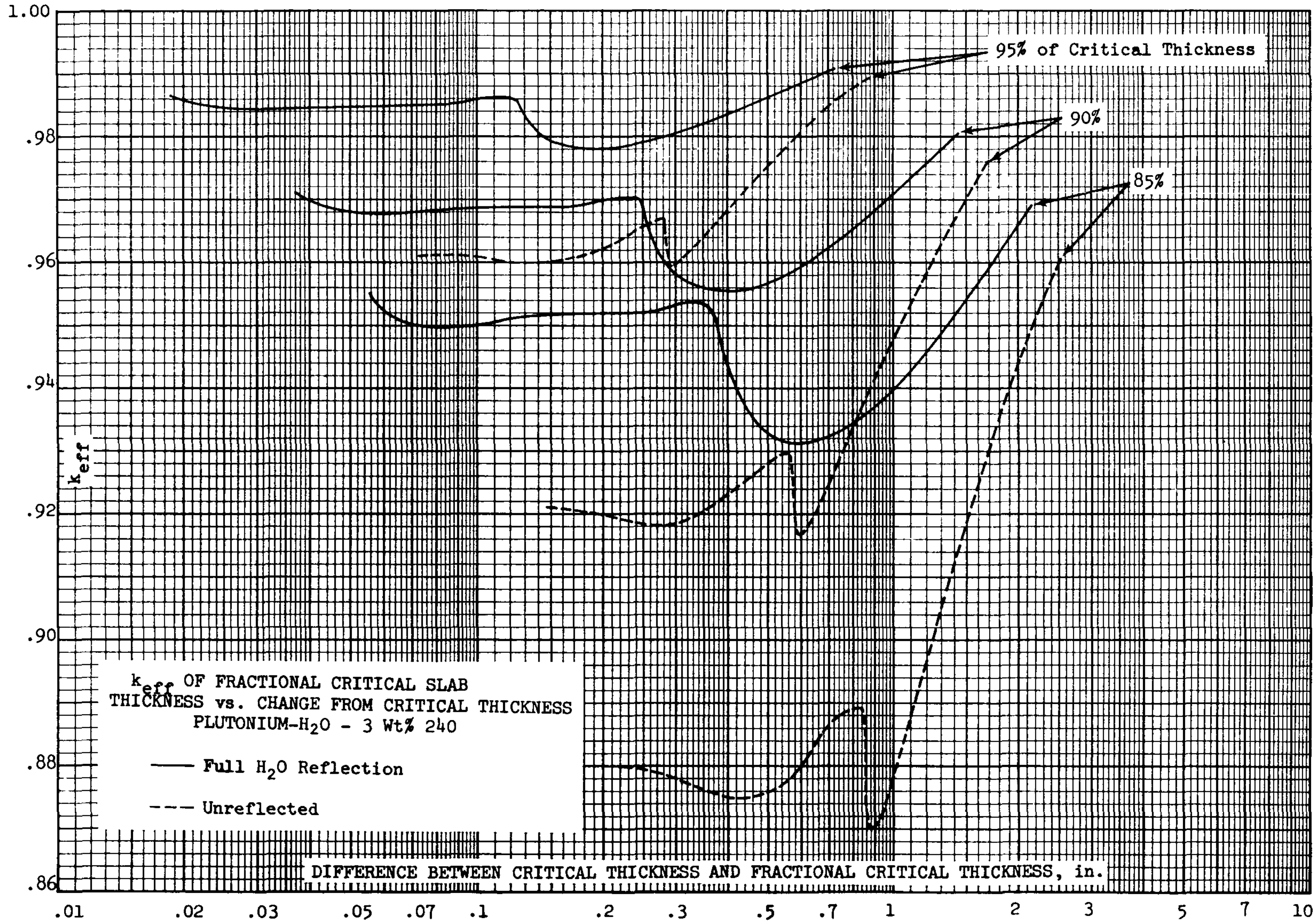

keff OF FRACTIONAL CRITICAL CYLINDER DIAMETER vs. CRITICAL CYLINDER DIAMETER
PLUTONIUM-H2O - 3 Wt% 240
GAMTEC II - HFN Calculation
GAMTEC II - DTF4 Calculation
Full H2O Reflection
Unreflected
95% of Critical Diameter
90%
85%
keff
CRITICAL CYLINDER DIAMETER, in.
1.00
.95
.90
.85
1
2
3
5
7
10
20
30
50
70
100



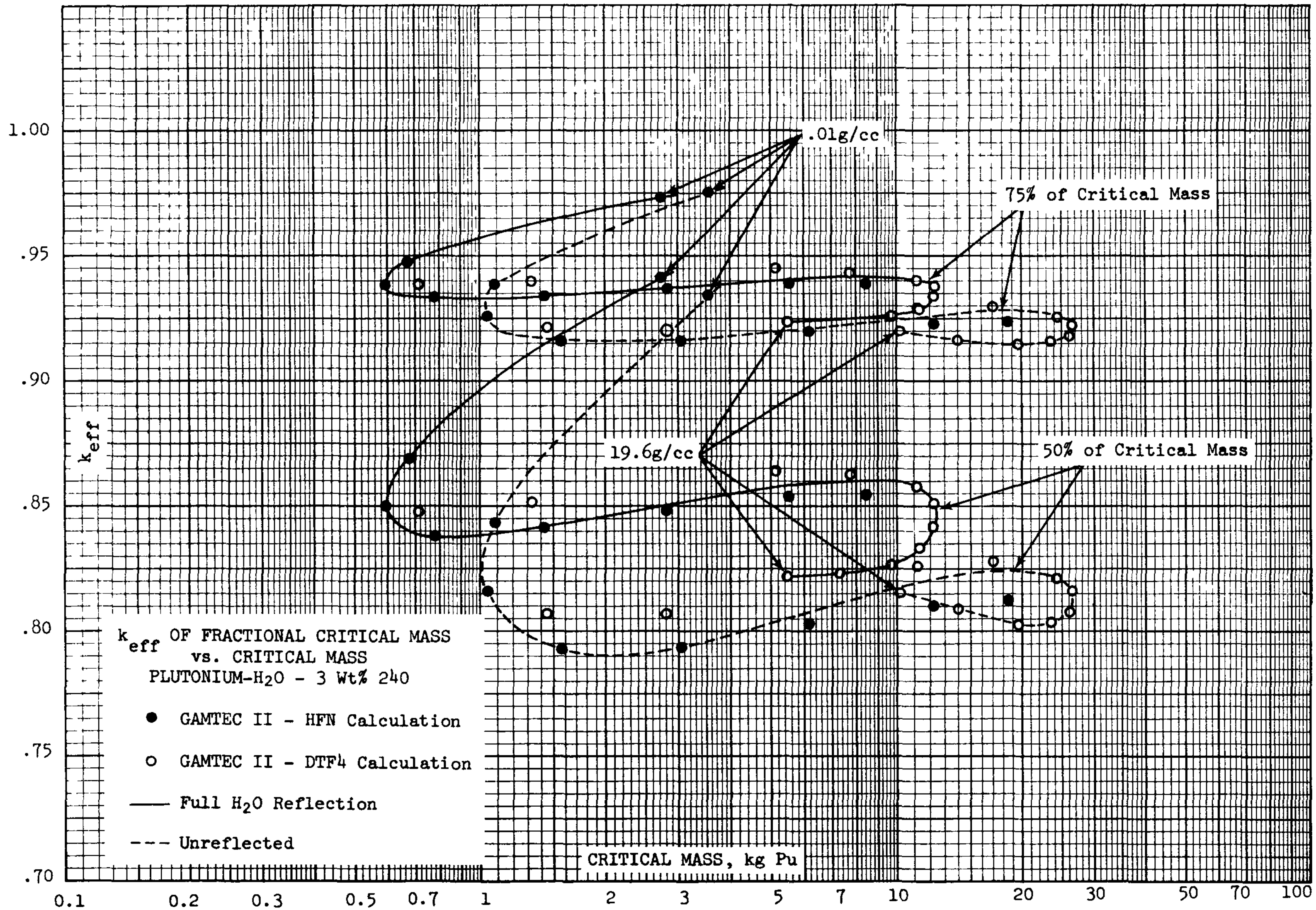
k_{eff} OF FRACTIONAL CRITICAL CYLINDER
DIAMETER vs. CHANGE FROM CRITICAL DIAMETER
PLUTONIUM-H_2O - 3 Wt% 240
Full H_2O Reflection
Unreflected
95% of Critical Diameter
90%
85%
1.00
.95
.90
.85
k_{eff}
.1
.2
.3
.5
.7
1
2
3
5
7
10
DIFFERENCE BETWEEN CRITICAL AND FRACTIONAL CRITICAL CYLINDER DIAMETER, in.

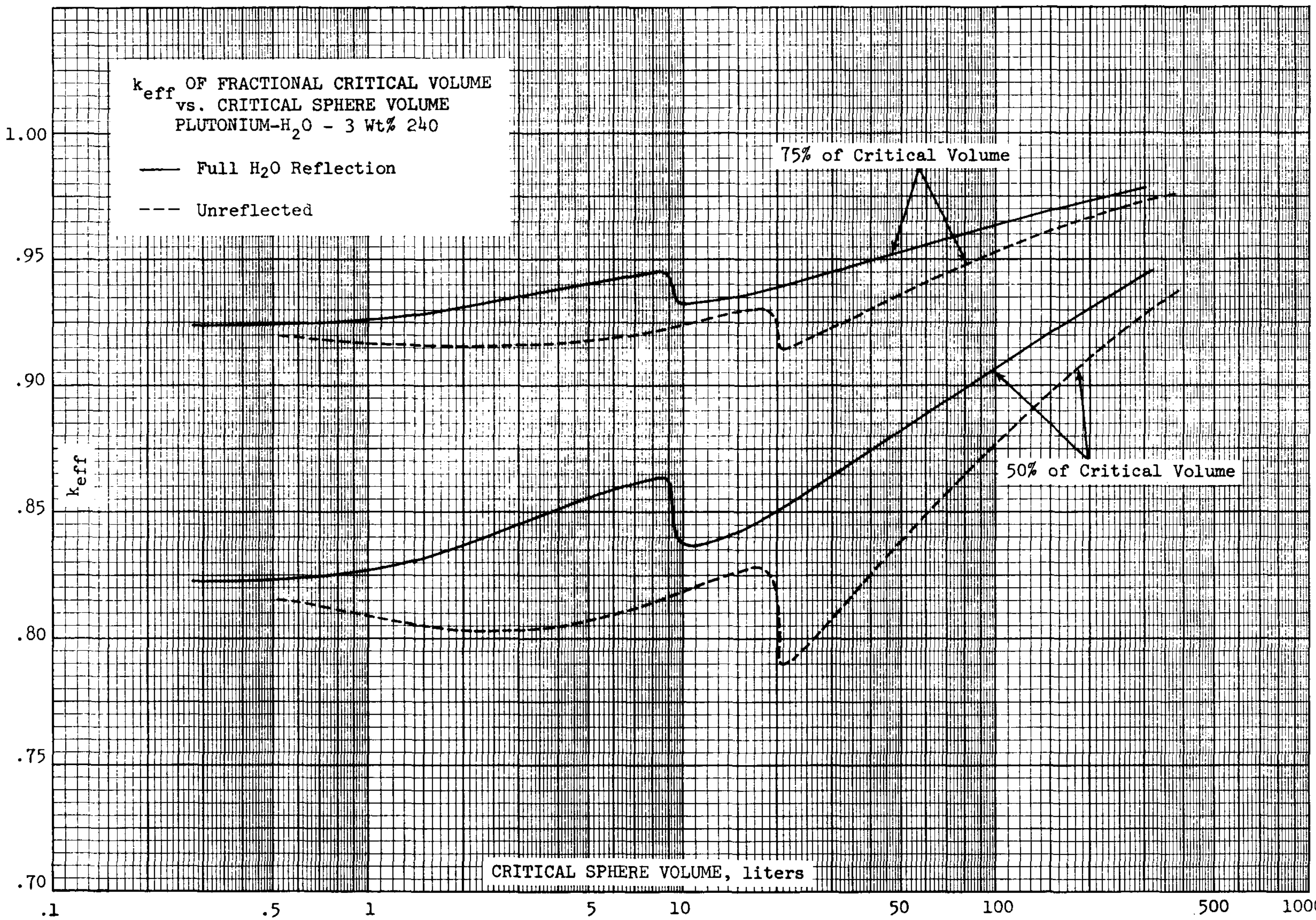


1.00
.98
.96
.94
.92
.90
.88
.86
k_{eff}
.1
.2
.3
.5
.7
1
2
3
5
7
10
20
30
50
70
100
CRITICAL SLAB THICKNESS, in.
95% of Critical Thickness
90%
85%
k_{eff} OF FRACTIONAL CRITICAL SLAB THICKNESS vs. CRITICAL SLAB THICKNESS
PLUTONIUM-H_2O - 3 Wt% 240
GAMTEC II - HFN Calculation
GAMTEC II - DTF4 Calculation
Full H_2O Reflection
Unreflected


1.00
.98
.96
.94
.92
.90
.88
.86
k_{eff}
95% of Critical Thickness
90%
85%
k_{eff} OF FRACTIONAL CRITICAL SLAB THICKNESS vs. CHANGE FROM CRITICAL THICKNESS
PLUTONIUM-H_2O - 3 Wt% 240
Full H_2O Reflection
Unreflected
DIFFERENCE BETWEEN CRITICAL THICKNESS AND FRACTIONAL CRITICAL THICKNESS, in.
.01
.02
.03
.05
.07
.1
.2
.3
.5
.7
1
2
3
5
7
10

II.B.1-11


1.00
.95
.90
.85
.80
.75
.70
keff
.01g/cc
75% of Critical Mass
19.6g/cc
50% of Critical Mass
keff OF FRACTIONAL CRITICAL MASS
vs. CRITICAL MASS
PLUTONIUM-H2O - 3 Wt% 240
GAMTEC II - HFN Calculation
GAMTEC II - DTF4 Calculation
Full H2O Reflection
Unreflected
CRITICAL MASS, kg Pu
0.1
0.2
0.3
0.5
0.7
1
2
3
5
7
10
20
30
50
70
100



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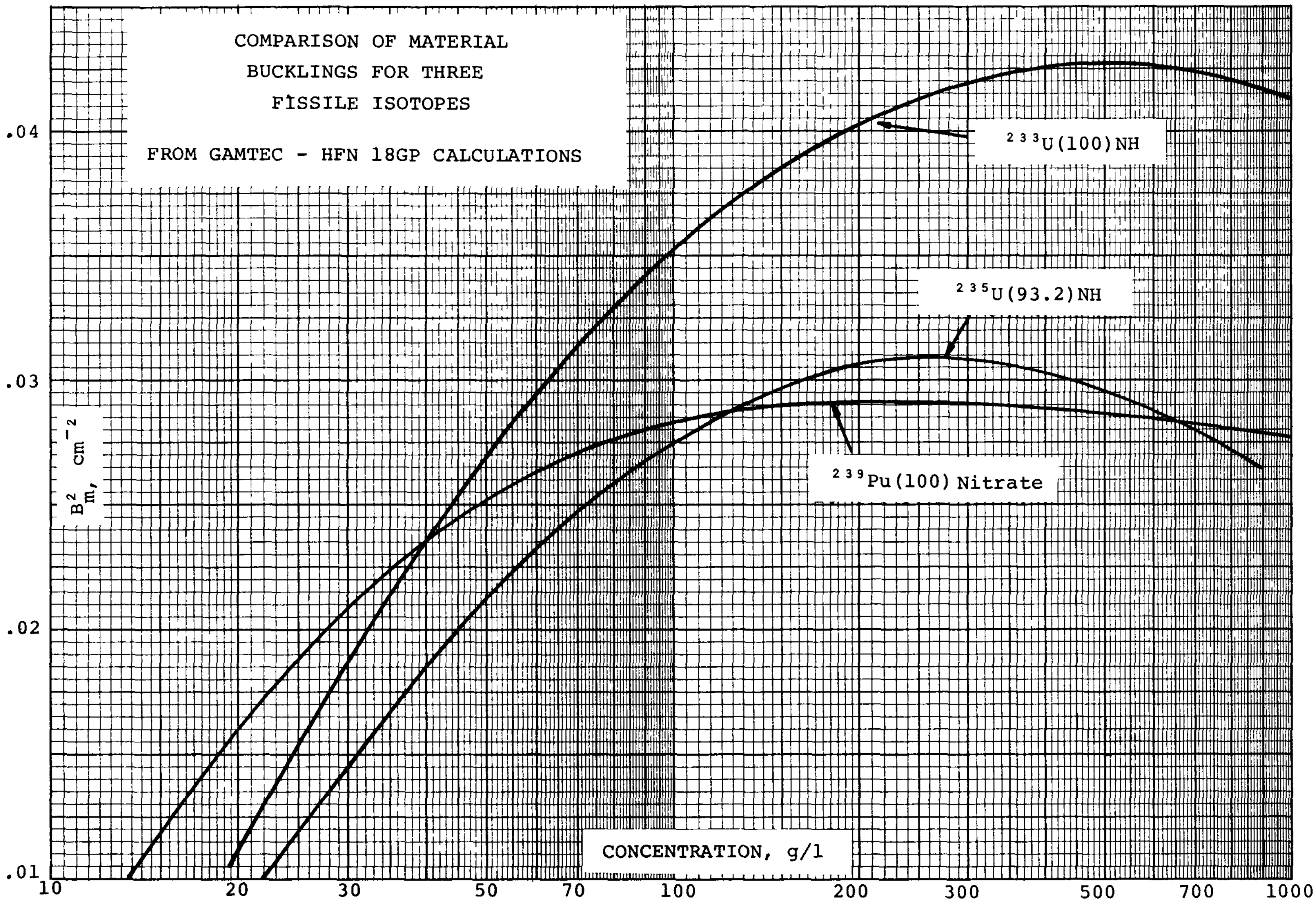

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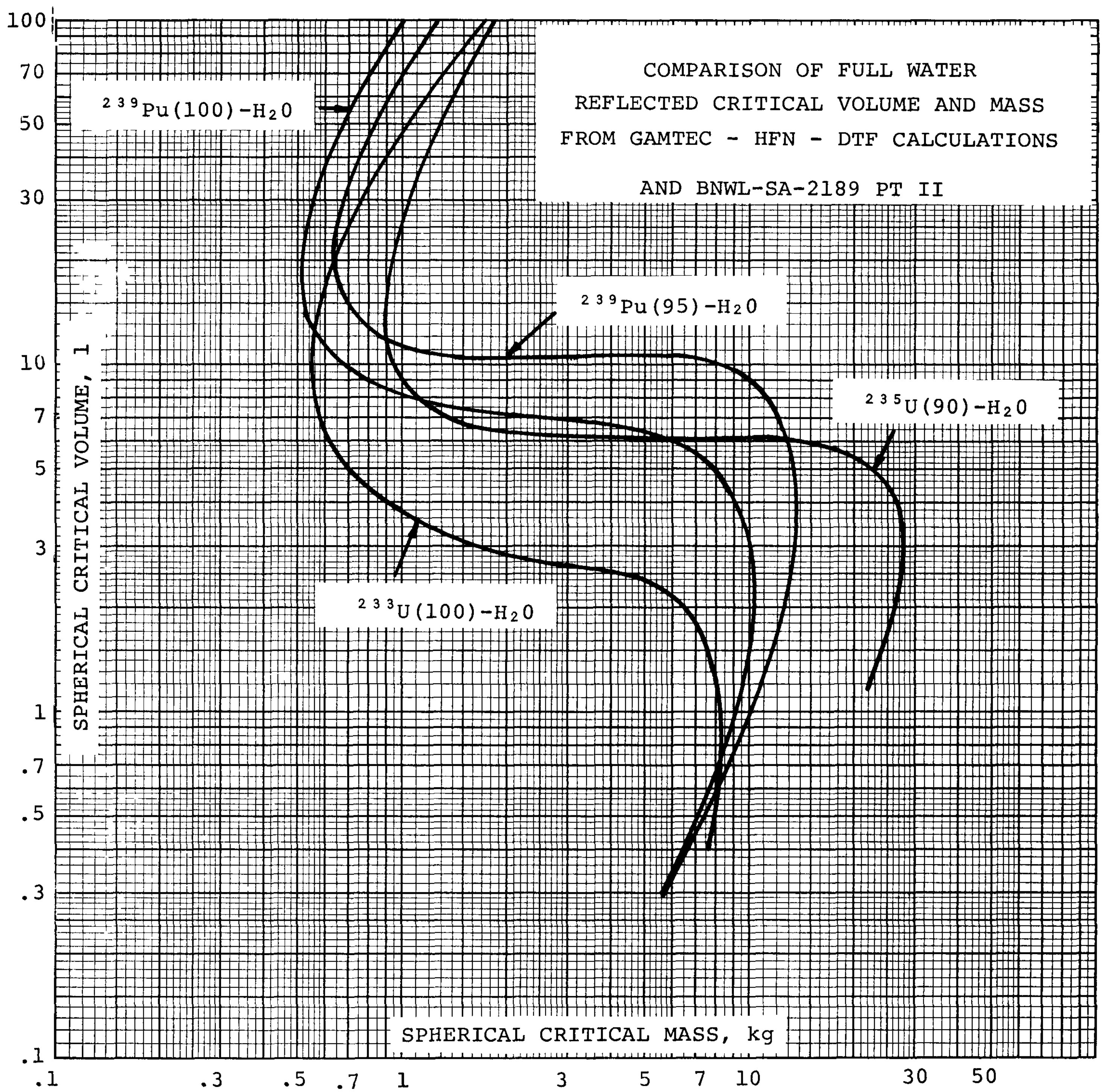

COMPARISON OF FULL WATER
REFLECTED CRITICAL VOLUME AND MASS
FROM GAMTEC - HFN - DTF CALCULATIONS
AND BNWL-SA-2189 PT II
239Pu(100)-H2O
239Pu(95)-H2O
235U(90)-H2O
233U(100)-H2O
SPHERICAL CRITICAL VOLUME, l
SPHERICAL CRITICAL MASS, kg
100
70
50
30
10
7
5
3
1
.7
.5
.3
.1
.1
.3
.5
.7
1
3
5
7
10
30
50

II.B.2 Geometric Buckling Formulas

Shape	B_g^2	
Infinite Slab:	$\frac{\pi^2}{(a + 2\lambda)^2}$	a = width of finite side λ^1 = extrapolation distance
Parallelepiped:	$\pi^2 \left[\frac{1}{(a + 2\lambda)^2} + \frac{1}{(b + 2\lambda)^2} + \frac{1}{(c + 2\lambda)^2}\right]$	a,b,c edges
Infinite Cylinder:[3]	$\frac{2.405^2}{(r + \lambda)^2}$	r = cylinder radius
Finite Cylinder:	$\frac{2.405^2}{(r + \lambda)^2} + \frac{\pi^2}{(h + 2\lambda)^2}$	r = cylinder radius h = cylinder height
Infinite Hemicylinder[2,3,4]	$\frac{(3.832)^2}{(r + \lambda)^2}$	r = hemicylinder radius
Sphere:[4]	$\frac{\pi^2}{(r + \lambda)^2}$	r = sphere radius
Hemisphere:	$\frac{(4.49)^2}{(r + \lambda)^2}$	r = hemisphere radius

1 λ depends upon the fissile material, the geometry and the systems surroundings.

2 For a sector of a cylinder, see Page II.B.2-3.

3 Critical cylinders and hemicylinders are related by:

$$r_{hc} = 1.5935 r_{cyl} + 0.5935\,\lambda$$

4 Critical spheres and hemicylinders are related by:

$$r_s = \frac{(r_{hc} + \lambda_{hc})(h_{hc} + 2\lambda_{hc})}{1.2198(h_{hc} + 2\lambda_{hc}) + (r_{hc} + \lambda_{hc})} - \lambda_s$$

Shape	B_g^2
Elliptic Cylinder*	The buckling equation for a right elliptic cylinder is of the form:

$$B_g^2 = B_z^2 + B_e^2 = (\pi/L)^2 + B_e^2(m,M)$$

where L is the cylinder height, m is the semi-minor axis and M is the semi-major axis (extrapolated dimensions).

The solution of elliptical buckling, B_e^2, takes the form:

$B_e^2 = K(c^2)/m^2$ where $c = M/m$ and $K(c^2)$ is a function which varies with c^2

Values of $K(c^2)$ can be determined from the accompanying table. Interpolation between points can be determined by the approximate formula:

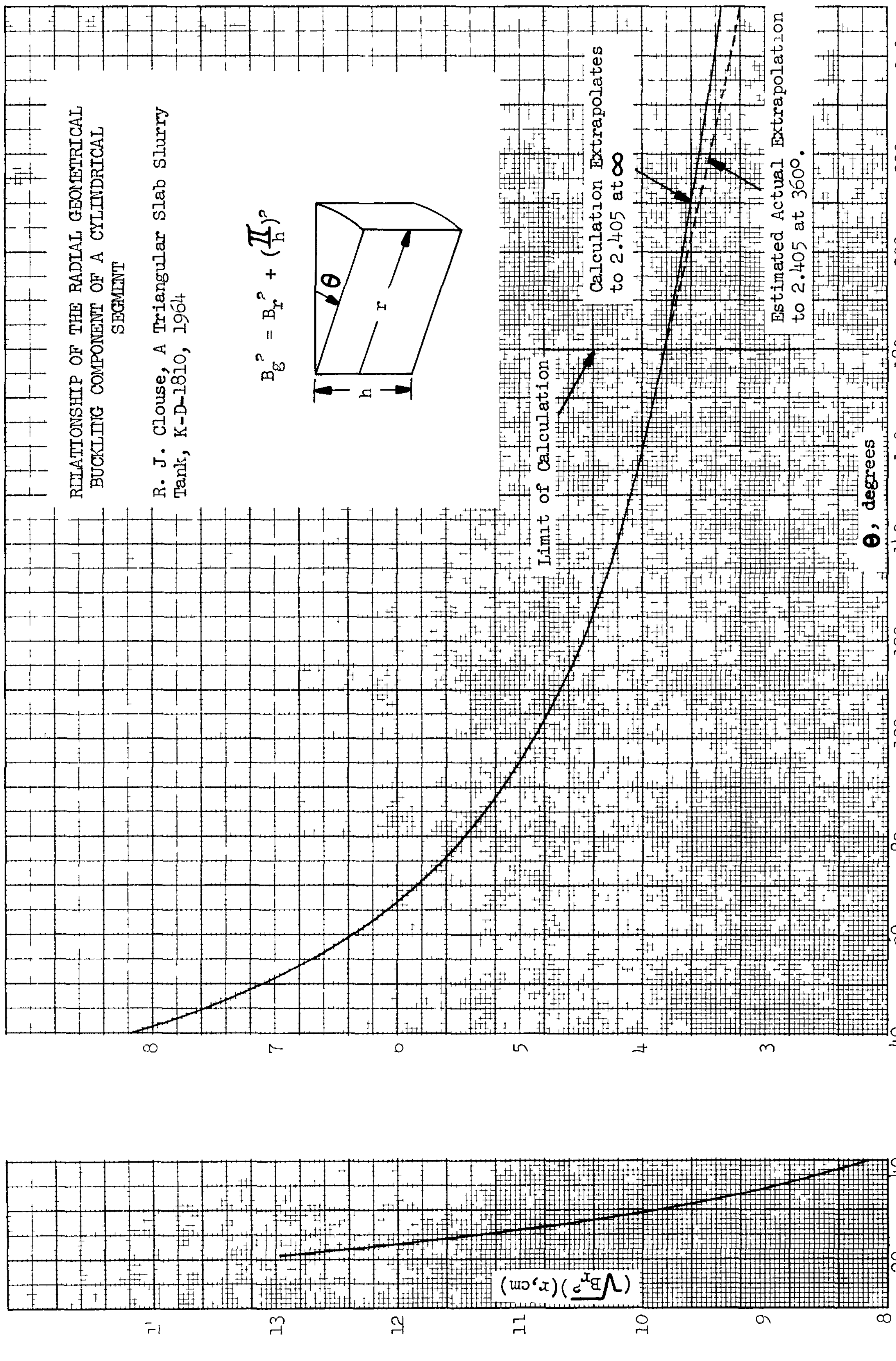
$$K(c^2) = K(c_2^2)(c_2^2/c^2)(c-c_1^2)/c_2^2-c_1)$$

$$+ K(c_1^2)(c_1^2/c^2)\left[1 - (c^2-c_1^2)/(c_2^2-c_1^2)\right]$$

where $c_1 < c < c_2$

c	$K(c^2)$	c	$K(c^2)$	c	$K(c^2)$	c	$K(c^2)$
1.0000	5.7832	1.2437	4.7519	1.5003	4.1576	1.7460	3.8074
1.0174	5.6819	1.2634	4.6961	1.5198	4.1239	1.7643	3.7869
1.0352	5.5898	1.2832	4.6398	1.5341	4.0915	1.8094	3.7384
1.0531	5.4983	1.3030	4.5860	1.5583	4.0603	1.8538	3.6940
1.0714	5.4100	1.3228	4.5344	1.5775	4.0303	1.8974	3.6528
1.0899	5.3249	1.3427	4.4851	1.5968	4.0018	1.9406	3.6152
1.1086	5.2431	1.3624	4.4378	1.6157	3.9741	1.9831	3.5801
1.1274	5.1642	1.3822	4.3925	1.6345	3.9475	2.0241	3.5518
1.1465	5.0886	1.4021	4.3490	1.6534	3.9220	2.6917	3.2021
1.1657	5.0162	1.4217	4.3075	1.6722	3.8973	3.0081	3.1059
1.1851	4.9469	1.4415	4.2676	1.6907	3.8737	3.8181	2.9159
1.2045	4.8801	1.4612	4.2292	1.7095	3.8507	5.0892	2.8112
1.2241	4.8161	1.4808	4.1926	1.7277	3.8284	6.093	2.7681
						∞	2.4674

* P. F. Gast and A. Bournia, Nucleonics, April, 1956.


RELATIONSHIP OF THE RADIAL GEOMETRICAL BUCKLING COMPONENT OF A CYLINDRICAL SEGMENT
R. J. Clouse, A Triangular Slab Slurry Tank, K-D-1810, 1964
$B_g^2 = B_r^2 + (\frac{\pi}{h})^2$
θ
r
h
Limit of Calculation
Calculation Extrapolates to 2.405 at ∞
Estimated Actual Extrapolation to 2.405 at 360°.
θ, degrees
$(\sqrt{B_r^2})(r, cm)$

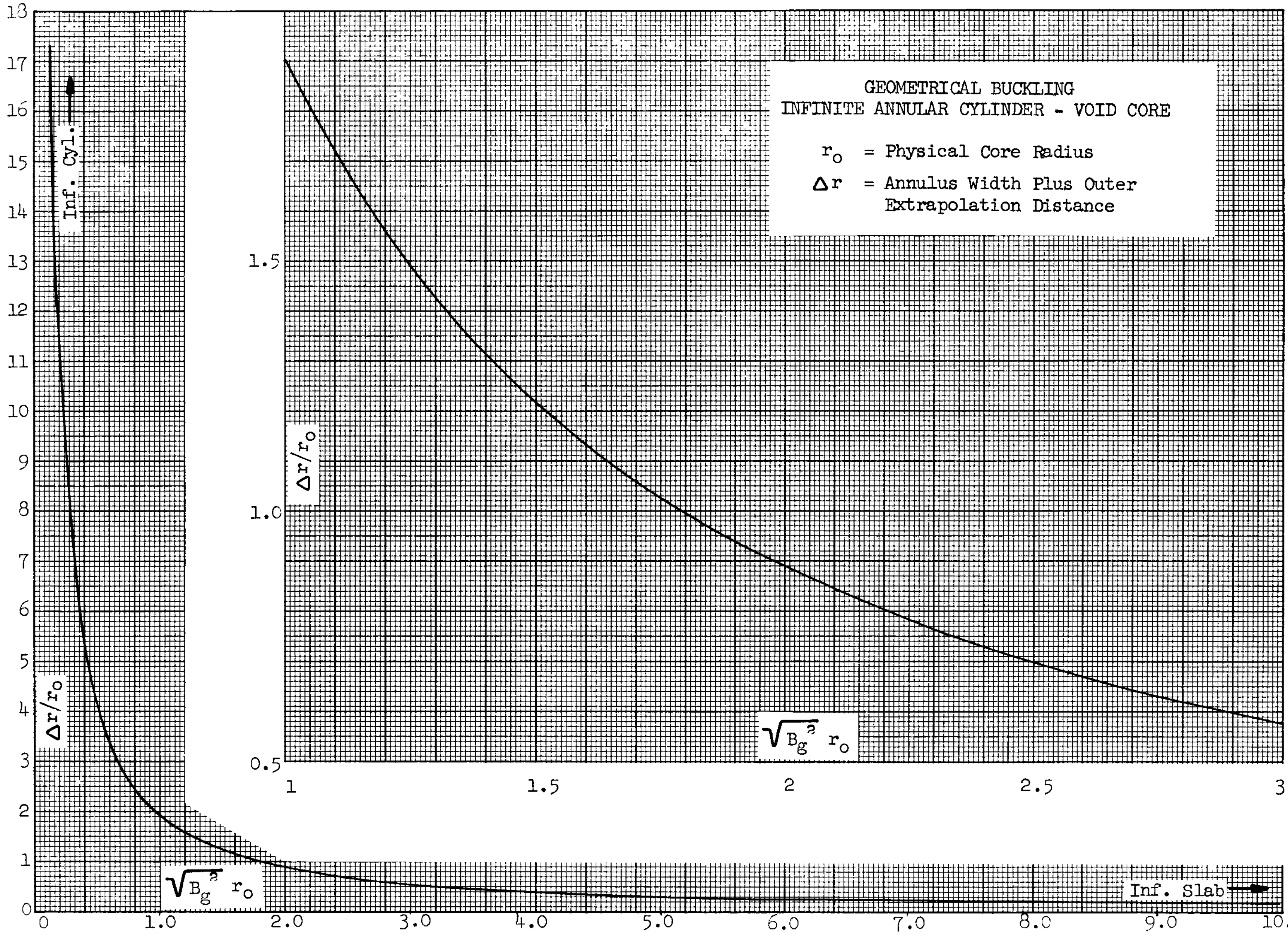
ANNULAR INFINITE CYLINDER

Void Core

An annular cylinder whose inner radius, r_o, and extrapolated annulus thickness, t, is known and which has a void in the center will have a geometrical buckling that is a function of r_o, t and the outer extrapolation distance, λ. The graph on page II.B.2-5 shows the relation. If $\Delta r = t + \lambda$, the value of $\Delta r/r_o$ will give a value for $\sqrt{B_g^2}\, r_o$. Dividing this by r_o and squaring will give the geometrical buckling of the system. Conversely, if the desired buckling is known, the inside radius or the annulus thickness can be found.

Isolating Core

Calculations have been made for the relationship between B^2, r_o and Δr for the annular cylinder which has its core filled with material which effectively eliminates interaction of the annulus across the core. However, since small cores are seldom isolating and since for large cores the annulus may be treated as a slab, the relationship will not be reproduced here.



UNCLASSIFIED

BUCKLING OF N-SIDED POLYGONS*

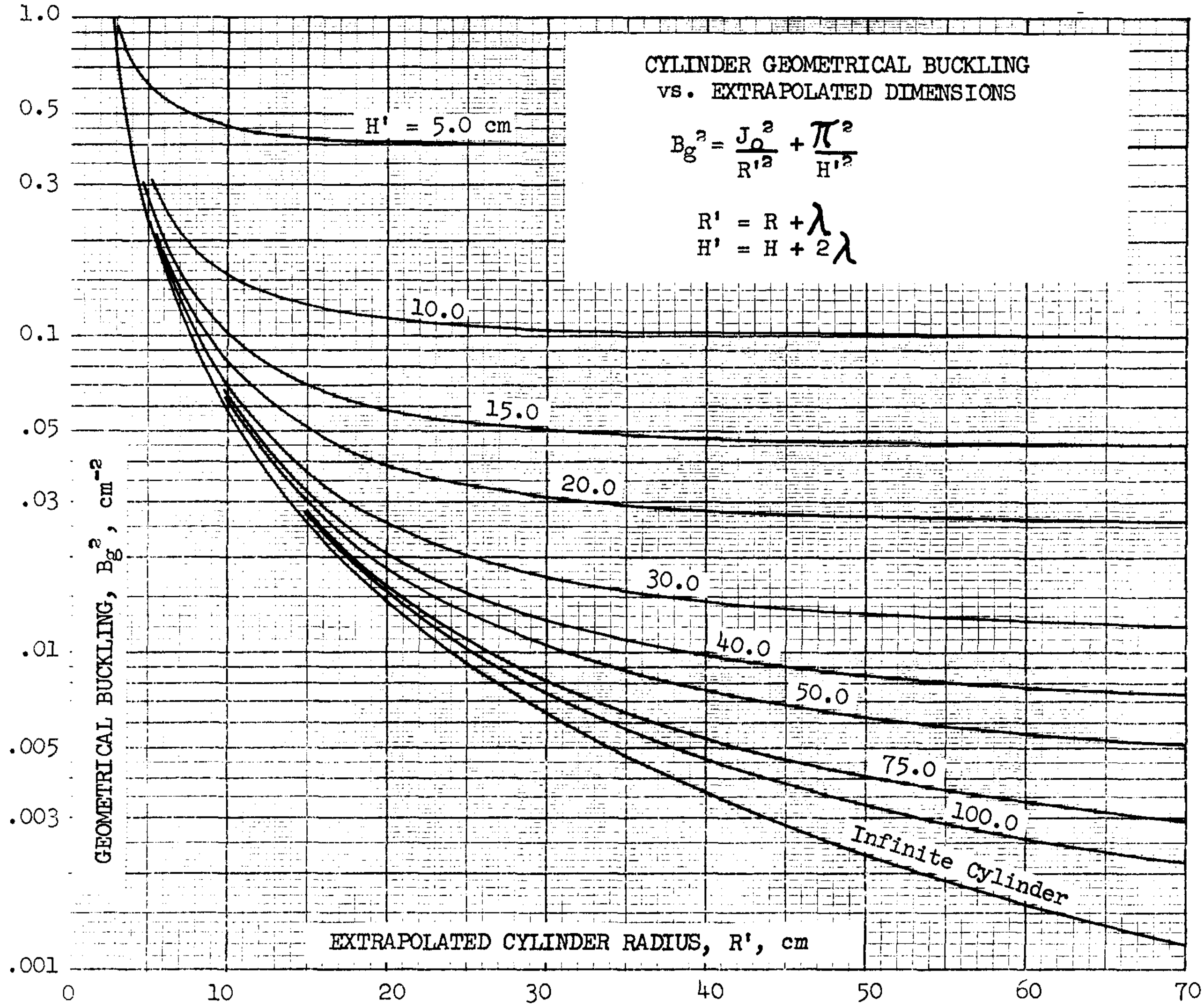
The radial (or horizontal) geometrical buckling of regular polygons, where R is the radius of the inscribed circular cylinder of height H within the polygon and (π^2/H^2) is the axial (or vertical) geometrical buckling, is as follows (all dimensions are extrapolated dimensions):

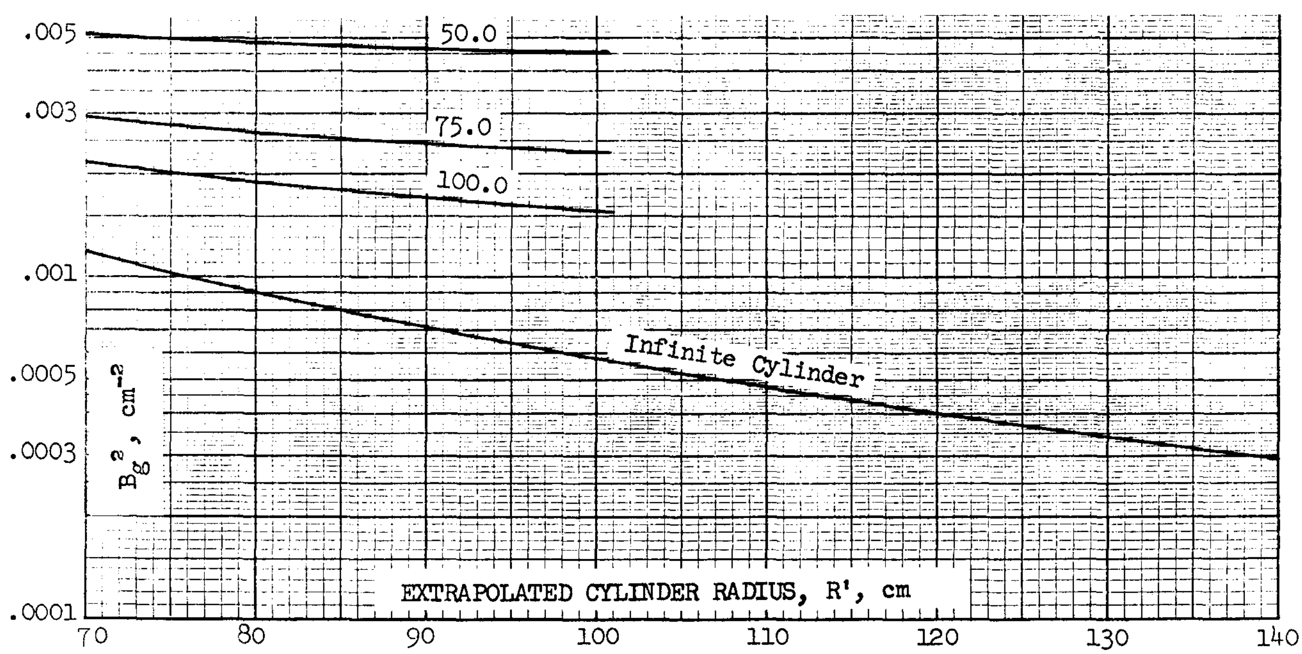
No. Sides	$B_g^2 - \pi^2/H^2$
3	$4.3865/R^2$
4	$4.9348/R^2$ ($=2\pi^2/D^2$ or square, see p. II.B.2-1)
5	$5.2080/R^2$
6	$5.3665/R^2$
7	$5.4672/R^2$
8	$5.5352/R^2$
9	$5.5834/R^2$
10	$5.6188/R^2$
11	$5.6456/R^2$
12	$5.6831/R^2$
13	$5.6826/R^2$
14	$5.6958/R^2$
15	$5.7056/R^2$

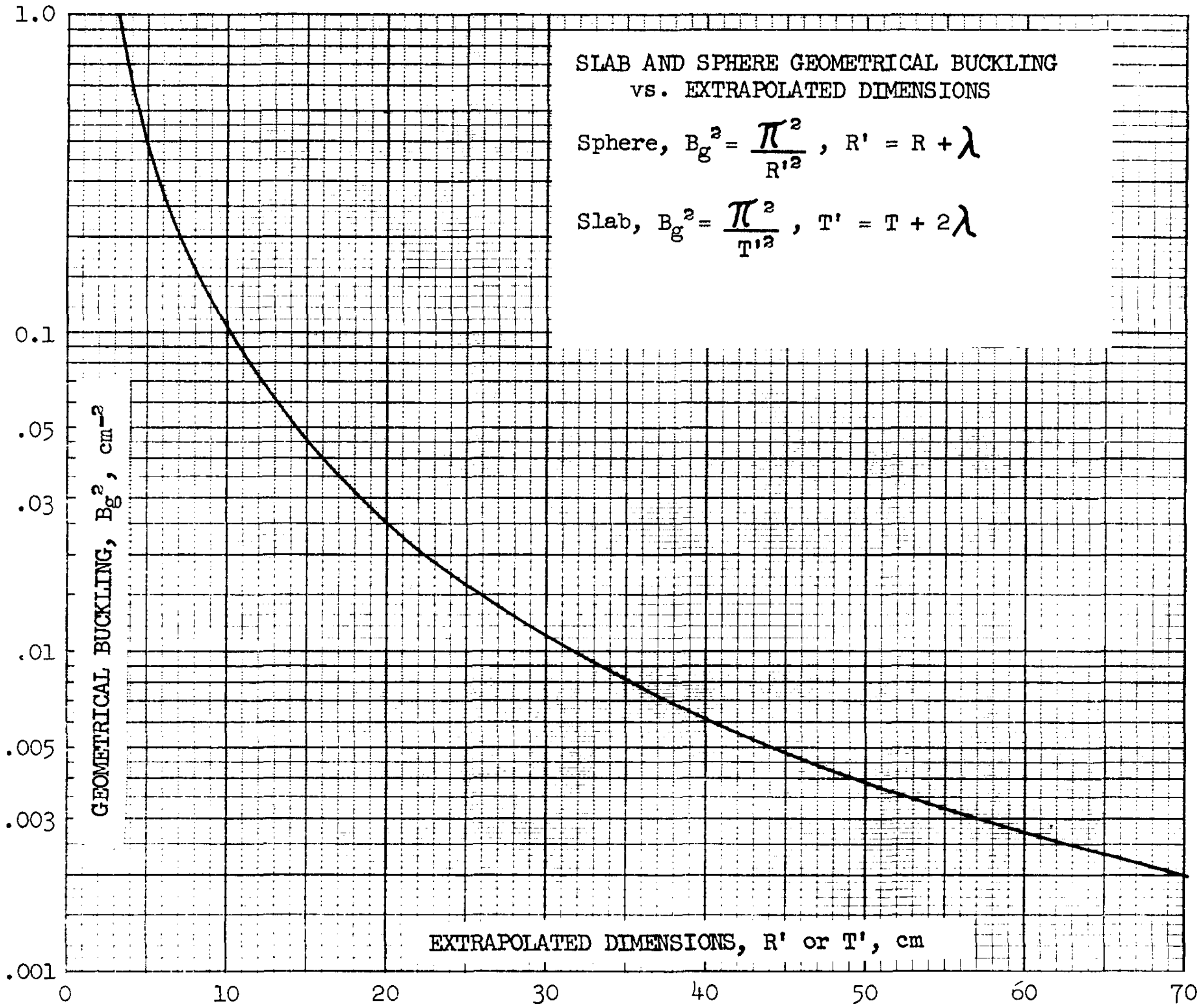
* Raymond L. Murray, et al, Nuclear Science and Engineering, October, 1968.

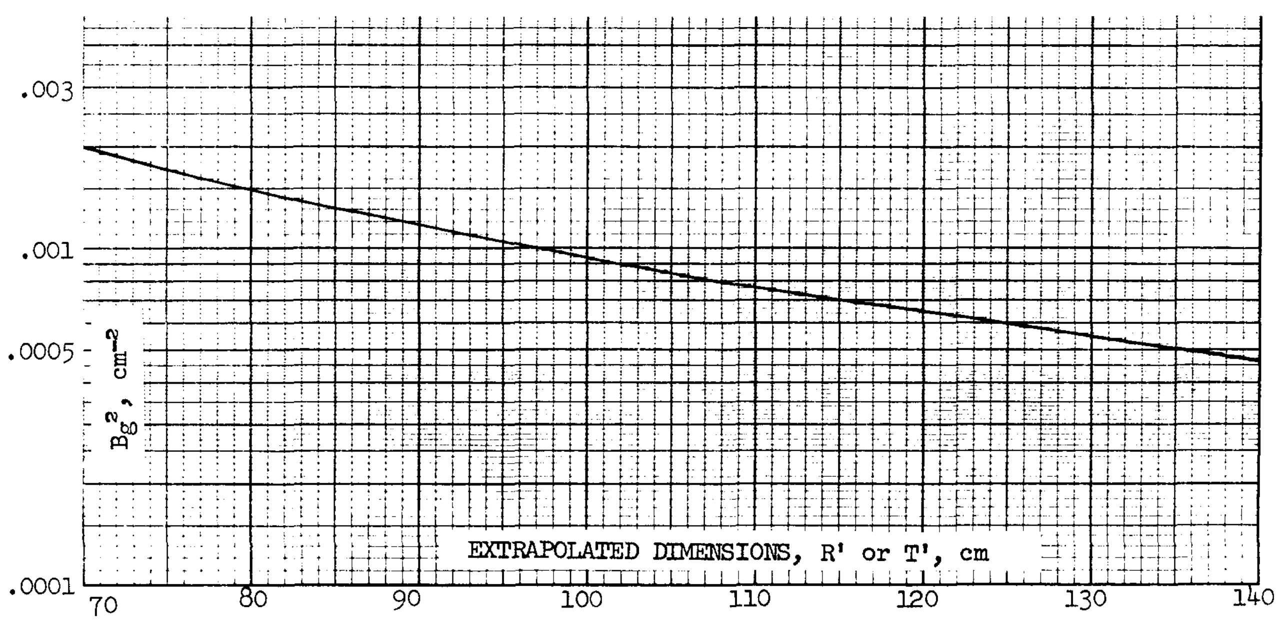
BUCKLING OF N-SIDED POLYGONS (CONTINUED)

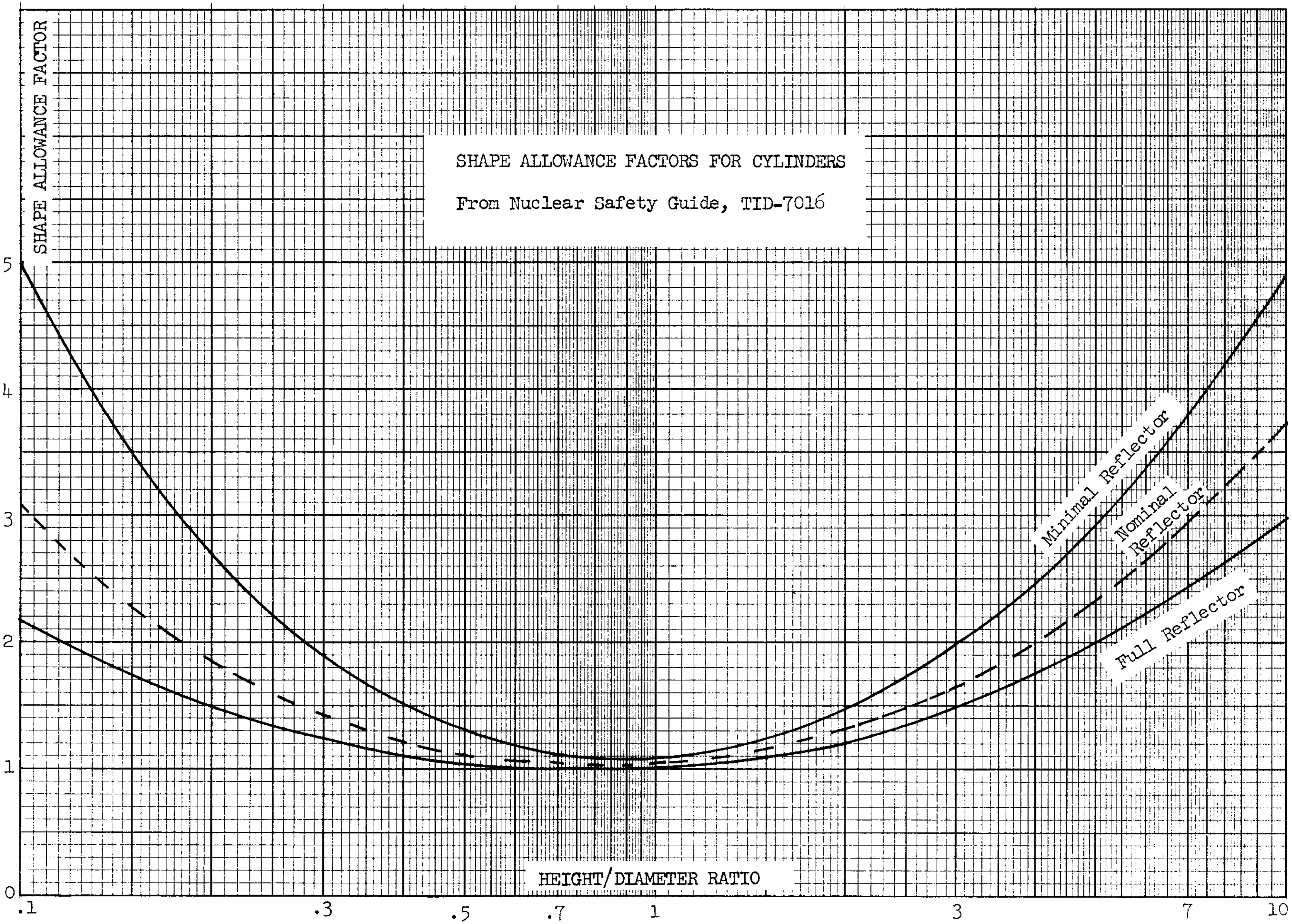
No. Sides	$B_g^2 - \pi^2/H^2$
16	$5.7154/R^2$
17	$5.7228/R^2$
18	$5.7291/R^2$
19	$5.7344/R^2$
20	$5.7390/R^2$
∞	$5.7831/R^2$ (= J_o^2/R^2 or cylinder, see p. II.B.2-1)


CYLINDER GEOMETRICAL BUCKLING
vs. EXTRAPOLATED DIMENSIONS
$B_g^2 = \frac{J_o^2}{R'^2} + \frac{\pi^2}{H'^2}$
$R' = R + \lambda$
$H' = H + 2\lambda$
H' = 5.0 cm
10.0
15.0
20.0
30.0
40.0
50.0
75.0
100.0
Infinite Cylinder
GEOMETRICAL BUCKLING, B_g^2, cm^{-2}
EXTRAPOLATED CYLINDER RADIUS, R', cm
1.0
0.5
0.3
0.1
.05
.03
.01
.005
.003
.001
0
10
20
30
40
50
60
70


50.0
75.0
100.0
Infinite Cylinder
B_g^2, cm^{-2}
EXTRAPOLATED CYLINDER RADIUS, R', cm
.005
.003
.001
.0005
.0003
.0001
70
80
90
100
110
120
130
140


SLAB AND SPHERE GEOMETRICAL BUCKLING
vs. EXTRAPOLATED DIMENSIONS
Sphere, $B_g^2 = \frac{\pi^2}{R'^2}$, R' = R + λ
Slab, $B_g^2 = \frac{\pi^2}{T'^2}$, T' = T + 2λ
GEOMETRICAL BUCKLING, B_g^2, cm^{-2}
EXTRAPOLATED DIMENSIONS, R' or T', cm
1.0
0.1
.05
.03
.01
.005
.003
.001
0
10
20
30
40
50
60
70


B_g^2, cm^{-2}
EXTRAPOLATED DIMENSIONS, R' or T', cm
.003
.001
.0005
.0001
70
80
90
100
110
120
130
140


SHAPE ALLOWANCE FACTORS FOR CYLINDERS
From Nuclear Safety Guide, TID-7016
SHAPE ALLOWANCE FACTOR
HEIGHT/DIAMETER RATIO
Minimal Reflector
Nominal Reflector
Full Reflector
0
1
2
3
4
5
.1
.3
.5
.7
1
3
7
10

PHYSICAL PROPERTIES OF Pu METAL AND ALLOYS[1]

Plutonium Metal

Density 19.6 g/cm^3 - solid   19.81 g/cm^3 theoretical[2]

16.62 g/cm - liquid metal 664°C   liquid Pu g/cm^3 = (17.66-1.52 x 10^{-3} °C)

Melting Point 640°C

Pu-Al Alloys

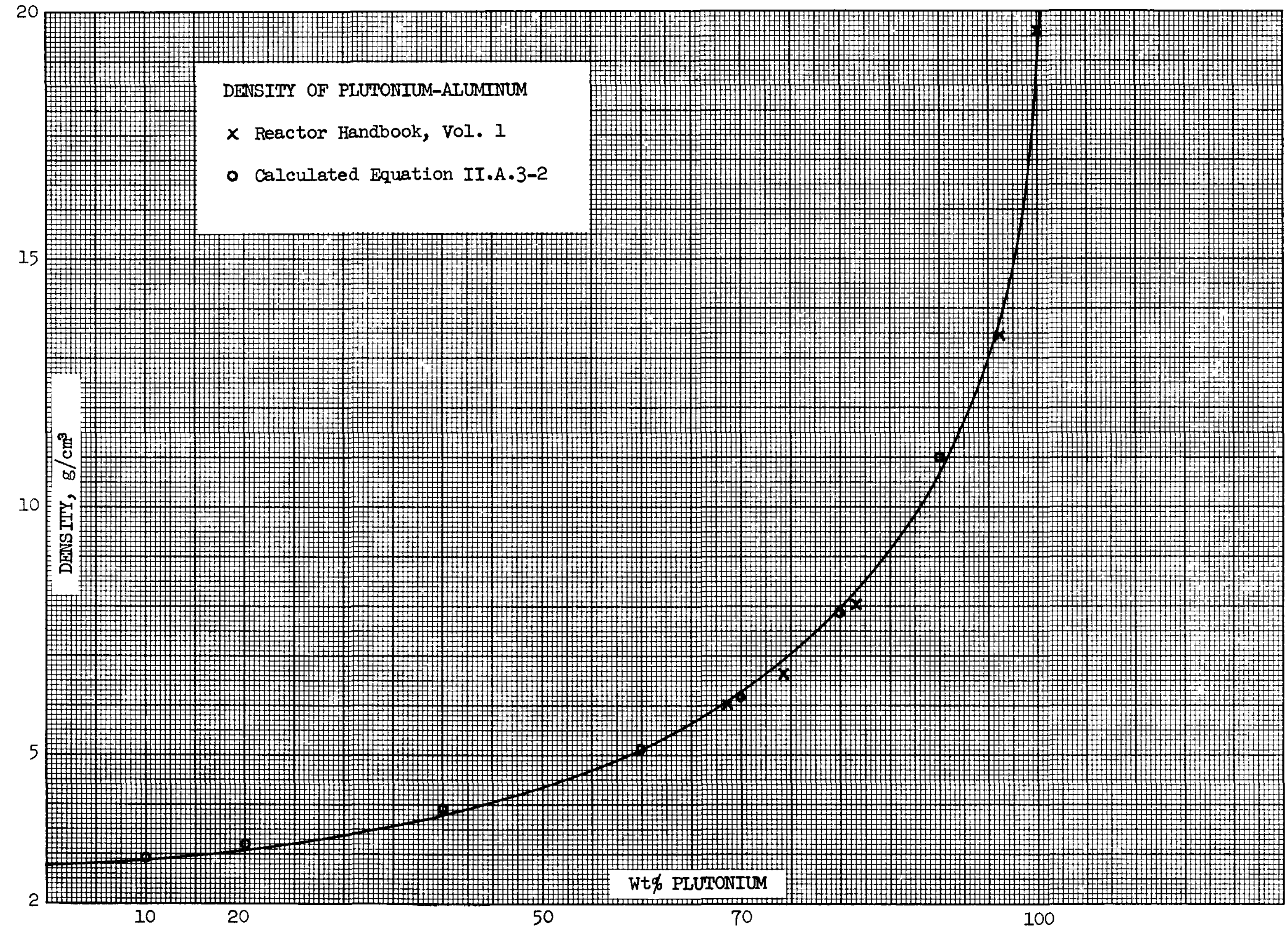
See II.A.3-2

Pu-U-Mo Alloys

Alloy Composition atom %	Density as Cast g/cm^3
20 Pu - 72U - 8 Mo	17.64
20 Pu - 70U - 10 Mo	17.26
20 Pu - 68U - 12 Mo	17.12
15 Pu - 70U - 15 Mo	17.54
20 Pu - 60U - 20 Mo	17.11

(1) Plutonium Handbook, Vol. 1, O. J. Wick, 1967.

(2) Under special conditions 19.8 g/cm^3 can be obtained.


DENSITY OF PLUTONIUM-ALUMINUM
x Reactor Handbook, Vol. 1
o Calculated Equation II.A.3-2
DENSITY, g/cm³
Wt% PLUTONIUM
20
15
10
5
2
10
20
50
70
100

PHYSICAL CONSTANTS OF PLUTONIUM COMPOUNDS[1]

Compound	Melting Point	Crystalline Color	Density Theoretical	Density Bulk	Density Tap
PuC	1654°C		13.6		
Pu_2C_3	2050		12.7		
PuC_2	2250		--		
$PuCl_3$	760	green	5.7	1.9[2]	
PuF_3	1425	violet	9.32		
PuF_4	1037	pale brown	7.0	1.38	
PuF_6	51	red-brown	--		
PuH_2	oxidizes @ 150	grey metallic	10.4		
PuH_3	oxidizes @ 150	black	9.61		
$Pu(OH)_4$	oxidizes @ 70	green	--		
$Pu(C_2O_4)_2$	decomposes @ 160	yellow-green	--	0.6[2]	
$Pu_2(C_2O_4)_3$	decomposes @ 260	--	--		
Pu Peroxide		green	3.71		0.7
PuO_2 (oxalate)	2390	yellow-green to brown	11.46	0.7	0.92
PuO_2 (nitrate)	2390	yellow-green to brown	11.46	1.48	1.58
Pu_2O_3	2085		10.2		
PuN	2584[3]	brown to black	14.22		
$Pu(NO_3)_4 \cdot 5H_2O$		brown	2.90		
$PuO_2(NO_3)_2$	decomposes @ 220	pink-brown			
$PuO_2(NO_3)_2$	unstable in air				
PuP			9.87		
$PuPO_4$	decomposes @1400	blue	7.55		
PuSi	1576		10.15		
Pu_3Si_5	1646		8.96		
PuS	2350	gold-brown	10.6		
$Pu(SO_4)_2$	decomposes @ 650	pink			

(1) Plutonium Handbook Volume I. O. J. Wick, editor.

(2) Reactor Handbook Volume II. S. M. Stoller, editor.

(3) In nitrogen atmosphere, volatile above 1600°C in vacuum.

BULK AND TAP DENSITIES OF PLUTONIUM OXIDE PREPARED IN SEVERAL DIFFERENT WAYS

Starting Material	Decomposition Temperature	Bulk Density g/cc	Tap Density g/cc
Pu Nitrate	240°C	1.7	2.1
"	400	1.9	2.4
"	600	1.7	1.8
"	800	2.9	3.6
"	1000	--	--
Pu Peroxide	240°C	3.5	4.1
"	400	3.8	4.3
"	600	3.9	4.4
"	800	4.5	4.8
"	1000	4.9	5.8
Pu(IV) Oxalate	240°C	1.0	1.4
"	400	1.1	1.5
"	600	1.2	1.5
"	800	1.4	1.7
"	1000	1.7	2.3
Pu Hydroxide	240°C *	2.9	3.2
"	400 *	3.7	4.2
"	600 *	3.5	4.0
"	800	3.2	3.7
"	1000	3.8	4.2
Pu Metal	Unknown	4.8	5.3

*Average of two or more measurements. Other data are single measurements.
RFP-503.

RELATIONSHIP OF COMPONENTS IN HOMOGENEOUS PLUTONIUM MIXTURES

Plutonium Metal - Water Systems

$$\rho_{Pu}(g/cc) = \frac{26.527}{1.353 + H/Pu} \quad (1)(2)$$

Plutonium Nitrate, $Pu(NO_3)_4$

$$\rho_{solution} = 1.0 + 0.031\ M_{HNO_3} + 0.00146\ Pu\ g/l,\ \pm 5\% \quad (4)$$

for $HNO_3 < 9M$ $Pu < 2.1M$

$$\rho_{solution} = 1.0 + 0.031\ M_{HNO_3} + 0.00134\ Pu\ g/l,\ \pm 5\%$$

for $HNO_3 > 9M$ $Pu \geq 2.1M$

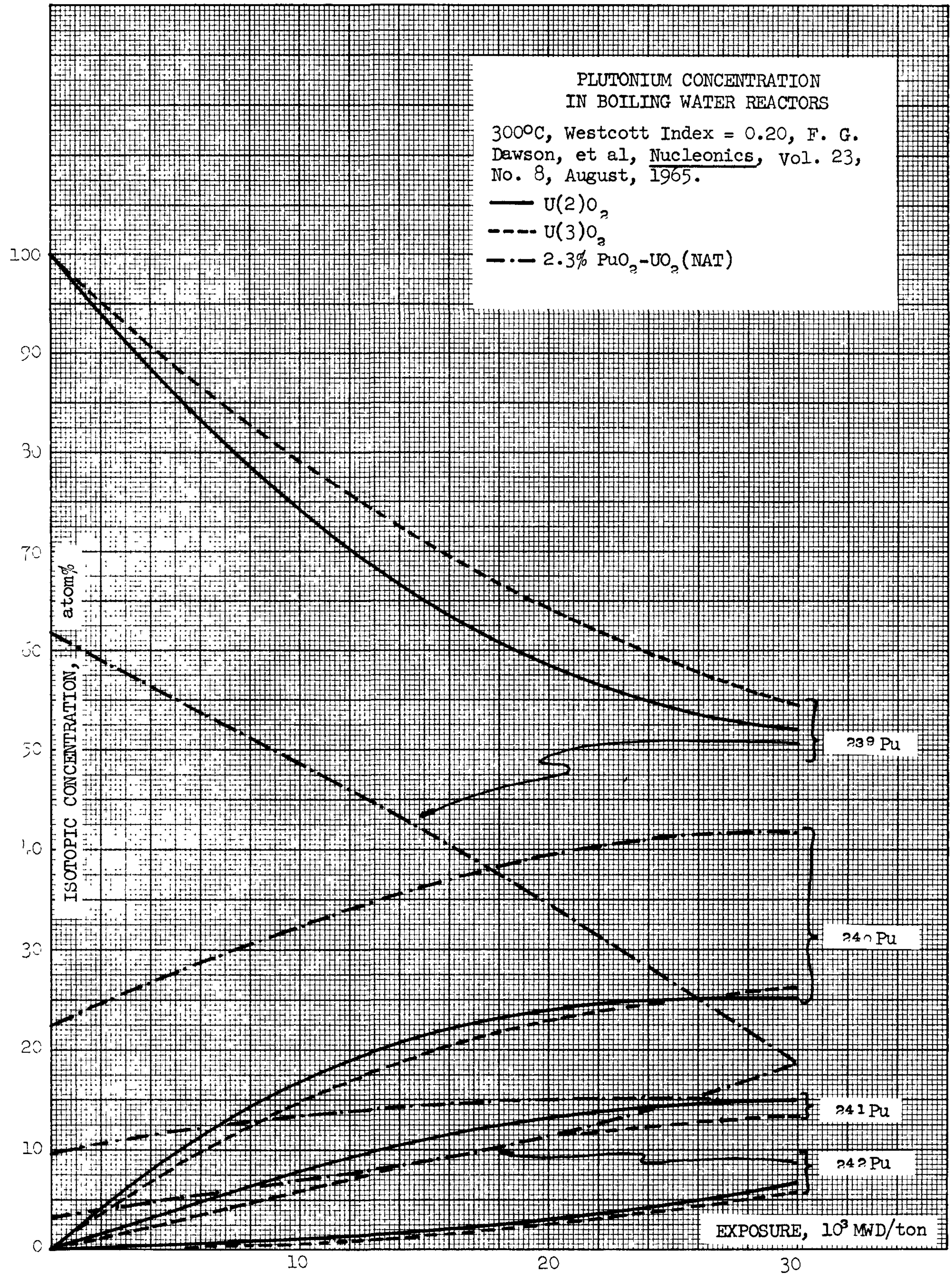
$$\rho_{H_2O}\ g/l = 1000 - \left[.362\ Pu\ g/l + 33.1\ M_{HNO_3}\ \text{Excess}\right] \quad (3)$$

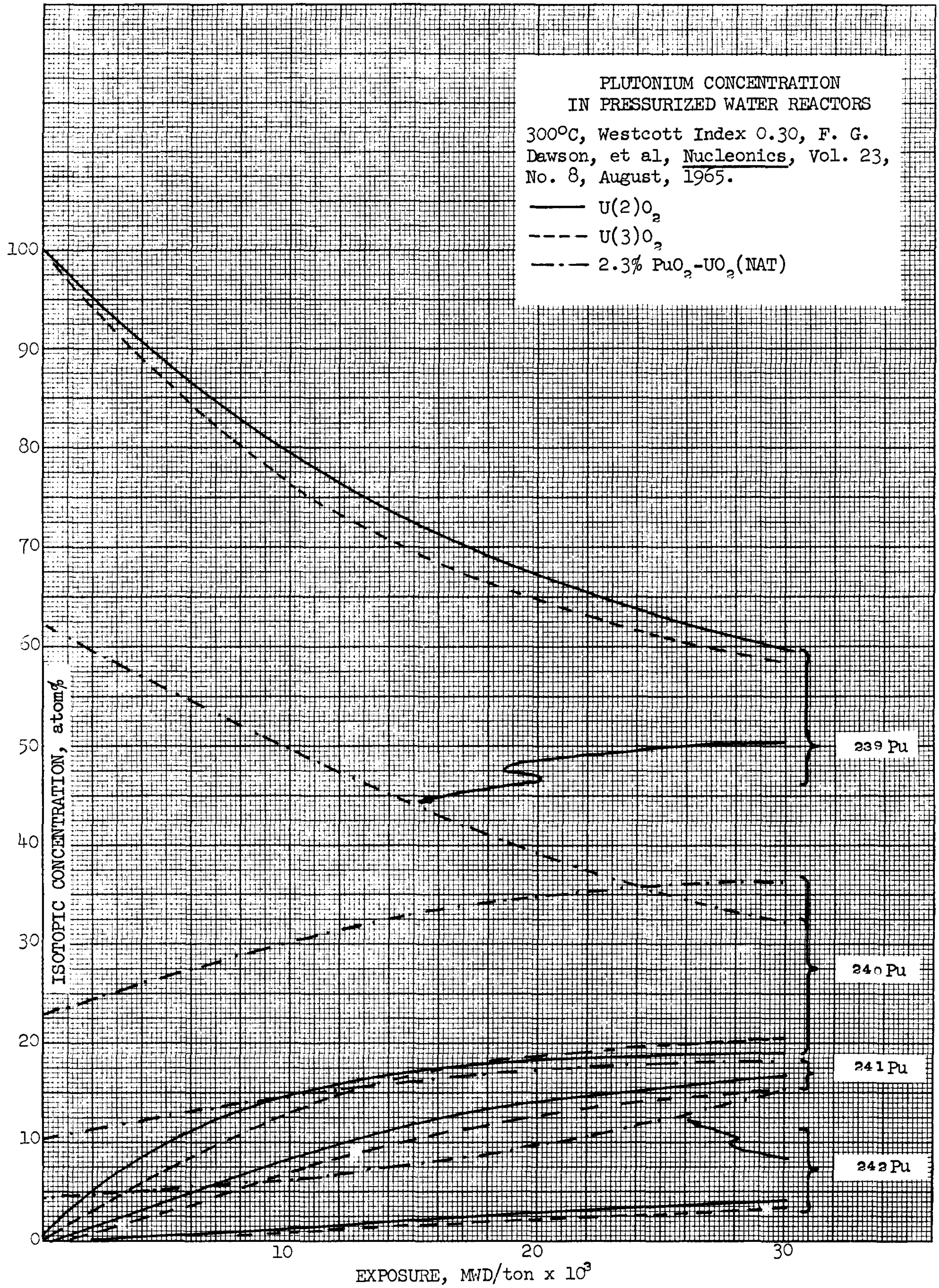
(1) H. C. Paxton, "Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu and ^{233}U," TID-7028, June, 1968.

(2) W. R. Stratton, "Criticality Data and Factors Affecting Criticality," LA-3612, 1967.

(3) C. R. Richey, Nuclear Science and Engineering, Vol. 31, No. 1, 1968.

(4) S. M. Stoller, Reactor Handbook, Vol. II, Interscience Pub., 1961.


PLUTONIUM CONCENTRATION
IN BOILING WATER REACTORS
300°C, Westcott Index = 0.20, F. G. Dawson, et al, Nucleonics, Vol. 23, No. 8, August, 1965.
U(2)O2
U(3)O2
2.3% PuO2-UO2(NAT)
ISOTOPIC CONCENTRATION, atom%
EXPOSURE, 10³ MWD/ton
239 Pu
240 Pu
241 Pu
242 Pu
0
10
20
30
40
50
60
70
80
90
100


PLUTONIUM CONCENTRATION
IN PRESSURIZED WATER REACTORS
300°C, Westcott Index 0.30, F. G. Dawson, et al, Nucleonics, Vol. 23, No. 8, August, 1965.
U(2)O2
U(3)O2
2.3% PuO2-UO2(NAT)
239 Pu
240 Pu
241 Pu
242 Pu
ISOTOPIC CONCENTRATION, atom%
EXPOSURE, MWD/ton x 10³
0
10
20
30
40
50
60
70
80
90
100

PHYSICAL PROPERTIES OF URANIUM METAL AND ALLOYS

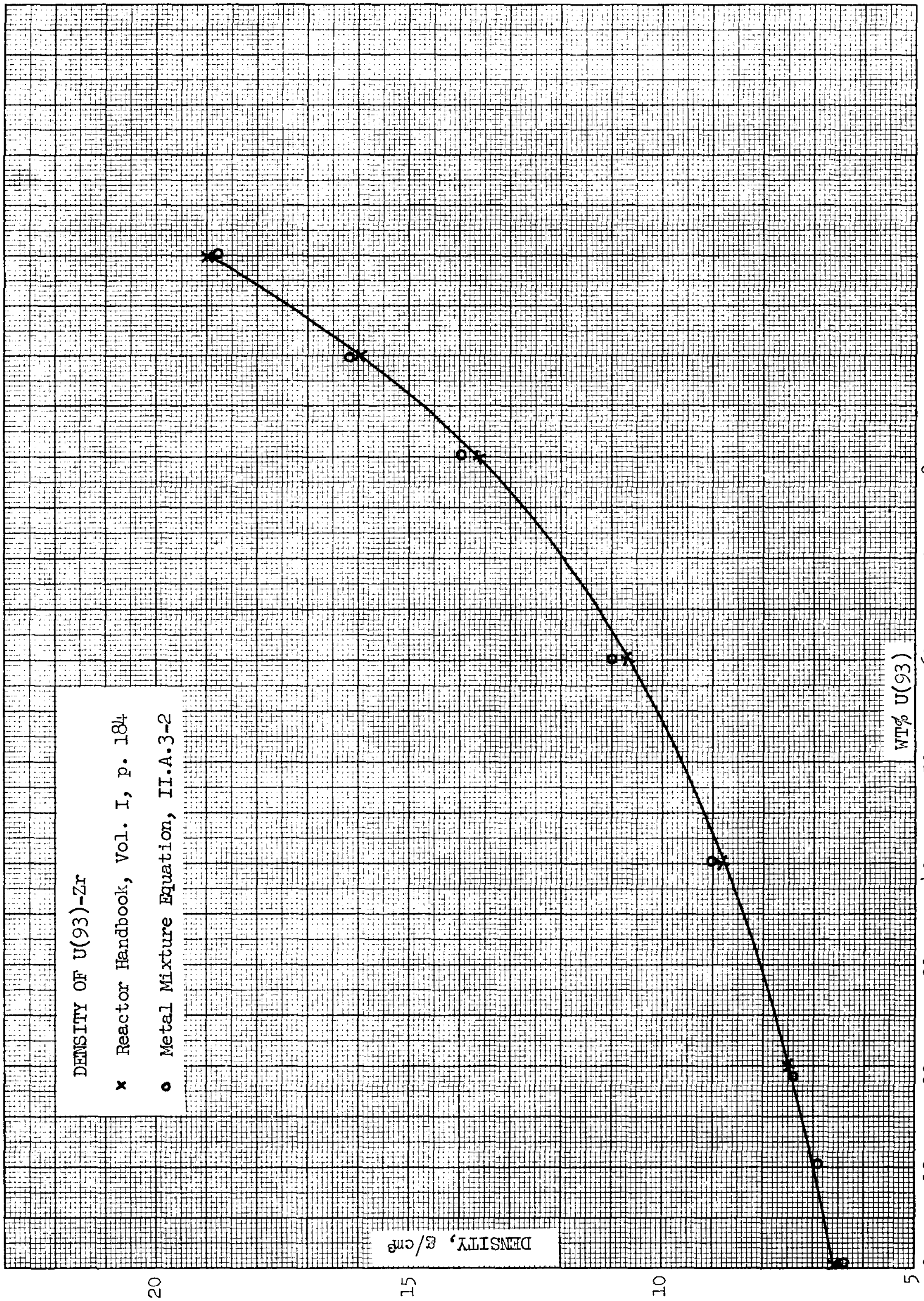
Uranium Metal

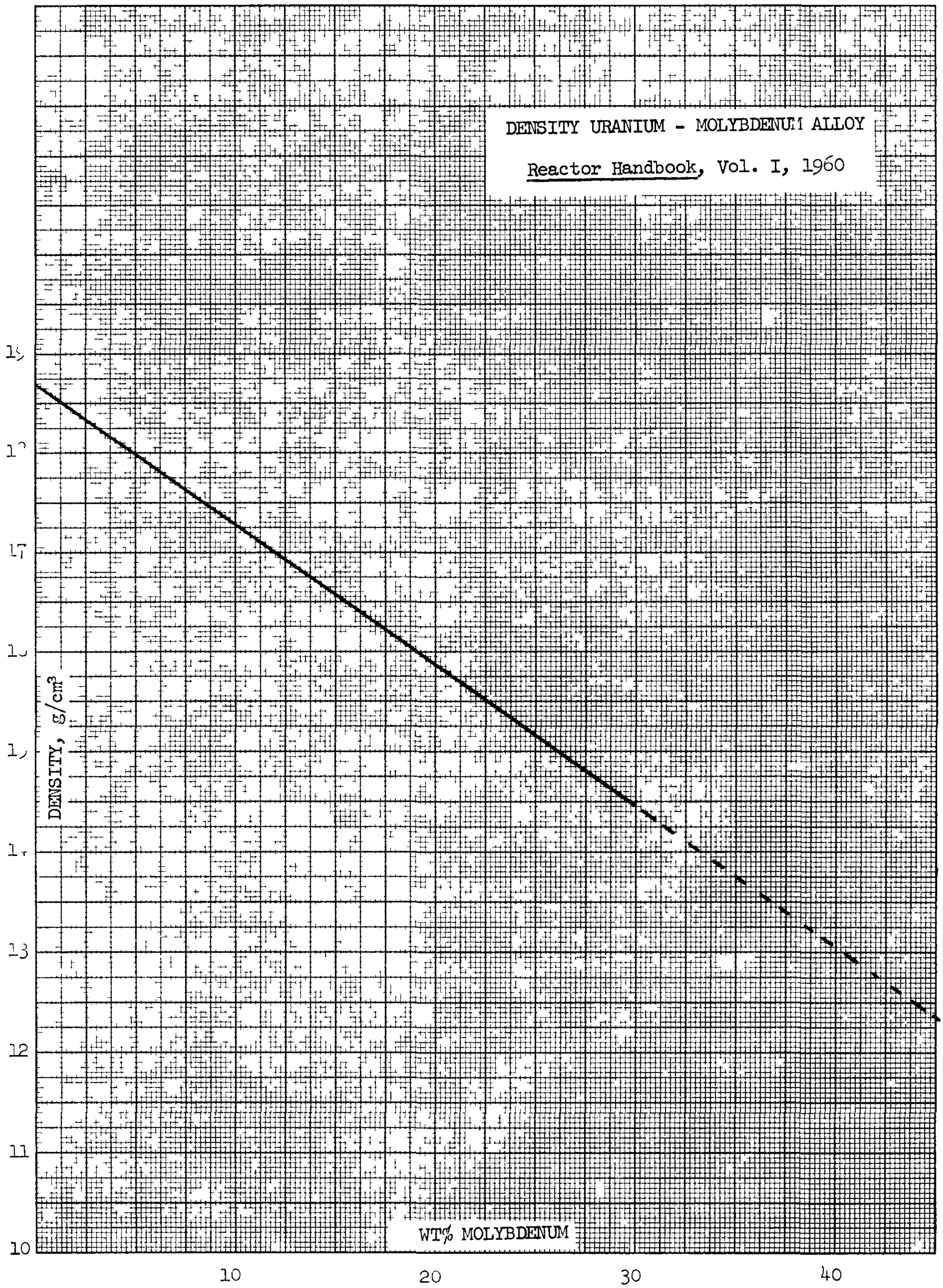
Density, 18.9[1] α 19.04 g/cm³ theoretical[1]

γ 18.0

Melting Point, 1130° C[1] Boiling Point, 3900° C

(1) C. R. Tipton, et al, Reactor Handbook, Vol. I, 1960.

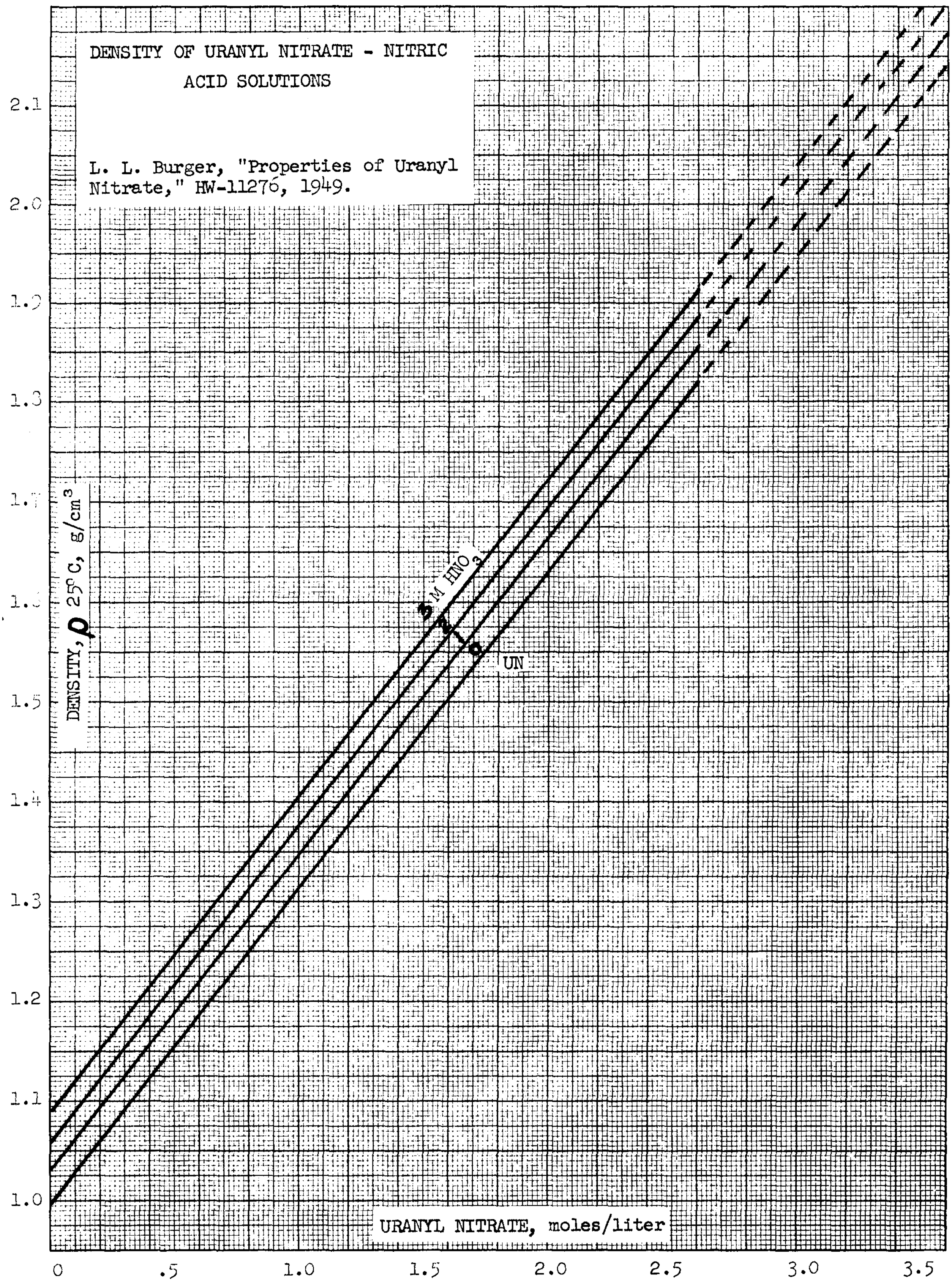

DENSITY OF U(93)-Zr
x Reactor Handbook, Vol. I, p. 184
o Metal Mixture Equation, II.A.3-2
WT% U(93)
DENSITY, g/cm³
0
10
20
30
40
50
60
70
80
90
100
5
10
15
20

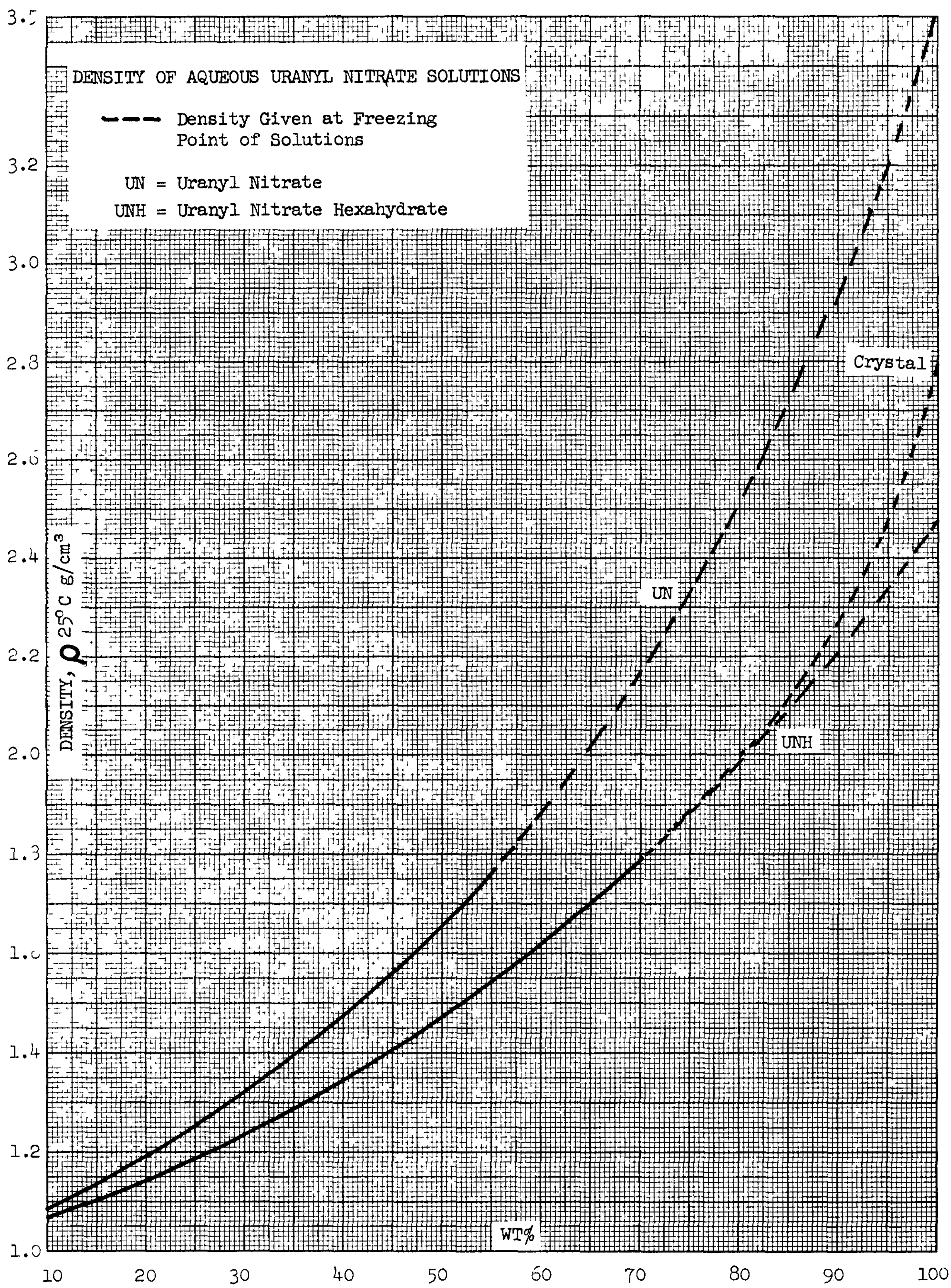

DENSITY URANIUM - MOLYBDENUM ALLOY
Reactor Handbook, Vol. I, 1960
DENSITY, g/cm^3
17
13
12
11
10
WT% MOLYBDENUM
10
20
30
40

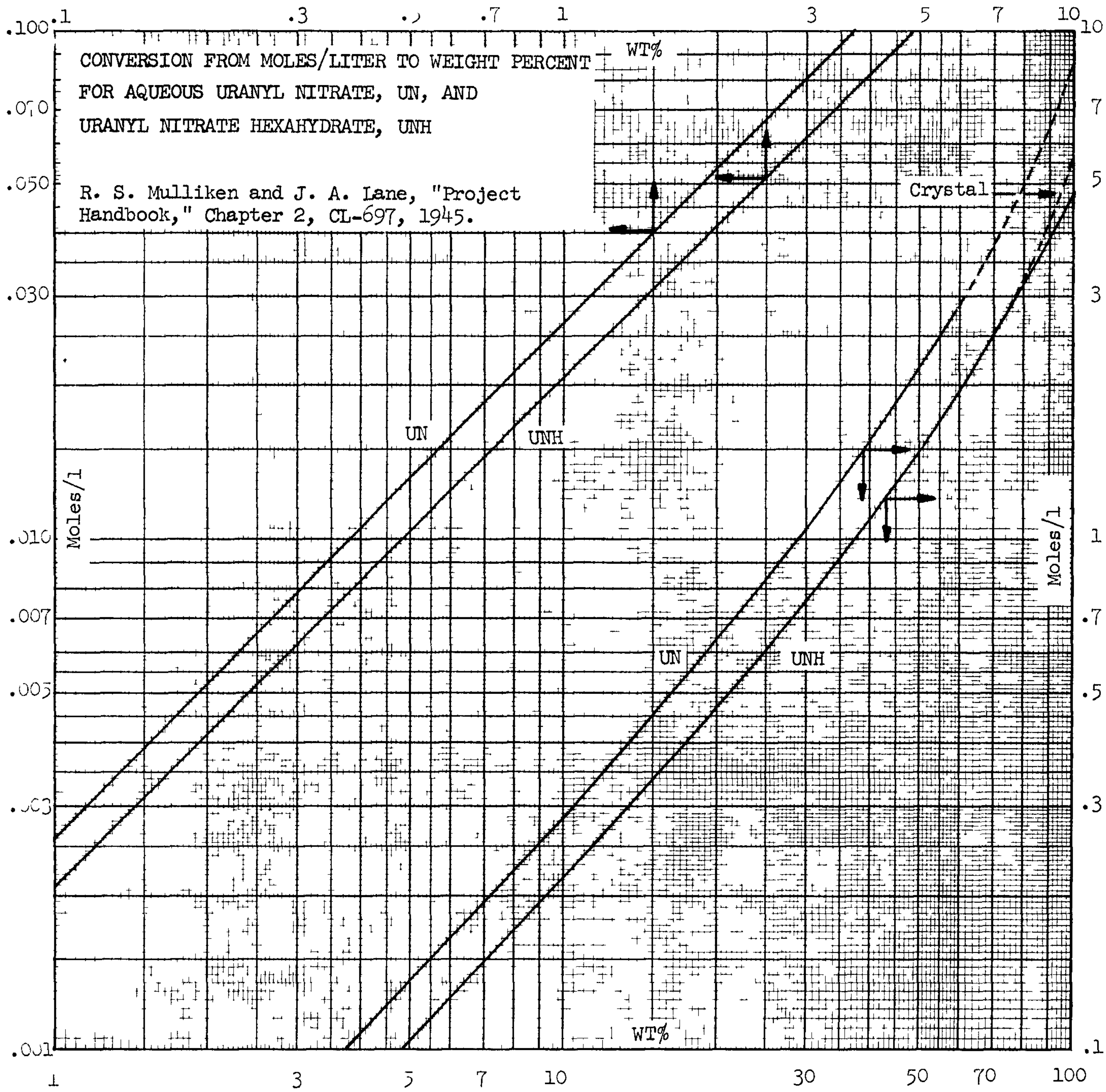
PHYSICAL PROPERTIES OF URANIUM COMPOUNDS[1]

Compound	Weight Percent Uranium	Crystalline Color	Theoretical Density
UCl_4	--	--	4.87
UCl_6	--	--	3.59
UF_4	0.758	Green	6.7
UF_6	0.676	Pale Yellow	5.06
UH_3	--	--	10.92
UO_2	0.882	Brown-Black	10.96
U_3O_8	0.849	Olive Green-Black	8.39
UO_3	0.833	Yellow-Red	8.34
$UO_4 \cdot 2\ H_2O$	0.704	Pale Yellow	--
$UO_2(NO_3)_2$	0.604	--	--
$UO_2(NO_3)_2 \cdot 6\ H_2O$	0.474	Yellow	2.807
UO_2SO_4	0.650	--	--
$UO_2SO_4 \cdot 3\ H_2O$	0.567	Yellow-Green	3.28
$2\ UO_2SO_4 \cdot 7\ H_2O$	0.555	Yellow	--
UO_2F_2	--	White	6.37

(1) J. W. Wachter, "Y-12 Plant Nuclear Safety Handbook," Y-1272, 1963.


DENSITY OF URANYL NITRATE - NITRIC ACID SOLUTIONS
L. L. Burger, "Properties of Uranyl Nitrate," HW-11276, 1949.
DENSITY, ρ 25° C, g/cm³
URANYL NITRATE, moles/liter
3 M HNO3
2
1
0
UN
2.1
2.0
1.5
1.4
1.3
1.2
1.1
1.0
0
.5
1.0
1.5
2.0
2.5
3.0
3.5


DENSITY OF AQUEOUS URANYL NITRATE SOLUTIONS
Density Given at Freezing Point of Solutions
UN = Uranyl Nitrate
UNH = Uranyl Nitrate Hexahydrate
Crystal
UN
UNH
DENSITY, ρ 25°C g/cm³
WT%
3.2
3.0
2.4
2.2
2.0
1.4
1.2
1.0
10
20
30
40
50
60
70
80
90
100


CONVERSION FROM MOLES/LITER TO WEIGHT PERCENT
FOR AQUEOUS URANYL NITRATE, UN, AND
URANYL NITRATE HEXAHYDRATE, UNH
R. S. Mulliken and J. A. Lane, "Project Handbook," Chapter 2, CL-697, 1945.
WT%
UN
UNH
Crystal
Moles/l
Moles/l
UN
UNH
WT%
.100
.070
.050
.030
.010
.007
.005
.003
.001
.1
.3
.5
.7
1
3
5
7
10
10
7
5
3
1
.7
.5
.3
.1
1
3
5
7
10
30
50
70
100

H/U RELATIONSHIPS OF URANIUM

^{235}U Metal - Water Systems

$$\rho_{235} = \frac{26.082}{(138.0/\text{Wt\% } ^{235}\text{U}) + \text{H}/^{235}\text{U}}$$

^{235}U Metal - Graphite Systems

$$\rho_{235} = \frac{37.176}{(196.7/\text{Wt\% } ^{235}\text{U}) + \text{C}/^{235}\text{U}}$$

^{233}U Metal - Water Systems

$$\rho_{233} = \frac{25.860}{(137.7/\text{Wt\% } ^{233}\text{U}) + \text{H}/^{233}\text{U}}$$

General Equation, U Metal - Water Systems

$$\rho_u = \frac{26.415}{\left[1 + (238.0/A_x - 1)f_x\right]\text{H/U} + 1.398}$$

where A_x = atomic weight of ^{233}U (233.0) or ^{235}U (235.0)

f_x = wt. fraction of ^{233}U or ^{235}U in Uranium

ρ_u (metal) = 18.9

Mol. wt. H_2O = 18.02

DENSITY FORMULAS

Uranyl Nitrate, UN, Natural Uranium

$$\rho_{SOL}^{\text{at } 25^\circ C} \text{ g/cm}^3 = 1.0012 + 0.3177\, M_{UN} + 0.03096\, M_{HNO_3} + 0.051\, M_{NaNO_3} \quad (1)$$

$$\rho_{SOL}^{\text{at } t^\circ C} = 1.0125\, \rho^{25^\circ} + 0.000145\, t - 0.0005\, t\, \rho^{25^\circ} - 0.0036 \quad (2)$$

where $t = {}^\circ C$

Uranium Hexafluoride, UF_6

$$\rho_{UF_6} \text{ g/cm}^3 = 3.668 - 1.553 \times 10^{-2} \Delta t + 7.356 \times 10^{-4} \Delta t^2 - 1.576 \times 10^{-5} \Delta t^3$$

$\rho = \text{g/cm}^3$

$\Delta t = {}^\circ C - 64.052^\circ C$ (triple point)

good over range 65 to 90° C

$$\rho_{UF_6} \text{ g/cm}^3 = 2.0843 - 0.0031\, t + 0.3710 (230.2 - t)^{0.3045}$$

$t = {}^\circ C$

good over range 90 to 230° C

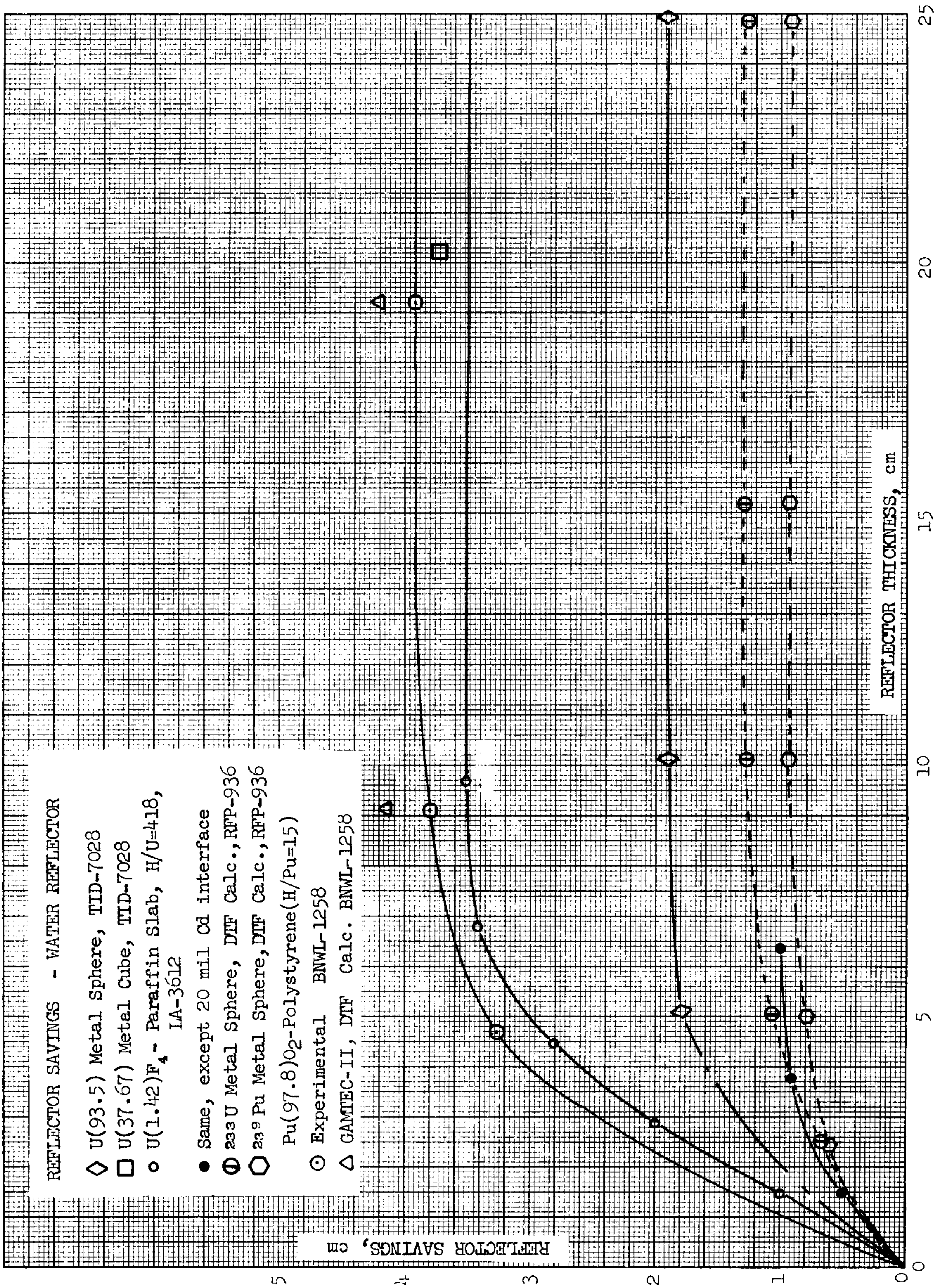
(1) H. W. Fox and W. A. Zisman, J. Coll. Science, 1950.

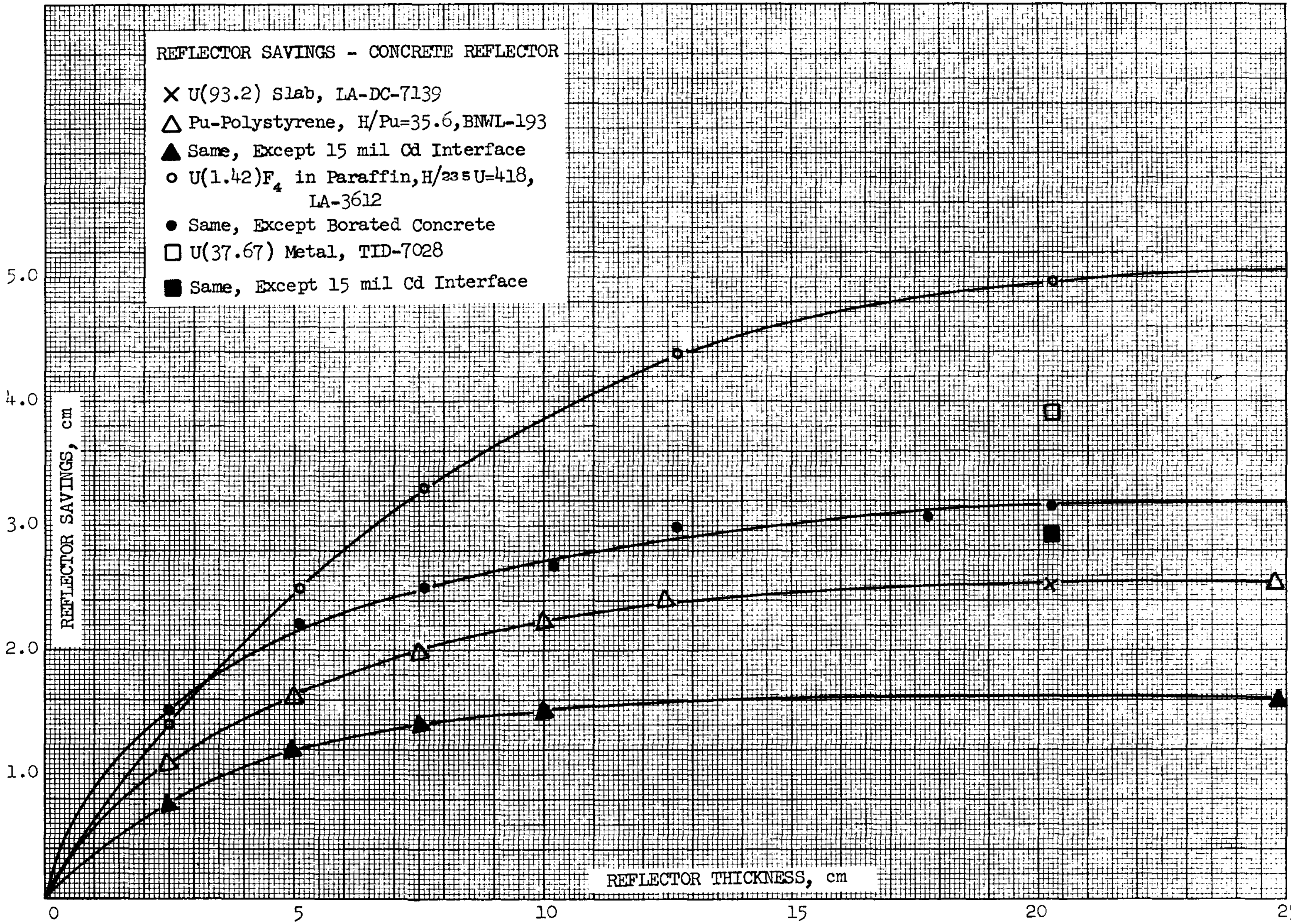
(2) F. H. Getman, Outlines of Physical Chem., John Wiley & Sons, 1946.

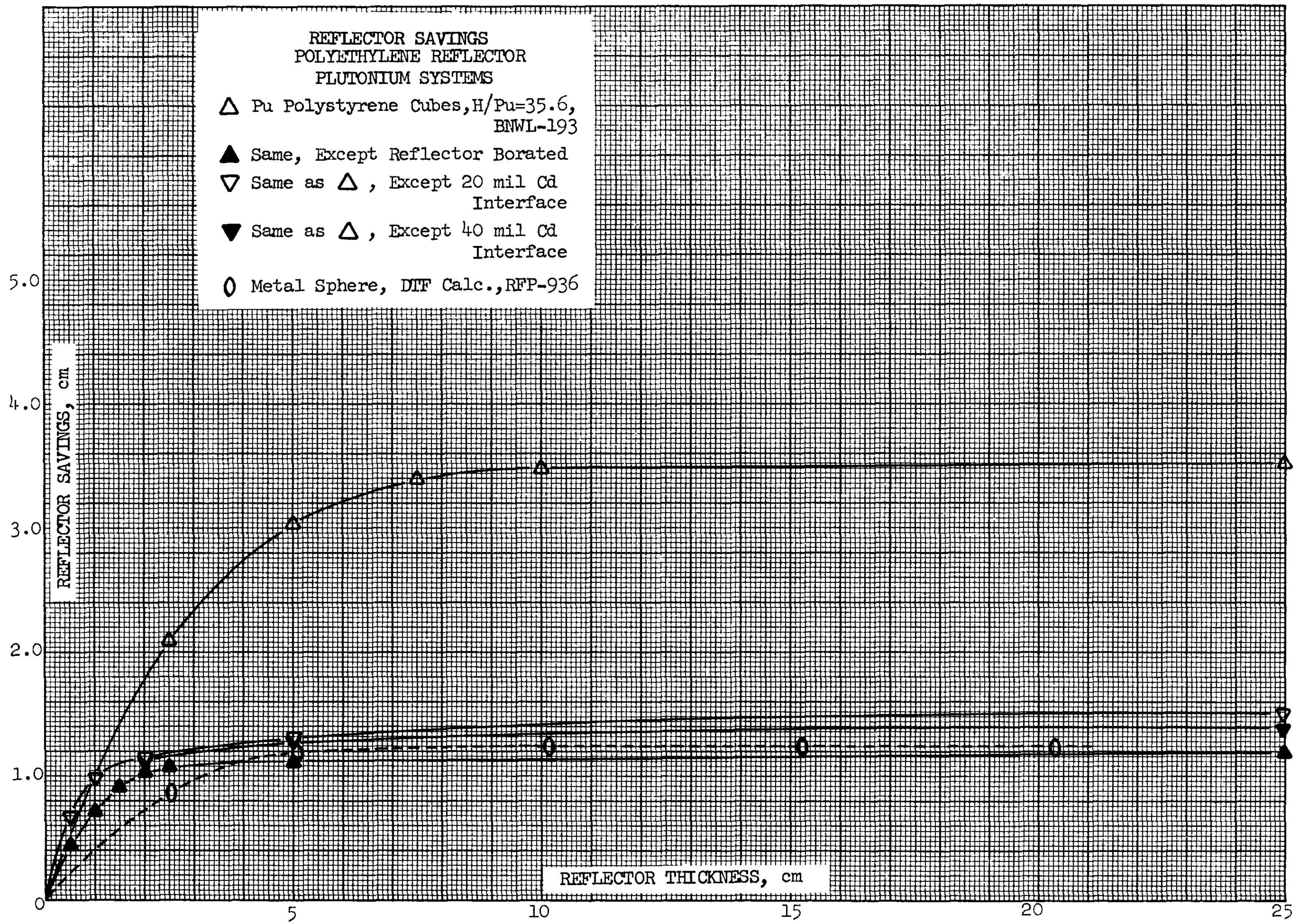
II.E. REFLECTOR SAVINGS AND EXTRAPOLATION DISTANCES

The reflector savings is the amount by which a reflector reduces the critical size of a system from the bare critical size. It can also be defined as the difference between the reflected extrapolation distance and the unreflected extrapolation distance. Whereas, the absolute value of the extrapolation distance is somewhat difficult to obtain experimentally, the reflector savings can be obtained more easily.

The following data is mainly derived from experiment; calculated values are shown by broken lines or otherwise specified.

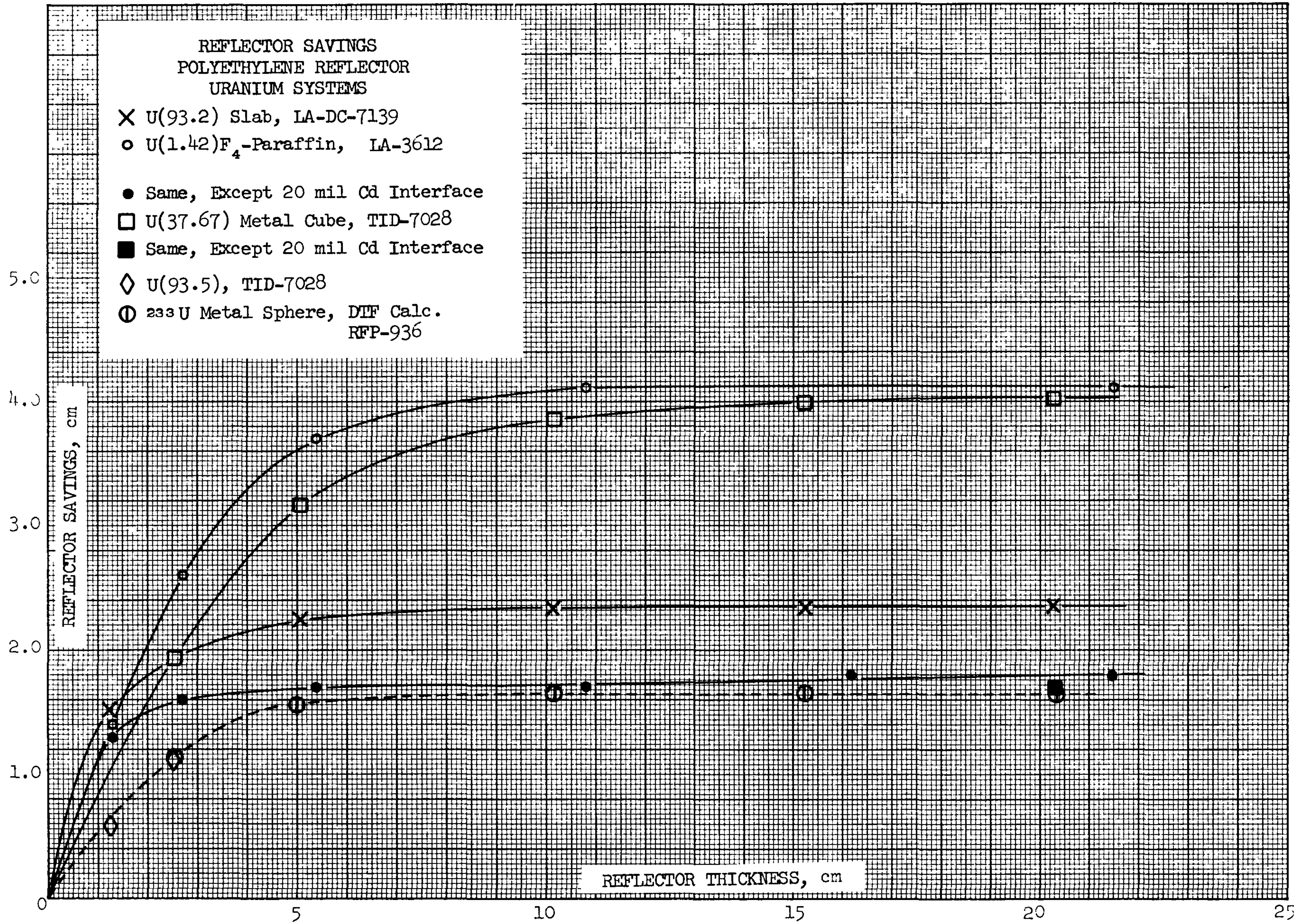

REFLECTOR SAVINGS - WATER REFLECTOR
◇ U(93.5) Metal Sphere, TID-7028
□ U(37.67) Metal Cube, TID-7028
○ U(1.42)F4 - Paraffin Slab, H/U=418, LA-3612
● Same, except 20 mil Cd interface
⊖ 233 U Metal Sphere, DTF Calc., RFP-936
⬡ 239 Pu Metal Sphere, DTF Calc., RFP-936
Pu(97.8)O2-Polystyrene(H/Pu=15)
⊙ Experimental BNWL-1258
△ GAMTEC-II, DTF Calc. BNWL-1258
REFLECTOR SAVINGS, cm
REFLECTOR THICKNESS, cm
0
1
2
3
4
5
10
15
20
25


REFLECTOR SAVINGS - CONCRETE REFLECTOR
× U(93.2) Slab, LA-DC-7139
△ Pu-Polystyrene, H/Pu=35.6, BNWL-193
▲ Same, Except 15 mil Cd Interface
○ U(1.42)F_4 in Paraffin, H/235U=418, LA-3612
● Same, Except Borated Concrete
□ U(37.67) Metal, TID-7028
■ Same, Except 15 mil Cd Interface
REFLECTOR SAVINGS, cm
REFLECTOR THICKNESS, cm
5.0
4.0
3.0
2.0
1.0
0
5
10
15
20
25

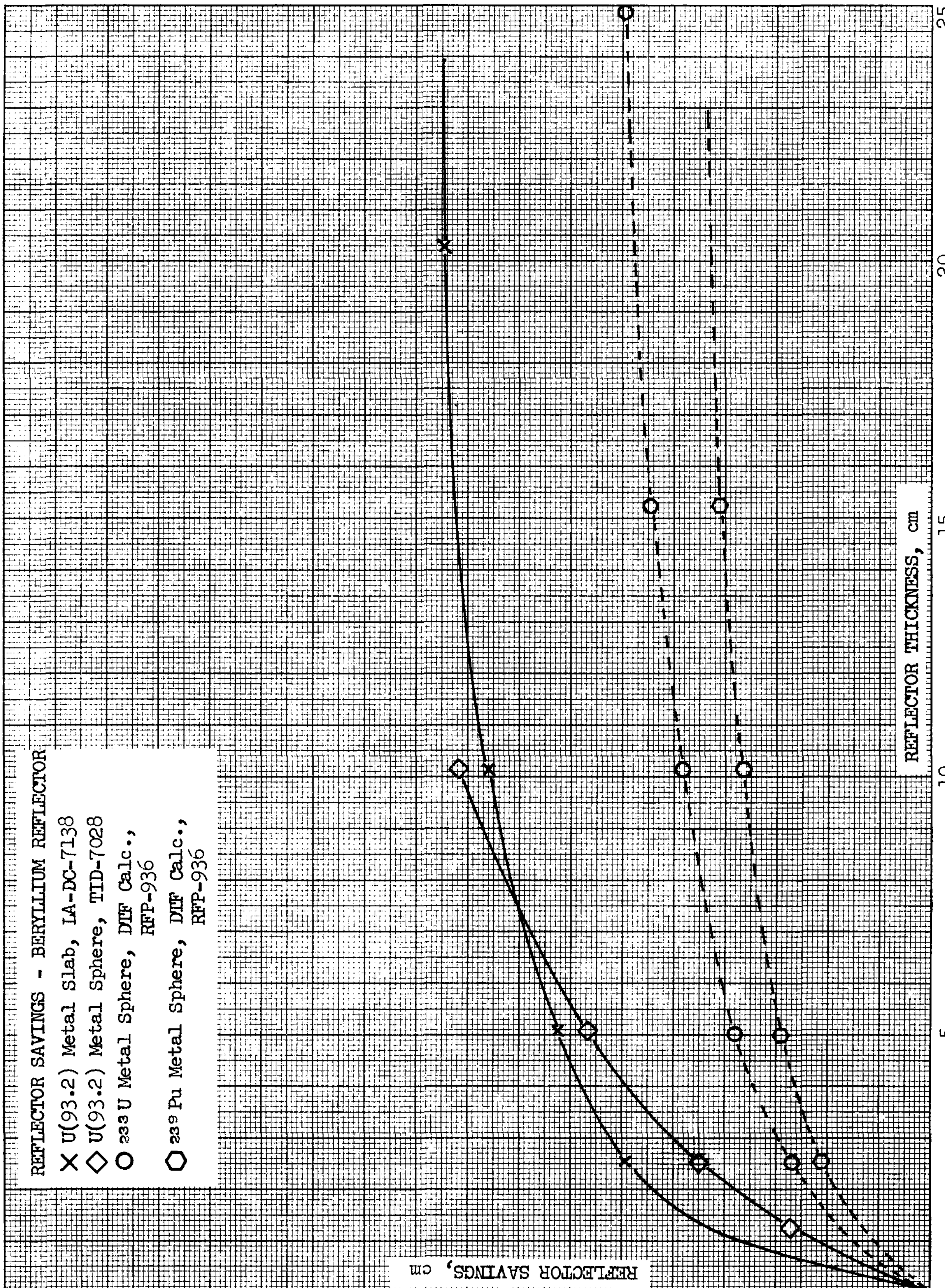

REFLECTOR SAVINGS
POLYETHYLENE REFLECTOR
PLUTONIUM SYSTEMS
△ Pu Polystyrene Cubes, H/Pu=35.6, BNWL-193
▲ Same, Except Reflector Borated
▽ Same as △, Except 20 mil Cd Interface
▼ Same as △, Except 40 mil Cd Interface
0 Metal Sphere, DTF Calc., RFP-936
REFLECTOR SAVINGS, cm
REFLECTOR THICKNESS, cm
0
1.0
2.0
3.0
4.0
5.0
5
10
15
20
25

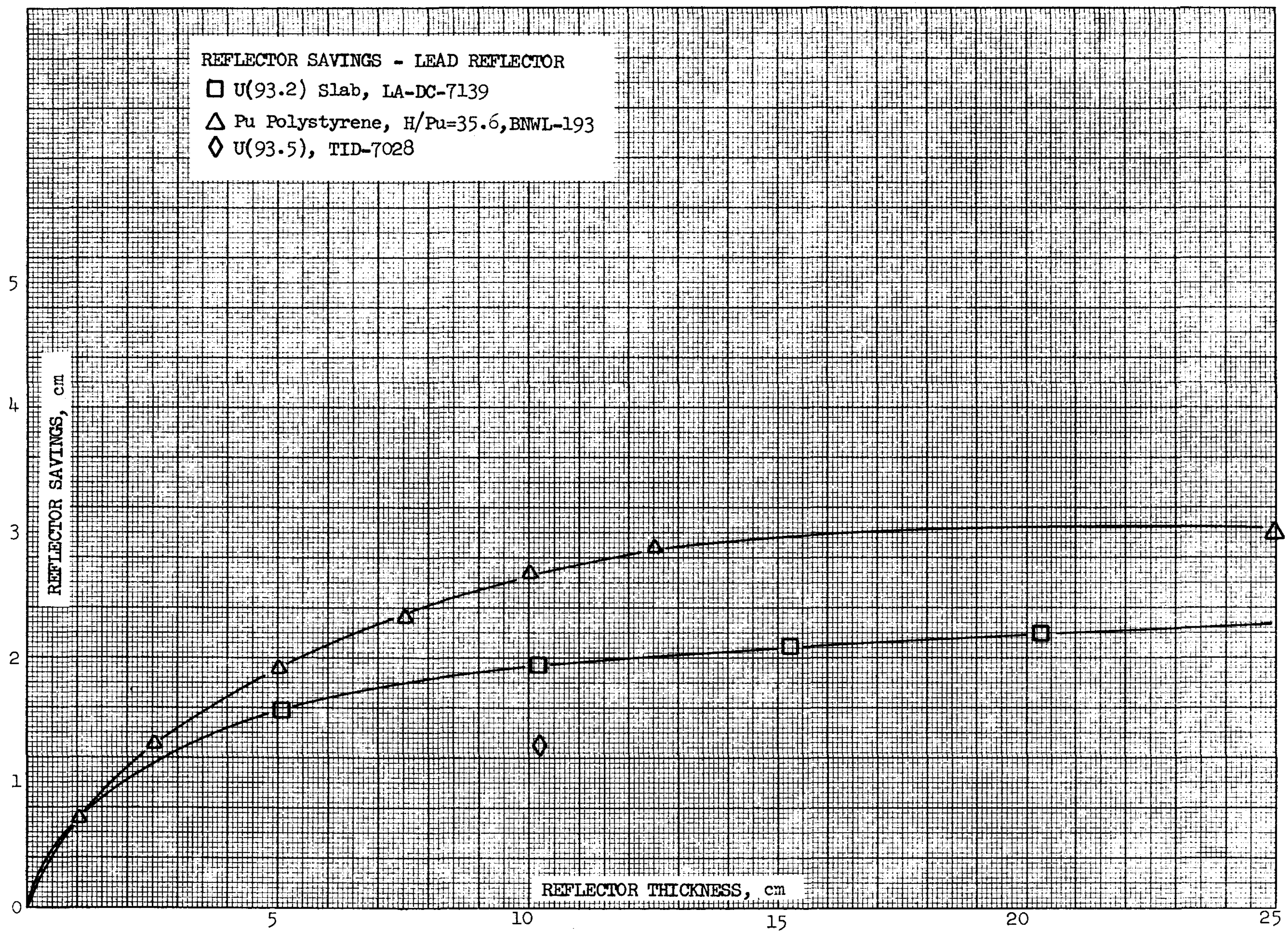
II.E-4

ARH-600

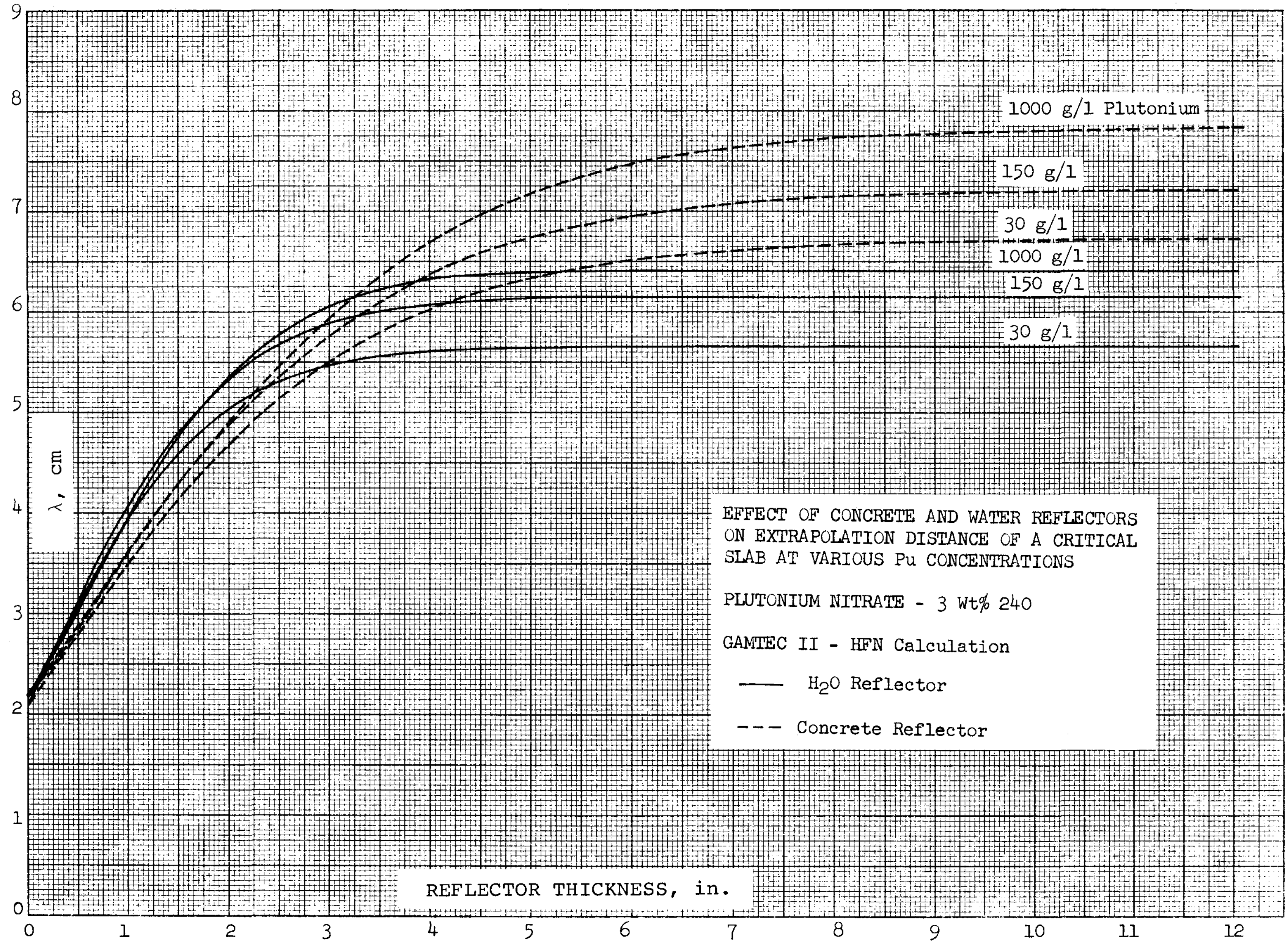


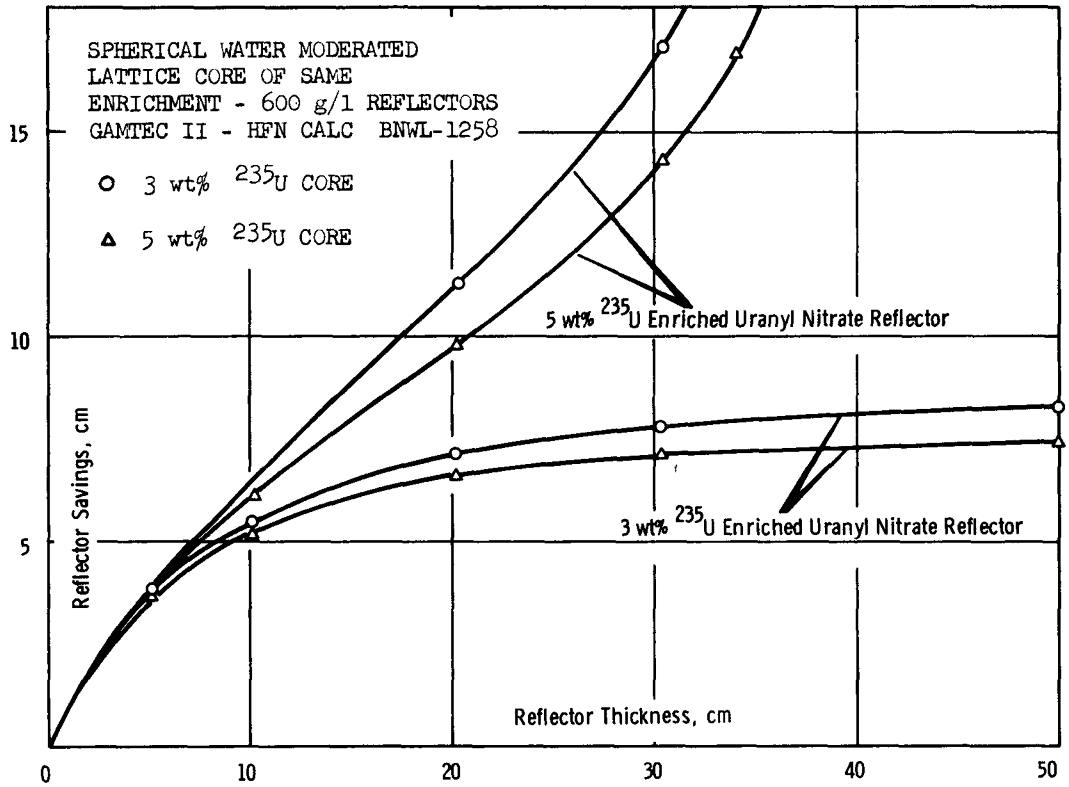
UNCLASSIFIED

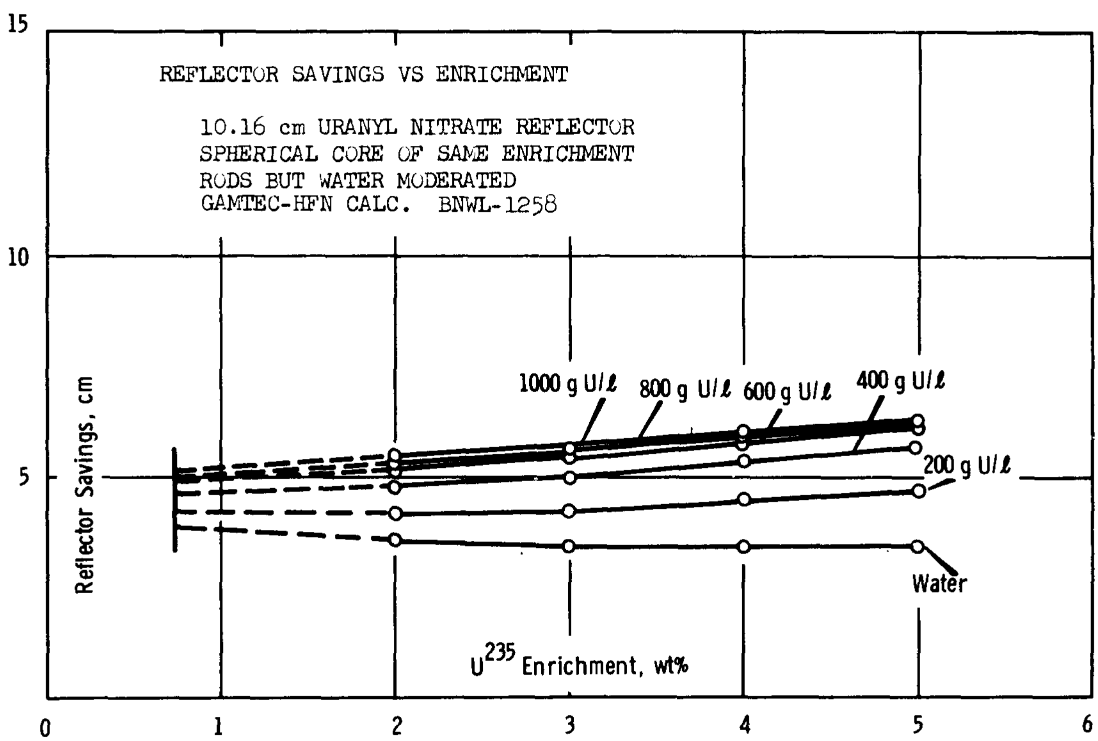

REFLECTOR SAVINGS - BERYLLIUM REFLECTOR
× U(93.2) Metal Slab, LA-DC-7138
◇ U(93.2) Metal Sphere, TID-7028
○ 233U Metal Sphere, DTF Calc., RFP-936
⬡ 239Pu Metal Sphere, DTF Calc., RFP-936
REFLECTOR SAVINGS, cm
REFLECTOR THICKNESS, cm
0
1
2
3
4
5
10
15
20
25

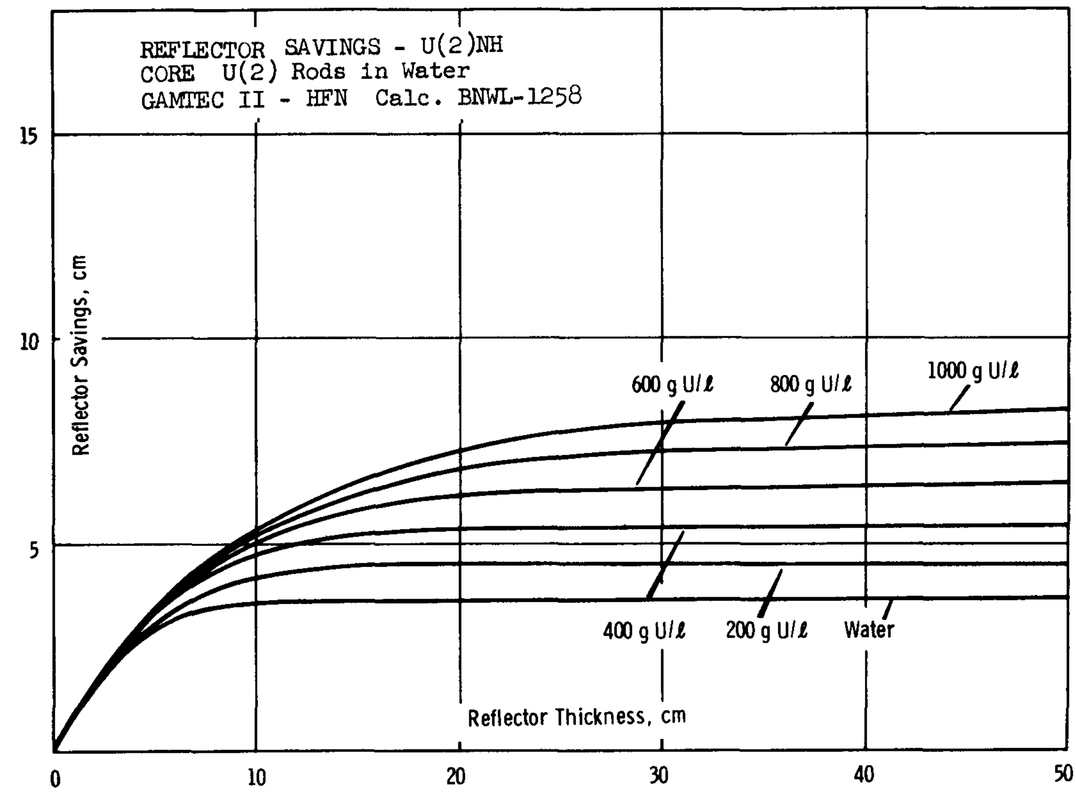


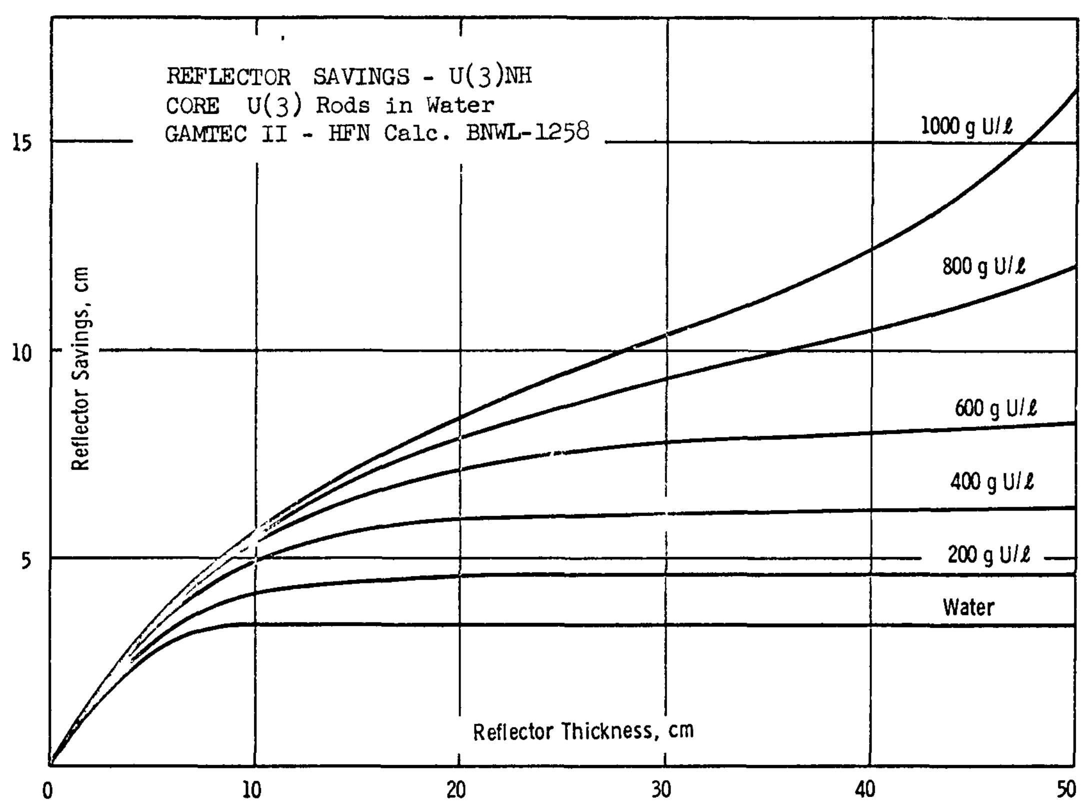
UNCLASSIFIED

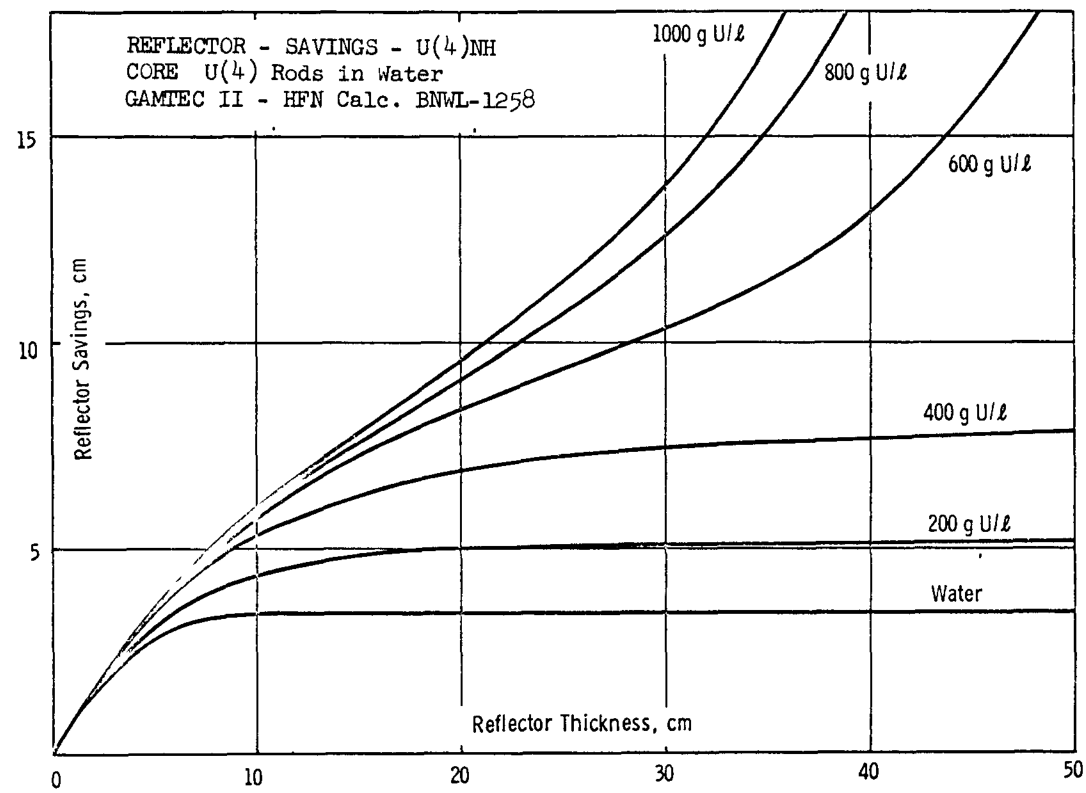

1000 g/l Plutonium
150 g/l
30 g/l
1000 g/l
150 g/l
30 g/l
λ, cm
REFLECTOR THICKNESS, in.
EFFECT OF CONCRETE AND WATER REFLECTORS ON EXTRAPOLATION DISTANCE OF A CRITICAL SLAB AT VARIOUS Pu CONCENTRATIONS
PLUTONIUM NITRATE - 3 Wt% 240
GAMTEC II - HFN Calculation
—— H_2O Reflector
--- Concrete Reflector

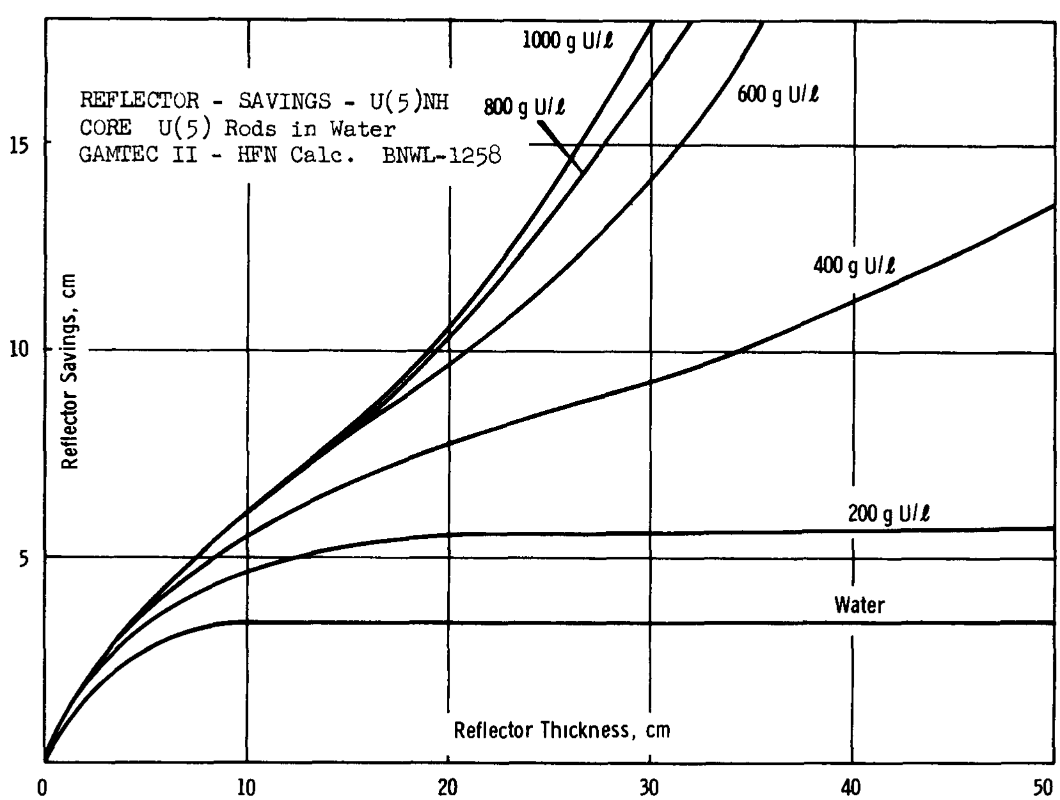

SPHERICAL WATER MODERATED
LATTICE CORE OF SAME
ENRICHMENT - 600 g/l REFLECTORS
GAMTEC II - HFN CALC BNWL-1258
○ 3 wt% 235U CORE
Δ 5 wt% 235U CORE
5 wt% 235U Enriched Uranyl Nitrate Reflector
3 wt% 235U Enriched Uranyl Nitrate Reflector
Reflector Savings, cm
Reflector Thickness, cm
0
5
10
15
10
20
30
40
50


REFLECTOR SAVINGS VS ENRICHMENT
10.16 cm URANYL NITRATE REFLECTOR
SPHERICAL CORE OF SAME ENRICHMENT
RODS BUT WATER MODERATED
GAMTEC-HFN CALC. BNWL-1258
1000 g U/ℓ
800 g U/ℓ
600 g U/ℓ
400 g U/ℓ
200 g U/ℓ
Water
Reflector Savings, cm
U235 Enrichment, wt%
15
10
5
0
1
2
3
4
5
6


REFLECTOR SAVINGS - U(2)NH
CORE U(2) Rods in Water
GAMTEC II - HFN Calc. BNWL-1258
Reflector Savings, cm
Reflector Thickness, cm
600 g U/ℓ
800 g U/ℓ
1000 g U/ℓ
400 g U/ℓ
200 g U/ℓ
Water
0
10
20
30
40
50
5
10
15


REFLECTOR SAVINGS - U(3)NH
CORE U(3) Rods in Water
GAMTEC II - HFN Calc. BNWL-1258
Reflector Savings, cm
Reflector Thickness, cm
1000 g U/ℓ
800 g U/ℓ
600 g U/ℓ
400 g U/ℓ
200 g U/ℓ
Water
0
10
20
30
40
50
5
10
15


REFLECTOR - SAVINGS - U(4)NH
CORE U(4) Rods in Water
GAMTEC II - HFN Calc. BNWL-1258
1000 g U/ℓ
800 g U/ℓ
600 g U/ℓ
400 g U/ℓ
200 g U/ℓ
Water
Reflector Savings, cm
Reflector Thickness, cm
15
10
5
0
10
20
30
40
50


REFLECTOR - SAVINGS - U(5)NH
CORE U(5) Rods in Water
GAMTEC II - HFN Calc. BNWL-1258
1000 g U/ℓ
800 g U/ℓ
600 g U/ℓ
400 g U/ℓ
200 g U/ℓ
Water
Reflector Savings, cm
Reflector Thickness, cm
15
10
5
0
10
20
30
40
50

COMMONLY USED MATERIALS[1]

Material	Formula	Density g/cm^3	M.P.[2] °C	Composition Element	Weight %	Atomic %	Atomic Density Atoms/ (barn-cm)
Aluminum	Al	2.699	660				.06027
Beryllia	BeO	3.02	2550	Be	36.03	50.0	.07287
				O	63.97	50.0	.07287
Beryllium	Be	1.847	1285				.12348
Bismuth	Bi	9.78	271				.02820
Boral[3]	B_4C-Al	2.53		B	27.4	45.4	.04036
(without Al clad, 65 Wt% Al, 35 Wt% B_4C)				C	7.6	11.4	.01008
				Al	65.0	43.2	.03837
Boral		2.67		B	15.7	30.3	.02334
(with Al clad, 1/4" sheet)				C	4.3	7.6	.00575
				Al	80.0	61.9	.04765
Borax	$Na_2B_4O_7 \cdot 10H_2O$	1.73	75	Na	12.06	4.65	.00547
				B	11.34	9.30	.01093
				O	71.32	39.54	.04646
				H	5.29	46.51	.05466
Boric Acid	H_3BO_3	1.435	184	H	4.89	42.86	.04195
				B	17.48	14.28	.01398
				O	77.63	42.86	.04195
Boron	B	2.48	2000				.13821

(1) C. R. Tipton, et al, Reactor Handbook, Vol. I, 1960. Most material was obtained from this reference. References for other material will be listed.

(2) Melting Point. For plastics this column will designate the recommended maximum continuous service temperature.

(3) Neutron absorption in Boral based on homogeneous boron distribution will be in error. Effectiveness of Boral depends upon B_4C particle size (see Nucleonics, Vol. 16, pp 91-94, 1958).

Material	Formula	Density g/cm^3	M.P. °C	Composition: Element	Composition: Weight %	Composition: Atomic %	Atomic Density Atoms/ (barn-cm)
Boron Carbide	B_4C	2.54	2450	B	78.26	80.0	.11078
				C	21.74	20.0	.02770
Boron Stainless Steel (1 Wt% Boron in 304 L)		7.87		B	1.0	4.9	.00439
				Fe	68.0	64.8	.05773
				Cr	19.0	19.4	.01733
				Ni	12.0	10.9	.00969
Boron Steel (1 Wt%)		7.87	1540	B	1.0	4.9	.00439
				Fe	98.8	94.2	.08388
				C	0.2	0.9	.00079
Borated Polyethylene (10 Wt% B as B_4C)		1.00		B	10.0	4.7	.00558
				C	77.4	32.5	.03885
				H	12.6	62.8	.07505
Bricks (common silica)		1.8	1680-1700	Al	0.5	0.4	.00021
				Ca	1.4	0.7	.00039
				Fe	0.7	0.3	.00014
				O	52.5	66.3	.03556
				Si	44.9	32.3	.01733
Bricks (fire clay)		2.1	1680-1740	Al	21.2	16.1	.00567
				Ca	0.7	0.4	.00013
				Fe	1.4	0.5	.00018
				O	49.7	63.6	.02245
				Mg	.6	.5	.00018
				Si	25.2	18.4	.00650
				Ti	1.2	0.5	.00018
Cadmium	Cd	8.65	321				.04637
Cadmium Nitrate	$Cd(NO_3)_2 \cdot 4H_2O$	2.46	59.5	Cd	36.44	4.76	.00480
				H	2.61	38.10	.03844
				N	9.08	9.52	.00961
				O	51.87	47.62	.04805
Carbon	C	1.71(1)	3700				.08578

(1) Average density of reactor grade - Hanford

Material	Formula	Density g/cm^3	M.P. °C	Composition Element	Weight %	Atomic %	Atomic Density Atoms/ (barn-cm)
Carbon Tetrachloride	CCl_4	1.6	-23	C	7.81	20.0	.00627
				Cl	2.19	80.0	.02507
Cellulose	$(C_6H_{10}O_5)_n$	1.45		C	44.44	28.57	.03233
				H	6.22	47.62	.05431
				O	49.34	23.81	.02694
Chromium	Cr	7.19	1875				.08331
Concrete (common Portland)(1)		2.3		Al	3.4	2.1	.00175
				Ca	4.4	1.9	.00152
				Fe	1.4	0.4	.00035
				H	1.0	16.9	.01375
				O	53.2	56.2	.04608
				Si	33.7	20.4	.01663
				Na	2.9	2.1	.00175
Deuterium Oxide	D_2O	$1.1054^{20°}$		D	20.11	66.67	.06651
				O	80.89	33.33	.03325
Felt (in KKD-1 or LLD-1)		0.185		C	43.46	31.6	.00403
				H	4.42	38.6	.00489
				O	34.47	18.8	.00240
				N	17.65	11.0	.00140
Gadolinium	Gd	7.868	1350				.03015
Glass, Foam(2)		0.128		B	1.5	2.7	.00011
				H	0.1	1.3	.00005
				O	53.4	63.3	.00262
				Si	27.9	18.8	.00109
				Na	16.1	13.3	.00055
				S	1.0	0.6	.00003

(1) See Reactor Handbook for other shielding concretes.

(2) From Y-KC-106

Material	Formula	Density g/cm^3	M.P. °C	Composition			Atomic Density
				Element	Weight %	Atomic %	Atoms/ (barn-cm)
Glass, plate (silica)		2.4	1425	Ca	10.7	5.6	.00387
				O	46.0	60.4	.04156
				Si	33.7	25.2	.01733
				Na	9.6	8.8	.00607
Glass, Pyrex		2.23	820	Al	1.0	0.7	.00053
				B	3.7	6.5	.00459
				O	53.5	63.8	.04492
				Si	37.7	25.6	.01802
				Na	4.1	3.4	.00238
Graphite	(see Carbon)						
Iron	(see Steel)						
Kernite	$Na_2B_4O_7 \cdot 4H_2O$	1.95		Na	16.83	8.0	.00860
				B	15.82	16.0	.01720
				O	64.40	44.0	.04729
				H	2.95	32.0	.03439
Kaowool		(2.65) To 0.192 bulk	1260(1)	Al	23.9	18.0	.00102
				Fe	.9	.3	.00002
				O	49.9	63.6	.00361
				Si	24.3	17.6	.00100
				Ti	1.0	.5	.00002
Kynar	CF_2CH_2	1.76	340	C	37.51	33.33	.03312
				H	3.15	33.33	.03312
				F	59.34	33.33	.03312
Lead	Pb	11.34	327				.03298
Lithium	Li	0.534	186				.04636
Lucite	$C_5H_8O_2$	1.2	185	C	59.99	33.33	.03611
				H	8.05	53.34	.05777
				O	31.96	13.33	.01444

(1) Recommended Maximum Temperature Usage

Material	Formula	Density g/cm3	M.P. °C	Composition			Atomic Density
				Element	Weight %	Atomic %	Atoms/ (barn/cm)
Magnesium	Mg	1.74	650				.04313
Magnesium Oxide	MgO	3.22	2800	Mg	60.30	50.00	.04814
				O	39.70	50.00	.04814
Masonite	$C_6H_{10}O_5$	1.3		C	44.44	28.57	.02898
				H	6.22	47.62	.04831
				O	49.34	23.81	.02415
Molybdenum	Mo	10.22	2622				.06418
Nickel	Ni	8.90	1455				.09133
Neoprene	$(C_4H_5Cl)_n$	1.23		C	54.27	40.0	.03348
				H	5.69	50.0	.04185
				Cl	40.04	10.0	.00837
Nylon	(see Polyamides)						
Oil, hydraulic	$C_{40}H_{33}O_4Cl_6P$	1.28		C	58.49	47.62	.03755
				H	4.05	39.29	.03098
				O	7.79	4.76	.00376
				Cl	25.90	7.14	.00563
				P	3.77	1.19	.00094
Lard Oil	$C_{10}H_{18}O$	0.915		C	77.87	34.48	.03574
				H	11.76	62.07	.06433
				O	10.37	3.45	.00357
Paraffin	$C_{25}H_{52}$	0.90	48	C	85.14	32.47	.03844
				H	14.86	67.53	.07995
Phenolformaldehyde (Bakelite, Durez, Resinox - composition depends upon filler used) With no Filler	$(C_6H_5O)_n$	1.27	121	C	79.98	53.85	.05094
				H	4.80	38.46	.03640
				O	15.22	7.69	.00728

Material	Formula	Density g/cm3	M.P. °C	Composition Element	Weight %	Atomic %	Atomic Density Atoms/ barn-cm)
Polyamides (Nylon)	$(C_6H_{11}ON)_n$	1.14	74	C	63.68	31.58	.03642
				H	9.80	57.90	.06677
				N	12.38	5.26	.00607
				O	14.14	5.26	.00607
Polyester (Dacron, Duraplex, Glyptal, Mylar - Many different compositions)				C	54 - 74		
				H	6 - 9		
				O	18 - 40		
Polyethylene	$(CH_2)_n$	0.92	99	C	85.63	33.33	.03952
				H	14.37	66.67	.07903
Polystyrene	$(CH)_n$	1.06	66	C	92.26	50.0	.04905
				H	7.74	50.0	.04905
Polysulfide	$(C_2H_4S_4)_n$	1.34		C	15.37	20.0	.01033
				H	2.58	40.0	.02066
				S	82.05	40.0	.02066
Polyvinyl Chloride	$(C_2H_3Cl)_n$	1.65	52	C	38.44	33.33	.03181
				H	4.84	50.00	.04772
				Cl	56.72	16.67	.01591
Pyrex (see glass)							
Stainless Steel	304 L	7.93	1450	Fe	74.0	73.3	.06331
				Cr	18.0	19.2	.01654
				Ni	8.0	7.5	.00651
1 Wt% Boron	(see Boron Steel)						
Steel (high strength)		7.84		Fe	98.0	98.1	.08289
				Ni(1)	2.0	1.9	.00161
Tantalum	Ta	16.6	2996				.05527

(1) All other elements were added as nickel which has an average total cross section of these elements.

Material	Formula	Density g/cm3	M.P. °C	Composition			Atomic Density Atoms/ (barn-cm)
				Element	Weight %	Atomic %	
Teflon	C_2F_4	2.20	204	C	24.02	33.33	.02651
				F	75.98	66.67	.05301
Thorium	Th	11.72	1750				.03043
Thorium Dioxide	ThO_2	10.03	3000	Th	87.88	33.33	.02289
				O	12.12	66.67	.04577
Titanium	Ti	4.51	1670				.05673
Titanium Dioxide	TiO_2	4.2	1640	Ti	59.95	33.33	.03167
				O	40.05	66.67	.06334
Tributyl Phosphate	$(C_4H_9O)_3PO$	0.973	-80	C	54.12	27.27	.02650
				H	10.22	61.37	.05962
				O	24.03	9.09	.00883
				P	11.63	2.27	.00221
Vermiculite[1]		0.134		Al	7.8	5.1	.00023
				Fe	6.3	2.0	.00009
				H	1.0	17.2	.00081
				K	5.8	2.6	.00012
				Mg	12.7	9.1	.00042
				O	48.1	52.6	.00242
				Si	18.3	11.4	.00052
Water	H_2O	1.00	0	H	11.19	66.67	.06689
				O	88.81	33.33	.03344
Wood, Hard		0.64					
Zirconium	Zr	6.51	1852				.04251

(1) From Y-KC-109

Material	Formula	Density g/cm^3	M.P. °C	Composition: Element	Composition: Weight %	Composition: Atomic %	Atomic Density Atoms/ (barn-cm)
Zircaloy-2	Zr-2	6.55		Zr	98.26	98.35	.04251
				Sn	1.45	0.12	.00048
				Cr	0.10	0.18	.00008
				Ni	0.05	0.08	.00003
				Fe	0.13	0.21	.00009
				N	0.01	0.06	.00003

PURFEX PLANT VESSEL SCHEDULE
URANIUM-PLUTONIUM PROCESSING

Vessel	Function	Nominal Volume Gallons	Size
TK-A3,B3,C3	Dissolver	5,000	9'3" OD x 4'11" ID x 16'
TK-A3,B3,C3-4	NH_3 Scrub Waste	2,100	4'0" x 8'6" x 10'
TK-D1	Dissolver Rinse	5,000	10'0" x 9'3"
TK-D2	Coating Waste	5,000	10'0" x 9'3"
TK-D3,D4	Metal Solution	7,700	10'6" x 12'8" x 9'2"
TK-D5	Metal Solution	5,000	10'0" x 9'3"
TK-E1	Centrifuge Product	1,700	7'0" x 6'9"
G-E2	Coating Waste Centrifuge	180	48"
TK-E3	Centrifuge Feed	5,000	10'0" x 9'3"
TK-E3-2	NH_3 Scrub Waste	215	3'2" x 4'6"
G-E4	Coating Waste Centrifuge	180	48"
TK-E5	Centrifuge Waste	5,000	10'0" x 9'3"
TK-E6	HAF Makeup	5,000	10'0" x 9'3"
TK-F3	AAA	5,000	10'0" x 9'3"
T-F5	Acid Absorber	300	10' OD x 9'3" - 3-1/2' OD x 17-1/2'
E-F6	1WW Concentrator	2,200	Two 4'5" barrels x 12' and One 2'6" barrel x 12'
TK-F7	1WF	3,800	6'9" x 10'6" x 9'2"
TK-F8	Waste Rework	5,000	10'0" x 9'3"
TK-F10	3WF Decanter	5,000	10'0" x 9'3"
E-F11	Concentrator (Utility)	2,500	Two 4'5" barrels x 12' and One 2'6" barrel x 12'
TK-F12	E-F11 Feed	5,000	10'0" x 9'3"
TK-F13	Rework Storage	5,000	10'0" x 9'3"
TK-F14	Utility	400	4'0" x 5'0"
TK-F15	1WW Denitration	5,000	10'0" x 9'3"
TK-F16	1WW Denitration	5,000	10'0" x 9'3"
TK-F17	Tube Bundle Flush	1,200	4'2" x 12'0"
TK-F18	Utility Waste	5,000	10'0" x 9'3"
TK-F26	1WW Receiver	3,600	6'9" x 10'6" x 9'2"
TK-G1	1OF	5,000	10'0" x 9'3"
T-G2	1O Column	2,000	34" Dia. x 32'
TK-G2	1OS	1,900	7'0" x 6'9"
TK-G5	1OO	15,000	10'6" x 16' x 14'
TK-G6	1OD Decanter	450	4' x 5'
TK-G7	Turbomixer	15,000	10'6" x 16' x 14'
TK-G8	1OW	5,000	10'0" x 9'3"
TK-H1	HAF	5,000	10'0" x 9'3"
T-H2	HA Column	1,850	26" Dia. x 40'
T-H3	HS Column	1,770	34" Dia. x 26'
E-H4	3WB Concentrator	2,700	Two 4'5" barrels x 12' and One 2'6" barrel x 12'
TK-J1	3WB	5,000	10'0" x 9'3"
TK-J2	1BSU	1,340	4'2" x 14'0"
TK-J3	1BXF	5,000	10'0" x 9'3"
TK-J5	2AF	370	8'6" OD x 8'0" ID x 8'11"
T-J6	1BX Column	1,600	32" Dia. x 33'
T-J7	1C Column	1,770	34" Dia. x 26'
E-J8	1CU Concentrator	3,700	Two 4'7" barrels x 10' and One 2'6" barrel x 14'
T-J4	1BS Column	130	8" x 14' Dia.
TK-J21	2NF	320	4'5" OD x 3'11" ID x 14'8"
T-J22	2N Column	150	7" Dia. x 38'
T-J23	2P Column	100	7" Dia. x 24'
TK-K1	2DF	5,000	10'0" x 9'3"
T-K2	2D Column	1,370	24" Dia. x 16' - 32" Dia. x 16'
T-K3	2E Column	1,770	34" Dia. x 26'
E-K4	2EU Concentrator	3,700	Two 4'7" barrels x 14' and One 2'6" barrel x 14'
TK-K5	2UC Receiver	5,000	10'0" x 9'3"
TK-K6	UNH Product	5,000	10'0" x 9'3"
T-L1	2A Column	130	7" Dia. x 40'
T-L2	2B Column	90	7" Dia. x 30'
TK-L3	3AF	120	34" OD x 30" ID x 12'
T-L4	3A Column	40	3-1/2"ID x 34'
T-L5	3B Column	30	3-1/2" ID x 22'
T-L6	Product Stripper	10	Two barrels 4" x 8', 3" Tower
E-L7-1	Product Concentrator	10	Two barrels 4" x 8', 3" Tower
TK-L8	Product Receiver	10	Two barrels 4" x 8'

Vessel	Function	Nominal Volume Gallons	Size
TK-I9	Pu Product Sampler	11	Three barrels 5" Dia. x 38"
TK-L10	Pu Product Sampler	14	6" Dia. x 10'
TK-L11	Pu Recycle	25	Three 4" Dia. barrels x 12'
TK-L13	Pu Loadout	2.4	6" x 21"
TK-M1		4,100	7'0" x 14'0"
TK-M2		1,800	5'0" x 14'0"
TK-N1	XAF Receiver	64	2-5/8" x 8' x 5'
T-N2	XA Column	10	5" Dia. x 10'
	Downcomer	4	3" Dia. x 10'
T-N3	XC Column	8	5" Dia. x 8'
	Resin Reservoir	7	4" Dia. x 10'
E-N6	ACP Concentrator	8.7	Two barrels 4.2" Dia. x 7'8"
TK-N7	XPC Receiver	10	Two barrels 4.3" Dia. x 5'3"
TK-N20	N Cell Vent Drain Tank	4	4" Dia. x 6'
TK-R1	20F	5,000	10' x 9'3"
T-R2	20 Column	2,000	34" Dia. x 32'
TK-R2	20S	1,900	8' x 7'9"
TK-R5	Utility	9,000	10' x 14'
TK-R6	Utility Decanter	430	4' x 5'10"
TK-R7	200	9,000	10' x 14'
TK-R8	20W	5,000	10' x 9'3"
TK-U1	Recovered Acid	14,000	10'6" x 16' x 14'
TK-U2	Recovered Acid	14,000	10'6" x 16' x 14'
TK-U5	Fractionator Feed	9,000	10' x 14'
T-U6	Fractionator	1,750	8' x 32'
SA	A Cell Sump	45	24" x 24" x 18"
SB	B Cell Sump	45	24" x 24" x 18"
SC	C Cell Sump	45	24" x 24" x 18"
SD	D Cell Sump	45	24" x 24" x 18"
SE	E Cell Sump	30	24" x 24" x 18" (Filled with 1" Boron Raschig Rings)
SFA	F Cell Sump	45	24" x 24" x 18"
SFB	F Cell Sump	45	24" x 24" x 18"
SG	G Cell Sump	45	24" x 24" x 18"
SH	T-H2 Sump	2,600	9'0" x 6'9" x 4'11"
SJ	J Cell Sump	60	30" x 24" x 18"
SJ-2	J Cell Package Sump	2,700	9'9" x 8'2" x 5'
SK	K Cell Sump	60	30" x 24" x 18"
SLB	TK-L13 Sump	0	2'2" x 2' x 2"
SLD	TK-L11 Sump	1" = 4.5	8'2" x 18" x 1" (Slope 1" in 8') 1" o'flow
SLF	TK-L9 Sump	0	16" x 19' (Slope 2-1/4" in 19')
SLF	TK-L10 Sump	0	16" x 19' (Slope 2-1/4" in 19')
SLK } old	TK-K6, T-L1 Sump	10	1-1/2" x 8" x 26', Then canyon floor
SLL } SLA	T-I2, Package Sump	1" ≅ 160	32' x 14' Canyon floor (Slope 7/8" in 7')
SN	N Cell Sump	1.9" ≈ 60	4' x 13' x 1.9"
SNA	TK-N1 Sump	3" ≈ 56	3' x 10' x 3" overflow

CONTAINERS USED FOR FISSILE MATERIAL AT HANFORD

	Diameter in.	Height in.	Wall Thickness in.	Volume in^3	Volume cm^3
Beaker, Stainless 1 liter	4 I.D.	5 5/8		70.68	1,159
Beaker, Stainless 2 liter	5 1/8 I.D.	6		123.8	2,028
Bottle, glass, 4 liter	6 1/2 O.D.	9	0.13	276.1	4,500
Bottle, (plastic jug), 1 gal	6 O.D.	10 1/2	0.1	286.8	4,700
Bottle, polyethylene, 3 l H-2-32973	4.6 I.D.	17 3/4	0.1	213.6	3,500
Bottle, polyethylene, 10 l shipping H-2-25917, H-2-26142, H-2-26289	4.37 I.D.	51	0.1	712.4	11,685

	Width in.	Length in.	Height in.	Volume ft^3	Volume Liters
Box, Cardboard	12	10 1/2	15	1.1	31
Box, Cardboard (crucible)	13	13	13	1.3	36.7
Box, cardboard (waste)	18 1/2	18 1/2	24 1/2	4.6	130
Box, wood (PV lids)	12 1/2	15 1/2	18	2.0	57

	Diameter in.	Height in.	Volume in^3	Volume cm^3
Can, tuna, 307 x 200.25 No. 1/2	3 1/2	2 1/4	18	295
Can, salmon, pineapple, 401 x 211, No. 1 flat	4	2 5/8	35	573
Can, tomato, 401 x 411, No. 2 1/2	4	4 1/2	56	918
Can, special, untinned, slag & crucible	4	5 1/2	69	1130
Can, lab sample, friction lid, 1# lard or grease can	3 1/2	3 1/2	33.7	552

	Diameter in.	Height in.	Volume Ft3	Volume Liters
Can, lard, grey	12	15 1/2	1.01	29
Can, lard, tinned	12	14 1/2	0.95	27
Can, paint	11	13	0.71	20
Can, paint	12	13 1/2	0.88	25
Can, trash	15 1/2	19	1.61	46
Can, PR, 6" Sch 30, 3"neck, .43" wall, rounded bottom, 1/2" lead & cadmium shield. H-2-52967	5.761 I.D.	23	0.36	10.22
Can, PR, Carrier, 1/4"C.S. plate H-2-52984	22 O.D.	32	7.04	199.3
Can, SN, 6" Sch 80 pipe, 3"neck .43"wall, round bottom, no shielding. H-2-58129	5.761 I.D.	23	0.36	10.22
Can, SN, Carrier, 55 gal drum with spacers and legs H-2-58130	23.5	35	8.73	208
Can, RC, 1/8"S.S. matl., round bottom on 18" radius, H-2-30719, H-2-3990	18 3/4 O.D.	14 1/8	2.0	56.8
Can, RC, Carrier, 1/8 C.S. walls. H-2-30720, H-2-3989	23 1/16 O.D.	21	4.97	140.7
Can, sample, 1/4"S.S. walls spherical shape with cylindrical neck. H-2-453, H-2-455	5 1/2 I.D.			1.3
Can, Sample, Carrier. H-2-389, HW-31967				
Carton, gal. ice cream	6 3/4 I.D.	6 1/2	0.135	3.8
Carton, qt. ice cream	3 3/8 I.D.	6 1/2		0.95
Carton, pt. ice cream		3 1/4		0.48
Drum, 30 gal. standard	19 1/2 O.D.	28 1/2	4.925	114
Drum, 50 gal. standard	23 1/2 O.D.	35	8.734	208
Pan, powder, H-2-23045	5 1/4	4 3/4		1.685

SHIPPING CONTAINERS

	Dia, In.	Height, In.	Volume Gal.	Volume Liter
		Inner		
"A", Aluminum Birdcage, 20 x 20 x 20, 1/4" thick frame,	9 1/2 I.D.	13 15/16	4.28	16.2
		Outer		
H-2-23845, H-4-39179(container)	16 1/2 I.D.	18 5/8	17.25	65.3
LLD-1, KKD-1, M-101, M-102,		Inner		
Birdcage. 16 x 16 x 25 frame	4.563 I.D.	12	0.85	3.22
with 18 Ga galv. st. cover,		Outer		
6 3/4" O.D., 1/4" wall x 14" high outer container. 5" Sch. 40 inner container. H-2-26260-64, H-2-26181, DOT Permit 4960	6.25 I.D.	14	1.56	7.04
United Kingdom Container For	Each Inner Compartment			
KKD-1 Birdcage. 3 Compartment C. steel, Cd plated. H-2-33282 & 3	2.875 I.D.	3.0	.085	.32
		Outer		
	4 Inch Hex. Stock	10		
Pu(NO$_3$)$_4$ L-10 Class II Shipping		Inner		
Container. Two 55 gal. drums	4.813	52 1/4	4.12	15.6
welded together, tubing frame		Outer		
work to center bird. 5" Sch. 80 pipe bird. Filled with vermiculite. H-2-26140,1,2.	23.5	66 3/4	125.3	474
Pu(NO$_3$)$_4$ L-3 Class II Shipping		Inner		
Container. 55 Gal. drum, tubing	4.813	17.75	1.4	5.29
frame work to center bird, 5"		Outer		
Sch. 80 pipe bird to hold 3L plastic bottle, voids filled with vermiculite. H-2-33695	23.5	35	55	208
Pu-Al Rod, Birdcage, 5" pipe in		Inner		
a 16 x 16 x 65 In. frame cage	4.0	62	3.37	12.8
		Outer		
	16x16	65	72.04	272.7

STORAGE CONTAINERS

	Dia, In.		Height, In.	Volume Gal.	Volume Liter
^{233}U Nitrate, 3L Storage		Inner			
5" O.D. S.S. tubing in a Std.	4.87 I.D.		20	1.61	6.1
30 gal. drum filled with con-		Outer			
crete, on legs. H-2-32920	19.5		4.5	5.82	22.0
Pu Nitrate, 10L Storage		Inner			
5" Sch. 10 pipe in two 50 gal.	5.295 I.D.		56	5.34	20.2
drums outer containers, no		Outer			
insulation, on legs.	23.5		66.75	125.3	474
H-2-25915,6,7 & 8.					

SHIPPING AND STORAGE CONTAINER ARRAYS

Container	Matl.	Conc. or Moder.	Quantity	ONSITE: No. in Array Store	ONSITE: No. in Array Trans*	ONSITE: Other Restrictions	OFFSITE: Transport Index# Class II	OFFSITE: Transport Index# Class III or No.	OFFSITE: Other Restrictions
LLD-1, KKD-1,	^{235}U	Metal(1)	7.0Kg	50	50		1.3	1.0	(1)Can be Pu-U alloys
16x16x25	^{235}U	Any	20.0Kg	50	50		None	1.0	
Birdcage,	Pu	Metal(1)	7.0Kg(2)	50	50		1.3	1.0	(2)Using "British Nut"
DOT SP4960	Pu	Metal(3)	4.5Kg	100	50		1.3	1.0	(3)Can be oxides
L-3(4)	^{235}U	Any	5.0Kg	200	50	1 tier	0.4	200	(4)<6M HNO_3, 30 day limit on bottle
(3 Liter Dow	$Pu(NO_3)_4$	250g/l	3.3 l	200	50	"	0.3	200	
55 Gal. Drum	PuO_2(5)	3.77g/cc	5.0Kg	200	50	"	0.4	200	(5)$^{240}Pu \leq 5.0$ wt% or Mixed Pu-U oxides
Birdcages),	^{233}U(6)	375g/l	3.0 l	124	50	"			
DOT SP5330									(6)Aqueous solution
L-3(7)	$Pu(NO_3)_4$	Any	2.35Kg	200	50	"	0.1		(7)For other oxide Mass limits see DOT special permit appendix
ORNL foam	^{235}U(6)	Any	2.35Kg	200	50	"	0.1		
glass,	^{233}U(6)	Any	1.58Kg	200	50	"	0.1		
DOT SP5795			2.06Kg		50	"	0.2		
L-10,	^{235}UNH(10)	350g/l(8)	10.5 l	200	50	"	1.5	68	(8)< 1.0 wt% ^{233}U and Pu
DOT SP5061		250g/l(9)	10.5 l	200	50	"	1.5	68	(9)≤ 20 wt% ^{233}U and 1.0 wt% Pu
	$Pu(NO_3)_4$	≤250g/l	10.5 l	200	50	"	1.5	68	
	Any(10)	Dry	4.5Kg			"	0.5	200	
	$Pu(NO_3)_4$	≤450g/l	4.5Kg	200	50	"	(not permitted)		(10)Pu-U compounds or mixes.
Approved DOT Cont.	As allowed	As allowed	As allowed	100TI@	50TI@		50TI	100TI	To receive, transport and store onsite

* ARH-145, 86.2 Transportation by Motor Truck.

Set for Criticality Safety, Radiation Dose Rates may dictate a higher number.

@ TI is Transport Index or Transport Units.

SHIPPING & STORAGE ARRAY ONSITE ONLY

Container	Matl.	Conc. or Moder.	Quantity	No. in Array Store	No. in Array Trans*	Other Restrictions
LLD-1, KKD-1,	^{235}U		(as allowed in DOT special permits)			
M-101, M-102,	Pu		(as allowed in DOT special permits)			
Type A & B	Pu	H/Pu ≤ 2	7.0Kg(1)	50	50	(1)Using British Nut
Birdcages	Pu	H/Pu ≤ 2	4.5Kg	100	50	
	Pu	H/Pu ≤ 20	2.5Kg	100	50	
10-L Storage,	Pu	450g/l	4.5Kg	200	50	1 tier
PR and SN	^{235}U	450g/l	4.5Kg	200	50	1 tier
3-L Storage	^{233}U	450g/l	1.4Kg	No limit	No limit	1 tier
(Concrete filled)	Pu	450g/l	1.4Kg	No limit	No limit	1 tier
1 cubic foot (lard cans)	Pu	H/Pu ≤ 20	400g	2 wide(2) 4 high	2 high(3)	(2)3 ft between rows (3)In Z Plant Truck
Waste Cartons	Pu		400 to 250g	Single row 1 high(4)	Same(4)	(4)3 ft between rows single tier
Waste Cartons	Pu		250 to 100g	Single row 2 high(5)	1 tier(6)	(5)or no limit on one tier array
Waste Cartons	Pu		≤100g	No limit	3 tiers(6)	(6)to dimensions of truck
55 Gal. Drum or any Cont.	Pu		≤15g	No limit	No limit	

*ARH-145, 86.2 Transportation by Motor Truck

Atlantic Richfield Hanford Company

Date:

To: Distribution

From: R. D. Carter

Subject: INDEX TO ARH-600

The following index may be placed in ARH-600 wherever the holder finds convenient. It may be used in one piece or it may be divided between the three volumes. It might be advisable to check this index against your page numbers to make sure of proper collation and reproduction.

RDC:pb

54-6000-030 (10-68)
AEC RL RICHLAND WASH

THIS LISTING IS THE PAGE BY PAGE SUMMARY OF ARH-600, CRITICALITY HANDBOOK, WHICH HAS LOOSE LEAF PAGINATION AND MAY BE ADDED TO OR SUBTRACTED FROM AT THE AUTHORS DISCRETION

LATEST UPDATING IS SEPT 1, 1971

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