70-36

ABB
ASEA BROWN BOVERI

January 28, 1994
ML-94-005

Docket No. 70-36
License No. SNM-33

Dr. Michael Tokar, Section Leader
  Licensing Section II, Licensing Branch
Division of Fuel Cycle Safety and Safeguards
Office of Nuclear Materials Safety and Safeguards
U. S. Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, D.C. 20555

Subject: **Hematite License Renewal - Chapters 4 and 14 Update**

Dear Dr. Tokar:

This letter completes the update to the Hematite License Renewal Application.

This submittal contains an update to Chapters 4 and 14 of our application, concerning criticality safety. In addition, a complete Table of Contents for the updated renewal application is provided.

Enclosure I provides an explanation of substantive changes from the previous renewal submittals. A "List of Effective Pages" is provided as Enclosure II for your information (it is realized that the renewal application is not actually "Effective" until it is approved). Enclosure III provides the replacement pages of the renewal application. These page changes are complete chapter changes. Six (6) copies of this document are provided for your use.

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If there are any questions or comments concerning this matter, please do not hesitate to call me or Mr. Mark A. Michelsen of my staff at (203) 285-5261.

Very truly yours,

COMBUSTION ENGINEERING, INC.

John F. Conant

John F. Conant
Manager
Nuclear Materials Licensing

Enclosures: As Stated

cc: G. France (NRC - Region III)
S. Soong (NRC)

Enclosure I to
ML-94-005

COMBUSTION ENGINEERING, INC.

HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY

LICENSE RENEWAL APPLICATION

UPDATE - CHAPTERS 4 AND 14

EXPLANATION OF CHANGES

January 1994

COMBUSTION ENGINEERING, INC.
HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY
LICENSE RENEWAL APPLICATION
UPDATE - CHAPTERS 4 AND 14

EXPLANATION OF CHANGES

This submittal is part of an update to the Hematite License Renewal Application. The former License Renewal Application was comprised of the original application of 11/22/89, as modified by letters dated 6/17/91, 10/11/91, 12/16/91, 10/2/92 and 11/4/92. This submittal consists of an update to Chapters 4 and 14 of the application, adding to and completing the update submittals of October 29, 1993, November 24, 1993, December 10, 1993, and January 14, 1994. These update submittals supercede the former license renewal application in its entirety. The substantive changes to the former Hematite License Renewal Application which are submitted herein are discussed below.

A new license application title page, a complete Table of Contents and a Part I title page is provided for the updated renewal application.

The changes of the approved Consolidation license amendment, as submitted in C-E letters dated August 5, 1992, November 6, 1992, February 19, 1993 and March 2, 1993, have been incorporated into the Hematite License Renewal Application. A few substantive changes differ from the Consolidation application, as noted below.

Part I - Chapter 4 Changes

Sections 4.1.2 and 4.1.7 have been changed as discussed in our submittal letter of October 29, 1993. The substance of these former sections has been moved to new Section 2.7.

In Section 4.1.3, the former requirement that production and line supervisory personnel assist in the preparation of written procedures and postings has been eliminated. This was eliminated since it was vague, not auditable and not an appropriate license condition.

Section 4.1.4 has been changed to add the requirement that procedures which contain criticality safety controls also specify the requirements for maintaining those controls.

The last paragraph in Section 4.2.1.2, concerning concentration controls, has been added.

The following changes are included in the criteria of Section 4.2.2.1:

1. The slab spacing requirements of item (a)(2) have been clarified.
2. Item (f) has been changed to clarify that verification of water content in powder storage cans is necessary only for cans stored on double tiered roller conveyors (it is not necessary for single tiered roller conveyor storage).
3. Items (i) and (j) have been added from the Consolidation amendment.

In the Technical Data of Section 4.2.3.1, the former 5 gallon covered metal container with the 35 Kg mass limit has been revised to 19 liters, consistent with the safety evaluation of Chapter 14. The volume limitation for stacked mass-limited units has been eliminated as unnecessary; the spacing separation is sufficient.

In the criteria of Section 4.2.3.3, it has been clarified that 0.95 K_{eff} criteria applies for both normal and abnormal credible operating conditions.

In the criteria of Section 4.2.4, the following changes are included:

1. Item (a) refers to the actual locations where fire hoses are not allowed, in lieu of the more general "in moderator control areas".
2. Item (i) has been reworded for clarity; there is no change to the intent of this control.
3. Items (n) through (u) have been added as a result of the Consolidation amendment.

Part II - Chapter 14 Changes

Section 14.2 has been changed to clarify that interaction effects are considered for both safe individual units and engineered safeguards with appropriate administrative controls.

Section 14.3.1.1.1 has been added from the Consolidation amendment. The definition of Safe Individual Units of Section 14.3.1.1.2 has been changed, as has that of Other Subcritical Units in Section 14.3.1.1.3.

In Section 14.3.1.2.1, the surface density model of Regulatory Guide 3.52 is referenced, and the text (especially the seventh paragraph of this section) has been modified.

Sections 14.3.4.5 and 14.3.4.6 have been changed, especially as a result of the Consolidation amendment.

The model validation discussion in Section 14.6 has been updated.

Enclosure II to
ML-94-005

COMBUSTION ENGINEERING, INC.

HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY

LICENSE RENEWAL APPLICATION

LIST OF EFFECTIVE PAGES

January 1994

COMBUSTION ENGINEERING, INC.
HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY
LICENSE RENEWAL APPLICATION

LIST OF EFFECTIVE PAGES

Combustion Engineering, Inc., has submitted a complete update to the Hematite license renewal application. The following is a comprehensive List of Effective Pages, summarizing the latest applicable submittal dates for each page of the application.

Pages	Revision	Date
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Table of Contents		
i through	0	1/28/94
Part I Title Page		
Chapter 1		
1-1 through 1-1-4	0	10/29/93
1-5	0	1/14/94
1-6 through 1-7	0	10/29/93
Chapter 2		
2-1 through 2-15	0	1/14/94
Chapter 3		
3-1 through 3-13	0	1/14/94
Chapter 4		
4-1 through 4-26	0	1/28/94
Chapter 5		
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Chapter 6		
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Pages	Revision	Date
Chapter 7		
7-1	0	1/14/94
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8-1	0	10/29/93
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Chapter 11		
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Chapter 12		
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Chapter 13		
13-1 through 13-25	0	12/10/93
Chapter 14		
14-1 through 14-97	0	1/28/94
Chapter 15		
15-1 through 15-309	0	1/14/94

Enclosure III to
ML-94-005

COMBUSTION ENGINEERING, INC.

HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY

LICENSE RENEWAL APPLICATION

AFFECTED PAGES

January 1994

COMBUSTION ENGINEERING, INC.

HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY

HEMATITE, MISSOURI

LICENSE RENEWAL APPLICATION

License No. SNM-33

Docket No. 70-36

Initial Submittal: November 22, 1989

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COMBUSTION ENGINEERING, INC.

HEMATITE NUCLEAR FUEL MANUFACTURING FACILITY

HEMATITE, MISSOURI

LICENSE RENEWAL APPLICATION

PART I

LICENSE CONDITIONS

License No. SNM-33

Docket No. 70-36

Initial Submittal: November 22, 1989

CHAPTER 4 NUCLEAR CRITICALITY SAFETY

Nuclear criticality safety shall be assured through the administrative conditions and technical criteria delineated in this chapter.

Administrative conditions define:

(a) the design philosophy employed in the definition of all processes involving the handling and storage of special nuclear materials (SNM),

(b) the lines of responsibility for assuring all criticality safety aspects of the process are reviewed, documented, and approved by management, and

(c) the written procedures and postings employed to define the approved processes for handling and storage of SNM.

Technical criteria provide details on the limits and controls employed in the distribution of SNM. Details on the technical bases and criteria employed in criticality evaluations are provided, as are criteria pertaining to engineered safeguards employed in process controls.

4.1 Administrative Conditions

4.1.1 Process Design Philosophy

The process design philosophy employed by Combustion Engineering, Inc. to assure nuclear criticality safety is based on the following key elements:

(a) Process design, with respect to the handling and storage of SNM, shall incorporate sufficient factors of safety such that at least two unlikely, independent, and concurrent changes in process conditions are required before a criticality accident can occur. Process design which does not meet this requirement shall be explicitly approved in Chapter 1, Section 1.6, of this application.

(b) Physical controls, e.g., safe geometry, and permanently engineered safeguards shall be the preferred method of criticality control so as to reduce dependence on administrative procedures. In some processes, types of control other than safe geometry, e.g., moderation, concentration, and/or poison, may be employed to achieve adequate process throughput. In these cases, controlled parameters, and their limits, shall be clearly specified, approved by management as part of the review and approval of operating procedures, and communicated to affected personnel through postings, operating procedures, or training.

(c) Before a new operation with SNM is begun or an existing operation is changed, it shall be determined that the entire process will be subcritical under normal and operating conditions, consistent with paragraph a) of this section and applicable technical criteria of Section 4.2.1.3.

4.1.2 Positions Responsible for Criticality Safety

Section 2.1 describes the responsibilities and authority for key organizational positions affecting safety; Section 2.2 gives the professional requirements for these positions.

4.1.3 Documenting Criticality Evaluations and Reviews

Criticality evaluations associated with facility changes affecting the handling and storage of SNM in Nuclear Manufacturing shall be documented by a nuclear criticality analyst and independently reviewed.

The criticality evaluations shall consider potential scenarios which could lead to criticality and barriers erected against criticality in establishing applicable criticality limits and controls.

These limits and controls shall be incorporated into applicable written procedures and postings and approved by a qualified Nuclear Criticality Specialist or the Manager, Regulatory Compliance. Day-to-day monitoring of workers for conformance to criticality limits and controls and administrative procedures is carried out by line supervision and health physics technicians.

Documentation of the criticality evaluations shall be sufficiently detailed such that an independent reviewer can reconstruct the analysis and bases for the conditions presented. Criticality evaluations shall include assumptions affecting criticality safety process limits and controls. If explicit analyses using validated methodologies are employed, the margin to criticality and a clear definition of off-nominal conditions shall be provided.

Criticality evaluations shall be reviewed by a qualified reviewer. The review shall be documented.

Records of the criticality evaluation and review shall be maintained according to the requirements of Section 2.9 of this license.

4.1.4 Written Procedures

All operations involving the handling and storage of SNM shall be performed according to written procedures. These procedures may be of the following types:

(a) Operation Sheets - An Operation Sheet specifies the requirements of how a given step, operation, or process must be performed. It specifies required process parameters and methods. It is specified by number in a Traveler when it is required.

(b) Traveler - This document specifies a sequence of operations required to process a given material, component, or assembly.

(c) Special Evaluation Traveler - The Special Evaluation Traveler (SET) is employed for those jobs involving the handling and/or storage of SNM which are not covered by standard procedures. A SET may supplant operation sheets.

Procedures which include criticality safety controls specify the inspection requirements, calibration requirements, or other requirements appropriate for maintaining the criticality controls.

4.1.5 Posting of Limits and Controls

Work and storage areas where SNM is handled, processed, or stored shall be posted with the nuclear safety limits and controls applicable to each area and approved by the Manager, Regulatory Compliance and a Nuclear Criticality Specialist. Regulatory Compliance shall maintain a current record of: 1) the review and approval of each posting, 2) the location of each posting, and 3) the content of each posting.

Production and line Supervisors shall monitor the day-to-day conformance of individual workers to the posted limits and controls.

4.1.6 Labeling of Special Nuclear Material

Mass-limited containers employed in the handling or storage of special nuclear material shall be labeled as to their contents. If SNM is in the container, the amount, enrichment and type shall be indicated; if empty, the container shall be so labeled or placed in designated areas for empty containers. Uncovered empty containers do not require an empty sign. Empty containers shall not be intermixed with loaded containers unless all containers are located within designated storage locations, rings, etc.

4.1.7 Preoperational Testing and Inspection

Preoperational testing and inspection is performed as described in Chapter 2, Section 2.7.

4.1.8 Criticality Safety Design

New processes or changes in existing processes affecting the handling and storage of special nuclear material are evaluated for nuclear criticality safety. Internal procedures require that all facility changes affecting the handling and storage of SNM receive appropriate safety reviews and evaluations.

4.2 Technical Criteria

4.2.1 Individual Units

4.2.1.1 Safe Individual Units (SIU)

Minimum critical values of safety parameters shall be based on either calculated or experimental data under conditions of optimum moderation and full reflection. To arrive at a SIU, these minimum critical values deduced from experimental data shall be reduced by the following safety margins:

Parameter	Safety Margin
Mass	2.3
Volume	1.3
Slab Thickness	1.2
Cylinder Diameter	1.1

For SIUs determined from calculated data, the calculations shall be performed using validated computer analysis methods. In this case, the subcritical (safe) limit values shall be calculated consistent with paragraph 4.2.3.3 (a).

The resulting units of SNM are Safe Individual Units when isolated from other units by distance or shielding (see Section 4.2.2).

4.2.1.2 Subcritical Units (Subcrits)

Other subcritical units may use multiparameter controls to achieve criticality safety. The controlled parameters may include, for example, U-235 mass limit or concentration, container volume, limits on internal and/or external moderator, etc.

The configuration and composition of these subcritical units may depend upon the process involved. Criticality safety is assured through defined limits and controls. These limits and controls may include allowed individual SNM unit geometries which are less conservative than safe geometry, defined configurations of individual SNM units in a given process layout, engineered safeguards where necessary, and administrative controls in the form of written and approved instructions sheets and postings.

Uranium concentration control safe units shall be limited to a maximum of 25 grams of uranium per liter. The effect of evaporation and/or precipitation shall be considered in the nuclear safety analysis, such that if precipitated a safe mass will not be exceeded. Concentration controlled safe units shall not be considered to contribute to interacting arrays, but shall be located outside exclusion areas assigned by the surface density method.

4.2.1.3 Criteria

(a) The possibility of accumulation of fissile materials in not readily accessible locations shall be minimized through equipment design or administrative controls or included in the nuclear safety evaluation of the process.

(b) Nuclear safety evaluations shall include credible sources of internal moderation.

(c) Criticality safety evaluations shall consider the neutron reflection properties of the environment to the SIU or subcrit as well as the heterogeneity of the fissile/fertile material within the SIU or subcrit on the effective multiplication factor.

(d) Nuclear criticality safety margins shall include consideration of credible accident conditions consistent with the double contingency criterion. Safety margins for SIUs are defined in 4.2.1.1. For subcrits defined in 4.2.1.2, the highest effective multiplication factor, under normal credible operating conditions, shall be less than 0.95 including a two-sigma statistical calculational uncertainty, where appropriate, as well as any other applicable uncertainties and biases.

(e) Reactivity hold-down by other than fixed poisons shall not be employed in criticality evaluations. Borosilicate Glass Raschig Rings may be employed in solutions of fissile material in a manner consistent with ANSI/ANS 8.5-1986. The effect of structural parasitics, either normal or enhanced, shall be evaluated in a manner which examines both elastic and inelastic scattering contributions to the multiplication factor. Use of enhanced structural parasitics, e.g., boron stainless steel, shall be contingent upon a program to periodically verify the presence of the parasitic additive.

(f) Whenever nuclear criticality safety is directly dependent on the integrity of a fixture, container, storage rack or other structure, design shall include consideration of structural integrity. The fulfillment of structural integrity requirements shall be established by physical test or by analysis by an engineer knowledgeable in structural design.

(g) Computer analysis methods shall be validated in accordance with the criteria of Section 4.2.3.2 and Regulatory Guide 3.4, Revision 2, dated March 1986, "Nuclear Criticality Safety in Operations with Fissionable Materials at Fuels and Materials Facilities". The highest effective multiplication factor derived by the validated analytical methods for credible operating conditions shall be less than or equal to 0.95 including applicable biases and calculational uncertainties.

(h) The analytical method(s) used for the safety evaluation of SIUs and the source of validation of the methods shall be specified.

4.2.2 Multiple Units and Arrays

Criticality safety of the less complex manufacturing operations may be based on the use of limiting parameters which are applied to simple geometries. This approach employs safe units which assume optimum moderation and full reflection using published criticality data. Safe units may be arrayed using the surface density method. An alternate empirical method is the Solid Angle Method.

A more rigorous method is based on two dimensional transport and/or three dimensional Monte Carlo methods. These methods permit the evaluation of more complex geometric configurations of SNM and the evaluation of multiparameter control methods.

4.2.2.1 Spacing of Safe Units

The following criteria shall be employed:

(a) Application of the surface density method of spacing safe mass, volume, or cylinder diameter limited units requires meeting the following criteria:

  (1) Safe mass, volume, or cylinder diameter limited units shall meet the maximum values defined in Table 4-1, Part A.

  (2) The spacing areas for the safe mass, volume, or cylinder diameter limited units of Table 4-1, Part A shall employ spacing areas no less than those defined in Table 4-3. All safe units shall employ a minimum spacing between units of twelve inches. Coplanar slabs specified in Table 4-1, Part A, require no additional spacing; non-coplanar slabs require a minimum spacing of twelve inches.

  (3) Each safe unit shall be centered in its respective spacing area.

(b) When the above criteria for the surface density model cannot be met, the spacing may be established by the solid angle method of TID-7016 (Rev. 2) providing that the applicable criteria on subcriticality of the primary unit and subtended solid angle of interacting units are met.

(c) Nuclear safety shall be independent of the degree of moderation between units up to the maximum credible mist density. The maximum mist density will be determined by studying all sources of water in the vicinity of the single units or arrays. The maximum mist density may be limited by design and/or by administrative controls.

(d) Safety margins for individual units and arrays shall be based on accident conditions such as flooding, multiple batching, and fire.

(e) Optimum conditions (limiting case) of water moderation and heterogeneity credible for the system shall be determined in all applicable calculations.

(f) The water content will be verified to be less than 1.0 w/o in powder storage cans which are arranged in two layers on rollers conveyors.

(g) Vessels and other items of equipment requiring exclusion areas shall have the limits of these areas clearly marked on the floor. Safe units in transit shall not be permitted to enter an exclusion area unless a criticality safety evaluation has been performed for such transit.

(h) The analytical method(s) used for the safety evaluation of the spacing of safe units and the source of validation of the methods shall be specified.

(i) Part B of Table 4-1 summarizes safe limits for pellets, pellet scrap, and Zircaloy clad pellet columns. For the purposes of this license, sintered pellet diameters may range from 0.32 to 0.40 inches. Pellet scrap can include a range of UO_2 sizes, i.e., from powder to 0.40 inch diameter pellets. The safe mass limit for pellet scrap is based on the most reactive pellet diameter (0.10"). Randomly stacked pellets are defined as having a volume averaged density of 5.804 ± 0.147 g/cc. The average void to UO_2 volume ratio for randomly stacked pellets is 0.79965 ± 0.04495. Loose packed rods are defined as rods of a given diameter stacked on square or triangular pitches having an average gap between rods of up to 6 percent or up to 14 percent, respectively, of the clad outer diameter. This definition is applicable to clad pellet columns containing UO_2 pellets having diameters in the range of 0.3224 to 0.40 inches.

(j) The safe mass limits of Table 4-1, Part B, include the double batching allowance. This allowance may be eliminated for operations where double batching is not credible.

4.2.3 Technical Data and Validation of Calculational Methods

4.2.3.1 Technical Data

Safe unit limits which meet the subcriticality criteria for spacing by the surface density method are listed in Table 4-1, Part A. Minimum spacing criteria are as listed in Table 4-3.

Mass limited units may be stacked on a vertical centerline with at least a 10 inch separation.

Table 4-2 provides safe limits for aqueous solutions with enrichments up to 5 w/o U-235. The uranyl fluoride data may be used for UO_4.

A 35 Kg mass limit may be employed for homogeneous or heterogeneous UO_2 in a covered, 19 liter or less, metal container. Heterogeneous UO_2 shall include hard, clean scrap, i.e., broken pellets and chips; hard contaminated scrap, i.e., broken pellets and chips admixed with possible moderating media, shall be limited to the SIU mass values listed in Table 4-1, Part A. These containers shall be separated by a minimum of 12 inches, edge to edge, in a planar array.

4.2.3.2 Validation of Calculational Methods

Criticality safety evaluations for SNM process/storage systems requiring the use of computerized methodologies such as transport and monte carlo codes shall employ validated models. These models shall be validated by analysis of pertinent critical or subcritical experiments to define the range of applicability of the model and associated bias in calculated eigenvalues. The validation analyses for each model shall be documented, consistent with ANSI/ANS-8.1-1983, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors", independently reviewed, and retained on file for the lifetime of the use of results of that model.

All computer codes employed in validated calculational models shall be subjected to formal configuration control procedures. These procedures shall provide security against unauthorized changes to the algorithms in the codes and if authorized changes to the codes are made, the procedures shall assure that appropriate testing is performed to verify the mathematical operations are performed as intended.

The following three types of calculational models have been validated for criticality safety analyses. Pertinent results from the validation studies are summarized below.

Four Broad Neutron Group Model - This model is for heterogeneous UO_2-water mixtures having a H/U greater than unity. The CEPAK Lattice code is employed as the four group cross section generator with S_n codes for the lattice spatial calculation. The four broad group CEPAK/Sn model has been validated by analysis of room temperature, reflected uniform UO_2 rod lattices having a range of rod pitches equivalent to H_2O/UO_2 volume fractions of 0.4347 to 5.067. The UO_2 enrichments of these lattices varied from 2.459 to 5.742 w/o U-235. The calculated multiplication factors were fit to an equation of the form: $Keff = a + b\ (H_2O/UO_2)$. The resulting lower critical tolerance limit, derived on a 95/95 confidence level basis, for twelve experiments is as follows.

$$Keff = (1.007927 + 0.0004183\ (H_2O/UO_2)) - (2.736 \times 0.002059)$$

where: 2.736 is the 95/95 multiplier, and
0.002059 is the methodology standard deviation in Keff.

The validation of this model is presently limited to the calculation of critical and safe dimensions of clad and unclad arrays of pellet columns with no interposed heterogeneities, i.e., water channels, structural members, and poison slabs.

Sixteen Broad Neutron Group Heterogeneous Model - This model is for more complex heterogeneous systems consisting of SNM/moderator/structural materials and is characterized by use of a KENO type spatial calculation. Sixteen group cross sections for these calculations are derived using the NITAWL and XSDRNPM codes and the 123 group GAM/THERMOS master library. The validation of this model is based on the analysis of experiments involving air, low density hydrogenous materials, and water interposed between four 18 x 18 clusters of 4.742 w/o UO_2 rods (J. C. Manaranche, et al, "Dissolution and Storage Experiment with 4.75 w/o U-235 Enriched UO_2 Rods", Nuclear Technology, Vol. 50, pg. 148, September 1980). A total of nine experiments were analyzed. The hydrogen densities in the cross shaped region between the four clusters vary from 0.0 to 0.0414 g/cc for the low hydrogen density materials plus water at 0.1119 g/cc. A primary objective of these analyses was to assess the accuracy of the model for interactive analyses of moderated units of SNM with interposed low density moderator. For the seven low hydrogen density and air lattices, the mean multiplication factor was 1.00449, the standard deviation is 0.00643, the 95/95 multiplier is 3.34, and the 95/95 confidence limits are 0.022. Thus, the lower critical tolerance limit is 1.00449 - 0.022 or 0.98249.

Sixteen Broad Neutron Group Homogeneous Model - This model is for homogeneous SNM/moderator systems and employs the Hansen-Roach sixteen group library. The validation of this model is based on using KENO-IV and the Hansen-Roach library in a recalculation of the forty experiments originally analyzed in Y-1948, (G. R. Handley and C. M. Hopper, Validation of the KENO Code for Nuclear Criticality Safety Calculations of Moderated, Low-Enriched Uranium Systems). A bias curve, defined as one minus the fitted expression to the calculated multiplication factors versus the average energy group causing fissions, ΔE, is as follows.

$$\text{Bias} = -2.19284 + 0.283367\ (\Delta E) - 0.00913413\ (\Delta E)^2$$

The methodology standard deviation in K_{eff} is calculated to be 0.00682. At a 95/95 confidence level, the multiplier on the standard deviation is 2.125. These experiments cover a range in H/U-235 between 133.4 to 971.7. In general, as the magnitude of H/U-235 decreases, the magnitude of ΔE decreases and, for values of ΔE less than 14.8, the fitted value of K_{eff} exceeds unity. Thus, the calculated values of K_{eff} become more conservative below the lowest value of H/U-235 in these experiments.

4.2.3.3 Other Criteria

(a) For validated computer analysis methods, the highest effective multiplication factor for normal or abnormal credible operating conditions shall be less than or equal to 0.95 including applicable biases and calculational uncertainties.

(b) The analytical method(s) used for criticality safety analyses and the source of validation of the methods shall be specified.

4.2.4 Special Controls

The following technical criteria shall be employed.

(a) Process areas containing fissile materials will not have fire sprinkler systems. Water hoses shall not be used to fight fires in the Oxide Building, and in Building Nos. 253, 254, 255, 256-1, and 230 (with the exception of the warehouse area).

(b) The hygrometers on the plant air to the Receivers in the Oxide Building and to the micronizers and blenders in Buildings 254 and 255 will be set to alarm at a dew point no higher than 0 °C and checked on a 6 month interval. The hygrometers on the cooler hopper at the exit of the screw cooler in the oxide building will be set to alarm at a dew point no higher than 15 °C and checked on a 6 month period. Upon alarm, automatic or manual action stops the process. The source of alarm must be investigated and the problem corrected before the process can be continued.

(c) The R-2 steam line will have two (redundant) fail-safe shut-off valves, each activated by two independent high and low temperature alarm setpoints on the R-2 reactor. The operability of this system will be ascertained at least once every 6 months.

(d) The moisture content of the UO_2 powder transferred into the bulk storage hoppers and the recycle storage hoppers will be verified as being ≤ 1 w/o. The instruments used for measuring moisture in UO_2 shall be calibrated on a 6 month interval. Loading and unloading of hoppers shall be done with hoods that prevent water ingress.

(e) The R-1, R-2 and R-3 inlet pressure switches will be calibrated at least once every 6 months.

(f) The two vertical dissolver vessels in the Recycle/Recovery Area (240-2) shall have a barrier to insure that no significant moderating material can be brought within 1 foot of the cylindrical tank surface.

(g) Dual independent verifications of moisture content in UO_2 shall be made prior to transfer of material into the bulk storage hoppers or into the blenders in Buildings 254 or 255.

(h) All moderation controlled containers shall be covered such that no moderator can enter the container when external to protective hoods.

(i) The number of 5 gallon or less containers allowed on the second and third floors of Building 254 shall be limited as follows: lubricant and/or poreformer, 12 on each floor; UO_2 powder, 24 spaced on 2 foot centers on each floor. Additionally, the second and third floors of Building 254 shall be limited on each floor to a maximum of 10 gallons total of water, cleaning solutions, paints and powder moderators (exclusive of lubricant and poreformer) when the poreformer or lubricant mixing operations have material in process.

(j) UO_2 powder charges added to each poreformer mixer in Building 254 shall not exceed 4.4 Kg U-235.

(k) Fissile aqueous solution transfers from safe to unsafe geometry vessels in the wet recovery system shall have at least two independent methods for control of the fissile content of the solution prior to release of the solution to the unsafe geometry vessel; solution transfers shall be limited such that the unsafe vessels never contain more than a fraction of the calculated critical mass. Physical barriers in piping systems shall exist to prevent the inadvertent transfer of fissile aqueous solutions to unsafe geometry vessels.

(l) Process systems shall be designed to minimize the likelihood for accumulation of fissile material within the system. In addition, process procedures shall have provisions for verifying that fissile material has not accumulated within the system, especially in those systems employing unsafe geometry containers.

(m) Measurement controls shall be used whenever geometry controls are not used to ensure criticality safety. Such measurement controls include both weight controls and moisture controls. Instrumentation used to measure parameters as part of such measurement controls is maintained as part of the calibration program or instrumentation qualification program.

(n) Pellets and pellet scrap transferred in quantities greater than a safe mass between Building 230 and non-contiguous buildings shall be transported within a container that maintains a safe slab geometry.

(o) Storage of sintered pellets in the Kardex storage device shall be limited to Kardex storage pans with a maximum of 70 Kgs of UO_2 in each pan. There shall be a minimum of two physical water barriers over Kardex pans to prevent the ingress of water. No more than 4 pounds of moderating media are allowed in each shelf in the Kardex storage device.

(p) Criticality safety evaluations for ventilated hoods may be based on either the limits of Table 4-1, Part B, or have specific safety evaluations. For hoods employing more than one limit, but based on Table 4-1, Part B, mechanical devices shall be employed to ensure that the required minimum separation distance between SNM containers in accordance with Section 4.2.2.1 is maintained.

(q) The rod box storage matrix shall be limited to 112 rod storage boxes and prestack boxes. There shall be a minimum of two physical water barriers over the rod storage boxes and prestack boxes to prevent the ingress of water. No unnecessary moderating material shall be stored within the rod box storage matrix. The limit shall be 20 pounds of moderating material in and around each storage location, of which no more than 5 pounds shall be stored in the fuel rod array. For the prestack boxes, the 20 pounds moderating material limit is in addition to the polyethylene spacers, which shall be a maximum number of 13 in each prestack box and shall be nominally one inch thick. The horizontal spacing between stored boxes shall be at least 3 inches. The vertical pitch of the stored boxes shall be at least 17 inches. The space between the bottom of the bottom box and the concrete floor shall be at least 15 inches. The horizontal spacing between adjacent storage boxes between matrix modules shall be at least 9 inches.

(r) Fuel assemblies, when wrapped and stored in the Fuel Assembly Storage Area shall have the bottom end open to ensure drainage of water.

A minimum spacing of 9.75 inches center to center shall be maintained between fuel assemblies within a row. A minimum center to center distance of 35.0 inches shall be maintained between rows of fuel assemblies within the double row racks. A minimum center to center distance of 37.0 inches shall be maintained between double row racks. The Fuel Assembly Storage Area shall be limited to a maximum of 320 14 x 14 and/or 16 x 16 fuel assemblies, unless otherwise analyzed.

(s) For isolated fuel assemblies, the fuel assembly rod array dimensions shall be limited to a maximum of 8.048" x 8.048", independent of the number of rods and independent of pellet diameter, for pellet diameters less than or equal to 0.40" and greater than or equal to 0.3224". Fuel assembly designs outside this envelope shall require a criticality safety evaluation to ensure the assembly and storage processes have adequate subcriticality margin.

(t) Fuel assembly shipping containers other than the 927A1 and 927C1 containers, shall be stored in an array size not exceeding a total transportation index (TI) of one hundred. The spacing between arrays of these loaded containers and other types of loaded shipping containers shall be at least twelve feet.

(u) The 927A1 and 927C1 shipping container arrays shall be stored within the security fence, in Building 230 or in the parking lot south of Building 230. The loaded 927A1 and 927C1 shipping containers shall be stored no more than three high. There are no container orientation restrictions in the horizontal plane.

Table 4-1

Uranium Oxide Handling and Storage Limits

PART A. Safe Unit Limits Meeting Fractional Critical Criteria for Surface Density Modeling

MASS (Kg UO2)

w/o U-235	Homogeneous	Heterogeneous
>1.0 - 2.5	54	50
>2.5 - 3.0	41	38
>3.0 - 3.2	36	36
>3.2 - 3.4	35	33
>3.4 - 3.6	32	30
>3.6 - 3.8	28	27
>3.8 - 4.1	24	24
>4.1 - 4.3	22	22
>4.3 - 4.5	20	20
>4.5 - 4.7	18	18
>4.7 - 5.0	16	16

VOLUME (L)

>1.0 - 3.5	31	22
>3.5 - 4.1	25	18
>4.1 - 5.0	22	17

CYLINDER DIAMETER (In.)

>1.0 - 3.5	10.7	9.5
>3.5 - 4.1	9.8	8.9
>4.1 - 5.0	9.2	8.4

SLAB THICKNESS (In.)

>1.0 - 5.0	4.0	(see Part B)

PART B. Other Operational Limits; 5 w/o U-235, or less, UO2

Pellets (1)	Slab Th. (In.)	Cyl. Dia. (In)	Vol. (L)	Kg UO2 (2)
Randomly Stacked	4.65	10.2	31.4	90.85
Optimally Moderated	3.75	8.3	17.0	17.45
Pellet Scrap	3.75	8.3	17.0	14.55

Zircaloy Clad Rods	Slab Th. (In.)	Cyl. Dia. (In)
Loose Packed (3)	7.15	14.7
Optimally Moderated	4.17	9.0

Notes:

(1) Pellet OD 0.32" to 0.4"
(2) Including Double Batching Allowance.
(3) See definition in third paragraph, Section 4.2.2.1.

Table 4-2

Aqueous Solution Limits for U-235 Enrichments Less Than or Equal to 5 w/o U-235

	UO_2F_2	$UO_2(NO_3)_2$
Mass (Kg U-235)(1)	0.82	1.77
Cylinder Diameter (in.)(1)	10.0	16.4
Slab Thickness (in.)(1)	4.42	8.33
Volume (liters)(1)	26.9	105.5
Concentration (g U-235/L)		
Critical Limit	273	298
Subcritical Limit(2)	261.0	283.0

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(1) With safety margins
(2) ANSI/ANS-8.1-1983

Table 4-3

Minimum Spacing Areas[1] for Homogeneous and Heterogeneous Mass and Geometric Limits

	Spacing Area (ft^2)
Mass	3.5
Volume	9.0
Cylinder (2)	5.0

---

(1) Subject to a minimum edge-to-edge unit separation of 12 inches.

(2) Per foot of cylinder height.

CHAPTER 14 NUCLEAR CRITICALITY SAFETY

14.1 Administrative and Technical Procedures

Administrative and technical procedures for ensuring criticality safety and their mode of implementation are described in the Nuclear Fuel Manufacturing Program Documentation System. The key features of these procedures relating to criticality safety are summarized below.

(a) Define individual (management, professional, and operations staff) responsibilities for nuclear safety through training, job descriptions, written procedures, and performance reviews.

(b) Ensure that criticality limits and controls, when implemented by engineered safeguards and physical controls, are implemented correctly and are reviewed and approved by both management and safety personnel.

(c) Ensure all facility changes and modifications are reviewed for criticality safety implications by qualified safety personnel.

(d) Ensure that all facility changes and modifications having criticality safety implications receive a criticality safety evaluation by qualified personnel, are reviewed by qualified personnel, and are reviewed for consistency with the safety evaluation, postings, and operating procedures prior to being placed in use.

(e) Ensure that criticality limits and controls established by safety evaluations are conservative at credible accident conditions.

(f) Ensure compliance with and applicability of criticality limits and controls through:

- Audits and inspections of equipment and facilities employed in the handling and storage of Special Nuclear Material (SNM),

- Testing of safety related instrumentation on a regular and defined schedule, and

- Review and update of operating procedures, engineered safeguards, and safety related documents on a regular and defined schedule by management and safety personnel.

14.2 Preferred Approach to Process Design

It is the intent of Combustion Engineering to employ physical controls and permanently engineered safeguards on processes and equipment in the establishment of nuclear safety limits, wherever practical. Physical controls may utilize safe geometry for enrichments permitted under the license or may use an alternate geometry in combination with multiple parameter controls. Safe geometry is defined herein as being consistent with safe individual unit (Section 14.3.1.1.2). When criticality safety is based on an approach other than safe geometry, engineered safeguards with appropriate administrative controls, if needed, will be employed to assure that key parameters are bounded within a regime that precludes criticality in the event of a single credible violation of the specified limits. Both definitions recognize the need to consider interaction effects in an operational environment.

All process designs are evaluated for criticality safety. The ensuing criticality limits and controls are based upon consideration of such factors as the consequences of added internal and external moderation, reflective properties of structures, container walls and personnel, interaction with other SNM, and inadvertent operator errors. For mass limited operations, precautions against SNM accumulations in process equipment are identified.

14.3 Basic Assumptions

14.3.1 Analytic Models

14.3.1.1 Individual Units

14.3.1.1.1 Database

The evaluation and selection of possible sources of experimental and analytical data are discussed below.

Homogeneous UO_2-Water Mixtures - Table 14-1 lists critical values of the optimally moderated, fully reflected critical spherical mass, spherical volume, infinite cylinder diameter, infinite slab thickness, and surface density versus U-235 enrichment extracted from the UKAEA Handbook(1) and DP-1014(2).

Figure 14-1 shows a plot of each of the critical parameters of Table 14-1. Surface density, gUO_2/cm^2, is not edited in the UKAEA Handbook, consequently only DP-1014 data are displayed for this parameter. The DP-1014 data are consistently more conservative than the UKAEA data with the exception of the critical mass parameter in the interval between 2 and 4 w/o U-235.

For purposes of this license, the DP-1014 data shall be employed for homogeneous mixtures of UO_2 and water.

<u>Other Aqueous Solutions</u> - Criticality data for aqueous solutions of uranyl fluoride and uranyl nitrate may be used in establishing safe limits for the chemical process equipment employed in recovery of SNM from scrap and waste materials. Table 14-2 provides the pertinent data for uranium enriched to 5 w/o U-235 and, for comparison purposes, data on homogeneous UO_2 are provided in the same units. Since the data source(3) is the same as for ANSI/ANS 8.1-1983 and this standard provides subcritical limit data, the aqueous solution data of Table 14-2 are corrected to critical using information provided in the data source. The objective is to place the data for aqueous solutions and UO_2 on a comparable basis. In this manner one can judge equivalence on the same bases.

It is noted additional conservatism may exist in the aqueous solution "critical" data since it is based on the most conservative of the three calculational models employed to fit experimental data and extrapolate or interpolate to points of interest.

Reflector Effects - The data discussed above for water reflected homogeneous UO_2-water mixtures and in subsequent paragraphs for heterogeneous UO_2-water mixtures may assume full reflection. Figure 14-2 shows the dependence of the spherical U-235 critical mass [U(93.5) metal spheres] versus thickness of various reflector materials. The point of interest here is that the reflector worth is a function not only of the thickness of the material but also of the composition of the material. Water is a convenient reference material but many structural materials are very effective materials. Consequently, the criticality safety of a given quantity of fissionable material must take into account the environment. If the environment is a more effective reflector than water, it must be considered and evaluated by appropriate analytical modelling.

Heterogeneous UO_2-Water Mixtures - UO_2 lump dimensions of interest in this license application extend from approximately zero to 0.40 inches; this interval covers the range of pellet pieces and whole pellets anticipated in the manufacturing operations. Other variables of interest are water-to-oxide volume ratio, enrichment, and presence or absence of pellet column clad material. The range of the water-to-oxide volume ratio variable required for criticality evaluations of the various heterogeneous UO_2 handling and storage operations extends from about 0.4 to 10.0, or more. This range should address the characteristics of randomly stacked UO_2 pellets, close packed clad pellet columns, and possible upset conditions involving optimally moderated pellets in water.

For the enrichment variable, the maximum process enrichment is 5 w/o U-235; lower enrichments are also of interest for SNM storage arrays; see Section 14.3.1.2.1. The presence or absence of Zircaloy clad is important since the introduction of this low absorption material usually increases the dimensions of critical systems.

Available data on UO_2-water mixtures in the open literature are limited in the range of parameters employed. For example, DP-1014 covers an adequate range of pellet diameters for this license application but the upper limit on the U-235 g/liter variable is only 190.13 which is equivalent to a water-to-oxide volume fraction of 1.522. The UKAEA Handbook provides extensive data compilations for UO_2 pellet diameters ≥ 0.40 inches and water-to-oxide volume ratios ≥ 1.0. Neither source provides information on the effect of clad materials or addresses subcritical limits on the bases employed in this license. Therefore, the limited scope of these two data sources require either the adoption of possible overly conservative limits or supplemental analyses.

To expand the available database, calculations using the validated model of Section 14.6.1.1 are made to define critical and subcritical limits for clad and unclad uranium dioxide pellets enriched to 5 w/o U-235 ($U(5)O_2$) for pellet diameters of 0.05, 0.10, 0.20, and 0.40 inches. For critical systems, the best estimate target multiplication factor derived from the analysis of critical experiments is employed for consistency with data in the open literature. For subcritical (safe) systems, the target multiplication factor is taken to be 5% less than the lower tolerance limit curve for critical systems.

Subsequent paragraphs summarize the results of these analyses as well as analyses with the "alternate" bias curve of Section 14.6.1.1. The purpose of the latter analyses is to make comparisons against the unclad, 0.40" OD $U(5)O_2$ pellet data from DP-1014 and the UKAEA Handbook and to establish a plausibility argument for the less conservative results obtained with the "reference" bias curve. One of the conclusions of the discussion to follow is that the CE derived limit data for heterogeneous $U(5)O_2$ is the primary database and the more conservative data of DP-1014 may be used as a supplementary database. Of course, when critical data are taken from DP-1014 the subcritical limit data has to be estimated using safety factors. Any nonconservatism in use of the safety factors here is usually offset by the inherent conservatism of the critical data.

Unclad, 0.40" OD $U(5)O_2$ Analyses, Alternate Bias Curve - Table 14-3 summarizes critical parameters calculated for 0.40 inch diameter $U(5)O_2$ pellets using the CE calculational model with the alternate bias curve. The purpose here is to more closely duplicate the experimental data base employed for the UO_2 validation of the DP-1014 calculational model. Tables 14-4 and 14-5 summarize the critical parameter data for 0.40 inch diameter $U(5)O_2$ pellets from DP-1014 and the UKAEA Handbook, respectively. Figures 14-3 through 14-7 show plots comparing data from Tables 14-3, 14-4, and 14-5 for the slab thickness, surface density, cylinder radius, spherical volume, and spherical mass parameters. Included in these figures are the CE calculated results for the reference bias curve for comparison purposes. In this manner one can see the impact of changing the bias basis on each parameter; the difference is negligible at low water to oxide ratios but becomes appreciable at optimum moderation and over-moderated conditions.

Figures 14-5, 14-6, 14-7 show good agreement on critical reflected cylinder radius, spherical volume, and spherical mass between the DP-1014 data and the CE (alternate bias curve basis) results. It is also noted the UKAEA data are consistently higher than the CE (alternate bias curve basis) data below a water-to-oxide ratio of about 5 and, for the over-moderated conditions, the UKAEA values are lower. The comparison of slab thickness data in Figure 14-3 shows the DP-1014 data to be lower than the CE (alternate bias curve basis) data by a nearly constant amount over the range of water to oxide displayed. Since this displacement is not evident in the cylinder or spherical data, it would appear an extraneous bias has entered the DP-1014 slab data. This bias is also evident in the surface density data of Figure 14-4. A more important observation from Figure 14-4 is the conservatism of the DP-1014 data for surface density relative to that based on the CE reference bias curve. Thus, the optimum moderated surface density from DP-1014, should it be used to supplement the CE $U(5)O_2$ database, has added conservatism relative to the cylindrical and spherical data.

The above discussion compares the CE, DP-1014, and UKAEA critical, reflected parameter data for $U(5)O_2$ pellets having a diameter of 0.40 inches. A second comparison of interest is the dependence of calculated data on pellet diameter below 0.40 inches since it is this regime which is of interest in pellet handling and storage operations under this license. This subject is addressed below.

Unclad, U(5)O_2 Analyses, Reference Bias Curve - Tables 14-6 and 14-7 summarize the critical and subcritical parameter limits calculated for pellet diameters of 0.05, 0.10, 0.20, and 0.40 inches using the reference bias curve. Table 14-8 summarizes calculated parameter data at pellet densities of 10.9 and 10.41 g/cc to quantify density derivatives for each parameter.

Figure 14-8 shows plots of the fully reflected, critical mass versus water to oxide ratio for pellet diameters of 0.05, 0.10, 0.20, and 0.40 inches. This figure illustrates the difference in dependence of critical mass on pellet diameter between the under-moderated and optimum moderation regimes. In the under-moderated regime, the larger pellets are more reactive whereas in the optimum moderated regime and above, the smaller pellets are more reactive.

Figure 14-9 compares the CE and DP-1014 data on critical mass of UO_2 versus pellet diameter at optimum moderation conditions; the same trend is observed in both data sets with the DP-1014 data being more conservative. At this point it is worth noting the results of Reference 4 which compares the experimentally determined optimum critical mass for unclad U(5)-metal rods in water versus rod diameter with the U(5) data reported in DP-1014. Reference 4 noted a similar dependence of critical mass on U(5)-metal rod diameter; the principal difference being the DP-1014 data are more conservative. This latter comparison supports the premise that the DP-1014 calculational model has inherent conservatism and provides added confidence in the CE data of Figure 14-9.

The enrichment dependence of the mass and geometric parameters is also examined. Table 14-9 lists the minimum critical and safe values of the fully reflected, optimally moderated mass, spherical volume, infinite cylinder diameter, infinite slab thickness, and surface density based on three sources: 1) the UKAEA Handbook, 2) DP-1014, and 3) CE calculations based on the reference bias curve. Here the minimum critical values are deduced for pellet dimensions of 0.40 inches, or less. The safe values for the UKAEA and DP-1014 data are derived from the published data using the safety factors of Section 14.3.1.1.2 whereas the CE critical and safe values are explicitly calculated for $U(5)O_2$ using the validated model of Section 14.6.1.1. Since the minimum pellet diameter for UC_2 pellets in the UKAEA Handbook is 0.40 inches, no mass data are included in Table 14-9 for the UKAEA data source. No surface density data are shown in Table 14-9 under the CE and UKAEA headings since this parameter is not edited in the UKAEA Handbook and the CE calculations were not extended to a sufficiently high water-to-oxide value to define the minimum in this parameter.

Figures 14-10 through 14-14 show plots of the minimum critical data of Table 14-9 to compare parameter differences versus enrichment. One general observation from these figures is the DP-1014 data on slab thickness, cylinder radius, and spherical volume are more conservative than the UKAEA data over varying portions of the enrichment interval plotted. In general, at the 5 w/o enrichment, the CE data are higher than the DP-1014 data but less than the UKAEA data. A point of interest here is the implied trend in critical mass of the UKAEA data. Figure 14-7, which displays the dependence of critical mass on water-to-oxide ratio for 5 w/o enriched, 0.40 inch OD pellets, shows a lower optimum moderated critical mass for the UKAEA data than for the DP-1014 data. This is due primarily to the smaller predicted critical spherical volume versus water-to-oxide (see Figure 14-6) in the over-moderated regime by the UKAEA Handbook. The inferred disparity in the UKAEA, DP-1014, and CE data (reference bias curve basis) in both critical volume and mass data in the over-moderated regime can be correlated with the database for normalization of the calculational model (see Section 14.6.1.1).

Based on the above discussion, the database employed for quantifying the magnitude of the fully reflected, optimally moderated critical parameters for unclad UO_2-water mixtures relies primarily on the CE calculational results; for data not defined therein, the more conservative data of DP-1014 may be employed.

<u>Zircaloy Clad $U(5)O_2$ Analyses, Reference Bias Curve</u> - The validated model of Section 14.6.1.1 is employed with the "reference" bias curve to calculate the fully reflected, critical and subcritical infinite slab thicknesses and infinite cylinder radii for Zircaloy clad, $U(5)O_2$ pellet columns moderated by room temperature water. The applicable pellet diameters are in the range of 0.32 to 0.40 inches. Other pertinent data utilized in this analysis are as follows:

a. The pellet stack density is taken to be 10.41 g/cc or 95% of the theoretical density. (Note that individual pellet densities may exceed 10.41 g/cc as long as the pellet stack density is, on the average, less than or equal to 10.41.)

b. The radial gas gap thickness is taken to be 0.0035 and 0.00335 inches respectively, for rods containing the 0.40 and 0.3224 inch OD $U(5)O_2$ pellets.

c. The clad thickness is taken to be 0.0306 and 0.0248 respectively, for rods containing the 0.40 and 0.3224 inch OD UO_2 pellets.

d. The Zircaloy density is taken to be 6.55 g/cc.

Tables 14-10 and 14-11 summarize the calculated parameters versus water to oxide ratio for Zircaloy-clad, 0.40" and 0.3224" OD $U(5)O_2$ pellet columns, respectively. Figure 14-15 shows plots of the reflected subcritical slab thickness and cylinder radius for the clad 0.32 and 0.40 $U(5)O_2$ pellet columns. At optimum moderation, there is only a small difference in subcritical slab thickness or cylinder radius between the two pellet column diameters. For clad pellet column stacking limits, i.e., at a water-to-oxide volume ratio of ~ 0.4, the larger diameter clad columns are more reactive consistent with the data of Figure 14-8.

14.3.1.1.2 Safe Individual Units

Definitions - A Safe Individual Unit (SIU) is defined as an individual, isolated subcritical unit of fully reflected, optimally moderated SNM whose characteristic mass or geometric parameter does not exceed a limiting value derived by one of the following methods.

1. The magnitude of the SIU may be calculated by a validated calculational model employing a subcritical margin of 0.05 plus applicable biases and calculational uncertainties. All variables affecting the magnitude of the SIU shall be considered in the analysis, e.g., optimum moderation, reflection characteristics, and SNM particle size and density, where applicable. For purposes of this definition, 30 centimeters of water shall be considered as full reflection.

2. Alternatively, the minimum critical value of a given parameter may be based on experimental data or analytic fitting of experimental data. Safe subcritical values are then derived by use of the following safety factors. The mass safety factor includes the double batching allowance.

Mass	2.3
Volume	1.3
Cylinder Diameter	1.1
Slab Thickness	1.2

This definition of SIUs is applicable to material compositions having a U-235 enrichment ≤ 5 w/o. For enrichments in excess of 5 w/o, the limiting value of 350 grams of U-235 shall be imposed under this license.

An isolated subcritical unit is defined as being separated from other subcritical units by a minimum of 8 inches of full density water, or the larger of: (a) 12 feet, or (b) the greatest distance across an orthographic projection of the largest of the SNM mass distributions on a plane perpendicular to the line joining their centers. The effectiveness of other intervening materials or separations shall be evaluated prior to their use.

14.3.1.1.3 Other Subcritical Individual Units

Definitions - The safe individual unit of the previous section was based on the use of either safe unit masses or dimensions defined by a validated calculational model or experimentally defined critical masses or dimensions reduced by safety factors to obtain safe values. In either case, full reflection and optimum moderation (and optimum pellet diameter for lumped UO_2) are implicit in the definition of the safe individual unit.

Other subcritical units may be defined using more stringent controls on the UO_2 environment. These controls may include limits on the degree of internal moderation, the amount of external moderation (reflectivity of the environment) in combination with limits on enrichment, mass and/or geometric characteristics of the UO_2 containers. In these cases, engineered safeguards and administrative controls are required to assure subcritical limits are not violated.

These controls are discussed in Section 14.3.4 on Administrative Control Models.

14.3.1.2 Nuclear Interaction Methods

Interaction between subcritical units which are not isolated may be evaluated by one or more of the three following methods, providing the prerequisites of the method are met: (1) surface density, (2) solid angle, and (3) transport or Monte Carlo analytical models. The minimum allowed spacing between adjacent subcritical units computed by these methods shall be no less than one foot.

14.3.1.2.1 Surface Density Model

The surface density model may be used to structure safe arrays of mass, volume, or cylinder diameter limited units of SNM. The generally acceptable surface density model of Regulatory Guide 3.52 (Revision 1, November 1986) is one wherein each individual unit has a fraction critical of ≤0.3 and the spacing of individual units within the array is such that the smeared surface density of fissionable material is no greater than 25 percent of the critical surface density of a water reflected slab of the same composition. A comparison of these limits to, for example, Figure 26 of Reference 5 indicates that the above model is conservative. However, for certain applications, it may be overly restrictive and not allow the use of unit sizes approaching those of a SIU at the possible expense of a smaller surface density ratio. If one examines the data of Figure 1 of Reference 6, there is evidence to suggest that larger values of the surface density ratio may be permitted in arrays having lower limits of the maximum achievable U-235 concentration, as in low enrichment processing facilities.

The surface density model implemented by this license is not defined by specific limits on fraction critical and ratio of smeared to critical surface density. Instead, limits are placed on the operational parameters such as mass, volume, cylinder diameter, and spacing area. The spacing area limits are independent of enrichment. One consequence of the latter choice is that both fraction critical and ratio of smeared to critical surface density may exhibit an enrichment dependence.

The concept of fraction critical is based on somewhat arbitrary definition deduced from correlations of experimental data; see, for example, Reference 7. The definition employed here takes the fraction critical as the ratio of the SIU mass, or equivalent spherical mass, to that of an unreflected critical sphere of the same composition.

In evaluating safe units for this license, non-spherical units are reduced to spherical shapes using buckling conversions based on the following equations:

$$B^2 = \left(\frac{\pi}{R_s + \lambda_s}\right)^2 \quad \text{Sphere}$$

$$= \left(\frac{\pi}{x + 2\lambda_t}\right)^2 + \left(\frac{\pi}{y + 2\lambda_t}\right)^2 + \left(\frac{\pi}{z + 2\lambda_t}\right)^2 \quad \text{Slab}$$

$$= \left(\frac{2.405}{R_c + \lambda_c}\right)^2 + \left(\frac{\pi}{H + 2\lambda_c}\right)^2 \quad \text{Cylinder}$$

For convenience, unreflected and water reflected extrapolation lengths, λ, are taken from Figure 2 of Reference 7:

Unreflected	Reflected
λs = 2.1 cm	5.9 cm
λt = 2.7 cm	6.6 cm
λc = 2.25 cm	6.3 cm

Although these data are for $U(93)O_2F_2$ solutions, their use in a consistent manner should have small impact on buckling conversions.

Table 14-12 summarizes the administrative limits on mass, volume and cylinder diameter limits versus enrichment applicable to surface density modelling in this license; the SIU limits are provided for comparison. The homogeneous and heterogeneous SIU limits in the data of Table 14-12 are derived from DP-1014. The discussion in Section 14.3.1.1.1 concludes the data of DP-1014 are conservative, consequently these SIUs are conservative. For homogeneous UO_2, the administratively implemented safe mass limits are lower than the SIU values and the fraction critical (fc) for the safe mass values are no greater than 0.25. The administratively implemented safe volume limits are less than the SIU limits and the fraction critical is no greater than 0.40. The administratively implemented safe cylinder diameter limits are also less than the SIU limits and the fraction critical does not exceed 0.32.

For heterogeneous UO_2, the safe mass limits are numerically equal to the homogeneous safe mass limits for enrichments greater than 4.1 w/o U-235. SIU limits are given for two types of heterogeneous UO_2. The lower SIU limits are based on optimum pellet diameter versus enrichment. The second (higher) SIU limits are based on a pellet diameter of 0.30 inches. The latter diameter is less than the diameter of pellets routinely manufactured and is close to the optimum pellet diameter at the lower end of the enrichment range of Table 14-12. Thus, these limits are the more practical limits and permit a standardization on the numerical value of the mass limits for both homogeneous and heterogeneous UO_2 at the higher enrichments. Possible concerns over pellet chips are addressed as follows. Broken pellets are not screened to segregate out the smaller pieces; rejected pellets and pieces are processed together. The average lump dimension within a scrap pellet lot is greater than 0.10 inches.

The fraction critical for each heterogeneous safe mass limit does not exceed 0.27. The safe volume limits for heterogeneous UO_2 are less than or equal to the SIU limits. Note that the entries in the two SIU columns are identical, thus the optimum pellet diameter is close to 0.30 inches. For the cylinder diameter limits, the fraction critical does not exceed 0.33 and again the entries in the two SIU columns are identical.

The minimum spacing areas for the safe mass, volume, and cylinder diameter limits are listed below; these minimum spacing areas are enrichment independent.

Unit Type	Spacing Area (ft^2)
Mass	3.5
Volume	9
Cylinder Diameter	5 (per foot of cylinder height)

The above spacing areas result in the following ratios of smeared to critical surface density for each unit type at 5 w/o U-235:

Unit Type	$\sigma s/\sigma c$ or ts/tc	fc
Mass	0.36	0.24
Volume	0.21	0.40
Cylinder Diameter	0.22	0.32

Since either the fraction critical or the surface density ratio violates the criteria of the generally acceptable surface density model of Regulatory Guide 3.52, KENO-IV(11) analyses of reflected, infinite arrays of air reflected mass, volume, and cylinder diameter limited units were performed to verify that the arrays were indeed subcritical. The following assumptions were employed in these analyses.

(1) The unit containers are assumed to be cylindrical in shape, uncovered, and have a 0.025 inch thick carbon steel side wall and floor. Container diameters were varied from 9.5 to 11.75 inches. Cylinder diameter limited containers are assumed to be 48 inches in height; mass and volume limited containers were varied in height to yield the required volume or mass (at appropriate density).

(2) The unit containers were assumed to be reflected from below by 16 inches of concrete and from above by 12 inches of water at the top of the container.

The homogeneous UO_2 and water mixture mass limited container analysis results are graphically summarized in Figure 14-16 where the KENO K_{eff}, including uncertainties and bias (see Section 14.6.2), is plotted versus uranium concentration. The lower curve is for a 17 Kg mass of UO_2 at 5 wt % U-235 in a 11.75 inch ID container. Each container has a spacing area of 3.5 ft^2. The maximum K_{eff} occurs at a uranium concentration of ~0.6 KgU/L, as expected, from the observed minimum in the tabulation of g U-235/cm^2 for 5 w/o enriched homogeneous UO_2 in Reference 2. At a concentration of 0.6 KgU/L the unit mass container diameter was decreased from 11.75 to 10.5 to 9.5 inches in successive calculations; the multiplication factor decreased with container diameter. In these analyses, the unit mass was preserved by increasing the container height.

The second curve is for a mass unit of 41 $KgUO_2$ at an enrichment of 3 w/o U-235 in a 11.75 inch ID container. Here we note the multiplication factor peaks out at ~1.1 KgU/L which again is reasonably consistent with the concentration at which the g U-235/cm^2 is minimized in Reference 2 for homogeneous UO_2 at this enrichment level.

From these two curves we may conclude that homogeneous safe mass limits of Table 14-12 at 5 and 3 w/o U-235 yield an acceptable subcritical margin when arrayed with a spacing area of 3.5 ft^2 per unit.

Figure 14-17 summarizes the results of the volume and cylinder diameter limited analyses. The curves of multiplication factor versus uranium concentration exhibit a maximum at approximately 1.8 KgU/L for 5 w/o enriched homogeneous UO_2. Once again, this is consistent with the concentration at which the minimum slab thickness occurs in Reference 2. The plots of multiplication factor versus ts/tc provide a measure of the sensitivity of the multiplication factor to changes in both ts/tc and cylinder diameter or unit volume.

The curves of Figure 14-17 demonstrate the acceptability of the safe volume and cylinder diameter limits of Table 14-12 for homogeneous UO_2 at 5 wt% U-235, when these units are arrayed with a spacing area of 9 ft^2 for a volume unit and 5 ft^2 per foot of height for a cylinder diameter limited unit container.

For postulated uniform mixtures of UO_2 pellets and water, it is noted that, at a given enrichment, the minimum g U-235/cm^2 and slab thickness occur at the same g U/cc of the mixture as with uniform mixtures of homogeneous UO_2 and water. A KENO array analysis for mass units of 17 $KgUO_2$ of 0.325 inch diameter, 5 w/o enriched pellets with a uranium concentration of 0.6 KgU/L yields a multiplication factor including uncertainties and bias, of 0.9091 versus 0.9066 for the comparable homogeneous UO_2 case. The only difference in the array analyses other than the degree of heterogeneity is that the heterogeneous calculation used 16 inches of water instead of concrete. The heterogeneous UO_2 array result provides an acceptable margin of subcriticality. The fact that the multiplication factor is slightly higher than for the homogeneous case is not surprising since the fraction critical is higher for the heterogeneous case. No analyses were done for the heterogeneous volume and cylinder diameter limits since the fraction critical values are in general less for the heterogeneous limits compared to the homogeneous limits. Thus, for the same spacing areas, the multiplication factors should be comparable, or less than, those computed for the arrays of homogeneous UO_2.

The safe mass, volume, and cylinder diameter limits of Table 14-12 are incorporated into Table 4-1, Part A of Chapter 4.

14.3.1.2.2 Solid Angle Model

When the limitations of the above defined surface density model cannot be met for interacting subcritical units, the spacing may be established by the solid angle method described in Reference 8, subject to the limitations described therein. If this method is employed in a nuclear safety evaluation, each criterion and limitation shall be addressed in the documentation of the safety evaluation.

14.3.1.2.3 Transport and Monte Carlo Codes

The interaction between subcritical units may be calculated explicitly using validated analytical models when the prerequisites for the previously defined interaction methods can not be fulfilled, the previously defined methods are too conservative, or the configuration and composition of various regions are too complex. When the multiplication factor is calculated explicitly, the target multiplication factor shall be no greater than k_T, where k_T is defined by the following equation.

$$k_T \leq k_c - \Delta k_u - \Delta k_s$$

where: k_c is the calculated multiplication factor for the benchmark critical experiments using the defined calculational model (cross sections, codes, etc.).

Δk_u is the uncertainty in the calculated results for the benchmark experiments at the 95% confidence level.

Δk_s is the allowed margin of subcriticality, i.e., 0.05.

14.3.2 Accident Conditions

The accident analysis process begins with a complete understanding of the system to be evaluated. Examples of the accident analysis process are given in Chapter 15. An evaluation of the system is used to determine the effect of adverse changes in the equipment or the process, or the consequences of an operator error which are then used as input to the criticality evaluation or analysis. Examples of accident conditions are outlined below. Validated computer programs are used to determine the K_{eff} for the accident conditions, where necessary. If the K_{eff} is unacceptable, the equipment or process design is modified and reanalyzed or preventative measures are employed so as to make the accident incredible.

The following accident conditions are normally considered in the criticality safety evaluation of a given process design.

(a) Adverse changes in dimensions and spacing within the process system;

(b) Adverse changes in density of SNM and the amount of admixed moderator;

(c) Adverse changes from mass or concentration limits, where applicable;

(d) Interactions with SNM in transit;

(e) Adverse changes in parasitic absorptions in fixed poisons, where required for reactivity control;

(f) The effect of cumulative errors or uncertainties on downstream criticality limits and controls;

(g) Adverse changes in interspersed moderation and reflector composition;

(h) The inadvertent introduction or accumulation of SNM in process operations;

(i) The non-failsafe consequences of process failures (mechanical failures, loss of air pressure, loss of electrical power, etc.);

(j) Potential water sources which may affect moderation controlled processes;

(k) Effects of fire fighting, flooding, and storms on criticality safety limits and controls.

When multiple events are correlated or follow as a natural consequence, they are treated as a single event. The facility has been designed so that no single postulated credible event can result in a predicted critical condition. Process or environmental design changes or other engineered safeguards are given a higher priority over administrative controls in achieving this process design criterion.

14.3.3 (this section has been deleted)

14.3.4 Administrative Control Models

14.3.4.1 Mass Controls

Homogeneous and heterogeneous mass limits for safe units are discussed in Section 14.3.1.1.1; use of these limits in storage arrays is discussed in Section 14.3.1.2.

Alternative mass limit controls may be employed for certain operations which, in reality, are multiparameter controls. For example, a mass limit associated with specific containers (volume limit); in addition, controls on internal and/or external moderation limits may be imposed.

Consider the case of a 35 Kg mass limit on UO_2 powder in a 5 gallon, or less, container with a cover. The cover is employed for radiological control, to maintain chemical purity, and to prevent the ingress of water. These containers are normally opened and closed in hooded enclosures to minimize the likelihood of water ingress. In the event of internal and external flooding of the container, criticality would not occur since the 5 gallon (19 liter) container is a safe volume for UO_2 powder enriched to 5 w/o U-235.

To assess the criticality safety of the 35 Kg mass limited, 5 gallon container in storage arrays, a KENO analysis was run for an infinite planar array of such containers.

Each container was modelled as a 10.75 inch inner diameter cylinder with a wall thickness of 0.025 inches and a height of 14.25 inches; the cylinder wall was treated as a void. The 35 Kg UO_2 (10.96 g/cc density) was homogeneously distributed in water to fill the container. A one foot thick water reflector was above and below the array. The results of the KENO IV analysis using 16 energy group Hansen-Roach cross sections are tabulated below versus separation distance between the containers.

Separation (inches)	Multiplication Factor
12	0.9584 ± 0.0065
14	0.9414 ± 0.0081
16	0.9268 ± 0.0070

Based on the analyses, it is concluded that the minimum separation distance of 12 inches between adjacent 35 Kg mass limited 5 gallon containers will result in a safe storage array for dry UO_2 powder when the containers are closed and stored in a mist free environment. In the event that all cans are flooded with water internally, the array is still subcritical. Should the cans become fully reflected, the array is still subcritical since the containers (19 liters) are a safe volume and adjacent containers are isolated by the 12 inches of water. Thus, the double contingency criterion is satisfied. It should be noted that the above analyses are conservative since the container volume exceeded that of a 5 gallon container by 12%.

Another case of interest is that for a 35 Kg mass limit of heterogeneous material in containers having a volume of 5 gallons, or less. For a 5 gallon container the volume (19 liters) exceeds the safe volume of 17 liters for optimum moderation conditions at a UO_2 enrichment of 5 w/o U-235 but is less than the critical reflected volume of 22 liters.

Additionally, the mass of 35 Kg is just about equal to the minimum critical reflected mass of 35.4 Kg UO_2 at a rod diameter of 0.1 inches. This latter dimension corresponds to the optimum moderation condition of Figure 14-8. A key difference between the experimental data employed to establish the heterogeneous mass limits of Section 14.3.1.1 and the case of interest here is the experimental data are for rods and the case of interest is a random array of pellets in a container.

Sintered 0.40"OD $U(5)O_2$ pellets when randomly stacked in a 2 x 5 x 10 inch pellet pan have an average bulk density of 5.8037 g/cc with one sigma variation of 0.147 g/cc, as determined by a series of 25 measurements (see Section 14.3.4.6). In the absence of upset conditions, the safe mass is 181.7 Kg UO_2. Therefore, it may be concluded that the 35 Kg mass limit on UO_2 pellets enriched to 5 w/o U-235 in a 5 gallon or less container results in a safe condition when stored at a minimum separation distance of 12 inches. Should these containers become internally flooded, the array is still safe. Thus, the double contingency criterion is met.

Clean, hard scrap, i.e., chipped pellets and pellet chips, having a known composition may be stored in 5 gallon or less containers. The irregular geometry of the UO_2 chips and broken pellets is such that the bulk density of the scrap in a container is higher than for whole pellets of regular geometry. Therefore, in the event of flooding of the containers, the critical mass should be higher than for whole pellets because of the reduced level of internal moderation. The data of Figure 14-8 show that pellet chips and broken pellets are less reactive than whole pellets at the highly under moderated condition expected to occur when this hard scrap is randomly loaded into a container.

The curves of Figure 14-8 are useful in establishing trends in critical mass versus pellet size and water to oxide volume ratio. However, they are of little value in making quantitative adjustments to an existing calculation for a change in pellet diameter. A simple method of estimating the change in multiplication factor when pellets of a different diameter are substituted for the pellets in an existing calculation, is by multiplying the calculated multiplication factor by the fractional change in infinite multiplication factor between the two pellet diameters. Figure 14-18 shows the variation of infinite multiplication factor versus pellet diameter at water to oxide volume ratios ranging from 0.74 to 1.784. The former value is slightly less than that expected for randomly stacked pellets immersed in water (0.84); values exceeding 0.84 correspond to pellets floating in water. An alternative description is in terms of unclad columns of UO_2 pellets arranged on a square pitch with the pitch to diameter ratio varying from 1.37 to 1.48.

As an illustration of the above estimation process, consider the case of estimating the increase in multiplication factor of a container of pellets when the pellet diameter is postulated to increase from 0.325 to 0.400 inches when the water-to-oxide volume ratio is 1.32. The change in infinite multiplication factor may be deduced from Figure 14-16 for the postulated changes in pellet diameter as approximately 0.0062. If the KENO calculated multiplication factor is 0.80, the increase in multiplication factor for the assumed pellet diameter change is only 0.005.

A similar technique can be employed for pellet density effects when the pellets are postulated to be homogeneously distributed in a fully flooded container. The following tabulation summarizes the infinite multiplication factor for 0.400 inch diameter unclad UO_2 rods in room temperature water versus pellet density and water to UO_2 volume ratio.

VH_2O/VUO_2	UO_2 Density (g/cc)	K∞
1.0	10.25	1.4319
1.0	10.50	1.4288
1.0	10.96	1.4232
1.5	10.25	1.4957
1.5	10.50	1.4936
1.5	10.96	1.4898
2.0	10.25	1.5249
2.0	10.50	1.5239
2.0	10.96	1.5218

Figure 14-19 summarizes the above data. Here it is noted that the infinite multiplication factor is linear with pellet density for a given water to oxide volume ratio. However, the dependence of the infinite multiplication factor on water to oxide volume ratio for fixed pellet density is not linear. For the purposes of this estimation process, it will be assumed to be linear between calculated points since the net adjustment to the effective multiplication factor will be small.

The change in effective multiplication factor, ΔK, is based on the following equation:

$$\Delta K = \frac{K}{K\infty} \left[\left(\frac{\Delta K\infty}{\Delta (g/cc)} \right) \Delta (g/cc) + \left(\frac{\Delta K\infty}{\Delta (VH_2O / VUO_2)} \right) \Delta \left(\frac{VH_2}{VUO_2} \right) \right]$$

Values of $\Delta K\infty/\Delta(g/cc)$ are -0.0044, -0.0083, and -0.0122 for water-to-oxide ratios of 2.0, 1.5, and 1.0, respectively. Values of $\Delta K\infty/\Delta(VH_2O/VUO_2)$ are taken to be 0.064 in the water to oxide ratio interval between 1.5 and 2.0, and 0.133 in the interval between 1.0 and 1.5.

As an example, consider the case where the pellet density increases from 10.25 to 10.50 g/cc and the volume ratio of water-to-oxide increases from 1.784 to 1.852. If the initial effective multiplication factor is 0.87281, the change in multiplication factor is

$$\begin{aligned} \Delta K &= 0.87281 \times [(-0.0083)(0.25) + (0.064)(0.068)] / 1.4957 \\ &= 0.0013 \end{aligned}$$

Thus, the change in the multiplication factor is less than 0.2% of the multiplication factor for this example.

14.3.4.2 Internal Moderation Controls

A useful control parameter for UO_2 of enrichment 5 w/o U-235 or less is the amount of admixed moderator. UO_2 has a relatively high theoretical density (10.96 g/cc) but the UO_2 encountered in the process steps prior to pelletizing has a much lower bulk density. The granular output of the UF_6 to UO_2 conversion process has a bulk density in the range of 3.0 to 3.5 g/cc, whereas the micronized UO_2 granules have a bulk density in the range of 1.8 to 2.4 g/cc. For these bulk densities, it is of interest to examine the degree of subcriticality when the UO_2 is saturated with water, i.e., all interstitial voids are filled with water and the UO_2 density in the mixture is the same as the bulk density.

Figure 14-20 shows the loci of the reflected minimum critical mass and geometric parameters such as volume, cylinder diameter, and slab thickness as a function of enrichment and bulk density. The effect of a deviation of ± 5% from the minimum critical value is also displayed so that an estimate of the breadth of the minimum in the given parametric dependence on UO_2 concentration can be related to a change in bulk density. These curves indicate the pre-micronized UO_2 is generally under moderated, as far as mass limits are concerned, when saturated with water. For the geometric parameters, the water saturated pre-micronized UO_2 is under moderated particularly at the higher enrichment, but at the lower enrichment it is at near optimum moderation. The micronized powder, when saturated with water, is at near optimum conditions for the geometric parameters at higher enrichments and for mass at the lower enrichments. As the enrichment increases, the micronized powder tends to be under moderated at the saturated water condition and would require an upset force plus added moderator to become optimally moderated.

There are two ranges of container volumes of interest when considering internal moderation controls. For safe $U(5)O_2$ container sizes, the container is subcritical regardless of the contents (≤ 5 w/o U-235) and the surrounding environment, i.e., water density, as long as other SNM bearing containers are not neutronically coupled to the container of interest.

For container sizes in excess of 31 liters and for UO_2 bulk densities encountered in the processing line, criticality can occur when the container is fully reflected. The bulk density of the micronized powder is typically in the range of 1.8 to 2.4 g/cc. Thus, when the powder is saturated with water, the mixture is near optimum for the minimum critical volume.

To assure criticality safety in large volume containers, moderation control procedures are implemented. These procedures are based on administrative controls of one form or another. Even when engineered safeguards are employed, they are dependent upon administrative controls for testing and periodic recalibration.

For purposes of this license, dry UO_2 is defined as UO_2 having a water content of 1.0 w/o or less. A homogeneous and isotropic distribution of UO_2 enriched to 5 w/o U-235 with 1 w/o water has an infinite multiplication factor of 1.010. Thus, subcriticality is assured for relatively large containers of "dry" 5 w/o enriched UO_2 even when fully reflected.

The 30-inch diameter UF_6 shipping containers employ internal moderation control. The hydrogen to uranium atomic ratio is less than 0.088 which is equivalent to the purity specification of 99.5% for the UF_6 (Reference 9). In this case, all impurities in the UF_6 are assumed to be hydrogen. Analyses reported in Reference 10 show the infinite multiplication factor of the 30-inch diameter UF_6 cylinders to be less than unity at this H/U ratio. Strict administrative controls on the handling, transfer of the UF_6 contents, and cleaning of these containers are required to assure safe handling of this material.

14.3.4.3 External Moderation Controls

External moderation controls affect the amount of moderating material external to the container bearing the SNM. As noted earlier, fire fighting in the production area at the Hematite Facility (specifically Buildings 253, 254, 255, 256-1, and 230; with the exception of the warehouse and specifically approved storage areas) is limited to dry techniques and there are no overhead sprinkler systems. Care has been taken to route water and steam pipes away from areas where large containers of UO_2 are employed. Thus, in the event of a rupture in these water or steam lines, there will be a reduced likelihood of potential criticality concerns.

In most cases equipment has been designed to be safe in the event of complete reflection, e.g., a tight fitting reflector of water. There may also be cases where such a precaution does not exist. In these instances a barrier is employed around the containers to prevent the approach of significant moderating material to within 1 foot of the cylindrical wall of the container. This barrier modifies the criticality limits of the container such that it may be treated as a partially reflected container. A measure of the effect of an annular gap between a container of U(93) solution and a six-inch thick annular water reflector is given on page 19 of Reference 5. It is concluded that for a gap of 7 inches, the reflector savings is just one half that of a close fitting water reflector. Caution must be employed with this criticality control procedure to preclude materials against which the barrier is ineffective.

14.3.4.4 Concentration Controls

Uranium concentration controlled containers shall be limited to a maximum concentration of 25 grams of uranium per liter. The effect of evaporation and/or precipitation shall be considered in the nuclear safety analysis, such that if precipitated a safe mass will not be exceeded.

Concentration controlled containers shall not be considered to contribute to interacting arrays, but shall be located outside exclusion areas assigned by the surface density method.

A safe mass of uranium shall be used for aqueous solutions only under administrative control. The safe mass limit does not apply to fixed poison systems.

14.3.4.5 Effective Density of Randomly Stacked Pellets in Pellet Pans

A 2" deep by 5" wide by 10" long pellet pan of known weight and volume was filled successively with randomly stacked pellets and the weight was measured. This process was repeated twenty five times. Results of these measurements are summarized in Table 14-13. Based on this data, the following conclusions may be drawn.

1. The average number of grams of randomly stacked UO_2 pellets in a "filled" pellet pan is 8253 ± 207.

2. The volume average density of UO_2 in the pans is 5.804 ± 0.147 grams per cubic centimeter. The 95/95 confidence band half width, based on the twenty five measurements, is 2.292 x 0.1473, or 0.3376.

3. The average void to UO_2 volume ratio in the pellet pans is 0.79965 ± 0.04495. The 95/95 confidence band half width is 2.292 x 0.04495, or 0.1030. Thus, the upper tolerance limit appropriate for assessments of the minimum critical mass limits, for example, is 0.9026.

14.3.4.6 Critical and Subcritical Limits for Unclad $U(5)O_2$ Pellets

Tables 14-6 and 14-7 summarize the results of CE calculations of the critical and safe limits for 10.90 g/cc $U(5)O_2$ pellets of different diameters over a range of water-to-oxide volume ratios. Figure 14-21 shows plots of the safe limits on slab thickness versus water to oxide ratio for each pellet diameter. The minima in the curves indicate the optimally moderated safe slab thickness versus pellet diameter has a broad minimum between 0.20 and 0.40 inches; in the under-moderated regime, the safe slab thickness varies inversely to the pellet diameter. Operational limits for unclad $U(5)O_2$ pellets are defined as follows.

Randomly Stacked Pellets - Section 14.3.4.5 discusses the effective bulk density of randomly stacked pellets and indicates the maximum water to oxide ratio for randomly stacked pellets in pellet pans is 0.9026. This value assumes a 95/95 confidence level for the 25 measurements. This inferred bulk density is conservative for deeper containers such as the sintering pans since the free volume at the top of the deeper pans is a smaller fraction of the total free volume of the container.

The following limits are derived using this value for the most limiting pellet diameter, 0.40 inches under fully moderated and reflected $U(5)O_2$ conditions. These values are conservative for pellets of density lower than 10.9 g/cc. No allowance for double batching has been explicitly included here in the mass limit. Also note some discretion must be employed when using these limits since they assume that no upset condition may occur in the possible scenarios. Upset, as applied here, refers to conditions that may change the inter-pellet spacing in the presence of moderating media for even a fraction of a second. If the latter criterion cannot be met for the safety evaluation, one should employ limits based on either the most adverse spacings appropriate to the UO_2 container and/or process/accident conditions, or the optimally moderated pellet limits discussed in paragraph 2) below.

Parameter	Safe	Critical
Slab Thickness	4.65"	5.71"
Cylinder Diameter	10.2"	11.9"
Spherical Volume	31.4 L	46.5 L
Spherical Mass	181.7 Kg	269.4 Kg

The safe, randomly stacked pellet limit data are incorporated into Table 4-1, Part B.

Optimally Moderated Pellets - Limit data for optimally moderated $U(5)O_2$ pellets are summarized below. For the intended application of this license, the minimum pellet diameter is 0.32 inches and the maximum is 0.40 inches. Slab thickness, cylinder diameter, and spherical volume are evaluated at a pellet diameter of 0.40 inches whereas spherical mass is evaluated at 0.32 inches (see Figure 14-8). The critical spherical mass was not calculated using the calculational model of Section 14.6.1 for 0.32 inch diameter unclad pellets. However, the dependence of critical spherical mass on pellet diameter, can be inferred from DP-1014. By plotting the logarithm of the mass versus pellet diameter, it is noted that the critical spherical mass data of DP-1014 for $U(5)O_2$ pellets exhibits a linear dependence for pellet diameters equal to and greater than 0.20 inches. Therefore, the critical spherical mass for 0.32 inch diameter pellets can be obtained by linear interpolation of the logarithm of the calculated critical masses for pellets having diameters of 0.20 and 0.40 inches. The safe mass at 0.32 inches is obtained using the safe to critical ratio for the 0.40 inch data. This ratio exceeds 1.3 and is used for consistency of the data as a whole. No allowance for double batching has been explicitly included here.

Parameter	Safe	Critical
Slab Thickness	3.75"	4.41"
Cylinder Diameter	8.3"	9.4"
Spherical Volume	17.0 L	23.3 L
Spherical Mass	34.9 Kg	48.8 Kg

The safe, optimally moderated pellet limit data are incorporated into Table 4-1, Part B. These limits are applicable to, for example, aligned pellet arrays on corrugated trays.

U(5)O_2 Pellet Scrap - Pellet scrap refers to broken pellets and pellet pieces. Note that a small number of pellet pieces does not warrant labelling a container of otherwise randomly stacked or optimally moderated pellets as pellet scrap. The volume fraction of pellet pieces must be significant, e.g., greater than about 25%. The choice of this volume fraction is based on the observation that pellet pieces vary in size with a small percentage at the optimum or near-optimum pellet diameter (0.10").

The applicable limits for pellet scrap are the same as for optimally moderated pellets, with one exception. The spherical mass limit must be defined on the basis of the most reactive pellet diameter, 0.10 inches. The critical spherical mass is reduced from 48.1 to 40.2 Kg UO_2. The safe spherical mass, with no allowance for double batching, is obtained in the same manner as in the above discussion on optimally moderated pellets by using the critical to safe mass ratio for 0.40 inch pellets. The safe spherical mass, with no allowance for double batching, is 29.1 Kg UO_2 for optimum moderation conditions. Alternative limits may be warranted if conditions exist that would limit the degree of moderation to a value less than optimum.

Safe limits for pellet scrap are incorporated into Table 4-1, Part B, of Chapter 4.

Pellet Pan Arrays - To determine the effect of external moderation on individual pellet pans in an infinite array of pans stacked two high, the following analysis was carried out. Here, the dependence of the multiplication factor on horizontal bidirectional separation of each vertical pair of pans and density of water within this spacing is examined with the KENO-IV(11) code. Sixteen broad group cross sections are generated for each region of the model using the XSDRNPM(30) and NITAWL(30) codes and the 123 group library (DLC-16(12)).

The following assumptions are employed in the horizontally infinite slab array of pellet pans.

(a) Each stainless steel pellet pan (10.25 inches long, 5 inches wide and 2 inches high) is assumed to contain 5 w/o enriched UO_2 pellets of nominal diameter 0.40 inches at an average UO_2 smeared density of 5.686 g/cc and the remaining volume containing full density water.

(b) The stainless steel walls (0.1984 cm thick) and cover (0.1270 cm thick) of each pan are represented explicitly.

(c) A 12 inch thick full density water reflector is placed in contact with the top and bottom of the four-inch thick slab.

The results of the analysis are summarized in Figure 14-22. Conclusions drawn from these results are as follows.

(a) A fully reflected 4.0 inch thick infinite slab of two thin walled stainless steel trays containing 0.40 inch diameter pellets having an average UO_2 density within the pan of 5.686 g/cc and the remaining volume filled with water, has an effective multiplication factor of 0.815 ± 0.008.

(b) For a range of spacings of up to 6 inches between the 4 inch high modules of the slab and for a range of water densities in the intra-module spaces varying between zero and full density, the effective multiplication factor is less than the value with zero spacing. Thus, the introduction of extraneous moderating materials between components of a large array of pellet trays arranged in a slab configuration will not result in an increase in the effective multiplication factor.

14.4 Fixed Poisons

Holding tanks may be poisoned with Raschig rings in accordance with Regulatory Guide 3.1, Revision 2, which states that the guidance contained in ANSI Standard ANS 8.5-1986 provides a procedure generally acceptable to the NRC staff. Raschig ring sample tubes will be provided to enable inspection for accumulation of solids and to provide samples for testing the physical and chemical properties of the rings. These inspections and tests will be conducted for the present use of the Raschig ring tanks within 13 months in accordance with the ANSI Standard.

14.5 Structural Integrity Policy and Review Program

All storage racks, furnaces, containment, and processing equipment which provide nuclear safety limiting parameters shall be designed to assure against failure under normal and reasonable overload conditions and under conditions of shock or collision foreseeable in the plant area. All equipment design shall conform to standard design practices, thereby assuring adequate structural integrity. Materials of construction shall be selected to assure, as far as possible, resistance to fire and corrosion. The individual engineer responsible for the purchasing or design of the new equipment shall assure that these criteria are incorporated into the design of the equipment.

14.6 Analytical Models and Their Validation

14.6.1 Heterogeneous UO_2 - Water Configurations

14.6.1.1 Four Broad Neutron Group Model

The four broad neutron group model employs the CEPAK Lattice Code to calculate the neutron spectrum in 83 multigroups and collapse spectrally averaged element-wise cross sections to four groups. Transport corrected Po region averaged cross sections are calculated from the CEPAK output and input to Sn codes such as ANISN(12) or DOT(13). For purposes of criticality safety calculations for the Fuel Manufacturing Facility, this model is used primarily for assessing the critical and safe dimensions of heterogeneous mixtures of UO_2 pellets, or pellet pieces, and water in systems having a H/U ratio greater than unity.

The CEPAK Lattice Code is a synthesis of the FORM(15), THERMOS(16), and CINDER(17) codes. The 83 group microscopic cross section library data base is derived from ENDF/B-IV. For most applications, the required input is limited to an engineering description of the UO_2 lattice configuration. Principal features of the code include: (1) thermal expansion of solids and liquids, (2) water densities based on the steam tables, (3) Dancoff correction factors calculated by a Sauer(18) corrected, Fukai(19) prescription, (4) a U-238 resonance integral based on an updated Hellstrand(20) correlation with temperature correction and a U-235 enrichment dependent resonance overlap correction, and (5) poison and buckling searches to critical.

Validation of this model is based on the analysis of rod lattice critical experiments at room temperature with unborated water and no lattice heterogeneities, i.e., no water channel or structural materials. Experiments were selected so as to span a range of water to oxide volume ratios between about 0.4 and 5.0. This range extends from just above optimum moderation to a value closely approximating clad rods on a nearly touching square array. Variables of secondary interest include pellet diameter, enrichment, and clad materials. The key characteristics of the initially selected lattices are summarized as follows.

Laboratory	wt% U-235	UO_2 Pellet Dia.	H_2O/UO_2
B&W	2.495	0.4054	1.37 - 1.84
B&W	4.02	0.444	0.96 - 1.14
Yankee	2.7	0.30	1.048 - 4.984
Winfrith	3.003	0.3984	0.779 - 3.164
WAPD/CRX	5.742	0.357	1.50 - 5.067
ANL/ZPR-7	3.042	0.3681	0.4347- 1.371

Tables 14-14a and -14b summarize the lattice characteristics for the 23 lattices.

Four group constants for the lattice cells were calculated by CEPAK in a critical spectrum mode which, in this case was approximated by use of the experimentally measured bucklings. Four group constants for the reflector region were calculated by CEPAK using a prescription calling for a group independent buckling of 0.008 cm^{-2}. Transport corrected, four group constants were calculated for input to core radial ANISNs since all of these lattices were nearly right circular cylinders and were approximated as such.

Table 14-15 summarizes the calculated multiplication factors for each lattice and Figure 14-23 shows a plot of the multiplication factors versus water to oxide volume fraction. Based on an analysis of the results, it was concluded that the Yankee and Winfrith experiments should be excluded from the reference data set. This action is based on the observation that these experiments exhibit a characteristic over-estimate of clad absorptions as noted in Figure 14-23 and by other attempts to rationalize these experimental results with analysis.

Various combinations of the analysis results by laboratory were fit to the expression $K_{eff} = a + b (H_2O/UO_2)$. Two groupings were of particular interest. The first group consists of twelve experiments, the B&W, WAPD/CRX, and the ANL/ZPR-7 experiments. These experiments are characterized by either low absorption aluminum clad, characterized stainless steel clad composition, or consistency of the data on K_{eff} when plotted versus pellet OD (see Figure 14-24) and enrichment (see Figure 14-25). This group is selected as the reference group for a bias determination in the analysis of unclad or Zircaloy clad pellet columns. The reference best estimate critical bias curve, expressed as the target multiplication factor entered into ANISN, is:

$$K_{eff})_{Ref.} = 1.007927 - 0.0004183\ H_2O/UO_2$$

The target subcritical (safe) multiplication factor is defined as 5% below the critical lower tolerance limit by the following equation.

$$K_{eff})_{Ref.} = (1.007927 + 0.0004183\ (H_2O/UO_2)) - (2.736 \times 0.002059) - 0.05$$

where: 2.736 is the 95/95 multiplier, and
0.002059 is the methodology standard deviation in K_{eff}.

The second grouping of experiments consists of 20 experiments: the B&W, Yankee, Winfrith, and ANL/ZPR-7 experiments. This set yields the lowest fitted K_{eff} at optimum moderation conditions and includes experiments typical of those included for normalization of the modelling for UO_2 fuel in DP-1014. This set of experiments defines the best estimate alternate critical bias curve as follows:

$$K_{eff})_{Alt.} = 1.09797 - 0.0028846\ H_2O/UO_2$$

As above, the target subcritical (safe) multiplication factor is defined by the following alternate bias curve:

$$K_{eff})_{Alt.} = (1.009797 - 0.0028846\ (H_2O/UO_2)) - (2.396 \times 0.004427) - 0.05$$

where: 2.396 is the 95/95 multiplier, and
0.004427 is the methodology standard deviation in K_{eff}.

To gain added confidence in the modelling of the validation procedure, the best estimate fit to the 20 experiments was employed in calculations of fully reflected critical dimensions of infinite slabs, infinite cylinders, and spheres containing 0.40 inch diameter, unclad pellet columns of $U(5)O_2$ at a density of 10.9 g/cc versus water to oxide volume fraction. The results closely agreed with those of DP-1014 and are discussed in Section 14.3.1.1.1.

The values of K_{eff} based on the above expressions meet the safe multiplication factor criterion of 0.95 minus applicable biases and uncertainties in deterministic analyses. Since this expression was derived by fitting data on K_{eff} over a range of water to oxide ratios between 0.4347 and 5.067 and for U-235 enrichments between 2.495 and 5.742, it can be used with a 95/95 level of confidence in that range.

14.6.1.2 Sixteen Broad Neutron Group Model

This model is similar to that employed for homogeneous UO_2 - water mixtures. It differs in that the broad group cross sections are calculated by the NITAWL and XSDRNPM code sequence to take into account the heterogeneity of the fuel moderator mixture.

Critical experiments on the interposition of low hydrogen density materials between four 18 x 18 clusters of 4.742 w/o enriched UO_2 rods were performed by the Department of Nuclear Safety of the French Atomic Energy Commission and reported in Reference 29. The fuel rods are spaced on a square pitch of 13.5 mm, contain UO_2 pellets 0.790 cm in diameter, and are clad in aluminum tubes 0.94 cm O.D. with a wall thickness of 0.12 cm; the elements are 100 cm long. Figure 14-26 shows the experimental setup. The four fuel clusters are supported by a mobile device which allows them to move along orthogonal directions in a horizontal plane.

Cross shaped boxes of different thickness were employed to separate the four fuel clusters and to successfully contain air and various hydrogenous materials including the following:

(1) expanded polyethylene $(C_8H_8)_n$,
(2) polyethylene powder $(CH_2)_n$,
(3) polyethylene balls $(CH_2)_n$,
(4) water

Water was then introduced into the bottom of the tank to fill the fuel rod clusters and reflector region; criticality was achieved on water height.

The computer codes employed in this analysis are KENO IV, NITAWL, and XSDRNPM. The reference microscopic cross section library is the 123 group super - XSDRN library, DLC-16(14). The NITAWL and XSDRNPM codes(11) are used to generate 16 broad neutron energy group cross sections. NITAWL is used to generate self shielded 123 group cross sections from 123 group super-XSDRN library (DLC-16). The resulting working library is then collapsed into a homogenized 16 energy group library in a typical fuel pin cell environment using XSDRNPM. XSDRNPM is also used to obtain separate 16 group cross section sets for structural materials and external moderators. The KENO model employed a homogenized fuel pin representation in the interior of the fuel rod cluster. The cross shaped box, the outside moderator, tank wall, lattice grid, fuel pin lower plug, bottom plate and support plate are all explicitly represented. Table 14-16 summarizes the multiplication factors computed by KENO IV for nine critical experiments.

The statistical uncertainty and bias of the criticality analysis of the experiments have been calculated. The only criticality analyses included in the uncertainty analysis are the low hydrogen and all air calculations as these are representative of the hydrogen density range of interest in the plant criticality analyses. The results are as follows:

Total Number of Results	7
Mean Value, $\bar{X}$	1.00449
Standard Deviation	0.00643
95/95 Multiplier	3.34
95/95 Confidence Limits	0.022
Bias ($\bar{X}$ -1)	0.00449

It may be concluded from the above analysis that the KENO model employing 16 broad group cross sections based on the NITAWL and XSDRNPM sequence of calculations does give acceptable agreement with experiments and an acceptable level of uncertainty for use in criticality safety calculations.

14.6.2 Homogeneous UO_2 - Water Configuration

Homogeneous fuel-water mixtures are analyzed with the KENO-IV code. In these cases the fuel may be in powder or granular form, admixed with other elements, and assumed to be uniformly mixed with water. The fuel-water mixture may be contained in vessels within a regular or irregular array. Moderator may be assumed to exist in the space between these vessels. In these analyses, the primary library source is the 16 group Hansen-Roach cross section library (revised version dated 9/17/90).

For purposes of assessing the magnitude of a possible bias in the KENO-IV code and revised sixteen group Hansen-Roach cross sections implemented on the engineering workstations, the experiments of Reference 31 were rerun. Figure 14-27 shows a second order polynomial fit to the KENO-IV results for the forty experiments. This polynomial is of the following form:

$$K_{eff}]_{KENO} = 3.19284 - 0.283367\ (\Delta E) + 0.00913413\ (\Delta E)^2$$

where ΔE is the average energy of the of the neutrons causing fissions.

The bias between the Keno calculated K_{eff} and the second order polynomial fit to the KENO results is given by the following expression:

$$\text{bias} = K_{eff}]_{KENO} - K_{eff}]_{fit}$$

Table 14-17 summarizes the evaluation of the methodology standard deviation. The methodology standard deviation is 0.00682 ΔK and the 95/95 confidence limit multiplier is 2.125.

14.7 Special Controls

Other special controls used to ensure nuclear safety are described, as applicable, where the various facilities or processes are presented.

14.8 Data Sources

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Table 14-1

Critical Reflected Parameters for Homogeneous UO_2-Water Systems

Source	w/o U-235	Kg UO2	Volume (L)	Cyl. Rad. (cm)	Slab Thick. (cm)	gUO2/cm2
DP-1014	1.5	1112.0	335.0	31.30	35.9	106.0
10.9g/cc	2.0	396.0	135.0	22.60	24.6	60.0
	3.0	127.9	58.2	16.70	16.8	28.6
	5.0	42.0	29.1	12.95	12.0	13.4
UKAEA	1.5	1305.0	405.0	33.80	39.6	
10.96g/cc	2.0	369.0	140.0	22.90	25.6	
	3.0	120.0	60.0	17.00	18.3	
	5.0	43.1	31.0	13.20	13.2	

Table 14-2

Critical Limits for UO_2, UO_2F_2, and $UO_2(NO_3)_2$ for Uranium Enriched to 5 w/o U-235 in Aqueous Solutions(1)

Parameter	UO_2	UO_2F_2	$UO_2(NO_3)_2$
Mass (Kg U-235)	1.85	1.89	4.08
Cylinder Radius (cm)	12.95	14.00	23.00
Slab Thickness (cm)	12.00	13.49	25.40
Volume (L)	29.10	35.00	137.20
Concentration (g U-235/L)	--	273.00	298.00

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(1) Data from H.K. Clark, "Subcritical Limits for Uranium-235 Systems", NSE 81, pg. 351 (1982). (see text)

Table 14-3

Critical Parameters for Unclad, 10.9 g/cc, 0.40" OD U(5)O_2 Pellet Columns in Water; Alternate Bias Curve Basis

REFLECTED					
H2O/UO2	SLAB T(cm)	g UO2/cm2	Cyl.R(cm)	Sph.Vol(L)	Kg.UO2
8.0	16.17	19.58	15,36	45.22	54.77
7.0	14.76	20.11	14.30	37.18	50.66
6.0	13.53	21.07	13.38	31.11	48.44
5.0	12.48	22.67	12.61	26.61	48.34
4.0	11.62	25.33	12.01	23.55	51.34
3.5	11.29	27.35	11.81	22.61	54.77
3.0	11.07	30.17	11.70	22.17	60.41
2.5	10.99	34.23	11.72	22.46	69.95
2.0	11.16	40.55	11.97	23.99	87.16
1.5	11.82	51.54	12.66	28.20	122.95
1.0	13.70	74.66	14.41	40.67	221.65
0.8	15.15	91.74	15.69	51.63	312.65
0.6	18.07	123.10	18.21	78.35	533.76
0.4	23.65	184.13	22.89	148.74	1158.05

Table 14-4

DP-1014 Critical Parameters for Unclad, 10.9 g/cc, 0.40" OD (U(5)O_2 Pellet Columns in Water

REFLECTED					
H2O/UO2	Slab T(cm)	g UO2/cm2	Cyl.R(cm)	Sph.Vol(L)	Kg UO2
1.52	11.2	48.41	12.55	27.3	118.0
2.03	10.6	38.14	11.95	23.5	84.6
2.54	10.6	32.66	11.75	22.3	68.9
3.05	10.7	28.84	11.75	22.3	60.0
3.55	11.0	26.34	11.90	22.9	54.8
4.06	11.3	24.34	12.15	23.9	51.6
5.08	12.2	21.88	12.75	27.1	48.6
6.09	13.3	20.45	13.50	31.6	48.6
7.11	14.5	19.50	14.40	37.5	50.5
8.12	15.9	19.01	15.44	45.4	54.3
9.14	17.5	18.83	16.70	55.9	60.2
10.15	19.4	18.97	18.15	70.2	68.6
12.18	24.3	20.13	21.89	119.0	98.4
14.21	31.8	22.82	27.65	231.0	165.0
16.24	44.9	28.42	37.69	561.0	354.0
18.27	71.6	40.47	58.00	1980.0	1120.0

Table 14-5

UKAEA Handbook Critical Parameters for Unclad, 10.96 g/cc, 0.40" OD (U(5)O_2 Pellet Columns in Water

REFLECTED				
H2O/UO2	Slab T(cm)	Cyl. R(cm)	Sph.Vol(L)	Kg UO2
1.0	15.85		47.6	
1.5	13.21	13.53	31.7	139.6
2.0	12.14	12.60	26.3	97.1
2.5	11.68	12.20	24.2	76.4
3.0	11.53	12.06	23.6	64.7
3.5	11.63	12.09	23.8	57.9
4.0	11.81	12.22	24.1	52.8
4.5	12.14	12.45	25.1	49.9
5.0	12.42	12.70	26.3	48.0
5.5	12.78	13.00	27.9	47.1
6.0	13.26	13.34	29.5	46.5
6.5	13.79	13.69	31.9	46.5
7.0	14.35	14.06	34.3	47.3

Table 14-6

Critical and Subcritical (0.95) Parameters for Unclad, 10.9 g/cc, 0.40" OD (U(5)O$_2$ Pellet Columns in Water; Reference Bias Curve Basis

REFLECTED

	Slab T(cm)		gUO2/cm2		Cyl. R(cm)		Sph. Vol(L)		Kg. UO2	
H2O/UO2	Critical	Subcrit.	Critical	Subcrit.	Critical	Subcrit.	Critical	Subcrit.	Critical	Subcrit.
8.0	17.51	14.83	21.20	17.96	16.41	14.31	54.29	37.10	65.75	44.93
7.0	15.76	13.45	21.47	18.33	15.08	13.26	43.10	30.21	58.72	41.16
6.0	14.28	12.24	22.24	19.06	13.97	12.35	34.99	25.00	54.48	38.93
5.0	13.02	11.19	23.65	20.33	13.04	11.58	29.14	21.13	52.94	38.38
4.0	12.01	10.31	26.18	22.48	12.32	10.96	25.21	18.44	54.96	40.21
3.5	11.62	9.96	28.15	24.13	12.06	10.74	23.94	17.55	58.00	42.50
3.0	11.34	9.69	30.90	26.41	11.91	10.59	23.27	17.03	63.40	46.40
2.5	11.21	9.53	34.91	29.68	11.89	10.56	23.35	17.03	72.71	53.03
2.0	11.33	9.57	41.17	34.77	12.10	10.71	24.72	17.91	89.80	65.07
1.5	11.95	9.98	52.10	43.51	12.76	11.21	28.82	20.51	125.66	89.41
1.0	13.78	11.29	75.10	61.53	14.46	12.53	41.11	28.15	224.04	153.39
0.8	15.21	12.32	92.11	74.60	15.73	13.50	51.97	34.68	314.70	210.01
0.6	18.10	14.35	123.31	97.76	18.22	15.35	78.66	49.71	535.87	338.67
0.4	23.60	18.06	183.74	140.61	22.85	18.62	148.22	85.23	1153.98	663.55

UNREFLECTED

8.0	25.04	22.32	30.33	27.03	20.21	18.08	84.85	61.15	102.77	74.06
7.0	23.38	21.02	31.86	28.64	18.93	17.07	69.95	51.70	95.30	70.44
6.0	22.02	19.92	34.29	31.02	17.87	16.23	59.15	44.54	92.10	69.36
5.0	20.94	19.05	38.04	34.61	17.03	15.55	51.36	39.29	93.31	71.38
4.0	20.20	18.45	44.04	40.22	16.46	15.08	46.51	35.98	101.40	78.44
3.5	19.99	18.27	48.42	44.25	16.29	14.95	45.15	35.09	109.37	85.00
3.0	19.93	18.23	54.31	49.68	16.25	14.92	44.78	34.89	122.04	95.06
2.5	20.10	18.38	62.60	57.24	16.36	15.04	45.89	35.67	142.92	111.07
2.0	20.64	18.85	74.99	68.49	16.81	15.40	49.45	38.30	179.67	139.14
1.5	21.90	19.91	95.48	86.81	17.78	16.23	58.20	44.54	253.73	194.20
1.0	24.82	22.34	135.27	121.75	20.02	18.10	82.26	61.22	448.34	333.67
0.8	26.88	24.00	162.77	145.33	21.60	19.39	102.69	74.82	621.84	453.06
0.6	30.80	27.12	209.83	184.76	24.62	21.78	150.40	105.15	1024.57	716.32
0.4	37.86	32.44	294.77	252.57	30.02	25.86	268.89	173.51	2093.48	1350.88

Table 14-7

Critical and Subcritical Parameters for Reflected, Unclad, 10.9 g/cc $(U(5)O_2$ Pellet Columns in Water

O.D. (IN)	H2O UO2	Slab T(cm) Critical	Slab T(cm) Subcrit.	gUO2 /cm2 Critical	gUO2 /cm2 Subcrit.	Cyl. R(cm) Critical	Cyl. R(cm) Subcrit.	Sph. Vol(L) Critical	Sph. Vol(L) Subcrit.	Kg. UO2 Critical	Kg. UO2 Subcrit.
0.05	10.0	15.44	13.10	15.30	12.98	14.91	13.06	42.04	29.23	41.66	28.96
	8.0	13.91	11.81	16.84	14.34	13.78	12.13	34.02	24.10	41.20	29.19
	6.0	12.69	10.79	19.76	16.80	12.92	11.41	28.82	20.58	44.88	32.05
	4.0	11.98	10.11	26.12	22.05	12.53	11.03	26.87	19.16	58.57	41.77
	3.0	12.05	10.08	32.84	27.47	12.71	11.14	28.28	19.93	77.06	54.32
	2.0	12.90	10.63	46.87	38.62	13.59	11.80	34.47	23.62	125.26	85.83
	1.0	16.89	13.39	92.05	72.98	17.14	14.43	66.16	41.75	360.57	227.51
	0.6	22.80	17.32	155.33	118.01	22.11	17.91	135.08	76.37	920.25	520.30
	0.4	30.24	21.90	235.44	170.51	28.18	21.82	267.88	132.80	2085.65	1033.97
0.10	10.0	15.54	13.22	15.40	13.10	14.95	13.12	41.98	29.46	41.60	29.20
	8.0	13.82	11.81	16.74	14.30	13.66	12.06	33.16	23.62	40.16	28.61
	6.0	12.44	10.64	19.37	16.56	12.68	11.23	27.26	19.68	42.45	30.65
	4.0	11.59	9.84	25.27	21.45	12.16	10.76	24.76	17.84	53.97	38.90
	3.0	11.57	9.74	31.53	26.55	12.27	10.81	25.63	18.31	69.84	49.89
	2.0	12.32	10.22	44.76	37.13	13.07	11.41	30.87	21.54	112.16	78.26
	1.0	16.05	12.83	87.47	69.95	16.44	13.94	58.85	37.91	320.74	206.62
	0.6	21.62	16.61	147.29	113.17	21.16	17.31	119.43	69.29	813.63	472.06
	0.4	28.58	20.98	222.52	163.34	26.88	21.08	234.05	120.26	1822.22	936.27
0.20	10.0	16.78	14.24	16.63	14.11	15.87	13.87	49.58	34.17	49.13	33.86
	8.0	14.49	12.39	17.55	15.01	14.14	12.47	36.19	25.71	43.83	31.14
	6.0	12.67	10.87	19.73	16.93	12.79	11.36	27.79	20.15	43.27	31.37
	4.0	11.43	9.76	24.92	21.28	11.96	10.63	23.50	17.13	51.24	37.33
	3.0	11.21	9.51	30.55	25.90	11.90	10.55	23.50	17.03	64.05	46.40
	2.0	11.69	9.78	42.47	35.54	12.50	10.99	27.22	19.33	98.89	70.25
	1.0	14.95	12.09	81.48	65.88	15.49	13.27	49.91	33.06	272.00	180.18
	0.6	20.02	15.60	136.39	106.30	19.84	16.44	99.65	60.10	678.83	409.43
	0.4	26.38	19.72	205.39	153.53	25.11	20.02	193.32	104.40	1505.15	812.83

Table 14-8

Critical Parameters for Unclad, 0.40" OD (U(5)O$_2$ Pellet Columns at Two Densities; Reference Bias Curve Basis

10.9 g/cc

H2O/UO2	Slab T(cm)	Cyl.R(cm)	Sph.Vol(L)	Kg.UO2
REFLECTED				
8.0	17.51			
6.0			34.99	54.48
3.0	11.34	12.94	23.27	63.40
0.4	23.60	30.18	148.22	1153.98
UNREFLECTED				
8.0	25.04			
6.0			59.15	92.10
3.0	19.93	17.55	44.78	122.04
0.4	37.86	38.70	268.89	2093.48

10.41 g/cc

H2O/UO2	Slab T(cm)	Cyl.R(cm)	Sph.Vol(L)	Kg.UO2
REFLECTED				
8.0	17.96			
6.0			36.51	54.30
3.0	12.27	12.62	27.13	70.60
0.4	23.76	23.06	152.73	1135.68
UNREFLECTED				
8.0	25.54			
6.0			61.45	91.39
3.0	20.80	16.93	50.50	131.43
0.4	38.32	30.43	279.91	2081.36

Table 14-9

Minimum Critical and Safe Reflected Parameters for Heterogeneous UO_2-Water Systems, Pellet Diameter ≤ 0.40 inches

Source	w/o	Kg UO2		Vol. (L)		Cyl. D.(in)		Slab T.(in)		gUO_2/cm^2	
	235	Crit.	Safe	Crit.	Safe	Crit.	Safe	Crit.	Safe	Crit.	Safe
DP-1014	1.5	500.0	375.0	149.0	111.7	15.58	16.7	10.28	8.70	77.9	70.1
	2.0	226.0	169.5	73.1	54.8	14.37	12.9	7.52	6.40	48.1	43.2
	3.0	92.7	69.5	38.2	28.6	11.34	10.2	5.55	4.72	25.2	22.7
	5.0	35.4	26.5	22.1	16.6	9.21	8.3	4.17	3.54	12.6	11.3
UKAEA	1.3			260.0	195.0	21.7	19.5	12.5	10.6		
	2.0			72.0	54.0	14.4	13.0	7.8	6.6		
	3.0			38.0	28.5	11.5	10.3	5.8	4.9		
	4.0			28.3	21.2	10.2	9.2	5.0	4.3		
	5.0			23.6	17.7	9.5	8.5	4.5	3.8		
CE	5.0	40.2	28.6	23.27	17.03	9.36	8.3	4.41	3.75		

Table 14-10

Critical and Subcritical (0.95) Parameters for Clad, 10.41 g/cc, 0.40" OD $(U(5)O_2$ Pellet Columns in Water; Reference Bias Curve Basis

	REFLECTED					
	Slab T(cm)		g UO2 /cm2		Cyl. R(cm)	
H2O/UO2	Critical	Subcrit.	Critical	Subcrit.	Critical	Subcrit.
4.0	13.04	11.19	27.15	23.30	13.20	11.74
3.5	12.71	10.90	29.40	25.22	13.01	11.58
3.0	12.52	10.70	32.58	27.85	12.94	11.50
2.5	12.52	10.66	37.24	31.71	13.04	11.57
2.0	12.84	10.87	44.55	37.72	13.44	11.89
1.5	13.83	11.58	57.59	48.22	14.41	12.66
1.0	16.47	13.54	85.73	70.48	16.82	14.55
0.8	18.75	15.20	108.44	87.91	18.80	16.07
0.6	22.90	18.15	148.99	118.09	22.31	18.69
0.4	32.40	24.44	240.92	181.73	30.18	24.10
	UNREFLECTED					
4.0	21.60	19.70	44.97	41.02	17.55	16.07
3.5	21.48	19.63	49.69	45.41	17.47	16.02
3.0	21.58	19.73	56.16	51.35	17.55	16.10
2.5	21.96	20.08	65.32	59.72	17.85	16.37
2.0	22.84	20.84	79.25	72.31	18.53	16.97
1.5	24.64	22.40	102.60	93.27	19.92	18.18
1.0	28.68	25.80	149.28	134.29	23.05	20.82
0.8	31.88	28.40	184.37	164.25	25.51	22.83
0.6	37.34	32.74	242.94	213.01	29.71	26.16
0.4	49.04	41.32	364.65	307.24	38.70	32.74

Table 14-11

Critical and Subcritical (0.95) Parameters for Clad, 10.41 g/cc, 0.3224" OD $(U(5)O_2$ Pellet Columns in Water; Reference Bias Curve Basis

	REFLECTED					
	Slab T(cm)		g UO2 /cm2		Cyl. R(cm)	
H2O/UO2	Critical	Subcrit.	Critical	Subcrit.	Critical	Subcrit.
4.0	12.75	10.93	26.55	22.76	13.01	11.57
3.5	12.52	10.71	28.96	24.78	12.89	11.46
3.0	12.41	10.59	32.29	27.56	12.89	11.45
2.5	12.51	10.63	37.21	31.62	13.08	11.59
2.0	12.95	10.93	44.94	37.93	13.57	11.97
1.5	14.08	11.75	58.63	48.93	14.66	12.83
1.0	17.00	13.91	88.49	72.40	17.28	14.89
0.8	19.48	15.70	112.66	90.80	19.42	16.52
0.6	24.04	18.91	156.41	123.03	23.27	19.34
0.4	34.76	25.86	258.47	192.29	32.09	25.26
	UNREFLECTED					
4.0	21.42	19.55	44.60	40.70	17.42	15.96
3.5	21.42	19.57	49.55	45.27	17.42	15.98
3.0	21.60	19.75	56.21	51.40	17.57	16.12
2.5	22.10	20.18	65.73	60.02	17.96	16.47
2.0	23.10	21.06	80.16	73.08	18.74	17.14
1.5	25.06	22.74	104.35	94.69	20.26	18.46
1.0	29.42	26.38	153.13	137.31	23.63	21.27
0.8	32.82	29.14	189.81	168.53	26.24	23.40
0.6	38.78	33.78	252.31	219.78	30.81	26.96
0.4	51.74	43.06	384.72	320.18	40.76	34.09

Table 14-12

Mass, Volume, and Cylinder Diameter Limits versus Enrichment

U-235 Enrichment w/o	Mass Limits						
	Homogeneous			Heterogeneous			
	KgUO$_2$	fc	SIU	KgUO$_2$	fc	SIU(1)	SIU(2)
>Nat. ≤ 2.5	54	.19	83	50	.23	57	58
>2.5 ≤ 3.0	41	.22	54	38	.25	41	41
>3.0 ≤ 3.2	36	.22	49	36	.26	36	37
>3.2 ≤ 3.4	35	.24	43	33	.27	32	34
>3.4 ≤ 3.6	32	.25	38	30	.27	29	30
>3.6 ≤ 3.8	28	.24	34	27	.26	26	28
>3.8 ≤ 4.1	24	.24	29	24	.27	23	25
>4.1 ≤ 4.3	22	.24	26	22	.27	21	23
>4.3 ≤ 4.5	20	.24	24	20	.26	19	22
>4.5 ≤ 4.7	18	.23	22	18	.26	18	20
>4.7 ≤ 5.0	16	.24	18	16	.26	15	18.6

Volume Limits

	L	fc	SIU	L	fc	SIU(1)	SIU(2)
>Nat. ≤ 3.5	31	.37	38	22	.37	25	25
>3.5 ≤ 4.1	25	.36	31	18	.35	21	21
>4.1 ≤ 5.0	22	.40	24	17	.39	17	17

Cylinder Diameter Limits

	in.	fc	SIU	in.	fc	SIU(1)	SIU(2)
>Nat. ≤ 3.5	10.7	.32	11.1	9.5	.33	9.5	9.5
>3.5 ≤ 4.1	9.8	.30	10.4	8.9	.31	8.9	8.9
>4.1 ≤ 5.0	9.2	.32	9.3	8.4	.31	8.4	8.4

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(1) SIU limit based on optimum pellet size.

(2) SIU limit based on 0.30 inch diameter pellets

Table 14-13

Summary of Data on Randomly Stacked UO_2 Pellets in 2x5x10" Pellet Pan Having Volume of 1422 cc

Meas. No.	Pellet Den (g/cc)	g UO2 in Pan	Vol. Avg. UO2 Den. (g/cc)	Void/UO2 Vol. Ratio
1	10.390	8170	5.7454	0.80839
2	10.405	8185	5.7560	0.80769
3	10.405	8250	5.8017	0.79344
4	10.400	8645	6.0795	0.71068
5	10.370	8370	5.8861	0.76178
6	10.385	8170	5.7454	0.80752
7	10.385	7790	5.4782	0.89570
8	10.370	8030	5.6470	*0.83638
9	10.375	8175	5.7489	0.80468
10	10.445	8345	5.8685	0.77984
11	10.445	8580	6.0338	0.73109
12	10.465	8505	5.9810	0.74970
13	10.465	8365	5.8826	0.77899
14	10.460	8255	5.8052	0.80183
15	10.460	8560	6.0197	0.73763
16	10.460	8200	5.7665	0.81392
17	10.480	8275	5.8193	0.80091
18	10.475	8215	5.7771	0.81320
19	10.445	8065	5.6716	0.84164
20	10.460	7830	5.5063	0.89963
21	10.460	8103	5.6983	0.83563
24	10.485	8415	5.9177	0.77180
25	10.485	8385	5.8966	0.77814
Average		8253	5.8037	0.79965
Std. Dev.		209	0.1473	0.04495

Table 14-14a

Summary of Lattice Parameters for 23 Critical Experiments

Expt. No.	Lattice	w/o U-235	UO2 OD (in)	UO2 g/cc	Gas Gap (in)	Clad t (in)	Clad Mt'l
1	B&W-1273,Core I	4.020	0.44400	9.46	0.0	0.016	SS
2	B&W-1273,Core X	4.020	0.44400	9.46	"	"	SS
3	B&W-1273,CoreXIII	2.459	0.40540	10.24	0.0027	0.032	AL
4	B&W-3647,Core I	2.459	0.40540	10.24	"	"	AL
5	Yankee(YAEC-94)	2.700	0.30000	10.18	0.0031	0.0161	SS
6	Yankee(YAEC-94)	2.700	0.30000	10.18	"	"	SS
7	Yankee(YAEC-94)	2.700	0.30000	10.18	"	"	SS
8	Yankee(WCAP-1433)	2.700	0.30000	10.18	"	"	SS
9	Yankee(WCAP-1412)	2.700	0.30000	10.18	"	"	SS
10	Yankee(WCAP-1412)	2.700	0.30000	10.18	"	"	SS
11	Yankee(WCAP-1412)	2.700	0.30000	10.18	"	"	SS
12	Yankee(WCAP-1433)	2.700	0.30000	10.18	"	"	SS
13	Winfrith,R1-20	3.003	0.39840	10.44	0.00535	0.01051	SS
14	Winfrith,R2-20	3.003	0.39840	10.44	"	"	SS
15	Winfrith,R3-20	3.003	0.39840	10.44	"	"	SS
16	WAPD/CRX	5.742	0.35700	10.20	0.001973	0.015	SS
17	WAPD/CRX	5.742	0.35700	10.20	"	"	SS
18	WAPD/CRX	5.742	0.35700	10.20	"	"	SS
19	ANL/ZPR-7	3.042	0.36811	10.17	0.005315	0.0189	AL
20	ANL/ZPR-7	3.042	0.36811	10.17	"	"	AL
21	ANL/ZPR-7	3.042	0.36811	10.17	"	"	AL
22	ANL/ZPR-7	3.042	0.36811	10.17	0.00449	0.01953	SS
23	ANL/ZPR-7	3.042	0.36811	10.17	0.005315	0.0189	AL

Table 14-14b

Summary of Lattice Parameters for 23 Critical Experiments

Expt. No.	Lattice	Pitch (in)		H2O / UO2	T(F)	Bz2 (m-2)	Bt2 (m-2)	Ref.
1	B&W-1273,Core I	0.59500	Sq.	1.1400	59.0	3.60	88.00	21
2	B&W-1273,Core X	0.57100	"	0.9590	71.6	3.95	79.00	21
3	B&W-1273,CoreXIII	0.59500	"	1.3710	71.6	4.07	70.10	21
4	B&W-3647,Core I	0.64449	"	1.8410	69.8	4.70	86.10	22
5	Yankee(YAEC-94)	0.40500	"	1.0480	68.0	5.40	40.75	23
6	Yankee(YAEC-94)	0.43500	"	1.4050	68.0	5.40	53.21	23
7	Yankee(YAEC-94)	0.47000	"	1.8550	68.0	5.40	63.30	23
8	Yankee(WCAP-1433)	0.49300	"	2.1660	68.0	10.96	68.80	24
9	Yankee(WCAP-1412)	0.57300	"	3.3720	71.6	5.53	65.64	25
10	Yankee(WCAP-1412)	0.61500	"	4.0780	78.3	5.48	60.07	25
11	Yankee(WCAP-1412)	0.66500	"	4.9840	73.4	5.41	52.92	25
12	Yankee(WCAP-1433)	0.41800	"	1.2000	68.0	12.10	47.50	24
13	Winfrith,R1-20	0.51968	"	1.0010	68.0	24.51	66.00	26
14	Winfrith,R2-20	0.73464	"	3.1640	68.0	48.56	100.44	26
15	Winfrith,R3-20	0.49236	"	0.7790	68.0	23.66	50.96	26
16	WAPD/CRX	0.52000	"	1.5020	63.7	9.00	117.00	27
17	WAPD/CRX	0.56000	"	1.9340	63.1	11.30	127.10	27
18	WAPD/CRX	0.79200	"	5.0670	63.1	10.50	136.80	27
19	ANL/ZPR-7	0.45910	Hex	0.4347	68.0	4.82	24.[illegible]6	28
20	ANL/ZPR-7	0.50000	Hex	0.7544	68.0	4.96	5[illegible].38	28
21	ANL/ZPR-7	0.48820	Sq.	0.9596	68.0	5.15	70.76	28
22	ANL/ZPR-7	0.48820	"	0.9620	68.0	5.43	47.47	28
23	ANL/ZPR-7	0.53110	"	1.3710	68.0	5.28	91.82	28

Table 14-15

Lattice Multiplication Factors

Expt.#	Lattice	w/o U-235	UO2 OD(in.)	H2O/UO2	Keff
1	B&W-1273,Core I	4.020	0.44400	1.1400	1.008910
2	B&W-1273,Core X	4.020	0.44400	0.9590	1.005370
3	B&W-1273,CoreXIII	[illegible]	0.40540	1.3710	1.009480
4	B&W-3647,Core I	[illegible]	0.40540	1.8410	1.007870
5	Yankee(YAEC-94)	2.700	0.30000	1.0480	1.002980
6	Yankee(YAEC-94)	2.700	0.30000	1.4050	1.003210
7	Yankee(YAEC-94)	2.700	0.30000	1.8550	1.003590
8	Yankee(WCAP-1433)	2.700	0.30000	2.1660	1.003350
9	Yankee(WCAP-1412)	2.700	[illegible]	3.3720	1.000510
10	Yankee(WCAP-1412)	2.700	[illegible]	4.0780	0.998381
11	Yankee(WCAP-1412)	2.700	0.30000	4.9840	0.995216
12	Yankee(WCAP-1433)	2.700	0.30000	1.2000	1.002730
13	Winfrith,R1-20	3.003	0.39840	1.0010	1.005260
14	Winfrith,R2-20	3.003	0.39840	3.1640	0.997782
15	Winfrith,R3-20	3.003	0.39840	0.7790	1.006610
16	WAPD/CRX	5.742	0.35700	1.5020	1.010640
17	WAPD/CRX	5.742	[illegible]	1.9340	1.006490
18	WAPD/CRX	5.742	[illegible]	5.0670	1.009830
19	ANL/ZPR-7	3.042	0.36811	0.4347	1.006170
20	ANL/ZPR-7	3.042	0.36811	0.7544	1.008860
21	ANL/ZPR-7	3.042	0.36811	0.9596	1.010930
22	ANL/ZPR-7	3.042	0.36811	0.9620	1.006590
23	ANL/ZPR-7	3.042	0.36811	1.3710	1.011640

Table 14-16

KENO IV Results for Noted Gap Widths

Description	Hydrogen Density gm/cm^3	KENO IV K_{eff}
	Gap Width = 2.5 cm Between Assemblies	
Aluminum Box + Air	0.0	0.99641 ± 0.00407
Aluminum Box + $(C_8H_8)_n$	0.0025	0.99913 ± 0.00384
Aluminum Box + Powder $(CH_2)_n$	0.0414	1.01567 ± 0.00378
Aluminum Box + Water	0.1119	1.02362 ± 0.00362
Water (No Aluminum Box)	0.1119	0.99775 ± 0.00391
	Gap Width = 5.0 cm Between Assemblies	
Aluminum Box + Air	0.0	1.00412 ± 0.00422
Aluminum Box + $(C_8H_8)_n$	0.0020	1.00748 ± 0.00421
	Gap Width = 10.0 cm Between Assemblies	
Aluminum Box + Air	0.0	1.00117 ± 0.00390
Aluminum Box + $(C_8H_8)_n$	0.0022	1.00748 ± 0.00378

Table 14-17

Calculation of Methodology Standard Deviation

Expt. No.	Av. Neut. Energy Grp	KENO K-eff	Keff Poly. Fit	Delta Keff	Diff.Sq'rd
1	14.8539	1.00292	0.99907	3.84575e-03	1.47898e-05
2	14.8634	0.99757	0.99896	-1.39096e-03	1.93476e-06
3	14.8664	1.00687	0.99893	7.94448e-03	6.31147e-05
4	14.8084	1.00672	0.99964	7.08029e-03	5.01305e-05
5	14.8107	1.00075	0.99961	1.13978e-03	1.29911e-06
6	14.8196	0.99834	0.99950	-1.15701e-03	1.33867e-06
7	14.7755	0.98474	1.00007	-1.53321e-02	2.35074e-0
8	14.7919	0.99528	0.99985	-4.57411e-03	2.09225e-05
9	14.9939	0.99028	0.99757	-7.29158e-03	5.31672e-05
10	15.1072	0.99605	0.99662	-5.67638e-04	3.22212e-07
11	14.4363	1.00986	1.00568	4.17660e-03	1.74440e-05
12	14.2973	1.00515	1.00859	-3.43996e-03	1.18334e-05
13	14.8391	1.00357	0.99925	4.31597e-03	1.86276e-05
14	14.7265	1.00633	1.00075	5.57716e-03	3.11047e-05
15	15.0905	1.00059	0.99674	3.84649e-03	1.47955e-05
16	15.1965	0.99362	0.99603	-2.41102e-03	5.81302e-06
17	15.3165	0.99081	0.99547	-4.66215e-03	2.17356e-05
18	15.2583	0.98069	0.99571	-1.50203e-02	2.25611e-04
19	15.5059	0.99957	0.99513	4.44468e-03	1.97552e-05
20	15.4858	0.99628	0.99513	1.14896e-03	1.32011e-06
21	14.3444	1.02009	1.00757	1.25245e-02	1.56862e-04
22	14.3683	1.01826	1.00706	1.11988e-02	1.25413e-04
23	14.3416	1.01304	1.00763	5.41469e-03	2.93189e-05
24	14.3310	1.00997	1.00785	2.11714e-03	4.48226e-06
25	14.3567	1.01011	1.00730	2.80531e-03	7.86978e-06
26	14.1106	1.00180	1.01305	-1.12494e-02	1.26549e-04
27	14.1011	1.01007	1.01329	-3.22333e-03	1.03899e-05
28	14.1039	1.00609	1.01322	-7.13126e-03	5.08549e-05
29	15.0206	1.00216	0.99733	4.83434e-03	2.33709e-05
30	14.8915	0.99504	0.99864	-3.59551e-03	1.29277e-05
31	14.8981	0.99901	0.99856	4.48843e-04	2.01460e-07
32	14.8881	0.99146	0.99867	-7.21412e-03	5.20435e-05
33	15.4248	0.98880	0.99519	-6.39360e-03	4.08781e-05
34	15.4362	0.99287	0.99518	-2.30674e-03	5.32107e-06
35	15.4263	0.98804	0.99519	-7.15125e-03	5.11403e-05
36	15.4365	0.98847	0.99518	-6.70633e-03	4.49749e-05
37	15.5075	1.00691	0.99513	1.17848e-02	1.38882e-04
38	15.5096	0.99887	0.99513	3.74493e-03	1.40245e-05
39	15.5233	0.99687	0.99513	1.74368e-03	3.04041e-06
40	15.5514	1.00548	0.99514	1.03404e-02	1.06923e-04
				Sum	1.81560e-03
				Variance	4.65539e-05
				Std.Dev.	6.82304e-03

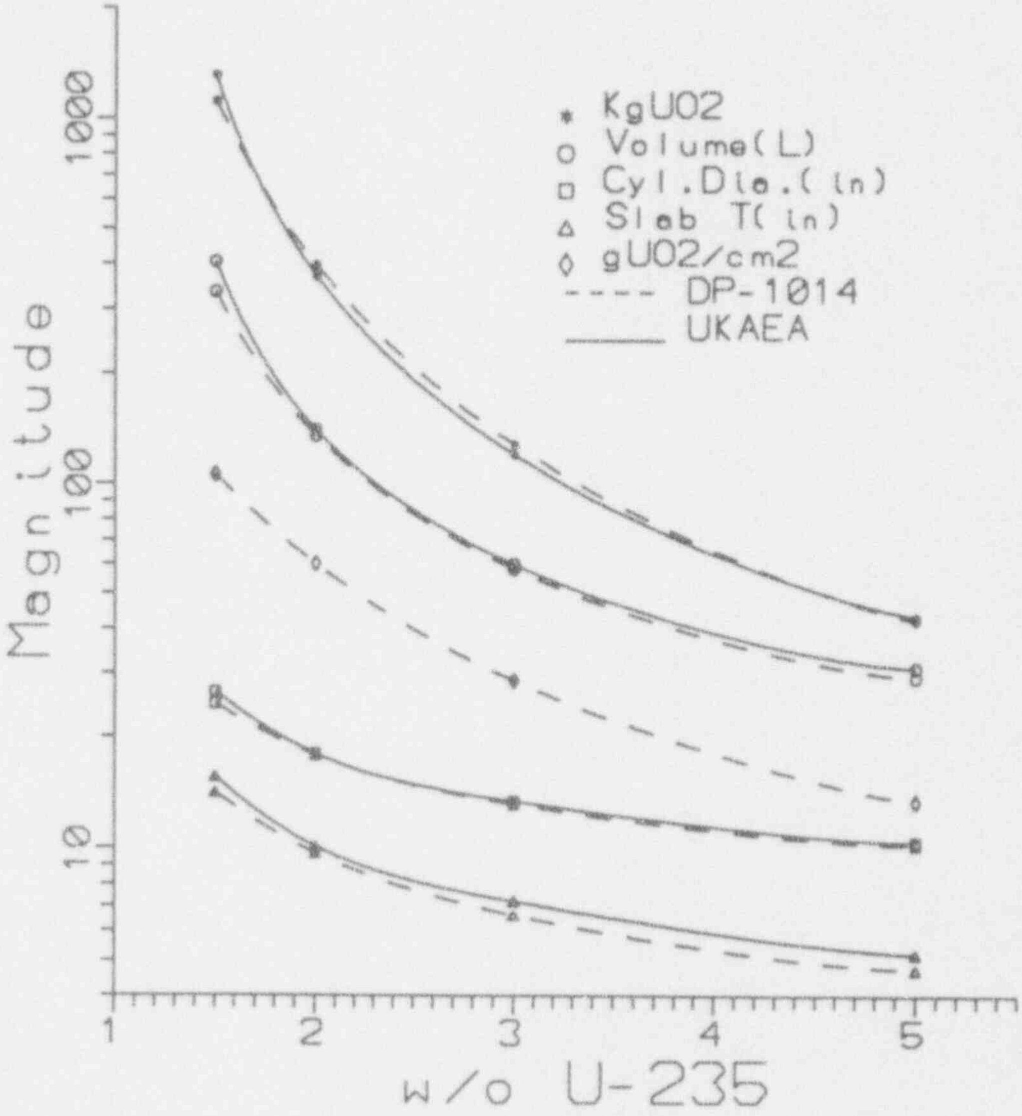


Figure 14-1

Reflected and Optimally Moderated, Critical Parameters versus Enrichment

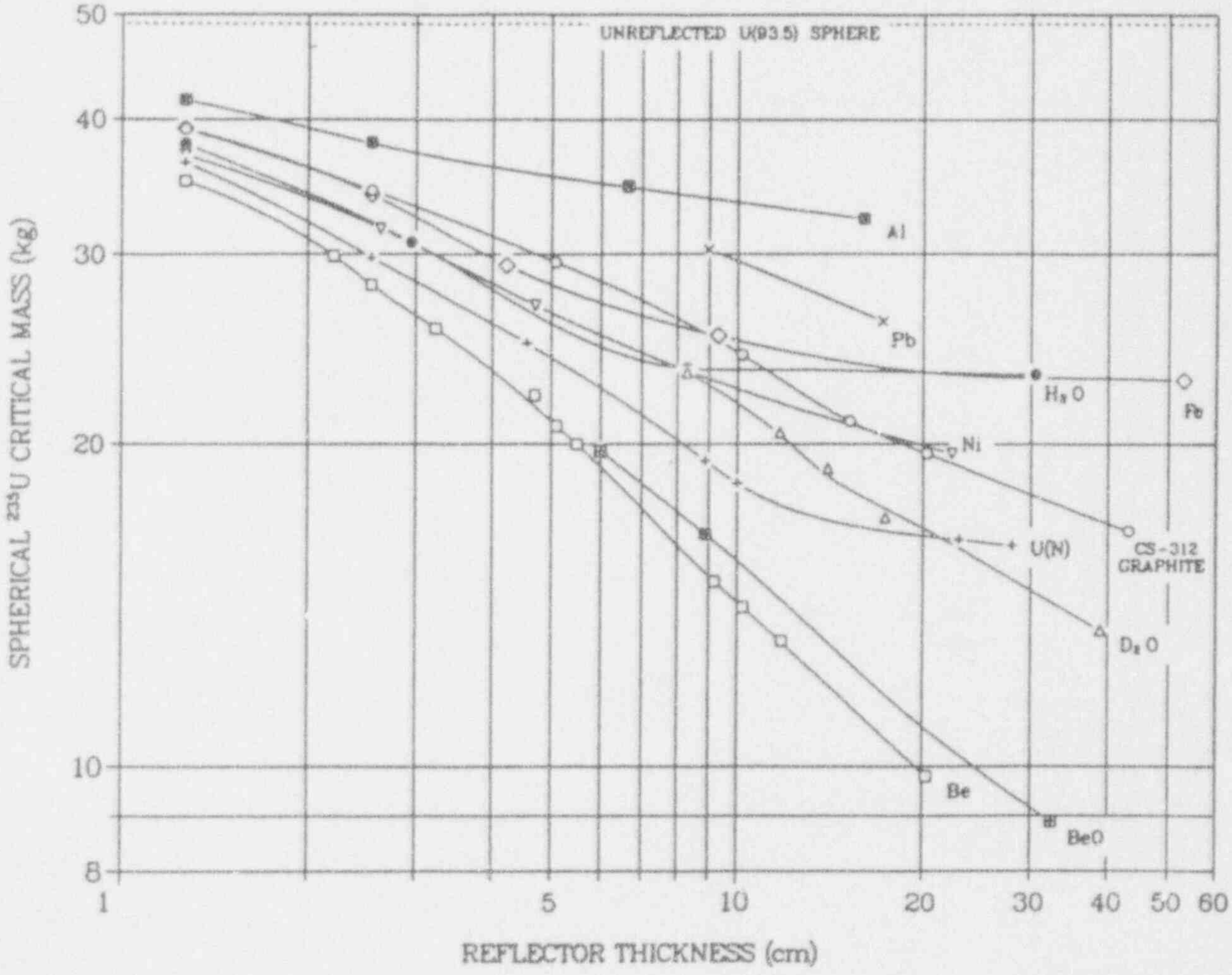


Figure 14-2

<u>Critical Masses of U(93.5) Metal Spheres in Various Reflectors</u>
<u>Uranium Density = 18.8 g/cc</u>
(from LA-10860-MS)

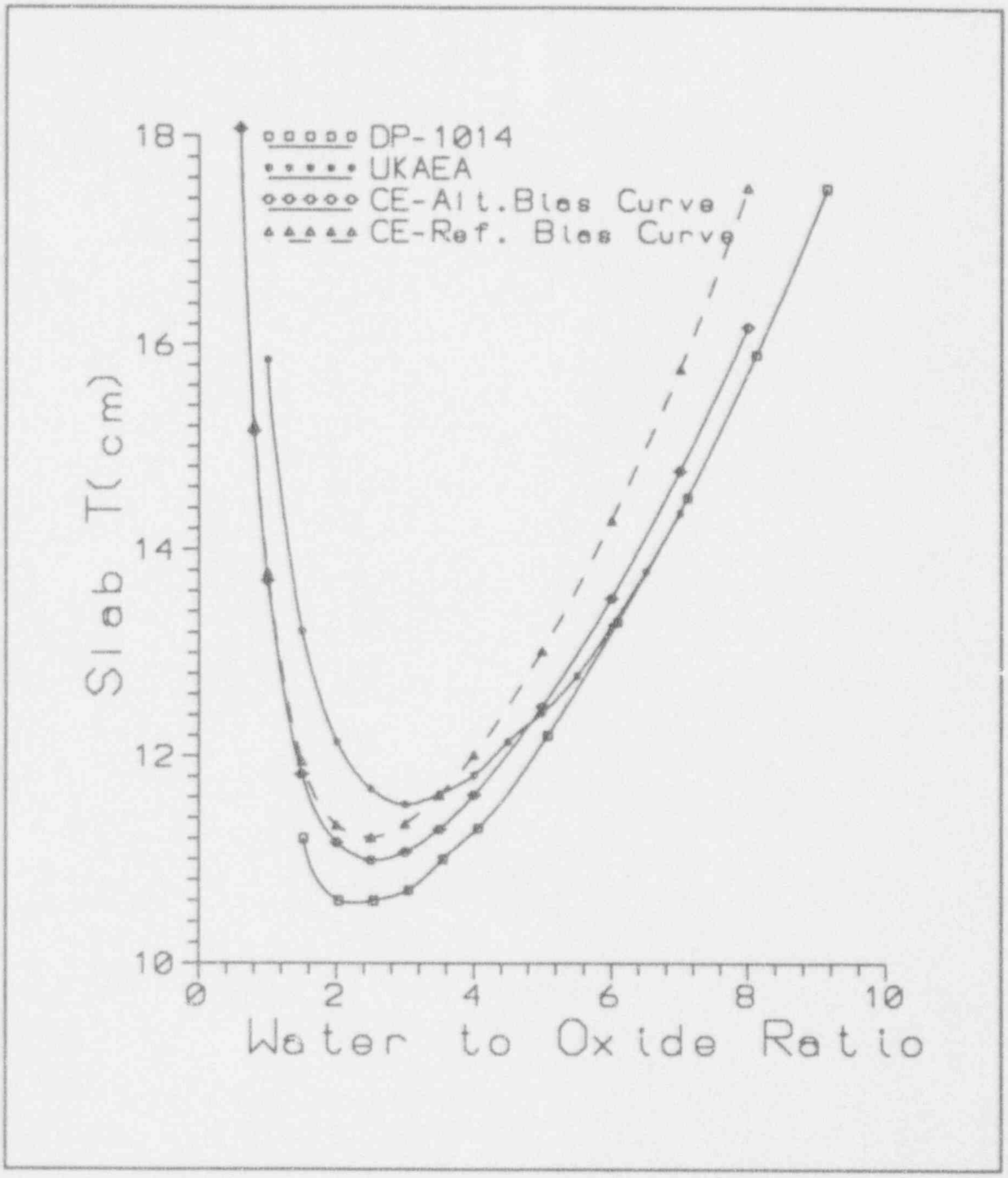


Figure 14-3

Reflected Critical Slab Thickness versus Water-to-Oxide Ratio for 0.40" OD $U(5)O_2$ Pellets Uniformly Distributed in Water

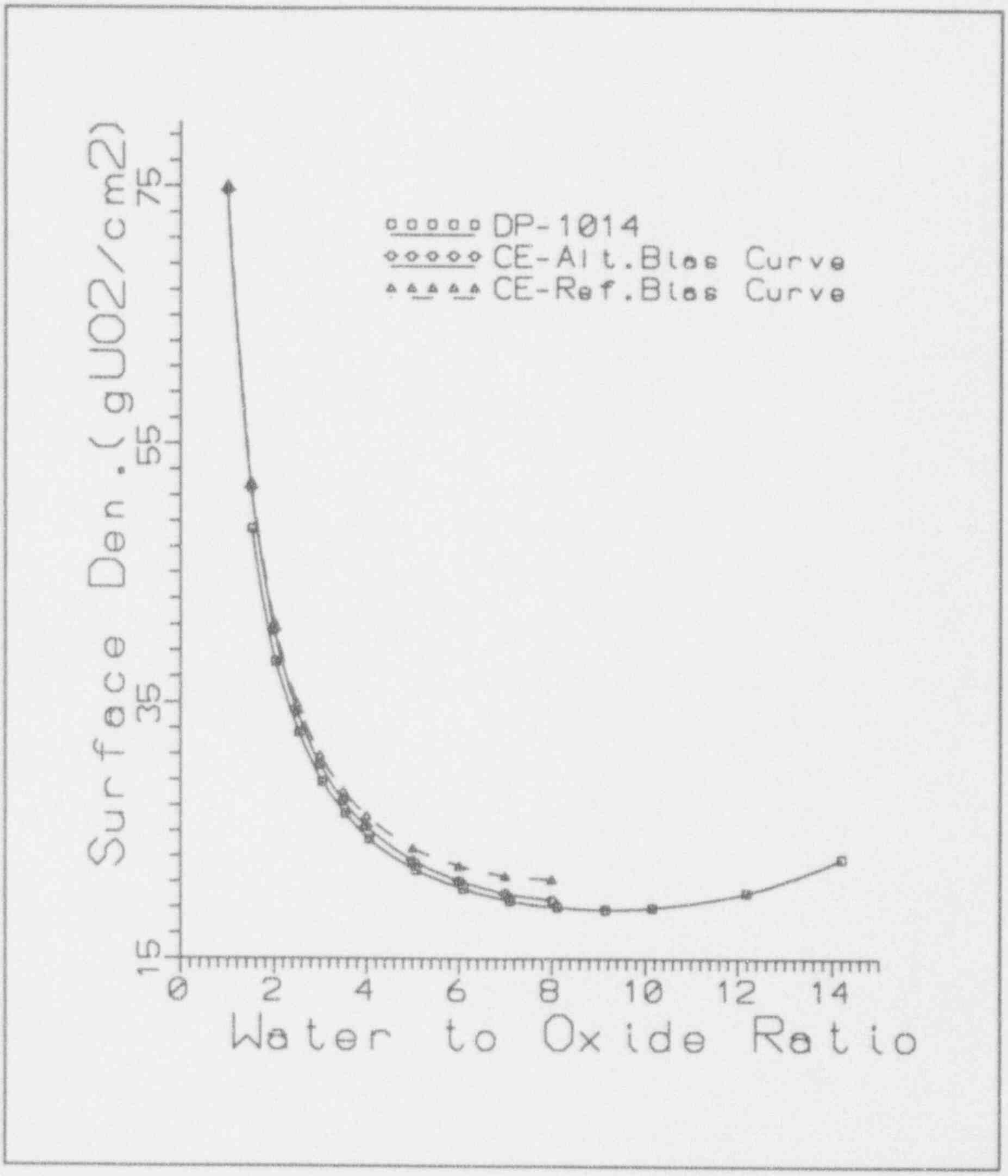


Figure 14-4

Reflected Critical Surface Density versus Water-to-Oxide Ratio for 0.40" OD $U(5)O_2$ Pellets Uniformly Distributed In Water

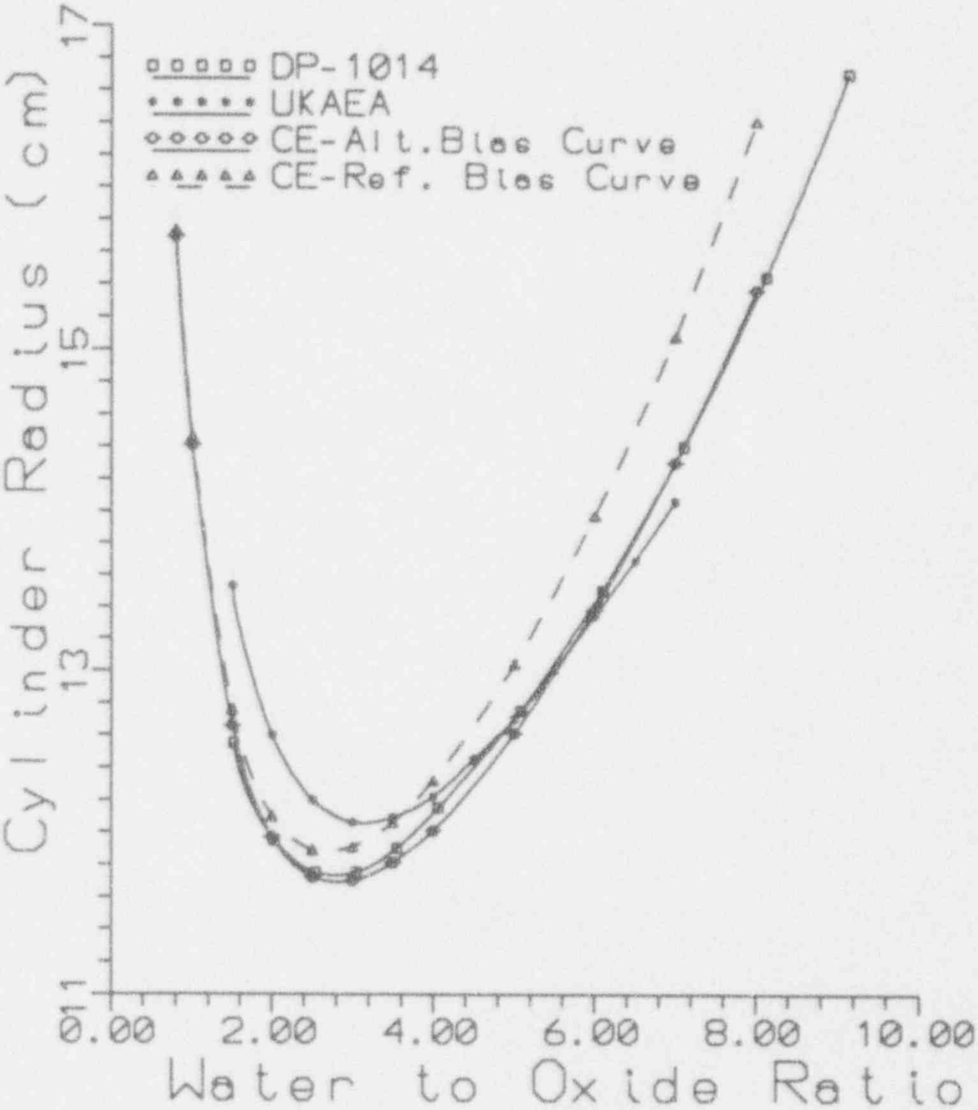


Figure 14-5

Reflected Critical Radius versus Water-to-Oxide Ratio for 0.40" OD U(5)O_2 Pellets Uniformly Distributed In Water

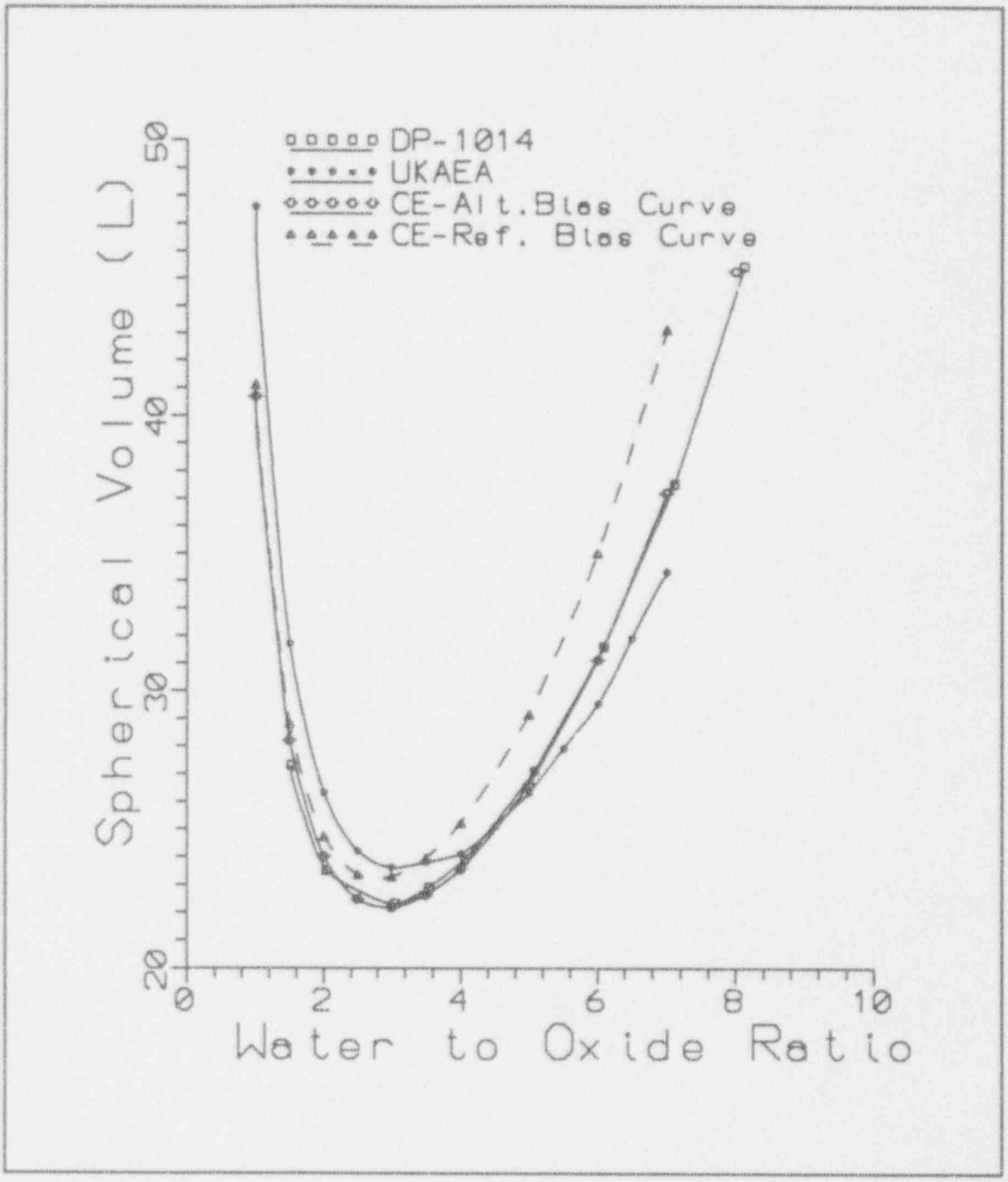


Figure 14-6

Reflected Critical Spherical Volume versus Water-to-Oxide Ratio for 0.40" OD U(5)O_2 Pellets Uniformly Distributed In Water

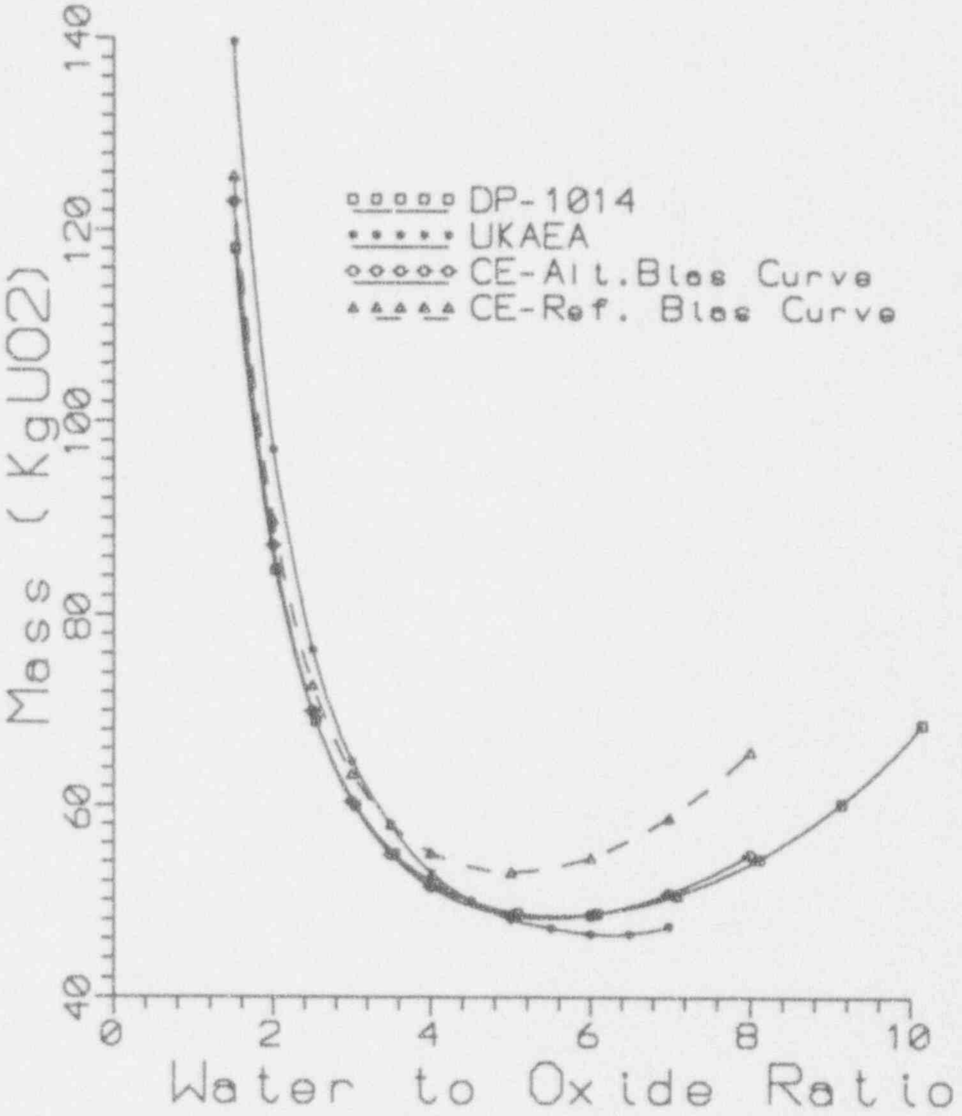


Figure 14-7

Reflected Critical Spherical Mass versus Water-to-Oxide Ratio for 0.40" OD U(5)O_2 Pellets Uniformly Distributed In Water

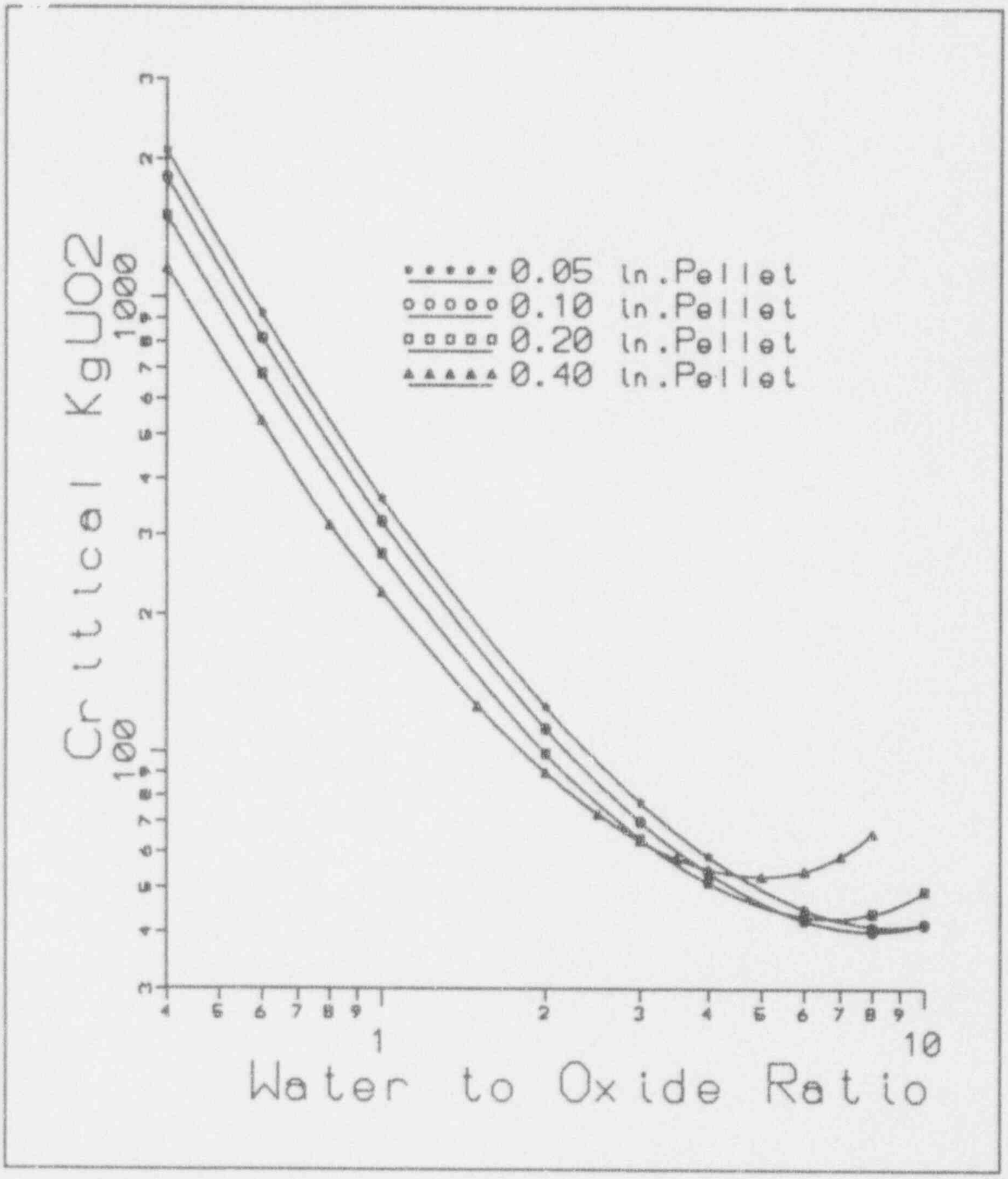


Figure 14-8

<u>Reflected Critical Mass versus Water-to-Oxide Ratio for $U(5)O_2$ Pellets of Different Diameters</u>

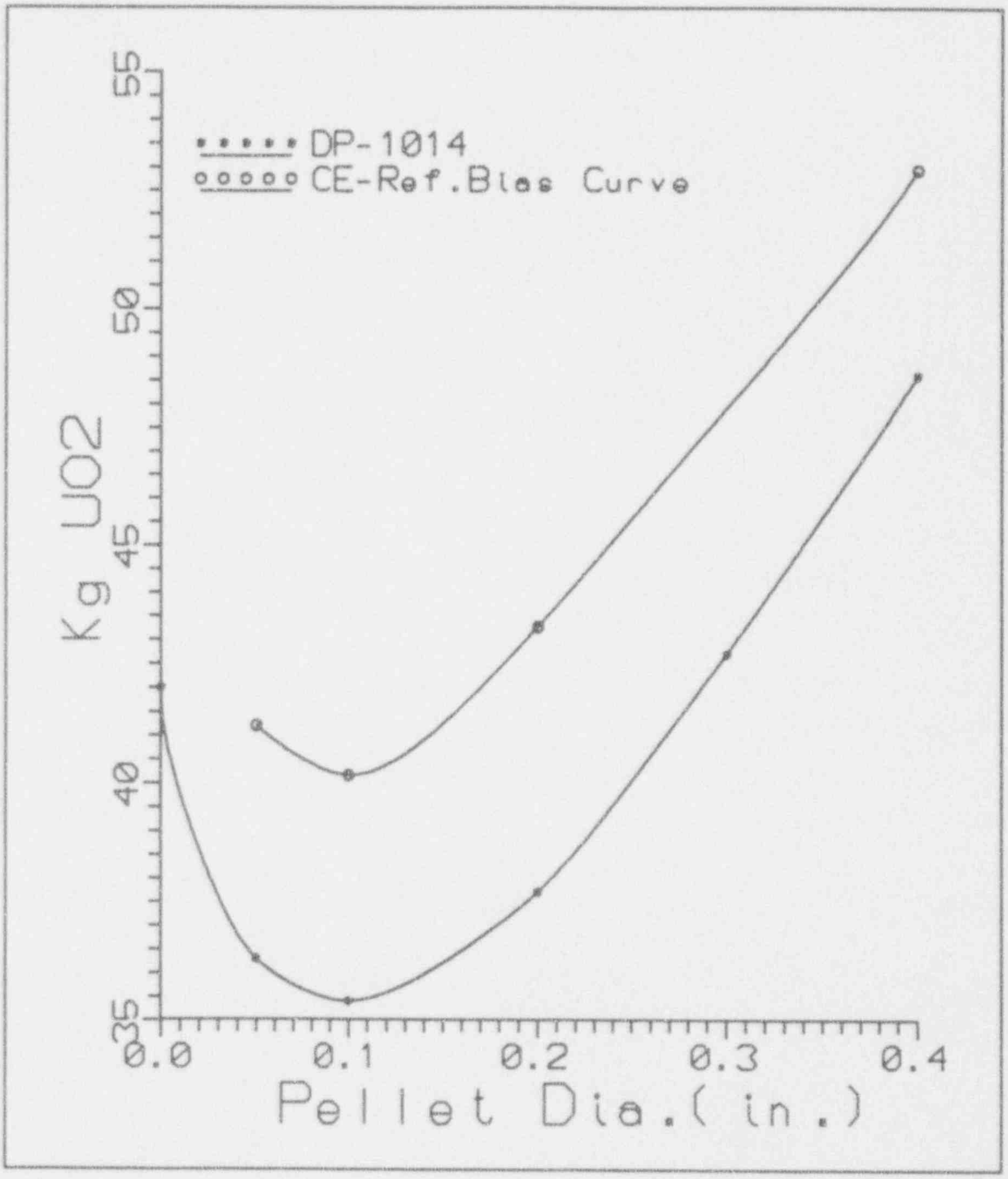


Figure 14-9

Comparison Between CE and DP-1014 Calculated Reflected and Optimally Moderated Critical Mass versus U(5)O_2 Pellet Diameter

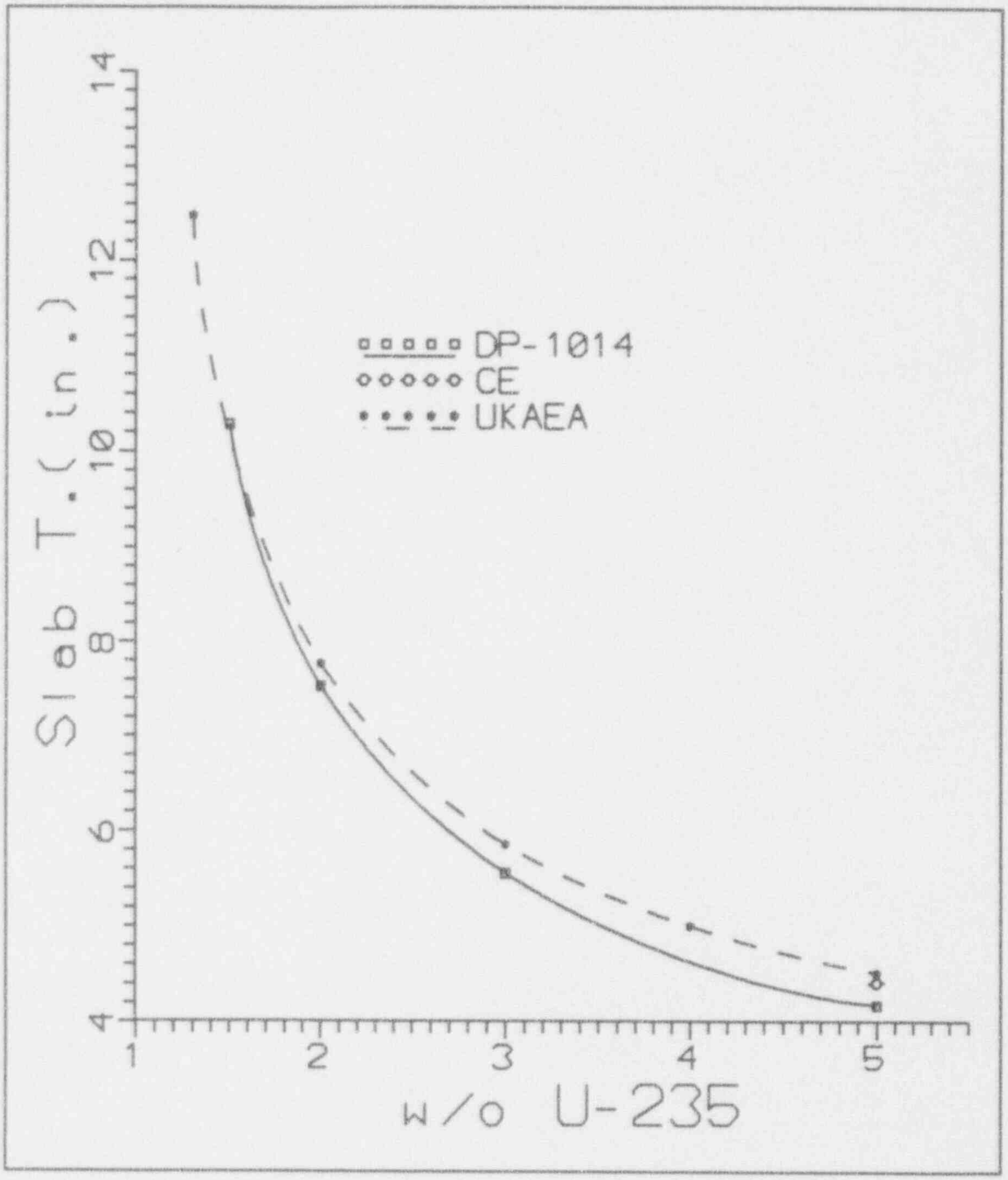


Figure 14-10

Comparison of Minimum Critical Reflected Heterogeneous Slab Thicknesses versus Enrichment

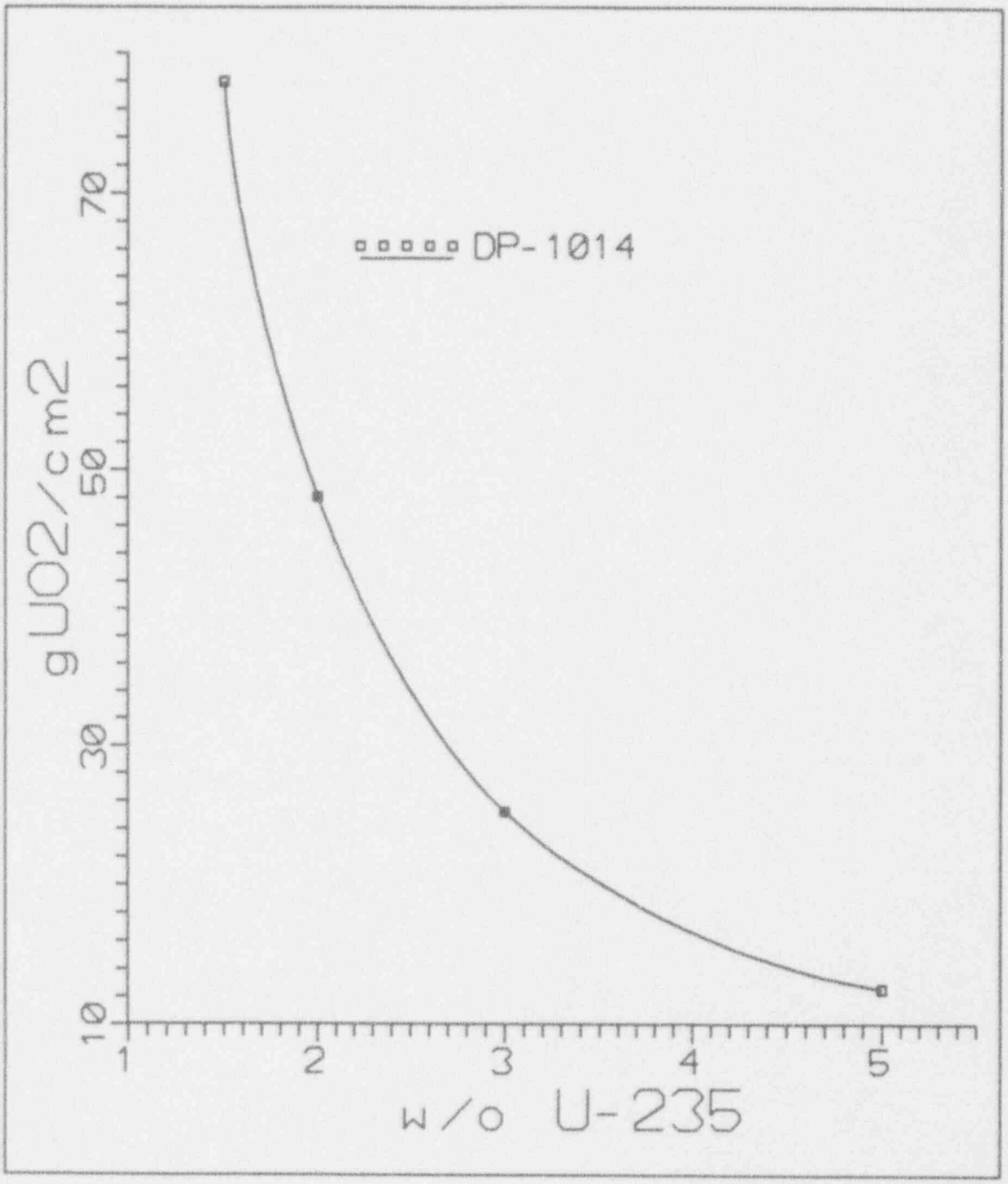


Figure 14-11

Minimum Critical Reflected Surface Density versus Enrichment for Heterogeneous UO_2 Slab

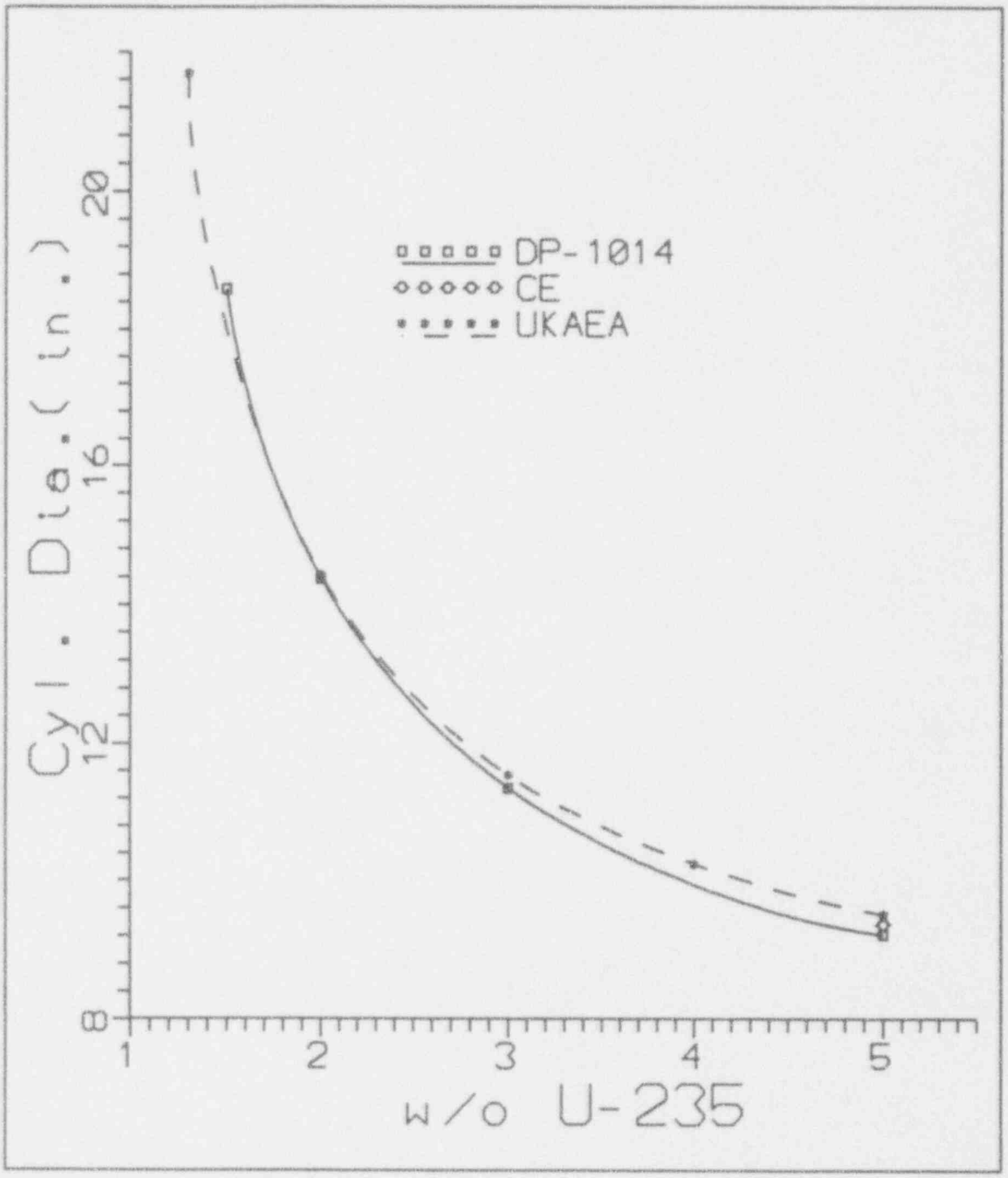


Figure 14-12

Minimum Critical Reflected Cylinder Diameter versus Enrichment for Heterogeneous UO_2-Water Mixture

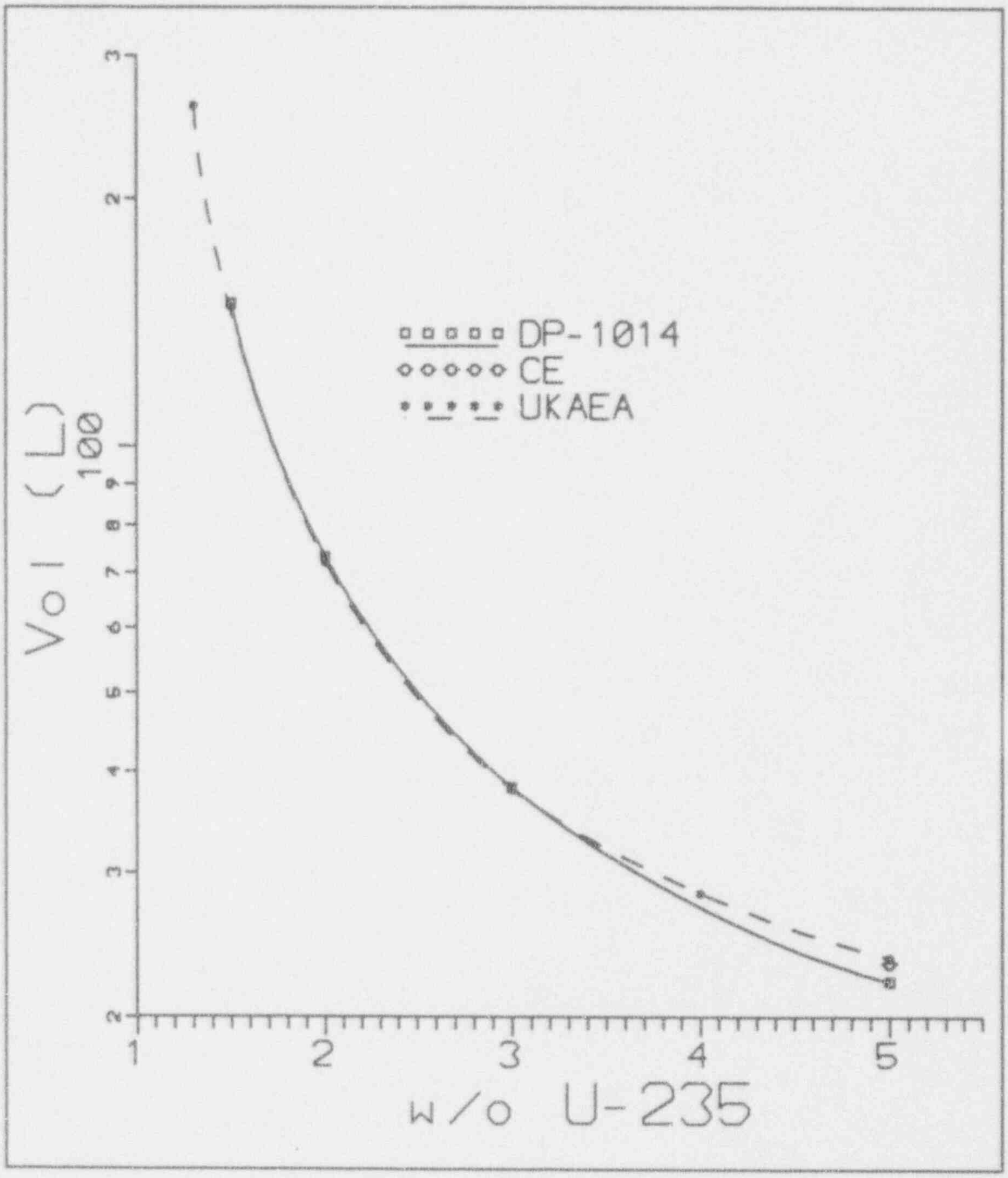


Figure 14-13

Minimum Critical Reflected Spherical Volume versus Enrichment for Heterogeneous UO_2-Water Mixture

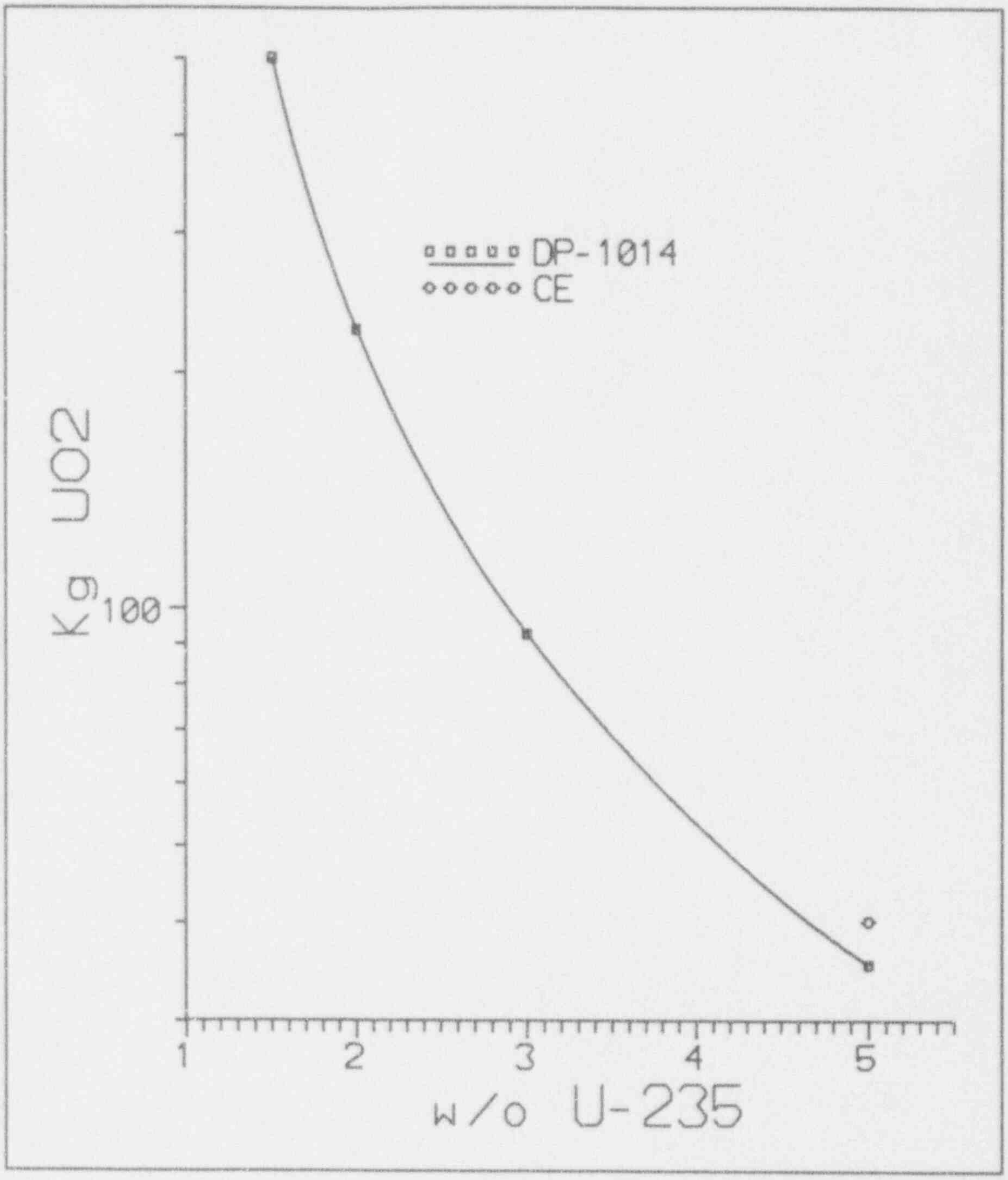


Figure 14-14

Minimum Critical Reflected Spherical Mass versus Enrichment for Heterogeneous UO_2-Water Mixture

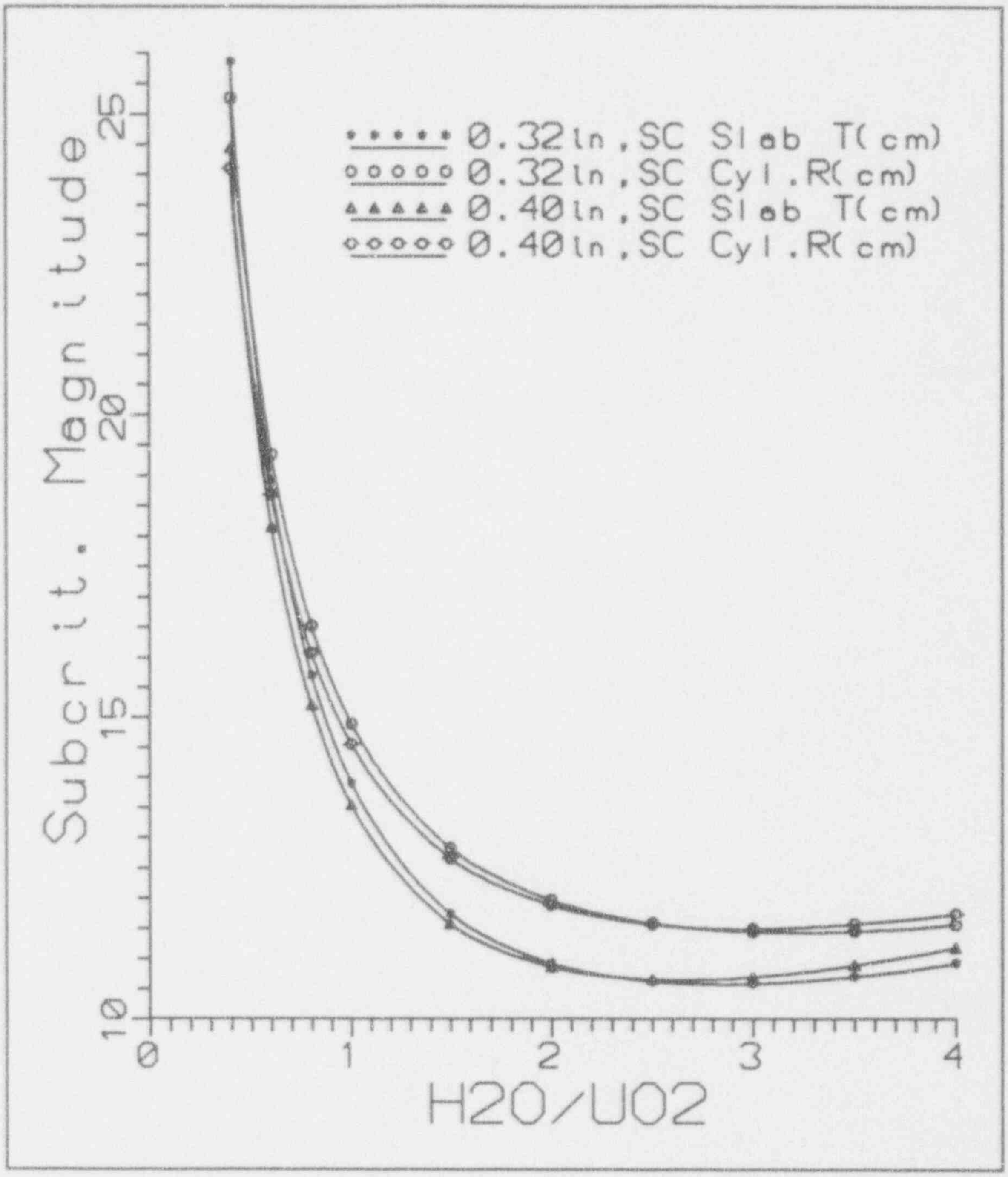


Figure 14-15

Minimum Subcritical Reflected Slab Thickness and Cylinder Radius versus Water-to-Oxide Ratio for Zircaloy Clad, U(5)O_2 Pellet Columns in Water

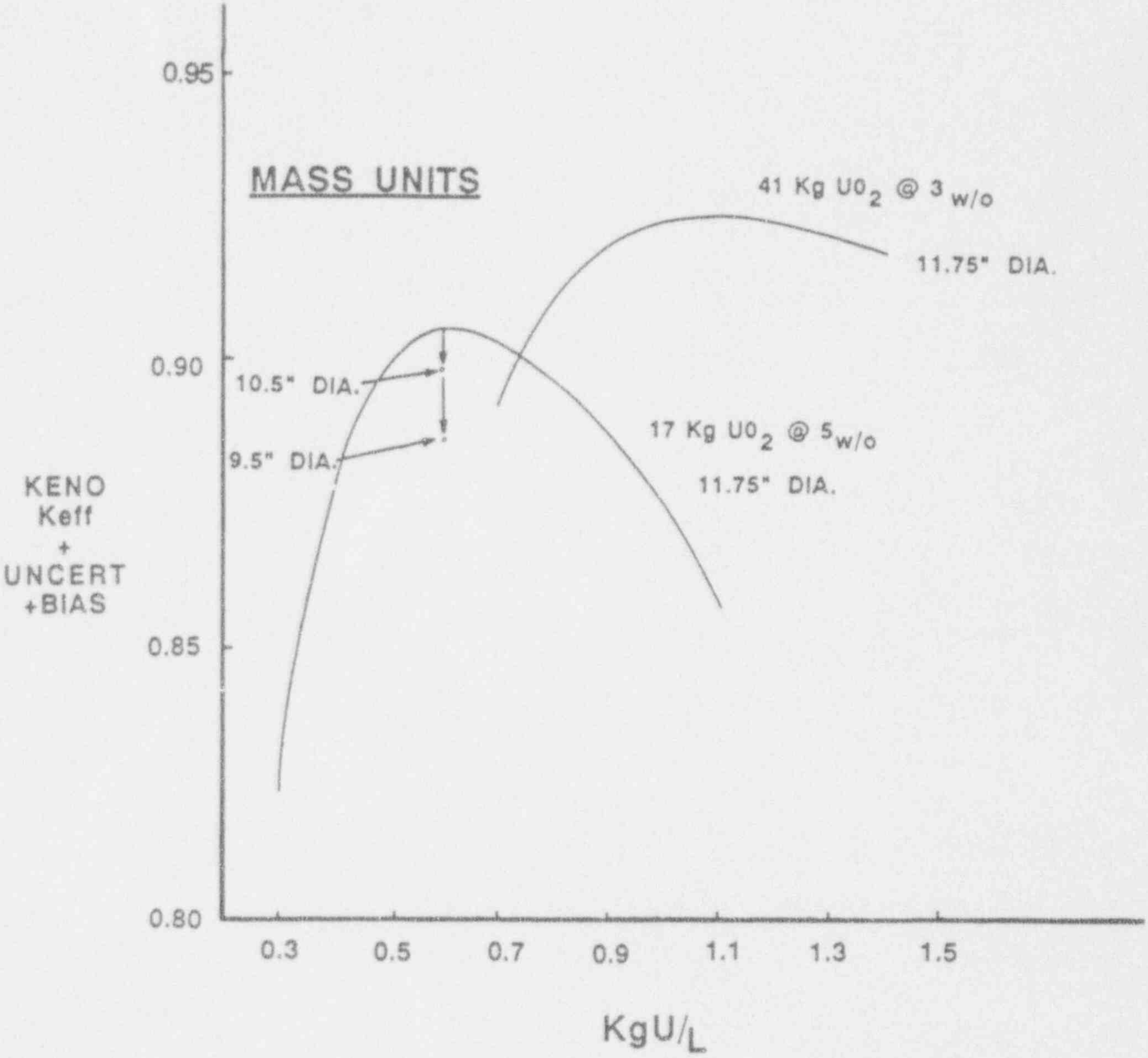


Figure 14-16

KENO K_{eff} Including Uncertainty and Bias, Versus Kilograms Uranium Per Liter for Mass Limited Unit Containers

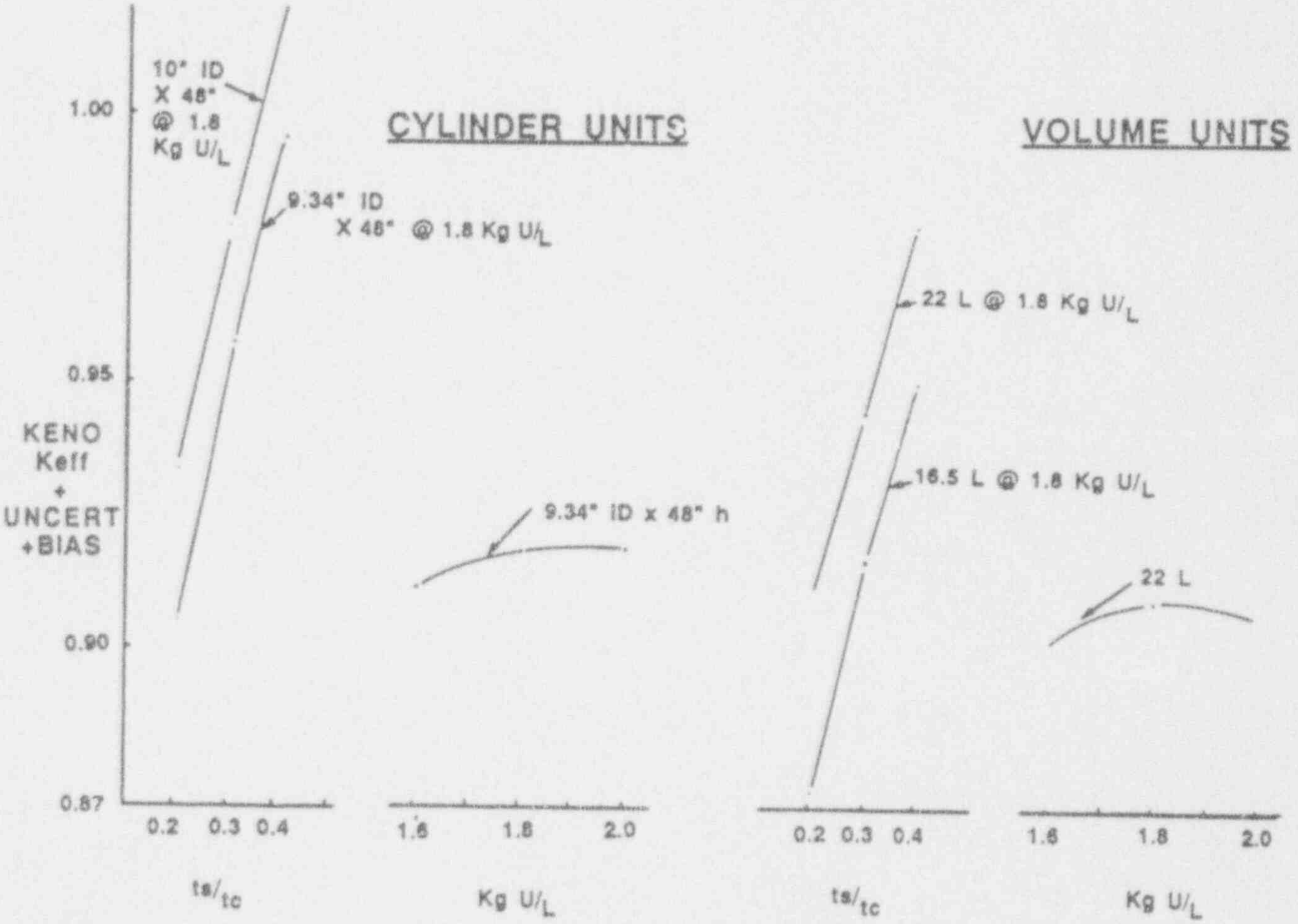


Figure 14-17

KENO K_{eff} Including Uncertainty and Bias Versus ts/tc and KgU/L for Cylinder Diameter and Volume Limited Unit Containers

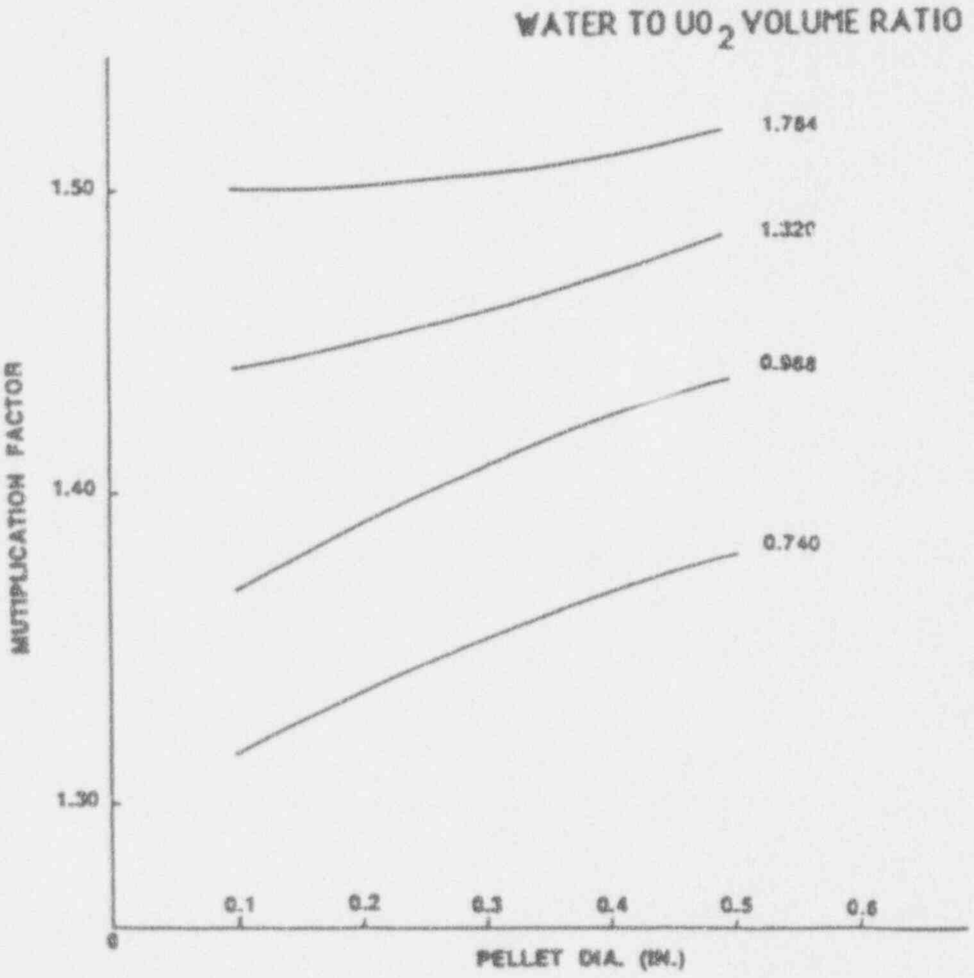


Figure 14-18

Infinite Multiplication Factor versus Pellet Diameter for Several Water-to-UO_2 Volume Ratios

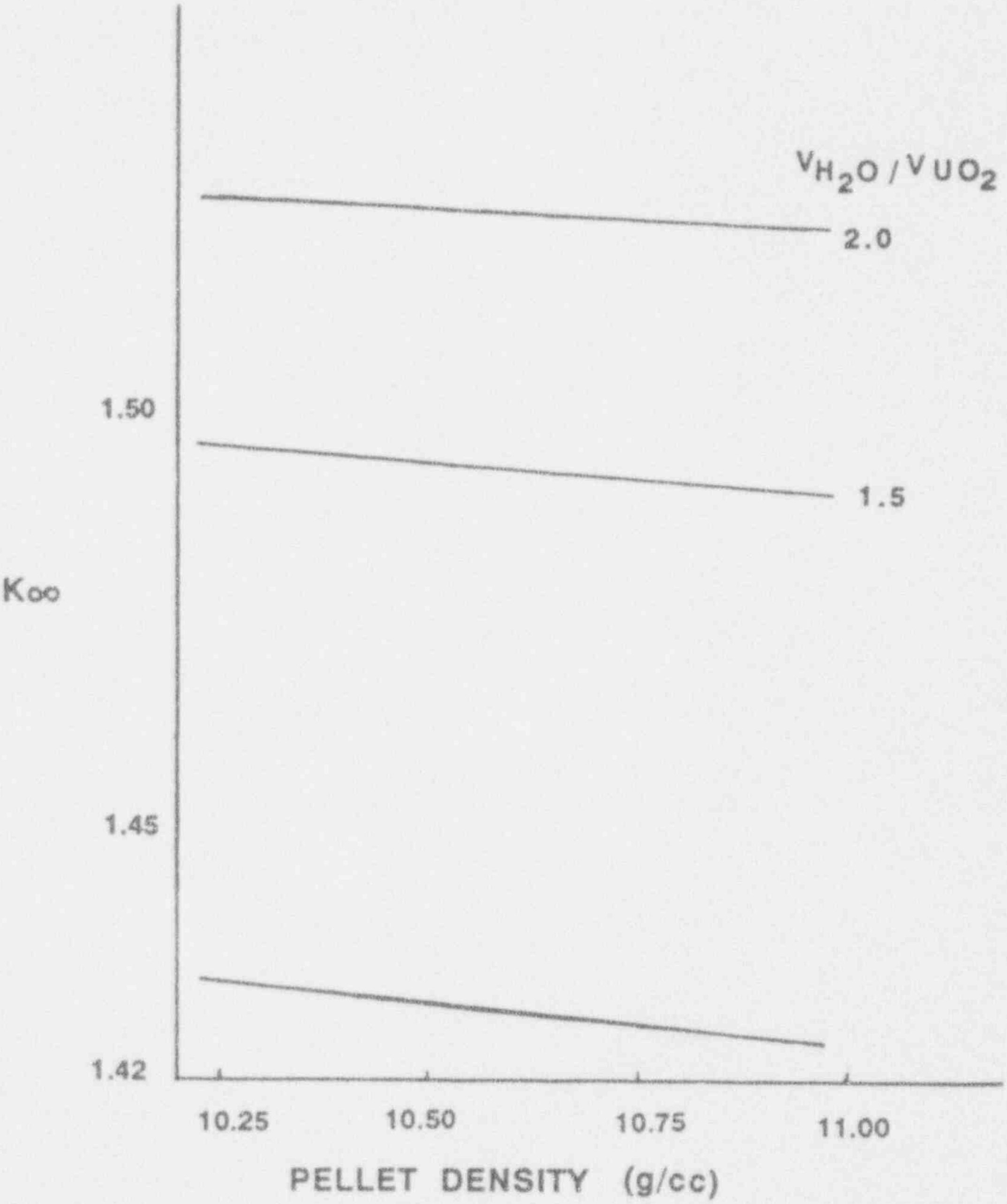


Figure 14-19

K_∞ Versus 0.400 Inch Diameter UO_2 Pellet Density at Various H_2O-to-UO_2 Volume Ratios

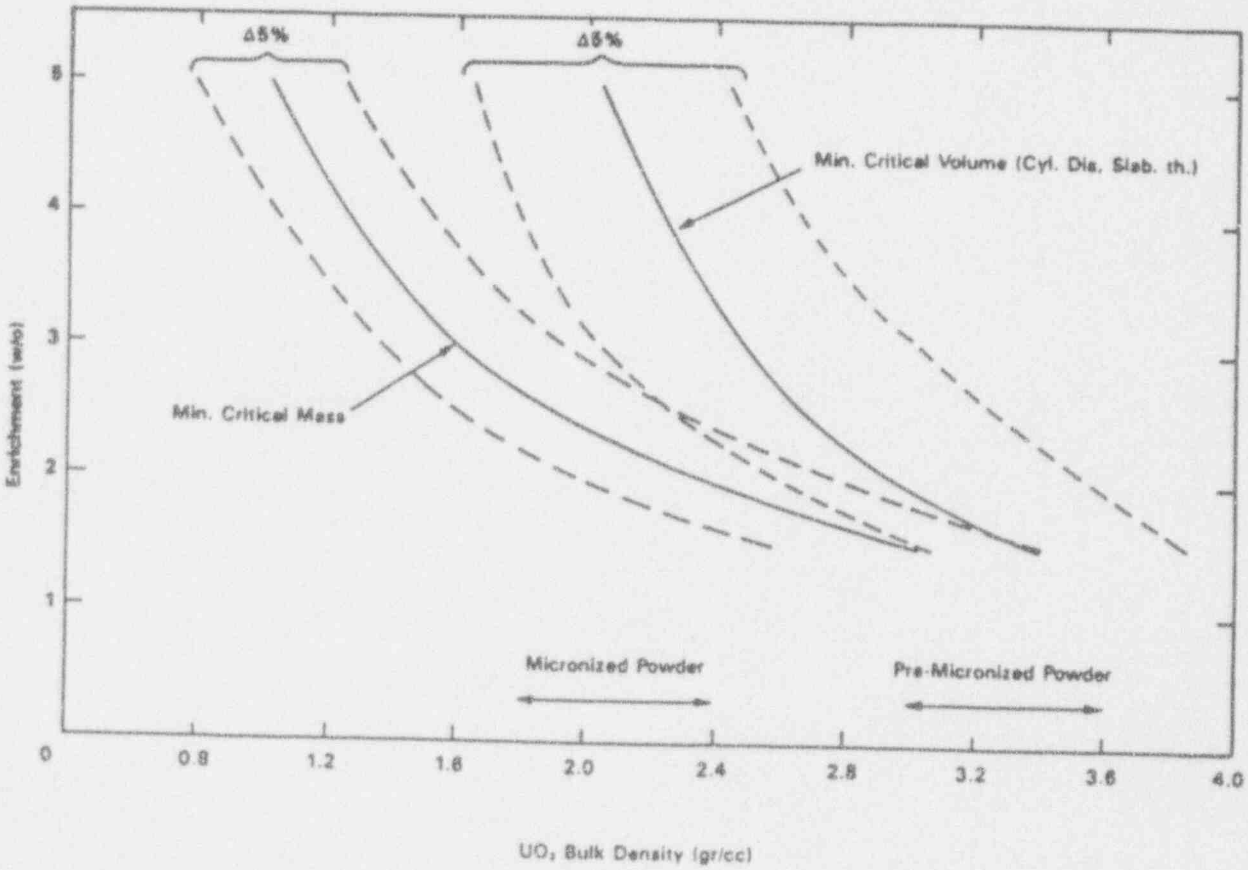


Figure 14-20

Loci of Minima in Reflected Minimum Critical Mass and Geometric Parameters with Enrichment and Bulk Density

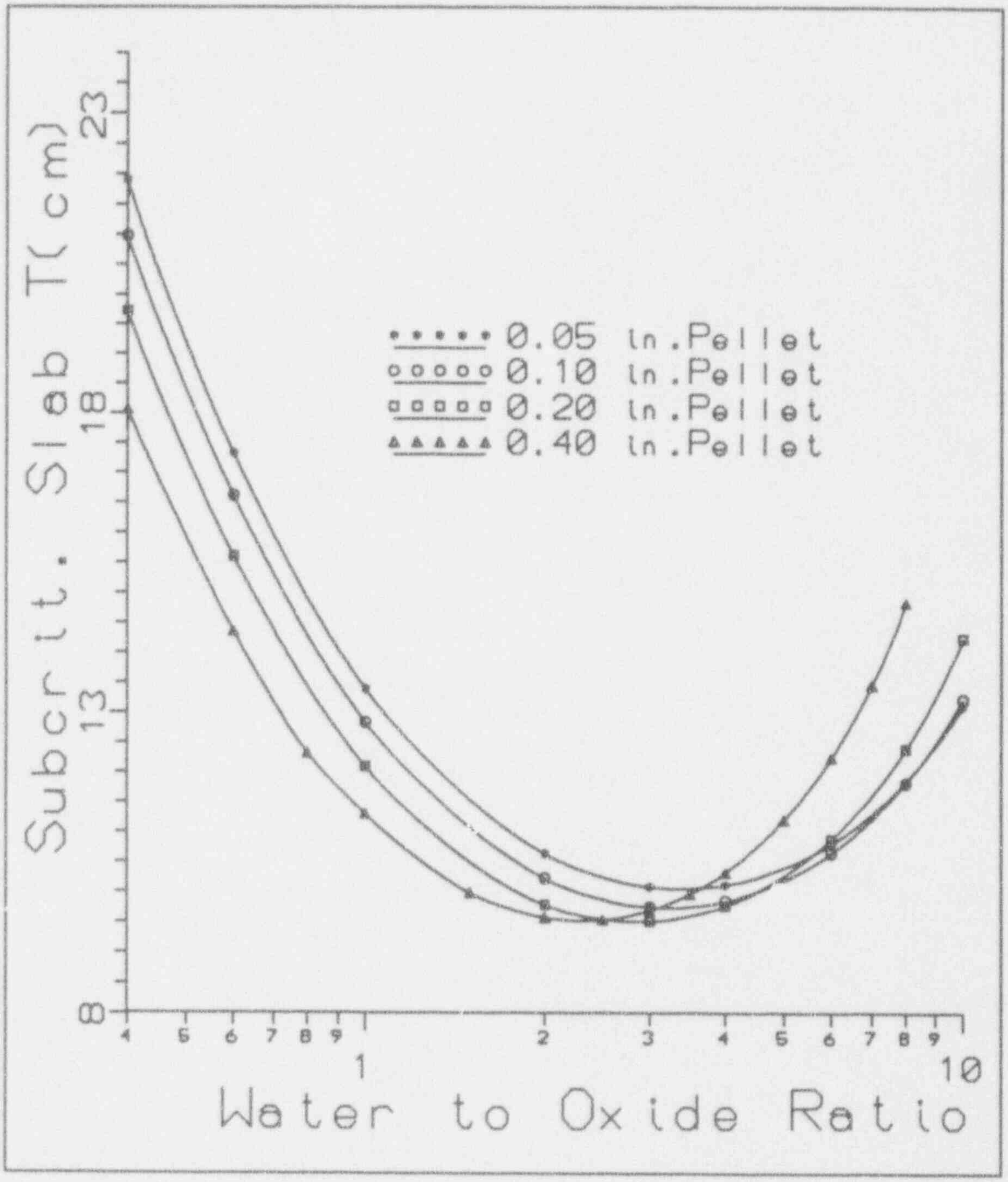


Figure 14-21

Reflected Subcritical (Safe) Slab Thickness versus Water-to-Oxide Ratio for Unclad U(5)O_2 Pellets of Various Outer Diameters

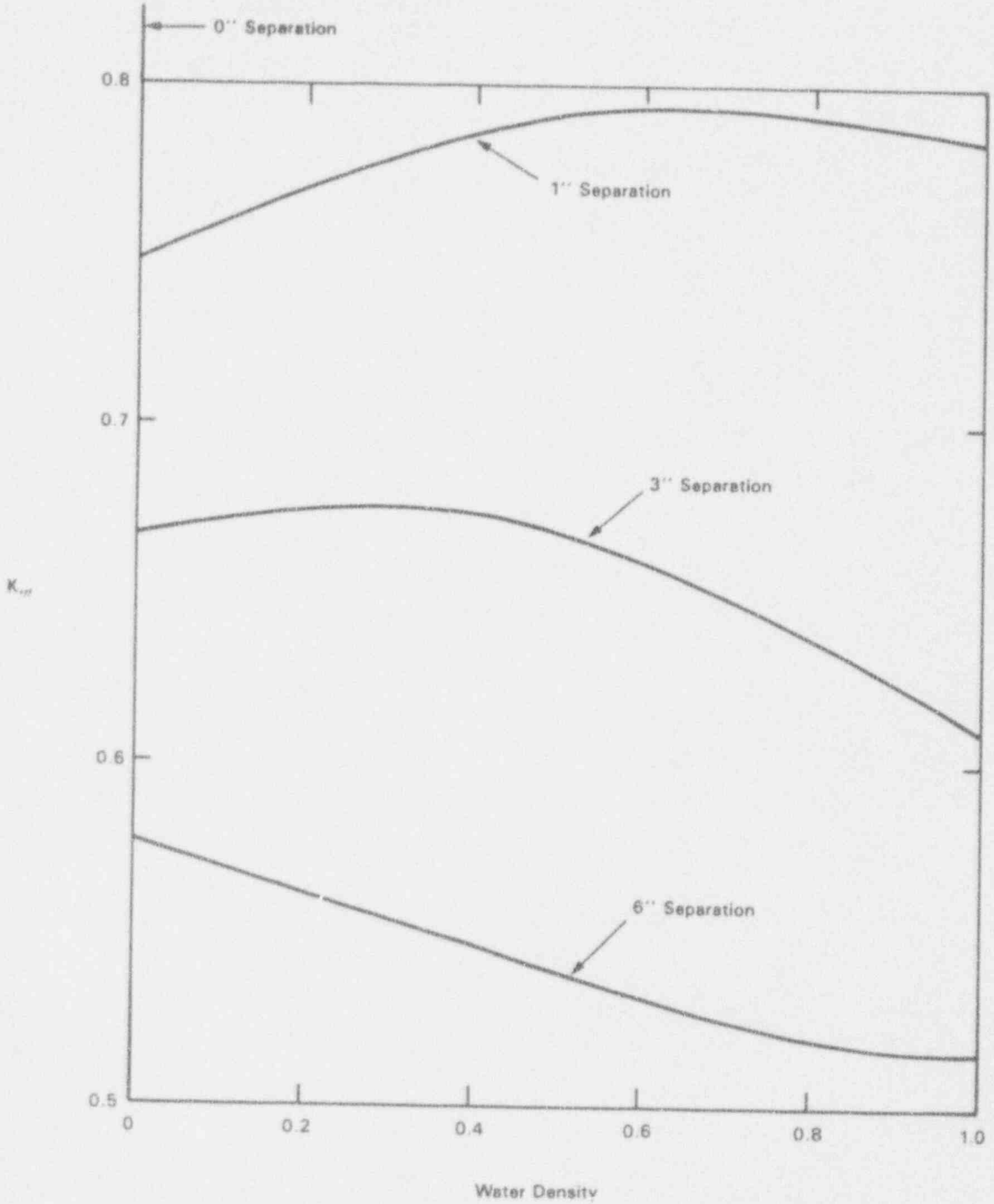


Figure 14-22

K_{eff} versus Water Density and Planar Separation in 4 Inch Thick Infinite Slab Array of Pellet Trays

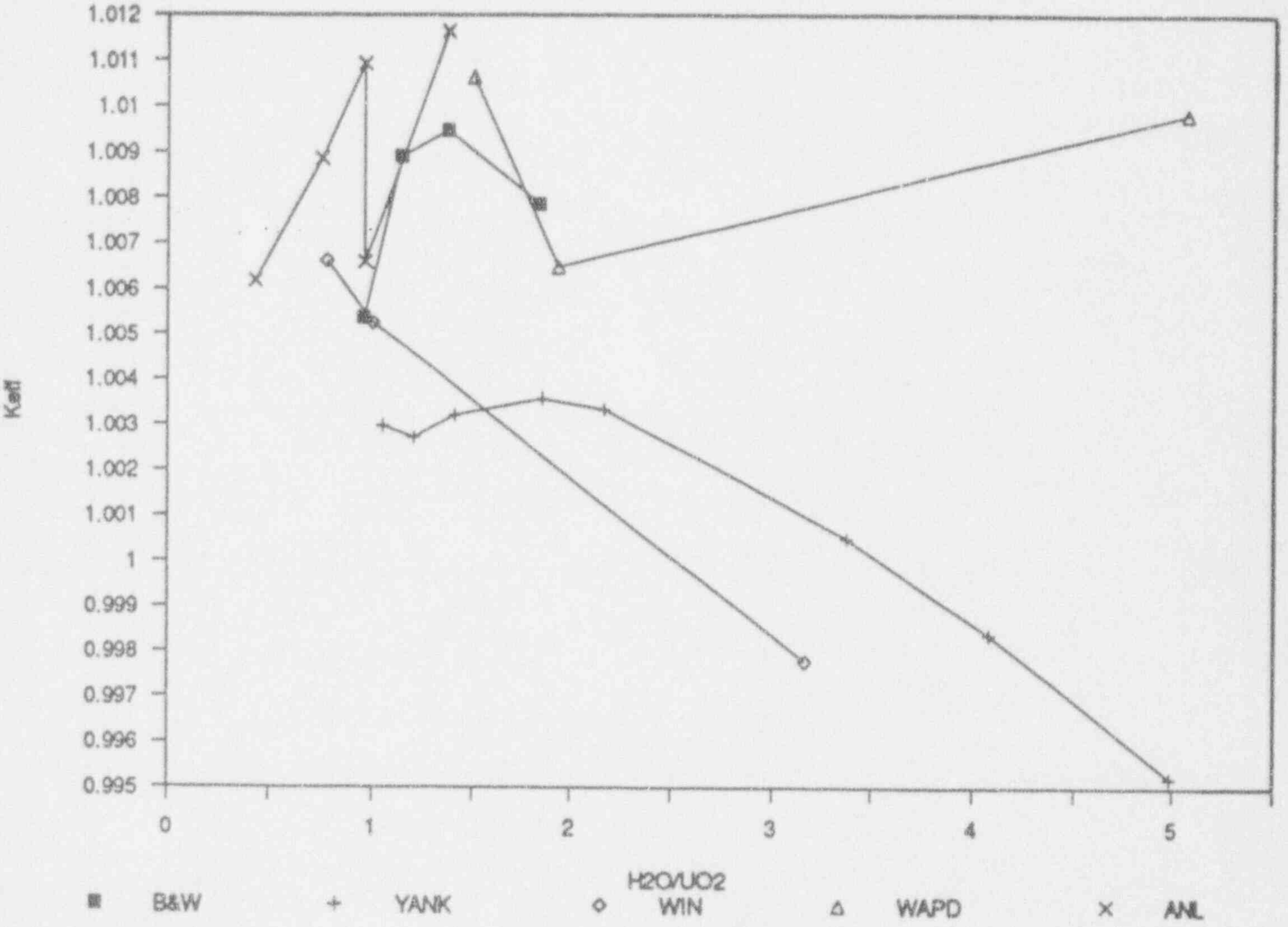


Figure 14-23

K_{eff} versus H_2O/UO_2, 23 Experiments

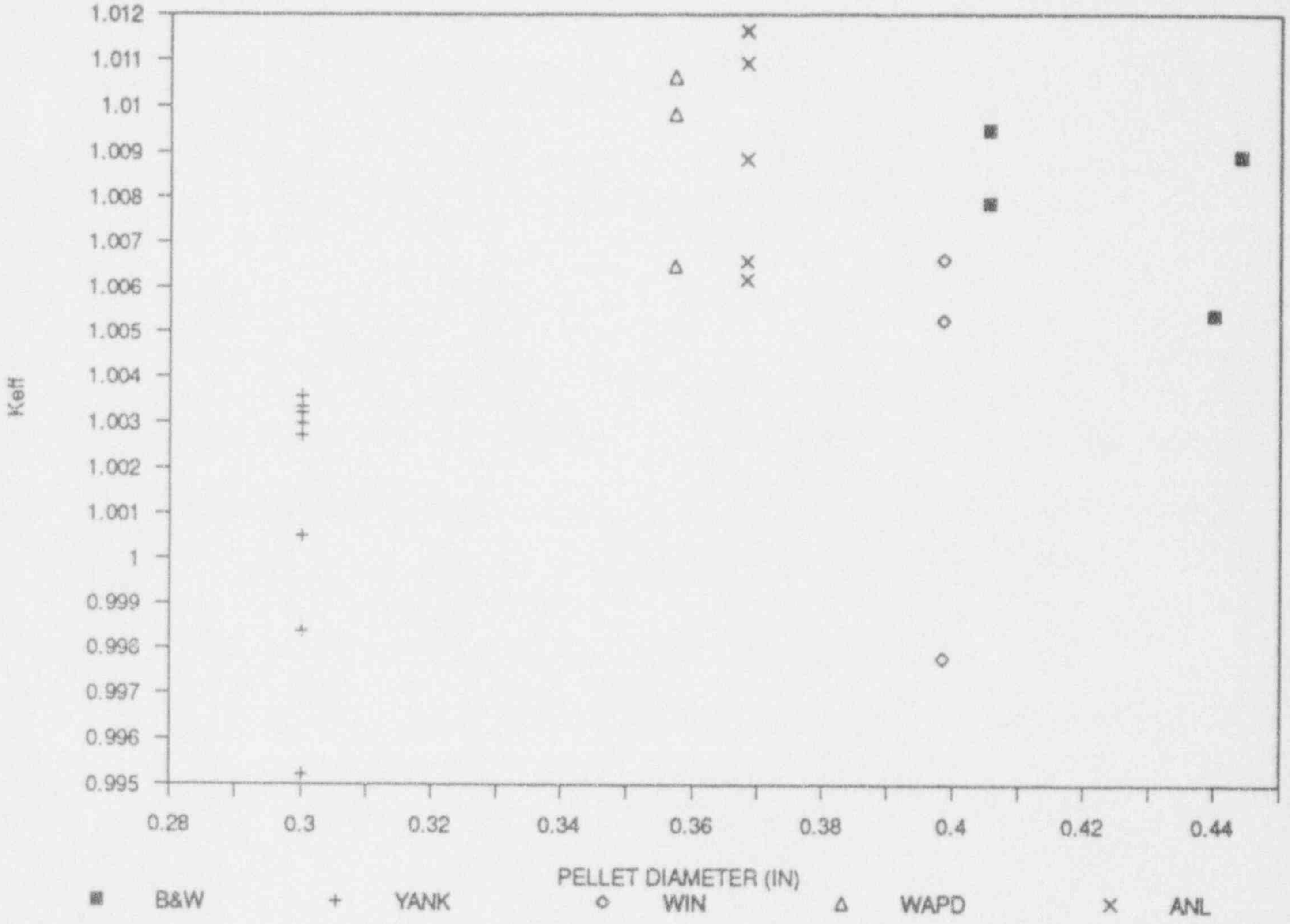


Figure 14-24

K_{eff} versus Pellet O.D.

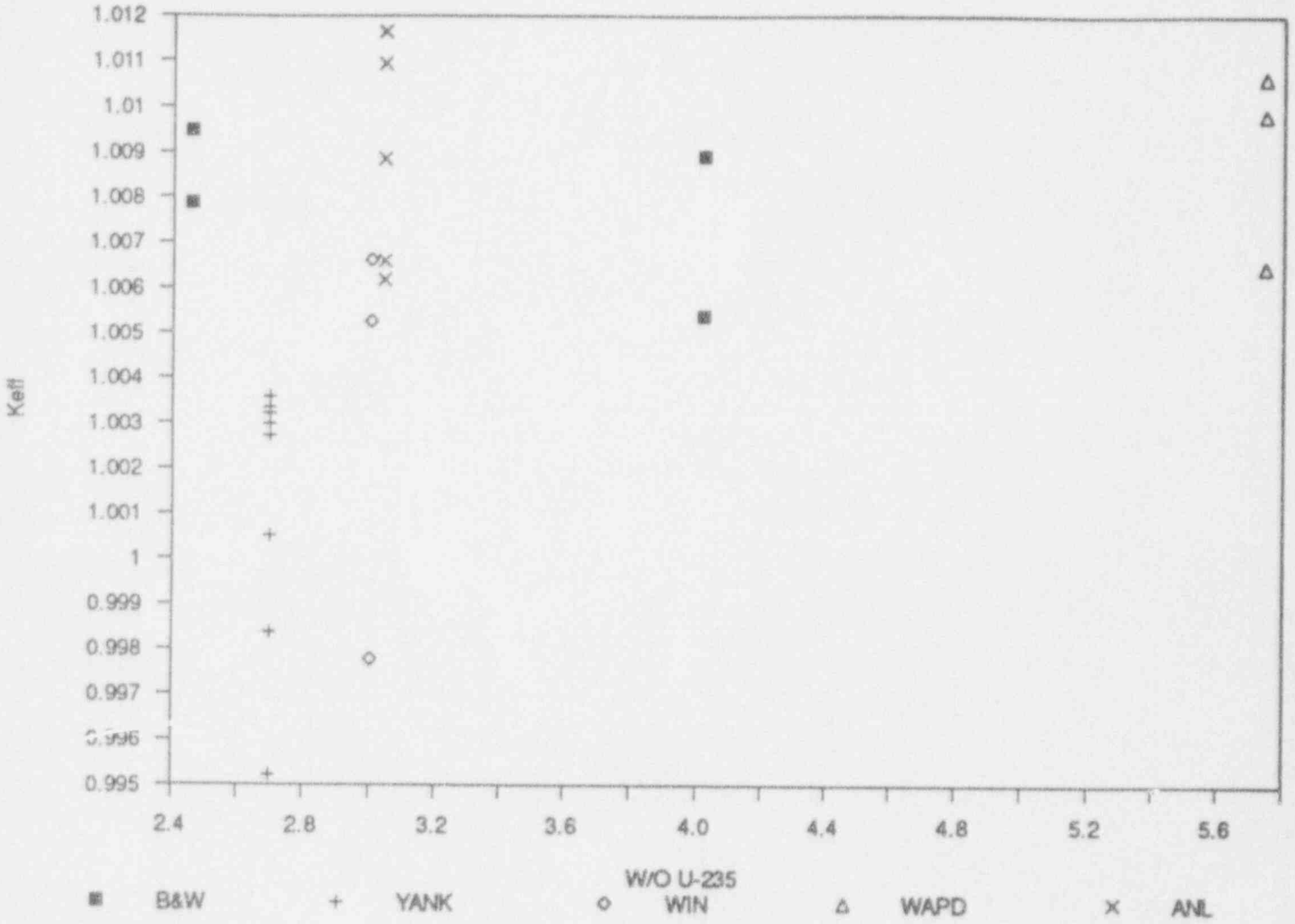
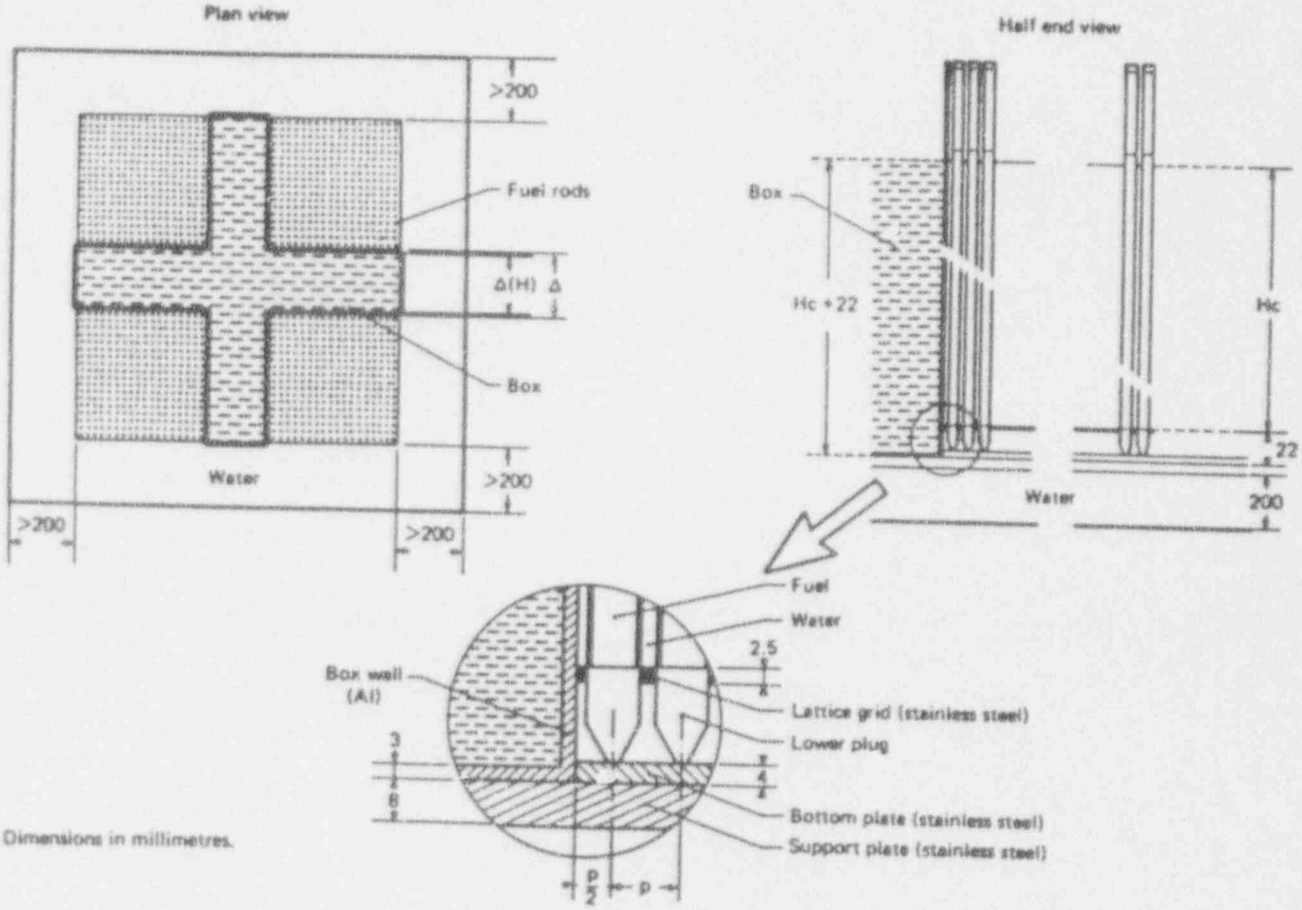


Figure 14-25

Keff versus Enrichment



Dimensions in millimetres.

Figure 14-26

Experimental Setup for Experiments of Reference 29

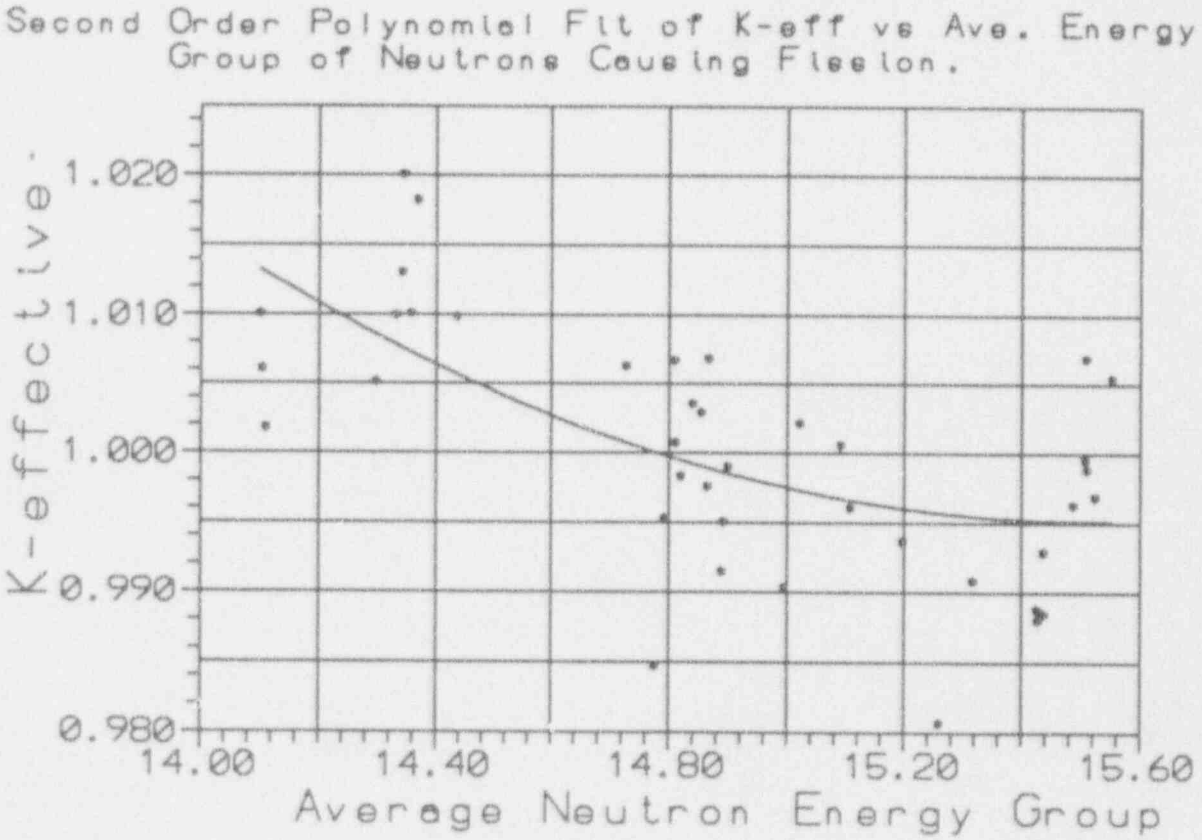


Figure 14-27

<u>Keff versus Average Energy Group of Neutrons Causing Fission</u>