LA--12415

DE93 002856

MCNP: Criticality Safety Benchmark Problems

John C. Wagner
James E. Sisolak
Gregg W. McKinney

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ERRATA
MCNP: CRITICALITY SAFETY BENCHMARK PROBLEMS
LA–12415

1. Figure 1 on page 10:
   The dimension of 26.02 cm should be 23.775 cm.
2. Figure 4 on page 16:
   The four metal units in Fig. 4 are beside the four solution units (not inside as the figure may imply), with a separation of 1.557 cm.
3. Figure 9 on page 23:
   The regions surrounding the uranyl nitrate solution and indicated as "water" are actually "water vapor."
4. Figure 10 on page 24:
   All references to uranyl "nitrate" should be changed to uranyl "fluoride."
5. Page 25:
   All references to uranyl "nitrate" in the description of Problem #20 should be changed to uranyl "fluoride."
   References which could have been cited for Problem #20 are ORNL–2367 and LA–10860–MS.
   In the description of Problem #21, the atomic ratio of "1099" should be "997."
6. TABLE I on page 28:
   For case 15, the results are: 1.0016, 0.0011, 1.0020, 0.0012, 0.0, 0.2, and 0.2.
   For case 18, the results are: 1.0302, 0.0013, 1.0084, 0.0013, 2.2, *, and *.
7. TABLE II on page 29:
   For case 1, the results are: 0.9960, 0.0009, 0.9996, 0.0011, -0.3, and -0.3.
   For case 15, the results are: 1.0294, 0.0010, 1.0020, 0.0012, 2.7, and 2.9.
   For case 18, the results are: 1.0670, 0.0011, 1.0084, 0.0013, 5.8, and *.
8. TABLE III on page 31:
   For case 15, the results are: 1.0016, 0.0011, 1.0189, 0.0012, 0.0, 1.7, 0.2, and 1.9.
   For case 18, the results are: 1.0302, 0.0013, 1.0479, 0.0012, 2.2, 3.9, *, and *.
9. Page 33:
   Under the heading Experimental Results, "Ref. 21" should read "Ref. 20."
10. Figure 20 on page 43:
    The reference to uranyl "nitrate" should be changed to uranyl "fluoride."
11. Page 46:
    Reference 21, **17** should read **7**.
12. Figure A20 on page 77:
    The reference to uranyl "nitrate" should be changed to uranyl "fluoride."
13. TABLE B1 on page 89:
    For case 15, the results are: 1.0025, 0.0010, 1.0020, 0.0012, 0.0, 0.2, and 0.2.
    For case 18, the results are: 1.0287, 0.0013, 1.0084, 0.0013,2.0, *, and *.
14. TABLE B2 on page 90:
    For case 1, the results are: 0.9960, 0.0009, 0.9996, 0.0011, -0.3, and -0.3.
    For case 15, the results are: 1.0292, 0.0010, 1.0020, 0.0012, 2.7, and 2.9.
    For case 18, the results are: 1.0670, 0.0011, 1.0084, 0.0013, 5.8, and *.
15. TABLE B3 on page 91:
    For case 15, the results are: 1.0025, 0.0010, 1.0189, 0.0012, 0.0, 1.7, 0.2, and 1.9.

MCNP: CRITICALITY SAFETY BENCHMARK PROBLEMS

by

John C. Wagner, James E. Sisolak, and Gregg W. McKinney

ABSTRACT

This report investigates the suitability of the general purpose Monte Carlo transport code MCNP for criticality safety calculations. The increased use of radiation transport codes for criticality problems has produced a greater user and institutional demand for assurances that such codes give correct results. Responding to these requirements for code validation, MCNP has been benchmarked against the KENO standard test set. MCNP results are compared to KENO calculations, as well as experimental results, where available. A comparison of MCNP continuous energy and multigroup results indicates that the continuous energy cross sections are more accurate, and MCNP successfully predicts the experimental results, in some cases better than KENO, within the expected data and statistical uncertainties. This benchmark study demonstrates that MCNP can accurately and efficiently model a relatively broad spectrum of criticality problems.

I. INTRODUCTION

A. The MCNP Benchmark Project

This document is the third in a series of LANL reports benchmarking the MCNP Monte Carlo computer code.[1] The first two documents, LA-12196,[2] and LA-12212,[3] demonstrate that MCNP accurately models analytic problems and a wide variety of photon and neutron experiments.[4,5] This document demonstrates that MCNP can accurately model experimental criticality problems and produce results consistent with the KENO Monte Carlo criticality code. An additional report published by General Electric Nuclear Energy, "MCNP: Light Water Reactor Critical Benchmarks,"[6] complements this report and demonstrates MCNP's applicability to light water reactors.

For the most part, the two companion reports, LA-12196 and LA-12212, model the same problems chosen to benchmark the COG Monte Carlo code developed at Lawrence Livermore National Laboratory.[7] The nine criticality problems reported in LA-12212 are the only serious departures from the set chosen for the COG benchmarks. The General Electric Nuclear Energy report, on the other hand, models a unique set of critical systems encompassing various temperatures and fuel types.

This report deals exclusively with criticality and models 25 sample problems used to test the KENO Monte Carlo code. These sample problems constitute the KENO standard benchmark set and represent a relatively wide variety of criticality problems.[8] The KENO Monte Carlo code was chosen because of its extensive benchmarking against analytical and experimental criticality results. Although the uncertainty in the experimental parameters prohibits code validation to better than about 1% in k_{eff}, the value of k_{eff} for criticality is considered unacceptable if it deviates more than a few percent from measurements.[9] It is essential that the computational methods used for nuclear criticality safety purposes be sufficiently accurate that one can be confident of subcriticality when adequate safety margins are applied. In almost all cases presented here, the MCNP calculated results are as good as, or better than, those of KENO and as accurate as could be reasonably expected in a numerical solution.

B. Motivation for Investigation

The reasons for a code validation are numerous. In the past, criticality safety information applicable to the handling and storage of fissile materials was obtained from critical experiments, nuclear safety guides, and handbooks based on critical experiments or various computer codes. Because critical experiments are costly and require a substantial amount of time, and because many of the critical experimental facilities have been closed, increasing reliance has been placed on computational methods. Presently, the KENO Monte Carlo criticality code is the most widely accepted and used tool for criticality safety calculations. With the increased reliance on computational methods comes the need and requirement for redundant validation by alternate criticality codes. For MCNP to be accepted by the criticality safety community in this role, it must be able to produce results that are consistent with KENO.

This investigation shows that MCNP can accurately reproduce the KENO results for the standard benchmark set and is an excellent tool for criticality safety calculations, in addition to being a general, multi-purpose Monte Carlo code.

C. Outline

This paper is organized as follows: Section II presents an overview of the MCNP and KENO transport codes used for the benchmark, such as the differences in the MCNP and KENO cross-section libraries. A brief explanation of the common input parameters for both codes is given in Section III, and a brief description of each sample problem is provided in Section IV. Section V contains the benchmarking results, and Section VI discusses various aspects of these results. The conclusions of this investigation are located in Section VII. MCNP input files are presented in Appendix A, giving an unambiguous description of the critical configurations.

II. OVERVIEW OF MCNP/KENO

This benchmark consisted of comparing results from KENO V.a installed on a Cray X-MP (CTSS operating system), and from MCNP version 4.2 installed on a Cray Y-MP (UNICOS operating system). The KENO 25 problem benchmark set provided with the version V.a manual was converted to MCNP input files for

comparison. Although some inputs are designed to demonstrate KENO V.a features, such as the restart feature, not directly related to calculating k_{eff}, these were also converted to MCNP format to illustrate that many of the same features are available in MCNP criticality computations.

A. Sample Problems

1. MCNP

Appendix A contains the MCNP input files for all 25 problems; these are discussed individually in Section IV. In many cases there are several equivalent translations of the KENO inputs, all of which model the same physical system. In these cases, a choice had to be made whether to specify the geometry using MCNP's repeated structures capability, or to model each geometric unit separately. Many problems were run with several equivalent setups; k_{eff} values calculated with alternate geometry specifications had no statistically significant differences. The input files in Appendix A do not necessarily use the simplest possible geometry specification but instead duplicate the geometry features employed in the KENO inputs. Whenever possible, a description of the actual experiment was used to verify the geometry specification and results. In addition, all volumes and material densities calculated by KENO and MCNP were compared to ensure consistency.

MCNP benchmarks were performed with both version 4.2 (latest publicly released version) and version 4x-c (a preliminary version of MCNP4A and the LANL "floor version" at the time of publication). All results presented in Sections V and VI are based upon version 4.2. For each version, three cases were considered:

(1) continuous energy
(2) multigroup (30 energy groups)
(3) continuous energy with S(α, β) thermal scattering

The inputs located in Appendix A correspond to case 3.

2. KENO

Most of the 25 problems in the KENO V.a[8] manual model criticality experiments performed at Oak Ridge National Laboratory. KENO results based on these input files appear in Ref. 10. These results were duplicated exactly by running the 25 problem benchmark set on a Cray X-MP. As discussed below, the KENO files were then changed to specify a larger number of histories, and a second set of results

generated. The comparison between MCNP and KENO is based upon this second set of numbers; Ref. 10 served only to verify that KENO was being run properly.

KENO can be run either "stand-alone" or as part of the SCALE package. SCALE provides facilities for, among other things, cross-section processing and criticality searches. MCNP was compared to stand-alone KENO results since a direct comparison between the criticality codes was the emphasis of this benchmark exercise.

B. Cross Sections

1. MCNP

All continuous energy inputs were run with the "recommended" cross-section set (i.e., atomic identifiers ending with .50c, based on ENDF/B-V as processed by the NJOY code). For the nuclides used, these cross-section sets are flagged in Appendix G of the MCNP User's Manual, Version 3A,[1] as the best available data. Multigroup inputs also used ENDF/B-V data, which was accessed by simply adding a single input card (**MGOPT F 30**) to the MCNP continuous energy input files.[11,12] This addition is the *only* difference between continuous energy and multigroup input files. Multigroup runs serve two purposes: (1) to benchmark the multigroup feature of MCNP for criticality calculations, and (2) to generate k_{eff} from a library more comparable to that used by KENO, which does not employ continuous energy cross sections. The MCNP multigroup library has 30 energy groups, whereas the Hansen-Roach library used by KENO (see below) has 16 groups.[13]

The third set of MCNP results employed the $S(\alpha,\beta)$ treatment to hydrogen cross sections in water and paraffin to account for molecular scattering of thermal neutrons. Since MCNP lacks $S(\alpha,\beta)$ information for paraffin, polyethylene was used instead, because it is the best available match for paraffin. Although the use of polyethylene as a substitute for paraffin is questionable, it did improve the MCNP results relative to both KENO and experimental values.

All cross sections, including those for $S(\alpha,\beta)$, were taken at a temperature of 300 K. Appendix G of the MCNP User's Manual[1] contains additional information about MCNP cross sections. Note that the $S(\alpha,\beta)$ thermal scattering treatment is not available with the MCNP multigroup cross sections.

Ideally, MCNP multigroup results should have been based upon the Hansen-Roach library, to enable a more direct comparison with KENO; however, at the time of this writing, an acceptable library does not exist in a form suitable for MCNP.[13]

All MCNP k_{eff} values reported herein used the covariance-weighted combined k_{eff} estimator. MCNP generates the following estimates of k_{eff}: collision, absorption, track length, and covariance-weighted combinations of the first three (collision/absorption, absorption/track length, track length/collision, and collision/absorption/track length). The last covariance-weighted combination is quoted in this report, because it is the most widely used estimator in the absence of other information and because it incorporates all the k_{eff} estimates generated by MCNP. MCNP provides correlation coefficients to help choose the optimal estimator. Although the optimal estimator is problem dependent, a single estimator was used for the benchmark to eliminate ambiguity.

2. KENO

Several cross-section libraries in the AMPX format are available for use with the SCALE package; however, only the Hansen-Roach 16 group library can be used if KENO is run stand-alone. Aside from the group structure, there is an important difference between the MCNP and Hansen-Roach multigroup cross sections. The Hansen-Roach library contains several entries for each isotope, differentiated by a σ_p (potential scattering cross section) value. When selecting cross sections for isotopes in a mixture, it is necessary to calculate σ_p for that mixture and choose the corresponding cross section from the Hansen-Roach library. Note that σ_p will be different for each resonance absorber in the mixture. This treatment accounts for resonance self-shielding (reduced absorption at lower energy resonances caused by a dip in the neutron energy spectrum that is produced by a strong higher energy resonance) and is described in Ref. 14.

Several KENO input files employ the σ_p adjusted U^{235} and U^{238} cross sections, whereas MCNP multigroup cross sections, as processed by NJOY, are based on an infinitely dilute absorber approximation ($\sigma_p = \infty$).

III. GENERAL INPUT PARAMETERS

Every effort was made to reproduce the KENO input files as closely as possible. In particular, the number of particles per cycle and the number of cycles sampled are consistent. As a result, the variances of the KENO and MCNP results were of the same order of magnitude ($\approx 0.3\%$).

A. MCNP

All MCNP input files share the following common features:

MODE n: mode card
Neutron transport only was considered; in particular, photon production was ignored, since the benchmark comparison involved only k_{eff} values. KENO will not track photons. If desired, however, photon production could be included with MCNP.

M*n* [isotope] [isotope fraction]: material card
The number densities for all isotopes were taken directly from the KENO inputs. These were added together and the total number density entered on the cell cards. The values on the material cards are isotope fractions which sum to 1.0.

MT*n* [material]: S(α, β) material card
Input files for continuous energy and continuous energy with S(α, β) thermal scattering differ only by the presence of **MT*n*** card(s). Here, n corresponds to the material card, **M*n***, which contains water or paraffin. As noted, the S(α, β) treatment was applied only to hydrogenous materials. For water, the material specification is **LWTR.01T**; for paraffin, it is **POLY.01T** (polyethylene).

F4:n: tally card
While computing k_{eff}, MCNP tallied the average flux in the fissile cells. In addition to providing insight into the problem, this tally duplicated the flux calculations performed by KENO on some of the sample problems. The energy bins used for this tally were chosen to match the Hansen-Roach group structure used in the KENO runs.

KCODE 3000 1.0 20 200 4500 0: criticality card
Each **KCODE** cycle consisted of approximately 3000 neutrons (the exact number varied slightly from cycle to cycle) started at source points determined in the previous cycle. The initial guess for k_{eff} for all problems was 1.0. In most cases, the computed value was near 1.0, and for the few exceptions, notably problems 6 and 9, a guess of unity proved sufficient. Results were based on 200 total cycles, the first 20 of which were skipped before tallying began (to ensure that the source distribution had stabilized). The only exception to the above is problem 11, which is a restart using data from cycle 50 of problem 10 (see Section IV). Originally, the

problems were run with 50 cycles, of which the first 10 were skipped. Extended calculations were performed to verify the stability of k_{eff}.

SDEF [parameters vary]: source definition card
With an **SDEF** card, a Watt fission spectrum and an initial source distribution (uniform in each fissile cell) could be specified. A uniform source was used instead of the **KSRC** card to mimic KENO; as a default, KENO employs a uniform initial source in any cell containing fissionable material. Two exceptions were made (problems 13 and 16), as discussed below. If E is the neutron energy in MeV and $p(E)\,dE$ is the probability of a neutron being born in the range dE about E, then the Watt fission spectrum is:

$$p(E) = C \exp(-E/a) \sinh(bE)^{1/2}$$

where

$$a = 0.965\,MeV; b = 2.29\,MeV^{-1}.$$

These particular values for a and b do not appear in the input files, since they are MCNP defaults; C is a normalization constant. MCNP uses the Watt spectrum by default if the initial source is specified on a **KSRC** card, but a **KSRC** card cannot provide a volumetric source.

MGOPT F 30: multigroup option card
Input files for continuous energy and multigroup differ only by the presence of this card, which selects the MCNP 30 group cross-section library.

PRDMP j j 1 j : print and dump cycle card
The prdmp card was added to produce an mctal file for future reference. A plot of k_{eff} vs. cycle can be generated from this file using mcplot.

PRINT: print card
This card simply generates full output for later reference.

With few exceptions, explained in Section IV, little effort was invested in the use of variance reduction techniques, since the focus of this benchmark exercise was on accuracy not speed. When properly used, of course, variance reduction will not produce statistically significant changes in k_{eff}.

B. KENO

Most of the KENO benchmark input files use defaults for the number of cycles (103), the number of cycles to skip before tallying (3), and the number of particles per cycle (300). These values produced large variances and, more importantly, 3 cycles were insufficient to converge the fission source. Therefore, KENO was rerun with the same parameters used in the MCNP input files (3000 particles per cycle and 200 cycles, of which the first 20 are skipped - see subsection III.A above). Note that in the KENO nomenclature, a cycle is referred to as a generation.

As noted above KENO uses a uniform source in each fissile cell for the first cycle. A uniform source is not always a good approximation, but it was adequate for all of the sample problems. Both MCNP and KENO provide for the entry of arbitrary initial sources; the choice of a uniform volume source was simply a matter of convenience. Several runs have verified that, with the above parameters, the converged value for k_{eff} is insensitive to the initial source distribution.

IV. BENCHMARK PROBLEM DESCRIPTION

This section contains a brief description of each of the 25 sample problems that make up the KENO standard benchmark set. For clarity, the title of each sample problem is taken directly from the KENO V.a manual. The purpose of these sample problems for KENO was twofold: (1) to benchmark the code against criticality experiments and (2) to demonstrate various options of the KENO code. The interested reader can find the associated input data in Appendix D of Ref. 8.

Sample Problem #1 - 2C8 Bare

This problem is a simple unreflected 2x2x2 array of 93.2% enriched uranium metal cylinders as described in Ref. 15. Figure 1 shows the critical experiment. The cylinders exhibit a surface separation of 2.244 cm in the x and y directions and 2.245 cm in the z direction, and are 10.765 cm in height and 11.496 cm in diameter. The cylinders and the cuboids in which they are contained are referred to as 2C units. The entire array of 2C units is referred to as a 2C8 unit.

This problem was utilized by KENO to demonstrate the array data card. Therefore, the repeated structures capability of MCNP was employed in the input for this problem.

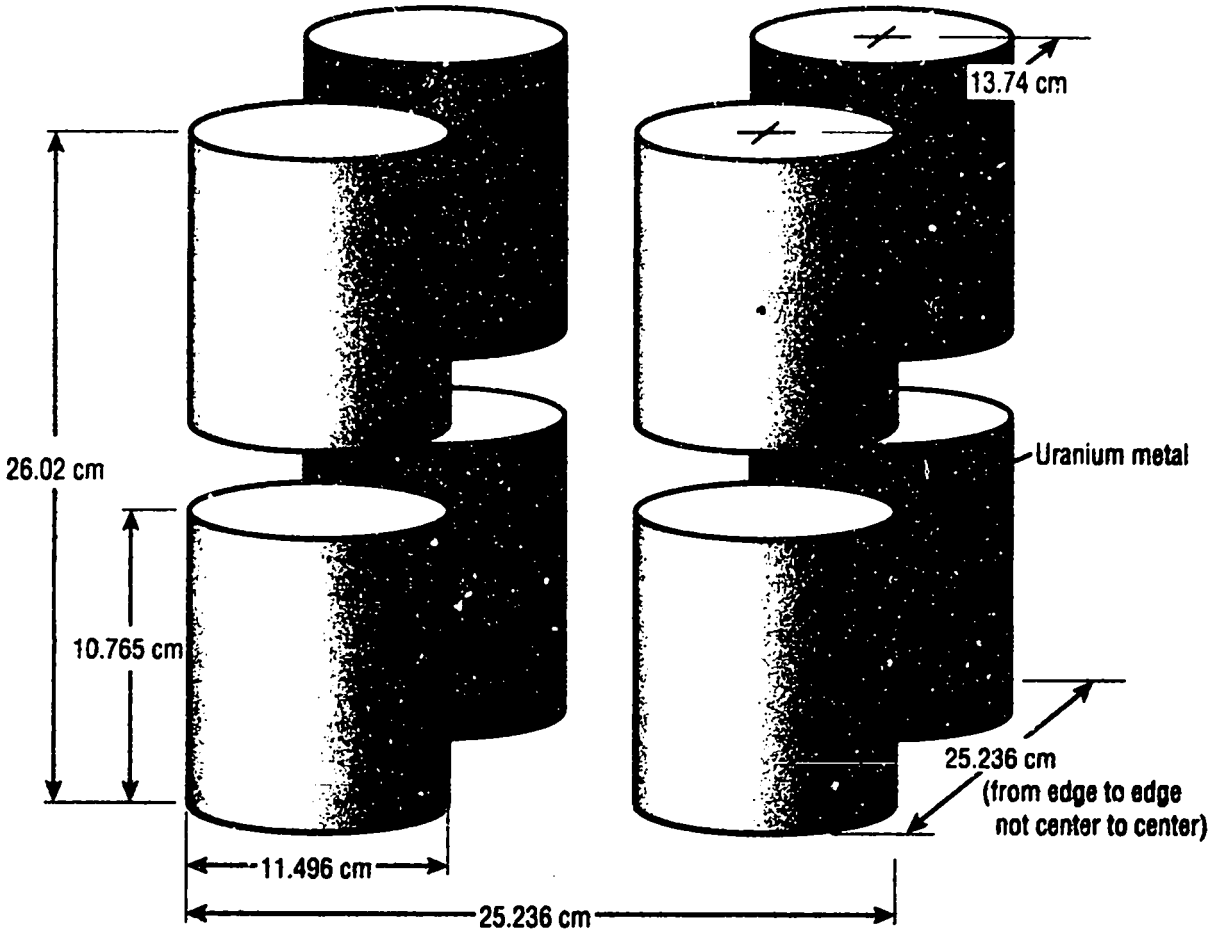


Fig. 1. Critical 2C8 Bare Assembly

Sample Problem #2 - Case 2C8 Bare with 8 Unit Types Matrix Calculation

This problem is the same as problem 1 except that the geometry is set up explicitly. More specifically, each cylinder and unit are defined separately. The corresponding MCNP input duplicated the KENO input by also defining each cylinder or unit separately.

Sample Problem #3 - 2C8 15.24 cm Paraffin Reflector

This problem involves a 2x2x2 array of 93.2% enriched uranium cylinders that is reflected by 15.24 cm of paraffin on all six faces. The components of this critical experiment are designated in Table II of Ref. 15. An illustration of this critical experiment is shown in Fig. 2. These cylinders are also 10.765 cm in height and 11.496 cm in diameter, but their surface separation has been increased to approximately 11.98 cm.

Sample Problem #4 - 2C8 15.24 cm Paraffin Reflector Automatic Reflector

This problem is the same as sample problem 3 except for the paraffin specifications. The materials and geometry are exactly the same.

KENO uses this problem to demonstrate its automatic reflector option, which is an input feature that allows the assignment of different importances to different regions of the reflector. Although MCNP does not offer an option such as this, the KENO input was duplicated by manually specifying the importances of the various regions. The only differences between the MCNP problem #3 input and this input are the importances of the various regions.

Sample Problem #5 - 2C8 12 inch Paraffin Albedo Reflector

This problem is the same as problems 3 and 4 except that the reflector is represented by 30.48 cm of paraffin. This problem was designed to demonstrate KENO's paraffin albedo. The KENO input for this problem was duplicated in MCNP by simply increasing the reflector thickness of problem 3 from 15.24 cm to 30.48 cm.

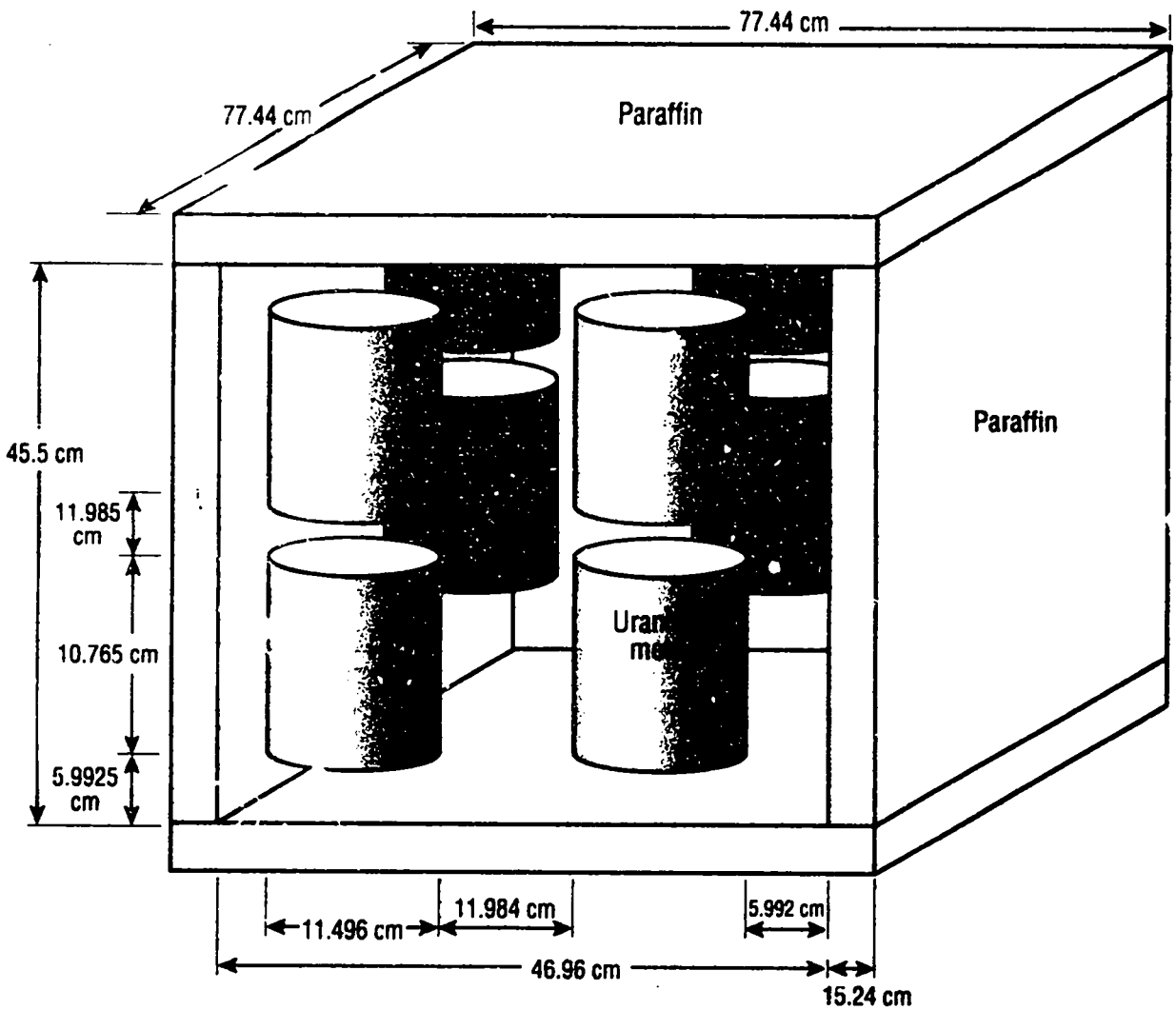


Fig. 2. Critical 2C8 Assembly with Paraffin Reflector

Sample Problem #6 - One 2C8 Unit (Single Unit)

This problem involves a single unreflected uranium metal cylinder, as shown in Fig. 3. This cylinder is characterized by the same enrichment and dimensions as the cylinders in the earlier problems.

Sample Problem #7 - Bare 2C8 Using Specular Reflection

This problem is designed to simulate problems 1 and 2, using specular reflection. It involves one of the 2C units that were used in problems 1 and 2, with specular reflection on the positive x, y, and z faces of the unit.

MCNP and KENO are both capable of applying a specularly reflective boundary condition to any surface.

Sample Problem #8 - Infinitely Long Cylinder from 2C8 Unit

This problem is designed to simulate an infinitely long cylinder.[15] The material and cylinder radius from sample problem 1 are used. The length of the cylinder was arbitrarily chosen to be 20 cm, and the unit is specularly reflected on the top and bottom.

Sample Problem #9 - Infinite Array of 2C8 Units

This problem involves one of the 2C units used in problem 1 and specular reflection to simulate an infinite array of 2C8 units. The parallelpiped containing a single uranium cylinder is specularly reflected on all faces to create an infinite array of 2C8 units having an edge-to-edge spacing of 2.244 cm in the x and y directions and 2.245 cm in the z direction.

Sample Problem #10 - 2C8 Bare Write Restart

This problem is the same as problem 1, a 2x2x2 array of uranium metal cylinders, except it is set up to write restart information on every fifth cycle which is the method that is used by KENO to prepare for a continuation of a run. KENO does not automatically write restart information; the default parameter must be changed, as it was in this particular problem.

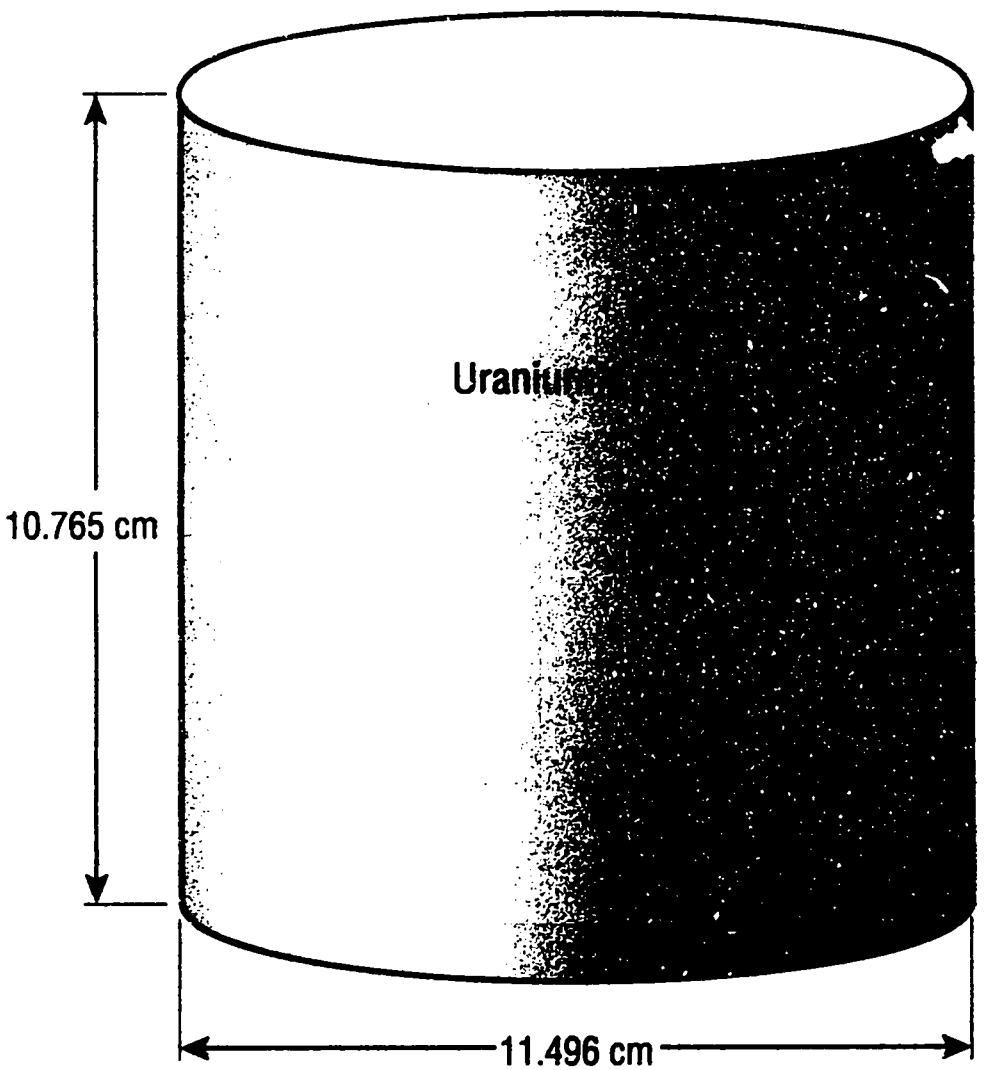


Fig. 3. One 2C Unit, Single Uranium Metal Cylinder

Sample Problem #11 - 2C8 Bare Read Restart Data

This problem is a restart of sample problem 10. The problem is restarted from the 10th set of restart data (50th cycle), which was written by sample problem 10, and run out to the 200th cycle.

While problems 10 and 11 were designed to demonstrate the restart capabilities of KENO, they are not necessary for MCNP. MCNP does not require separate restart data input. It writes the restart data automatically, so that the restart information is available if it is required.

Sample Problem #12 - 4 Aqueous 4 Metal

This problem consists of a composite array of four highly enriched (93.2%) uranium metal cylinders and four cylindrical Plexiglas containers filled with a highly enriched (92.6%) uranyl nitrate solution. The relevant experimental information describing this critical experiment can be found in Ref. 15. An illustration of this experiment is located in Fig. 4.

Sample Problem #13 - Two Cuboids in a Cylindrical Annulus

This critical experiment consists of two assemblies of highly enriched (93.2%) uranium metal stacked vertically.[16] The bottom assembly contains a uranium metal cuboid offset to the right within a uranium metal cylindrical annulus. The top assembly contains a uranium metal cuboid offset to the left within a uranium metal cylindrical annulus. The cuboid extends above the annulus. A drawing of this configuration is given in Fig. 5. A point source at the center of the geometry was used in place of the uniform volume source for this problem.

Sample Problem #14 - U Metal Cylinder in an Annulus

This problem involves a highly enriched (93.2%) uranium metal cylinder within a cylindrical annulus of the same material.[16] The uranium metal specification is identical to that used in sample problem 13. A schematic of this critical experiment is located in Fig. 6.

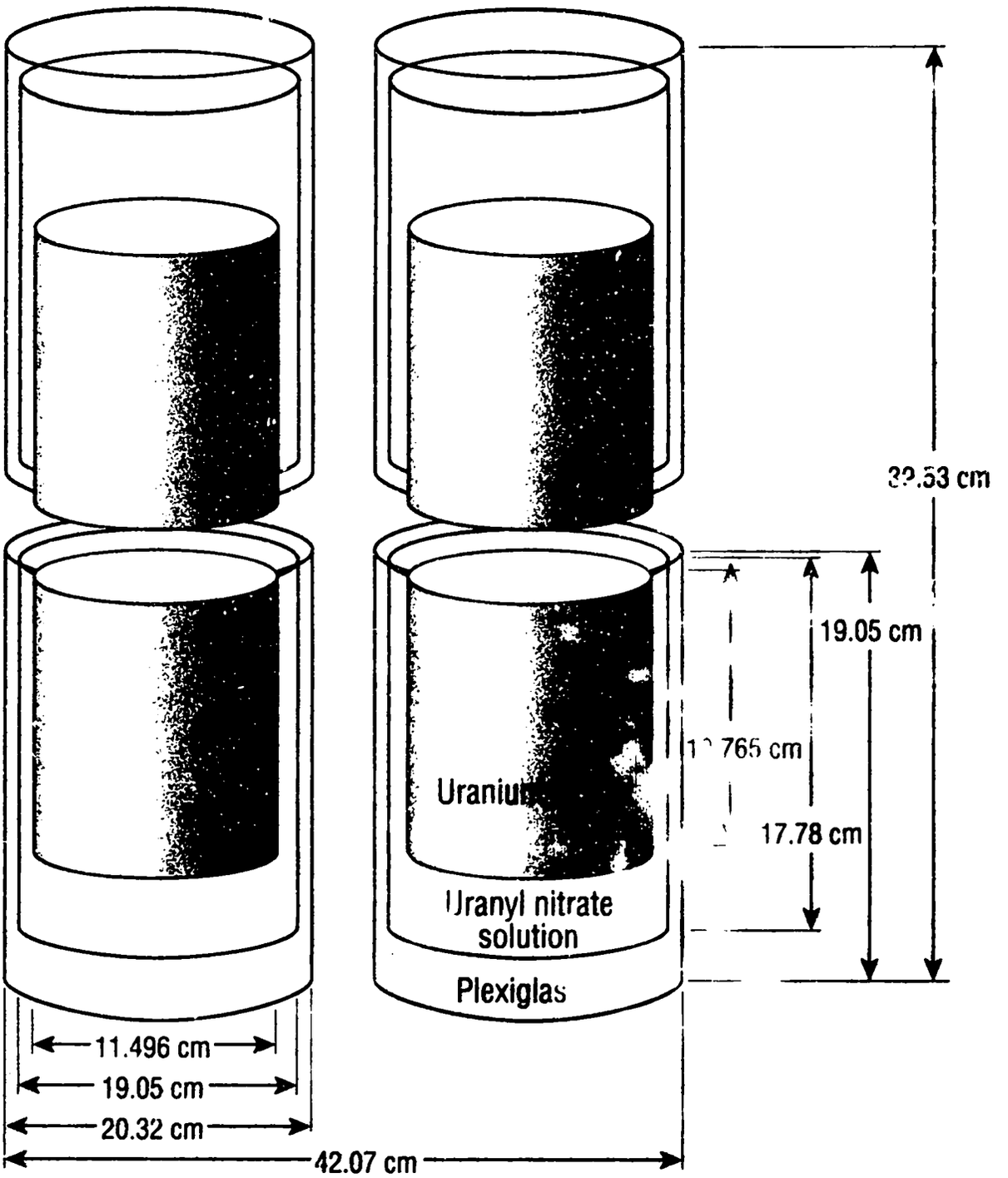


Fig. 4. Critical Assembly of 4 Solution Units and 4 Metal Units

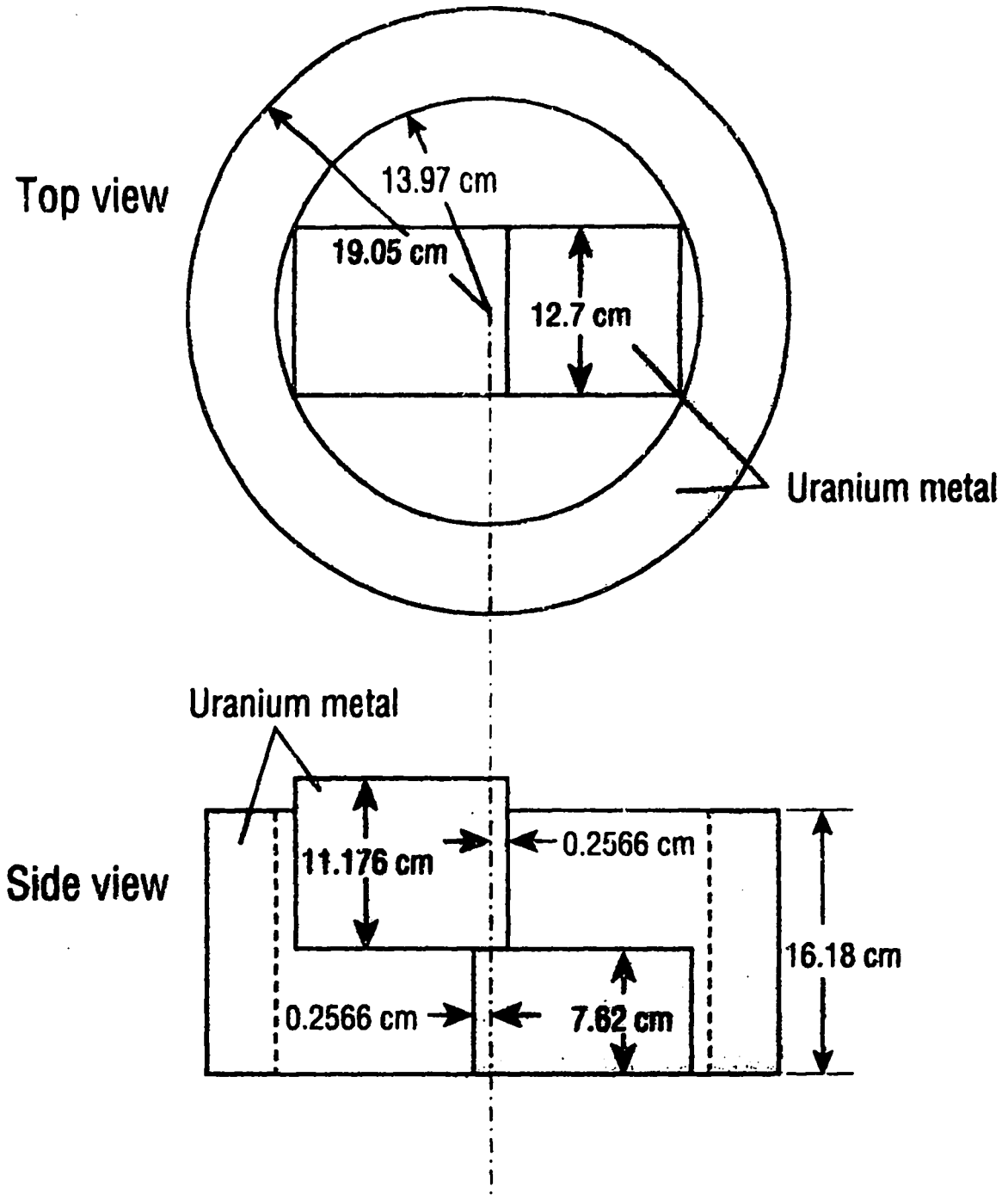


Fig. 5. Critical Aesembly of Two Cuboids in a Cylindrical Annulus

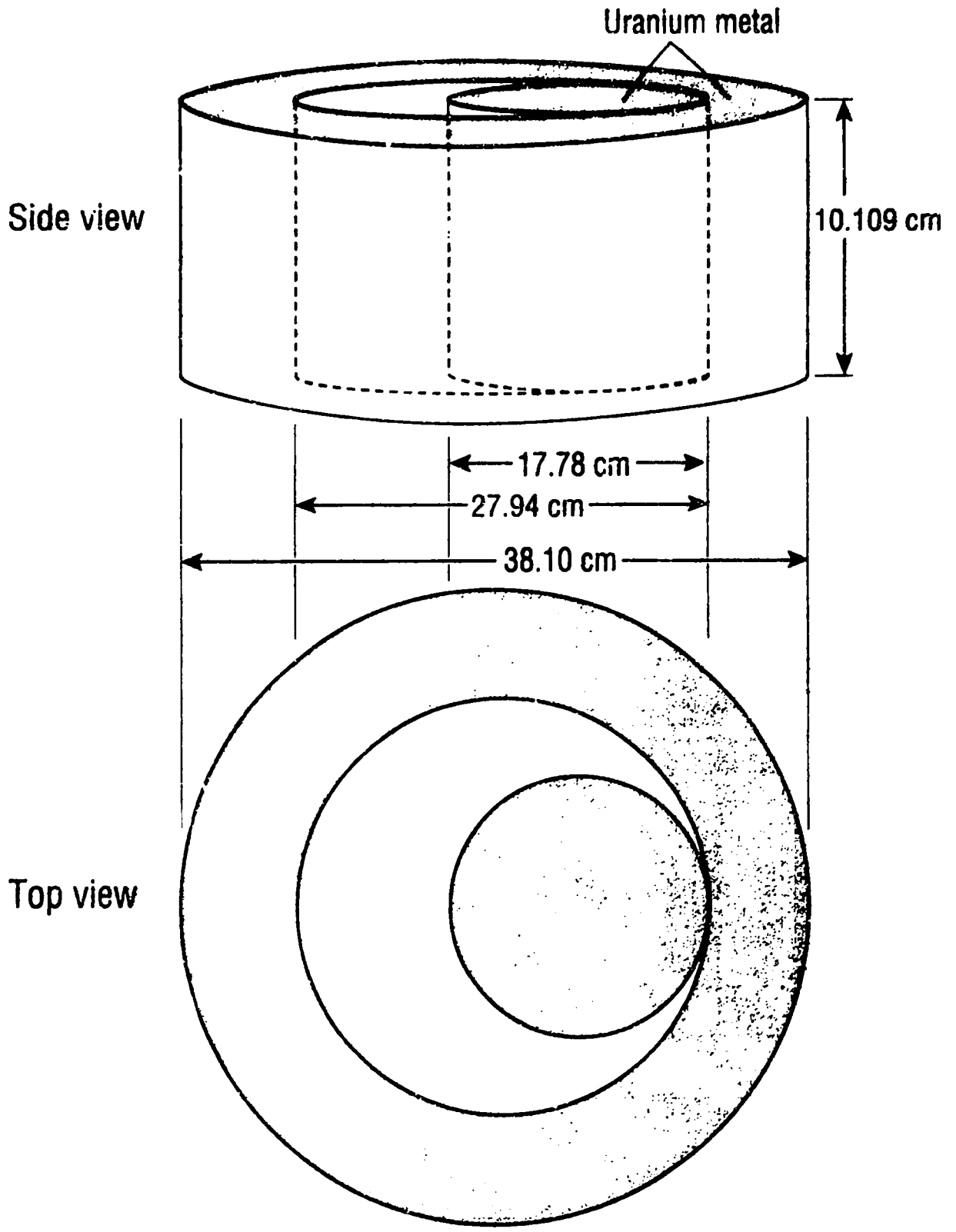


Fig. 6. Critical Assembly of a Cylinder within a Cylindrical Annulus

Sample Problem #15 - Small Water Reflected Sphere on Plexiglas Collar

This critical experiment is a small highly enriched (97.6%) uranium metal sphere supported by a Plexiglas doughnut in a tank of water.[17] The sphere extends down through the doughnut, as shown in Fig. 7. The uranium sphere has a diameter of approximately 13 cm and is located in a cylinder of water that has a height of 44.1844 cm and a diameter of 65.94 cm.

The KENO V.a geometry package cannot rigorously describe a doughnut. Therefore, the KENO description of this problem models the doughnut as an annular cylindrical plate, and the sphere is supported by it. Modeling the torus as a cylindrical plate should not change the problem significantly since the material making up this doughnut is Plexiglas, and both the sphere and the doughnut are contained in a tank of water. Although the geometry modeled by KENO was duplicated for this comparison, MCNP is capable of specifically describing the geometry of the experiment. For the sake of thoroughness, the experimental geometry in MCNP was modeled exactly, and the resulting k_{eff} values were found to agree within the statistics.

Sample Problem #16 - UO_2F_2 Infinite Slab K-Infinity

This problem models an infinite number of slabs of uranyl fluoride solution contained in Pyrex glass and separated by borated uranyl fluoride solution. The uranyl fluoride slab is 4.958 cm thick, 93.2% enriched, and has a density of 578.7 g U/liter. The Pyrex glass is 1.27 cm thick and is present on both faces of the uranyl fluoride solution. A total of 27.46 cm of borated solution separates the Pyrex glass of adjacent slabs of solution. Once again, the specularly reflective boundary condition was utilized to simulate the infinite array. Instead of a uniform volume source, the initial source consisted of one point in each slab of uranyl fluoride. An illustration of the unit that is reflected on all sides is given in Fig. 8.

Sample Problem #17 - 93% UO_2F_2 Solution Sphere Adjoint Calculation

This problem consists of a single 93% enriched uranyl fluoride sphere. The sphere is unreflected and has a diameter of 32.0 cm.

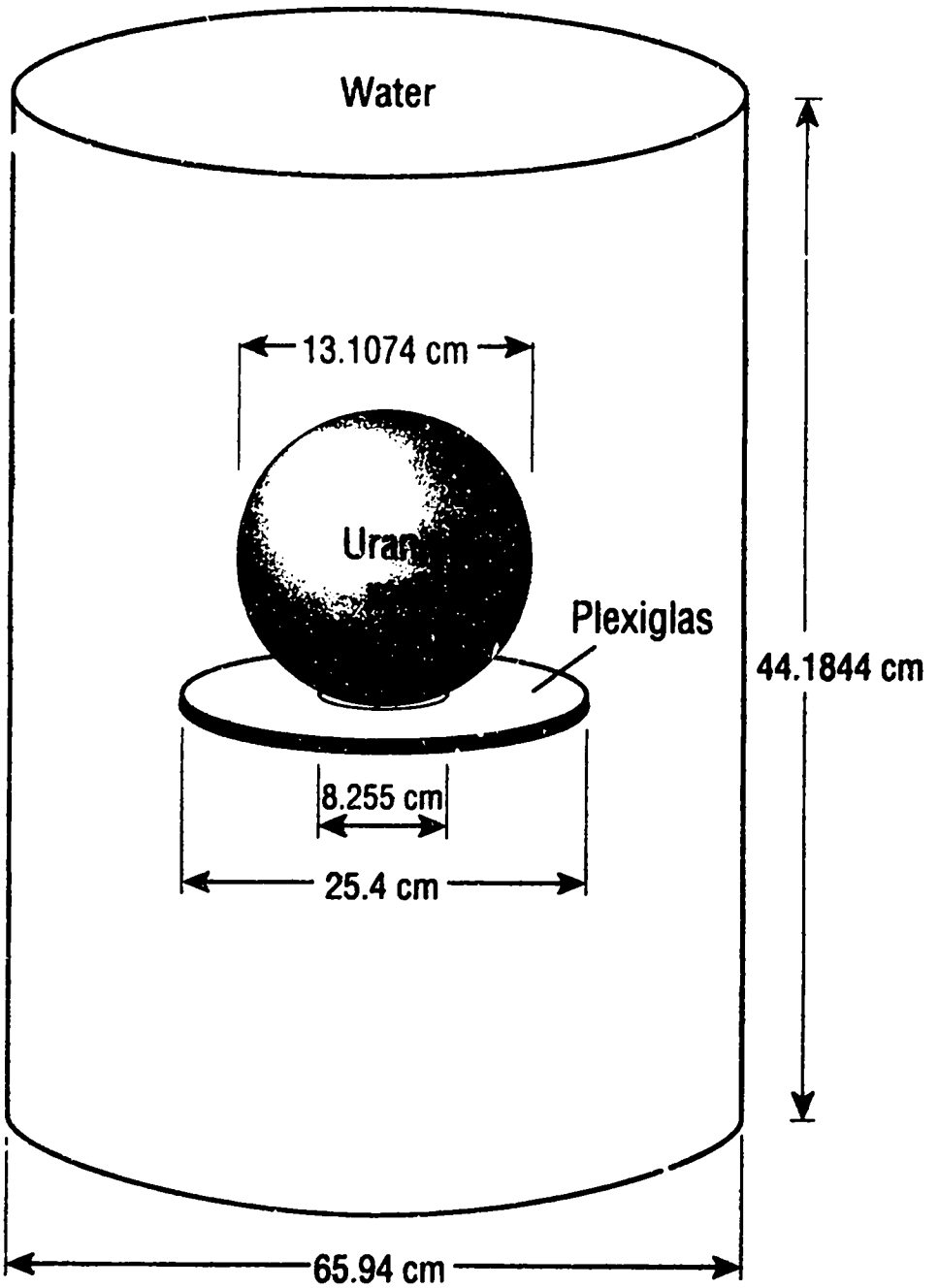


Fig. 7. Critical Assembly Consisting of a Uranium Sphere on a Plexiglas Collar with a Cylindrical Water Reflector

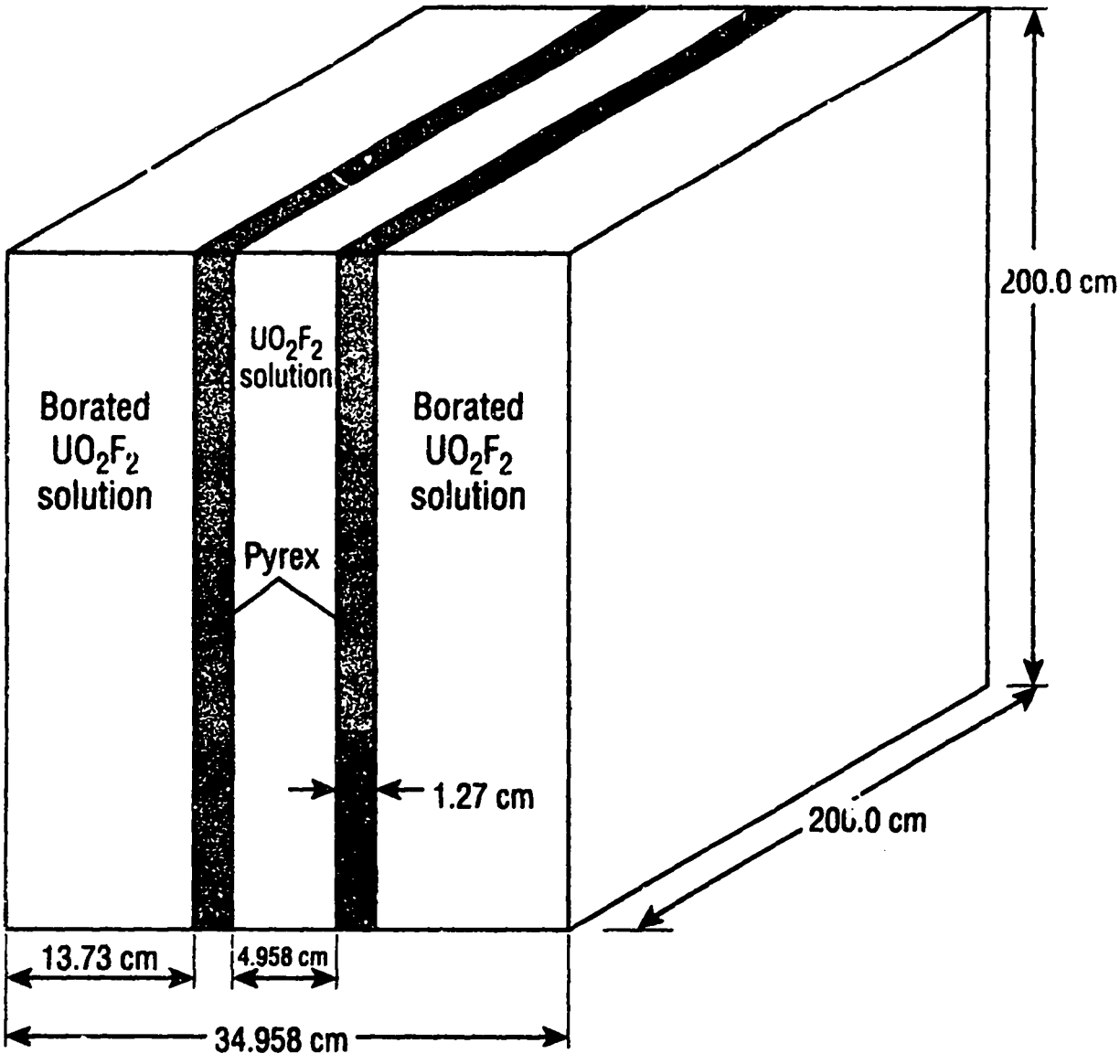


Fig. 8. Assembly Consisting of Glass and Solution Slabs

This problem demonstrates KENO's adjoint calculation option. The results for the forward and adjoint k_{eff} should be the same, within statistical error, when the problem is run both ways. Although MCNP is capable of performing an adjoint transport calculation, it cannot perform adjoint k_{eff} calculations.[18] Thus, only a forward calculation was performed and is reported for this problem.

Sample Problem #18 - 1F27 Demonstration of Options

This problem involved a reflected cubic array of 27 cylinders of aqueous uranyl nitrate in Plexiglas bottles.[19,20] The walls of the bottles were 0.64 cm thick, and each bottle was filled with 5.0 liters of 92.6% enriched solution at an H/U^{235} atomic ratio of 59 and an N/U^{235} atomic ratio of 2.006. The 3x3x3 array was surrounded by a 15.24 cm paraffin reflector. An additional 30.48 cm water reflector, located on the negative z face of the paraffin, was simulated by KENO with the help of the albedo data card. An illustration of this experiment, excluding the water slab, is given in Fig. 9.

Besides describing a relatively complicated geometry, this problem was used to demonstrate the albedo boundary condition, as well as many of the print options that are available with KENO. Due to the fact that MCNP does not offer a water reflecting boundary condition, a slab of water was physically placed at that point in the geometry. Also, while MCNP has numerous print options of its own, print options were not the concern of this investigation.

Sample Problem #19 - 4 Aqueous 4 Metal Array of Arrays

This problem was previously described as sample problem 12. Although the critical experiment this problem models is the same, the KENO array of arrays option is utilized to describe the geometry. A similar method, namely repeated structures, is used in MCNP.

Sample Problem #20 - Triangular Pitched Array

This problem represents a critical experiment consisting of seven cylinders in a triangular pitched unreflected array. The central cylinder has six cylinders around it, as shown in Fig. 10. Each unit consists of a 0.152-cm-thick aluminum can with

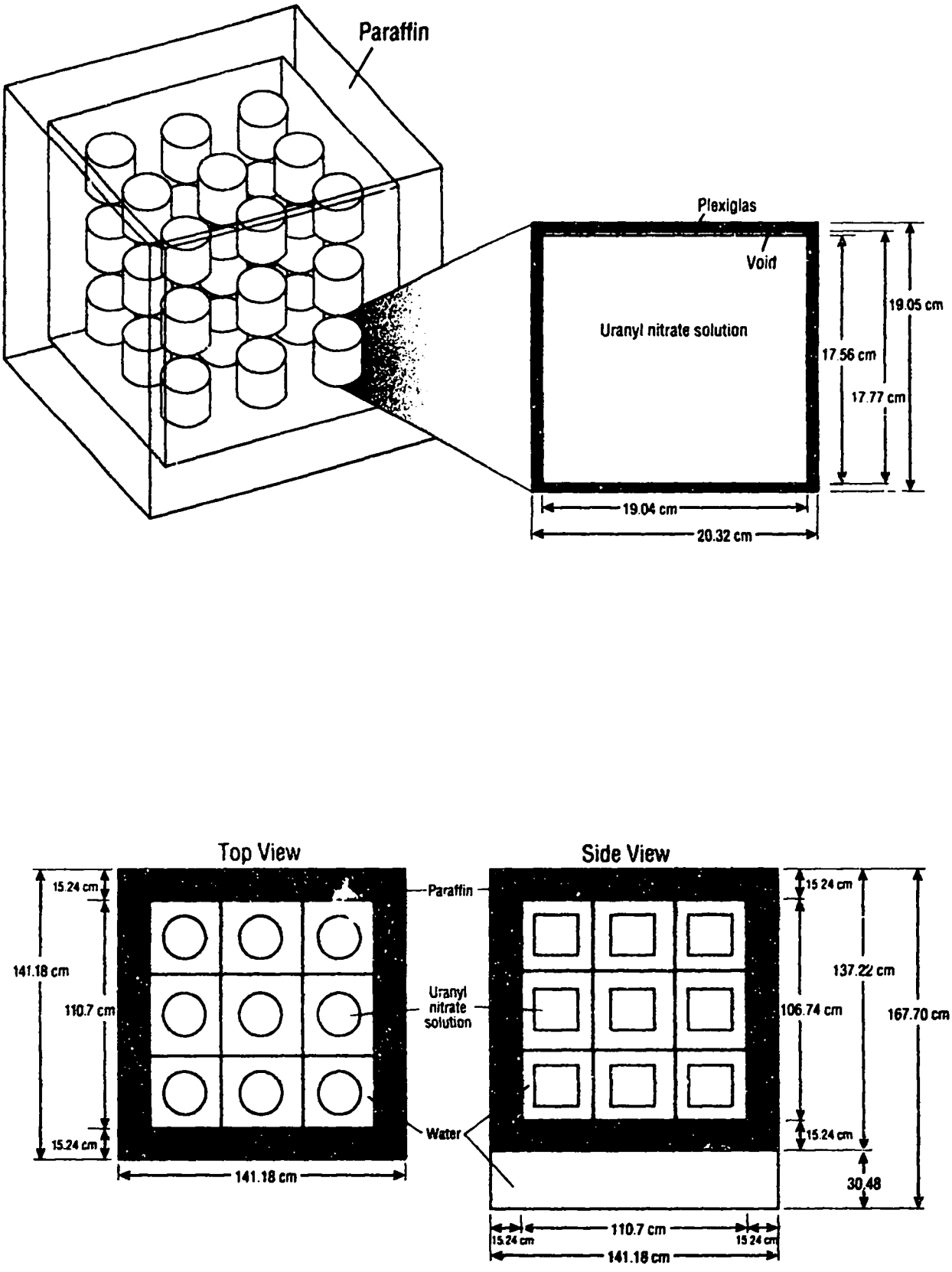


Fig. 9. Paraffin Reflected 3x3x3 Array of Cylinders of Uranyl Nitrate

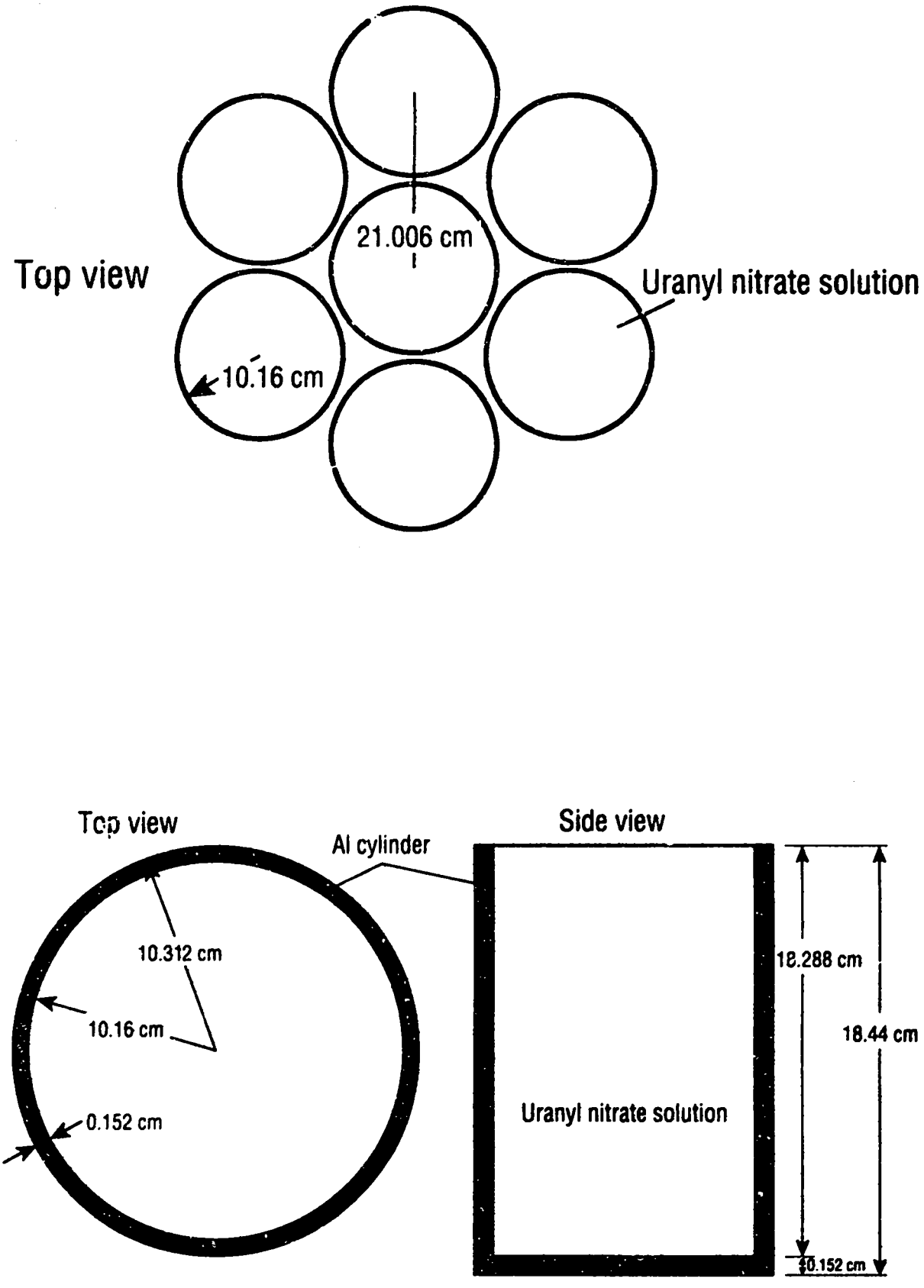


Fig. 10. Critical Assembly Consisting of Seven Cylinders of Uranyl Nitrate

a 20.32 cm inside diameter, filled with a solution of 93.2% enriched uranyl nitrate with a H/U^{235} atomic ratio of 44.3 and a density of 576.87 g U/liter.

ıple Problem #21 - Partially Filled Sphere

This problem describes a critical experiment consisting of a partially filled unreflected spherical container.[21] This aluminum container had an inside diameter of 69.2 cm and a wall thickness of 0.159 cm. The sphere was 98% filled with uranyl fluoride at an enrichment of 4.89% with an H/U^{235} atomic ratio of 1099. The height of the solution in the sphere was 64.6 cm above the bottom of the sphere. A diagram of the container is given in Fig. 11.

Sample Problem #22 - Case 2C8 Bare with 3 Nested Holes; Each is Equal Volume

This problem describes the same critical experiment as sample problem 1. It is a 2x2x2 array of highly enriched (93.2%) uranium metal cylinders. This problem defines a uranium cylinder in a void spacing cuboid using nested holes. Eight of these units are stacked together in a 2x2x2 array.

Sample Problem #23 - Case 2C8 Bare as Mixed Zhemicylinders

The physical representation of this sample problem is the critical experiment described in sample problem 1. This problem describes each of the 8 units in the critical 2x2x2 array using hemi-cylinders. The hemi-cylinders, with their axes parallel to the z axis, are used to form the cylinders that make up problem 1.

Sample Problem #24 - Case 2C8 Bare as Mixed Xhemicylinders

The physical representation of this sample problem is the critical experiment described in sample problem 1. This sample problem describes each of the 8 units in the critical 2x2x2 array using hemi-cylinders whose axes are in the x direction.

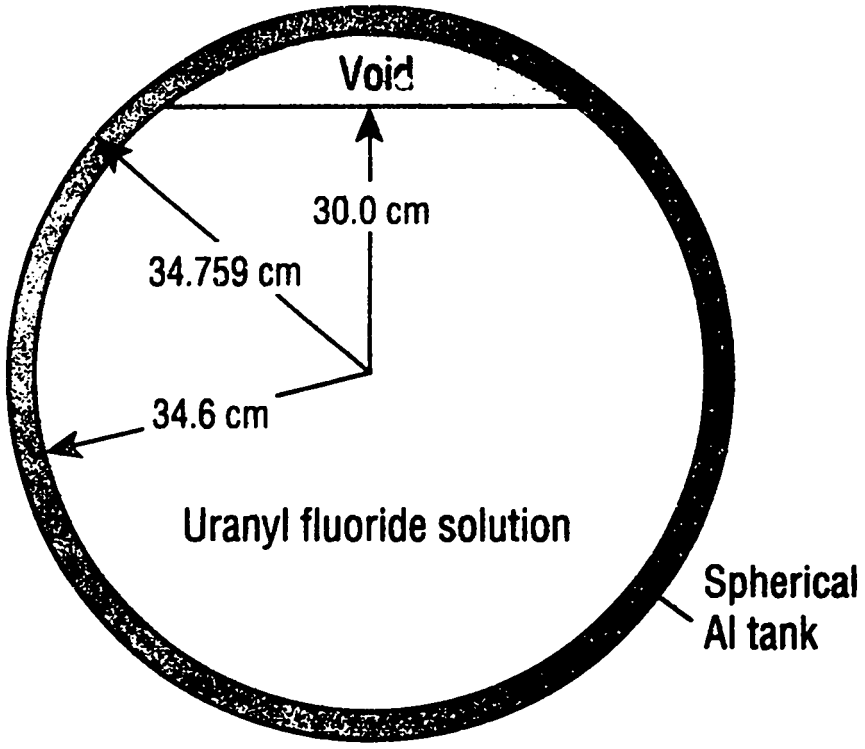


Fig. 11. Critical Assembly Consisting of a Bare Sphere Partially Filled with Uranyl Fluoride.

Sample Problem #25 - Case 2C8 Bare as Mixed Yhemicylinders

The physical representation of this sample problem is the critical experiment described in sample problem 1. This sample problem describes each of the 8 units in the critical 2x2x2 array using hemi-cylinders whose axes are in the y direction.

V. RESULTS

The MCNP results for continuous energy, with the S(α, β) thermal treatment, and the KENO results are given in Table I. The percent differences between the MCNP results and the KENO results, $100 \times (k_{MCNP} - k_{KENO})/k_{KENO}$, are listed in the column labeled *mcnp from keno*. The percent differences between MCNP and the experimental results, where available, are listed in the column labeled *mcnp from exp*. The last column contains the percent difference between KENO and experimental results. All values of k_{eff} for MCNP were generated by version 4.2 and correspond to the combined average of the collision, absorption, and track length estimators. Also, the two codes were run on different machines; KENO was executed on CTSS (Cray X-MP) while MCNP was executed on UNICOS (Cray Y-MP). This machine difference should not cause any significant discrepancies, because MCNP gives the same results on both machines.

The results for the multigroup MCNP and KENO are listed in Table II. The percent differences between MCNP and KENO, defined above, are located in the second column from the right. The percent differences between MCNP multigroup and experiment, where available, are listed in the last column. As mentioned earlier, the MCNP multigroup cross sections use thirty energy groups whereas KENO uses the sixteen group Hansen-Roach cross-section library.

A comparison of these MCNP results with the results from MCNP version 4x-c can be found in Appendix B.

VI. DISCUSSION OF RESULTS

A. Multigroup Cross-Section Problems

Test problems 18 and 21 demonstrate that MCNP multigroup cross sections are not adequate for certain applications. Since the multigroup errors for these problems clearly exceed the statistical uncertainties of MCNP or KENO, further investigation was necessary.

TABLE I

k_{eff} Values for KENO and MCNP Continuous Energy with the S(α,β) Treatment

	MCNP†		KENO		%DIFFERENCE		
case	k_{cc}	*relative error*	k_{keno}	*relative error*	*mcnp from keno*	*mcnp from exp*	*keno from exp*
1	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
2	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
3	0.9990	0.0011	1.0009	0.0013	-0.2	-0.1	0.1
4	0.9945	0.0028	1.0016	0.0015	-0.7	-0.5	0.2
5	0.9995	0.0027	1.0210	0.0009	-2.1	-0.0	2.1
6	0.7461	0.0010	0.7487	0.0013	-0.3	*	*
7	0.9993	0.0009	0.9984	0.0011	0.1	-0.1	-0.2
8	0.9401	0.0009	0.9430	0.0012	-0.3	*	*
9	2.2905	0.0005	2.2617	0.0004	1.3	*	*
10	0.9979	0.0014	0.9996	0.0011	-0.2	-0.2	-0.0
11	0.9979	0.0014	0.9982	0.0012	-0.0	-0.2	-0.2
12	0.9997	0.0012	1.0055	0.0013	-0.6	-0.0	0.6
13	0.9942	0.0009	1.0026	0.0012	-0.8	-0.6	0.3
14	0.9991	0.0009	1.0011	0.0010	-0.2	-0.1	0.1
15	1.0016	0.0011	1.0012	0.0020	0.0	0.2	0.1
16	0.9902	0.0009	0.9936	0.0007	-0.3	*	*
17	1.0029	0.0014	0.9783	0.0023	2.5	*	*
18	1.0302	0.0013	1.0088	0.0015	2.1	*	*
19	0.9997	0.0012	1.0044	0.0013	-0.5	-0.0	0.4
20	0.9960	0.0012	0.9791	0.0014	1.7	-0.4	-2.1
21	0.9962	0.0008	1.0012	0.0009	-0.5	-0.4	0.1
22	0.9992	0.0009	0.9996	0.0011	-0.0	-0.1	-0.0
23	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
24	0.9994	0.0008	0.9999	0.0011	-0.1	-0.1	-0.0
25	1.0004	0.0008	0.9987	0.0011	0.2	0.0	-0.1

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

TABLE II

k_{eff} Values for KENO and MCNP Multigroup

	MCNP†		KENO		%DIFFERENCE	
case	k_{mg}	*relative error*	k_{keno}	*relative error*	*mcnp from keno*	*mcnp from exp*
1	0.9971	0.0009	0.9996	0.0011	-0.3	-0.3
2	0.9960	0.0009	0.9996	0.0011	-0.4	-0.4
3	1.0199	0.0010	1.0009	0.0013	1.9	2.0
4	1.0166	0.0027	1.0016	0.0015	1.5	1.7
5	1.0187	0.0030	1.0210	0.0009	-0.2	1.9
6	0.7426	0.0008	0.7487	0.0013	-0.8	*
7	0.9966	0.0008	0.9984	0.0011	-0.2	-0.3
8	0.9357	0.0008	0.9430	0.0012	-0.8	*
9	2.2955	0.0005	2.2617	0.0004	1.5	*
10	0.9976	0.0014	0.9996	0.0011	-0.2	-0.2
11	0.9976	0.0014	0.9982	0.0012	-0.1	-0.2
12	1.0013	0.0012	1.0055	0.0013	-0.4	0.1
13	0.9918	0.0009	1.0026	0.0012	-1.1	-0.8
14	0.9944	0.0009	1.0011	0.0010	-0.7	-0.6
15	1.0294	0.0010	1.0012	0.0020	2.8	2.9
16	1.0132	0.0010	0.9936	0.0007	2.0	*
17	0.9873	0.0016	0.9783	0.0023	0.9	*
18	1.0670	0.0011	1.0088	0.0015	5.8	*
19	1.0013	0.0012	1.0044	0.0013	-0.3	0.1
20	1.0013	0.0015	0.9791	0.0014	2.3	0.1
21	0.8362	0.0011	1.0012	0.0009	-16.5	-16.4
22	0.9961	0.0008	0.9996	0.0011	-0.4	-0.4
23	0.9960	0.0009	0.9996	0.0011	-0.4	-0.4
24	0.9970	0.0008	0.9999	0.0011	-0.3	-0.3
25	0.9976	0.0008	0.9987	0.0011	-0.1	-0.2

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

Especially troublesome is problem 21, for which the MCNP multigroup result underestimates the experimental value of k_{eff} (1.0) by 16%. Problem 21 consists of a spherical aluminum tank partially filled with uranyl fluoride of low U^{235} enrichment (4.89%). With such a low enrichment, the "infinitely dilute absorber" approximation, used to process the MCNP multigroup library, incorrectly calculates the U^{238} resonance integral. This approximation always overestimates the resonance integral and thus the absorption in U^{238}. Resonance self-shielding in U^{235} has less effect on k_{eff} (U^{235} has competing fission and capture resonances).[14] Therefore, the error in the multigroup result should decrease as enrichment increases. By varying the enrichment in aqueous solutions of uranyl fluoride and uranyl nitrate, this decrease was demonstrated to be so.

As an additional test, the σ_p corrected cross sections called for in KENO input # 21 were replaced with "infinitely dilute" values ($\sigma_p = \infty$), and KENO was rerun to produce $k_{eff} = 0.8503$, which agrees well with the MCNP multigroup value of 0.8374. Such a significant change in the KENO result emphasizes the importance of resonance self-shielding in this problem.

The error in problem 18 is not as pronounced as that in problem 21, since it is both smaller in magnitude and positive (overestimate of k_{eff}). Nevertheless, it is large enough to cause concern. Since the percent differences for both multigroup and continuous energy without $S(\alpha,\beta)$ scattering are comparable, the majority of the error appears to be due to the lack of $S(\alpha,\beta)$ thermal scattering with the multigroup cross sections (see Tables II and III). Like problem 21, the fissile material is in solution, but unlike 21, it is highly enriched in U^{235}. A fissile solution enhances resonance effects since it has a softer spectrum. In U^{235}, however, the infinite dilution approximation overestimates the fission resonance integral, and thus k_{eff} is overestimated. Results from similar problems imply that this is a minor effect.

Lack of $S(\alpha,\beta)$ thermal scattering also causes difficulty in problem 15, as shown in Table III. The 3% multigroup error is nearly identical to the error in the continuous energy run without $S(\alpha,\beta)$. The effects are particularly large in this problem because of the large volume of water. MCNP and KENO are in very close agreement when the water is removed.

Multigroup cross sections in MCNP must be used with care. Whenever possible, the continuous energy cross sections should be employed. The test cases included in this benchmark study indicate that the MCNP 30 group cross sections are unreliable in criticality calculations involving solutions with low U^{235} enrichment. Moreover,

TABLE III

k_{eff} Values for KENO and MCNP Continuous Energy with and without the S(α, β) Treatment

	MCNP† with S(α, β)		MCNP† no S(α, β)		%DIFFERENCE			
case	$k_{\alpha\beta}$	*relative error*	k_{ce}	*relative error*	with S(α, β) *from keno*	no S(α, β) *from keno*	with S(α, β) *from exp*	no S(α, β) *from exp*
3	0.9990	0.0011	1.0168	0.0011	-0.2	1.6	-0.1	1.7
4	0.9945	0.0028	1.0181	0.0025	-0.7	1.6	-0.5	1.8
5	0.9995	0.0027	1.0156	0.0028	-2.1	-0.3	-0.0	1.6
12	0.9997	0.0012	1.0010	0.0013	-0.6	-0.4	-0.0	0.1
15	1.0016	0.0011	1.0189	0.0012	0.0	1.8	0.2	1.9
16	0.9902	0.0009	0.9953	0.0009	-0.3	0.2	*	*
17	1.0029	0.0014	0.9830	0.0015	2.5	0.5	*	*
18	1.0302	0.0013	1.0479	0.0012	2.1	3.9	*	*
19	0.9997	0.0012	1.0010	0.0013	-0.5	-0.3	-0.0	0.1
20	0.9960	0.0012	0.9932	0.0016	1.7	1.4	-0.4	-0.7
21	0.9962	0.0008	0.9811	0.0010	-0.5	-2.0	-0.4	-1.9

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

$S(\alpha,\beta)$ treatment is unavailable with multigroup cross sections. Thus, continuous energy cross sections with the thermal scattering treatment should be used for highly moderated systems.

B. Effects of $S(\alpha,\beta)$ Card

The MCNP results for continuous energy, with and without the $S(\alpha,\beta)$ thermal treatment, and the percent differences from experiment are given in Table III. Only the problems that were affected by $S(\alpha,\beta)$ scattering are listed. The first set of MCNP results was generated with the $S(\alpha,\beta)$ scattering treatment, whereas the second set was generated without. The percent differences between the MCNP results and the KENO results, $100 \times (k_{MCNP} - k_{KENO})/k_{KENO}$, are also listed. All values of k_{eff} for MCNP were generated with version 4.2, and correspond to the combined average of the track length, absorption, and collision estimators.

The MCNP results with the $S(\alpha,\beta)$ thermal treatment, where applicable, are considered to be the most accurate because they account for molecular scattering. Problems with fissile material in metal form, for which $S(\alpha,\beta)$ treatment is unimportant, are not listed in Table III. The results without the $S(\alpha,\beta)$ treatment are reported to demonstrate its importance in applications in which there is thermal scattering with light nuclei.

By accounting for molecular scattering in MCNP the results for five of the problems are in better agreement with KENO, whereas the results for six of the problems are not. Of these six, problems 12, 16, 19, and 20 varied very little, and problems 5 and 17 became much closer to unity (problem 17 is believed to be a critical experiment). In fact, the last two columns in Table III demonstrate that $S(\alpha,\beta)$ thermal scattering improves the results with respect to the available experimental data. Therefore, the $S(\alpha,\beta)$ treatment should be employed when applicable.

It should be noted that $S(\alpha,\beta)$ treatment for paraffin is not presently available in MCNP. Therefore, the $S(\alpha,\beta)$ treatment for polyethylene was used for paraffin. Although the use of polyethylene is questionable, it did improve the MCNP results relative to both KENO and experimental values (see problems 3, 4, 5, and 18).

C. Version 4x-c vs. Version 4.2

Appendix B presents k_{eff} values produced by MCNP version 4x-c, the preliminary version of MCNP4A at the time of publication. Although version 4.2, the

most recent public version, was used for the benchmark study, it was thought that the sample problems should also be run using the latest LANL version. Some 4x-c runs show small differences (within statistical uncertainty), but most track the 4.2 results exactly.

D. Experimental Results

Table I, above, contains two columns that compare the MCNP and KENO results to the experimental results. As noted in this table, the experimental results were not available for all the sample problems. The experimental results used in Table I are all for problems that were exactly critical.

The experimental results that were not found correspond to sample problems 6, 9, 16, and 17. The results for problem 18 are located in Ref. 21, but it appears to be incorrectly modeled in the KENO input. The original experiment does not contain a 30.48 cm slab of water on the negative z face. Therefore, a percent difference for that problem is not included. The result for problem 8, which is located in Ref. 15, simply states that the experiment is subcritical. Although the experimental results for problem 17 have not been reviewed, it appears to represent a critical experiment. The result of problem 1 implies that problem 6 is subcritical; however, the experimental value of k_{eff} is unknown. The experimental results for the remaining two, problems 9 and 16, most likely do not exist since they involve infinite geometric features.

E. k_{eff} Plots

The following pages contain selected plots of k_{eff} as a function of generation or cycle; these are called **KCODE** plots in MCNP. The abcissa represents the number of cycles over which k_{eff} has been averaged (i.e., the number after the initial "settling cycles"); for these plots, 20 cycles were skipped before averaging, so the actual cycle is the x-coordinate + 20. On the vertical axis is the cumulative average of the track length estimate of k_{eff} using continuous energy cross sections (with the S(α, β) treatment, where applicable). Note that the values appearing in Tables I-III are combined averages of collision, absorption, and track length estimates; MCNP does not plot the combined average. In general, the collision, absorption, and track length estimators are in close agreement; this agreement was

true for all 25 sample problems. The plots that follow, Figs. 12 through 21, illustrate that sufficient cycles were used to allow k_{eff} to converge.

VII. CONCLUSIONS

The 25 sample problems that make up the KENO criticality safety benchmark set have been run with MCNP, versions 4.2 and 4x-c. These criticality problems were chosen as benchmarks because they represent a relatively wide variety of criticality problems and because they were originally used to validate the KENO Monte Carlo criticality code. The comparison of the MCNP results for both continuous energy and multigroup cross sections indicates that the continuous energy cross sections are more accurate than the standard MCNP multigroup set. With the continuous energy cross sections, MCNP successfully predicts the experimental results, in some cases better than KENO, within the expected data and statistical uncertainties. This benchmark study demonstrates that MCNP can accurately model a variety of criticality problems.

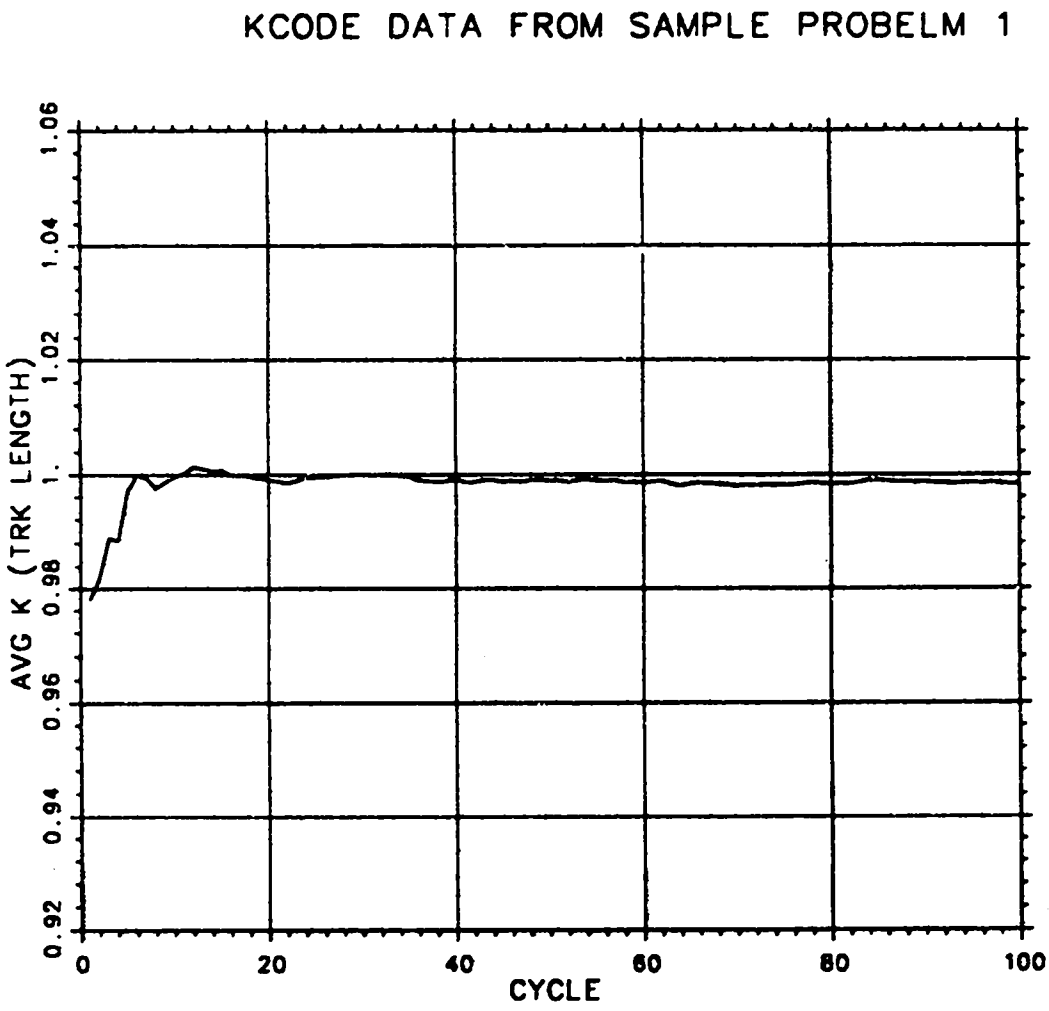


Fig. 12. Cumulative Average k_{eff} vs Cycle - Problem 1. Problem 1 is an array of 8 U-metal cylinders

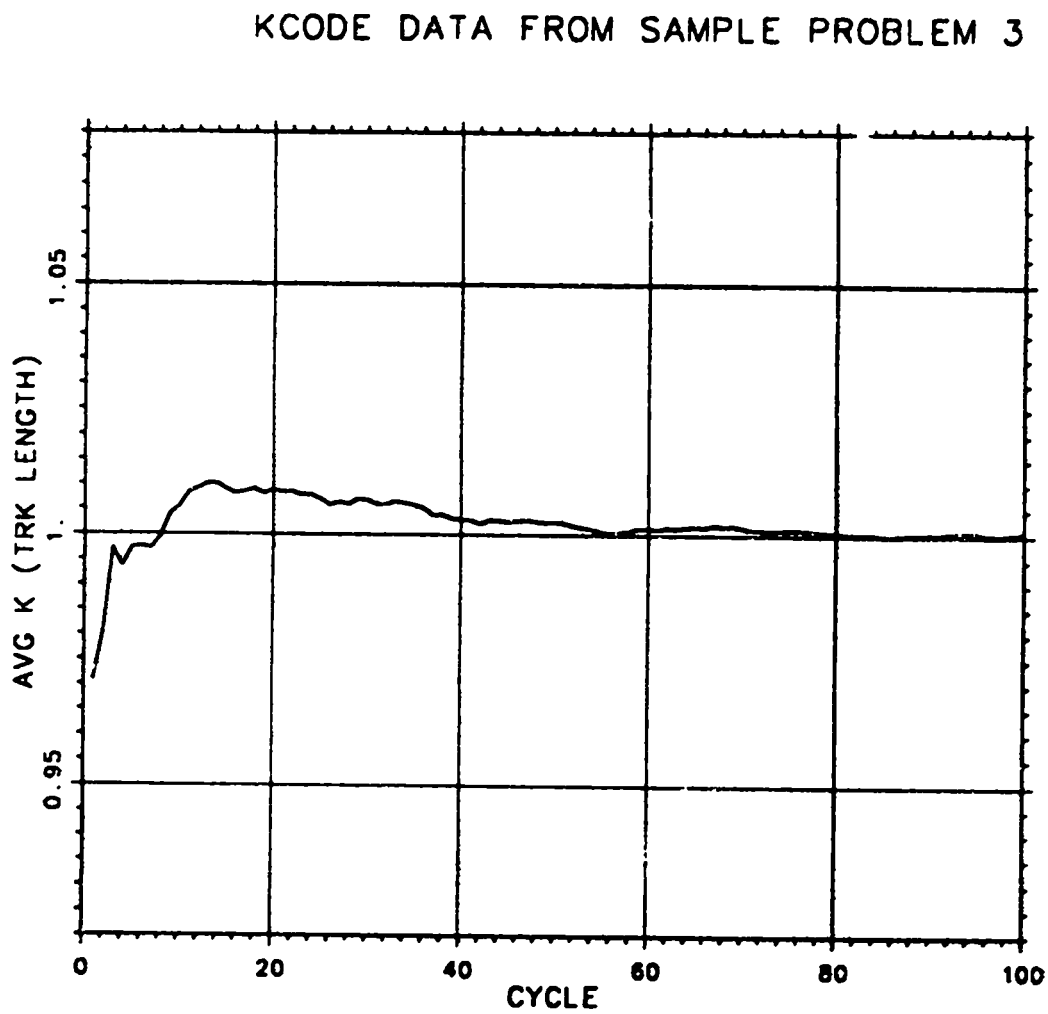


Fig. 13. Cumulative Average k_{eff} vs Cycle - Problem 3. Problem 3 is an array of 8 U-metal cylinders with paraffin reflectors

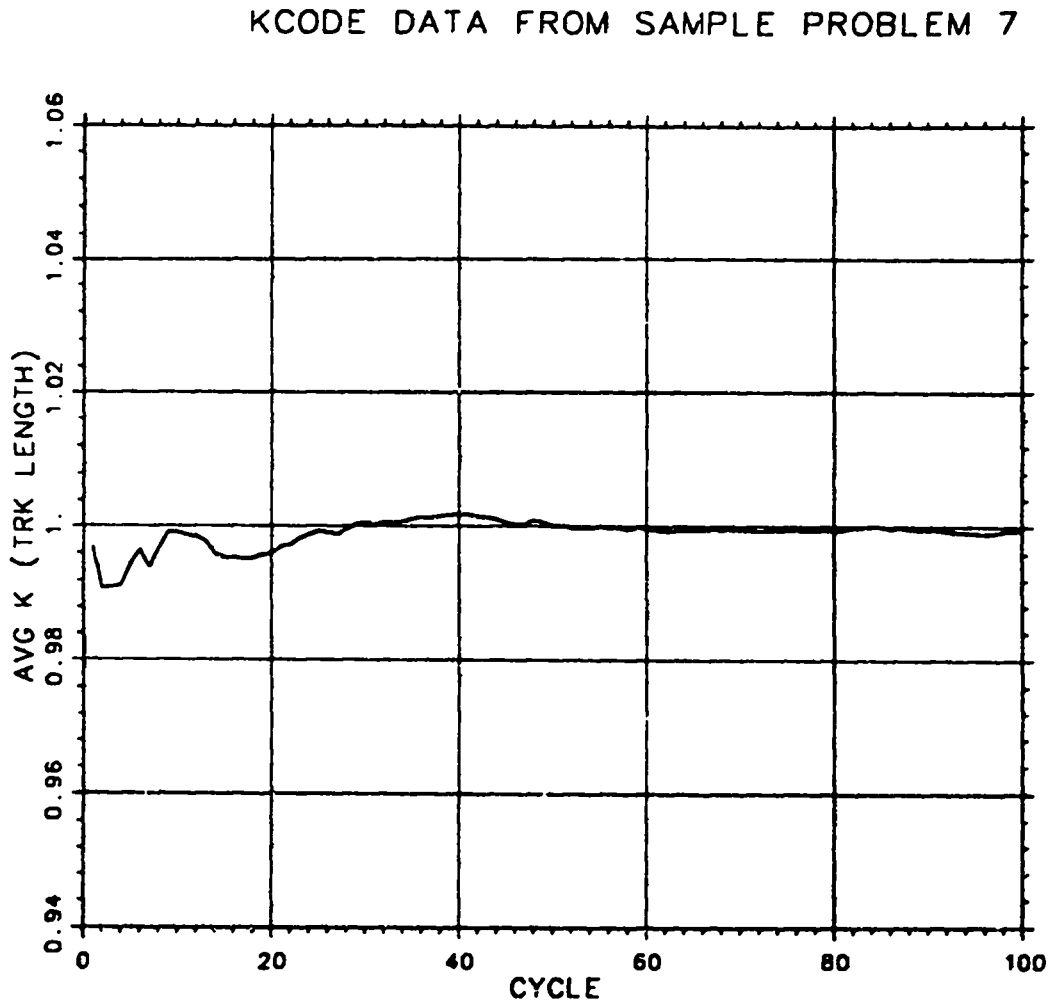


Fig. 14. Cumulative Average k_{eff} vs Cycle - Problem 7. Problem 7 is a single U-metal cylinder inside a cube with 3 perfectly reflecting surfaces

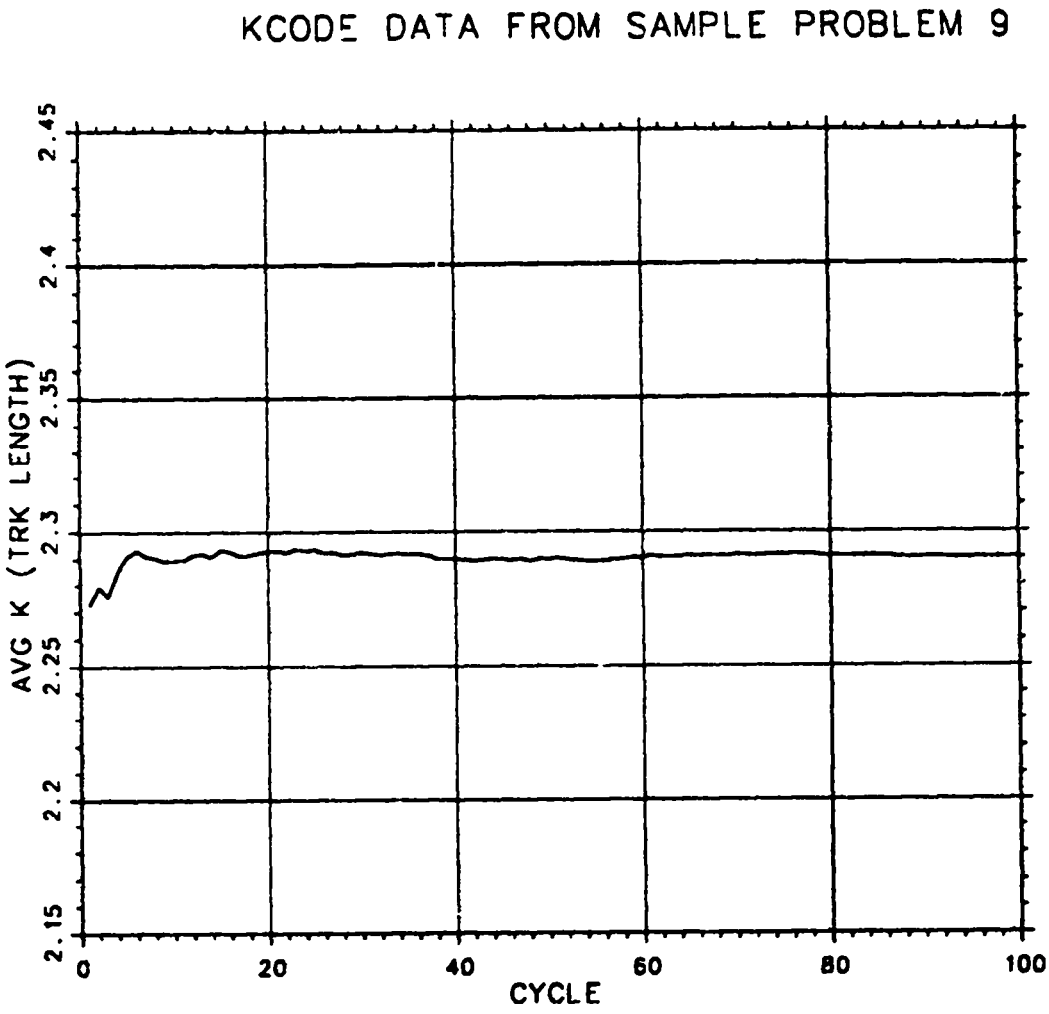


Fig. 15. Cumulative Average k_{eff} vs Cycle - Problem 9. Problem 9 models an infinite array of U-metal cylinders

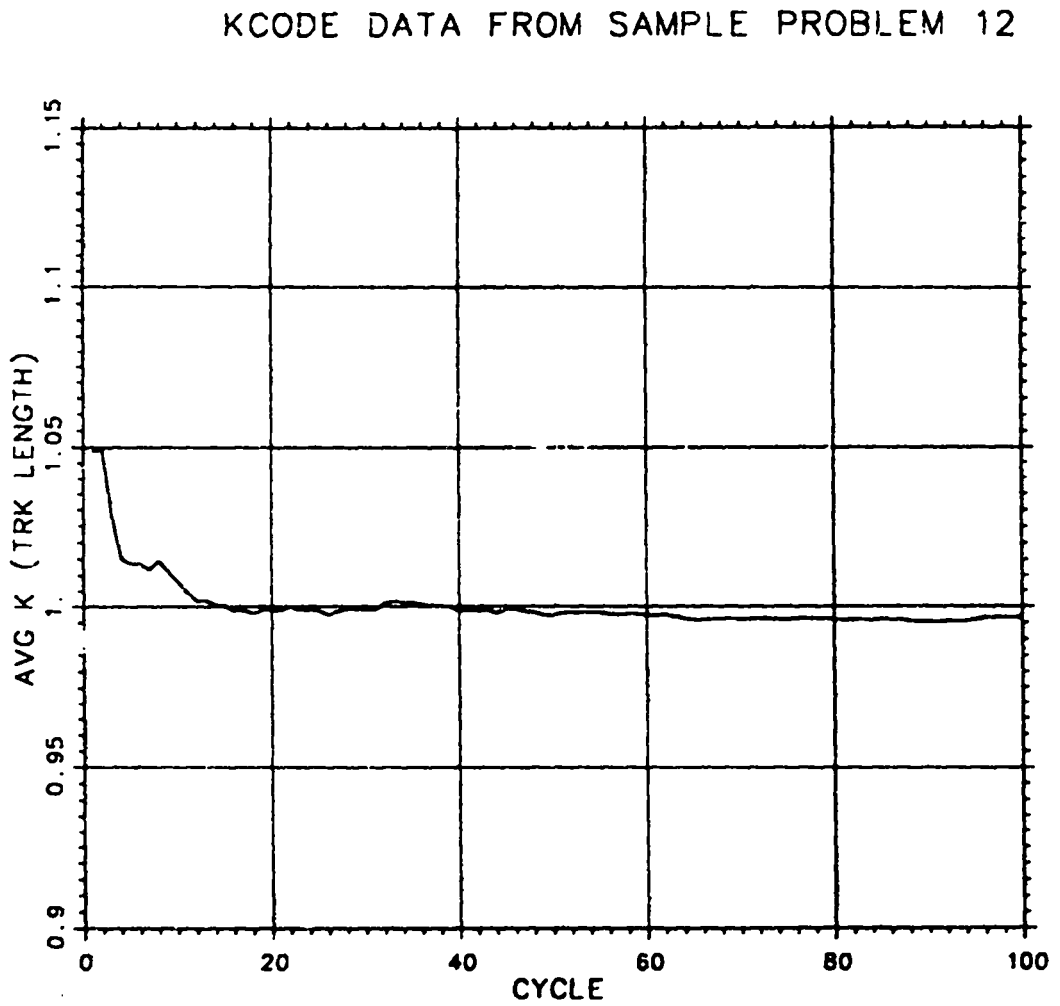


Fig. 16 Cumulative Average k_{eff} vs Cycle - Problem 12. Problem 12 consists of 4 U-metal cylinders and 4 containers of uranyl nitrate

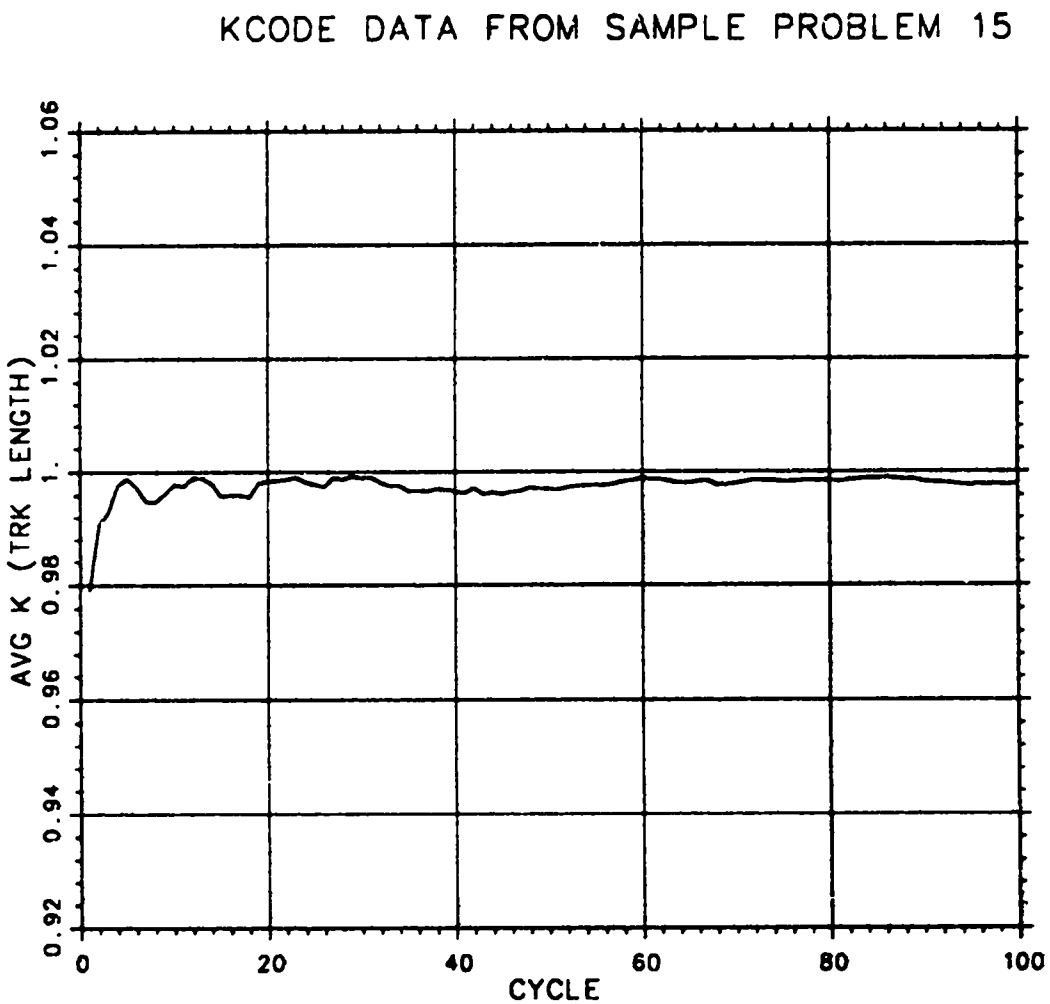


Fig. 17. Cumulative Average k_{eff} vs Cycle - Problem 15. Problem 15 is a U-metal sphere in water

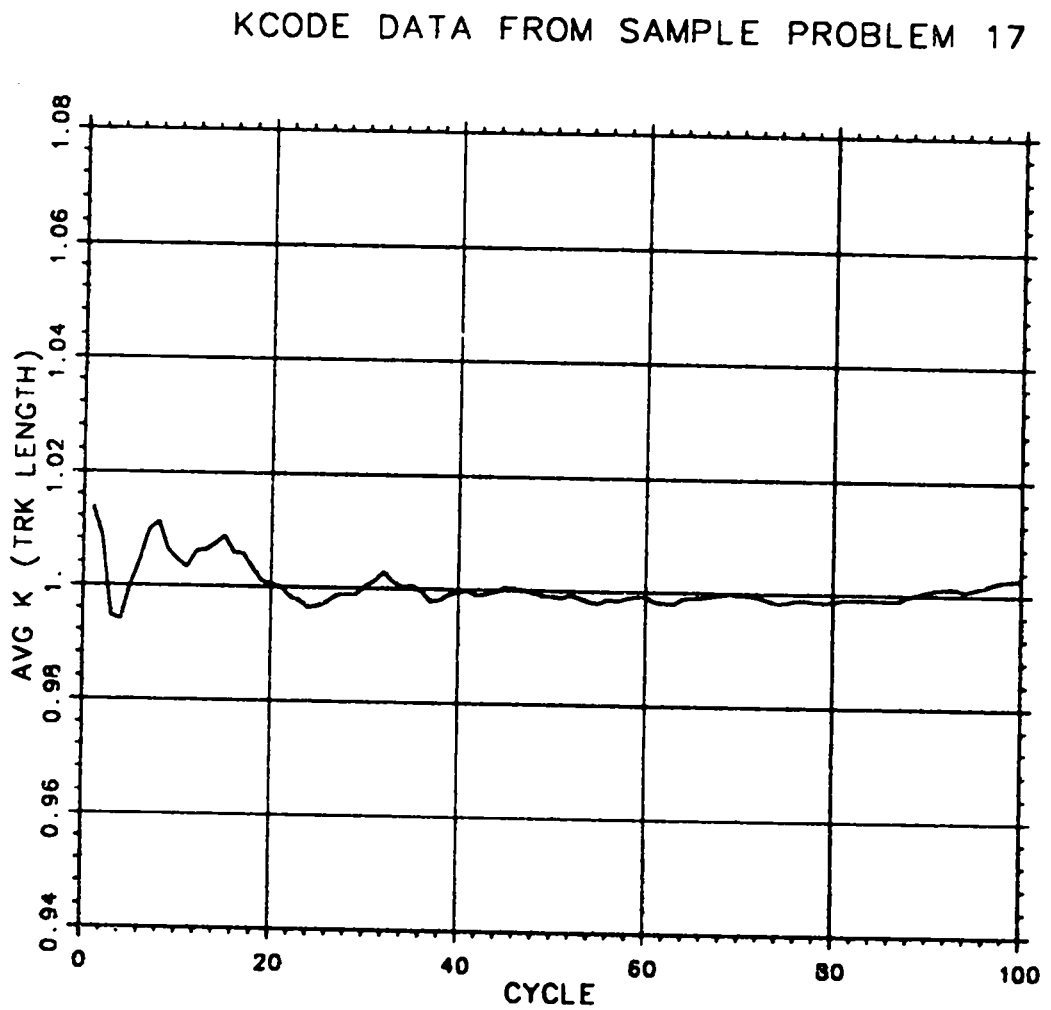
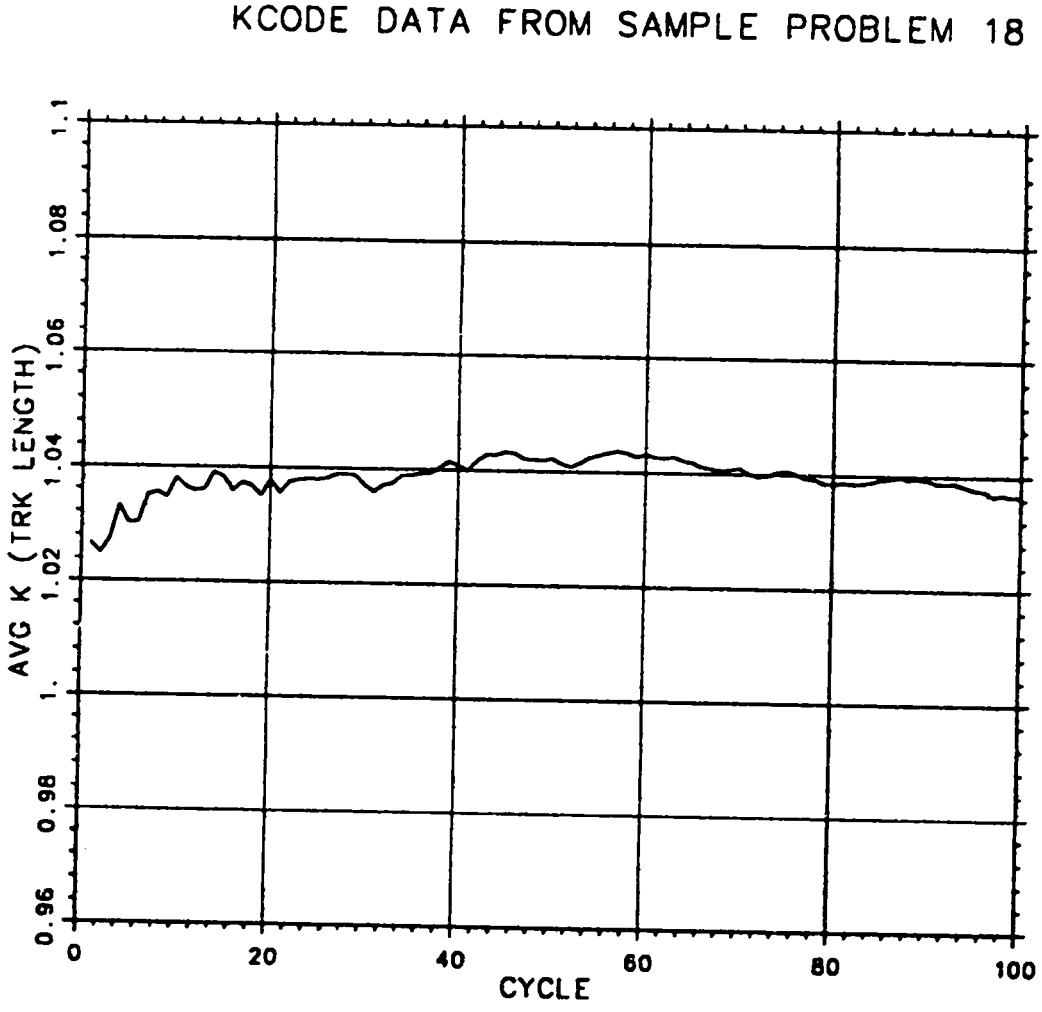


Fig. 18. Cumulative Average k_{eff} vs Cycle - Problem 17. Problem 17 is a spherical tank of uranyl fluoride solution



Fig, 19. Cumulative Average k_{eff} vs Cycle - Problem 18. Problem 18 consists of 27 containers of uranyl nitrate solution with paraffin and water reflectors

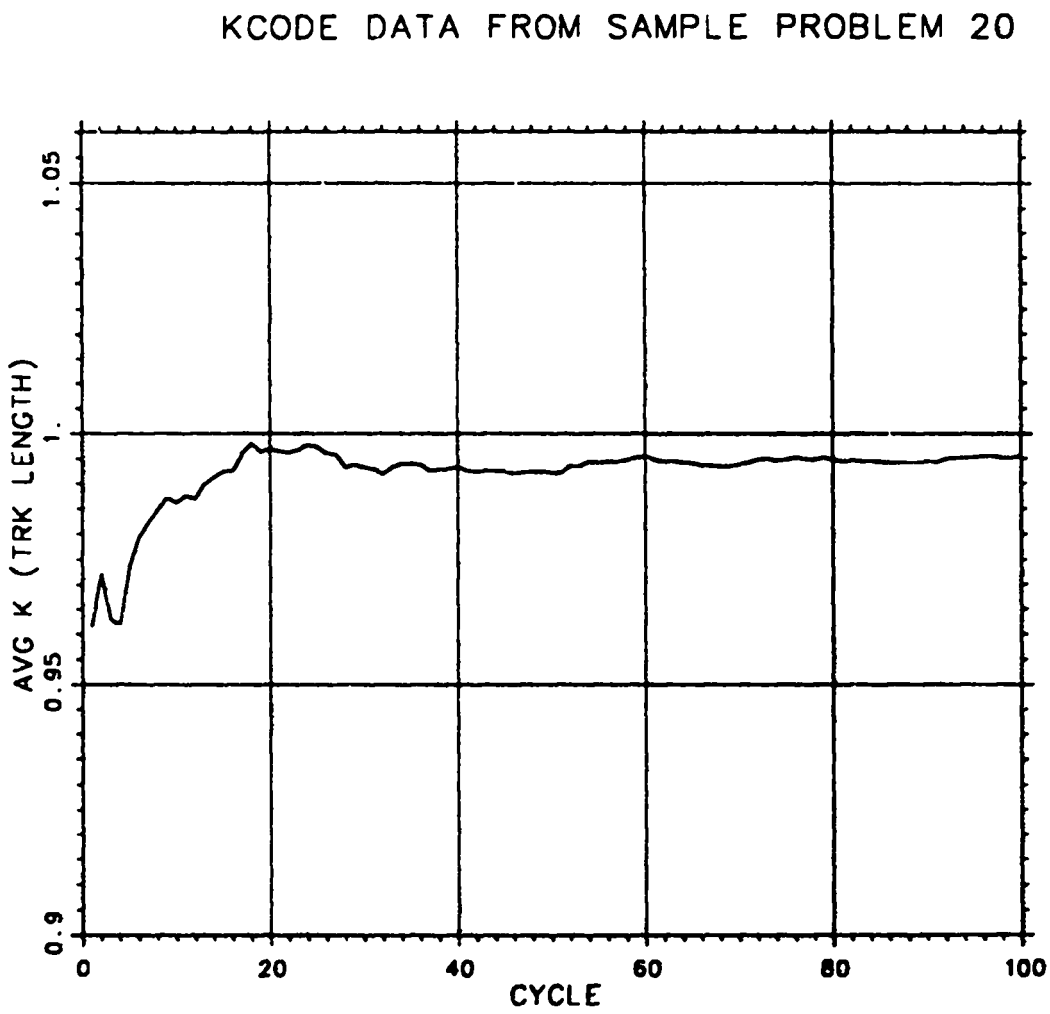


Fig. 20. Cumulative Average k_{eff} vs Cycle - Problem 20. Problem 20 comprises 7 cylinders of uranyl nitrate in a triangular pitched array

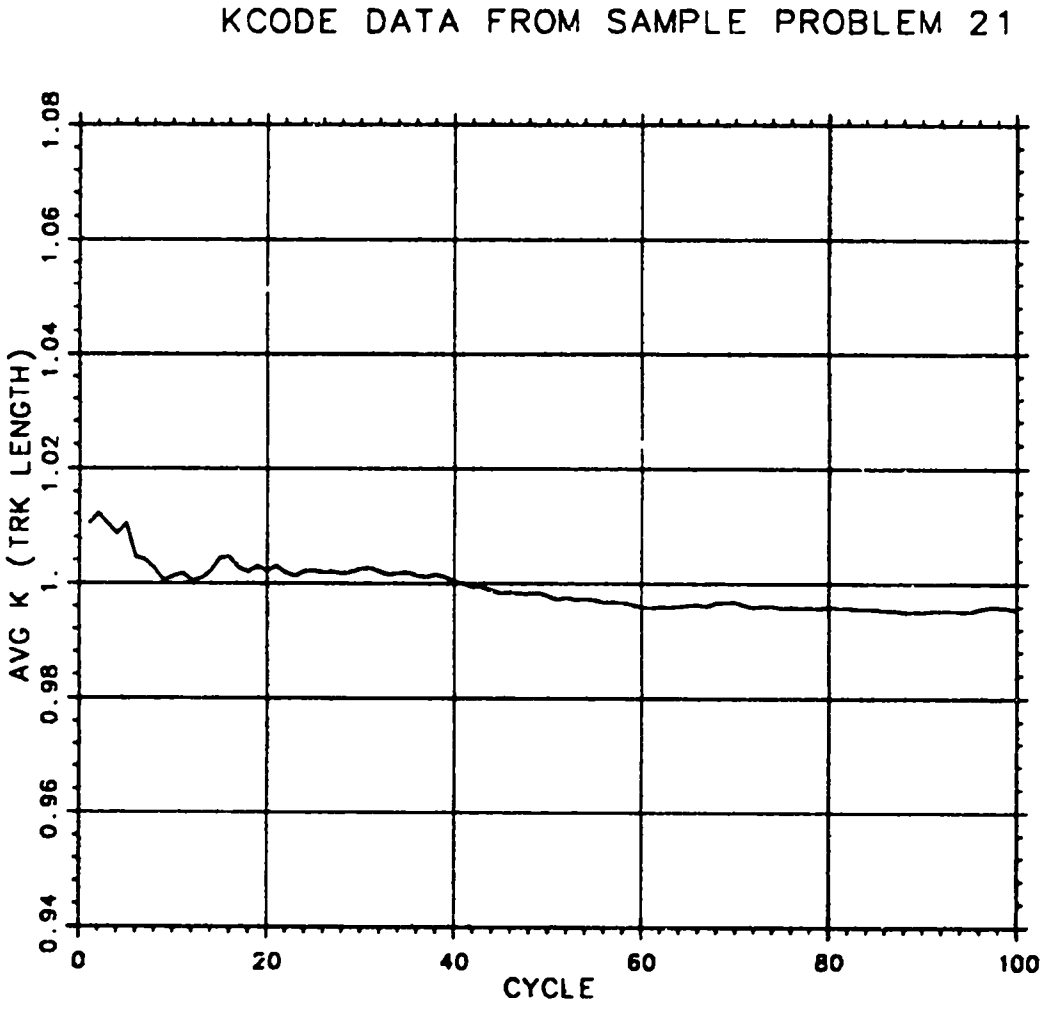


Fig. 21. Cumulative Average k_{eff} vs Cycle - Problem 21. Problem 21 is a partially filled spherical tank of uranyl fluoride

REFERENCES

1. J. F. Briesmeister, Editor, "MCNP - A General Monte Carlo Code for Neutron and Photon Transport, Version 3A," Los Alamos National Laboratory report LA-7396-M, Rev. 2 (1986).

2. D. J. Whalen, D. E. Hollowell, and J. S. Hendricks, "MCNP: Photon Benchmark Problems," Los Alamos National Laboratory report LA-12196 (1991).

3. D. J. Whalen, D. A. Cardon, J. L. Uhle, and J. S. Hendricks, "MCNP: Neutron Benchmark Problems," Los Alamos National Laboratory report LA-12212 (1991).

4. John S. Hendricks, Daniel J. Whalen, David A. Cardon, Jennifer L. Uhle, "MCNP Neutron Benchmarks," *Trans. Am. Nuc. Soc.*, **65**, 262 (1992).

5. Daniel J. Whalen, David E. Hollowell, and J.S. Hendricks, "Monte Carlo Photon Benchmark Problems," *Proceedings of the International Topical Meeting on Advances in Mathematics, Computations, and Reactor Physics, (American Nuclear Society)*, 5, 30.1 5-1 (April 1991).

6. S. Sitaraman, "MCNP: Light Water Reactor Critical Benchmarks," GE Nuclear Energy report, NEDO-32028 (March 1992).

7. Thomas P. Wilcox, Jr. and Edward M. Lent, "COG - A Particle Transport Code Designed to Solve the Boltzmann Equation for Deep-Penetration (Shielding) Problems," Volume 4, "Benchmark Problems," Lawrence Livermore National Laboratory report M-221-4 (December 2, 1988).

8. L. M. Petrie and N. F. Landers, "KENO V.a An Improved Monte Carlo Criticality Program with Supergrouping," Section F11, NUREG/CR-0200, Vol. 2, U.S. Nuclear Regulatory Commission (December 1984).

9. W. C. Jordon, N. F. Landers, and L. M. Petrie, "Validation of KENO V.a Comparison with Critical Experiments," ORNL/CSD/TM-238, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory (December 1986).

10. D. W. Nigg, C. A. Atkinson, J. B. Briggs, and J. T. Taylor, "A PC-Based Version of KENO V.a," *Trans. Am. Nucl. Soc.*, **61**, 188 (June 1990).

11. J. F. Briesmeister, "MCNP3B Newsletter," X-6:JFB-88-292, Los Alamos National Laboratory (July 1988).

12. Judi Briesmeister and John Hendricks, "MCNP4 Newsletter," X-6:JFB-91-177, Los Alamos National Laboratory (April 1991).

13. R. E. Seamon, "Hanson-Roach 16-Group Cross Sections for MCNP," X-6:RES-90-223, Los Alamos National Laboratory (April 1990).

14. R. D. Busch and R. D. O'Dell, "Validity of Hansen-Roach Cross Sections in Low-Enriched Uranium Systems," *Proc. of the Int'l Conf. on Nucl. Criticality Safety*, Sept. 9-13, 1991, Oxford, United Kingdom, Vol. I, pp IV-45 through IV-52.

15. J. T. Thomas, "Critical Three-Dimensional Arrays of Neutron Interacting Units, Part II - U(93.2) Metal," ORNL-TM-868, Union Carbide Corporation, Nuclear Division, Oak Ridge National Laboratory (1964).

16. D. C. Irving and J. T. Mihalczo, "Monte Carlo Calculations for Enriched Uranium Metal Assemblies," *Trans. Am. Nucl. Soc.*, **4**, 302 (1961).

17. C. C. Byers, J. J. Koelling, G. E. Hansen, D. R. Smith, and H. R. Dyer, "Critical Measurements of a Water-Reflected Enriched Uranium Sphere," *Trans. Am. Nucl. Soc.*, **27**, 412 (1977).

18. D. G. Collins, "Normalization of Forward and Adjoint MCNP Runs," X-6:DGC-87-187, Los Alamos National Laboratory (March 1987).

19. J. R. Knight, "Validation of the Monte Carlo Criticality Program KENO V.a for Highly Enriched Uranium Systems," ORNL/CSD/TM-221, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory (1984).

20. J. T. Thomas, "Critical Three-Dimensional Arrays of Neutron Interacting Units," ORNL-TM-719, Union Carbide Corporation, Nuclear Division, Oak Ridge National Laboratory (1963).

21. E. B. Johnson and D. F. Cronin, "Critical Dimensions of Aqueous UO_2F_2 Solutions Containing 4.9% Uranium-235-Enriched Uranium," *Trans. Am. Nucl. Soc.*, **17**, 301 (1964).

APPENDIX A:

MCNP INPUT FILES

```
e5mt.1:  converted from keno file k.1; continuous energy; endf/b-5
c    8 bare cylinders of U-metal
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1 u=-1
2     0             #1                      imp:n=1 u=1
3     0             -1  2 -3  4 -5  6       imp:n=1 u=2 lat=1
      fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4     0             -11 12 -13 14 -15 16    imp:n=1      fill=2
5     0              #4                     imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -13.74
3     py  0.0
4     py -13.74
5     pz  0.0
6     pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225
9     pz  -11.8875
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    px  13.7399
12    px -13.7399
13    py  13.7399
14    py -13.7399
15    pz  13.0099
16    pz -13.0099
c
c    Data Cards
c
mode  n                                     $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c 0.932631                    $ U-235
      92238.50c 0.055328                    $ U-238
      92234.50c 0.010049                    $ U-234
      92236.50c 0.001992                    $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                    $ ave flux in cell 1
```

A1. Input File for Problem 1

```
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    UNIFORM VOLUME SOURCE IN FISSILE CELLS
c    uniformly distributed volume source in each cylinder
c    You have to set up distributions from which to choose:
c    cell, energy, radius(from axis), and z displacement (from pos).
c    Since the cylinder is in a repeated structure, but always
c    called cell 1, you must specify the path of cells which uniquely
c    defines the cylinder you want.    The path begins with the outermost
c    cell and works down.    When cell 3 is reached, the lattice position
c    must also be given.
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=0 0 1
c
si1   1 4:3(1 1 0):1                $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                $ etc.
        4:3(0 1 0):1                $ this ordering chosen to match
        4:3(0 0 0):1                $   sampling in e5ce.2
        4:3(1 1 1):1                $
        4:3(1 0 1):1                $
        4:3(0 1 1):1                $
        4:3(0 0 1):1                $
sp1     1 1 1 1 1 1 1 1             $ equal probability for all paths above
c
sp2   -3                            $ Watt fission spectrum
c
si3       0.0  5.748                $ radial distribution
sp3  -21  1                         $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825            $ axial distribution
sp4  -21  0                         $ p(x) = const
c
prdmp  j j 1 j                      $ write mctal file
c
print                               $ full output
```

A1. Input File for Problem 1 (continued)

```
e5mt.2:  converted from keno file k.2; continuous energy; endf/b-5
c    8 bare U-metal cylinders
c    explicit geometry specification
c
c    Cell Cards
c
1     1 4.80368e-2  -1  5 -6                    imp:n=1
2     1 4.80368e-2  -2  5 -6                    imp:n=1
3     1 4.80368e-2  -3  5 -6                    imp:n=1
4     1 4.80368e-2  -4  5 -6                    imp:n=1
5     1 4.80368e-2  -1  7 -8                    imp:n=1
6     1 4.80368e-2  -2  7 -8                    imp:n=1
7     1 4.80368e-2  -3  7 -8                    imp:n=1
8     1 4.80368e-2  -4  7 -8                    imp:n=1
9     0             #1 #2 #3 #4 #5 #6 #7 #8 #10  imp:n=1
10    0             -11:  12:-13:  14:-15:  16      imp:n=0
c
c    Surface Cards
c
c    cylinder
1     c/z  6.87  6.87  5.748
2     c/z  6.87 -6.87  5.748
3     c/z -6.87  6.87  5.748
4     c/z -6.87 -6.87  5.748
5     pz  -11.8875
6     pz  -1.1225
7     pz   1.1225
8     pz   11.8875
c    parallelpiped
11    px -13.74
12    px  13.74
13    py -13.74
14    py  13.74
15    pz -13.01
16    pz  13.01
c
c    Data Cards
c
mode  n                                 $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c 0.932631                $ U-235
      92238.50c 0.055328                $ U-238
      92234.50c 0.010049                $ U-234
      92236.50c 0.001992                $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0     1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5
       1.0e-4 5.5e-4 3.0e-3 1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                $ ave flux in cell 1
```

A2. Input File for Problem 2

```
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    uniform volume source in each cell
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=fcel d5 axs=0 0 1
c
si1   1 1 2 3 4 5 6 7 8                $ cells
sp1     1 1 1 1 1 1 1 1                $ equal probability for all cells above
c
sp2   -3                               $ Watt fission spectrum
c
si3       0.0  5.748                   $ radial distribution
sp3  -21  1                            $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825               $ axial distribution
sp4  -21  0                            $ p(x) = const
c
ds5   t   1  6.87  6.87 -6.505        $ if cel=1, then pos=6.87 6.87 -6.595
          2  6.87 -6.87 -6.505        $ etc.
          3 -6.87  6.87 -6.505        $
          4 -6.87 -6.87 -6.505        $
          5  6.87  6.87  6.505        $
          6  6.87 -6.87  6.505        $
          7 -6.87  6.87  6.505        $
          8 -6.87 -6.87  6.505        $
c
prdmp  j j 1 j                         $ write mctal file
c
print                                  $ full output
```

A2. Input File for Problem 2 (continued)

```
e5mt.3:  converted from keno file k.3; continuous energy; endf/b-5
c    universes of paraffin with constant importance surrounding core
c
c    Cell Cards
c
c    lattice with cylinders of U fuel
1     1 0.0480368  -7 -8  9                imp:n=1   u=1        $ U cylinder
2     0            81                     imp:n=1   u=1        $ outside
3     0            -1  2 -3  4 -5  6      imp:n=1   u=2 lat=1 $ 2x2x2 lattice
        fill=0:1 0:1 0:1   1 1  1 1  1 1   1 1                 $ filling u's
4     2 0.122282   83                     imp:n=1   u=2        $ outside
c
c    concentric boxes of constant importance
10    0            -11 12 -13 14 -15 16   imp:n=1    u=10 fill=2
11    2 0.122282   810                    imp:n=1    u=10
20    0            -21 22 -23 24 -25 26   imp:n=1    u=20 fill=10
21    2 0.122282   820                    imp:n=1    u=20
30    0            -31 32 -33 34 -35 36   imp:n=1    u=30 fill=20
31    2 0.122282   830                    imp:n=1    u=30
40    0            -41 42 -43 44 -45 46   imp:n=1    u=40 fill=30
41    2 0.122282   840                    imp:n=1    u=40
50    0            -51 52 -53 54 -55 56   imp:n=1    u=50 fill=40
51    2 0.122282   850                    imp:n=1    u=50
60    0            -61 62 -63 64 -65 66   imp:n=1         fill=50
61    0            860                    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -23.48
3     py  0.0
4     py -23.48
5     pz  0.0
6     pz -22.75
c    cylinder
7     c/z -11.74 -11.74 5.748
8     pz  -5.9925
9     pz  -16.7575
c    parallelpiped (dimensions shrunk by 0.001 to avoid fill problems)
11    px  23.479
12    px -23.479
13    py  23.479
14    py -23.479
15    pz  22.749
16    pz -22.749
c    parallelpiped
21    px  26.48
22    px -26.48
23    py  26.48
24    py -26.48
25    pz  25.75
26    pz -25.75
c    parallelpiped
31    px  29.48
32    px -29.48
33    py  29.48
34    py -29.48
35    pz  28.75
36    pz -28.75
c    parallelpiped
41    px  32.48
42    px -32.48
43    py  32.48
44    py -32.48
45    pz  31.75
46    pz -31.75
```

A3. Input File for Problem 3

```
c    parallelpiped
51    px  35.48
52    px -35.48
53    py  35.48
54    py -35.48
55    pz  34.75
56    pz -34.75
c    parallelpiped
61    px  38.72
62    px -38.72
63    py  38.72
64    py -38.72
65    pz  37.99
66    pz -37.99
c
c    Data Cards
c
mode  n                        $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c 0.932631        $ U-235
     92238.50c 0.055328        $ U-238
     92234.50c 0.010049        $ U-234
     92236.50c 0.001992        $ U-236
c    paraffin
m2    1001.50c 0.675324        $ H ( in paraffin )
      6000.50c 0.324676        $ C ( in paraffin )
c
c    S(alpha, beta)
mt2   poly.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5
      1.0e-4 5.5e-4 3.0e-3 1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1     $ tally the ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-11.74 -11.74 -11.375  axs=0 0 1
c
si1   l 60:50:40:30:20:10:3(0 0 0):1 $ path:  /cell60/cell50/.../cell1
        60:50:40:30:20:10:3(1 0 0):1 $ path to cell 1 thru lattice(1,0,0)
        60:50:40:30:20:10:3(1 1 0):1 $ path to cell 1 thru lattice(1,1,0)
        60:50:40:30:20:10:3(0 1 0):1 $ etc.
        60:50:40:30:20:10:3(0 0 1):1 $
        60:50:40:30:20:10:3(1 0 1):1 $
        60:50:40:30:20:10:3(0 1 1):1 $
        60:50:40:30:20:10:3(1 1 1):1 $
sp1     1 1 1 1 1 1 1 1              $ equal probability for all paths above
c
sp2   -3                             $ Watt fission spectrum
c
si3       0.0  5.748                 $ radial distribution
sp3  -21  1                          $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825             $ axial distribution
sp4  -21  0                          $ p(x) = const
c
prdmp  j j 1 j                       $ write mctal file
c
print                                $ full output
```

A3. Input File for Problem 3 (continued)

```
e5mt.4:  converted from keno file k.4; continuous energy; endf/b-5
c    universes of paraffin with decreasing importance surrounding core
c
c    Cell Cards
c
c    lattice with cylinders of U fuel
1     1 0.0480368  -7 -8  9              imp:n=1    u=1        $ U cylinder
2     0            #1                   imp:n=1    u=1        $ outside
3     0            -1  2 -3  4 -5  6    imp:n=1    u=2 lat=1 $ 2x2x2 lattice
        fill=0:1 0:1 0:1   1 1  1 1  1 1  1 1                 $ filling u's
4     2 0.122282   #3                   imp:n=1    u=2        $ outside
c
c    concentric boxes with decreasing importances
10    0            -11 12 -13 14 -15 16  imp:n=1     u=10 fill=2
11    2 0.122282   #10                   imp:n=0.1   u=10
20    0            -21 22 -23 24 -25 26  imp:n=1.0   u=20 fill=10
21    2 0.122282   #20                   imp:n=0.1   u=20
30    0            -31 32 -33 34 -35 36  imp:n=1.0   u=30 fill=20
31    2 0.122282   #30                   imp:n=0.05  u=30
40    0            -41 42 -43 44 -45 46  imp:n=1.0   u=40 fill=30
41    2 0.122282   #40                   imp:n=0.05  u=40
50    0            -51 52 -53 54 -55 56  imp:n=1.0   u=50 fill=40
51    2 0.122282   #50                   imp:n=0.01  u=50
60    0            -61 62 -63 64 -65 66  imp:n=1.0        fill=50
61    0            #60                   imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0 0
2     px -23.48
3     py  0.0
4     py -23.48
5     pz  0.0
6     pz -22.75
c    cylinder
7     c/z -11.74 -11.74 5.748
8     pz  -5.9925
9     pz  -16.7575
c    parallelpiped (dimensions shrunk by 0.001 to avoid fill problems)
11    px  23.479
12    px -23.479
13    py  23.479
14    py -23.479
15    pz  22.749
16    pz -22.749
c    parallelpiped
21    px  26.48
22    px -26.48
23    py  26.48
24    py -26.48
25    pz  25.75
26    pz -25.75
c    parallelpiped
31    px  29.48
32    px -29.48
33    py  29.48
34    py -29.48
35    pz  28.75
36    pz -28.75
c    parallelpiped
41    px  32.48
42    px -32.48
43    py  32.48
44    py -32.48
45    pz  31.75
46    pz -31.75
```

A4. Input File for Problem 4

```
c    parallelpiped
51    px  35.48
52    px -35.48
53    py  35.48
54    py -35.48
55    pz  34.75
56    pz -34.75
c    parallelpiped
61    px  38.72
62    px -38.72
63    py  38.72
64    py -38.72
65    pz  37.99
66    pz -37.99
c
c    Data Cards
c
mode  n                          $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c 0.932631          $ U-235
     92238.50c 0.055328          $ U-238
     92234.50c 0.010049          $ U-234
     92236.50c 0.001992          $ U-236
c    paraffin
m2    1001.50c 0.675324          $ H ( in paraffin )
      6000.50c 0.324676          $ C ( in paraffin )
c
c    S(alpha, beta)
mt2   poly.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5
      1.0e-4 5.5e-4 3.0e-3 1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1     $ tally the ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-11.74 -11.74 -11.375  axs=0 0 1
c
si1   l 60:50:40:30:20:10:3(0 0 0):1 $ path:  /cell60/cell50/.../cell1
        60:50:40:30:20:10:3(1 0 0):1 $ path to cell 1 thru lattice(1,0,0)
        60:50:40:30:20:10:3(1 1 0):1 $ path to cell 1 thru lattice(1,1,0)
        60:50:40:30:20:10:3(0 1 0):1 $ etc.
        60:50:40:30:20:10:3(0 0 1):1 $
        60:50:40:30:20:10:3(1 0 1):1 $
        60:50:40:30:20:10:3(0 1 1):1 $
        60:50:40:30:20:10:3(1 1 1):1 $
sp1     1 1 1 1 1 1 1 1              $ equal probability for all paths above
c
sp2   -3                             $ Watt fission spectrum
c
si3       0.0  5.748                 $ radial distribution
sp3  -21  1                          $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825             $ axial distribution
sp4  -21  0                          $ p(x) = const
c
prdmp  j j 1 j                       $ write mctal file
c
print                                $ full output
```

A4. Input File for Problem 4 (continued)

```
c5mt.5:  converted from keno file k.4; continuous energy; endf/b-5
c    30.48 cm of paraffin surrounding metal cylinders
c    Models the KENO albedo option.
c
c    Cell Cards
c
c    lattice with cylinders of U fuel
1     1 0.0480368  -7 -8  9              imp:n=1   u=1        $ U cylinder
2     0            #1                   imp:n=1   u=1        $ outside
3     0            -1  2 -3  4 -5  6    imp:n=1   u=2 lat=1 $ 2x2x2 lattice
        fill=0:1 0:1 0:1   1 1  1 1  1 1  1 1                $ filling u's
4     2 0.122282   #3                   imp:n=1   u=2        $ outside
c
c    concentric boxes with decreasing importances
10    0            -11 12 -13 14 -15 16  imp:n=1    u=10 fill=2
11    2 0.122282   #10                   imp:n=0.1  u=10
20    0            -21 22 -23 24 -25 26  imp:n=1.0  u=20 fill=10
21    2 0.122282   #20                   imp:n=0.1  u=20
30    0            -31 32 -33 34 -35 36  imp:n=1.0  u=30 fill=20
31    2 0.122282   #30                   imp:n=0.05 u=30
40    0            -41 42 -43 44 -45 46  imp:n=1.0  u=40 fill=30
41    2 0.122282   #40                   imp:n=0.05 u=40
50    0            -51 52 -53 54 -55 56  imp:n=1.0  u=50 fill=40
51    2 0.122282   #50                   imp:n=0.01 u=50
60    0            -61 62 -63 64 -65 66  imp:n=1.0       fill=50
61    0            #60                   imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -23.48
3     py  0.0
4     py -23.48
5     pz  0.0
6     pz -22.75
c    cylinder
7     c/z -11.74 -11.74 5.748
8     pz  -5.9925
9     pz  -16.7575
c    parallelpiped (dimensions shrunk by 0.001 to avoid fill problems)
11    px  23.479
12    px -23.479
13    py  23.479
14    py -23.479
15    pz  22.749
16    pz -22.749
c    parallelpiped
21    px  26.48
22    px -26.48
23    py  26.48
24    py -26.48
25    pz  25.75
26    pz -25.75
c    parallelpiped
31    px  29.48
32    px -29.48
33    py  29.48
34    py -29.48
35    pz  28.75
36    pz -28.75
c    parallelpiped
41    px  32.48
42    px -32.48
43    py  32.48
44    py -32.48
45    pz  31.75
46    pz -31.75
```

A5. Input File for Problem 5

```
c    parallelpiped
51    px  35.48
52    px -35.48
53    py  35.48
54    py -35.48
55    pz  34.75
56    pz -34.75
c    parallelpiped
61    px  53.48
62    px -53.48
63    py  53.48
64    py -53.48
65    pz  53.23
66    pz -53.23
c
c    Data Cards
c
mode  n                        $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c 0.932631       $ U-235
      92238.50c 0.055328       $ U-238
      92234.50c 0.010049       $ U-234
      92236.50c 0.001992       $ U-236
c    paraffin
m2     1001.50c 0.675324       $ H ( in paraffin )
       6000.50c 0.324676       $ C ( in paraffin )
c
c    S(alpha, beta)
mt2   poly.01t
c
c    default energy bins; Hansen-Roach structure
e0     1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5
       1.0e-4 5.5e-4 3.0e-3 1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1     $ tally the ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-11.74 -11.74 -11.375  axs=0 0 1
c
si1   l 60:50:40:30:20:10:3(0 0 0):1 $ path:  /cell60/cell50/.../cell1
        60:50:40:30:20:10:3(1 0 0):1 $ path to cell 1 thru lattice(1,0,0)
        60:50:40:30:20:10:3(1 1 0):1 $ path to cell 1 thru lattice(1,1,0)
        60:50:40:30:20:10:3(0 1 0):1 $ etc.
        60:50:40:30 20:10:3(0 0 1):1 $
        60:50:40:30:20:10:3(1 0 1):1 $
        60:50:40:30:20:10:3(0 1 1):1 $
        60:50:40:30:20:10:3(1 1 1):1 $
sp1     1 1 1 1 1 1 1 1              $ equal probability for all paths above
c
sp2   -3                             $ Watt fission spectrum
c
si3       0.0  5.748                 $ radial distribution
sp3  -21  1                          $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825             $ axial distribution
sp4  -21  0                          $ p(x) = const
c
prdmp  j j 1 j                       $ write mctal file
c
print                                $ full output
```

A5. Input File for Problem 5 (continued)

```
e5mt.6:  converted from keno file k.6; continuous energy; endf/b-5
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1
2     0             (-1  2 -3  4 -5  6) #1 imp:n=1
3     0             1:  -2:  3:  -4:  5:  -6    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  6.87
2     px -6.87
3     py  6.87
4     py -6.87
5     pz  6.505
6     pz -6.505
c    cylinder
7     cz  5.748
8     pz  5.3825
9     pz -5.3825
c
c    Data Cards
c
mode  n                                    $ transport neutrons only
c
c    material cards  endf/b-5 data
c    same composition as mcnp.1
m1   92235.50c 0.932631                    $ U-235
     92238.50c 0.055328                    $ U-238
     92234.50c 0.010049                    $ U-234
     92236.50c 0.001992                    $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=1 pos=0 0 0 axs=0 0 1 rad=d1 ext=d2 erg=d3
c
si1    0.0 5.748                           $ be sure this encloses cell 1
c
si2   -5.3825 5.3825                       $ be sure this encloses cell 1
c
sp3   -3                                   $ Watt fission spectrum
c
prdmp  j j 1 j                             $ write mctal file
c
print                                      $ full output
```

A6. Input File for Problem 6

```
e5mt.7:  converted from keno file k.7; continuous energy; endf/b-5 data
c    reflection on 3 sides
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1
2     0             (-1  2 -3  4 -5  6) #1 imp:n=1
3     0             1:  -2:  3:  -4:  5:  -6    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
*1    px  6.87                               $ reflecting surface
2     px -6.87
*3    py  6.87                               $ reflecting surface
4     py -6.87
*5    pz  6.505                              $ reflecting surface
6     pz -6.505
c    cylinder
7     cz  5.748
8     pz  5.3825
9     pz -5.3825
c    enclosing sphere
10    so  11.0
c
c    Data Cards
c
mode  n                                      $ transport neutrons only
c
c    material cards  endf/b-5 data
c    same composition as mcnp.1
m1   92235.50c 0.932631                      $ U-235
     92238.50c 0.055328                      $ U-238
     92234.50c 0.010049                      $ U-234
     92236.50c 0.001992                      $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins
e0    0.025e-6 1.0e-6 1.0e-4 1.0e-2 1.0e-1 5.0e-1 1.0 2.0 4.0 10.0 14.0 20.0
c
c    tallies
f4:n   1                                     $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=i pos=0 0 0 axs=0 0 1 rad=d1 ext=d2 erg=d3
c
si1    0.0 5.748                             $ be sure this encloses cell 1
c
si2   -5.3825 5.3825                         $ be sure this encloses cell 1
c
sp3   -3                                     $ Watt fission spectrum
c
prdmp  j j 1 j                               $ write mctal file
c
print                                        $ full output
```

A7. Input File for Problem 7

```
e5mt.8:  converted from keno file k.8
c    reflection on Z faces only
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -5  6                imp:n=1
2     0             (-1  2 -3  4 -5  6) 7   imp:n=1
3     0             1:  -2:  3:  -4:  5:  -6    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  6.87
2     px -6.87
3     py  6.87
4     py -6.87
*5    pz  10.00                              $ reflecting surface
*6    pz -10.00                              $ reflecting surface
c    cylinder
7     cz  5.748
c
c    Data Cards
c
mode  n                                      $ transport neutrons only
c
c    material cards  endf/b-5 data
m1    92235.50c  0.932631                     $ U-235
      92238.50c  0.055328                     $ U-238
      92234.50c  0.010049                     $ U-234
      92236.50c  0.001992                     $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins
e0    0.025e-6 1.0e-6 1.0e-4 1.0e-2 1.0e-1 5.0e-1 1.0 2.0 4.0 10.0 14.0 20.0
c
c    tallies
f4:n   1                                     $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=1 pos=0 0 0 axs=0 0 1 rad=d1 ext=d2 erg=d3
c
si1    0.0 5.748                             $ be sure this encloses cell 1
c
si2   -10.0 10.0                             $ be sure this encloses cell 1
c
sp3   -3                                     $ Watt fission spectrum
c
prdmp  j j 1 j                               $ write mctal file
c
print                                        $ full output
```

A8. Input File for Problem 8

```
e5mt.9:  converted from keno file k.9; continuous energy; endf/b-5
c    infinite array of cylinder-in-box units
c    model by making all box walls reflective
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9              imp:n=1 u=1
2     0             81                    imp:n=1 u=1
3     0             -1  2 -3  4 -5  6     imp:n=1 fill=1
4     0              1:-2:  3:-4:  5:-6     imp:n=0
c
c    Surface Cards
c
c    parallelpiped
*1    px  0.0
*2    px -13.74
*3    py  0.0
*4    py -13.74
*5    pz  0.0
*6    pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225
9     pz  -11.8875
c
c    Data Cards
c
mode  n                                   $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c  0.932631                  $ U-235
     92238.50c  0.055328                  $ U-238
     92234.50c  0.010049                  $ U-234
     92236.50c  0.001992                  $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                  $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    uniform volume source in cell 1
sdef  cel=d1  rad=d2  ext=d3  erg=d4  pos=-6.87 -6.87 -6.505  axs=0 0 1
si1    1   3:1                            $ path to cell 1
sp1    d   1                              $ choose above with prob 1
si2    h   0.0  5.748                     $ radial limits (from pos)
sp2   -21  1                              $ p(r) = constor
si3    h  -5.3825 5.3825                  $ axial limits (from pos)
sp3   -21  0                              $ p(z) = const
sp4   -3                                  $ Watt fission spectrum
c
prdmp  j j 1 j                            $ write mctal file
c
print                                     $ full output
```

A9. Input File for Problem 9

```
e5mt.10:  converted from keno file k.10; continuous energy; endf/b-5
c    8 bare cylinders of U-metal
c    to demonstrate restart
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1 u=-1
2     0             #1                      imp:n=1 u=1
3     0             -1  2 -3  4 -5  6       imp:n=1 u=2 lat=1
      fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4     0             -11 12 -13 14 -15 16    imp:n=1     fill=2
5     0              #4                     imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -13.74
3     py  0.0
4     py -13.74
5     pz  0.0
6     pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225
9     pz  -11.8875
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    px  13.7399
12    px -13.7399
13    py  13.7399
14    py -13.7399
15    pz  13.0099
16    pz -13.0099
c
c    Data Cards
c
mode  n                                     $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c 0.932631
      92238.50c 0.055328
      92234.50c 0.010049
      92236.50c 0.001992
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                    $ are flux in cell 1
```

A10. Input File for Problem 10

```
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=0 0 1
c
si1   l 4:3(1 1 0):1                  $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                  $ etc.
        4:3(0 1 0):1                  $ this ordering chosen to match
        4:3(0 0 0):1                  $   sampling in e5ce.2
        4:3(1 1 1):1                  $
        4:3(1 0 1):1                  $
        4:3(0 1 1):1                  $
        4:3(0 0 1):1                  $
sp1     1 1 1 1 1 1 1 1               $ equal probability for all paths above
c
sp2   -3                              $ Watt fission spectrum
c
si3       0.0  5.748                  $ radial distribution
sp3  -21  1                           $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825              $ axial distribution
sp4  -21  0                           $ p(x) = const
c
prdmp  5  5  1  j                     $ print tallies/write every 5 cycles
c
print                                 $ full output
```

A10. Input File for Problem 10 (conti...

```
message:  c 11 runtpe=cmt.10
e5mt.11:  converted from keno file k.10; continuous energy; endf/b-5
c    8 bare cylinders of U-metal
c    to demonstrate restart
c    same as e5ce 10
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1 u=-1
2     0             81                      imp:n=1 u=1
3     0             -1  2 -3  4 -5  6       imp:n=1 u=2 lat=1
      fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4     0             -11 12 -13 14 -15 16    imp:n=1     fill=2
5     0              84                     imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -13.74
3     py  0.0
4     py -13.74
5     pz  0.0
6     pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225
9     pz  -11.8875
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    px  13.7399
12    px -13.7399
13    py  13.7399
14    py -13.7399
15    pz  13.0099
16    pz -13.0099
```

A11. Input File for Problem 11

```
c
c    Data Cards
c
mode  n                                    $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c 0.932631
     92238.50c 0.055328
     92234.50c 0.010049
     92236.50c 0.001992
c
c    S(alpha, beta):  not applicable
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=0 0 1
c
si1   1 4:3(1 1 0):1                  $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                  $ etc.
        4:3(0 1 0):1                  $ this ordering chosen to match
        4:3(0 0 0):1                  $   sampling in e5ce.2
        4:3(1 1 1):1                  $
        4:3(1 0 1):1                  $
        4:3(0 1 1):1                  $
        4:3(0 0 1):1                  $
sp1     1 1 1 1 1 1 1 1               $ equal probability for all paths above
c
sp2   -3                              $ Watt fission spectrum
c
si3       0.0  5.748                  $ radial distribution
sp3  -21  1                           $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825              $ axial distribution
sp4  -21  0                           $ p(x) = const
c
prdmp  5  5  1  20                    $ print tallies/write every 5 cycles
c
print                                 $ full output
```

A11. Input File for Problem 11 (continued)

```
e5mt.12:  converted from keno file k.12; cont energy; endf/b-5
c
c    Cell Cards
c
1     1 0.0480295    -7  -8   9          imp:n=1
2     2 0.09806472  -17 -18  19          imp:n=1 u=1
3     3 0.106657     17:  18:-19          imp:n=1 u=1
4     0             -27 -38  29          imp:n=1     fill=1
c
11    like 1 but   trcl=(0.00  13.18   0.00)
14    like 4 but   trcl=(0.00  21.75   0.00)
c
21    like 1 but   trcl=(0.00   0.00  12.45)
24    like 4 but   trcl=(0.00   0.00  20.48)
c
31    like 1 but   trcl=(0.00  13.18  12.45)
34    like 4 but   trcl=(0.00  21.75  20.48)
c
40    0 -30 #1 #4 #11 #14 #21 #24 #31 #34 imp:n=1   $ btwn cylinder & sphere
c
50    0  30                               imp:n=0   $ outside of sphere
c
c    Surface Cards
c
c    finite cylinders
7     c/z   -6.59 -6.59  5.748
8     pz     -0.8425                    $ 5.3925 above midplane
9     pz    -11.6075                    $ 5.3825 below midplane
c
17    c/z   10.875 -10.875  9.525
18    pz     -1.35                      $ 8.89 above midplane
19    pz    -19.13                      $ 8.89 below midplane
c
27    c/z   10.875 -10.875  10.16
28    pz     -0.715                     $ 9.525 above midplane
29    pz    -19.765                     $ 9.525 below midplane
c
30    so     35.0                       $ enclosing sphere
c
c    Data Cards
c
mode  n                                $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92238.50c 0.067198
      92235.50c 0.932802
c     uranyl nitrate
m2     1001.50c 0.592466
       7014.50c 0.020143
       8016.50c 0.376557
      92235.50c 0.010041
      92238.50c 0.000792
c     Plexiglas
m3     6000.50c 0.333330
       1001.50c 0.533336
       8016.50c 0.133334
c
c    S(alpha, beta)
mt2   lstr.01t
```

A12. Input File for Problem 12

```
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    uniform volume source in fissile cells
c
sdef  cel=d1  erg=d2  rad=fcel d3  ext=fcel d4
      pos=fcel d5  axs=0 0 1
c
si1    l 1 11 21 31                 $ cells
         4:2  14:2  24:2  34:2      $ path to cell 2
sp1    v                            $ prob proportional to volume
c
sp2   -3                            $ Watt fission spectrum
c
ds3    s  31 31 31 31               $ radial distrib numbers based on cel
          32 32 32 32               $ correspond to si1 card
si31      0.0 5.748                 $ radial limits:  source in cell 1
sp31 -21  1                         $ p(x) = const*abs(x)
si32      0.0 9.525                 $ radial limits:  source in cell 2
sp32 -21  1                         $ p(x) = const*abs(x)
c
ds4    s  41 41 41 41               $ radial distrib numbers based on cel
          42 42 42 42               $ correspond to si1 card
si41      -5.3825 5.3825            $ axial limits:  source in cell 1
sp41  -21  0                        $ p(x) = const
si42      -8.89 8.89                $ axial limits:  source in cell 2
sp42  -21  0                        $ p(x) = const
c
ds5    l  -6.59 -6.59 -6.225        $ pos variable based on cel
          -6.59  6.59 -6.225        $ correspond to si1 card
          -6.59 -6.59  6.225        $
          -6.59  6.59  6.225        $
           10.875  -10.875 -10.24   $ when path is given (see si1)
           10.875  -10.875 -10.24   $  the position of the
           10.875  -10.875 -10.24   $  UNTRANSLATED cell is given, so
           10.875  -10.875 -10.24   $  pos is the same each time
c
prdmp  j j 1 j                      $ write mctal file
c
print
```

A12. Input File for Problem 12 (continued)

```
e5mt.13:  converted from keno file k.13; continuous energy; endf/b-5
c    2 offset cubes of enriched U-235 surrounded by a cylindrical
c    annulus of enriched U-235
c
c    Cell Cards
c
1     1 4.80368e-2  -1  2 -3  4 -5  6  imp:n=1  trcl=(-0.2566  -6.35 0.00)
2     1 4.80368e-2  -1  2 -3  4 -7  6  imp:n=1  trcl=(-12.4434 -6.35 7.62)
3     1 4.80368e-2  -12 -13  6  11     imp:n=1  $ annulus
4     0             -11 -13  6 #1 #2   imp:n=1  $ btwn boxes and cylinder
5     0              (12:  13:-6) #2    imp:n=0  $ outside
c
c    Surface Cards
c
c    planes
1     px  12.7
2     px  0.0
3     py  12.7
4     py  0.0
5     pz  7.62
6     pz  0.0
7     pz  11.176
c    cylinders
11    cz  13.97
12    cz  19.05
13    pz  16.18
c
c    Data Cards
c
mode  n                                        $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c  0.932631
      92238.50c  0.055328
      92234.50c  0.010049
      92236.50c  0.001992
c
c    S(alpha, beta):  not applicable
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                       $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
ksrc  6.35 0.0 3.81  -6.35 0.0 13.2            $ point in each block
c
prdmp  j j 1 j                                 $ write mctal file
c
print                                          $ full output
```

A13. Input File for Problem 13

```
e5mt.14:  converted from keno file k.14; continuous energy; endf/b-5
c
c     Cell Cards
c
1      1 4.80362e-2  -1 -8  9                     imp:n=1
2      0              1 -8  9 -2                  imp:n=1
       1 4.80362e-2  -3 -8  9  2                  imp:n=1
[illegible]      0              3:  8:-9                     imp:n=0
c
c     Surface Cards
c
c     cylinders
[illegible]      c/z   [illegible]08 0.0  8.89
[illegible]      cz    [illegible]7
[illegible]      cz    [illegible]
c     planes
[illegible]      pz    10.1[illegible]9
[illegible]      pz    0.0
c
c     Data Cards
c
mode  n                                           $ transport neutrons only
c
c     material cards  endf/b-5 data
m1    92235.50c [illegible].932631                          $ U-235
      92238.50c [illegible] 055328                          $ U-238
      92234.50c 0.010049                          $ U-234
      92236.50c [illegible].001992                          $ U-236
c
c     S(alpha, beta):  not applicable
c
c     default energy bins; Hansen-Roach structure
e0     1.0e-7 [illegible]0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
       1.7e-2 [illegible].1 0.4 0.9 1.4 3.0 20.0
c
c     tallies
f4:n   1                                          $ ave flux in cell 1
c
c     criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1  pos=fcel d2  ext=fcel d3  rad=fcel d4  erg=d5 axs=0 0 1
c
si1   1  1 3                                      $ cells
sp1   v                                           $ prob proportional to volume
c
ds2   t  1  5.08 0.0 0.0                          $ pos for cel=1
         3  0.0  0.0 0.0                          $ pos for cel = 2
c
ds3   s   31 32                                   $ ext distrib numbers based on cel
si31       0.0  10.109                            $ axial range about pos
sp31  -21  0                                      $ p(z) = const
si32       0.0  10.109                            $ axial range about pos
sp32  -21  0                                      $ p(z) = const
c
ds4   s   41 42                                   $ rad distrib numbers based on cel
si41       0.0    8.89                            $ radial range about pos
sp41  -21  1                                      $ p(r) = const*abs(r)
si42       13.97  19.05                           $ radial range about pos
sp42  -21  1                                      $ p(r) = const*abs(r)
c
sp5   -3
c
prdmp  j j 1 j                                    $ write mctal file
c
print                                             $ full output
```

A14. Input File for Problem 14

```
e5mt.15:  converted from keno file k.15; continuous energy; endf/b-5
c
c    cell cards
c
1    1  0.04817212  -5                              imp:n=1
2    2  0.106857     1 -2  3 -4                     imp:n=1
3    3  0.100113     6 -7 -8 #1 #2                  imp:n=1
4    0              #3 #2 #1                        imp:n=0
c
c    surface cards
c
1     pz   -7.092175
2     pz   -4.552185
3     cz    4.1275
4     cz   12.7
5     sz    0.538475 6.5537
6     pz  -22.092175
7     pz   22.092175
8     cz   32.97
c
c    data cards
c
mode   n
kcode  3000 1.0 20 200 4500 0
sdef  cel=1  erg=d1  rad=d2  pos=0.0 0.0 0.538475
c
sp1   -3
c
si2     0.0  6.56
sp2   -21  2
c
c      continuous   endf/b-v
c
m1     92234.50c   0.01177258        $ U-234
       92235.50c   0.97656128        $ U-235
       92236.50c   0.0019912319      $ U-236
       92238.50c   0.009674906       $ U-238
c     Plexiglas
m2       1001.50c   0.5333358        $ H
         6000.50c   0.3333302        $ C
         8016.50c   0.13333396       $ O
c     water
m3       1001.50c   0.666667         $ H
         8016.50c   0.333333         $ O
c
c    S(alpha, beta)
mt3   lwtr.01t
c
prdmp  j j 1 j                       $ write mctal file
c
print                                $ full output
```

A15. Input File for Problem 15

```
e5mt.16:  converted from keno file k.16; continuous energy; endf/b-5
c    UO2F2 infinite slab
c
c    Cell Cards
c
1     1 0.09872456  (-1   2 -3  4 -5  6)            imp:n=1
2     2 0.07044000  (-11 12 -3  4 -5  6)( 1:  -2 )   imp:n=1
3     3 0.1         (-21 22 -3  4 -5  6)(11:  -12)   imp:n=1
4     0             (21:-22:  3:-4:  5:-6)            imp:n=0
c
c    Surface Cards
c
c    planes
1     px  2.479
2     px -2.479
*3    py  100.0
*4    py -100.0
*5    pz  100.0
*6    pz -100.0
c
11     px  3.749
12     px -3.749
c
*21    px  17.479
*22    px -17.479
c
c    Data Cards
c
mode  n                                    $ transport neutrons only
c
c    material cards; endf/b-5 data
c    UO2F2 soln
m1   92235.50c  0.013999
     92238.50c  0.001008
      9019.50c  0.030013
      8016.50c  0.338315
      1001.50c  0.616665
c    pyrex
m2   13027.50c  0.007524
      5000.01c  0.065162                   $ natural Boron
      8016.50c  0.637706
     14000.50c  0.255821
     11023.50c  0.033788
c    borated UO2F2 soln
m3    5000.01c  0.014789                   $ natural Boron
     92235.50c  0.013792
     92238.50c  0.0009935
      9019.50c  0.029549
      8016.50c  0.333312
      1001.50c  0.607545
c
c    S(alpha, beta)
mt1   lwtr.01t
mt3   lwtr.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.8e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
ksrc    0.0  0.0 0.0                       $ point in material 1
      -10.61 0.0 0.0                       $ point in material 3
       10.61 0.0 0.0                       $ point in material 3
c
prdmp  j j 1 j                             $ write mctal file
c
print                                      $ full output
```

A16. Input File for Problem 16

```
e5mt.17:  converted from keno file k.17; continuous energy; endf/b-5
c
c    Cell Cards
c
1     1 0.0995739   -1     imp:n=1
2     0              1     imp:n=0
c
c    Surface Cards
c
1    so   16.0
c
c    Data Cards
c
mode  n                                  $ transport neutrons only
c
c     aterial cards; endf/b-5 data
c    U02F2 soln
m1   92235.50c  0.0032197
     92238.50c  0.0002349
      1001.50c  0.6551517
      8016.50c  0.3344853
      9019.50c  0.0069084
c
c    S(alpha, beta)
mt1   lwtr.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                 $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    uniform volume source
sdef  cel=1  erg=d1  rad=d2  pos=0.0 0.0 0.0
c
sp1   -3                                 $ Watt fission spectrum
c
si2       0.0 16.0                       $ radial limits
sp2  -21  2                              $ p(x) = const*x^2
c
prdmp  j j 1 j                           $ write mctal file
c
print                                    $ full output
```

A17. Input File for Problem 17

```
e5mt.18:  converted from keno file k.18; continuous energy; endf/b-5
c
c    cell cards
c
1    1  0.0981986   1 -2 -3                                  imp:n=1 u=1
2    0              1 -4 -3 #1                               imp:n=1 u=1
3    2  0.106857    5 -6 -7 #1 #2                            imp:n=1 u=1
4    4  0.100113-9  -5:6:7                                   imp:n=1 u=1
5    0              14 -15 16 -17 18 -19                       imp:n=1 u=3 lat=1
       fill=-1:1 -1:1    :1
       1 1 1  1 1 1  1 1 1
       1 1 1  1 1 1  1 1 1
       1 1 1  1 1 1  1 1 1
6    0              20 -21 22 -23 24 -25                     imp:n=1 fill= 3
7    3  0.122268    30 -31 32 -33 34 -35 (-20:21:-22:23:-24:25) imp:n=1
8    5  0.100113    30 -31 32 -33 44 -34                          imp:n=1
9    0              (-30:31:-32:33:-44:35)                        imp:n=0
c
c    surface cards
c
c     uranyl-nitrate cylinder
1     pz    -8.7804
2     pz     8.7804
3     cz     9.52
c
c     void cylinder - used to account for the fact that the Plexiglas
c                     cylinder is NOT completely full.
4     pz     8.9896
c
c     Plexiglas cylinder
5     pz    -9.4204
6     pz     9.6296
7     cz    10.16
c
c     water filled cuboid that contains the cylinders
14    px   -18.45
15    px    18.45
16    py   -18.45
17    py    18.45
18    pz   -17.6854
19    pz    17.8946
c
c     cuboid that contains all the other cuboids
20    px   -55.3499
21    px    55.3499
22    py   -55.3499
23    py    55.3499
24    pz   -52.9199
25    pz    52.9199
c
c     cuboid that contains the paraffin
30    px   -70.591
31    px    70.591
32    py   -70.591
33    py    70.591
34    pz   -68.6100999
35    pz    68.6100999
c
c     slab of water - on the negative z face
44    pz   -99.09
c
```

A18. Input File for Problem 18

```
c
c    data cards
c
mode   n
c
c      Material #1  -   aqueous uranyl nitrate
c      Material #2  -   Plexiglas
c      Material #3  -   paraffin
c      Material #4  -   water, very low density (water vapor)
c      Material #5  -   water, normal density
c
c      continuous   endf/b-v
c
m1     92238.50c   0.00079085                $ U-238
       92235.50c   0.01002407                $ U-235
        8016.50c   0.37766319                $ O
        7014.50c   0.02010823                $ N
        1001.50c   0.59141367                $ H
mt1    lwtr.01t
c
m2     1001.50c    0.5333358                $ H
       6000.50c    0.3333302                $ C
       8016.50c    0.13333396               $ O
c
m3     1001.50c    0.67532797               $ H
       6000.50c    0.32467203               $ C
mt3    poly.01t
c
m4     1001.50c    0.66666667               $ H
       8016.50c    0.33333333               $ O
mt4    lwtr.01t
c
m5     1001.50c    0.66666667               $ H
       8016.50c    0.33333333               $ O
mt5    lwtr.01t
c
kcode  3000 1.0 20 200 4500 0
sdef  cel=d1  erg=d2  rad=d3  ext=d4  pos=0.0 0.0 0.0  axs=0 0 1
c
c    path to each of 27 source cells
si1   l 6:5( 1  1  1):1  6:5(-1 -1  0):1  6:5(-1 -1  1):1
        6:5(-1  0 -1):1  6:5(-1  0  0):1  6:5(-1  0  1):1
        6:5(-1  1 -1):1  6:5(-1  1  0):1  6:5(-1  1  1):1
        6:5( 0 -1 -1):1  6:5( 0 -1  0):1  6:5( 0 -1  1):1
        6:5( 0  0 -1):1  6:5( 0  0  0):1  6:5( 0  0  1):1
        6:5( 0  1 -1):1  6:5( 0  1  0):1  6:5( 0  1  1):1
        6:5( 1 -1 -1):1  6:5( 1 -1  0):1  6:5( 1 -1  1):1
        6:5( 1  0 -1):1  6:5( 1  0  0):1  6:5( 1  0  1):1
        6:5( 1  1 -1):1  6:5( 1  1  0):1  6:5( 1  1  1):1
sp1    1 1 1  1 1 1  1 1 1          $ equal probability for all paths above
       1 1 1  1 1 1  1 1 1          $
       1 1 1  1 1 1  1 1 1          $
c
sp2   -3                            $ Watt fission spectrum
c
si3       0.0  9.52                 $ radial distribution
sp3   -21  1                        $ p(x) = const*abs(x)
c
si4      -8.7804  8.7804            $ axial distribution
sp4   -21  0                        $ p(x) = const
c
prdmp  j j 1 j                      $ write mctal file
print
```

A18. Input File for Problem 18 (continued)

```
e5mt.19:  converted from keno file k.19; cont energy; endf/b-5
c
c    Cell Cards
c
1     1 0.0480295    -7  -8   9          imp:n=1
2     2 0.09806472  -17 -18  19          imp:n=1 u=1
3     3 0.106657     17:  18:-19          imp:n=1 u=1
4     0             -27 -28  29          imp:n=1     fill=1
c
11    like 1 but   trcl=(0.00  13.18   0.00)
14    like 4 but   trcl=(0.00  21.75   0.00)
c
21    like 1 but   trcl=(0.00   0.00  12.45)
24    like 4 but   trcl=(0.00   0.00  20.48)
c
31    like 1 but   trcl=(0.00  13.18  12.45)
34    like 4 but   trcl=(0.00  21.75  20.48)
c
40    0 -30 #1 #4 #11 #14 #21 #24 #31 #34 imp:n=1   $ btwn cylinder & sphere
c
50    0  30                               imp:n=0   $ outside of sphere
c
c    Surface Cards
c
c    finite cylinders
7    c/z   -6.59 -6.59  5.748
8    pz     -0.8425                      $ 5.3825 above midplane
9    pz    -11.6075                      $ 5.3825 below midplane
c
17   c/z   10.875 -10.875  9.525
18   pz     -1.35                        $ 8.89 above midplane
19   pz    -19.13                        $ 8.89 below midplane
c
27   c/z   10.875 -10.875  10.16
28   pz     -0.715                       $ 9.525 above midplane
29   pz    -19.765                       $ 9.525 below midplane
c
30   so     35.0                         $ enclosing sphere
c
c    Data Cards
c
mode  n                                 $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92238.50c  0.067198
     92235.50c  0.932802
c    uranyl nitrate
m2    1001.50c  0.592466
      7014.50c  0.020143
      8016.50c  0.376557
     92235.50c  0.010041
     92238.50c  0.000792
c    Plexiglas
m3    6000.50c  0.333330
      1001.50c  0.533336
      8016.50c  0.133334
c
c    S(alpha, beta)
mt2   lwtr.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                    $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
```

A19. Input File for Problem 19

```
c
c    uniform volume source in fissile cells
c
sdef  cel=d1  erg=d2  rad=fcel d3  ext=fcel d4
      pos=fcel d5  axs=0 0 1
c
si1    l 1 11 21 31                  $ cells
         4:2  14:2  24:2  34:2       $ path to cell 2
sp1    v                             $ prob proportional to volume
c
sp2   -3                             $ Watt fission spectrum
c
ds3    s  31 31 31 31                $ radial distrib numbers based on cel
          32 32 32 32                $ correspond to si1 card
si31      0.0 5.748                  $ radial limits:  source in cell 1
sp31 -21  1                          $ p(x) = const*abs(x)
si32      0.0 9.525                  $ radial limits:  source in cell 2
sp32 -21  1                          $ p(x) = const*abs(x)
c
ds4    s  41 41 41 41                $ radial distrib numbers based on cel
          42 42 42 42                $ correspond to si1 card
si41      -5.3825 5.3825             $ axial limits:  source in cell 1
sp41  -21  0                         $ p(x) = const
si42      -8.89 8.89                 $ axial limits:  source in cell 2
sp42  -21  0                         $ p(x) = const
c
ds5    l  -6.59 -6.59 -6.225         $ pos variable based on cel
          -6.59  6.59 -6.225         $ correspond to si1 card
          -6.59 -6.59  6.225         $
          -6.59  6.59  6.225         $
           10.875  -10.875 -10.24    $ when path is given (see si1)
           10.875  -10.875 -10.24    $  the position of the
           10.875  -10.875 -10.24    $  UNTRANSLATED cell is given, so
           10.875  -10.875 -10.24    $  pos is the same each time
c
prdmp  j j 1 j                       $ write mctal file
c
print
```

A19. Input File for Problem 19 (continued)

```
e5mt.20:  converted from keno f... x 20; continuous energy, endf/...
c
c    Cell Cards
c
c    Aluminum can with uranyl nitrate
1     1 0.0982616   -17 -18  19            imp:n=1 u=...
2     2 0.060242     17:  18:-19            imp:n=1 u=1
3     0             -27 -28  29            imp:n=1     fill=...
c    Make a triangular array of the above cans
13    like 3 but  trcl=( 21.006   0.000  0.000)
23    like 3 but  trcl=(-21.006   0.000  0.000)
33    like 3 but  trcl=( 10.503  18.192  0.000)
43    like 3 but  trcl=(-10.503  18.192  0.000)
53    like 3 but  trcl=( 10.503 -18.192  0.000)
63    like 3 but  trcl=(-10.503 -18.192  0.000)
c    Enclose the array in a box
101   0     -1  2 -3  4 -5  6 #3 #13 #23 #33 #43 #53 #63  imp:n=1   $ btwn
102   0      1:-2:  3:-4:  5:-6                           imp:n=0   $ outside
c
c    Surface Cards
c
1     px   50.0
2     px  -50.0
3     py   50.0
4     py  -50.0
5     pz   50.0
6     pz   -0.152
c    finite cylinders
17    cz   10.16
18    pz   18.288
19    pz    0.0
c
27    cz   10.312
28    pz   18.288
29    pz   -0.152
c
c    Data Cards
c
mode  n                              $ transport neutrons only
c
c    material cards; endf/b-5 data
c    uranyl fluoride
m1    92235.50c  0.014017            $ U-235
      92238.50c  0.001010            $ U-238
       8016.50c  0.338342            $ O
       9019.50c  0.030053            $ F
       1001.50c  0.616578            $ H
m2    13027.50c  1.0                 $ Al can
c
c    S(alpha, beta)
mt1   lwtr.01t
```

A20. Input File for Problem 20

```
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                  $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4600 0
c
c    Uniformly distributed volume source in each cylinder.
c    You have to set up distributions from which to choose:
c    cell, energy, radius (from axs), and z displacement (from pos).
c    Since the cylinder is in a repeated structure, but always
c    has the same cell number, you must specify the path of cells
c    which uniquely defines the cylinder you want.    The path begins
c    with the outermost cell and works down.
c
sdef  cel=d1  erg=d2  rad=d3  ext=d4  pos=0.0 0.0 9.144  axs=0 0 1
c
si1    1  3:1                             $ path:  /cell13/cell1
         13:1                             $ etc.
         23:1                             $
                                          $
         43:1                             $
         53:1                             $
         63:1                             :
sp1          1 1 1 1 1 1 1                $ equal prob for all the above
c
sp2   -3                                  $ Watt fission spectrum
c
si3       0 0 10.16                       $ radial limits
sp3  -21  1                               $ p(x) = const*abs(x)
c
si4      -9.144 9.144                     $ axial limits
sp4  -21  0                               $ p(x) = const
c
prdmp  j j 1 j                            $ write mctal file
c
print                                     $ full output
```

A20. Input File for Problem 20 (continued)

```
e5mt.21:  converted from keno file k.21; continuous energy; endf/b-5
c    Partially filled sphere.
c
c    Cell Cards
c
1     1 0.098536445   -1 -3     imp:n=1  $ partially filled sphere
2     0               -1  3     imp:n=1  $ empty part of sphere
3     2 0.060242      -2  1     imp:n=1  $ spherical tank
4     0                2        imp:n=0  $ outside of tank
c
c    Surface Cards
c
1    so   34.6
2    so   34.759
3    px   30.0
c
c    Data Cards
c
mode  n                                  $ transport neutrons only
c
c    material cards; endf/b-5 data
c    uranyl fluoride
m1   92234.50c  2.57773e-6              $ U-234
     92235.50c  6.26580e-4              $ U-235
     92238.50c  1.206203-2              $ U-238
      8016.50c  3.37540e-1              $ O
      9019.50c  2.53196e-2              $ F
      1001.50c  6.24449e-1              $ H
m2   13027.50c  1.0                    $ Al
c
c    S(alpha, beta)
mt1   lwtr.01t
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                 $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c    uniform volume source
sdef  cel=1  erg=d1  rad=d2  pos=0.0 0.0 0.0
c
sp1   -3                                 $ Watt fission spectrum
c
si2       0.0 34.6                       $ radial limits
sp2  -21  2                              $ p(x) = const*x^2
c
prdmp  j j 1 j                           $ write mctal file
c
print                                    $ full output
```

A21. Input File for Problem 21

```
e5mt.22:  converted from keno file k.22; continuous energy; endf/b-5
c
c    Cell Cards
c    This is not the optimal way to set this up; see problem 1 for
c    a better method.    This mimics KENO.
c
1     1 4.80368e-2  -37 -38 39              imp:n=1 u=1
2     1 4.80368e-2   81                     imp:n=1 u=1
3     1 4.80368e-2  -27 -28 29              imp:n=1 u=2 fill=1
4     1 4.80368e-2   83                     imp:n=1 u=2
5     1 4.80368e-2  -17 -18 19              imp:n=1 u=3 fill=2
6     1 4.80368e-2   85                     imp:n=1 u=3
7     1 4.80368e-2   -7  -8  9              imp:n=1 u=4 fill=3
8     0              87                     imp:n=1 u=4
9     0             -1  2 -3  4 -5  6       imp:n=1 u=5 lat=1
      fill=0:1 0:1 0:1  4 4  4 4  4 4  4 4
10    0             -11 12 -13 14 -15 16    imp:n=1     fill=5
11    0              810                    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -13.74
3     py  0.0
4     py -13.74
5     pz  0.0
6     pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225                $ 5.3825 above midplane
9     pz  -11.8875               $ 5.3825 below midplane
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    px  13.739
12    px -13.739
13    py  13.739
14    py -13.739
15    pz  13.009
16    pz -13.009
c    cylinder
17     c/z -6.87 -6.87  5.2224
18     pz  -1.6147               $ 4.8903 above midplane
19     pz  -11.3953              $ 4.8903 below midplane
c    cylinder
27     c/z -6.87 -6.87  4.5622
28     pz  -2.2329               $ 4.2721 above midplane
29     pz  -10.7671              $ 4.2721 below midplane
c    cylinder
37     c/z -6.87 -6.87  3.521
38     pz  -3.1193               $ 3.1307 above midplane
39     pz  -9.8557               $ 9.4307 below midplane
```

A22. Input File for Problem 22

```
c
c    Data Cards
c
mode  n                                        $ transport neutrons only
c
c    material cards; endf/b-5 data
m1    92235.50c  0.932631                      $ U-235
      92238.50c  0.0553294                     $ U-238
      92234.50c  0.0100485                     $ U-234
      92236.50c  0.00199222                    $ U-236
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                        $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
c     don't bother with uniform volume source
ksrc   6.87  6.87  6.505 -6.87  6.87  6.505 $ 1 point per cylinder
       6.87 -6.87  6.505 -6.87 -6.87  6.505
       6.87  6.87 -6.505 -6.87  6.87 -6.505
       6.87 -6.87 -6.505 -6.87 -6.87 -6.505
c
prdmp  j j 1 j                                  $ write mctal file
c
print                                           $ full output
```

A22. Input File for Problem 22 (continued)

```
e5mt.23:  converted from keno file k.23; continuous energy; endf/b-5
c    same geometry as problem 1
c    8 bare cylinders of U-metal
c
c    Cell Cards
c
1     1 4.80368e-2   7 -8  9                imp:n=1 u=-1
2     0                                     imp:n=1 u=1
3     0              -1  2 -3  4 -5  6      imp:n=1 u=2 lat=1
      fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4     0              -11 12 -13 14 -15 16   imp:n=1     fill=2
5     0               84                    imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     px  0.0
2     px -13.74
3     py  0.0
4     py -13.74
5     pz  0.0
6     pz -13.01
c    cylinder
7     c/z -6.87 -6.87  5.748
8     pz  -1.1225
9     pz  -11.8875
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    px  13.7399
12    px -13.7399
13    py  13.7399
14    py -13.7399
15    pz  13.0099
16    pz -13.0099
```

A23. Input File for Problem 23

```
c
c    Data Cards
c
mode  n                                        $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c 0.932631
     92238.50c 0.055328
     92234.50c 0.010049
     92236.50c 0.001992
c
c    S(alpha, beta):  not applicable
c
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                       $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=0 0 1
c
si1   l 4:3(1 1 0):1                    $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                    $ etc.
        4:3(0 1 0):1                    $ this ordering chosen to match
        4:3(0 0 0):1                    $   sampling in e5ce.2
        4:3(1 1 1):1                    $
        4:3(1 0 1):1                    $
        4:3(0 1 1):1                    $
        4:3(0 0 1):1                    $
sp1     1 1 1 1 1 1 1 1                 $ equal probability for all paths above
c
sp2   -3                                $ Watt fission spectrum
c
si3       0.0  5.748                    $ radial distribution
sp3  -21  1                             $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825                $ axial distribution
sp4  -21  0                             $ p(x) = const
c
prdmp  j j 1 j                          $ write mctal file
c
print                                   $ full output
```

A23. Input File for Problem 23 (continued)

```
e6mt.24:  converted from keno file k.24; continuous energy; endf/b-5
c    same geometry as problem 1, but oriented along x
c    8 bare cylinders of U-metal
c
c    Cell Cards
c
1     1 4.80368e-2  -7 -8  9                imp:n=1 u=-1
2     0             #1                      imp:n=1 u=1
3     0             -1  2 -3  4 -5  6       imp:n=1 u=2 lat=1
      fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4     0             -11 12 -13 14 -15 16    imp:n=1     fill=2
5     0              #4                     imp:n=0
c
c    Surface Cards
c
c    parallelpiped
1     pz  0.0
2     pz -13.74
3     py  0.0
4     py -13.74
5     px  0.0
6     px -13.01
c    cylinder
7     c/x -6.87 -6.87  5.748
8     px  -1.1225
9     px  -11.8875
c    parallelpiped (shrink dimensions slightly to avoid fill trouble)
11    pz  13.7399
12    pz -13.7399
13    py  13.7399
14    py -13.7399
15    px  13.0099
16    px -13.0099
c
c    Data Cards
c
mode  n                                     $ transport neutrons only
c
c    material cards; endf/b-5 data
m1   92235.50c 0.932631
     92238.50c 0.055328
     92234.50c 0.010049
     92236.50c 0.001992
c
c    S(alpha, beta):  not applicable
c
```

A24. Input File for Problem 24

```
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.0e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=1 0 0
c
si1   l 4:3(1 1 0):1                  $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                  $ etc.
        4:3(0 1 0):1                  $ this ordering chosen to match
        4:3(0 0 0):1                  $   sampling in e5cc.2
        4:3(1 1 1):1                  $
        4:3(1 0 1):1                  $
        4:3(0 1 1):1                  $
        4:3(0 0 1):1                  $
sp1     1 1 1 1 1 1 1 1               $ equal probability for all paths above
c
sp2   -3                              $ Watt fission spectrum
c
si3       0.0  5.748                  $ radial distribution
sp3  -21   1                          $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825              $ axial distribution
sp4  -21   0                          $ p(x) = const
c
prdmp  j j 1 j                        $ write mctal file
c
print                                 $ full output
```

A24. Input File for Problem 24 (continued)

```
e5mt.25:  converted from keno file t.25; continuous energy; endf/b-5
c     same geometry as problem 1, but oriented along y
c     8 bare cylinders of U-metal
c
c     Cell Cards
c
1      1 4.80368e-2  -7 -8  9                imp:n=1 u=-1
2      0             #1                      imp:n=1 u=1
3      0             -1  2 -3  4 -5  6       imp:n=1 u=2 lat=1
       fill=0:1 0:1 0:1  1 1  1 1  1 1  1 1
4      0             -11 12 -13 14 -15 16    imp:n=1      fill=2
5      0              #4                     imp:n=0
c
c     Surface Cards
c
c     parallelpiped
1      px  0.0
2      px -13.74
3      pz  0.0
4      pz -13.74
5      py  0.0
6      py -13.01
c     cylinder
7      c/y -6.87 -6.87  5.748
8      py  -1.1225
9      py  -11.8875
c     parallelpiped (shrink dimensions slightly to avoid fill trouble)
11     px  13.7399
12     px -13.7399
13     pz  13.7399
14     pz -13.7399
15     py  13.0099
16     py -13.0099
c
c     Data Cards
c
mode  n                                      $ transport neutrons only
c
c     material cards; endf/b-5 data
m1    92235.50c 0.932631
      92238.50c 0.055328
      92234.50c 0.010049
      92236.50c 0.001992
c
c     S(alpha, beta):  not applicable
```

A25. Input File for Problem 25

```
c
c    default energy bins; Hansen-Roach structure
e0    1.0e-7 4.0e-7 1.0e-6 3.0e-6 1.0e-5 3.0e-5 1.0e-4 5.5e-4 3.0e-3
      1.7e-2 0.1 0.4 0.9 1.4 3.0 20.0
c
c    tallies
f4:n   1                                   $ ave flux in cell 1
c
c    criticality cards
kcode  3000 1.0 20 200 4500 0
c
sdef  cel=d1 erg=d2 rad=d3  ext=d4  pos=-6.87 -6.87 -6.505  axs=0 1 0
c
si1   l 4:3(1 1 0):1                  $ path:  /cell4/cell3/lattice(1,1,0)/cell1
        4:3(1 0 0):1                  $ etc.
        4:3(0 1 0):1                  $ this ordering chosen to match
        4:3(0 0 0):1                  $   sampling in e5ce.2
        4:3(1 1 1):1                  $
        4:3(1 0 1):1                  $
        4:3(0 1 1):1                  $
        4:3(0 0 1):1                  $
sp1     1 1 1 1 1 1 1 1               $ equal probability for all paths above
c
sp2   -3                              $ Watt fission spectrum
c
si3       0.0  5.748                  $ radial distribution
sp3  -21  1                           $ p(x) = const*abs(x)
c
si4      -5.3825  5.3825              $ axial distribution
sp4  -21  0                           $ p(x) = const
c
prdmp  j j 1 j                        $ write mctal file
c
print                                 $ full output
```

A25. Input File for Problem 25 (continued)

APPENDIX B:

MCNP 4x-c RESULTS

MCNP version 4.2, which is the most recent MCNP release, was used to produce all of the results that are located in the main body of this report. The problems were also run with a preliminary version of MCNP4A, version 4x-c, to determine whether any discrepancies exist between the two. As these results indicate, the two versions produce the same results within statistical uncertainties.

The three tables that are included in the body of this report are reproduced below, with the 4x-c results. Table B1 contains the KENO results and the MCNP results for continuous energy, with the S(α,β) card. The percent differences between the MCNP results and the KENO results are listed in the column labeled *mcnp from keno*. The percent differences between MCNP and experimental and KENO and experimental, where available, are listed in the last two columns.

TABLE B1
k_{eff} Values for KENO and MCNP Continuous Energy with the S(α,β) Treatment

	MCNP†		KENO		%DIFFERENCE		
case	k_{ce}	*relative error*	k_{keno}	*relative error*	*mcnp from keno*	*mcnp from exp*	*keno from exp*
1	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
2	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
3	0.9990	0.0011	1.0009	0.0013	-0.2	-0.1	0.1
4	0.9945	0.0028	1.0016	0.0015	-0.7	-0.5	0.2
5	0.9995	0.0027	1.0210	0.0009	-2.1	-0.0	2.1
6	0.7461	0.0010	0.7487	0.0013	-0.3	*	*
7	0.9993	0.0009	0.9984	0.0011	0.1	-0.1	-0.2
8	0.9401	0.0009	0.9430	0.0012	-0.3	*	*
9	2.2905	0.0005	2.2617	0.0004	1.3	*	*
10	0.9979	0.0014	0.9996	0.0011	-0.2	-0.2	-0.0
11	0.9979	0.0014	0.9982	0.0012	-0.0	-0.2	-0.2
12	0.9986	0.0012	1.0055	0.0013	-0.7	-0.1	0.6
13	0.9942	0.0009	1.0026	0.0012	-0.8	-0.6	0.3
14	0.9991	0.0009	1.0011	0.0010	-0.2	-0.1	0.1
15	1.0025	0.0010	1.0012	0.0020	0.1	0.2	0.1
16	0.9887	0.0008	0.9936	0.0007	-0.5	*	*
17	1.0029	0.0014	0.9783	0.0023	2.5	*	*
18	1.0287	0.0013	1.0088	0.0015	2.0	*	*
19	0.9986	0.0012	1.0044	0.0013	-0.6	-0.1	0.4
20	0.9981	0.0014	0.9791	0.0014	1.9	-0.2	-2.1
21	0.9948	0.0009	1.0012	0.0009	-0.6	-0.5	0.1
22	0.9992	0.0009	0.9996	0.0011	-0.0	-0.1	-0.0
23	0.9999	0.0009	0.9996	0.0011	0.0	-0.0	-0.0
24	0.9982	0.0008	0.9999	0.0011	-0.2	-0.2	-0.0
25	1.0011	0.0009	0.9987	0.0011	0.2	0.1	-0.1

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

The results for the multigroup MCNP and KENO are listed in Table B2.

TABLE B2
k_{eff} Values for KENO and MCNP Multigroup

	MCNP†		KENO		%DIFFERENCE	
case	k_{mg}	*relative error*	k_{keno}	*relative error*	*mcnp from keno*	*mcnp from exp*
1	0.9971	0.0009	0.9996	0.0011	-0.3	-0.3
2	0.9960	0.0009	0.9996	0.0011	-0.4	-0.4
3	1.0199	0.0010	1.0009	0.0013	1.9	2.0
4	1.0166	0.0027	1.0016	0.0015	1.5	1.7
5	1.0187	0.0030	1.0210	0.0009	-0.2	1.9
6	0.7426	0.0008	0.7487	0.0013	-0.8	*
7	0.9966	0.0008	0.9984	0.0011	-0.2	-0.3
8	0.9357	0.0008	0.9430	0.0012	-0.8	*
9	2.2955	0.0005	2.2617	0.0004	1.5	*
10	0.9976	0.0014	0.9996	0.0011	-0.2	-0.2
11	0.9976	0.0014	0.9982	0.0012	-0.1	-0.2
12	1.0013	0.0012	1.0055	0.0013	-0.4	0.1
13	0.9918	0.0009	1.0026	0.0012	-1.1	-0.8
14	0.9944	0.0009	1.0011	0.0010	-0.7	-0.6
15	1.0292	0.0010	1.0012	0.0020	2.8	2.9
16	1.0132	0.0010	0.9936	0.0007	2.0	*
17	0.9873	0.0016	0.9783	0.0023	0.9	*
18	1.0670	0.0011	1.0088	0.0015	5.8	*
19	1.0013	0.0012	1.0044	0.0013	-0.3	0.1
20	1.0013	0.0015	0.9791	0.0014	2.3	0.1
21	0.8353	0.0009	1.0012	0.0009	-16.6	-16.5
22	0.9961	0.0008	0.9996	0.0011	-0.4	-0.4
23	0.9960	0.0009	0.9996	0.0011	-0.4	-0.4
24	0.9980	0.0008	0.9990		-0.2	-0.2
25	0.9974	0.0009	0.9987		-0.1	-0.3

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

The MCNP results for continuous energy [illegible] with the $S(\alpha,\beta)$ card, and the KENO results are given in Table B.

TABLE B3

k_{eff} Values for KENO and MCNP Continuous Energy with and without the $S(\alpha,\beta)$ Treatment

	MCNP† with $S(\alpha,\beta)$		MCNP† no $S(\alpha,\beta)$		%DIFFERENCE			
case	$k_{\alpha\beta}$	*relative error*	k_{ce}	*relative error*	with $S(\alpha,\beta)$ *no*	no $S(\alpha,\beta)$ *from keno*	with $S(\alpha,\beta)$ *from exp*	no $S(\alpha,\beta)$ *from exp*
3	0.9990	0.0011	1.0168	0.0011	-0.2	1.6	-0.1	1.7
4	0.9945	0.0028	1.0181	0.0025	-0.7	1.6	-0.5	1.8
5	0.9995	0.0027	1.0156	0.0028	-2.1	-0.5	-0.0	1.6
12	0.9986	0.0012	1.0016	0.0012	-0.7	-0.4	-0.1	0.2
15	1.0025	0.0010	1.0189	0.0012	0.1	1.8	0.2	1.9
16	0.9887	0.0008	0.9954	0.0009	-0.5	0.2	*	*
17	1.0029	0.0014	0.9830	0.0015	2.5	0.5	*	*
18	1.0287	0.0013	1.0487	0.0012	2.0	4.0	*	*
19	0.9986	0.0012	1.0016	0.0012	-0.6	-0.3	-0.1	0.2
20	0.9981	0.0014	0.9948	0.0014	1.9	1.6	-0.2	-0.5
21	0.9948	0.0009	0.9830	0.0009	-0.6	-1.8	-0.5	-1.7

* Experimental values of k_{eff} could not be located for these problems.
†Values reported are for the covariance-weighted combined estimator.

*U.S. Government Printing Office: 1992-673-036/67049