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CSNI Report No. 71

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NEA

STANDARD PROBLEM EXERCISE ON CRITICALITY CODES FOR SPENT LWR FUEL TRANSPORT CONTAINERS

by a
CSNI Working Group

FINAL REPORT
May 1982

Edited and Published by
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 U. S. A.
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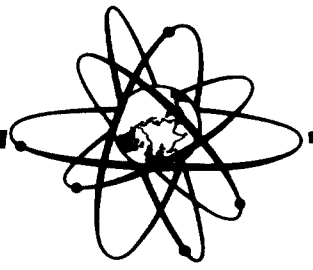

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS
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ORGANISATION FOR ECONOMIC
CO-OPERATION AND DEVELOPMENT

NUCLEAR ENERGY AGENCY

RESTRICTED

Paris, 17th November 1982

CORRIGENDUM TO
CSNI REPORT NO. 71

STEERING COMMITTEE FOR NUCLEAR ENERGY

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Swedish and Swiss members of the Working Group on the Standard Problem Exercise on Criticality Codes for LWR Fuel Transport Containers have submitted the following corrections, which should be made in the results given in CSNI Report No. 71:-

Sweden

Problem No.	$k_{eff} \pm$ st. dev.	total absorption
4.A	0.663 ± 0.006	0.947
4.A (optional)	0.649 ± 0.005	0.996
4.B	0.669 ± 0.006	0.958

Note: The previously reported results for Problem 4 were the only ones obtained using stand-alone modules of SCALE (NITAWL, KSDRNPM, KENO-IV). (The 27-group ENDF/B-IV library was used for all calculations.)
Just after the calculations reported earlier were carried out, an error in the boron isotope distribution was found. (The Boron-10 number density was over-estimated by 10%).

.../...

The same statistical input parameters, as in the Monte Carlo (KENO-IV) calculations, were used. The k_{inf}'s obtained by XSDRNPM were identical: 1.312.

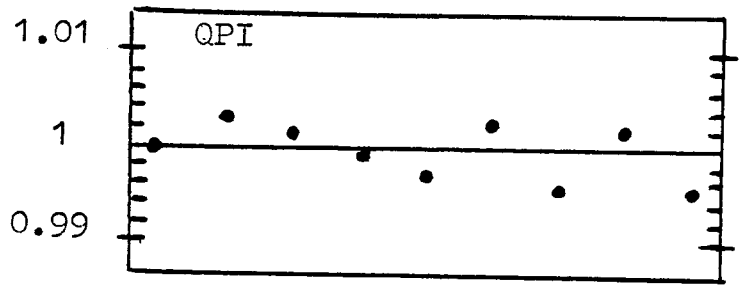
It may be noted that there was an almost identical reactivity increase in all three cases: 0.006 - 0.007. This corresponds to the changed boron isotope distribution.

The changed results affect pages 14 and 17 of CSNI Report No. 71.

Switzerland

In the Figure on p. 65 giving the Swiss QP_1 results, the vertical scale used is incorrect and should be replaced by:-

EIR Results



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by a CSNI Group of Experts
on Nuclear Criticality Safety Computations

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Committee on the Safety of Nuclear Installation
OECD Nuclear Energy Agency
38 boulevard Suchet
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The Nuclear Energy Agency (NEA) is a specialized Agency of the Organization for Economic Co-operation and Development (OECD) in Paris. The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers who have responsibilities for nuclear safety research and nuclear licensing. The Committee was set up in 1973 to develop and coordinate the Nuclear Energy Agency's work in nuclear safety matters, replacing the former Committee on Reactor Safety Technology (CREST) with its more limited scope.

The Committee's purpose is to foster international cooperation in nuclear safety among the OECD Member countries. This is done essentially by:

i) exchanging information about progress in safety research and regulatory matters in the different countries, and maintaining banks of specific data; these arrangements are of immediate benefit to the countries concerned;

ii) setting up working groups or task forces and arranging specialist meetings, in order to implement cooperation on specific subjects, and establishing international projects; the output of the study groups and meetings goes to enrich the data base available to national regulatory authorities and to the scientific community at large. If it reveals substantial gaps in knowledge or differences between national practices, the Committee may recommend that a unified approach be adopted to the problems involved. The aim here is to minimize differences and to achieve an international consensus wherever possible.

The main CSNI activities cover particular aspects of safety research relative to water reactors and fast reactors; probabilistic assessment and reliability analysis, especially with regard to rare events; siting research; fuel cycle safety research; various safety aspects of steel components in nuclear installations; and a number of specific exchanges of information.

* * *

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Table of Contents

List of Tables

List of Figures

I. Introduction

CSNI convened a meeting in June 1979 to investigate the possibility of setting up international projects on fuel cycle safety. Interest was expressed by most NEA Member countries in exchanging information and experience on various aspects of spent reactor fuel transportation, particularly criticality, shielding, and heat transfer computer code development and testing.

Following the meeting, a proposal was made by the United States for a procedure to be used in a cooperative criticality code comparison. While the basic procedure outlined in the United States proposal dealt only with criticality assessment codes, it suggested that, if successful, it would provide an incentive to pursue the other two disciplines.

Criticality assessment for nuclear materials shipping packages requires the use of highly specialized calculational techniques. The complex three-dimensional geometries and presence of large amounts of highly absorbing materials, voids, and materials not normally found in reactor analysis, present special problems in transport cask analysis.

Packages approved by national authorities for transport of fissile materials, including spent fuel, may not be accepted for international shipment unless the certification process in the originating country is examined and approved by the other countries in which the transport will occur. It is apparent that an internationally acceptable method of intercomparison and validation of criticality computational methods is required to provide increased assurance that criticality control has been accomplished in a manner which is understandable and technically confirmable both for domestic and international transport applications.

The basic concept of the U.S. proposal was that the results from different calculational techniques must be compared to actual experimental data as well as among one another for specific test problems. The assessment should thereby give a measure of both consistency and accuracy of the techniques. This would be accomplished by each participating country calculating a series of problems based upon actual experiments and transportation scenarios important to package certification procedures. Computer code results would be made available to all the participants, and a report of the results issued for CSNI endorsement.

In response to this proposal, a Working Group meeting was first convened on May 28-29, 1980, for the purpose of drawing up a problem set for the exercise. Five problems were prepared. The first three were a series of critical experiments, and the last two consisted of hypothetical casks which had characteristics similar to existing designs.

This report details the work of the group, specifications of the five problems, a summary of the results obtained by the participants, and the conclusions reached on the results presented.

The success of this exercise can be measured through the results obtained by the various calculational methods used. The specific area of application for this exercise was casks designed to transport spent light water reactor fuel. The casks were assumed to use either steel or lead as the biological shield, boron-aluminum plates between the fuel elements as a neutron poison, and water as the moderator. The range of enrichment considered was 2.35 to 4.75 % ^{235}U. The results demonstrate that the Monte Carlo and other transport methods can give satisfactory results for spent LWR fuel cask criticality calculations. The results also demonstrate that diffusion theory methods must be used with great care. Problems of the type used in this exercise have characteristics which may violate the assumptions required to use the diffusion equation as an approximation of the transport equation. It should be noted, however, that one of the diffusion calculations which use a sophisticated homogenization scheme, coupled with a bias established by comparison with transport calculations, gave good results.

II. Objective of the Exercise

The first objective of the Working Group was to establish a set of criticality problems which could be used in validating of a computation method* for evaluating the criticality safety of casks for the transport of spent light water reactor (LWR) fuel. The Working Group recognized that this exercise could not possibly cover all parameters (materials, geometries, etc.) of potential importance for spent fuel package criticality safety evaluation. It does, however, cover many of the parameters that are specific for spent fuel transport. These parameters include ^{235}U enrichment, moderation, water reflection, aluminum and zircaloy fuel claddings, boron-aluminum plates, water gaps between the boron-aluminum plates, and reflectors of lead and steel. For the purpose of this study the assumption was made that the fuel present in the cask had materials and concentrations similar to fresh LWR fuel, with no burnable poisons present. This assumption is commonly made for this type of analysis in the absence of information about the materials and concentrations present in spent fuel. The k_{eff} for this system should always be greater than that for the actual spent fuel. The additional assumption has been made that the cask has not been subjected to damage which would result in fuel pin or fuel element displacement.

A second objective of the Working Group was the evaluation of solutions submitted by the participating organizations to the set of criticality problems. These problems were submitted to the four problem coordinators who reviewed the solutions for possible errors or discrepancies. After reconciling difficulties, the four problem coordinators produced a first draft of this report, which was submitted to the entire work group.

The third objective of the Working Group was to document the problems and the solutions submitted by the participating organizations. This document would be issued as a CSNI report for review by CSNI members.

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* The definition of "method" is that as used in ANSI N16.9 (1975) - "...the mathematical equations, approximations, assumptions, associated numerical parameters (e.g., cross sections), and calculated procedures which yield the calculated results."

III. Basis for Choosing the Problems to be Used

Exact analytical solutions are not known to the mathematical equations which determine the k_{eff} of a cask. It is therefore necessary to compare computations with experimental data pertinent to actual designs of LWR cask. By observing differences between the calculated and experimental data, it is possible to assess the accuracy and precision of the calculational method for that particular system. By comparing calculated and experimental data over a range of parameters, it is possible to establish the validity of the method for performing a specified class of problems.

The set of problems chosen for this exercise was intended to provide a step-by-step procedure for establishing the validity of a computational method in determining the k_{eff} of an LWR spent fuel shipping cask which uses a boron-aluminum material, Boral, as a neutron poison, is moderated by light water, and uses steel or lead as the biological shield around the fuel. The cask and fuel configurations were assumed to be as designed. No transportation accidents which could result in changes in the cask and fuel configuration were considered. The fuel considered in these problems was assumed to be fresh fuel with no burnable poison present.

The experimental data used as Problems 1 through 3, were chosen from experiments performed in France and the United States. These data were chosen to present several important parameter variations necessary for the validation of a method to be used in LWR cask evaluations. The data are presented in the form provided the experimentalists, and gave most of the detailed information about the experiment. While much of the detail may seem unimportant, it was included since this is the form of presentation usually encountered. Indeed, using the data in this form is an important exercise since failure to learn how to correctly read and understand the experimental data report could lead to difficulty in validating a method.

The experiments chosen for Problem 1 consisted of simple arrays of fuel pin clusters moderated and reflected by light water. The intent of this exercise was to establish the validity of the basic neutronics calculations of a method.

Problem 2 consisted of experiments in which arrays of clusters of fuel pins, moderated and reflected by light water, had plates of Boral placed between the clusters. Boral was chosen for this exercise since it has been considered as a likely neutron absorber for casks.

The French-supplied portions of Problem 3 added an additional feature to Problem 2 by placing a thick lead or steel reflector around the array. The U.S.-supplied portions of Problem 3 were neutronically similar to Problem 1 with a thick lead or steel reflector. While experiments exist involving depleted uranium as a biological shield, they were not considered in this exercise.

As the reader will observe, these problems exercise the various elements of a code necessary to perform a LWR cask criticality calculation. These elements were put together in Problem 4, comprising a hypothetical cask design, with the validity of the solution being determined by the results of Problems 1 though 3. After reviewing the initial results of Problem 4, the working group agreed that a second hypothetical cask, Problem 5, should be added. It included a higher fuel enrichment with the water density between the fuel elements reduced sufficiently to produce a k_{eff} of at least 0.90.

An essential and important element of Problems 4 and 5 was that the code user must go through the additional steps necessary to move from an often idealized experiment and to apply the method to a real problem for which the solution is not known. In particular, the user encountered the need to model complex geometrical features in their calculation.

As noted above, the problems chosen for this exercise were designed to validate computations for spent fuel transport casks which use lead or steel as the biological shield, Boral as the neutron poison, and water as the moderator. To validate calculations for transport casks which use other materials as the biological shield, neutron poison or moderator, corresponding experimental data will have to be used.

Finally, the logic used in choosing experiments was to establish the validity in a stepwise fashion, a new parameter being introduced with each new problem. In this way the effect of the new parameter on the validity of the method can be observed. This will prevent the masking of errors by a combination of negative and positive bias in the results of the total system which could lead to unwarranted confidence in the results. Similar logic in choosing experiments should be used in extending the validation.

IV. The Benchmark Problems Chosen

1.1 Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water

1.2.1 and 1.2.2 Critical Array of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods in Water

2.1 Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Three Fuel Assemblies (3x1 array) With Boral Poison Plates Between the Assemblies

2.2 Critical Array of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Four Fuel Assemblies (2x2 array) With Boral Poison Plates Between the Assemblies

3.A.1 Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Three Fuel Assemblies (3x1 array) With a Lead Reflector on Two Faces

3.A.2 Critical Array of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Four Fuel Assemblies (2x2 array) With Boral Poison Plates Between the Assemblies and With Lead Reflecting Walls on Four Faces

3.B.1 Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Three Fuel Assemblies (3x1 array) With a Steel Reflector on Two Faces

3.B.2 Critical Array of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods in Water Arranged to Simulate Four Fuel Assemblies (2x2 array) With Boral Poison Plates Between the Assemblies and With Steel Reflecting Walls on Four Faces

4.A Simulated PWR Spent Fuel Shipping Cask Containing Seven Fuel Elements Made up of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods, Flooded With Water, Boral Plates Surrounding Each Fuel Element, and a Biological Shield of Thick Lead

4.A Optional Same as 4.A Except With Water Added Between the Rectangular Box Containing the Fuel and the Circular Biological Shield

4.B Same as 4.A Except With a Biological Shield of Thick Steel

5. Simulated PWR Spent Fuel Shipping Cask Containing Seven Fuel Elements Made up of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods, Flooded With Water Between the Pins but With Reduced Water Density Between the Fuel Elements, Boral Plates Surrounding Each Fuel Element, and a Biological Shield of Thick Steel

V. Summary of the Methods Used by Participating Organizations

Table R0 Data Flow of Calculation

Member	X-Section Data Base	Fine group Constants Generation	Fine Group Constants	Broad Group Constants Generation	Broad Group Constants	Transport Calculation
IRS			69-Group LWR-WIMS Lib.	WIMS-D	5-Group Constants	EXTERMINA-TOR-2
BN	(UKNDL)*		69-group UKNDL-Lib.	PERSEUS	16-Group Constants	KENO-IV
	69-Group UKNDL-Lib.	Weighting by Typical Spectra	28 Group Standard Lib.		6-Groups Constants	GOG
EIR	(ENDF/B-4)*	ETOBOX	28 Fast + 42 Thermal Groups	BOXER	6-Groups Constants	CODIFF QP1
PTB	(ENDF/B-4)*	(RSYST-)* Moduls	99 Fast + 126 Therm. Groups	via 60-Grp. Microscop. Constants	20-Group Macroscop. Constants	MORSE-K (CG)
GRS			GAM-I BRT-I Libs.	GAMTEC-2, BRT-1	16-Group Constants	KENO-IV
CEA	(ENDF/B UKAEA SACLAY)*		99-Group Standard Lib. (52 Fast + 47 Thermal)	Transport Correction B_1-Appr.	16-Group APOLLO and Hansen Roach Constants	MORET
SRD	(UKNDL)*	POND*	MONK data library (point X-sections)			MONK-5.3
CNEN	(UKNDL)*	POND*	MONK data Library (point X-sections)			MONK-5
	(GENERAL ATOMIC LIBRARY)*	GAM-GATHER	13 Gam Grp 16 Gather Grp 29 Combine Grp for ANISN Calculation	ANISN Brd. Grp. Y-SECT.	16 Group ANISN and HANSEN-ROACH CONSTANTS	KENO-IV
JAERI	(ENDF/B-4)*	Several MGCL-ACE Moduls	137-Group MGCL-Lib.	MAIL	137-Group Macroscop. Constants	KENO-IV
Studs-vik	(UKNDL)*		UKNDL-25-Group Lib.	CASMO	6-Group Constants	DIXY
EMS	(218 Group SCALE Lib. (ENDF/B-4 -Based))*		27-Group SCALE-Lib.	SCALE-System	27-Group Constants	KENO-IV
ASEA	(UKNDL)*		UKNDL-25 and 69 Group Lib.	PHOENIX and MICO	13-Group Constants	KENO-IV
VTT	(ENDF/B-3)*		27-Group* Lib.	CASMO-HEX	6-Group Constants	GOG
ORNL	218 Group SCALE Lib. (ENDF/B-4 -Based)*	Westfall-* Procedure	27-Group SCALE Lib.	SCALE (NITAWL)	27-Group Constants	KENO-IV
				SCALE (NITAWL, XSDRN-PM)	27-Group Constants	KENO-IV

( )* : No explicit use for benchmark calculations

VI. Summary of Results

Table R1 Comparison of Results: k_{∞} k_{eff} $\pm$ σ Absorption*

Member		Benchmark		
		1.1	1.2.1	1.2.2
IRS	Broad Grp. Macrosc. Constants/2-dim. Diffusion Calc.	-- 0.99318 0.9773	-- -- --	-- -- --
BN	Generation of Group Constants/ Monte Carlo Calc.	-- 0.99776 ± 5.49-3 0.9813	-- -- --	-- -- --
	Generation of Group Constants/ Diffusion Calc.	-- 0.98992 --	-- 0.98920 --	-- 0.98826 --
EIR	Broad GP Constant Diffusion	-- 0.9923 0.9675	-- 0.9920 0.9576	-- 0.9870 0.95082
	Broad GP Constant Transport	1.3095 0.9999 0.9583	1.48413 1.0037 0.9438	1.50481 1.0019 0.9345
PTB	RSYST Group Constants/Monte Carlo-Calculation	1.30188 0.9960 ± 0.0074 --	1.4565 0.9987 ± 0.0089 --	1.4969 1.001 ± 0.0099 --
GRS	GAMTEC+BRT Group Const./Monte Carlo	-- 1.012 ± 0.002 0.9722	-- 1.007 ± 0.003 0.9869	-- 1.015 ± 0.003 0.9726
CEA	Group Constants By Transp. Corr./M.C.	1.3158 0.9993 ± 0.0045 0.9815	1.4898 1.0033 ± 0.0075 0.970	1.5129 1.0090 ± 0.0060 0.960
	Group Constants By B_1-Appr./M.C.	1.3157 0.9931 ± 0.0045 0.9873	1.4897 1.0048 ± 0.0051 0.9698	1.5128 1.0063 ± 0.0059 0.960
SRD	MONK-Point Data/ Monte Carlo Calc.	1.3109 ± 0.0104 1.0076 ± 0.0102 0.9707	1.4812 ± 0.0106 1.0058 ± 0.0098 0.956	1.5169 ± 0.0100 1.0018 ± 0.0102 0.9531
	MONK-Point Data/ Monte Carlo Calc.	-- 1.0077 ± 0.0079 --	-- 1.0137 ± 0.0084 --	-- 1.0128 ± 0.0092 --
CNEN	Homogenized Brd. Grp. Const/Monte Carlo Calculation (KENO-IV)			
	ZONE Brd. Grp. Const/Explicit Assembly Desc. Monte Carlo Calc. (KENO IV)			
JAERI	Monte Carlo	-- 0.9926 ± 0.0027 0.998	-- 0.9908 ± 0.0017 0.963	-- 0.9889 ± 0.0016 0.955
Studs-vik	1-D Integral Transp 2-D S_4 Transport 2-D Diffusion	1.311 1.003 --	1.4804 1.002 --	1.506 1.004 --
EMS	Resonance Corr. + Cell Homo Monte Carlo	1.304 0.996 ± 0.005 0.975	1.475 0.990 ± 0.006 0.941	1.500 1.001 ± 0.007 0.933
ASEA	1-D Integral Transp Monte Carlo	1.309 1.017 ± 0.005 0.996	1.479 1.017 ± 0.006 0.961	1.504 1.017 ± 0.006 0.951
VTT	Homogenized Brd. Grp. Const. 2-D Diffusion	1.3018 0.9951 0.9582	1.4818 1.0192 0.9581	1.4992 1.0072 0.9486
	Resonance Calc./ Monte Carlo Resonance Corr. + Cell Homogeniz./ Monte Carlo Calc.	-- 0.994 ± 0.003 -- 0.996 ± 0.003 0.9918	-- 0.994 ± 0.004 -- 0.989 ± 0.004 0.991	-- 0.997 ± 0.004 -- 0.990 ± 0.004 0.967

*Due to varying water reflector thicknesses used in some computational models, and two-dimensional methods which ignored absorptions in the axial reflector, the values quoted for absorption do not necessarily have a common base of definition.

Table R1 Comparison of Results: k_{∞} k_{eff} $\pm \sigma$ Absorption*

Member	Comp. Scheme X-Sections / Transp. Calc.	Benchmark 2.1	Benchmark 2.2
IRS	Broad Grp. Macrosc. Constants/2-dim. Diffusion Calc.	--	--
BN	Generation of Group Constants/ Monte Carlo Calc.	--	--
		0.99313 ± 0.00506	--
		0.9908	--
	Generation of Group Constants/ Diffusion Calc.	--	--
		0.99301	0.99924
		--	--
EIR	Broad GP Constant Diffusion	--	--
		0.9921	0.9876
		0.96964	0.9580
	Broad GP Constant Transport	1.30951	1.50481
		0.9983	0.9952
		0.9623	0.9499
PTB	RSYST Group Constants/Monte Carlo-Calculation	1.3018	1.4969
		1.003 ± 0.0068	0.9976 ± 0.0075
GRS	GAMTEC+BRT Group Const./Monte Carlo	--	--
		1.008 ± 0.003	1.020 ± 0.003
		0.9969	0.9787
CEA	Group Constants By Transp. Corr./M.C.	1.3158	1.5129
		1.0095 ± 0.0045	1.015 ± 0.0045
		0.9932	0.9782
	Group Constants By B_1-Appr./M.C.	1.3157	1.5128
		1.0130 ± 0.0045	1.0160 ± 0.0054
		0.9956	0.9764
SRD	MONK-Point Data/ Monte Carlo Calc.	1.3109 ± 0.0104	1.5169 ± 0.0100
		1.0064 ± 0.0103	1.0202 ± 0.0103
		0.9967	0.9763
CNEN	MONK-Point Data/ Monte Carlo Calc.	--	--
		1.0158 ± 0.0075	1.0056 ± 0.0086
		0.9968	0.9705
	Homogenized Brd. Grp. Const/Monte Carlo Calculation (KENO-IV)		
	ZONE Brd. Grp. Const/Explicit Assembly Descript Monte Carlo Calc. (KENO IV)		
JAERI	Monte Carlo	--	--
		0.9910 ± 0.0022	0.9921 ± 0.0035
		1.0007	0.9623
Studs-vik	1-D Integral Transp	1.311	1.506
	2-D S_n Transport	1.006	1.010
	2-D Diffusion	--	--
EMS	Resonance Corr. + Cell Homo Monte Carlo	1.304	1.500
		1.000 ± 0.006	1.011 ± 0.006
		0.982	0.978
ASEA	1-D Integral Transp Monte Carlo	1.309	1.504
		1.006 ± 0.006	1.017 ± 0.007
		0.994	0.971
VTT	Homogenized Brd. Grp. Const. 2-D Diffusion	1.3018	1.4992
		1.01104	1.02573
		0.9994	0.9957
ORNL	Resonance Calc./ Monte Carlo	--	--
		0.997 ± 0.003	0.994 ± 0.004
		0.9850	0.9725
	Resonance Corr. + Cell Homogeniz. Monte Carlo Calc.	--	--
		0.991 ± 0.003	0.996 ± 0.003
		0.9997	0.9787

*Due to varying water reflector thicknesses used in some computational models, and two-dimensional methods which ignored absorptions in the axial reflector, the values quoted for absorption do not necessarily have a common base of definition.

Table R1 Comparison of Results: k_∞ / $k_{eff} \pm \sigma$ / Absorption[a]

Member	Comp. Scheme X-Sections / Transport Calc.	Benchmark 3A1	3B1	3A2	3B2
IRS	Broad Grp. Macrosc. Constants/2-dim. Diffusion Calc.	-- 0.9945 0.967	-- -- --	-- -- --	-- -- --
BN	Generation of Group Constants/ Monte Carlo Calc.	-- 1.0072 ± 0.0051 0.989	-- 1.0095 ± 0.0041 0.9964	-- 1.020 ± 0.004 0.949	-- 1.023 ± 0.005 0.946
	Generation of Group Constants/ Diffusion Calc.	-- -- --	-- -- --	--	--
EIR	Broad GP Constant Diffusion	-- 0.9932 0.9614	-- 0.9947 0.9652	-- 0.9884 0.9080	-- 0.9908 0.9040
	Broad GP Constant Transport	1.30951 1.0035 0.9509	1.3095 1.0032 0.9565	1.50481 09933 0.9047	1.50481 0.9941 0.9020
PTB	RSYST Group Constants/Monte Carlo-Calculation	1.3018 0.9960 ± 0.010 --	1.3018 0.993 ± 0.007 --	1.4969 1.006 ± 0.0099 --	1.4969 1.007 ± 0.005
GRS	GAMTEC+BRT Group Const./Monte Carlo	-- 1.005 ± 0.003 0.992	-- 1.009 ± 0.002 0.993	-- 1.018 ± 0.003 0.965	-- 1.025 ± 0.003 0.965
CEA	Group Constants By Transp. Corr./M.C.	1.3158 1.011 ± 0.0045 0.995	1.3158 1.007 ± 0.0045 0.993	1.5129 1.019 ± 0.0045 0.956	1.5129 1.008 ± 0.0045 0.967
	Group Constants By B1-Appr./M.C.	1.3157 1.007 ± 0.0045 0.995	1.3157 0.995 ± 0.0045 0.993	1.5128 1.015 ± 0.0045 0.963	1.5128 1.013 ± 0.0045 0.961
SRD	Monte Carlo Calc.	1.3109 ± 0.0104 1.0098 ± 0.010 0.9978	1.3109 ± 0.0104 1.018 ± 0.010 0.9967	1.5169 ± 0.0100 1.018 ± 0.011 0.9634	1.5169 ± 0.0100 1.018 ± 0.0088 0.9650
CNEN	MONK-Point Data/ Monte Carlo Calc.	-- 1.0134 ± 0.0091 --	-- 1.0025 ± 0.0088 --	-- 1.016 ± 0.008 --	-- 1.023 ± 0.0078 --
	Homogenized Brd. Grp. Const/Monte Carlo Calculation (KENO-IV)				
	ZONE Brd. Grp. Const/Explicit Assembly Descript Monte Carlo Calc. (KENO IV)				
JAERI	Monte Carlo	-- 0.9930 ± 0.0015 --	-- 0.990 ± 0.0014 --	-- 0.9876 ± 0.0020 --	-- 0.9927 ± 0.0046 --
Studs-vik	1-D Integral Transp 2-D S_4 Transport 2-D Diffusion	1.311 0.998 --	1.311 0.994 --	1.506 1.000 --	1.506 1.006 --
EMS	Resonance Corr. + Cell Homo Monte Carlo	1.304 0.997 ± 0.006 0.968	1.304 0.998 ± 0.005 0.99	1.500 0.999 ± 0.007 0.928	1.500 1.003 ± 0.006 0.939
ASEA	1-D Integral Transp Monte Carlo	1.309 0.997 ± 0.004 0.987	1.309 1.004 ± 0.005 0.996	1.504 0.998 ± 0.005 0.938	1.504 1.020 ± 0.005 0.945
VTT	Homogenized Brd. Grp. Const. 2-D Diffusion	1.302 0.9887 0.961	1.302 0.9856 0.9635	1.499 0.9927 0.9038	1.499 0.9756 0.8919
ORNL	Resonance Calc./ Monte Carlo	-- 0.997 ± 0.004 0.9914	-- 0.994 ± 0.004 0.997	-- 0.994 ± 0.004 0.967	-- 0.994 ± 0.0037 0.968
	Resonance Corr. + Cell Homogeniz. Monte Carlo Calc.	-- 0.995 ± 0.004 0.9956	-- 0.997 ± 0.004 0.997	-- 0.994 ± 0.003 0.967	-- 1.005 ± 0.0040 0.968

[a]Due to varying water reflector thicknesses used in some computational models, and two-dimensional methods which ignored absorptions in the axial reflector, the values quoted for absorption do not necessarily have a common base of definition.

Table R1 Comparison of Results: k_∞ / k_{eff} ± σ Absorption*

Member	Comp. Scheme X-Sections / Transp. Calc.	Benchmark 4.A	Benchmark 4.A (Optional)	Benchmark 4.B
IRS	Broad Grp. Macrosc. Constants/2-dim. Diffusion Calc.	-- -- --	-- -- --	-- -- --
BN	Generation of Group Constants/ Monte Carlo Calc.	1.33274 0.676 ± .004 0.937516	1.33274 0.678 ± .004 0.993124	1.33274 0.683 ± .004 0.953597
	Generation of Group Constants/ Diffusion Calc.			
EIR	Broad GP Constant Diffusion	1.32105 0.6449 .9481	1.32105 0.6523 .9936	1.32105 0.6452 .9608
	Broad GP Constant Transport	1.32105 0.6769 .9441	1.32105 0.6675 .9925	1.32105 0.6779 .9575
PTB	RSYST Group Constants/Monte Carlo-Calculation	-- 0.6779 ± 0.0061 --	-- 0.6782 ± 0.0078 --	-- 0.683 ± 0.003 --
GRS	GAMTEC+BRT Group Const./Monte Carlo	-- 0.683 ± 0.003 --	-- 0.681 ± 0.002 --	-- 0.685 ± 0.003 --
CEA	Group Constants By Transp. Corr./M.C.	1.32481 0.6935 ± .0045 0.950	1.32481 0.6830 ± .0045 0.9935	1.32481 0.6965 ± .0045 0.9613
	Group Constants By B_1-Appr./M.C.	-- -- --	-- -- --	-- -- --
SRD	Monte Carlo Calc.	1.3318 ± 0.0099 0.6754 ± 0.0095 0.9436	1.3318 ± 0.0099 0.6760 ± 0.0091 0.9911	1.3318 ± 0.0099 0.6754 ± 0.0095 0.9543
CNEN	MONK-Point Data/ Monte Carlo Calc.	-- 0.6826 ± 0.0077 --	-- 0.6739 ± 0.0077 --	-- 0.6864 ± 0.0077 --
	Homogenized Brd. Grp. Const/Monte Carlo Calculation (KENO-IV)	1.33085 0.687 ± 0.004 0.9642	1.33085 0.676 ± 0.004 1.00839	1.33085 0.691 ± 0.004 0.97786
	ZONE Brd. Grp. Const/Explicit Assembly Descript Monte Carlo Calc. (KENO IV)	1.33545 0.6861 ± 0.0041 1.00103	1.33545 0.6896 ± 0.0039 0.96041	1.33545 0.6894 ± 0.0039 0.9658
JAERI	Monte Carlo	0.6691 ± 0.0020 --	0.6592 ± 0.0018 --	0.6691 ± 0.0017 --
Studsvik	1-D Integral Transp 2-D S_N Transport 2-D Diffusion	1.321 0.670 --	1.321 0.665 --	1.321 0.672 --
EMS	Resonance Corr. + Cell Homo Monte Carlo	1.312 0.656 ± 0.005 0.940	1.312 0.643 ± 0.006 0.993	1.312 0.663 ± 0.005 0.960
ASEA	1-D Integral Transp Monte Carlo	1.316 0.682 ± 0.009 0.939	1.316 0.665 ± 0.007 0.995	1.316 0.675 ± 0.007 0.947
VTT	Homogenized Brd. Grp. Const. 2-D Diffusion	1.320 0.700 --	1.320 0.667 --	1.320 0.701 --
ORNL	Resonance Calc./ Monte Carlo			
	Resonance Corr. + Cell Homogeniz. Monte Carlo Calc.	1.3114 0.663 ± 0.004 0.9537	1.3114 0.655 ± 0.004 0.9988	1.3114 0.656 ± 0.004 0.9581

*Due to varying water reflector thicknesses used in some computational models, and two-dimensional methods which ignored absorptions in the axial reflector, the values quoted for absorption do not necessarily have a common base of definition.

Table R1 Comparison of Results: k_∞ / k_{eff} ± σ / Absorption*

Member	Comp. Scheme X-Sections / Transp. Calc.	Benchmark 5
IRS	Broad Grp. Macrosc. Constants/2-dim. Diffusion Calc.	-- -- --
BW	Generation of Group Constants/ Monte Carlo Calc.	1.4829 0.937 ± 0.003 0.92915
	Generation of Group Constants/ Diffusion Calc.	-- -- --
EIR	Broad GP Constant Diffusion	1.47115 0.8997 .9066
	Broad GP Constant Transport	1.47115 0.9222 .9216
PTB	RSYST Group Constants/Monte Carlo-Calculation	1.453 0.9166 ± 0.0079 --
GRS	GAMTEC+BRT Group Const./Monte Carlo	-- 0.9384 ± 0.003 0.9218
CEA	Group Constants By Transp. Corr./M.C.	1.4773 0.9405 ± 0.0045 0.927
	Group Constants By B_1-Appr./M.C.	-- -- --
SRD	Monte Carlo Calc.	1.4889 ± .0098 0.9187 ± .0108 0.9579
CNEN	MONK-Point Data/ Monte Carlo Calc.	-- 0.9548 ± 0.0067 0.9969
	Homogenized Brd. Grp. Const/Monte Carlo Calculation (KENO-IV)	1.489 0.936 ± 0.004 0.918
	ZONE Brd. Grp. Const/Explicit Assembly Descript Monte Carlo Calc. (KENO IV)	-- -- --
JAERI	Monte Carlo	-- 0.9277 ± 0.0021 --
Studs-vik	1-D Integral Transp 2-D S_N Transport 2-D Diffusion	-- 0.932 --
EMS	Resonance Corr. + Cell Homo Monte Carlo	1.463 0.914 ± 0.005 0.925
ASEA	1-D Integral Transp Monte Carlo	1.467 0.932 ± .009 0.956
VTT	Homogenized Brd. Grp. Const. 1-D Diffusion	-- 0.92 ± 0.030
ORNL	Resonance Calc./ Monte Carlo	-- -- --
	Resonance Corr. + Cell Homogeniz. Monte Carlo Calc.	1.46312 0.918 ± 0.004 0.9302

*Due to varying water reflector thicknesses used in some computational models, and two-dimensional methods which ignored absorptions in the axial reflector, the values quoted for absorption do not necessarily have a common base of definition.

VII. Conclusions Reached About the Results

All of the results obtained for Problems 1, 2, and 3 are very satisfactory. The calculated k_{eff} values agree with the experiments to within about ± 2%.

Results of theoretical configurations proposed in Problems 4 and 5 (which are neither critical nor experimental) present a bigger spread:

For Problem 4A	$0.645 < k_{eff} < 0.700$
For Problem 4A Opt.	$0.643 < k_{eff} < 0.690$
For Problem 4B	$0.645 < k_{eff} < 0.701$
For Problem 5	$0.900 < k_{eff} < 0.955$

The graphic representation of results in Appendix II leads us to conclude that all of the results obtained by each organization are coherent (i.e., if we detect a tendency of the calculation method to overestimate the k_{eff} in Problem 1, 2, and 3, this is also observed in Problems 4 and 5).

It was observed that good results were obtained from all methods with the exception of some of the diffusion methods. One diffusion method which used a specialized homogenization procedure gave good results.

VIII. Conclusions Reached About the Benchmark Exercise

The Working Group has established a set of benchmark problems which can be useful during the validation of a method for determining the k_{eff} of casks designed to transport LWR fuel. These problems have been used to judge the validity of several methods currently being used by Working Group members, listed in Appendix III, as a part of this exercise.

The problem set outlined in Section 3 will be useful to anyone in attempting to establish the validity of a method. By observing the logic used in choosing the experiments, it will be possible for a user to extend the validation procedure to cover other parameters as needed. In validation it is important that either parameters of a problem be present in the experiments used for validation or that allowance be made in the computed results to allow for any uncertainty resulting from this lack of information.

Those attempting to use Section 3 to learn the validation procedure should be cautioned that they are now being supplied in this report the estimated values of k_{eff} for Problems 4 and 5. The original participants did not have the values of k_{eff} available. Having the estimated k_{eff}'s available will be an important disadvantage since by knowing the answer it will be easier to reach the correct solution by correcting one's own errors. This eliminates the lessons learned by having errors found and pointed out by a third party.

One of the features which emerged very clearly from the evaluation of Problem 4 was the wide range of the initial results; whereas, the results for Problems 1-3 (which were known in advance) showed comparatively little spread. Even though the results of Problems 1-3 were more consistent, the importance of the role of the Problem Coordinators in collecting and reviewing the results was clearly evident. Each installation had been requested to submit sufficient information so that an independent assessment could be made of whether the problems had been specified correctly. Most installations submitted a copy of the output listing from the computer solutions. Generally these outputs contained sufficient reproduction of the input data so that it was possible to determine the problem specification input accuracy. This step in the problem evaluation provided an excellent control measure in comparing the results. Since as noted elsewhere in this report, the experimental data was presented in the form reported by the experimentalists, there were a variety of interpretations made for several parameter specifications. Through the review process, a number of incorrect parameter specifications were observed and corrected. This experience emphasizes that an adequate review of input specifications and computer code usage is an important aspect of a calculational method validation.

In addition to providing a benchmark procedure and providing an opportunity to validate several methods, the Working Group experience has enabled the participants to discuss and compare a variety of methods. The latter has been most useful in allowing each participant to observe and discuss the methods being used by the other participants. This should lead to improved methods and to more extensive use of methods which have been shown to be successful.

IX. Possible Extensions

The set of problems documented in this report constitutes a typical procedure for validating calculations for a single undamaged LWR cask. To analyze completely the criticality safety of such a cask, it is also necessary to determine and evaluate the consequences of an accident and the interaction with either another cask or other fissile material which might be in the vicinity of the cask. The first problem requires considering a change in the fuel moderation, a change in the position of the Boral with respect to the fuel rods, and a change in the distance from the fuel rods to the biological shield. While it would be possible to describe the analysis required, this is considerably beyond the scope of the present study.

The effects of interaction with other casks or fissile material was also considered beyond the scope. However, the effect on k_{eff} of interaction between casks of the type described in Problems 4 and 5 should be very minimal. In the case with the greatest amount of leakage, less than 8 % of the neutrons leak from the system. The geometric attenuation, along with the fact that after a neutron struck another cask it would have to penetrate the shield of the cask before causing another fission; makes it highly unlikely that interaction between casks of this type could have a significant effect on k_{eff}. However, shipping packages with a higher potential for neutron interaction should always be evaluated.

X. Appendices

Appendix I
Detailed Specifications

Listing of Benchmark Problems

Benchmark Problem 1-1

Title:	Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water
Geometry:	Single array of 20 x 18.08 ± 0.02 rods with at least 152 mm water reflector on all sides. Experimental task facilities description shown in Fig. 1. Pins are arranged in a square pitch with a center-to-center spacing of 20.32 mm.
Fuel Design:	See Figure 2.
Aluminum Composition:	See Table 1.
General Comments:	Note that while the cladding of each fuel rod is 6061 aluminum, the end caps and fittings are slightly different, as is the case for some of the structure described in Fig. 1. The information given in Table 1 for 6061 aluminum can be used for all aluminum. The acrylic shown in Fig. 1 is actually Plexiglas and for calculational purposes can be considered to be water. The effect of using 20 x 18 rods rather than 20 x 18.08 as reported in the experiment will result in a ΔK less than 0.001. Hence 20 x 18 rods may be used if desirable. Figure 1 shows poison plates and biological shields which were not present in this experiment.
Reference:	S. R. Bierman et al., "Critical Separation Between Subcritical Clusters of 2.35 wt % and 4.29 wt % ^{235}U Enriched UO_2 Rods in Water With Fixed Neutron Poisons," PNL 2438 (1977).

Benchmark Problem 1-2-1
and 1-2-2

Title:	Lattices of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods In Water
Geometry:	See Figure 3.
Fuel Design:	See Figure 3 and Table 2.
Critical Dimensions:	See Table 2.
Reference:	J. C. Manaranche et al., "Critical Experiments With Lattices of 4.75 wt % ^{235}U Enriched UO_2 Rods in Water," Nuclear Science Engineering 71, 154 - 163 (1979).

Benchmark Problem 2-1

Title:	Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods with Boral Plates in Water
Geometry:	An array of three fuel assemblies (3X1 array) with boral poison plates between the assemblies. Geometric details are shown in Fig. 1.
Fuel Design:	See Figure 2.
Boral and Aluminum Composition:	See Table 1.
Critical Dimensions:	See Table 3.
General Comments:	Note that while the cladding of each fuel rod is 6061 aluminum, the end caps and fittings are slightly different, as is the case for some of the structure described in Fig. 1. The information given in Table 1 for 6061 aluminum can be used for all aluminum. The acrylic shown in Fig. 1 is actually Plexiglas and for calculational purposes can be considered to be water. Figure 1 shows biological shields which were not present in this experiment.
References:	S. R. Bierman et al., "Critical Separation Between Subcritical Clusters of 2.35 wt % and 4.29 wt % ^{235}U Enriched UO_2 Rods in Water With Fixed Neutron Poisons," PNL 2438 (1977).

Benchmark Problem 2-2

Title:	4 Clusters of 4.75 wt % ^{235}U Enriched Rods UO_2 With Boral Plates In Water
Geometry:	See Figure 4(a).
Fuel Design:	See Figure 4 and Table 4.
Shielding Plates Design:	See Figure 4.
Reference:	D. Haon et al., "Validation of the APOLLO-MORET Neutronic Codes on Critical Experimental Configurations Simulating the Shipping Casks for Light Water Fuels," PATRAM '80, p. 872-880 (1980).

Benchmark Problem 3-A-1

Title:	Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water With Lead Reflecting Walls
Geometry:	3X1 array of fuel assemblies with lead reflector on two faces. Geometry is shown in Fig. 5.
Fuel Design:	See Figure 2.
Aluminum Composition:	See Table 1.
Shielding Wall Design:	See Figure 6.
Critical Dimensions:	See Table 5.
Reference:	S. R. Bierman et al., "Criticality Experiments With Subcritical Clusters of 2.35% and 4.29 wt % ^{235}U Enriched UO_2 Rods in Water With Uranium or Lead Reflecting Walls," PNL-2827 (1979).

Benchmark Problem 3-A-2

Title:	4 Clusters of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods In Water With Boral Plates and Lead Reflecting Walls
Geometry:	See Figure 7 (a).
Fuel Design:	See Figure 7 and Table 4.
Boral Plates Design:	See Figure 7 and Table 4.
Reflecting Walls:	See Figure 7 (a) and Table 4.
Reference:	D. Haon et al., "Validation of the APOLLO-MORET Neutronic Codes on Critical Experimental Configurations Simulating the Shipping Casks for Light Water Fuels," PATRAM '80, p. 872-880 (1980).

Benchmark Problem 3-B-1

Title:	Critical Array of 2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in Water With Steel Reflecting Walls
Geometry:	3 x 1 array of fuel assemblies with a steel reflector on two faces. Geometry is shown in Fig. 5.
Fuel Design:	See Figure 2.
Aluminum Composition:	See Table 1.
Shielding Wall Design:	See Figure 8.
Critical Dimensions:	See Table 6.
Reference:	S. R. Bierman et al., "Criticality Experiments With Subcritical Clusters of 2.35 wt % and 4.31 wt % ^{235}U Enriched UO_2 Rods in Water With Steel Reflecting Walls," PNL-3602 (1981).

Benchmark Problem 3-B-2

Title:	4 Clusters of 4.75 wt % ^{235}U Enriched UO_2 Fuel Rods In Water With Boral Plates and Steel Reflecting Walls
Geometry:	See Figure 7 (b).
Fuel Design:	See Figure 7 and Table 4.
Boral Plates Design:	See Figure 7 and Table 4.
Reflecting Walls:	See Figure 7 (b) and Table 4.
Reference:	D. Haon et al., "Validation of the APPOLO-MORET Neutronic Codes on Critical Experimental Configurations Simulating the Shipping Casks for Light Water Fuels," PATRAM '80, p. 872-880 (1980).

Benchmark Problem 4-A

Title:	2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in a PWR Fuel Shipping Cask With Lead Shield
Geometry:	See Figures 9 and 10.
Fuel Design:	See Table 7.
Boral, Zircaloy-4, SS-304L Composition:	See Table 1.

Benchmark Problem 4-A
Optional

Title:	2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in a PWR Fuel Shipping Cask with Lead Shield and with the Cavity Filled with Water
Geometry:	See Figures 9 and 10.
Fuel Design:	See Table 7.
Boral, Zircaloy-4, SS-304L Composition:	See Table 1.

Benchmark Problem 4-B

Title:	2.35 wt % ^{235}U Enriched UO_2 Fuel Rods in a PWR Fuel Shipping Cask with Steel Shield
Geometry:	See Figures 9 and 10.
Fuel Design:	See Table 7.
Boral, Zircaloy-4, SS-304L Composition:	See Table 1.

Benchmark Problem 5

Title:	4.75 wt % ^{235}U Enriched UO_2 Fuel Rods in a PWR Cask with Steel Shield
Geometry:	See Figures 9 and 10.
Fuel Design:	See Table 8.
Boral, Zircaloy-4, SS-304L Composition:	See Table 1.

Water density within fuel elements (inside Boral sleeve): 1 gm/cm^3

Water density between fuel elements (outside Boral sleeve): 0.16 gm/cm^3

Table 1

Composition of Neutron Absorber Plates[1]

Element	Boral (2.49 mg/mm^3) wt %	Copper-Cadmium (8.910 mg/mm^3) wt %	Copper (8.913 mg/mm^3) wt %	6061 Alumium (2.692 mg/mm^3) wt %	Zircaloy-4 (6.32 mg/mm^3) wt %	304-L S Steel (7.930 mg/mm^3) wt %
Al	62.39 ± 2.8	--	--	97.15 ± 0.21	--	--
B	28.70 ± 0.25	0.005	--	--	--	--
C	7.97 ± 0.41	0.002	0.340	--	--	--
Cd	--	0.989 ± 0.003	--	--	--	--
Cr	0.05	--	--	0.21	0.13 ± 0.04	18.56 ± 0.10
Cu	0.09	98.685 ± 0.300	99.60 ± 0.14	0.12	--	0.27 ± 0.05
Fe	0.33 ± 0.04	0.020	0.004	0.82	0.21 ± 0.03	68.24 ± 0.34
Mg	0.05	--	0.002	--	--	--
Mn	0.05	0.009	--	0.21	--	1.58 ± 0.05
Mo	--	--	--	--	--	1.26 ± 0.05
Na	0.02	--	0.002	--	--	--
Ni	0.02	0.010			--	11.09 ± 0.06
O	--	0.019	0.030	--	--	--
Si	0.20	0.004	0.020	0.82	--	--
Sn	--	0.250	--	--	1.50 ± 0.27	--
S	0.03	--	0.002	0.06	--	--
Ti	--	--	--	0.61	--	--
Zn	0.10	0.007	--	--	--	--
Zr	--	--	--	--	98.16 ± 0.35	--

[1] Error limits were shown are one standard deviation based on multiple chemical analyses. Error limits are not shown for minor impurities. The impurities distribution are based on spark source mass spectrographic analysis and represent best estimates of maximum concentration for each element present in significant quantity.

TABLE 2 - Composition

Atomic Concentration $10^{24}/cm^3$

				Pitch = 1.26 cm (b)		Pitch = 1.6 cm (b)			
				Lower Grid	Water	Lower Grid	Water	Fuel Rods	
	Air	Stainless Steel Z3 CN 18/10	Water	Water + Plug + Stainless Steel	+ Plug	Water + Plug + Stainless Steel	+ Plug	Fuel(c)	Clad(a)
Density	0.001293	7.90	0.99820	5.225	1.483	6.2394	1.2989	10.38	2.70
Element									
Al				0.02626	0.01722	0.01626	0.01068		0.059535
B								0.00000029	
Cr		0.016467		0.00832		0.01141			
Fe		0.061341		0.0310		0.04252			0.000064
H			0.066742	0.003836	0.0476	0.002380	0.054872		
Mg									0.000334
Ni		0.008107		0.0041		0.00562			
N	0.00004325								
O	0.0000108		0.033371	0.00192	0.02380	0.001190	0.027436	0.046406	
Si									0.00024
^{235}U								0.0011118	
^{238}U								0.022051	

(a) wt % : AL 98.85 - Mg 0.5 - Si 0.42 - Fe 0.022

(b) average atomic concentrations

(c) exact enrichment = 4.742 %

Remark: upper plugs, upper grid and spring may be neglected

Table 3

Experimental Data on Clusters of 2.35 wt % ^{235}U Enriched UO_2 Rods In Water With Boral Plates Between Fuel Clusters(1)

Fuel Clusters		Boral Plates		
Number In Array (2)	Length x Width 20.32 mm sq. Pitch (Fuel Rods)	Thickness(3) (tp,mm)	Distance To Fuel Cluster(4) (G,mm)	Critical Separation Between Fuel Clusters(5) (X_c,mm)
3	20 x 17	7.13 ± 0.11	6.45 ± 0.06	63.4 ± 0.2

(1) Error limits shown are one standard deviation.

(2) Clusters of fuel rods aligned in a single row.

(3) Includes 1.02 mm thick cladding of type 1100 AL on either side of the B_4C-AL core material plates. 356 mm wide by 915 mm long.

(4) Perpendicular distance between the cell boundary of the center fuel cluster and the near surface of the boral plate.

(5) Perpendicular distance between the cell boundaries of the fuel clusters

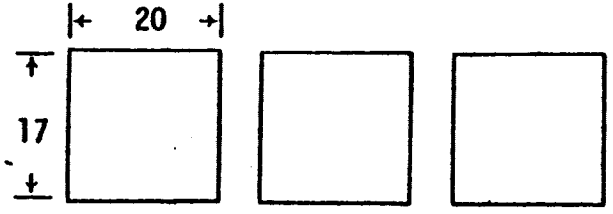


Table 4 - Composition

(Atomic Concentrations in $10^{24}/cm^3$)

	Air	Stainless Steel Z3CN18/10	Bottom Plug + Water (b)	Lower Grid Water + Plug + Stainless Steel(b)	Water	Boral Plate Clad	Boral Plate Boral	Reflecting Walls Lead	Reflecting Walls Steel	Fuel Rods Fuel(c)	Fuel Rods Clad(a)
Density	0.001293	7.90	1.2989	6.2394	0.99820	2.651	2.6189	11.34	7.8	10.38	2.70
Element											
Al			0.01068	0.01626		0.059177	0.041858				0.059535
B							0.032375			0.00000029	
C							0.008089		0.000548		
Cr		0.016467		0.01141							
Fe		0.061341		0.042520					0.083831		0.000064
H			0.054872	0.002380	0.066742						
Mg											0.000334
Ni		0.008107		0.00562							
N	0.00004325										
O	0.0000108		0.027436	0.001190	0.033371					0.046406	
Pb								0.032965			
Si									0.0003348		0.0002
^{235}U										0.0011118	
^{235}U										0.022051	

(a) wt % : Al 98-85 - Mg 0.5 - Si 0.43 - Fe 0.022

(b) average atomic concentrations

(c) exact enrichment : 4.742 %

Remark : upper plugs, upper grid and spring may be neglected

Table 5

Experimental Data on Clusters of 2.35 wt % ^{235}U Enriched UO_2 Rods in Water With Lead Reflecting Walls(1)

	2.35 wt % Enriched Fuel	
Distance Between Reflecting Walls and Fuel Clusters(2) Y (mm)	Fuel Clusters 20.32 mm Sq. Pitch (3)	Critical Separation Between Fuel Clusters(4) X_c (mm)
26.16 ± 0.76	3-19 x 16	104.9 ± 0.8

(1) Error limits shown are one standard deviation

(2) Perpendicular distance between the cell boundary of the fuel clusters and the reflecting walls

(3) Number of fuel clusters, rods long x rods wide, aligned in a row

(4) Perpendicular distance between the cell boundaries of the fuel clusters

Table 6

Experimental Data on Clusters of 2.35 wt % ^{235}U Enriched UO_2 Rods in Water With Steel Reflecting Walls(1)

	2.35 wt % Enriched Fuel	
Distance Between Reflecting Walls and Fuel Clusters(2) Y (mm)	Fuel Clusters 20.32 mm Sq. Pitch (3)	Critical Separation Between Fuel Clusters(4) X_c (mm)
26.16 ± 0.76	3-19 x 16	96.0 ± 0.1

(1) Error limits shown are one standard deviation

(2) Perpendicular distance between the cell boundary of the fuel clusters and the reflecting walls

(3) Number of fuel clusters, rods long x rods wide, aligned in a row

(4) Perpendicular distance between the cell boundaries of the fuel clusters

Table 7

Simulated PWR Fuel Assembly

Array Size: 17 x 17 (square lattice)

Lattice Pitch: 1.26 cm

Active Length: 371 cm

Fuel OD: 0.819 cm

Gap OD: 0.836 cm

Clad OD: 0.950 cm

Clad Type: Zircaloy-4

Fuel Enrichment: 2.35 wt% $^{235}UO_2$

Fuel Density: 10.41 g/cm^3 (95% of theoretical)

Table 8

Simulated PWR Fuel Assembly

Array Size: 17 x 17 (square lattice)

Lattice Pitch: 1.26 cm

Active Length: 371 cm

Fuel OD: 0.819 cm

Gap OD: 0.836 cm

Clad OD: 0.950 cm

Clad Type: Zircaloy-4

Fuel Enrichment: 4.75 wt % $^{235}UO_2$

Fuel Density: 10.41 g/cm^3 (95% of theoretical)

ORNL DWG 82-12622

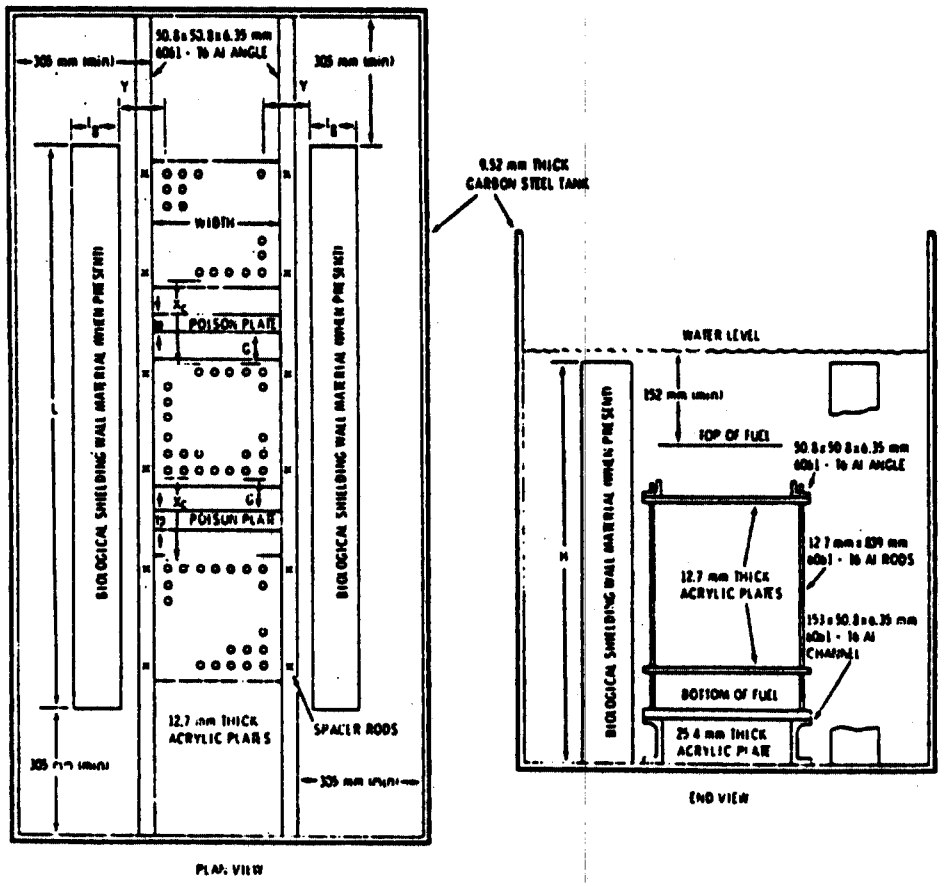
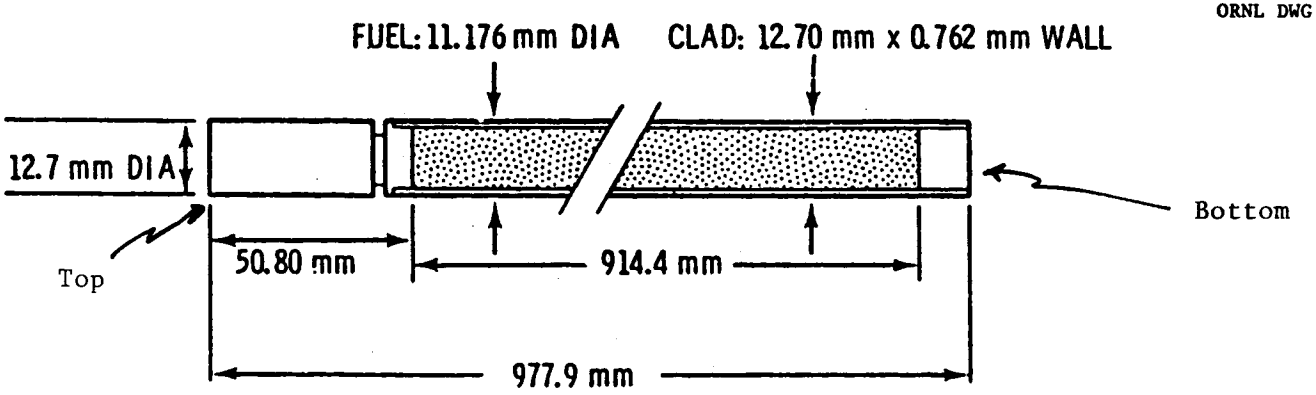


Fig. 1 Experimental Geometry Description for 2.35 wt % ^{235}U Enriched UO_2 Rods in Water With and Without Boral Poison

ORNL DWG 82-12623



CLADDING: 6061 ALUMINUM TUBING SEAL WELDED WITH A LOWER END PLUG OF 5052-H32 ALUMINUM AND A TOP PLUG OF 1100 ALUMINUM

TOTAL WEIGHT OF LOADED FUEL RODS: 917 gm (AVERAGE)

LOADING:

825 gm OF UO_2 POWDER/ROD, 726 gm OF U/ROD, 17.08 gm OF U-235/ROD
ENRICHMENT - 2.35 ± 0.05 w/o U-235
FUEL DENSITY - 9.20 mg/mm^3 (84% THEORETICAL DENSITY)

Fig. 2 DESCRIPTION OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS

ORNL DWG 82-12624

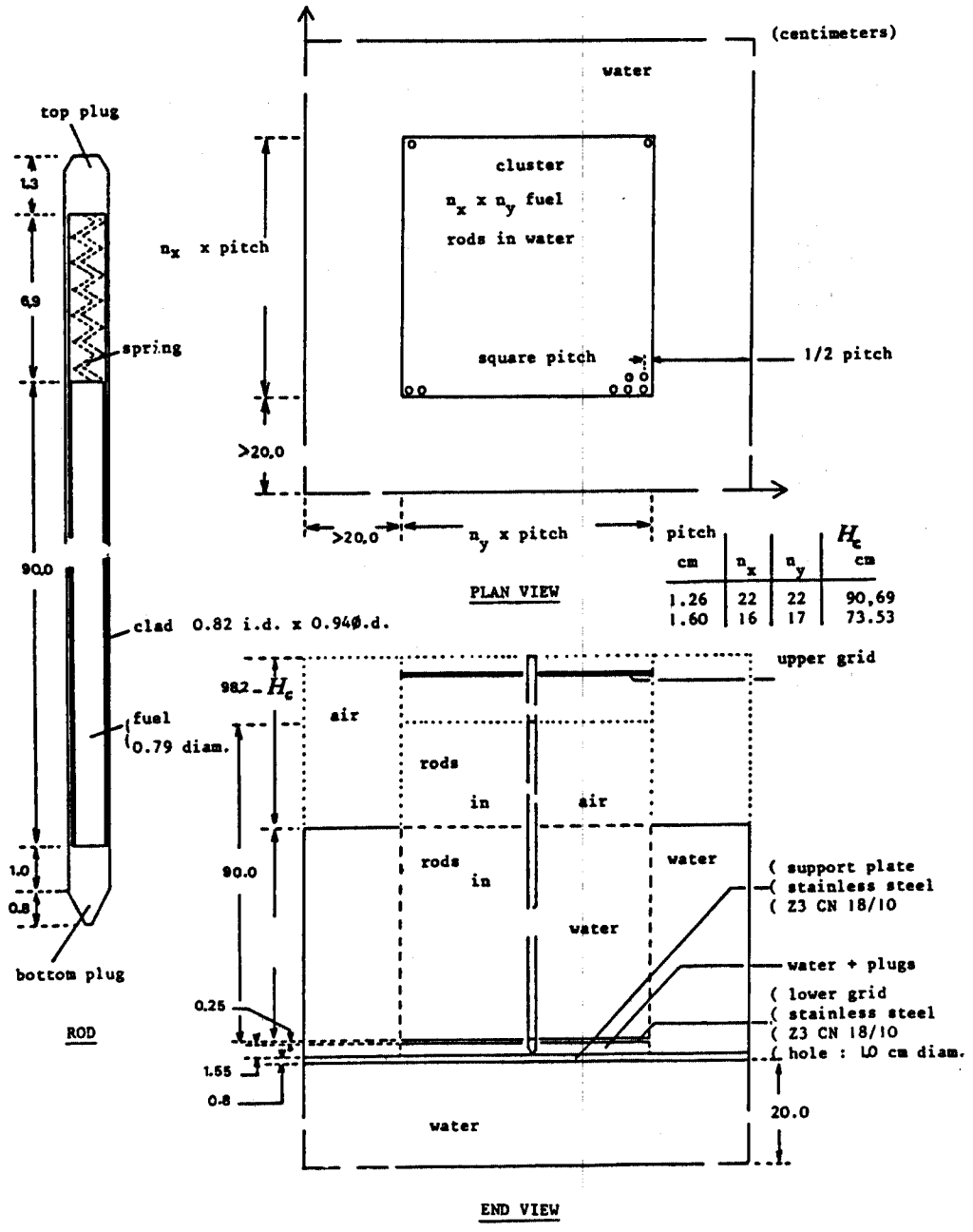
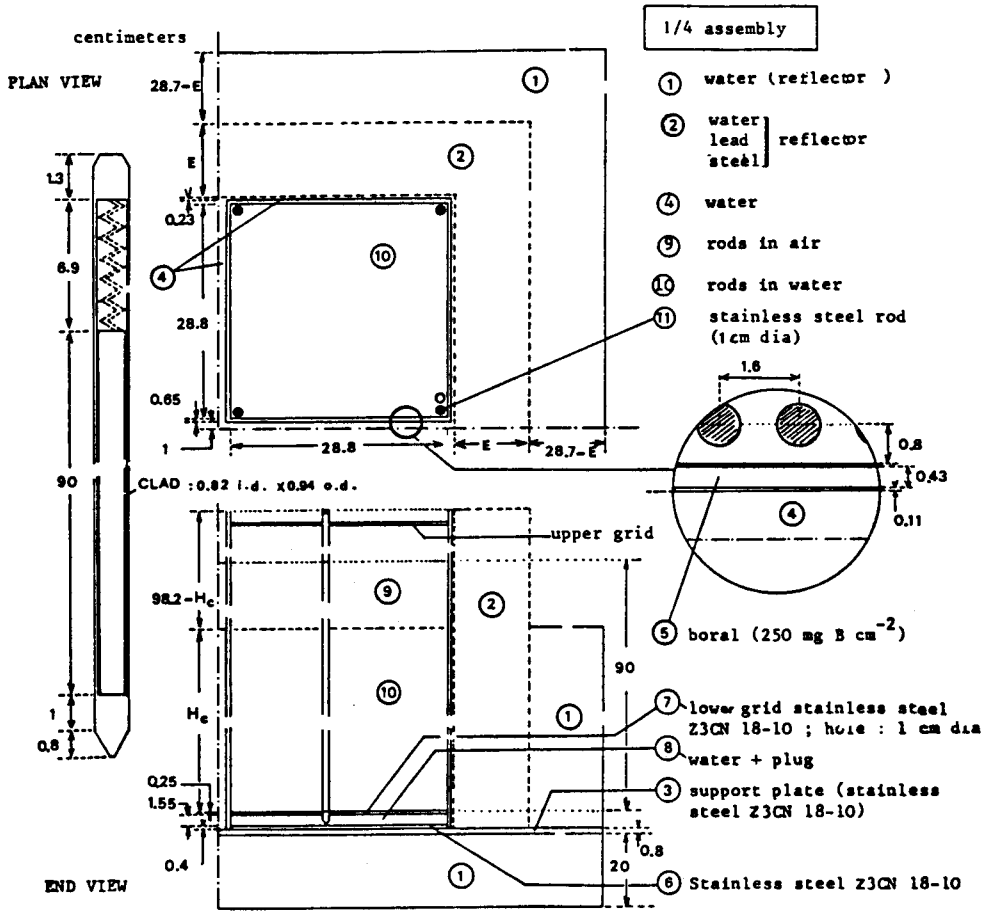


Fig. 3 Experimental Geometry Description for 4.75 wt % ^{235}U Enriched UO_2 Rods in Water

ORNL DWG 82-12625



1/4 experimental criticality assembly: 4 clusters (18 X 18 - 4) 4,75 wt % ^{235}U enriched UO_2 rods in water with boral plates and water with lead or steel reflecting walls.

	problem	reflector	$E_{(cm)}$	$H_{c(cm)}$
(b)	3 A2	lead	10	53.98
(c)	3 B2	steel	15	51.5
(a)	2-2	water	0.0	72.96

Fig. 4 Experimental Geometry Description for 4.75 wt % ^{235}U Enriched UO_2 Rods in Water With Boral Poison

ORNL DWG 82-12626

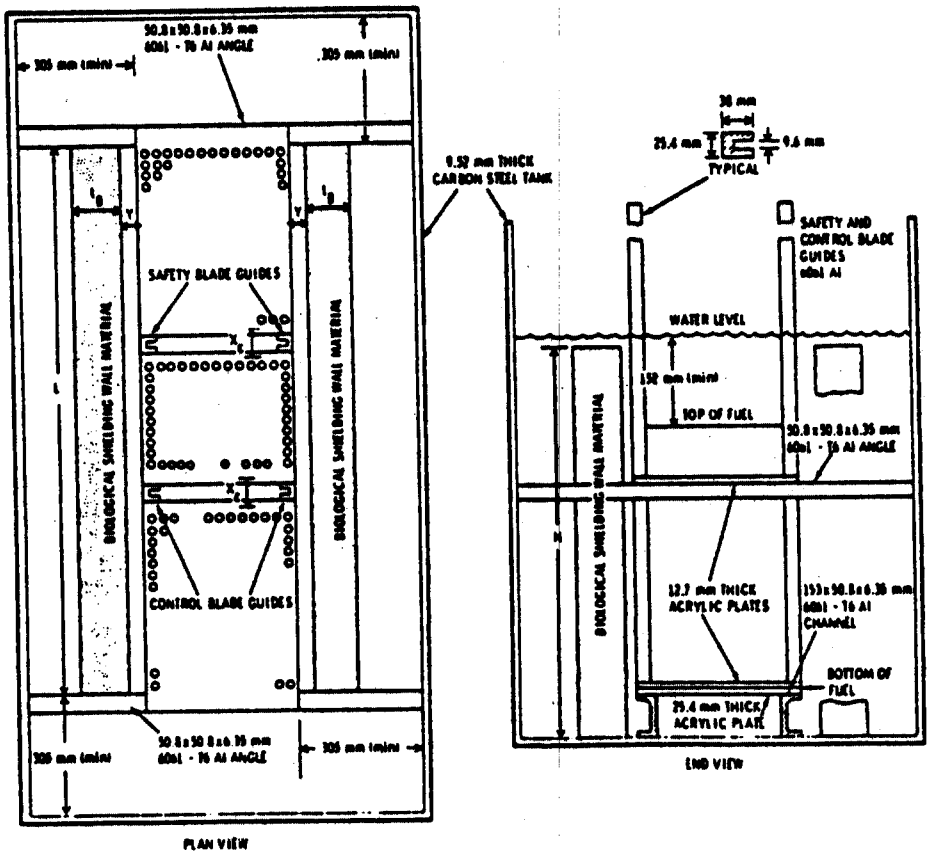


Fig. 5 Experimental Geometry Description for 2.35 wt % ^{235}U Enriched UO_2 Rods in Water With Heavy Metal Reflector

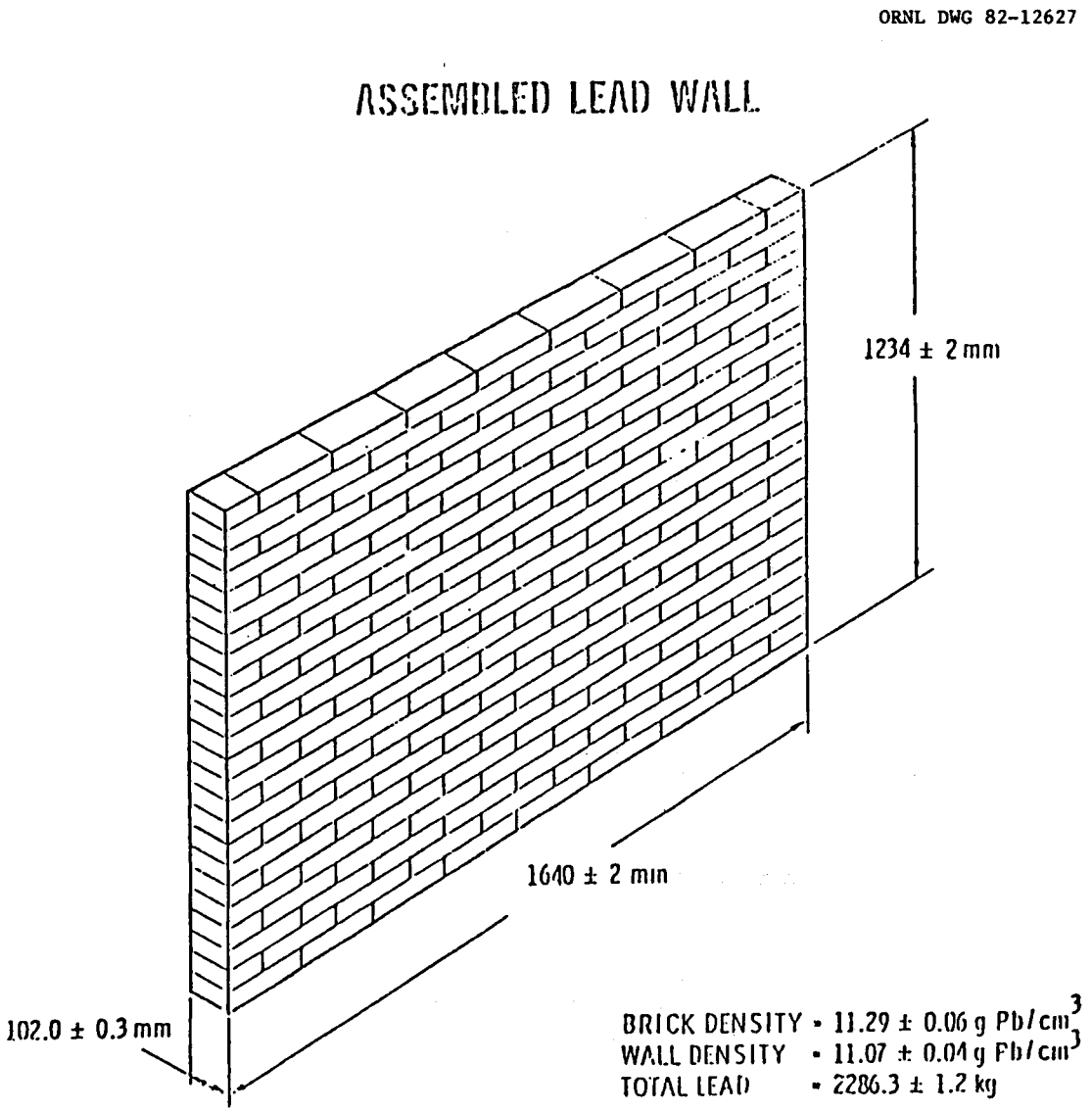
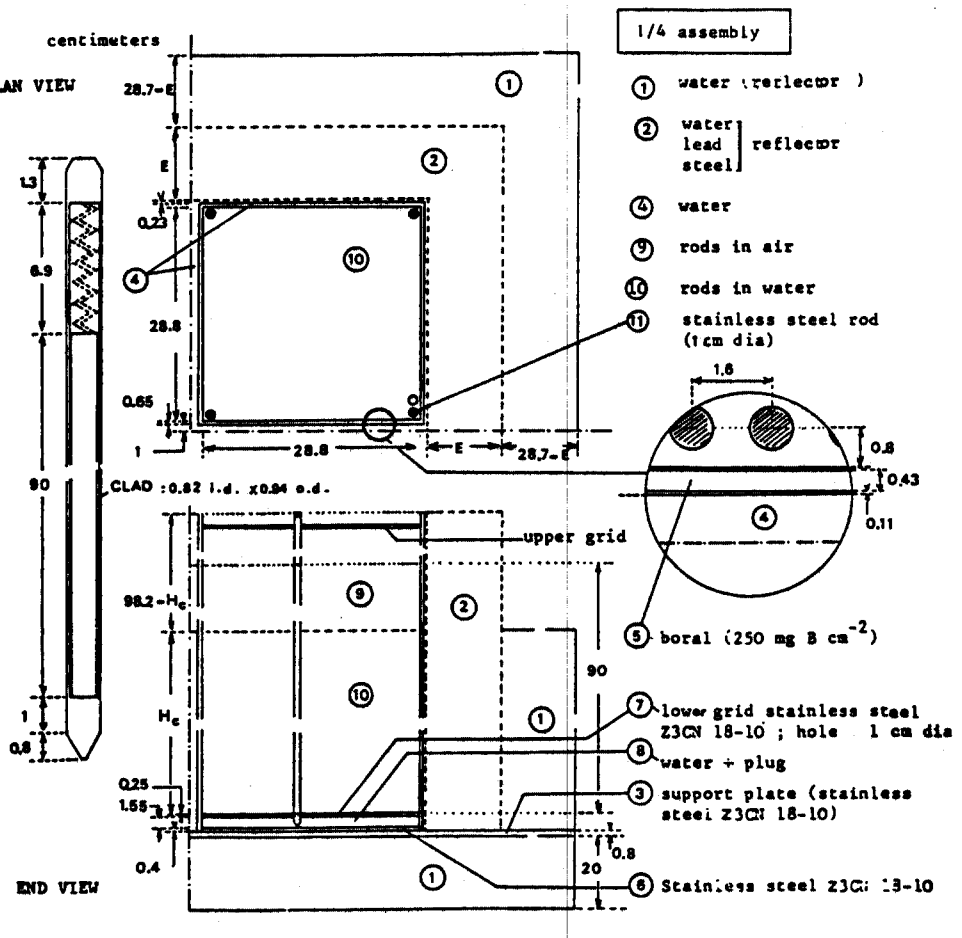


Fig. 6 Geometrical Description of Lead Reflector Assembly

ORNL DWG 82-12628



1/4 experimental criticality assembly: 4 clusters (18 X 18 - 4) 4,75 wt % ^{235}U enriched UO_2 rods in water with boral plates and water with lead or steel reflecting walls.

	problem	reflector	$E_{(cm)}$	$H_{c(cm)}$
(a)	3 A2	lead	10	53.98
(b)	3 B2	steel	15	51.5

Fig. 7 Experimental Geometry Description for 4.75 wt % ^{235}U Enriched UO_2 Rods in Water With Boral Poison and Heavy Metal Reflector

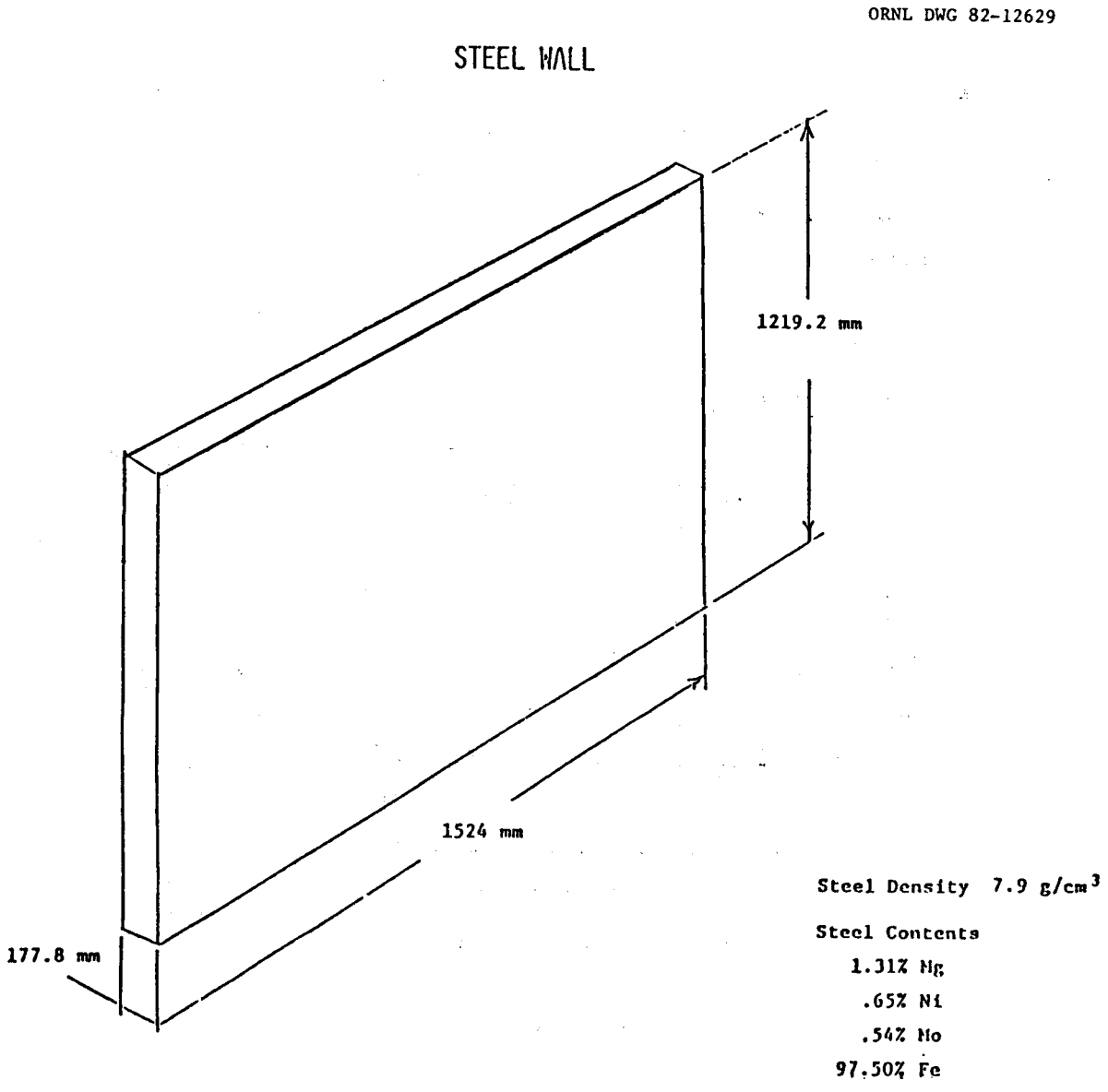


Fig. 8 Geometrical Description of Steel Reflector Assembly

ORNL DWG 82-12630

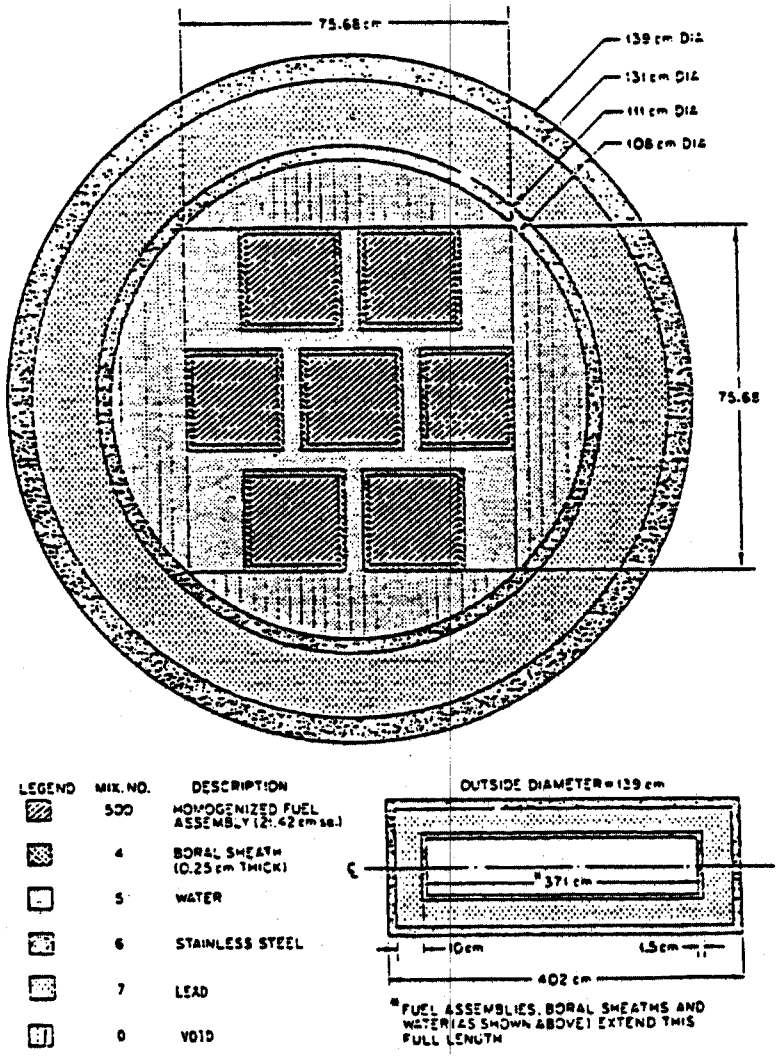


Fig. 9 Geometrical Description of Simulated Spent PWR Fuel Shipping Cask

ORNL DWG 82-12631

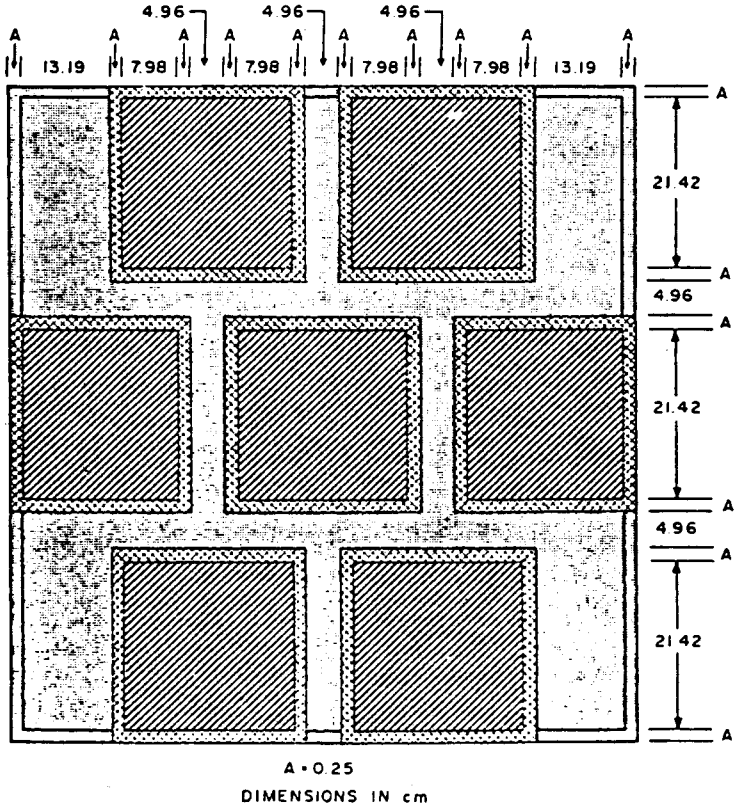
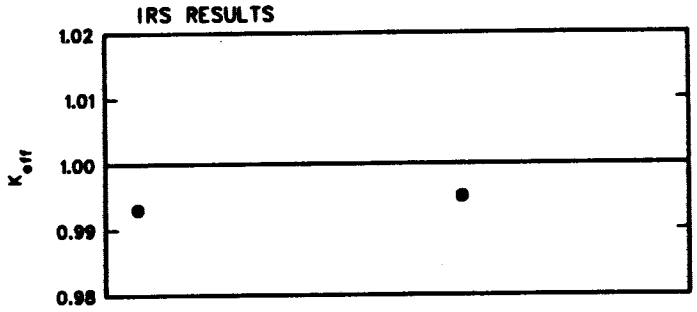


Fig. 10 Geometrical Detail of Boral Poison Plates in Simulated Spent PWR Fuel Shipping Cask

Appendix II
Detailed Results of the Participants

IRS Results (Austria)

ORNL-DWG 82C-11939



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2

4A	4A (opt.)	4B

5

BN Results (Belgium)

Comments on BN results

The benchmark problems were calculated with the KENO IV Monte Carlo code using 16-group cross sections generated by LWR-WIMS.

The critical experiments in Problems 1-3 are adequately calculated with a tendency to overestimate k_{eff} by about 1-2%.

The results obtained for Problems 4 and 5 are consistent with those of the other participants with the same tendency to overestimate k_{eff} (1%) if compared to the average k_{eff} of all the participants.

It is concluded that this code system is adequate for calculations on LWR fuel casks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
WIMS LIB.	69(42 thermal)	UKNDL	GALAXY - weighting by typical spectra

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
LWR-WIMS	1 dimension cylindrical for rod cell and multicell for assy	Discrete integral transport eq. with collision probabilities	42 groups, thermal	Obtained in the exact cell description during the cell calculation using a very fine group library overriding the main 69 group library

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	16	Weighting by LWR-WIMS cell calculation provided flux
other	16	Weighting by LWR-WIMS multicell calculation provided flux or/and HANSEN-ROACH library.

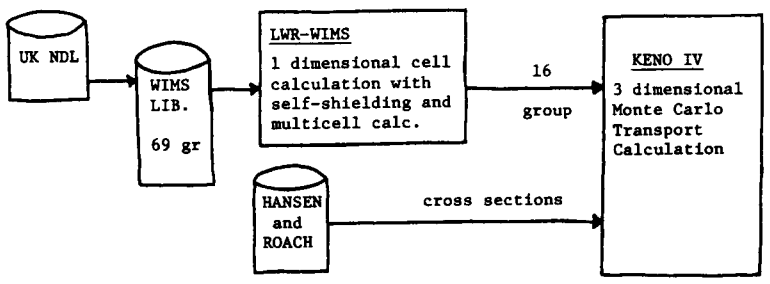
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	
Extrapolation Distance	

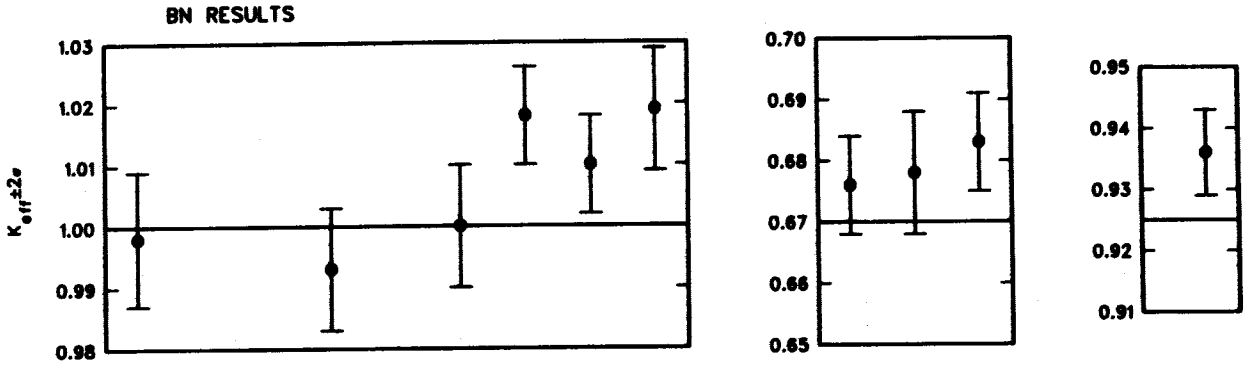
d) k_{eff} calculation

Computer code	Geometry	Method
KENO IV	Three-dimensional fuel assembly homogenized	Multigroup (16-group) transport theory Monte Carlo code

Flow Diagram



ORNL-DWG 82C-11940



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2	4A	4A (opt.)	4B	5

EIR Results (Switzerland)

Comments on EIR results

Two options of the code BOXER, CODIFF (diffusion) and QP_1 (transport), were used to calculate all the problems. From the Problems 1-3, one can see that QP is able to calculate such configurations with a good accuracy, the mean k_{eff} value over the nine problems being 0.9992 ± 0.0039. For the Problems 4-5, the QP_1 results are always near the mean value $\overline{k_{eff}}$ over the results of all participants (16 results):

	$\overline{k_{eff}}$	$\overline{k_{eff}}(QP_1)$
4B	0.6781	0.6779
4A (option)	0.6694	0.6675
4A	0.6765	0.6769
5	0.9272	0.9222

The diffusion option CODIFF underestimates k_{eff} in Problems 1-3 by about 1%. In Problems 4-5, however, the difference against QP_1 reaches about 3%. As a conclusion we believe that

-- BOXER with QP_1 is adequate for calculations of LWR fuel flasks of the type considered.

-- In contrast, the diffusion option is not sufficient in such heterogeneous geometries.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
BOXLIB	70 42 thermal	ENDF/B-4	ENDF Group, modification by EIR. ETOBOX: condensation over typical spectra

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
BOXER	1 dimension cylindrical	integral transport (mixed method)	70 42 thermal	2-zone CPM with ∿2000 lethargy points in resonance range for the right cell

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	6 (3 thermal)	BOXER (spectrum from cell calculation)
other	6 (3 thermal)	BOXER (spectrum from 1-dim. X-calculation)

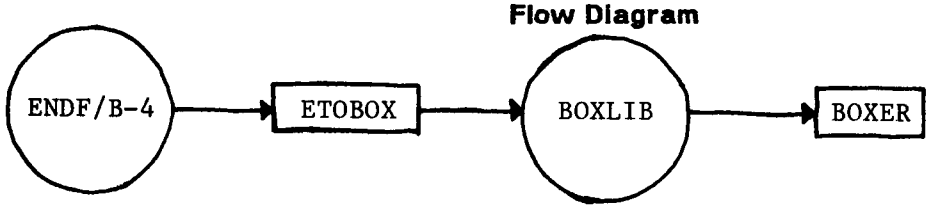
c') Method and code used to obtain other constraints necessary in diffusion theory

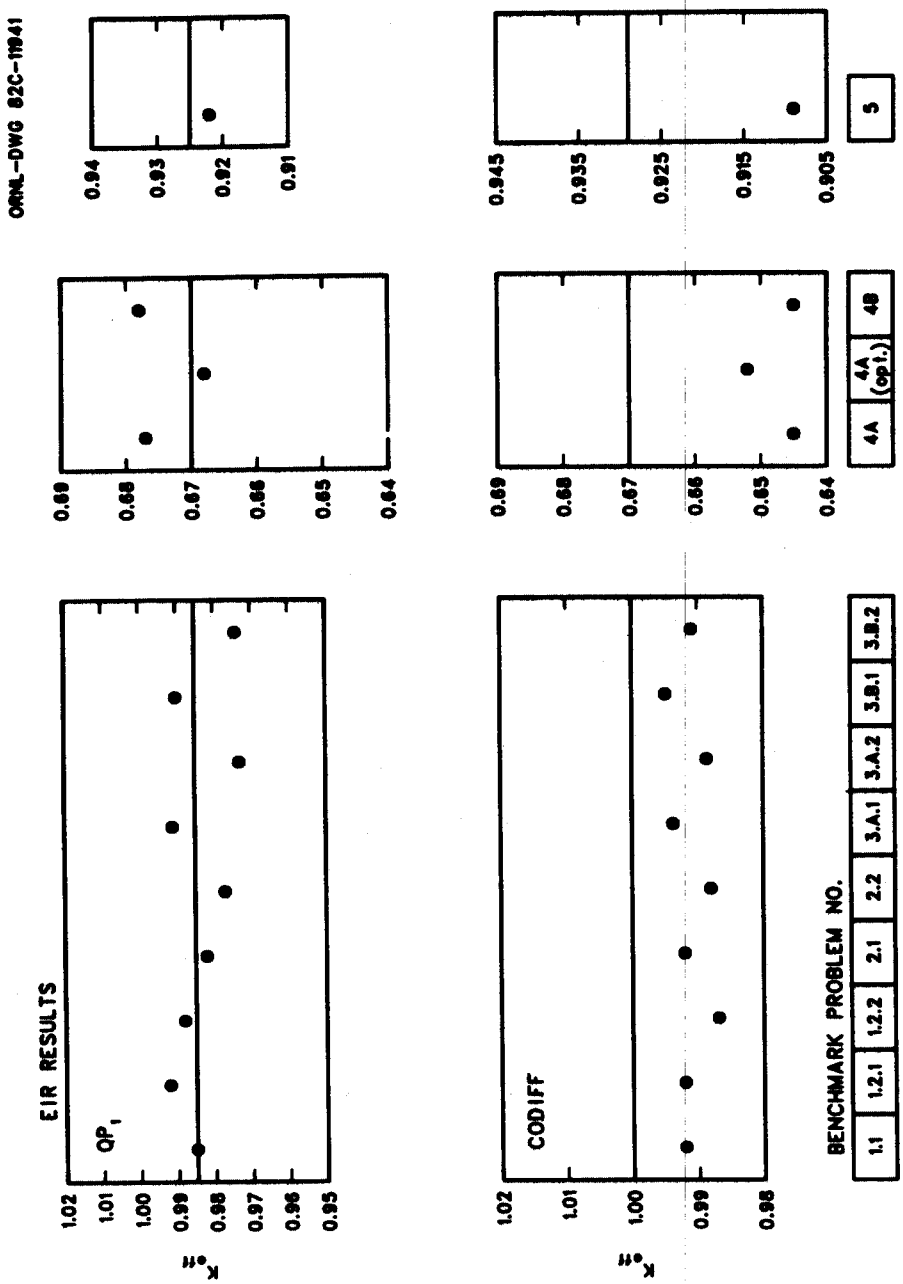
$D, B^2 or M^2 \ldots$	D: formula by Bell-Glasstone B^2: 1-dim. axial calculation, fit of the power density by means of a cos function
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
BOXER	2-dim. with an axial buckling	QP_1: transport CODIFF: diffusion

Flow Diagram




ORNL-DWG 82C-11941
EIR RESULTS
QP1
CODIFF
K∞
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.69
0.68
0.67
0.66
0.65
0.64
0.945
0.935
0.925
0.915
0.905
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

GRS and PTB Results (Germany)

Comments on GRS results

The calculations of benchmark Problem 1-3 show an overestimation of k_{eff} by 1-2%. The standard deviations were about 0.005 or below. It is felt that this overestimation is mostly due to the cross-sections generated by the combination of GAMTEC-BRT and to a lesser extent to the MC-program KENO-IV. The tendency of overestimation also is reflected in comparing the results of benchmark Problems 4-5 with the results of the other participants as our results are at the upper end of the spread. It is concluded that the calculational procedure is adequate for the calculations on LWR spent fuel casks and for establishing conservative k_{eff}'s.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
GAMTEC-II and BRT-I libraries	68 fast + thermal 30 thermal		

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
GAMTEC-II	cylinder	B_1 - approx.	68	Adler-Nordheim method
BRT-I	cylinder	discrete integral transp.ec.	30	

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	15 fast + 1 thermal grp.	GAMTEC-II, thermal group by BRT
other	15 fast + 1 thermal grp.	all groups by GAMTEC-II

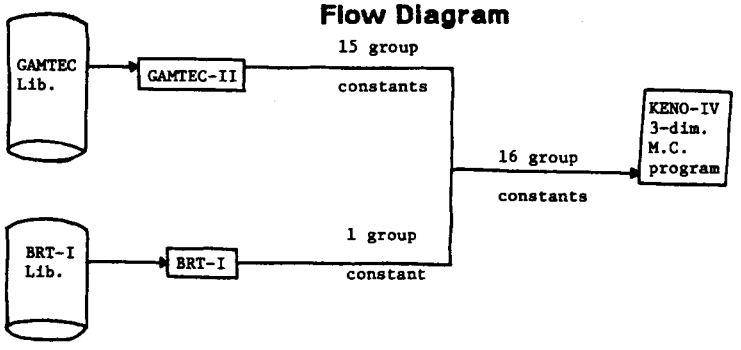
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	no diffusion programs used
Extrapolation Distance	no diffusion programs used

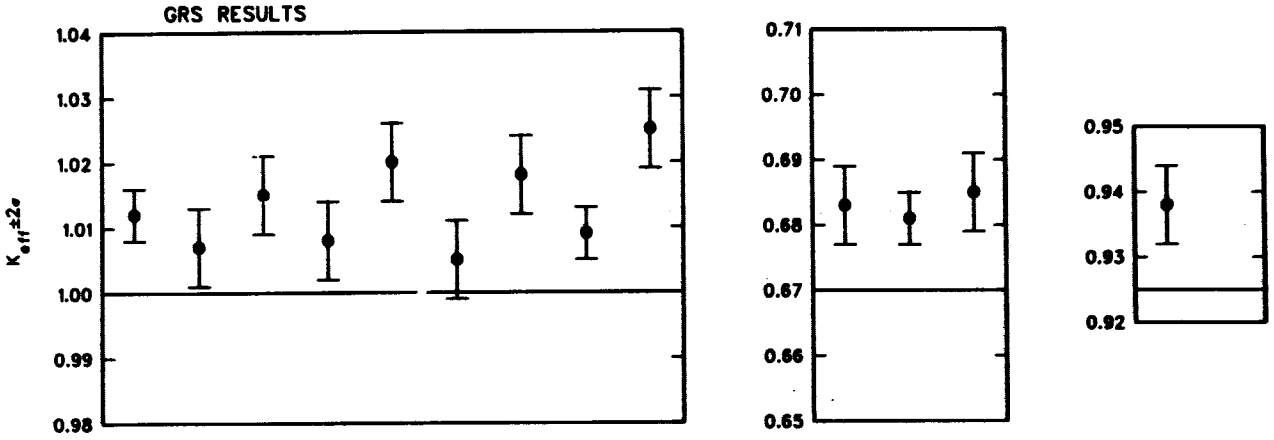
d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	3-dimensional; fuel homogenized	16-group Monte Carlo calculation

Flow Diagram



ORNL-DWG 82C-11942



BENCHMARK PROBLEM NO.								
1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2

4A	4A (opt.)	4B

5

Comments on PTB results

MORSE-K calculated the critical experiments in Problem 1-3 adequately, the difference between the expected value and the calculated value is smaller than the standard deviations which were about 0.01 or less. The results obtained for Problems 4 and 5 are consistent with those of other members of the group. It is therefore concluded that the code and the cross sections used for these calculations on flasks of fuel elements are adequate.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
GAM-II lib. Therm-126	99 fast group 126 thermal group thermal lib.	ENDF/B-IV, provided by IKE Univ. of Stuttgart	RSYST-Program-System B_1-calculations in fast and thermal energy range

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self shielded cross sections
RSYST-Module "ISOSTO"	cylindrical geometry	Collision probability	60, 36 thermal groups	Cross sections for fuel rods obtained by flux weighting (99 fast groups) with ISOSTO-Module

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	20	Weighting by ANISN provided flux (60 groups)
other	20	See above: condensed to 20 groups

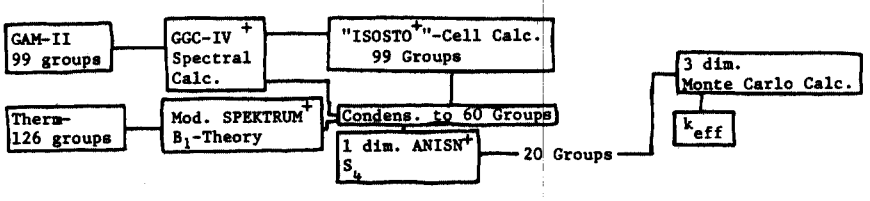
c') Method and code used to obtain other constraints necessary in diffusion theory

$D, B^2 or M^2 \cdots$	
Extrapolation Distance	

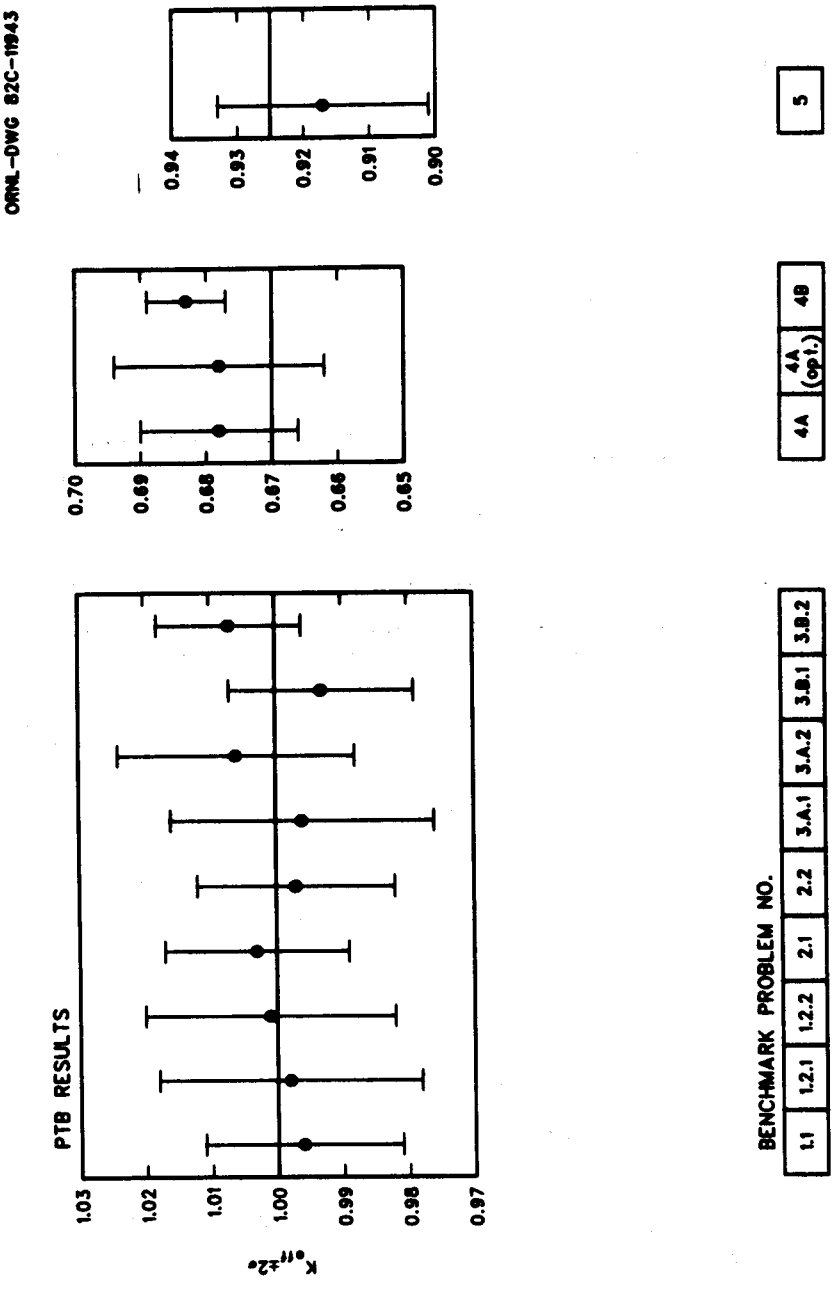
d) k_{eff} calculation

Computer code	Geometry	Method
MORSE-K	Three-dimensional, fuel assembly homogenized: some other regions homogenized too	Multigroup (20 groups) transport theory Monte Carlo Code Code "MORSE-K"

Flow Diagram



+) Modules of "RSYST"-Progr. System


ORNL-DWG 82C-11943
PTB RESULTS
k_{eff}
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.70
0.69
0.68
0.67
0.66
0.65
0.94
0.93
0.92
0.91
0.90
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

CEA Results (France)

Comments on CEA results

The system code MORET-APOLLO calculated the critical experiment in Problems 1-3 adequately with a tendency to overestimate k_{eff} by about 1%. The option of APOLLO B_1, anisotropic scattering P_1 does not seem to be better than the transport correction option. The results obtained for Problems 4 and 5 are consistent with those of the other benchmark problems.

It is concluded that these codes are adequate for calculations on LWR fuel flasks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
APOLLO-LIB.	gg(47 thermal)	UKAEA and ENDF/B CEA	SACLAY - weighting by typical spectra

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
APOLLO	dimension cylindrical	Discrete integral transport eq. with collision probabilities	gg groups, 47 thermal	Obtained in the exact cell description during the cell calculation using a very fine group library over-riding the main gg group library

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	16	Weighting by APOLLO - cell calculation provided flux
other	16	HANSEN and ROACH library except for lead which is supplied from GAMTEC LIBRARY

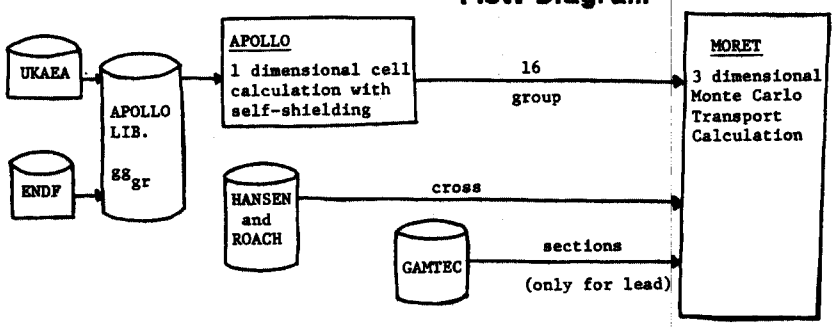
c') Method and code used to obtain other constraints necessary in diffusion theory

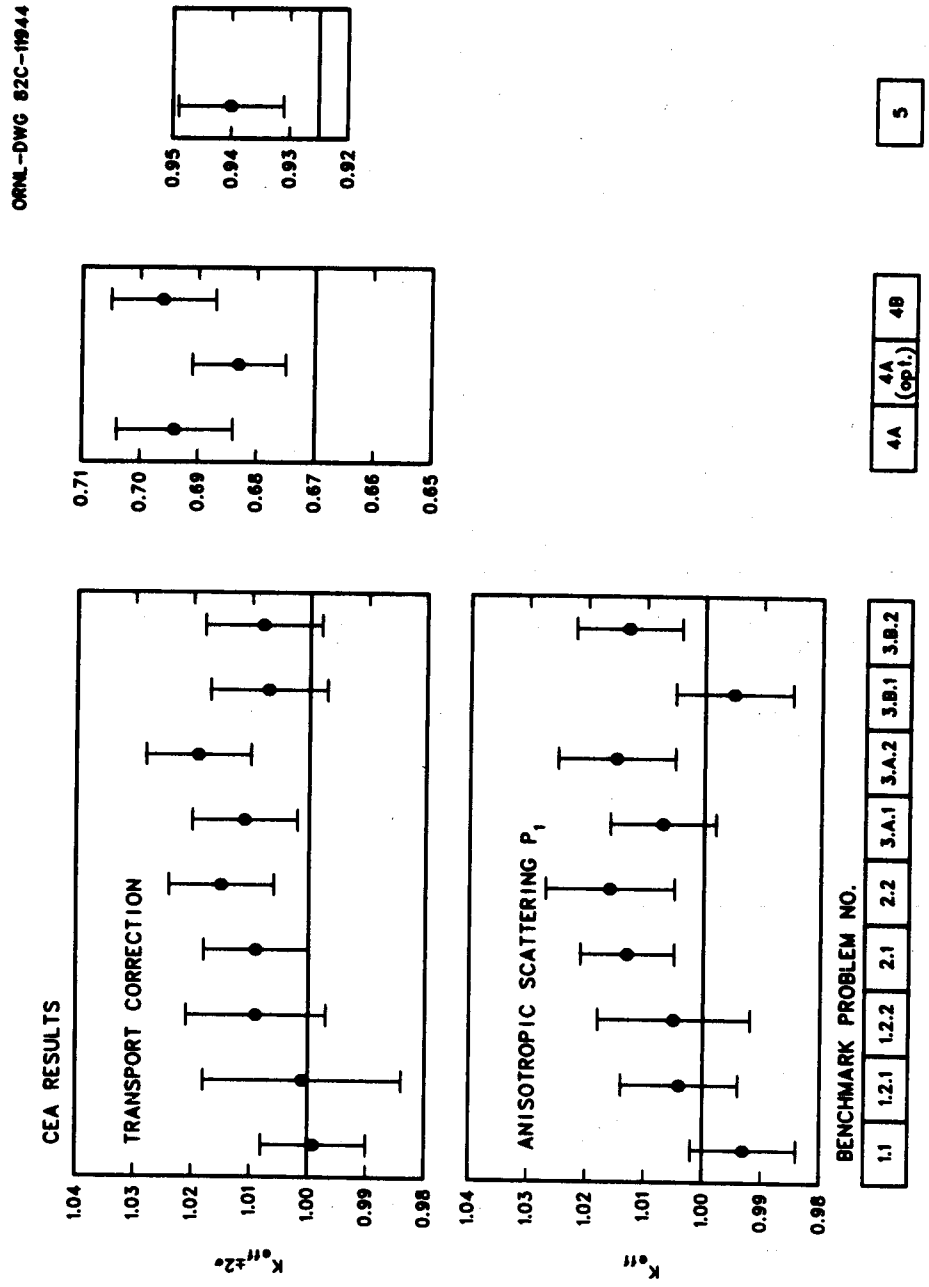
$D, B^2 or M^2 \cdots$	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
MORET	Three dimensional fuel assembly homogenized	Multigroup (16 group) transport theory Monte Carlo code

Flow Diagram




ORNL-DWG 82C-11944
CEA RESULTS
TRANSPORT CORRECTION
ANISOTROPIC SCATTERING P1
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
APOLLO-LIB.	gg(47 thermal)	UKAEA and ENDF/B CEA	SACLAY - weighting by typical spectra

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
APOLLO	dimension cylindrical	Discrete integral transport eq. with collision probabilities	gg groups, 47 thermal	Obtained in the exact cell description during the cell calculation using a very fine group library overriding the main gg group library

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	16	Weighting by APOLLO - cell calculation provided flux
other	16	HANSEN and ROACH library except for lead which is supplied from GAMTEC LIBRARY

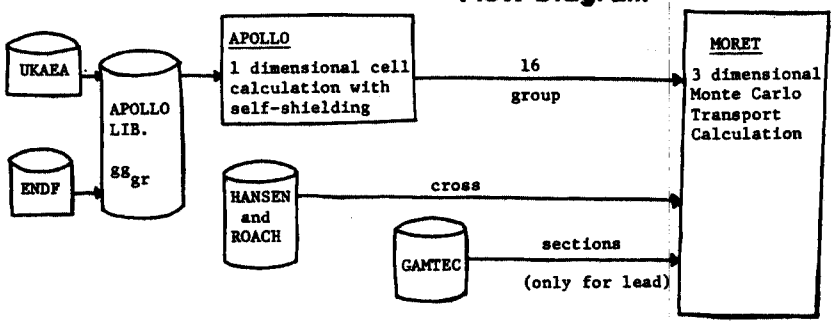
c') Method and code used to obtain other constraints necessary in diffusion theory

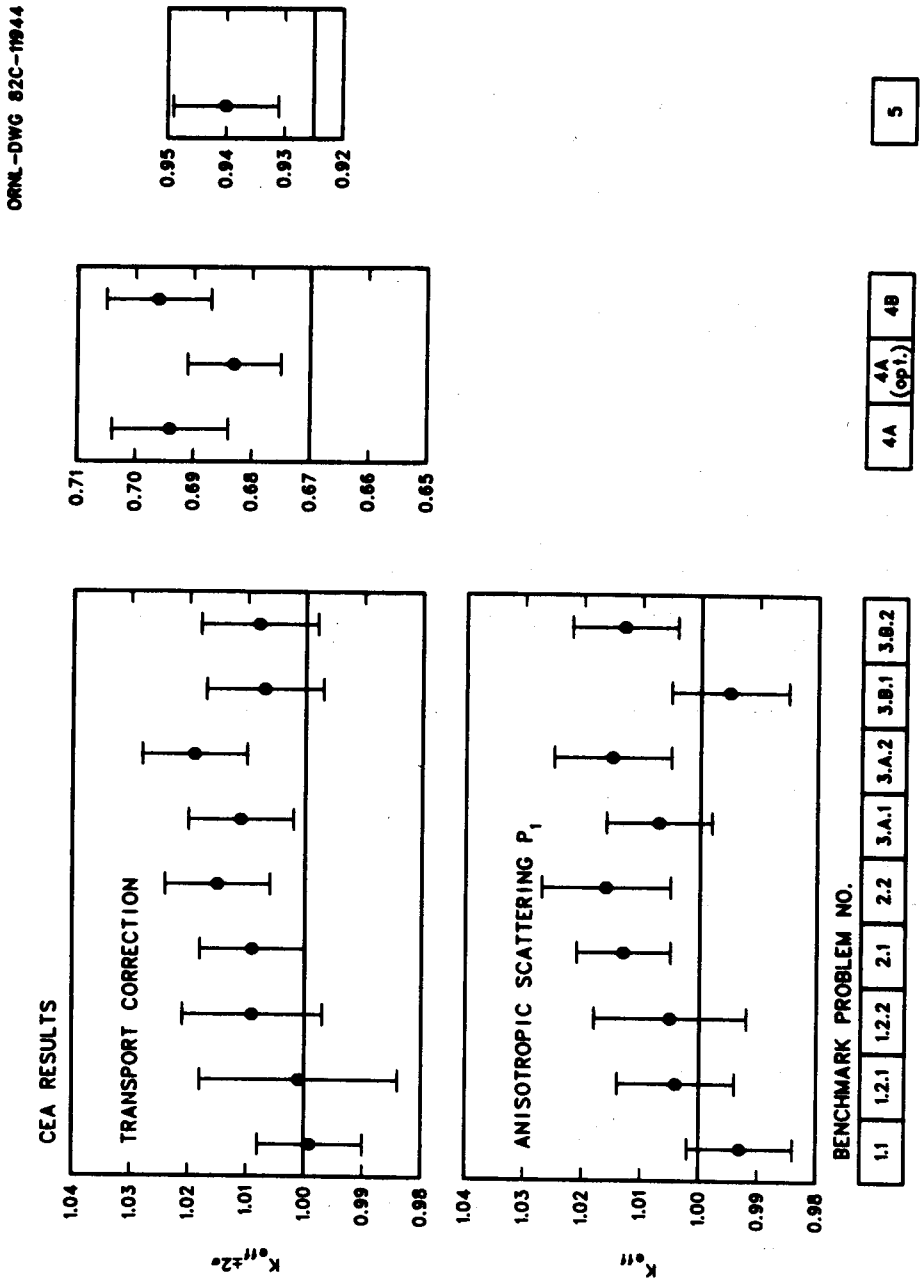
$D, B^2 or M^2 \cdots$	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
MORET	Three dimensional fuel assembly homogenized	Multigroup (16 group) transport theory Monte Carlo code

Flow Diagram




ORNL-DWG 82C-11944
CEA RESULTS
TRANSPORT CORRECTION
ANISOTROPIC SCATTERING P1
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

SRD Results (United Kingdom)

Comments on SRD results

MONK 5.3 calculated the critical experiment in Problems 1-3 adequately with a tendency to overestimate k_{eff} by up to 2%. The standard deviations were about 0.01 but this is in agreement with our experience of the use of the code. The results obtained for Problems 4 and 5 are consistent with those of the other benchmark problems. It is concluded that this code is adequate for calculations on LWR fuel flasks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
MONK LIB.		UKNDL	POND Processing Code

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel		
other		

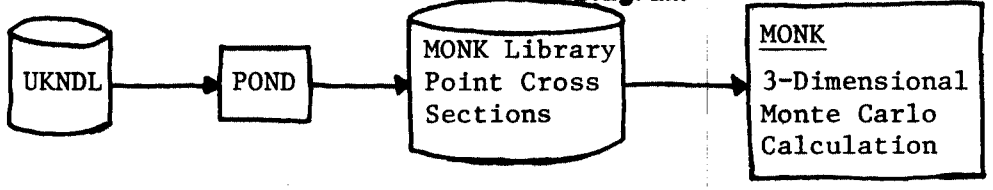
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	
Extrapolation Distance	

d) k_{eff} calculation

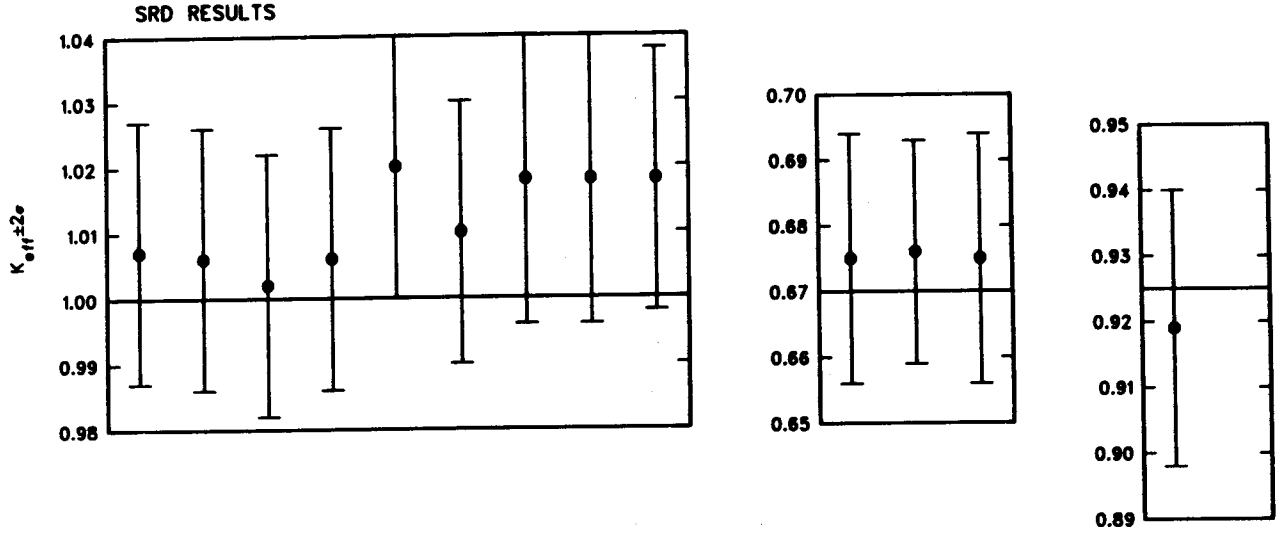
Computer code	Geometry	Method
MONK	Three dimensional explicit representation	Monte Carlo

Flow Diagram



Note: The MONK Library is an integral part of the MONK Code.

ORNL-DWG 82C-11945



CNEN Results (Italy)

Comments on CNEN results

MONK-5 - The comments and the conclusions are the same as those of the UK on the MONK 5.3 code.

KENO-4 - The results of the code for benchmark Problems 4 and 5 are consistent with those of the other members of the working group. The accuracy and the detail of the procedure for cell calculation and weighting the broad group constants show the adequacy of the code for calculations on LWR fuel flasks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants for all problems solved with MONK-5 problems.

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel		
other		

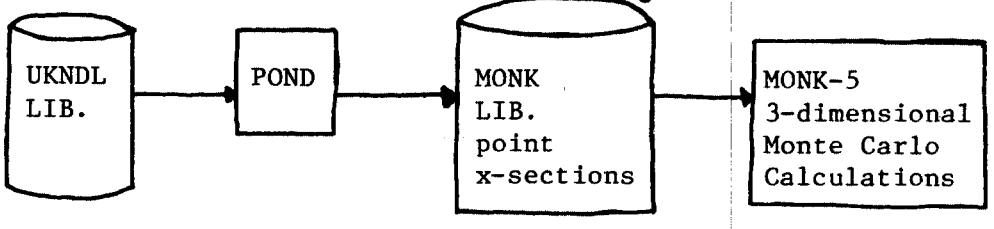
c') Method and code used to obtain other constraints necessary in diffusion theory

$D, B^2 or M^2 \cdots$	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
MONK-5	Three-dimensional with explicit description of fuel pins.	Monte Carlo Transport Methods

Flow Diagram



Summary of Calculation Method

a) Fine group constants 4-A, 4-A optional and 4-B (non-homogenized fuel assembly)

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
GAM-Library GATHER Library	99 + 101	GENERAL ATOMIC	GGC-4 FAST and THERMAL B-1 SPECTRUM CALCULATION. RESONANCE TREATMENT: NORDHEIM

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
ANISN	1-dim. cylinder	S-n P-1 Transp.	29	ZONE X-sect. flux weighted/collapsing 16 groups (Hansen-Roach)

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	16	3 sets of flux-weighted X-sect.
other	16	HANSEN-ROACH

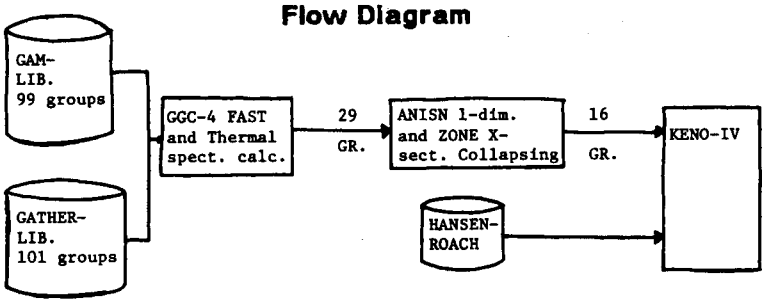
c') Method and code used to obtain other constraints necessary in diffusion theory

$D, B^2 or M^2 \cdots$	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	3-dimensional fuel assembly not homogenized	Multigroup (16 groups) transport theory Monte Carlo Code

Flow Diagram



Summary of Calculation Method

a) Fine group constants 4-A, 4-A optional and 4-B (homogenized fuel assembly)

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
GAM-LIB. GATHER-LIB.	99 fast 101 therm	GENERAL ATOMIC + some CNEN isotope eval.	GAM-P-1 or B-1 fast spectr calculations and 13 group constant production. Resonances: NORDHEIM INTEGRAL METHOD GATHER: B-1 spectr. calc. 16-group const.

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
ANISN	1 dim. cylindr.	S-n P-0 Transp.	29	CELL weighted X-secs. collapsing to 16 group Hansen-Roach en. structure

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	16	weighting by ANISN-cell calculation provided flux
other	16	Hansen-Roach Library

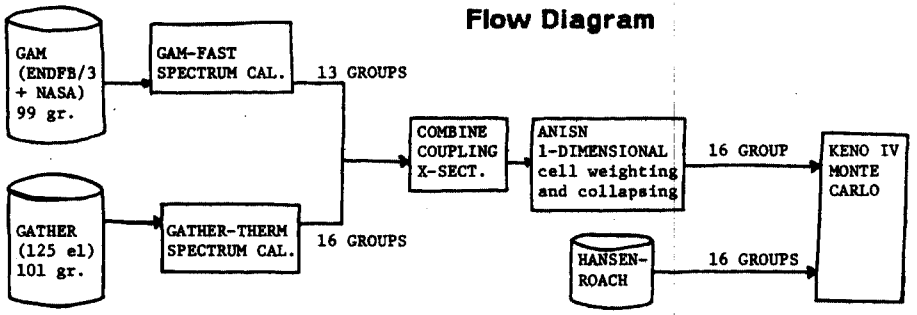
c') Method and code used to obtain other constraints necessary in diffusion theory

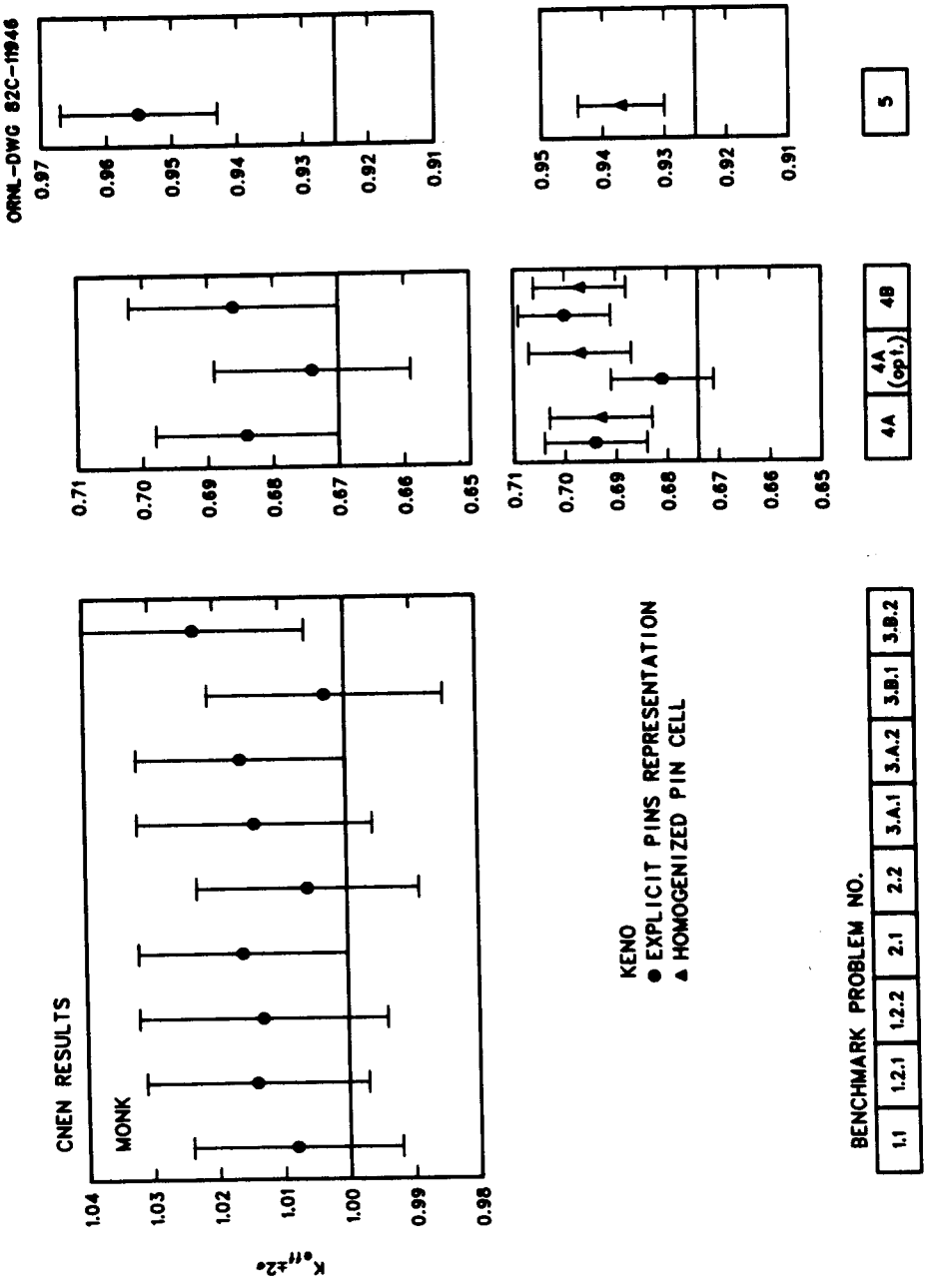
D', B^2 or M^2 ...	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	3-DIMENSIONAL fuel ASSEMBLY homogenized	Multigroup (16 group) transport theory Monte Carlo Code

Flow Diagram




ORNL-DWG 82C-11946
CNEN RESULTS
MONK
KENO
● EXPLICIT PINS REPRESENTATION
▲ HOMOGENIZED PIN CELL
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

JAERI Results (Japan)

Comments on JAERI results

JACS is a computer code system for evaluating nuclear criticality safety which consists of many subsystems; MGCL-ACE, MAIL, KENO-IV, YENMA and so on. KENO-IV in JACS calculated the critical experiment in Problems 1-3 adequately with a tendency to underestimate k_{eff} by about 0.9%. With many benchmark calculations (more than 50 cases), we know the computed k_{eff} by KENO-IV must be corrected by +0.7%. This correction is performed by YENMA of JACS. The tendency of our present results for Problems 1-3 is consistent with our experience. The average k_{eff} for Problems 1-3 by KENO-IV is 0.9910 0.0018, and the k_{eff} estimated by YEHMA is 0.9979±0.0026. Our results obtained by KENO-IV for Problems 4 and 5 should also be corrected by +0.7%. It is concluded that this code system is adequate for calculations on LWR fuel flasks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
MGCL	137		MGCL-ACE RESEND-D: 7×10^4 group const. generation SUPERTOG: Scattering cross section generation FLANGE: Scattering cross section generation in thermal group FINESPEC: Ultra-fine neutron energy spectrum cal. for obtaining shielding factor

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
MAIL			137	Table look-up using background cross section σ_0 with Dancoff correction factor

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel		
other		

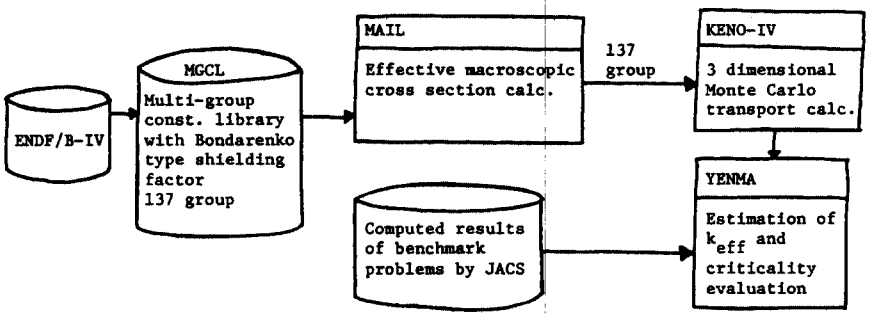
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	
Extrapolation Distance	

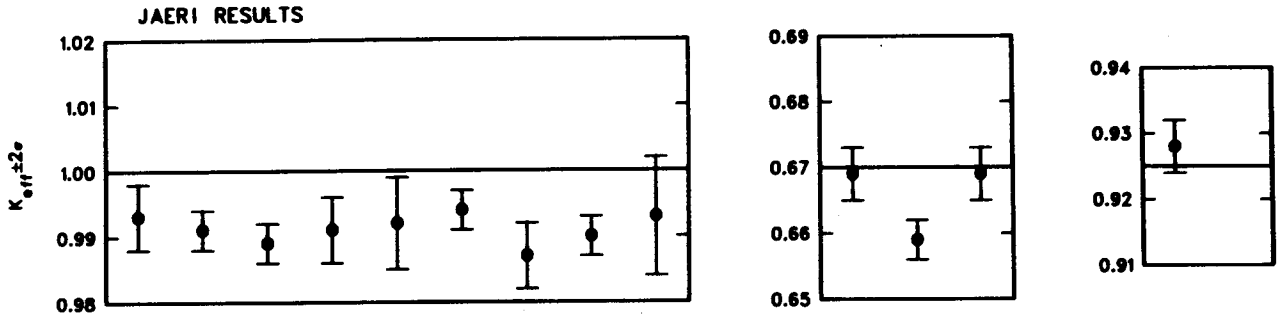
d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	Three-dimensional exact geometry	Multigroup (137 group) transport theory Monte Carlo code

Flow Diagram



ORNL-DWG 82C-11947



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2	4A	4A (opt.)	4B	5

EMS, Studsvik and ASEA-ATOM Results (Sweden)

Comments on EMS results

The results using SCALE and 27-group cross sections show the average k_{eff} for Problems 1-3 to be close to 1.00. This is a little higher than expected, based on earlier validation calculations.

For Problems 4 and 5, however, k_{eff} seems to be underestimated. As the true answers to these problems are not known, it is difficult to say how much k_{eff} is underestimated. It seems as if the underprediction could be as much as 0.02.

The conclusion is that the current version of SCALE0 as used in Sweden is adequate for calculations on PWR fuel casks of the type considered in this exercise. However, an extra safety margin of 0.02 should be used.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
CSRL-27	27	CSRL 218 group cross sections derived from ENDF/B-IV	AMPX-II Codes

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
NITAWL	1-d	Nordheim	27 groups & point data	27-group library
XSDRNPM	1-d	S_8 Transport Theory	27	27-group cell weighted library

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	27	Response Treatment- NITAWL Cell Homogenization - XSDRNPM
other		

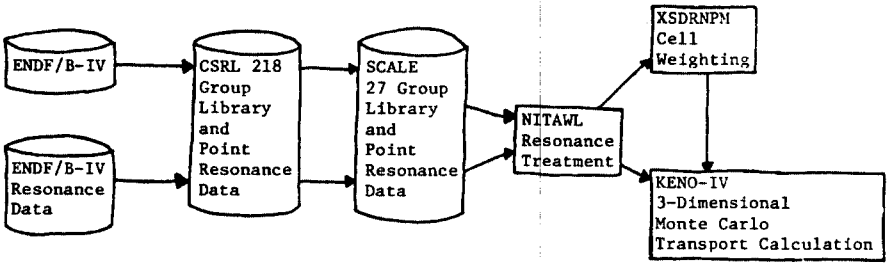
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	
Extrapolation Distance	

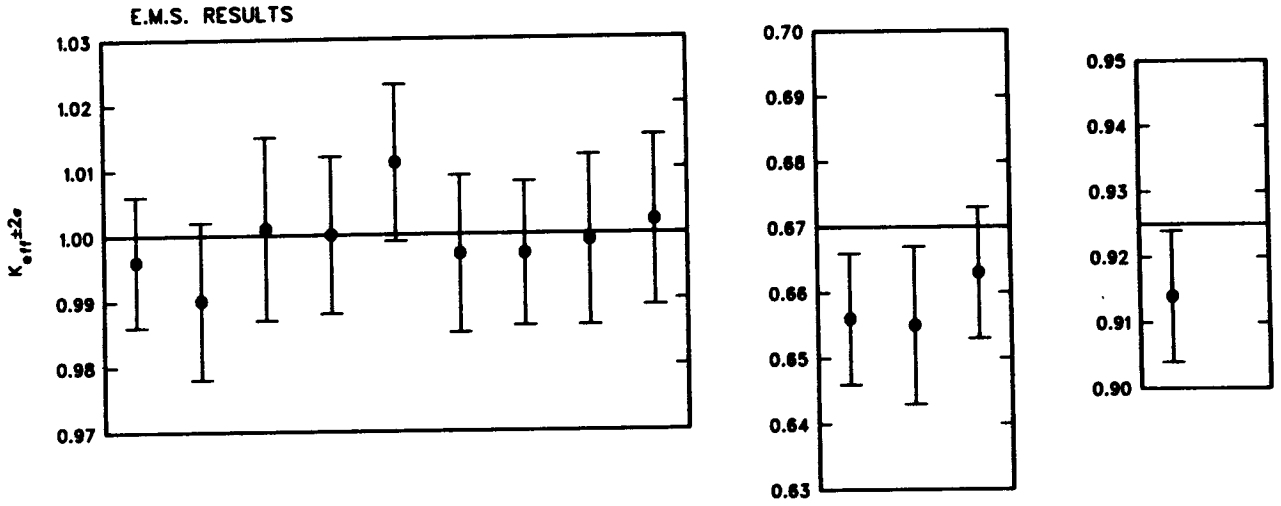
d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	Actual 3-dimensional geometry except each fuel rod and surrounding moderator homogenized	Monte Carlo

Flow Diagram



ORNL-DWG 82C-11948



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2

4A	4A (opt.)	4B

5

Comments on Studsvik results

The diffusion theory code DIXY, when used in combination with the transport code CASMO in the way indicated by the flow diagram, produces an average k_{eff} close to 1.00 for the Problems 1-3.

The geometries in these problems are not typical for LWR fuel transport, which means that some additional calculations had to be carried out with both CASMO and DIXY. The version of CASMO used could treat square PWR assemblies containing up to 17x17 rods per assembly. This meant that complete homogenization of fuel assembly, water gaps and for some problems boral absorbers could not be carried out by CASMO. The short fuel assemblies used in the experiments introduces a leakage in the third dimension, which can be neglected for realistic LWR fuel. This motivated geometrical buckling corrections. These were calculated using DIXY.

There was no significant difficulty in calculating Problems 1-3.

For Problems 4 and 5 typical PWR fuel assemblies were used. This meant that the full homogenization capability of CASMO could be used. The void in Problems 4.A and 4.B was avoided by moving the shielding close to the fuel square. This is conservative but has a small effect on k_{eff}. Because the shielding is close to the fuel in Problems 4.A, 4.B and 5, it was necessary to divide the outer fuel assemblies into two halves. As the models used for Problems 1-3 had been much more complicated, no difficulty was expected.

It turned out, however, that the very wide water gaps in Problems 4.A and 4.B were more difficult to model than expected. By comparing DIXY calculations with identical CASMO calculations, it was concluded that the water gaps can be modeled adequately by dividing them into several regions. However, due to limited time, the results reported here for Problems 4.A and 4.B were obtained using an adjustment. The adjustment was based on calculations carried out with CASMO and DIXY. Problem 4.A.Optional is easy to model using completely homogenized fuel, water and boral plates. A comparison with CASMO for an infinite array of such "fuel assembly cells" gave almost identical results. It was concluded that the results for Problem 4.A.Optional was accurate.

To find the error in the results for Problems 4.A and 4.B, an identical model was also used to calculate Problem 4.A.Optional. The difference between the results for the correct and the "rough" models used in solving Problem 4.A.Optional was the basis for the adjustment of the results for Problems 4.A and 4.B.

Problem 5 did not need any adjustment as the effective water gaps are very small.

The conclusion is that DIXY and CASMO together are adequate for calculations on PWR fuel casks of the type considered in this exercise. There is now a new version of CASMO that can treat more complicated geometries, including more water regions and larger PWR assemblies (20x20 rods).

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
LWR-WIMS	25	UKNDL	

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
CASMO Sequence 1	1-D Cylinder	Discrete integral transport	25	Library with each fuel cell and region explicit
CASMO Sequence 2	2-D Fuel Assembly	S_4 trans-port theory	10	Completely or partially homogenized assembly cell

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	6	Self-shielding - CASMO Cell Homogenization - CASMO
other	6	2-D region weighted - CASMO

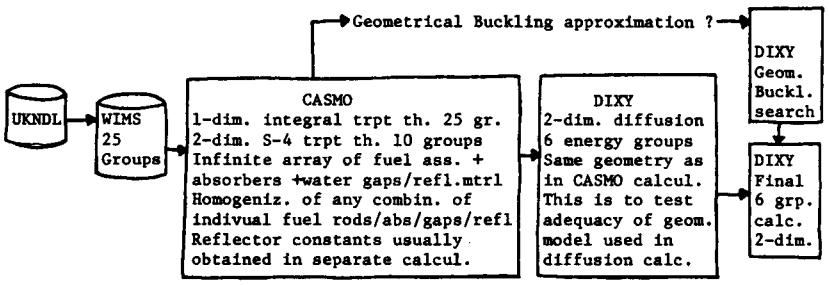
c') Method and code used to obtain other constraints necessary in diffusion theory

$D, B^2 or M^2 \cdots$	D_2 obtained from CASMO B^2 obtainted from basic buckling calculations
Extrapolation Distance	Obtained from comparisons of 1-D and 2-D R-Z DIXY calculations

d) k_{eff} calculation

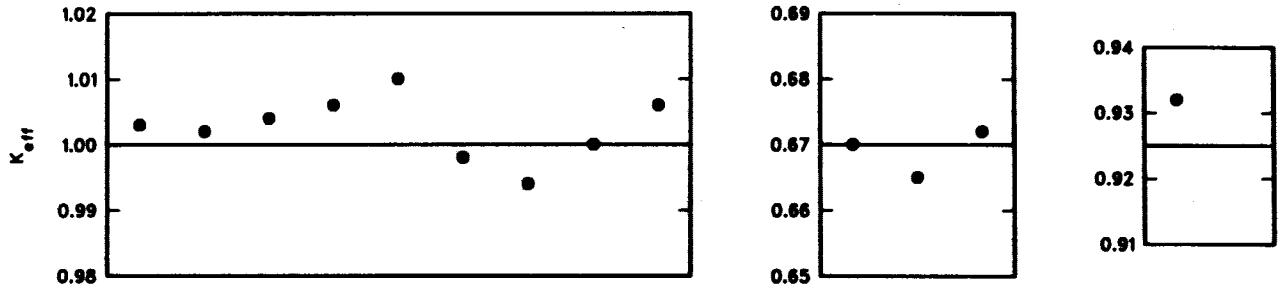
Computer code	Geometry	Method
DIXY	2-D X-Y. Finite array + reflector	Diffusion theory. Adequacy of model checked with CASMO.
CASMO	2-D X-Y. Infinite array	Integral + S_4 transport theory

Flow Diagram



ORNL-DWG 82C-11949

STUDSUIK RESULTS



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2	4A	4A (opt.)	4B	5

Comments on Asea-Atom results

KENO-IV using WIMS cross sections processed by PHOENIX calculated an average k_{eff} a little higher than 1.00 for Problems 1-3.

The results for Problems 4 and 5 seem to be consistent with the results for the Problems 1-3.

The conclusion is that KENO-IV and PHOENIX together are adequate for calculations on PWR fuel casks of the type considered in this exercise.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
LWR-WIMS	25 69	UKNDL UKNDL	

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
PHOENIX	1-d	Discrete integral transport theory	25	13-group macroscopical cross sections

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	13	Self-shielding - PHOENIX Cell homogenization - PHOENIX
other	13	Fundamental mode - MICO From 69 groups to 13

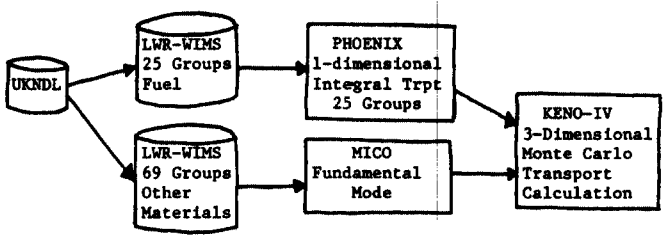
c') Method and code used to obtain other constraints necessary in diffusion theory

D, B^2 or M^2 ...	
Extrapolation Distance	

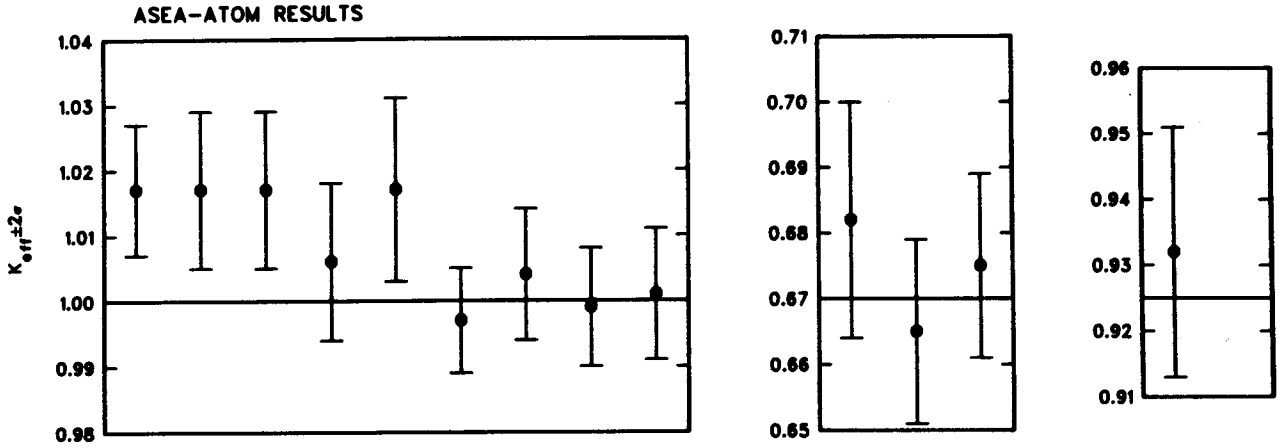
d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	Actual 3-dimensional geometry except each fuel rod and surrounding moderator homogenized	Monte Carlo

Flow Diagram



ORNL-DWG 82C-11950



BENCHMARK PROBLEM NO.

1.1	1.2.1	1.2.2	2.1	2.2	3.A.1	3.A.2	3.B.1	3.B.2	4A	4A (opt.)	4B	5

VTT Results (Finland)

Comments on VTT results

The use of a diffusion program (in this case, GOG) with broad group constants calculated by CASMO-HEX appears to give reasonable results for all problems treated in this benchmark exercise. For the cases with absorber plates between the fuel assemblies and experimental results available (i.e., Problems 2 and 3), k_{eff} is somewhat underestimated when axial buckling is included, but in no case by more than 3%. Some difficulties encountered in these calculations were the inappropriateness of diffusion theory to a system containing strong absorbers, the difficulty of choosing an axial buckling for a system with short fuel pins having one end in air and the failure of GOG to converge fully for a system containing voids. None of these difficulties has arisen in applications where the combination of CASMO-HEX and a diffusion program (TRIGON) has been applied to real spent fuel casks, so an error margin of 0.03 is presumed to be adequate for these calculations also.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
CASMO-HEX-LIBRARY	27	ENDF/B-III	CASMO-HEX-library is based on the data library of the Swedish code CASMO

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
CASMO-HEX	1-D(cylindrical) or 2-D(hexagonal)	Discrete integral transport equation	27	IR approximation with 2-term collision probability for U-235 and U-238

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	6 or 10	Weighting by CASMO-HEX
other	6 or 10	Weighting by CASMO-HEX

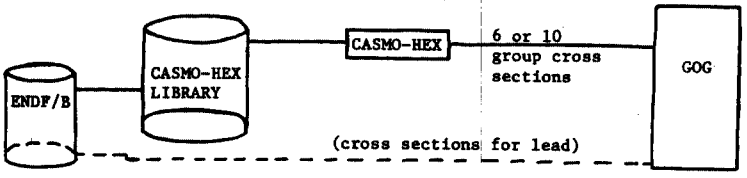
c') Method and code used to obtain other constraints necessary in diffusion theory

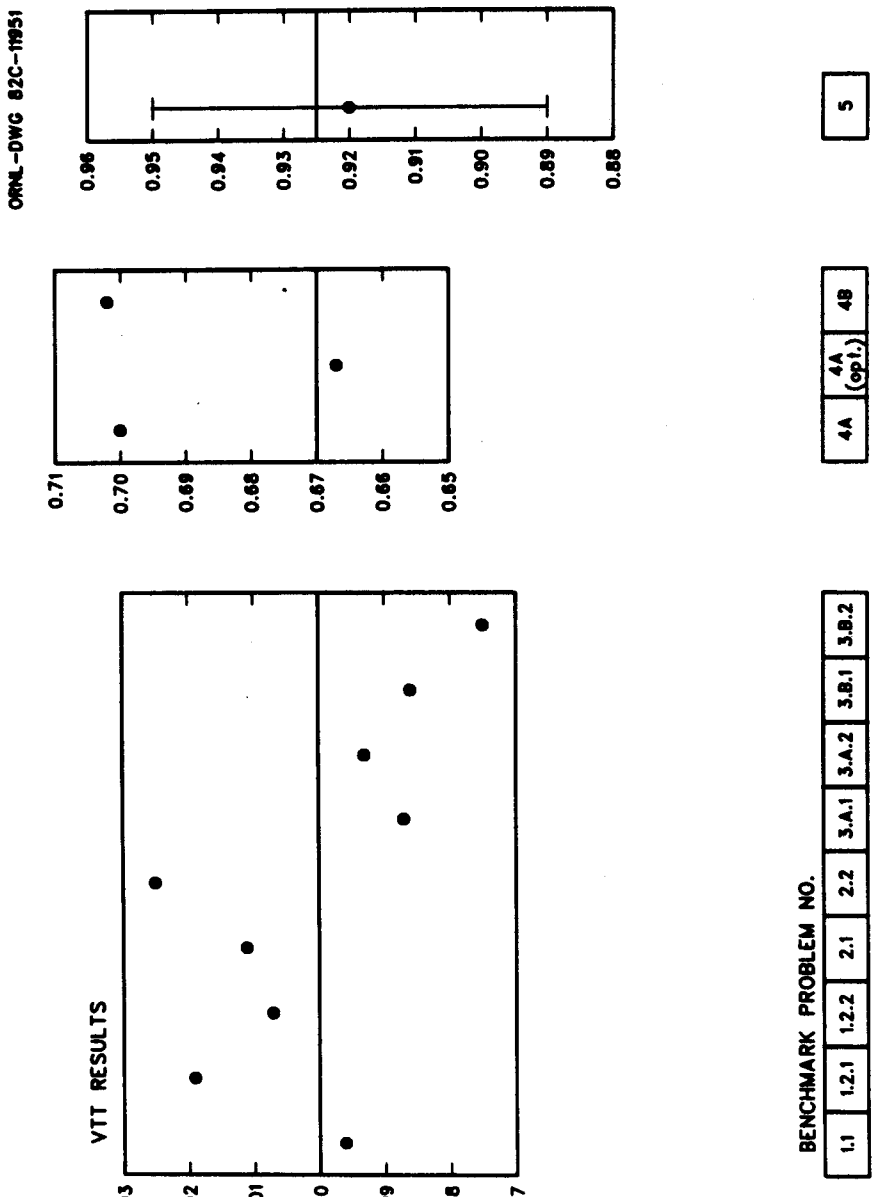
D, B^2 or M^2 ...	B^2_{axial} = 0 (problem class 2) geometrical buckling (otherwise)
Extrapolation Distance	assumed (7 cm for water)

d) k_{eff} calculation

Computer code	Geometry	Method
GOG	xy-geometry (problems 1-3), 1 D cylindrical (problem 4 and 5)	Diffusion theory

Flow Diagram




ORNL-DWG 82C-11951
VTT RESULTS
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.71
0.70
0.69
0.68
0.67
0.66
0.65
0.96
0.95
0.94
0.93
0.92
0.91
0.90
0.89
0.88
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2
4A
4A (opt.)
4B
5

US Results

Comments on ORNL results

The results obtained using the KENO-IV program with the CSRL-27 group cross sections are adequate to evaluate transport casks of the type considered in this exercise. The computed values of k_{eff} for both explicit pin representation and for the pins homogenized with the surrounding water are low by 0.005 - 0.010. This bias must be considered in using this method.

Summary of Calculation Method

a) Fine group constants

Name of the library	Number of groups	Source of cross sections	Processor of the source of cross sections. Processing method and code name.
CSRL-27	27	CSRL 218 group cross sections derived from ENDF/B-IV	AMPX-II Codes

b) Cell calculations for homogenizing fuel assembly — Method of self-shielding

Computer code	Geometry	Method	Number of groups	Self-shielded cross sections
NITAWL	1-D	Nordheim	27 groups & point data	27-group library
XSDRN	1-D	S_n Transport Theory	27	27-group cell weighted library

c) Broad group constants

Material	Number of groups	Method and codes used to obtain it
fuel	27	Resonance Treatment - NITAWL Cell Homogenization - XSDRNPM
other	27	

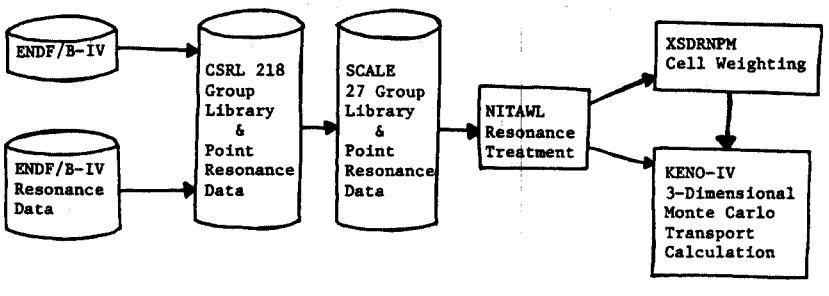
c') Method and code used to obtain other constraints necessary in diffusion theory

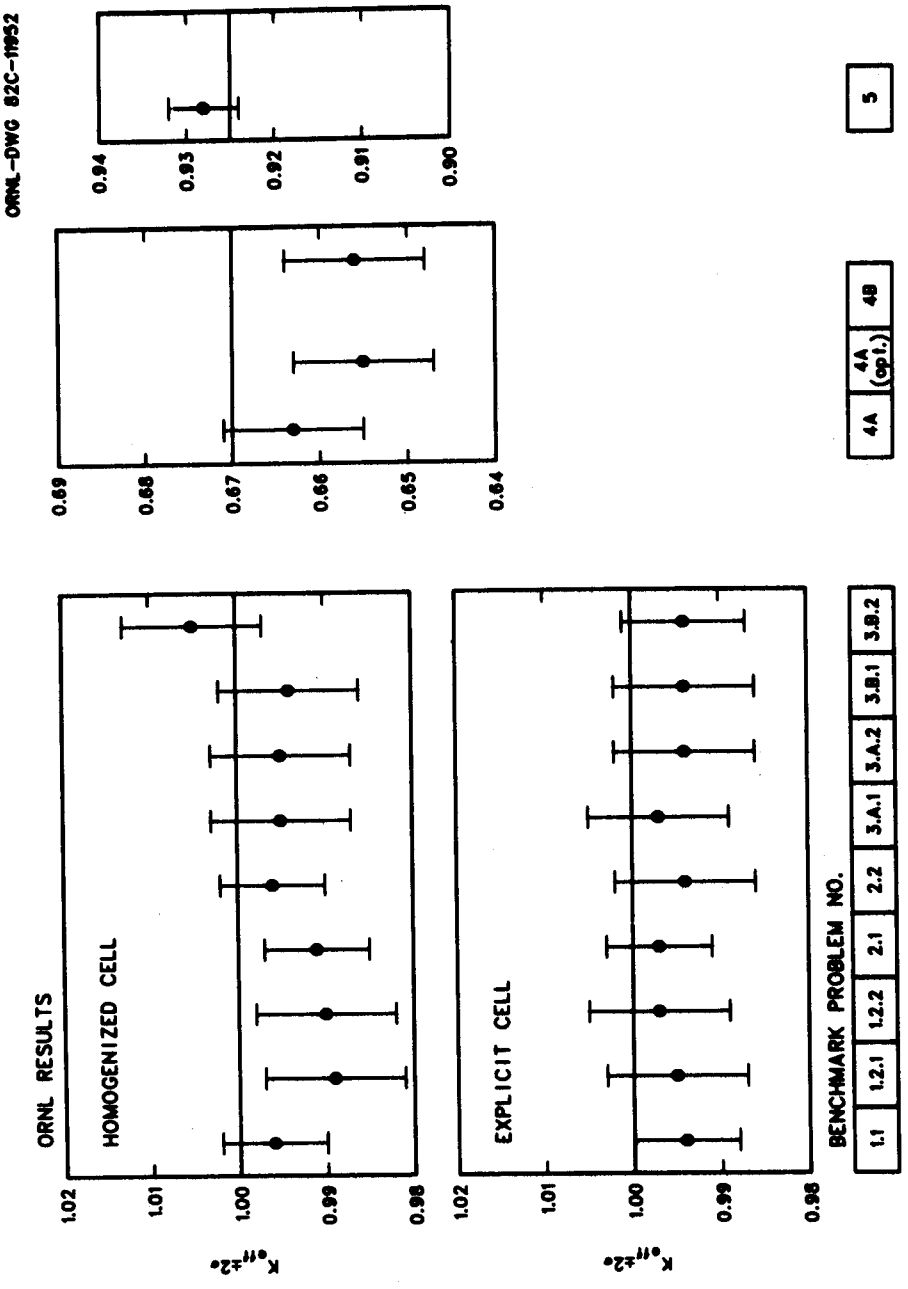
D, B^2 or M^2 ...	
Extrapolation Distance	

d) k_{eff} calculation

Computer code	Geometry	Method
KENO-IV	Actual 3-dimension geometry or actual 3-dimension geometry except fuel and surrounding moderator homogenized	Monte Carlo

Flow Diagram




ORNL-DWG 82C-11952
ORNL RESULTS
HOMOGENIZED CELL
EXPLICIT CELL
$K_{eff} \pm 2\sigma$
1.02
1.01
1.00
0.99
0.98
0.69
0.68
0.67
0.66
0.65
0.64
0.94
0.93
0.92
0.91
0.90
4A
4A (cpl.)
4B
5
BENCHMARK PROBLEM NO.
1.1
1.2.1
1.2.2
2.1
2.2
3.A.1
3.A.2
3.B.1
3.B.2

Appendix III

Members of the Working Group

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