Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

AEC Research and Development Report

COMPARISON OF CALCULATED AND
MEASURED VALUES OF ρ^{28} AND δ^{28}_{25}
FOR 26 LATTICES OF UO_2 RODS
IN A LIGHT WATER MODERATOR

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
U.S. ATOMIC ENERGY COMMISSION
Under Contract AT(45-1)-1830

3 3679 00062 1005

BNWL-1589

~~Special Distribution~~

COMPARISON OF CALCULATED AND MEASURED VALUES
OF ρ^{28} AND δ_{25}^{28} FOR 26 LATTICES
OF UO_2 RODS IN A LIGHT WATER MODERATOR

D. R. Oden

Reactor Physics Department

May 1971

BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORIES
RICHLAND, WASHINGTON 99352

ABSTRACT

A study was undertaken to test the adequacy of current theoretical models used to predict ^{238}U reaction rates in uniform lattice cells containing UO_2 rods in a light water moderator. Calculations were made with two analytical models on data for 26 lattices for which ρ^{28} and δ_{25}^{28} had been measured. Large discrepancies were observed between the measured and calculated results which could be attributed to systematic experimental errors and/or biases in the analytical models.

The influence that the typical discrepancies observed would have on the calculated eigenvalue was demonstrated to be appreciable and would generally lead to an underprediction of this quantity, especially for under-moderated lattices. It is recommended that a more detailed study be undertaken to determine the cause of the differences observed between theory and experiment.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	iii
LIST OF FIGURES	vii
LIST OF TABLES	ix
I INTRODUCTION	1
II SUMMARY AND CONCLUSIONS	3
III DISCUSSION	5
IV DESCRIPTION OF EXPERIMENTAL LATTICES	9
V DESCRIPTION OF CALCULATIONS AND MODELS USED	12
VI THEORY-EXPERIMENT COMPARISONS	14
A. ρ^{28}	14
1. BAPL Lattices	14
2. WAPD Lattices	16
3. BNL Lattices	18
4. ANL Lattices	18
5. General Remarks	18
B. δ_{25}^{28}	23
1. BAPL Lattices	24
2. WAPD Lattices	24
3. BNL Lattices	24
4. ANL Lattices	24
5. General Remarks	24
ACKNOWLEDGMENTS	30
APPENDIX	A-1

LIST OF FIGURES

<u>Number</u>		<u>Page</u>
1	Measured Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice	11
2	Measured Values of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice	11
3	Measured and Calculated Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice; BAPL Lattices 1-5	15
4	Measured and Calculated Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: BAPL Lattices 4-8	15
5	Measured and Calculated Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: WAPD Lattices 1-7	17
6	Measured and Calculated Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: BNL Lattices 1-5	19
7	Measured and Calculated Values of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: ANL Lattices 1-6	20
8	Ratio (R^{28}) of Calculated to Measured Value of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: BRT-1/EGGNIT Results	21
9	Ratio (R^{28}) of Calculated to Measured Value of ρ^{28} vs. H/U^{238} Atom Ratio of the Lattice: BRT-1/HRG3 Results	21
10	Measured and Calculated Values of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice: BAPL Lattices 1-8	25
11	Measured and Calculated Values of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice: WAPD Lattices 2-7	26
12	Measured and Calculated Values of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice: BNL Lattices 1-5	27
13	Measured and Calculated Values of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice: ANL Lattices 1-6	28
14	Ratio (R_{25}^{28}) of Calculated to Measured Value of δ_{25}^{28} vs. H/U^{238} Atom Ratio of the Lattice: BRT-1/EGGNIT Results	29

LIST OF TABLES

<u>Number</u>		<u>Page</u>
I	$\Delta k/k$ as a Function of ρ^{28}	6
II	Description of Experimental Lattices	10

COMPARISON OF CALCULATED AND MEASURED VALUES
OF ρ^{28} AND δ_{25}^{28} 26 LATTICES
OF UO_2 RODS IN A LIGHT WATER MODERATOR

By
D. R. Oden

I. INTRODUCTION

Neutron capture and fission rates in ^{238}U strongly influence the lattice physics characteristics in typical water moderated thermal power reactors. This is true for conventional LWR's utilizing slightly enriched UO_2 fuel as well as for Pu-recycle cores which contain UO_2 - PuO_2 fuel. This particular study was performed under the Plutonium Utilization Program (PUP) in order to assess how well the capture and fission rates for ^{238}U are predicted by reactor design codes developed under the PUP. Measurements of ^{238}U reaction rates as a rule have not been performed in lattices of mixed oxide rods. Therefore, for this study, we have drawn upon the wealth of such measurements that have been reported for UO_2 lattices. The measurements in UO_2 lattices provide a valid test of design methods intended for use in UO_2 - PuO_2 core design, because the amount of ^{238}U is about the same in both types of fuel.

Thermal neutron capture in ^{238}U typically represents 5-15% of the total thermal neutron captures in power reactors. The resonance neutron capture rate in ^{238}U , however, represents essentially all of the epithermal capture in these lattices and is typically one to four times the thermal capture rate in ^{238}U . In addition, fast fissions in ^{238}U typically account for 4-8 percent of the total fissions in these lattices. Both neutron capture and fission

rates in ^{238}U influence lattice reactivity. An accurate knowledge of neutron capture is also important for predicting fuel economy since the attainable fuel burnup is sensitive to the initial conversion ratio, defined as the number of neutrons captured in ^{238}U per neutron absorbed in ^{235}U .

Measurements of ^{238}U reaction rates in lattices are usually performed on a relative rather than absolute basis due to the comparative simplicity with which the former measurements can be made. What is usually quoted as a result of these measurements is then a ratio of measured reaction rates. In the case of ^{238}U capture, a ratio commonly quoted is

$$\rho^{28} = \frac{1}{\text{CdR}-1} = \frac{\text{EPI-CADMIUM CAPTURE RATE IN } ^{238}\text{U}}{\text{SUB-CADMIUM CAPTURE RATE IN } ^{238}\text{U}}$$

where CdR is the ^{238}U cadmium ratio in the fuel rod.

Other ratios which are sometimes quoted include the initial conversion ratio, the modified conversion ratio, and the relative modified conversion ratio, but ρ^{28} is the only ratio which separates epi-cadmium from sub-cadmium captures in ^{238}U . By comparing measured and calculated values of ρ^{28} one can test the ability of calculational methods to predict the correct ^{238}U resonance neutron reaction rates. This is a more direct approach than using the other ratios mentioned since they involve total reaction rates in ^{238}U and ^{235}U .

Fast fissions in ^{238}U are usually measured relative to total fissions in ^{235}U . The ratio commonly quoted is δ_{25}^{28} defined as

$$\delta_{25}^{28} = \frac{\text{TOTAL FISSION RATE IN } ^{238}\text{U}}{\text{TOTAL FISSION RATE IN } ^{235}\text{U}}$$

Since fast fission in ^{238}U occurs only for neutrons whose energies exceed 1.35 MeV, this represents a ratio of a reaction rate for fission spectrum neutrons to a reaction rate for thermal and resonance energy neutrons.

II. SUMMARY AND CONCLUSIONS

The results of this comparison of calculated and measured values of ρ^{28} and δ_{25}^{28} for twenty-six lattices of UO_2 rods in a light water moderator indicate large discrepancies between theory and experiment. In the case of the parameter ρ^{28} , both calculational models indicated similar trends within a given data set, in the ratio of calculated to experimental value vs. H/U^{238} atom ratio of the lattice. However, each data set indicates a different variation of the ratio with H/U^{238} ratio of the lattice. Considering the experimental values to be accurate, there also appears to be a large positive bias in the BRT-1/EGGNIT results relative to both those from BRT-1/HRG3 and the experiment. In general, the deviation of the ratio of calculated to experimental value from unity increases with decreasing H/U^{238} values of the lattice.

In the case of δ_{25}^{28} , the BRT-1/EGGNIT model generally predicted a lower value than that measured. All four sets of data indicate a linear increase in the ratio of calculated to measured value of δ_{25}^{28} as the H/U^{238} ratio of the lattice is increased.

It has not yet been determined whether the cause of the discrepancies observed between measured and calculated values of ρ^{28} and δ_{25}^{28} is due to systematic experimental errors or biases in the analytical models. Both types of errors appear to be present in the case of ρ^{28} while either could cause the discrepancies observed between measured and calculated values of δ_{25}^{28} . This apparent tendency of a calculational model to predict higher values of ρ^{28} and lower values of δ_{25}^{28} than the respective measured values has been observed by others. (1,2)

The general overprediction of ρ^{28} and underprediction of δ_{25}^{28} observed in this study will both lead to an underprediction of the reactor eigenvalue in the absence of compensating errors. The magnitude of the differences observed between measured and calculated values of ρ^{28} and δ_{25}^{28} were shown to produce an appreciable difference in the calculated eigenvalue. It is noted, however, that theory-experiment correlations⁽³⁾ of k_{eff} for clean lattices of UO_2 and of UO_2 - PuO_2 rods using these calculational methods indicated excellent agreement over a wide range of plutonium enrichments and H/Pu ratios. The discrepancies brought to light by the present analysis indicate that there probably are other compensating errors in the calculational methods which result in correct values of k_{eff} . Many inconsistencies and compensating errors can be buried in a calculational method, and would go undetected if one merely normalized the methods to yield good agreement in k_{eff} for clean lattices. This study illustrates the need to investigate the accuracy of the various detailed portions of a calculational method as well.

Furthermore, the results of this study help to point out the difficulties which could arise if an analytical model were to be indiscriminately normalized to a given set (or sets) of experimental ρ^{28} data. In this respect, it is hoped that a more detailed study will be undertaken to evaluate both the experimental data and analytical methods and thus determine the cause of the differences observed.

III. DISCUSSION

An intuitive feeling as to the importance of being able to calculate ρ^{28} and δ_{25}^{28} accurately is obtained by considering as components of the effective multiplication factor, k , the four factor formula for k_{∞} and a leakage term. Using a neutron balance model, the expression relating the reactor multiplication, k , to the infinite medium multiplication k_{∞} and a finite medium leakage term is

$$k = k_{\infty} L = \eta f p \epsilon L \quad (1)$$

where η and f are the neutron regeneration factor and thermal utilization respectively, and L is the non-leakage probability. Writing p , the resonance escape probability, and ϵ , the fast fission factor in terms of ρ^{28} and δ_{25}^{28} we have from (1)

$$k = \eta f \left[\frac{1}{1 + \rho^{28} fG} \right] \left[1 + \delta_{25}^{28} \left(\frac{\nu^{28} - 1 - \alpha^{28}}{\nu^{25}} \right) \right] L \quad (2)$$

where

$$G = \frac{\text{Sub-cadmium capture rate in } ^{238}\text{U}}{\text{Total sub-cadmium absorption in the fuel}}$$

$$f = \frac{\text{Total sub-cadmium absorption in the fuel}}{\text{Total sub-cadmium absorption in the cell}}$$

$$\nu^{28} = \text{Average number of neutrons per fission in } ^{238}\text{U}$$

$$\nu^{25} = \text{Average number of neutrons per fission in } ^{235}\text{U}$$

$$\alpha^{28} = \text{Capture to fission ratio for } ^{238}\text{U in the fast region.}$$

From the definition of f and G we have

$$fG = \left[\frac{\Sigma_c^{28}}{\Sigma_a} / \Sigma_a^{\text{cell}} \right]_{\text{Sub-Cd}}$$

where Σ_C^{28} and Σ_a^{cell} are the cell averaged, subcadmium, macroscopic cross sections for ^{238}U capture and total cell absorption, respectively.

Thus

$$k = \eta f \left[\frac{1}{1 + \rho^{28} \left(\Sigma_C^{28} / \Sigma_a^{cell} \right)} \right]_{\text{Sub-Cd}} \left[1 + \delta_{25}^{28} \left(\frac{\nu^{28} - 1 - \alpha^{28}}{\nu^{25}} \right) \right] L \quad (3)$$

We are now in a position to estimate the effects of biases in the calculated values of ρ^{28} and δ_{25}^{28} on the eigenvalue. Taking the partial derivative of Equation (3) with respect to ρ^{28} and simplifying we get

$$\frac{\partial k}{\partial \rho^{28}} = -k \left[\frac{1}{\rho^{28} + \left(\Sigma_a^{cell} / \Sigma_C^{28} \right)_{\text{Sub-Cd}}} \right] \quad (4)$$

or

$$\frac{\Delta k}{k} = - \left(\frac{\Delta \rho^{28}}{\rho^{28}} \right) \left[\frac{1}{1 + \left(\Sigma_a^{cell} / \Sigma_C^{28} \right)_{\text{Sub-Cd}} / \rho^{28}} \right] \quad (5)$$

Assuming a 10 percent positive bias in calculated values of ρ^{28} and using a representative value of $\left(\Sigma_a^{cell} / \Sigma_C^{28} \right)_{\text{Sub-Cd}}$ of 10, we have from (5)

$$\frac{\Delta k}{k} = -0.1 \left[\frac{1}{1 + 10/\rho^{28}} \right] \quad (6)$$

Table I below shows $\Delta k/k$ as a function of ρ^{28} calculated from Equation (6).

TABLE I

$\Delta k/k$ as a Function of ρ^{28}

<u>ρ^{28}</u>	<u>$\Delta k/k$</u>
1	-0.009
2	-0.017
5	-0.033
10	-0.050

To determine the effect of biases in calculated values of δ_{25}^{28} on the calculated eigenvalue we take the partial derivative of Equation (3) with respect to δ_{25}^{28} which yields after some simplification

$$\frac{\partial k}{\partial \delta_{25}^{28}} = k \left(\frac{1}{\delta_{25}^{28}} - \frac{1}{\epsilon \delta_{25}^{28}} \right) \quad (7)$$

or

$$\frac{\Delta k}{k} = \left(\frac{\Delta \delta_{25}^{28}}{\delta_{25}^{28}} \right) \left(\frac{\epsilon - 1}{\epsilon} \right) \quad (8)$$

Assuming a negative 10 percent bias in calculated values of δ_{25}^{28} results in

$$\frac{\Delta k}{k} = -0.1 \left(\frac{\epsilon - 1}{\epsilon} \right) \quad (9)$$

Since ϵ is typically in the range 1.04-1.08, Equation (9) indicates that $\frac{\Delta k}{k}$ will range from -0.004 to -0.008 under the assumed conditions.

Although the model used in the preceeding analyses is relatively simplified it does illustrate the order of magnitude uncertainties involved. A few observations based on the above analysis are enumerated below.

1. For a given percentage bias in the calculated parameter, the largest bias in the calculated eigenvalue occurs in the case of ρ^{28} .
2. A positive bias in the calculated value of ρ^{28} and a negative bias in the calculated value of δ_{25}^{28} both lead to an underprediction of the eigenvalue.

3. If the biases assumed in the calculated values of ρ^{28} and δ_{25}^{28} are the correct order of magnitude, relatively large biases in calculated eigenvalues are possible.

4. If the biases are present at all in the calculated values of ρ^{28} , it is expected that they would be the largest for lattices with low H/U^{238} values where resonance effects are most pronounced. The largest under-predictions of the eigenvalue would therefore be expected to occur at the tightest lattice pitches.

In order to determine if biases do exist in calculated values of ρ^{28} and δ_{25}^{28} , calculations were performed with different models on four sets of lattices for which ρ^{28} and δ_{25}^{28} have been measured and reported in the literature.⁽⁴⁻⁷⁾ A description of these 26 lattices is given in the next section.

IV. DESCRIPTION OF EXPERIMENTAL LATTICES

A description of the experimental lattices⁽⁴⁻⁷⁾ utilized in this study is given in Table II. Lattices are grouped in the table according to the laboratory reporting the measurements. All lattices contain UO_2 rods in a light water moderator.

These four sets of lattices were chosen for this study since they were deemed best suited to indicate the presence or absence of systematic errors or trends in the measured and calculated data. For example, the eight BAPL lattices contain 1.311 weight percent ^{235}U enriched rods of three diameters and pellet densities; 0.383 inch diameter at 10.53 g/cc (3 lattices), 0.388 inch diameter at 7.52 g/cc (2 lattices) and 0.601 inch diameter at 7.53 g/cc (3 lattices). This, in principle, allows the effect of rod diameter and pellet density on the calculated or experimental parameter to be studied as well as the variations with H/U^{238} ratio of the lattice. The seven WAPD lattices (0.300 inch diameter, 2.7 percent enriched rods), the five BNL lattices (0.441 inch diameter, 3.006 percent enriched rods) and the six ANL lattices (0.368 inch diameter, 3.044 percent enriched rods) allow the effect of H/U^{238} ratio of the lattice on the measured and calculated parameters to be observed for a given fuel enrichment. Furthermore, intercomparison of the four sets of measured and/or calculated data allow possible systematic effects due to fuel enrichment, pellet diameter and pellet density to be evaluated.

Figures 1 and 2 are plots of the measured values of ρ^{28} and δ_{25}^{28} , respectively, as a function of H/U^{238} ratio of the lattice. These figures illustrate the broad range of values of ρ^{28} , δ_{25}^{28} , and H/U^{238} covered by the four sets of lattices.

TABLE II
(4-7)
DESCRIPTION OF EXPERIMENTAL LATTICES

Lattice	Fuel			Cladding			Lattice				Measured Parameters		
	Enrichment	Diameter	Density	Material	O.D.	Thickness	Geometry	Pitch	W/UO ₂ Vol. Ratio	H/U ²³⁸	B _m ²	ρ ²⁸	δ ₂₅ ²⁸
Name	(w/o U ²³⁵)	(in.)	(g/cc)		(in.)	(in.)	(□ or Δ)	(in.)			(m ⁻²)		
BAPL-1	1.311	0.383	10.53	A1	0.453	0.028	Δ	0.613	1.426	4.117	32.59	1.43 ± .01	0.078 ± .004
BAPL-2	1.311	0.383	10.53	A1	0.453	0.028	Δ	0.650	1.779	5.133	35.47	1.15 ± .01	0.070 ± .004
BAPL-3	1.311	0.383	10.53	A1	0.453	0.028	Δ	0.711	2.396	6.931	34.22	0.934 ± .01	0.057 ± .003
BAPL-4	1.311	0.388	7.52	A1	0.453	0.028	Δ	0.613	1.386	5.615	25.28	1.04 ± .05	0.063 ± .003
BAPL-5	1.311	0.388	7.52	A1	0.453	0.028	Δ	0.650	1.734	7.001	25.21	0.90 ± .02	0.054 ± .003
BAPL-6	1.311	0.601	7.53	A1	0.666	0.028	Δ	0.868	1.071	4.328	28.37	1.19 ± .04	0.071 ± .007
BAPL-7	1.311	0.601	7.53	A1	0.666	0.028	Δ	0.929	1.405	5.680	30.17	0.994 ± .013	0.059 ± .006
BAPL-8	1.311	0.601	7.53	A1	0.666	0.028	Δ	0.989	1.756	7.097	29.06	0.807 ± .014	0.051 ± .004
WAPD-1	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.405	1.048	3.168	40.70	2.77 ± .08	
WAPD-2	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.418	1.200	3.621	47.10	2.78 ± .16	0.097 ± .007
WAPD-3	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.435	1.405	4.244	53.20	2.22 ± .05	0.076 ± .002
WAPD-4	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.470	1.853	5.601	63.30	1.83 ± .10	0.060 ± .005
WAPD-5	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.493	2.166	6.544	68.80	1.72 ± .07	0.066 ± .002
WAPD-6	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.573	3.372	10.196	59.50	1.22 ± .10	0.037 ± .001
WAPD-7	2.700	0.300	10.20	304SS	0.3384	0.0161	□	0.615	4.078	12.330	54.40	1.06 ± .06	0.037 ± .001
BNL-1	3.006	0.441	9.28	304SS	0.499	0.029	Δ	0.6767	1.319	4.386	54.44	2.92 ± .09	0.065
BNL-2	3.006	0.441	9.28	304SS	0.499	0.029	Δ	0.7163	1.632	5.429	62.45	2.41 ± .04	0.056
BNL-3	3.006	0.441	9.28	304SS	0.499	0.029	Δ	0.7706	2.091	6.956	68.03	1.81 ± .06	0.048
BNL-4	3.006	0.441	9.28	304SS	0.499	0.029	Δ	0.8542	2.863	9.522	67.98	1.41 ± .02	0.037
BNL-5	3.006	0.441	9.28	304SS	0.499	0.029	Δ	0.9707	4.071	13.538	59.98	1.04 ± .02	0.031
ANL-1	3.044	0.368	10.17	304SS	0.416	0.019	□	0.5311	1.380	4.176	67.13	3.05 ± .04	0.0742 ± .0011
ANL-2	3.044	0.368	10.17	304SS	0.416	0.019	□	0.4882	0.962	2.928	47.47	4.12 ± .03	0.1011 ± .0004
ANL-3	3.044	0.368	10.17	304SS	0.416	0.019	Δ	0.5000	0.757	2.290	37.86	5.40 ± .09	0.116 ± .0017
ANL-4	3.044	0.368	10.17	304SS	0.416	0.019	Δ	0.4591	0.438	1.330	7.54	10.0 ± 0.1	0.1539 ± .0039
ANL-5	3.044	0.368	10.17	304SS	0.416	0.019	Δ	0.4437	0.326	0.986	-4.80	14.5 ± 0.4	0.1877 ± .0020
ANL-6	3.044	0.368	10.17	304SS	0.416	0.019	Δ	0.4209	0.165	0.499	-27.73	28.6 ± 0.8	0.2622 ± .0036

Figure 1. Measured Values of ρ^{28} VS. H/U^{238} Atom Ratio of the Lattice

Figure 2. Measured Values of δ_{25}^{28} VS. H/U^{238} Atom Ratio of the Lattice

V. DESCRIPTION OF CALCULATIONS AND MODELS USED

Calculated values of ρ^{28} and δ_{25}^{28} were based on a two energy group model. Thermal group (0-0.683 eV) constants were obtained from BRT-1,⁽⁸⁾ a Battelle revised version of the integral transport theory, thermal spectrum code THERMOS,⁽⁹⁾ with a "white" boundary condition. The Nelkin model for H₂O was used for the scattering kernel with a correction applied for linear anisotropic scattering.⁽¹⁰⁾ Two sets of epithermal (0.683 eV - 10 MeV) group constants were generated; one set from HRG3,⁽¹¹⁾ the latest Battelle revised version of GAM-I,⁽¹²⁾ a space independent slowing down spectrum code, and the other from EGGNIT,⁽¹³⁾ which is a revised version of the GAMTEC II code.⁽¹⁴⁾ The same basic cross section data and energy group structure were used in both models employing the B₁ approximation. This was done to assure that any differences observed in calculated parameters from the two codes could be attributed to differences in the calculational model only and not due in part to differences in cross section libraries. The differences between HRG3 and EGGNIT which affect the ρ^{28} and δ_{25}^{28} calculations are in the treatment of resonance absorption and fast fissions.

The major difference between the HRG3 and EGGNIT treatments of resonance absorption arises in the resolved resonance region. In HRG3, Doppler broadening and spatial self-shielding effects are computed using an adaptation of the Adler-Hinman-Nordheim method⁽¹⁵⁾ to include an intermediate resonance approximation for both the absorber nuclide and an admixed moderator. In EGGNIT, the Adler-Hinman-Nordheim method is replaced by the Nordheim numerical integration technique⁽¹⁶⁾ which permits treating both absorber and admixed scatterers exactly. In addition, EGGNIT includes a treatment of resonance overlap, i.e., interference absorption due to a nearby resonance line, as well as including interference scattering in the Nordheim method. Neither of these interference

effects are presently included in the HRG3 code. The treatment of unresolved resonances is the same in both codes. Dancoff shielding corrections were computed by Carlvik's DASQUE program⁽¹⁷⁾ for both codes.

Calculation of the fast fissions in ^{238}U are performed on a homogeneous basis in HRG3. In EGGNIT, corrections are applied to account for lattice heterogeneity by extending Bonalumi's method⁽¹⁸⁾ for calculating first-flight collision probabilities to include n-flight contributions to the collision probabilities for neutrons whose energies exceed 1.35 MeV, the approximate ^{238}U fission threshold. In addition, interaction effects between neighboring fuel elements are approximated by isotropically reflecting neutrons that escape to the equivalent unit cell boundary with energies exceeding 1.35 MeV.

The calculated values of ρ^{28} and δ_{25}^{28} were generated from HRG3 and EGGNIT fast group constants and BRT-1 thermal group constants via the standard two group formulae;

$$\rho^{28} = \left(\frac{\sigma_{c1}}{\sigma_{a2}} \right)_{28} / \left(\frac{\phi_2}{\phi_1} \right)$$

and

$$\delta_{25}^{28} = \frac{N_{28}}{N_{25}} \frac{(\sigma_{f1})_{28}}{(\sigma_{f1})_{25} + (\sigma_{f2})_{25} (\phi_2/\phi_1)}$$

where

$$\frac{\phi_2}{\phi_1} = \frac{\Sigma_1^{\text{out}}}{\Sigma_{a2} + D_2 B^2},$$

and other parameters are:

N_{28} and N_{25} = Nuclei densities of ^{238}U and ^{235}U , respectively.

- $(\sigma_{f1})_{28}$ and $(\sigma_{f1})_{25}$ = Microscopic fission cross sections for ^{238}U and ^{235}U , respectively, from HRG3 (or EGGNIT).
- $(\sigma_{f2})_{25}$ = Microscopic fission cross section for ^{235}U from BRT-1.
- $(\sigma_{c1})_{28}$ = Microscopic capture cross section for ^{238}U from HRG3 (or EGGNIT).
- $(\sigma_{a2})_{28}$ = Microscopic absorption cross section for ^{238}U from BRT-1.
- Σ_1^{out} = Macroscopic cell averaged down scattering cross section from fast to thermal group from HRG3 (or EGGNIT).
- Σ_{a2} = Macroscopic cell averaged absorption cross section from BRT-1.
- D_2 = Cell averaged diffusion coefficient from BRT-1.
- B^2 = Geometrical buckling (Measured material buckling used).

VI. THEORY-EXPERIMENT COMPARISONS

A. ρ^{28}

Calculated values of ρ^{28} , via BRT-1/HRG3 and BRT-1/EGGNIT, are tabulated in the Appendix and plotted along with the corresponding experimental values (filled symbols) in Figures 3 through 7. Error bars are indicated on the experimental points for cases in which experimental uncertainties were available and were greater than the height of the plotting symbols. A discussion of each set of experimental and calculated results is given in the following sections.

1. BAPL Lattices

The BAPL data shown in Figure 3 indicate essentially no change (a slight decrease, but within experimental uncertainties) in ρ^{28} as the pellet

Figure 3. Measured and Calculated Values of ρ^{28} VS. H/U^{238}
Atom Ratio of the Lattice: BAPL Lattices 1-5

Figure 4. Measured and Calculated Values of ρ^{28} VS. H/U^{238}
Atom Ratio of the Lattice: BAPL Lattices 4-8

density is decreased from 10.53 g/cc in lattices 1-3 to 7.52 g/cc in lattices 4 and 5. Both sets of calculations, however, indicate an increase of ~ 8 percent in ρ^{28} as the pellet density is decreased. For lattices 1-3 BRT-1/EGGNIT results are in good agreement with experiment, while HRG3 underpredicts ρ^{28} by ~ 7 percent. In lattices 4 and 5, BRT-1/EGGNIT overpredicts ρ^{28} by 6 percent and 4 percent, respectively.

In Figure 4 data from BAPL lattices 6-8 are plotted with that from lattices 4 and 5. The major difference between these two sets of lattices is the fuel pellet diameter which was 0.601 inches in the former set and 0.388 inches in the latter. The experimental points for these lattices indicate about the same percentage drop in ρ^{28} with increased fuel pellet diameter as that predicted by both BRT-1/EGGNIT (~ 11 percent decrease) and BRT-1/HRG3 (~ 8 percent decrease). As was the case in lattices 4 and 5, the BRT-1/HRG3 model slightly overpredicts ρ^{28} (1-5 percent) for lattices 6-8 while BRT-1/EGGNIT overpredicts it by from 6 - 13 percent.

2. WAPD Lattices

Experimental and calculated results for the seven WAPD lattices are shown in Figure 5. The experimental points at $H/U^{238} = 3.621$ and 6.544 were measured with 12 and 10 mil thick cadmium, respectively, while 20 mil thick cadmium was used in the remaining five lattices. (5)

We see from Figure 5 that both calculational methods overpredict ρ^{28} and that the discrepancy between theory and experiment increases as the H/U^{238} ratio decreases. The amount of overprediction ranges from 3-24 percent in the case of BRT-1/HRG3 and 8-39 percent in the case of BRT-1/EGGNIT.

Figure 5. Measured and Calculated Values of ρ^{28} VS. H/U^{238}
Atom Ratio of the Lattice: WAPD Lattices 1-7

3. BNL Lattices

Data for the five BNL Lattices is shown in Figure 6. Considering the shape of the theoretical curves and a smooth fit to the experimental data it would appear that the point measured at $H/U^{238} = 6.956$ is systematically low. Calculated values for this lattice from BRT-1/HRG3 and BRT-1/EGGNIT are respectively 5 and 9 percent higher than the experimental values. However, neglecting this point the BRT-1/HRG3 results are in excellent agreement with experiment ranging from 1 percent too low to 3 percent too high while the BRT-1/EGGNIT model overpredicts ρ^{28} by from 3-6 percent. For both models there is a slight tendency toward increased overprediction of ρ^{28} as the H/U^{238} ratio is increased. In contrast, the WAPD lattice calculations indicated an appreciable increase in overprediction of the measured value of ρ^{28} as the H/U^{238} ratio was decreased.

4. ANL Lattices

Data from the six ANL lattices is shown in Figure 7. The validity of the experimental point at $H/U^{238} = 0.5$ is questionable due to the absence of a radial cadmium sleeve in the cadmium covered foil irradiation.⁽⁶⁾ Neglecting this point we see that BRT-1/EGGNIT tends to give the best agreement with experiment for these lattices with calculated values ranging from 3 percent too low to 8 percent too high. The BRT-1/HRG3 model on the other hand always yields a smaller value of ρ^{28} than the experiment with the discrepancy generally increasing as the H/U^{238} ratio decreases. Calculated values from this model range from 5 to 19 percent lower than the experimental values.

5. General Remarks

The theory-experiment correlation for ρ^{28} is best summarized by Figures 8 and 9. The ratio of calculated to experimental ρ^{28} versus H/U^{238}

Figure 6. Measured and Calculated Values of ρ^{28} VS. H/U^{238}
Atom Ratio of the Lattice; BNL Lattices 1-5

Figure 7. Measured and Calculated Values of ρ^{28} VS. H/U^{238}
Atom Ratio of the Lattice: ANL Lattices 1-6

Figure 8. Ratio (R^{28}) of Calculated to Measured Value of ρ^{28} VS. H/U^{238} Atom Ratio of the Lattice: BRT-1/EGGNIT Results

Figure 9. Ratio (R^{28}) of Calculated to Measured Value of ρ^{28} VS. H/U^{238} Atom Ratio of the Lattice: BRT-1/HRG3 Results

ratio is shown in Figure 8 for all 26 lattices via the BRT-1/EGGNIT model. Figure 9 provides the corresponding data utilizing the BRT-1/HRG3 model. From these two figures we see that the general trends, as indicated by the shape of the curves for a given data set, are quite similar for the two models. There does, however, appear to be a large positive bias in the BRT-1/EGGNIT results relative to those from BRT-1/HRG3. The more sophisticated BRT-1/EGGNIT model overpredicts ρ^{28} in all but two of the experimental lattices.

Although both models indicate the same trends in the ratio of the calculated to experimental value of ρ^{28} with H/U^{238} ratio for a given set of experimental data, each set of experimental data indicates a different trend. This suggests the possible presence of systematic experimental errors in one or more of the data sets which would be well in excess of the statistical uncertainties involved. Although apparently arising from different sources these systematic errors appear to increase in absolute value as the H/U^{238} ratio of the lattice is decreased. No attempt has been made to determine possible sources of systematic experimental errors in any of the data sets. Furthermore, the possibility exists that one or more of the indicated trends could be caused by systematic biases in the analytical models used.

A few words concerning the influence of the cadmium cutoff energy chosen for the calculations seem appropriate here. The value of 0.683 eV, corresponding to a cadmium thickness of ~ 40 mils,⁽¹⁹⁾ was chosen since it provides a convenient interface between the code generating the thermal group constants (BRT-1) and those generating the fast group constants (HRG3 and EGGNIT). The actual thickness of cadmium used in the experiments ranged

from ~15-20 mils which would correspond to a cutoff energy of ~0.515-0.555 eV. (19) Had it been possible to use this lower cadmium cutoff energy in the calculations, we would have observed a slightly higher calculated value of ρ^{28} which would be in even poorer agreement with the experimental values. Use of the lower cadmium cutoff energy would not, however, be expected to appreciably change the trends observed with the higher cutoff energy.

In summary, these results illustrate the relatively large systematic discrepancies which exist between theoretical and experimental values of ρ^{28} although at this time the source (or sources) of these discrepancies has yet to be determined. Detailed examination of experimental techniques and analytical models would be required for this determination.

B. δ_{25}^{28}

Values of δ_{25}^{28} calculated via BRT-1/EGGNIT and BRT-1/HRG3 are tabulated in the Appendix and the former are shown with the corresponding experimental values (filled symbols) in Figures 10 through 13. Error bars are indicated on the experimental points for cases in which experimental uncertainties were available and were greater than the height of the plotting symbols.

Note that calculated values of δ_{25}^{28} via BRT-1/HRG3 are not shown in the figures. Since fast fissions in HRG3 are treated on a homogenized cell basis, a correction for the presence of a spatial advantage factor due to lattice heterogeneity would have to be applied to the HRG3 results before these δ_{25}^{28} values can be directly comparable to measured values. In that the HRG3 and EGGNIT treatments of fast fissions differ only in this respect, only the BRT-1/EGGNIT results are shown. A discussion of each set of experimental and calculated results is given in the following sections.

1. BAPL Lattices

Calculated and experimental values of δ_{25}^{28} for BAPL lattices 1-8 are shown in Figure 10. Agreement between theory and experiment is relatively poor for lattices 1-5 with the calculated values ranging from 6-9 percent lower than the experimental values. In lattices 6-8, however, the agreement is excellent with the calculated value ranging from 0-2.4 percent greater than the experimental value. The calculated values of δ_{25}^{28} show much less sensitivity to changes in rod diameter and pellet density than do the measured values.

2. WAPD Lattices

Measured and calculated values of δ_{25}^{28} are shown in Figure 11 for WAPD lattices 2-7. Again agreement between theory and experiment is generally poor with the calculated values being as much as 27 percent lower than the measured values.

3. BNL Lattices

As seen in Figure 12 the agreement between theoretical and experimental values of δ_{25}^{28} for the five BNL lattices is excellent. Calculated values range from 2 percent lower to 4 percent higher than the experimental values.

4. ANL Lattices

Figure 13 shows the measured and calculated data for the six ANL lattices. Here again the calculated value of δ_{25}^{28} is low relative to the experimental value. The discrepancy ranges from 13-22 percent, the largest difference occurring for the tightest pitch lattice.

5. General Remarks

The theory-experiment correlation is summarized in Figure 14 which shows the ratio of calculated to experimental value of δ_{25}^{28} versus the H/U^{238} ratio

Figure 10. Measured and Calculated Values of δ_{25}^{28} VS. H/U^{238}
Atom Ratio of the Lattice: BAPL Lattices 1-8

Figure 11. Measured and Calculated Values of δ_{25}^{28} VS. H/U^{238}
Atom Ratio of the Lattice: WAPD Lattices 2-7

Figure 12. Measured and Calculated Values of δ_{25}^{28} VS. H/U^{238}
Atom Ratio of the Lattice: BNL Lattices 1-5

Figure 13. Measured and Calculated Values of δ_{25}^{28} VS. H/U^{238}
Atom Ratio of the Lattice: ANL Lattices 1-6

Figure 14. Ratio (R_{25}^{28}) of Calculated to Measured Value of δ_{25}^{28} VS. H/U²³⁸ Atom Ratio of the Lattice: BRT-1/EGGNIT Results

for all 26 lattices. As seen in this figure, the BRT-1/EGGNIT model generally predicts a lower value for δ_{25}^{28} than the measured value. In addition all four sets of data indicate a linear increase in the ratio of calculated to measured value of δ_{25}^{28} as the H/U^{238} ratio is increased. Whether these discrepancies between theory and experiment are due to biases in the analytical model or to systematic experimental errors, or both, is still undetermined.

ACKNOWLEDGMENTS

The author wishes to thank R. C. Liikala, J. L. Carter, C. R. Richey and V. O. Uotinen for many helpful discussions and suggestions during the course of this study.

REFERENCES

1. P. W. Davison, J. D. Cleary, B. Jennings, H. A. Risti, and G. H. Minton "Multi-Region Reactor Lattice Studies, Microscopic Lattice Parameters in Single- and Multi-Region Cores: A Comparison of Theory and Experiment," WCAP 1434, June 1961.
2. E. M. Pennington, "Analysis of High Conversion Critical Experiments," ANL-7270, March 1967.
3. F. G. Dawson, M. D. Freshley, R. C. Liikala, D. L. Prezbindowski, V. O. Uotinen, and H. H. Van Tuyl, "Results From USAEC Plutonium Utilization Program Conducted by Battelle-Northwest, "BNWL-SA-3865, 1971.
4. R. L. Hellens and Glenn A. Price, "Reactor Physics Data For Water Moderated Lattices of Slightly Enriched Uranium, "Reactor Technology Selected Reviews - 1964, TID-8540, pp 529-609, 1964.
5. Glenn A. Price, "Uranium - Water Lattice Compilation Part I, BNL Exponential Assemblies, BNL-50035, December 30, 1966.
6. A. R. Boynton, Q. L. Baird, K. E. Plumlee, W. C. Redman, W. R. Robinson, and G. S. Stanford, "High Conversion Critical Experiments," ANL-7203, January, 1967.
7. K. E. Plumlee, "Addendum to the Report on High Conversion Critical Experiments," ANL-7203 ADDENDUM, August, 1968.
8. C. L. Bennet and W. L. Purcell, "BRT-1: Battelle-Revised-Thermos," BNWL-1434, June 1970.
9. H. C. Honeck, "THERMOS - A Thermalization Transport Theory Code for Reactor Lattice Calculations," BNL-5826, September, 1961.
10. B. J. Toppel and I. Baksys, "The Argonne-Revised THERMOS Code," ANL-7023, March, 1965.
11. J. L. Carter, "HRG3: A Code for Calculating the Slowing-Down Spectrum in the P_1 or B_1 Approximation," BNWL-1432, June, 1970.
12. G. D. Joanou and J. S. Dudek, "GAM-I: A Consistent P_1 Multigroup Code for the Calculation of Fast Neutron Spectra and Multigroup Constants," GA-1850, June 28, 1961.
13. C. R. Richey, "EGGNIT: A Multigroup Cross Section Code," BNWL-1203, November, 1969.
14. L. L. Carter, C. R. Richey, and C. E. Hughey, "GAMTEC II: A Code for Generating Consistent Multi-group Constants Utilized in Diffusion and Transport Theory Calculations," BNWL-35, March, 1965.

15. F. T. Adler, G. W. Hinman, and L. W. Nordheim, "The Quantitative Evaluation of Resonance Integrals," Paper No. P/1988, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 16, pp 155-171, United Nations, Geneva, 1958.
16. G. F. Kuncir, "A Program for the Calculation of Resonance Integrals," GA 2525, August 28, 1961.
17. I. Carlvik, "The Dancoff Correction in Square and Hexagonal Lattices," NSE, 29, 325-336, (1967).
18. R. Bonalumi, "Neutron First Flight Collision Probabilities in Reactor Physics," Energia Nucleare, 8, No. 5, 326-336 (1961).
19. N. P. Baumann, "Resonance Integrals and Self Shielding Factors For Detector Foils," DP-817, January, 1963.

APPENDIX

APPENDIX

TABULATION OF MEASURED AND CALCULATED VALUES OF ρ^{28} AND δ_{25}^{28}

Lattice	H/U ²³⁸	ρ^{28}			δ_{25}^{28}		
		(4-7) Measured	BRT-1/ EGGNIT	BRT-1/ HRG3	(4-7) Measured	BRT-1/ EGGNIT (Heterogeneous)	BRT-1/ HRG3 (Homogeneous)
BAPL-1	4.117	1.43 ± .01	1.447	1.316	0.078 ± .004	0.0731	0.0698
BAPL-2	5.133	1.15 ± .01	1.190	1.100	0.070 ± .004	0.0634	0.0596
BAPL-3	6.931	0.934 ± .01	0.920	0.866	0.057 ± .003	0.0525	0.0479
BAPL-4	5.615	1.04 ± .05	1.203	1.105	0.063 ± .003	0.0588	0.0558
BAPL-5	7.001	0.90 ± .02	1.000	0.933	0.054 ± .003	0.0509	0.0476
BAPL-6	4.328	1.19 ± .04	1.342	1.256	0.071 ± .007	0.0711	0.0676
BAPL-7	5.680	0.994 ± .013	1.057	1.005	0.059 ± .006	0.0598	0.0556
BAPL-8	7.097	0.807 ± .014	0.876	0.840	0.051 ± .004	0.0522	0.0473
WAPD-1	3.168	2.77 ± .08	3.859	3.446		0.0787	0.0774
WAPD-2	3.621	2.78 ± .16	3.399	3.068	0.097 ± .007	0.0721	0.0705
WAPD-3	4.244	2.22 ± .05	2.932	2.676	0.076 ± .002	0.0649	0.0629
WAPD-4	5.601	1.83 ± .10	2.276	2.113	0.060 ± .005	0.0537	0.0511
WAPD-5	6.544	1.72 ± .07	1.982	1.855	0.066 ± .002	0.0484	0.0455
WAPD-6	10.196	1.22 ± .10	1.342	1.280	0.037 ± .001	0.0355	0.0320
WAPD-7	12.330	1.06 ± .06	1.140	1.093	0.037 ± .001	0.0313	0.0275
BNL-1	4.386	2.92 ± .09	3.039	2.893	0.065	0.0635	0.0609
BNL-2	5.429	2.41 ± .04	2.487	2.380	0.056	0.0553	0.0520
BNL-3	6.956	1.81 ± .06	1.975	1.900	0.048	0.0488	0.0431
BNL-4	9.522	1.41 ± .02	1.490	1.441	0.037	0.0385	0.0339
BNL-5	13.538	1.04 ± .02	1.104	1.073	0.031	0.0313	0.0259
ANL-1	4.176	3.05 ± .04	3.148	2.891	0.0742 ± .0011	0.0646	0.0622
ANL-2	2.928	4.12 ± .03	4.434	3.963	0.1011 ± .0004	0.0810	0.0796
ANL-3	2.290	5.40 ± .09	5.690	4.986	0.116 ± .0017	0.0943	0.0938
ANL-4	1.330	10.0 ± 0.1	9.728	8.490	0.1539 ± .0039	0.1246	0.1277
ANL-5	0.986	14.5 ± 0.4	14.58	11.69	0.1877 ± .0020	0.1458	0.1490
ANL-6	0.499	28.6 ± 0.8	36.81	27.26	0.2622 ± .0036	0.2002	0.2075

A-1

BNWL-1589

DISTRIBUTION

No. of
Copies

OFFSITE

1	<u>AEC Chicago Patent Group</u> G. H. Lee
8	<u>AEC Division of Reactor Development and Technology</u> Director RDT Asst. Dir. for Project Management Chief, Water Reactors Branch (2) Asst. Dire. for Reactor Technology Chief, Reactor Physics Branch (2) Chief, Fuels Recycle Branch
1	<u>AEC Division of Reactor Licensing</u> R. E. Baker
3	<u>AEC Division of Technical Information Extension</u>
4	<u>Argonne National Laboratory</u> R. Avery W. C. Redman E. M. Pennington W. B. Seefeldt
2	<u>Atomic Energy of Canada, Ltd.</u> Chalk River Nuclear Laboratory Reactor Physics Branch Chalk River, Ontario, Canada M. Duret J. Griffiths
1	<u>Babcock and Wilcox</u> P.O. Box 1260 Lynchburg, VA 24505 H. M. Jones
1	<u>Bhabha Atomic Research Centre</u> Theoretical Physics Section/RED Central Complex Building Trombay, Bombay-85, India S. R. Dwivedi
1	<u>Brookhaven National Laboratory</u> G. A. Price

No. of
Copies

BNWL-1589

- 5 Combustion Engineering
P. O. Box 500
Windsor, Connecticut 06095
W. P. Chernock
R. Harding
R. L. Hellens
S. Visner
H. H. Windsor
- 1 CNEN - Centro Studi-Nucleaire
Casaccia, Rome, Italy
Ugo Farinelli
- 3 Edison Electric Institute
750 Third Avenue
New York, New York 10017
John J. Kearney
Harvey Wagner
George Watkins
- 2 E. I. du Pont de Nemours & Co., Inc., SRL
G. Dessauer
H. Honeck
- 1 ENEL
Via G. B. Martini
(Piazza Verdi)
Rome, Italy
Mr. Paoletti Gualandi
- 3 General Electric Co., San Jose
Nuc. Dev. and Eng.
175 Curtner Avenue
San Jose, California 95112
D. L. Fischer
S. Levy
R. B. Richards
- 4 General Electric Co., Vallecitos Atomic Lab.
P. O. Box 846
Pleasanton, California 94566
B. F. Judson
T. M. Snyder
R. E. Harris
E. Kurtz
- 1 Idaho Nuclear Corporation
R. Grimsey
- 1 Japan Atomic Energy Research Institute
TCA-JPDR
Tokai-Mura, Naka-Gun, Ibaraki-Ken
JAPAN
Shojiro Matsuura

No. of
Copies

BNWL-1589

1	<u>Kerr-McGee</u>
Kerr-McGee Bldg.
133 NW Robert S. Kerr Ave.
Oklahoma City, Okla. 73102
Dr. Frank Pittman
Dr. I. D. Thomas
2	<u>Nuclear Fuels Services</u>
Suite 600
6000 Executive Blvd.
Rockville, Md. 20852
J. D. McDaniels, Jr.
W. Eich
2	<u>Nuclear Materials and Equipment Corp.</u>
Penn Center
Apollo, Penn. 15613
K. Puechl
J. R. Tulenko
1	<u>NUKEM</u>
D-645, HANAU
POSTFACH 869
Germany
Mr. W. K. L. Jager
1	<u>Pakistan Institute of Nuclear Sci. & Tech.</u>
P. O. Nilore
Rawalpindi, Pakistan
M. A. Mannan
1	<u>Power Reactor & Nuclear Fuel Development Corp.</u>
9-13, 1-chome, Akasaka
Minato-ku, Yokyo, Japan
Setsuo Kobayashi
1	<u>S. C. K. - C. E. N.</u>
MOL-DONK
Belgium
Dr. H. Van den Broeck
2	<u>United Nuclear Corporation</u>
Research & Engineering Center
Grasslands Road
Elmsford, New York 10523
R. D. Schamberger
J. R. Tomonto

No. of
Copies

BNWL-1589

- 4 Westinghouse Electric Corporation
 Atomic Power Division
 P. O. Box 355
 Pittsburgh, Penn. 15230
 R. J. French
 W. L. Orr
 J. R. Worden
 C. L. Bennett
- 3 Westinghouse Electric Corporation
 J. Hardy, Jr.
 B. Klein
 J. J. Volpe

ONSITE - HANFORD

- 1 AEC Chicago Patent Group
 R. M. Poteat
- 4 RDT Assistant Director for Pacific Northwest Programs
 W. E. Fry
 P. G. Holsted
 J. B. Kitchen
 T. A. Nemzek
- 2 AEC Richland Operations Office
 H. A. House
 M. R. Scheller
- 53 Battelle-Northwest
S. H. Bush	R. C. Liikala
J. L. Carter	C. W. Lindenmeier
N. E. Carter	D. F. Newman
D. E. Christensen	D. R. Oden (15)
F. G. Dawson	R. S. Paul
D. E. Deonigi	D. L. Prezbindowski
J. Morgan	W. D. Richmond
L. J. Federico	L. C. Schmid
J. C. Fox	R. I. Smith
M. D. Freshley	V. O. Uotinen
S. Goldsmith	W. C. Wolkenhauer
U. P. Jenquin	M. G. Zimmerman
D. A. Kottwitz	BNW Legal (2)
J. W. Kutcher	Technical Information (5)
B. R. Leonard	Technical Publications (2)

No. of
Copies

BNWL-1589

8

WADCO Corporation

R. E. Heineman

P. L. Hofmann

J. W. Weber

WADCO Document Control (5)