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OXIDE PARTICLE SIZE DISTRIBUTION FROM SHEARING IRRADIATED AND
UNIRRADIATED LWR FUELS IN ZIRCALOY AND STAINLESS STEEL CLADDING:
SIGNIFICANCE FOR RISK ASSESSMENT

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ABSTRACT

Sieve fractionation was performed with oxide particles dislodged during shearing of unirradiated or irradiated fuel bundles or single rods of UO_2 or 96-97% ThO_2 -3-4% UO_2 . Analyses of these data by nonlinear least-squares techniques demonstrated that the particle size distribution is lognormal. Variables involved in the numerical analyses include lognormal median size, lognormal standard deviation, and shear cut length. Sieve-fractionation data are presented for unirradiated bundles of stainless-steel-clad or Zircaloy-2-clad UO_2 or ThO_2 - UO_2 sheared into lengths from 0.5 to 2.0 in. Data are also presented for irradiated single rods (sheared into lengths of 0.25 to 2.0 in.) of Zircaloy-2-clad UO_2 from the Big Rock Point, Dresden-3, and Peach Bottom-2 boiling water reactors (BWRs) and of Zircaloy-4-clad UO_2 from the H. B. Robinson-2, Oconee-1, and Point Beach-1 pressurized water reactors (PWRs). Median particle sizes of UO_2 from shearing unirradiated stainless-steel-clad fuel ranged from 103 to 182 μm ; particle sizes of ThO_2 - UO_2 , under these same conditions, ranged from 137 to 202 μm . Similarly, median particle sizes of UO_2 from shearing unirradiated Zircaloy-2-clad fuel ranged from 230 to 957 μm .

Irradiation levels of fuels from reactors ranged from 9,000 to 28,000 MWd/MTU . In general, particle sizes from shearing these irradiated fuels are larger than those from the unirradiated fuels; however, unirradiated fuel from vendors was not available for performing comparative shearing experiments. In addition, variations in particle size parameters pertaining to samples of a single vendor varied as much as those between different vendors.

The fraction of fuel dislodged from the cladding is nearly proportional to the reciprocal of the shear cut length, until the cut length attains some minimum value below which all fuel is dislodged. Particles of fuel are generally elongated with a long-to-short axis ratio usually less than 3.

Using parameters of the lognormal distribution deduced from experimental data, realistic estimates can be made of fractions of dislodged fuel having dimensions less than

specified values. Such estimates are necessary for an accurate assessment of the potential risks associated with intentional or unintentional shearing of fuel that is then exposed to high-speed wind.

1. INTRODUCTION

Shearing bundles of rods is a likely head-end step in reprocessing nuclear fuels. This operation produces particulate matter from UO_2 or other fuels and from stainless steel or Zircaloy cladding. Knowledge of the distribution of sizes of the fuel particles from shearing operations is important in the assessment of the consequences of the radiological risks of several types of accidents that could lead to a release of fuel into the environment. Breaking of rods during their transfer in an away-from-reactor fuel storage facility, during their storage in a geological formation if an earthquake occurs, and as a result of a tornado at a fuel reprocessing plant are examples of potential accidents. The most extensive set of particle size distribution data previously published is that of Finney et al.¹ pertaining to shearing bundles of unirradiated stainless-steel-clad or Zircaloy-2-clad UO_2 or $\text{UO}_2\text{-ThO}_2$. Similar data on irradiated fuel bundles apparently do not exist. The purpose of this report is to present data from sieve fractionation of both unirradiated and irradiated fuels and to describe their analysis in terms of the lognormal distribution function. The unirradiated fuels have been described previously, but the sieve-fractionation data have been summarized only briefly.¹ Irradiated fuels were obtained from a number of operating reactors. Results from shearing and sieve fractionation of fuels from six of these reactors are presented here.

2. PARTICLE SIZE DATA

Finney et al.¹ have already described the shearing of ORNL Mark I prototype fuel assemblies containing UO_2 or 96-97% ThO_2 -3-4% UO_2 and the shearing of loose bundles of Zircaloy-2-clad UO_2 . The Mark I assemblies

were made of stainless steel and served to simulate first-generation power reactor fuels in subsequent leaching steps associated with the development of fuel reprocessing. Finney et al.¹ also presented some of the sieve-fractionation data obtained during the fuel reprocessing studies. However, many additional sieve-fractionation experiments were performed. Detailed data are presented in Table 1 (sieve dimensions were taken from the Chemical Engineers' Handbook² and from ANSI/ASTM Specification E-11³). There was so little stainless steel in material that passed through the 0.375-in. first screen that no corrections to weights retained on the finer-mesh screens were necessary. The first 24 rows of data in Table 1, pertaining to stainless steel cladding, contain measured weights. The situation with Zircaloy-2 cladding was different because the two or three largest-mesh sieves did contain some zirconium. Sieve fractions were analyzed for uranium and zirconium in six of the ten experiments. The last six rows of data in Table 1 contain weights of UO_2 (i.e., measured weights corrected by use of the analytical data). The weight listed as being retained on the No. 4 or 0.375-in. sieves is the measured weight plus the quantity of Zircaloy-2 that accompanied the UO_2 to smaller-mesh sieves.

Similar shearing and sieving experiments were performed with single irradiated fuel rods. The data have been summarized by Stacy and Goode.⁴ The most extensive sets pertain to the shearing of Zircaloy-clad UO_2 rod segments from several light water reactors (LWRs):

Reactor	Type	Rod No.	Irradiation level (MWd/MTU)
H. B. Robinson-2	PWR	G-10, J-10	28,000
Oconee-1	PWR	47-107 (cycle 1), 32-038 (cycle 2)	11,000 19,000
Point Beach-1	PWR	048	28,000
Big Rock Point	BWR	DY-0001	18,000
Dresden-3	BWR	KE-3038	18,000
Peach Bottom-2	BWR	F-6	11,000

Table 1. Particle size distribution data^a from shearing unirradiated fuel

Heavy metal oxide	Cladding ^b	Batch No.	Shear cut length, ℓ (in.)	Weight of material retained by the specified sieve (g)									Weight <44 μ m (g)	Total weight (g)
				9.51 mm (0.375 in.)	4.76 mm (No. 4)	2.00 mm (No. 10)	1.19 mm (No. 16)	595 μ m (No. 30)	297 μ m (No. 50)	149 μ m (No. 100)	74 μ m (No. 200)	44 μ m (No. 325)		
UO ₂	SS	1-125	0.5	2344.3	37.2	77.5	142.9	417.7	813.8	1001.5	1037.5	609.9	1482.1	6840.7
		2-125	0.5	2968.0	78.6	83.0	185.4	425.2	862.6	1039.6	1059.1	646.4	1529.9	8877.8
		3-125	0.5	2893.5	92.2	70.6	150.4	448.2	851.8	1003.2	1076.7	756.7	1226.3	8569.7
		4-125	1.0	6547.5	12.9	49.0	105.2	254.9	400.0	418.8	415.7	294.5	499.3	8997.8
		5-125	1.0	6667.0	3.6	46.7	105.0	257.2	411.5	400.4	372.3	213.8	460.7	8938.2
		6-125	1.0	6437.0	13.4	47.3	94.1	239.1	424.9	439.3	429.8	266.2	562.3	8953.4
		7-125	1.5	7117.9	30.7	36.7	52.8	113.2	182.5	195.0	213.3	125.4	302.6	8370.1
		8-125	1.5	7268.9	9.9	27.6	41.5	92.9	177.0	201.1	219.0	137.7	308.0	8483.6
		9-125	1.5	5694.6	4.3	9.3	17.4	36.0	124.0	149.6	149.2	88.5	264.1	6537.0
		38-087	2.0	7032.2	5.0	13.7	23.2	54.7	123.1	145.0	147.2	93.7	250.7	7888.5
		39-087	2.0	6954.8	4.5	24.4	39.6	68.9	141.9	154.8	148.0	99.4	264.1	7900.4
		40-087	2.0	7182.3	5.0	17.0	25.0	50.3	115.7	141.4	141.5	95.8	265.3	8039.3
	SS	15-108	0.5	2623.8	46.4	66.8	150.5	470.8	840.0	979.2	934.3	481.8	1388.5	7982.1
		16-108	0.5	2594.1	85.2	69.7	165.1	459.9	855.2	992.6	945.4	517.5	1452.2	8136.9
		17-108	0.5	2724.3	52.9	81.8	170.5	443.3	849.5	992.7	969.0	545.9	1521.9	8351.8
		2-103	1.0	5807.2	13.8	54.7	134.2	284.3	441.4	435.0	397.3	204.9	611.9	8404.7
		3-103	1.0	5934.0	19.4	58.7	102.3	229.2	412.8	429.7	389.3	197.7	568.3	8341.4
		4-103	1.0	5915.2	33.2	52.9	104.7	221.5	416.8	414.3	284.9	187.9	587.0	8248.5
		12-118	1.5	7176.2	22.4	33.0	52.7	127.1	239.5	261.0	246.6	162.8	375.5	8696.8
		14-113	1.5	7322.1	11.4	61.7	94.0	176.0	271.6	264.6	241.0	152.5	360.1	8955.0
		15-113	1.5	7093.1	33.8	72.7	116.3	206.8	307.5	287.6	262.9	165.2	380.4	8943.1
		5-118	2.0	7075.0	15.7	20.0	36.4	81.7	142.5	152.1	155.4	98.8	215.5	7993.1
		6-118	2.0	6950.7	15.2	22.6	40.6	91.3	166.8	175.5	165.6	106.3	251.8	7986.4
		7-118	2.0	6848.2	28.3	26.1	43.9	88.9	171.8	178.6	164.6	99.6	262.6	7812.6
UO ₂	Zircaloy-2	2-1	1.0		4552.	151.	263.	560.	718.	696.	551.	292.	564.	8346.
		2-2	1.0		5120.	123.	346.	399.	1025.	1006.	840.	437.	905.	10701.
		2-3	1.0		5243.	114.	233.	528.	714.	702.	589.	274.	650.	9047.
		50	1.0	2490.	38.	119.	274.	584.	870.	804.	675.	387.	719.	7218.
		54	1.5	2715.	96.	368.	427.	628.	673.	545.	417.	220.	391.	6480.
		60	2.0	2367.	209.	536.	440.	520.	518.	391.	281.	145.	270.	5677.

^aSee Table 21-12 of ref. 2, or see ref. 3 [ANSI/ASTM E-11 (1977)].^bSS = stainless steel.

The PWR fuels were clad in Zircaloy-4 tubing; cladding for the BWR fuels was Zircaloy-2. Average pellet density of the fuels was about 94% of theoretical density, excepting the Point Beach fuel which was 96% of theoretical. Shearing was accomplished with a hydraulically operated single-rod fuel shear; cut lengths ranged from 0.25 to 2.0 in. The clad fuel pieces and Zircaloy fragments were separated from the dislodged fuel materials prior to the sieve-fractionation experiments. Except for the H. B. Robinson and Peach Bottom fuels, most of the unclad UO_2 was sieved through a series of ten screens between 20 and 1410 μm . The detailed data are presented in Tables 2 and 3.

3. PARTICLE SIZE DATA ANALYSIS

The nature of the particle size distribution function applicable to the UO_2 and $\text{UO}_2\text{-ThO}_2$ data presented by Finney et al.¹ can be seen readily if they are renormalized. First, these authors normalized weights of UO_2 or $\text{UO}_2\text{-ThO}_2$ dislodged from sheared segments by dividing by the total weight of cladding plus all UO_2 or $\text{UO}_2\text{-ThO}_2$ (dislodged and not dislodged); second, they reported that approximately 90 to 95% of the weight of dislodged core material was of size less than 10,000 μm . To aid in identifying the distribution function, each value in columns 2, 3, and 4 of Table 1 of ORNL-3984¹ was multiplied by a value equal to 92.5 (the average of the reported range of 90 to 95%) divided by the first-row value. For example, the listed percentages of UO_2 obtained from a 0.5-in. shear length were multiplied by 92.5/84.5. This procedure renormalizes the data to the basis: $100 \times (\text{weight of dislodged material of size less than specified size}) / (\text{total weight of oxide plus cladding})$. Five sets of renormalized data, three for UO_2 and two for $\text{UO}_2\text{-ThO}_2$, are plotted as ranges in Fig. 1. It is apparent from this plot that the lognormal distribution function provides an excellent representation of the data.

3.1 Data from Shearing Unirradiated Fuel Bundles

On the basis of the appearance of the renormalized data of Finney et al.¹ plotted in Fig. 1, computer subroutines were written for use with

Table 2. Particle size distribution data from sheared H. B. Robinson-2^a fuel

Segment No. ^b	Shear cut length, ℓ (in.)	Weight of material retained by the specified sieve (g)					
		1.41 mm (No. 14)	1.00 mm (No. 18)	500 μm (No. 35)	149 μm (No. 100)	74 μm (No. 200)	<149 μm <74 μm
G-10-3	0.25	90.9	38.7	72.8	62.3		32.3
G-10-4	0.25	88.7	45.8	79.7	56.0		34.5
J-10-5 } J-10-6 }	0.25	188.3	90.3	141.2	127.6		67.0
G-10-7	0.375	83.6	44.9	73.1	70.4		35.6
J-10-9	0.5		75.3	41.7	41.1	9.9	12.0
G-10-5 } G-10-6 }	1.0			69.9	25.0	6.5	7.3
J-10-1	1.5		31.6	9.9	12.0	3.2	4.0

^aWestinghouse PWR.

^bRods G-10 and J-10 (cladding OD = 0.42 in.) received a peak burnup of 31,000 MWd/MTU. Average fuel burnup for the rods was approximately 28,000 MWd/MTU.

Table 3. Particle size distribution data from sheared LWR fuel

Segment No.	Shear cut length, ℓ (in.)	Weight of material retained by the specified sieve (g)											
		1.41 mm (No. 14)	1.00 mm (No. 18)	650 μ m (No. 20)	500 μ m (No. 35)	300 μ m (No. 50)	149 μ m (No. 100)	74 μ m (No. 200)	44 μ m (No. 325)	38 μ m (No. 400)	20 μ m (No. 635)	<44 μ m	<20 μ m
<u>Oconee-1^a: rod 32-028, cycle 2; fuel burnup = 19,000 MWd/MTU; cladding OD = 0.43 in.</u>													
5B	0.312	38.1	4.1	2.2	5.8	4.3	3.9	2.4	0.8	0.6	0.6		0.8
6A	0.5	25.2	2.6	1.4	3.2	1.9	1.8	0.9	0.4	0.1	0.2		0.3
7	1.0	38.4	3.0	1.7	4.2	3.3	2.8	1.6	0.6	0.3	0.4		0.6
5	2.0	7.3	1.8	1.1	2.7	1.9	1.7	1.1	0.4	0.2	0.2		0.3
<u>Oconee-1: rod 47-107, cycle 1; fuel burnup = 11,000 MWd/MTU; cladding OD = 0.43 in.</u>													
B (bottom)	0.5	55.3	7.6	4.3	10.0	7.5	7.1	4.0	1.6	1.1	1.0		1.1
B (bottom)	2.0	10.1	2.5	1.2	3.4	2.6	2.4	1.6	0.5	0.3	0.4		0.6
<u>Point Beach-1^b: rod 048; fuel burnup = 28,000 MWd/MTU; cladding OD = 0.42 in.</u>													
5A	0.5	3.9	3.7	2.3	6.6	5.5	5.6	4.0	3.1	3.2	3.1		2.1
5B	2.0	1.2	0.7	0.3	1.2	1.1	0.9	0.8	0.5	0.4	0.7		0.6
<u>Big Rock Point^c: rod DY-0001; fuel burnup = 18,000 MWd/MTU; cladding OD = 0.56 in.</u>													
3	0.5	29.2	11.7	6.4	15.5	10.6	11.3	8.6	5.3	2.9	3.0		1.8
4	2.0	7.1	2.7	1.6	3.6	2.6	2.6	2.0	1.0	0.5	0.8		1.1
<u>Dresden-3^c: rod KE-3038; fuel burnup = 18,000 MWd/MTU; cladding OD = 0.56 in.</u>													
5 and 6 ^b	0.5	138.6	20.1	11.2	25.1	16.2	13.1	7.2	2.8	1.8	3.2		4.9
6	1.0	117.8	9.8	5.8	12.4	8.1	6.4	3.5	1.3	1.0	1.9		3.0
5	2.0	44.0	4.6	2.5	5.6	3.8	3.2	1.8	0.7	0.6	1.0		1.0
<u>Peach Bottom-2^c: rod F-6; fuel burnup = 11,000 MWd/MTU; cladding OD = 0.56 in.</u>													
10	1.0	123.4	18.4		30.5		28.0	6.4	2.8			7.8	
12 and Bottom ^d	1.0	178.0	28.9		44.8		41.1	9.8	4.1			14.4	

^aBabcock and Wilcox PWR.^bWestinghouse PWR.^cGeneral Electric BWR.^dUnclad fuel portions were combined prior to sieving.

Fig. 1. Plot of five sets of renormalized data for $\text{UO}_2\text{-ThO}_2$ (drawing used as basis for assumption of lognormal distribution). Data source: Finney et al. (ref. 1).

the Marquardt program^{5,6} for estimating the one linear and two nonlinear parameters of the lognormal distribution function. This function, discussed in detail by Aitchison and Brown,⁷ is given as

$$d\Lambda(x) = B \frac{e^{-(\ln x - m)^2/(2s^2)}}{xs} dx \quad (1)$$

where

$d\Lambda(x)$ = probability that a particle will have a size (diameter) between x and $x + dx$,

$B = 1/\sqrt{2\pi}$ if only dislodged fuel is measured, or

$= (1/\sqrt{2\pi}) \times (\text{fraction of fuel dislodged}) \times (\text{weight of the fuel}) / (\text{weight of fuel} + \text{hardware}),$

x = particle size,

s = estimated standard deviation of the natural logarithms of particle sizes,

m = estimated median of the natural logarithms of particle sizes.

Three individual data sets¹ on percentages of weights of UO_2 available as particles of a size less than the specified values are shown in Fig. 2. These pertain to unirradiated fuel bundles sheared at lengths of 0.5, 1.0, and 1.5 in. Solid curves drawn through the data and extrapolated to a 1- μm particle size were calculated from the parameters obtained from a nonlinear least-squares analysis of the lognormal distribution function. This analysis is based on numerical integration of Eq. (1):

$$\Lambda(x) = \Lambda(x') + B \int_{x'}^x \frac{e^{-(\ln t - m)^2/(2s^2)}}{ts} dt \quad (2)$$

where

$$\Lambda(x') = B \int_0^{x'} \frac{e^{-(\ln t - m)^2/(2s^2)}}{ts} dt \quad (3)$$

and t is a dummy integration variable.

Fig. 2. Particle size distribution of UO_2 dislodged from unirradiated, sheared stainless steel fuel bundles. Data source: Finney et al. (ref. 1).

Splitting $\Lambda(x)$ into two terms, one of which, namely $\Lambda(x')$, is very small in comparison with the other, provides an easy method for avoiding the numerical difficulties of $-\infty$ due to $\ln t$ as $t \rightarrow 0$. In particular, $\Lambda(x')$ is in the order of 10^{-5} to 10^{-9} for x' in the range 0.1 to 0.01 μm ; by contrast, the integral term of Eq. (2) is in the range 0.1 to 0.8, corresponding to 10 to 80% of the weight being in the form of particles between 10 and 10,000 μm . Once a set of parameters B , m , and s has been estimated, these can be used with graphical or numerical methods to improve the estimate of $\Lambda(x')$, where x' can be made a very small positive number.

The integration indicated in Eq. (2) was performed with the KUTTA subroutine.⁸ Called from subroutine FCODE of the Marquardt program⁶ (see Appendix), KUTTA is used once with the input estimates of the parameters and once for each of the three parameters for numerical determination of the derivatives $\partial\Lambda/\partial m$, $\partial\Lambda/\partial s$, and $\partial\Lambda/\partial B$. Parameters obtained from this fitting of the data of Finney et al.¹ were used to draw the solid lines (extrapolated to a 1- μm particle size) shown in Fig. 2. The two broken lines summarize these calculations in terms of particles dislodged from the cladding. This corresponds to the standard lognormal expression with linear coefficient B equal to $1/\sqrt{2\pi}$:

$$\Lambda(x) = \frac{1}{\sqrt{2\pi}} \int_0^x \frac{e^{-(\ln t - m)^2/(2s^2)}}{ts} dt . \quad (4)$$

Finally, the distribution function $d\Lambda(x)/dt$ is plotted in Fig. 3 for UO_2 in stainless steel cladding sheared to 1.0-in. lengths. In this case the median size is 149 μm .

Finney et al.¹ presented only a small portion of the many data listed in Table 1 that were obtained during studies of particle size distributions of sheared, unirradiated fuel bundles. These studies included sieve fractionation of material from (1) 12 shearings of UO_2 , at lengths of 0.5 to 2.0 in., and 12 of 96-97% ThO_2 -3-4% UO_2 in ORNL Mark I prototype, stainless-steel-clad fuel assemblies (Table 1) and (2) 10 shearings of UO_2 , at lengths of 1.0 to 2.0 in., in Zircaloy-2-clad loose bundles. Parameters derived from the lognormal distribution analyses of data from Table 1 are presented in Tables 4, 5, and 6. These three tables show that the parameters of the

Fig. 3. Calculated lognormal distribution function for particles of UO_2 dislodged during shearing of stainless-steel-clad, unirradiated fuel bundles (cut length = 1.0 in.).

Table 4. Analysis of data on particle sizes of UO_2 from shearing ORNL Mark I, stainless-steel-clad prototype fuel assemblies^a

Sample No.	Shear cut length, ℓ (in.)	Parameters ^b			Standard deviation of fit	Mode ^c (μm)	Median ^c (μm)	Mean ^c (μm)	$B/\sqrt{2\pi}$
		m and $\hat{S}_m$	s and $\hat{S}_s$	B and $\hat{S}_B$					
1-125	0.5	4.805 0.039	1.559 0.042	0.2871 0.0041	0.0021	10.78	122	411	0.720
2-125	0.5	4.825 0.033	1.569 0.035	0.2691 0.0033	0.0017	10.64	125	426	0.675
3-125	0.5	4.853 0.020	1.377 0.020	0.2626 0.0021	0.0012	19.29	128	330	0.658
4-125	1.0	5.041 0.030	1.510 0.028	0.1100 0.0012	0.0006	15.84	155	483	0.276
5-125	1.0	5.200 0.058	1.632 0.051	0.1055 0.0021	0.0009	12.70	182	686	0.264
6-125	1.0	5.028 0.037	1.587 0.035	0.1150 0.0015	0.0007	12.35	153	536	0.288
7-125	1.5	4.972 0.024	1.676 0.024	0.06000 0.00050	0.00023	8.73	144	586	0.125
8-125	1.5	4.835 0.017	1.562 0.018	0.05763 0.00036	0.00018	11.00	126	426	0.144
9-125	1.5	4.634 0.066	1.635 0.079	0.05287 0.00126	0.00065	7.14	103	391	0.133
38-087	2.0	4.718 0.041	1.640 0.047	0.04423 0.00065	0.00032	7.59	112	430	0.111
39-087	2.0	4.844 0.041	1.740 0.043	0.04895 0.00068	0.00030	6.15	127	577	0.123
40-087	2.0	4.647 0.035	1.673 0.042	0.04326 0.00054	0.00027	6.36	104	423	0.108

^a $\text{UO}_2/(\text{UO}_2 + \text{SS}) \simeq 0.745$.

^b See Eq. (1) for definitions of m, s, and B as used in this table and in Tables 5-9. The symbol $\hat{S}$ is used to specify standard deviation of the parameter estimated from the data. Thus, $\hat{S}_m$ is the estimated standard deviation of m, $\hat{S}_s$ is the estimated standard deviation of s, etc. The statistical weighting factor was assumed to be the number of weighings that were added in calculating the fraction of material sized less than the specified sieve size.

^c Mode = $\exp(m - s^2)$; Median = $\exp(m)$; Mean = $\exp(m + s^2/2)$ (ref. 7).

Table 5. Analysis of data on particle sizes of ThO₂-UO₂ from shearing ORNL Mark I, stainless-steel-clad prototype fuel assemblies^a

Sample No.	Shear cut length, ℓ (in.)	Parameters ^b			Standard deviation of fit	Mode ^c (μm)	Median ^c (μm)	Mean ^c (μm)	$B\sqrt{2\pi}$
		m and S_m	s and S_s	B and S_B					
15-108	0.5	4.942 0.081	1.681 0.082	0.2778 0.0078	0.0035	8.29	140	576	0.696
16-108	0.5	4.917 0.071	1.685 0.072	0.2798 0.0068	0.0031	7.97	137	565	0.701
17-108	0.5	4.866 0.063	1.677 0.066	0.2767 0.0060	0.0028	7.78	130	530	0.694
2-103	1.0	5.186 0.108	1.859 0.098	0.1307 0.0045	0.0017	5.65	179	1001	0.327
3-103	1.0	5.127 0.095	1.751 0.088	0.1203 0.0038	0.0012	7.85	169	781	0.302
4-103	1.0	5.202 0.153	1.959 0.139	0.1193 0.0056	0.0019	3.91	182	1237	0.299
12-118	1.5	4.938 0.037	1.645 0.037	0.07099 0.00091	0.00043	9.33	140	539	0.178
14-113	1.5	5.216 0.049	1.782 0.044	0.07555 0.00121	0.00047	7.69	184	901	0.189
15-113	1.5	5.309 0.048	1.806 0.041	0.08487 0.00131	0.00049	7.76	202	1032	0.213
5-118	2.0	4.967 0.023	1.612 0.022	0.04633 0.00037	0.00017	10.70	144	527	0.116
6-118	2.0	4.990 0.042	1.679 0.041	0.05290 0.00077	0.00035	8.76	147	602	0.133
7-118	2.0	5.027 0.059	1.753 0.058	0.05481 0.00109	0.00046	7.05	153	709	0.137

^a(ThO₂ + UO₂)/(ThO₂ + UO₂ + SS) $\approx$ 0.745. ThO₂ constituted 96 to 97% of the heavy metal oxide.

^bSee note b of Table 4.

^cMode = $\exp(m - s^2)$; Median = $\exp(m)$; Mean = $\exp(m + s^2/2)$ (ref. 7).

Table 6. Analysis of data on particle sizes of UO_2 from shearing loose bundles of Zircaloy-2-clad elements^a

Sample No.	Shear cut length, ℓ (in.)	Parameters ^b			Standard deviation of fit	Mode ^c (μm)	Median ^c (μm)	Mean ^c (μm)	$B\sqrt{2\pi}$
		m and $\hat{S}_m$	s and $\hat{S}_s$	B and $\hat{S}_B$					
Z-1	1.0	5.636 0.085	1.677 0.059	0.1964 0.0060	0.0017	16.87	280	1143	0.492
Z-2	1.0	5.586 0.102	1.705 0.073	0.2278 0.0082	0.0023	14.57	267	1141	0.571
Z-3	1.0	5.550 0.123	1.721 0.089	0.1830 0.0079	0.0022	13.29	257	1132	0.459
50	1.0	5.437 0.062	1.608 0.049	0.2670 0.0058	0.0023	17.31	230	837	0.693
54	1.5	6.176 0.079	1.814 0.050	0.2517 0.0066	0.0017	17.93	481	2493	0.631
60	2.0	6.864 0.099	2.060 0.053	0.2848 0.0088	0.0013	13.72	957	7990	0.689

^a $UO_2/(UO_2 + \text{Zircaloy-2}) \approx 0.797$.

^b See note b of Table 4.

^c Mode = $\exp(m - s^2)$; Median = $\exp(m)$; Mean = $\exp(m + s^2/2)$ (ref. 7).

distribution function are essentially independent of cut length for stainless steel cladding on the one hand or Zircaloy-2 cladding on the other.

3.2 Data from Shearing Irradiated Fuel Rods

Data listed in Tables 2 and 3 also were analyzed in terms of the log-normal particle size distribution; results of these analyses are presented in Tables 7, 8, and 9. In addition, some of the data are plotted in Figs. 4 and 5 to demonstrate the apparent correctness of the assumptions of a log-normal distribution. It should be noted that the data of Tables 2 and 3 pertain to weights of dislodged fuel and not to total fuel plus cladding. For this reason the parameter B equals $1/\sqrt{2\pi}$, as described in the definitions following Eq. (1).

4. PARTICLE SHAPES

Figures 6 and 7 contain photographs and photomicrographs, respectively, of some sieve fractions of H. B. Robinson irradiated fuels from shearings of single rods. The particles are obviously not spherical, but long axes in general do not exceed short axes by a factor much in excess of 3. The elongated shape leads to the presence of some particles on a sieve that appear to have been too large to pass through the next larger sieve in the series used in Hot-Cell sieving experiments. An example of this is shown in photographs M4393 and M4394 (Fig. 7), wherein M4394 is of the field in the lower right corner of M4393. The two large particles in these fields would not have been expected to pass through the 200-mesh sieve.

5. FRACTIONAL DISLODGEEMENT OF FUELS

In addition to particle size distribution, the fraction of the fuel dislodged from the cladding during shearing operations will be an important variable in assessing the potential effects of accidents in facilities containing nuclear fuels. In fuel reprocessing plants the cut length would be short enough to ensure dislodgement of most of the fuel, but

Table 7. Analysis of particle size data on H. B. Robinson irradiated UO_2

Segment No.	Points	Shear cut length, ℓ (in.)	Parameters ^a		Standard deviation of fit	Mode ^b (μm)	Median ^b (μm)	Mean ^b (μm)
			$\hat{m}$ and $\hat{S}_m$	$\hat{s}$ and $\hat{S}_s$				
G-10-3	4	0.25	6.737 0.091	1.361 0.115	0.0152	132	843	2128
G-10-4	4	0.25	6.768 0.143	1.391 0.181	0.0232	126	869	2288
G-10-7	4	0.375	6.649 0.082	1.338 0.104	0.0146	129	772	1889
J-10-1	4	1.5	7.047 0.062	1.792 0.061	0.0043	46.4	1149	5721
J-10-5} J-10-6}	4	0.25	6.762 0.093	1.385 0.118	0.0152	127	864	2255
J-10-9	4	0.5	6.725 0.110	1.559 0.111	0.0103	73.3	833	2806

^aSee note b of Table 4.

^bMode = $\exp(m - s^2)$; Median = $\exp(m)$; Mean = $\exp(m + s^2/2)$ (ref. 7).

Table 8. Analysis of particle size data from shearing fuels from 3 BWRs

Reactor	Sample specifications				Number of sieves	Shear cut length, ℓ (in.)	Parameters ^a		Standard deviation of fit	Mode ^b (μm)	Median ^b (μm)	Mean ^b (μm)
	Rod No.	Segment No.	Clad diam (in.)	Burnup (MWd/MTU)			$\hat{m}$ and $\hat{S}_m$	$\hat{s}$ and $\hat{S}_s$				
Big Rock Point	DY-0001	3	0.56	18,000	10	0.5	6.4133 0.0635	1.6626 0.0597	0.0043	38.4	610	2,429
		4			10	2.0	6.4547 0.0849	1.9677 0.0749	0.0050	13.2	636	4,405
Dresden-3	KE-3038	5, 6	0.563	18,000	10	0.5	7.8853 0.1580	2.2831 0.1273	0.0041	14.5	2,658	36,010
		6			10	1.0	8.7750 0.1904	2.6707 0.1364	0.0029	5.2	6,471	229,000
		5			10	2.0	8.2363 0.1280	2.3767 0.0993	0.0027	13.3	3,776	63,630
Peach Bottom-2	F-6	10	0.563	9,000-11,000	6	1.0	7.7834 0.1450	2.1263 0.1274	0.0058	26.1	2,400	23,020
	12 and Bottom				6	1.0	7.7914 0.1786	2.2616 0.1546	0.0070	14.5	2,420	31,220

^aSee note b of Table 4.^bMode = $\exp(\hat{m} - \hat{s}^2)$; Median = $\exp(\hat{m})$; Mean = $\exp(\hat{m} + \hat{s}^2/2)$ (ref. 7).

Table 9. Analysis of particle size data from shearing fuels from 3 PWRs

Reactor	Manufacturer	Sample specifications				Number of sieves	Shear cut length, ℓ (in.)	Parameters ^a		Standard deviation of fit	Mode ^b (μm)	Median ^b (μm)	Mean ^b (μm)
		Rod No.	Segment No.	Clad diam (in.)	Burnup (MWd/MTU)			m and $\hat{S}_m$	s and $\hat{S}_s$				
Oconee-1 Cycle 1	Babcock and Wilcox	47-107	Bottom	0.430	11,000	10	0.5	7.5099 0.0685	1.9178 0.0632	0.0023	46.2	1,826	11,490
			Bottom			10	2.0	6.9158 0.0894	1.8677 0.0816	0.0045	30.8	1,008	5,767
Oconee-1 Cycle 2	Babcock and Wilcox	32-028	6	0.430	19,000	10	0.3125	7.7805 0.0828	2.0746 0.0713	0.0023	32.4	2,393	20,590
			6			10	0.5	8.1419 0.1093	1.9980 0.0953	0.0022	63.4	3,435	25,290
			7			10	1.0	8.2359 0.0981	2.1925 0.0797	0.0020	30.8	3,774	41,750
			5			10	2.0	6.8975 0.0795	1.6894 0.0799	0.0043	57.0	990	4,124
Point Beach-1	Westinghouse	048	5A	0.422	28,000	10	0.5	5.5130 0.1019	1.6060 0.0939	0.0096	18.8	248	900
			5B			10	2.0	5.5902 0.0933	1.8417 0.0897	0.0078	9.0	268	1,460

^a See note b of Table 4.^b Mode = $\exp(m - s^2)$; Median = $\exp(m)$; Mean = $\exp(m + s^2/2)$ (ref. 7).

Fig. 4. Particle size distributions of materials dislodged from shearing three samples of irradiated BWR fuels.

Fig. 5. Particle size distributions of materials dislodged from shearing three samples of irradiated PWR fuels.

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(+10 MESH)

(-10+20 MESH)

(-20+40 MESH)

(-40+100 MESH)

GRID = 1mm x 1mm

Fig. 6. Photomicrographs of sieve fractions from shearing one rod of irradiated fuel from the H. B. Robinson reactor.

Fig. 7. Photomicrographs of fine particles from shearing H. B. Robinson fuel rods.

accidental shearing probably would cause dislodgement of only a small fraction of the fuel. Tables 4 and 5 show that the fraction of fuel dislodged from the Mark I prototype assemblies is a function of the shear cut length. Over a cut length of 0.5 to 2 in., values of the parameter $B\sqrt{2\pi}$ [Eq. (2)], which is a measure of the fraction of metal oxide dislodged during shearing, are plotted versus the reciprocal of shear cut length in Fig. 8. The basis for use of reciprocal cut length is the simplistic model of all fuel being dislodged at short cut lengths, perhaps 0.5 in. or less, but with longer cuts one segment of the fuel rod is unaffected by the shear blades. Such a model would predict that the fraction dislodged will tend in a straight line to 0 as $1/(\text{cut spacing}) \rightarrow 0$ ($\text{cut spacing} \rightarrow \infty$). Figure 8 shows that the data apparently follow the $1/l$ model for cuts of spacing 0.5 to 2 in. However, the straight lines do not intercept at (0,0); instead, the data on UO_2 extrapolate to a fractional dislodgement of zero at a cut spacing of 3.8 in., while the $\text{ThO}_2\text{-UO}_2$ data extrapolate to a fractional dislodgement of zero at a cut spacing of 6.1 in.

Data on fraction of fuel dislodged from Zircaloy-2 (Table 6) do not show the same $1/l$ behavior as do UO_2 and $\text{ThO}_2\text{-UO}_2$ in stainless steel. However, there are data at cut lengths of only 1, 1.5, and 2 in.

Examination of the data in Table 10 shows a similar variation of the fractional dislodgement of fuel with the reciprocal of cut length. Figure 9 displays data from the shearing of H. B. Robinson-2 and Ocone-1 (cycle 2, rod 32-028) fuels. The data indicate that shear cut lengths need to be as short as 0.25 and 0.3 in., respectively, to achieve 100% dislodgement. This is somewhat shorter than the 0.5-in. length needed to achieve complete dislodgement of unirradiated fuel bundles (Fig. 8).

6. DISCUSSION AND CONCLUSIONS

Several variables are considered in Sects. 2 through 5 that will be important in the assessment of the consequences of accidents involving shearing of fuel tubes, as well as the reentrainment of particles of fuel that follows accidental or intentional shearing. These include (1) the type of cladding material, (2) the fuel burnup and associated changes in

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Fig. 8. Variation of $B\sqrt{2\pi}$, or of the fraction f of fuel dislodged, during shearing of unirradiated stainless-steel-clad fuel.

Table 10. Dislodgement of LWR fuels during shearing

Reactor	Rod No.	Segment No.	Shear cut length, $\frac{1}{2}$ (in.)	Total fuel weight (g)	Dislodged fuel weight (g)	Fraction of total weight dislodged
H. B. Robinson-2						
	G-10	3	0.25	314.9	299.2	0.950
	G-10	4	0.25	311.0	305.4	0.982
	J-10	5 and 6	0.25	626.7	620.7	0.989
	G-10	7	0.375	310.2	206.0	0.664
	J-10	9	0.5	315.2	182.2	0.578
	G-10	5 and 6	1.0	602.2	108.4	0.180
	J-10	1	1.5	328.0	61.0	0.186
Oconee-1						
	32-028	6B	0.312	64.8	63.8	0.985
	32-028	6A	0.5	50.7	38.1	0.752
	32-028	7	1.0	125.6	56.9	0.433
	32-028	5	2.0	125.6	19.0	0.151
	47-107	B (bottom)	0.5	117.8	100.8	0.856
	47-107	B (bottom)	2.0	183.8	25.7	0.140
Point Beach-1						
	048	5A	0.5	204.9	43.3	0.211
	048	5B	2.0	209.5	8.4	0.040
Big Rock Point						
	DY-0001	3	0.5	238.2	106.3	0.446
	DY-0001	4	2.0	283.6	25.7	0.091
Dresden-3						
	KE-3038	5 and 6	0.5	245.0	244.2	0.998
	KE-3038	6	1.0	227.0	171.0	0.753
	KE-3038	5	2.0	220.9	68.8	0.311
Peach Bottom-2						
	F-6	10	1.0	362.6	217.3	0.665
	F-6	12 and Bottom	1.0	682.6	321.1	0.470

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Fig. 9. Variation of fractional dislodgement of two irradiated fuels with reciprocal cut length.

mechanical properties of the cladding, and (3) the distance between accidental or intentional shearing cuts, to which the fractional dislodgement of fuel from the cladding is related. Tables 4 and 5 and Fig. 8 indicate that the parameters describing fractional release of fuel produced by shearing unirradiated stainless steel fuel assemblies and of the lognormal distribution of the resulting particulate matter were essentially the same for the two prototype fuel materials (UO_2 or 96-97% ThO_2 -3-4% UO_2) used by Finney et al.¹ For example, the median particle size from bundles of UO_2 ranged from 103 to 182 μm , while that from ThO_2 - UO_2 fuel was 137 to 202 μm . Cladding material does have some effect on particle size distribution resulting from shearing. Thus, Table 6 shows median particle sizes from shearing Zircaloy-2-clad UO_2 of 230 to 957 μm — values that are at least twice as large as the corresponding values from shearing stainless-steel-clad UO_2 . It should be noted, however, that the Zircaloy-2 bundles were of loose tubes and were not prototype fuel assemblies.

Because no samples of unirradiated material from the several vendors were available for shear-sieve experiments, the data presented in this report do not appear capable of providing an answer to the question of whether burnup has any effect on particle size distribution. However, there do appear to be different distribution-size parameters for material produced by Westinghouse, Babcock and Wilcox, and General Electric, although there are great variations within materials produced by a single vendor.

Any analysis of the potential environmental impact of the production of small radioactive particles during the intentional or accidental shearing of nuclear fuels requires the use of information such as particle size distribution and the fraction of the fuel dislodged and thereby made available for dispersal. It is beyond the scope of this report to consider the fractional dislodgement of fuel under accident conditions; however, Figs. 8 and 9 show that the fractional dislodgement can be specified with relatively small uncertainty (20 to 30% of the value) in the case of intentionally sheared fuel bundles or single fuel rods. Such small uncertainty does not pertain to specifying the distribution of particle sizes. Instead, as shown in Fig. 10 and Table 11, it is apparent that there is a large relative range of the weight percent of material of size less than any stated size.

Fig. 10. Maximum and minimum quantities of irradiated fuels of size less than (or greater than) a specified value.

Table 11. Ranges of mass distribution by particle size for irradiated fuels^a

Particle sieve size (μm)	Weight in sizes less than the indicated value (%)		Particle sieve size (μm)	Weight in sizes less than the indicated value (%)	
	Minimum	Maximum		Minimum	Maximum
1	0.000038	0.12	140	7.56	36.2
2	0.00045	0.39	160	8.30	39.3
4	0.0042	1.12	180	8.99	42.1
6	0.014	1.96	200	9.65	44.7
8	0.031	2.83	250	11.2	50.2
10	0.056	3.71	300	12.5	54.7
15	0.15	5.88	350	13.7	58.5
20	0.30	7.95	400	14.9	61.7
30	0.71	11.7	450	15.9	64.5
40	1.26	15.1	500	16.9	66.9
50	1.90	18.1	600	18.7	70.9
60	2.61	20.8	700	20.3	74.1
80	4.18	25.6	800	21.7	76.7
100	5.87	29.6	900	23.0	78.9
120	6.77	33.2	1000	24.2	80.7

^a Minimum and maximum values reflect the parameters m and s of Tables 7, 8, and 9; uncertainties in m and s are not included either in this table or in Fig. 10.

For example, the 21 shearing tests with single irradiated fuel rods (Tables 7, 8, and 9) show a range of 0.056 to 3.71 wt % of dislodged material to be no larger than 10 μm ; similarly, 5.87 to 29.6 wt % is not larger than 100 μm . Conservatism in estimating potential environmental impacts will normally require use of the maximum values in Table 11 or Fig. 10.

7. ACKNOWLEDGEMENTS

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8. APPENDIX:

SUBROUTINES USED WITH THE MARQUARDT NONLINEAR LEAST-SQUARES PROGRAM

The version of the least-squares program used in this study differs from the one presented by Marquardt⁶ primarily in the use of a subroutine INPUT, instead of reading data into the main program. As usual, subroutine FCODE is used to define the function being fitted. Numerical integration of Eq. (2) is performed by use of subroutine KUTTA,⁸ for which the differential equation is defined in subroutine EQUA. This appendix contains listings of subroutines EQUA, FCODE, INPUT, and OUTPUT. The latter subroutine is used primarily to calculate data such as those plotted in Figs. 2 and 3.

```

SUBROUTINE EQUA(SIZE, A, DER)
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION A(10), DER(10)
COMMON/LBCOM1/B(10), DUM(24), HALF
DLNS = DLOG(SIZE)
TERM = (DLNS - B(1)) / B(2)
EXPO = TERM * TERM * HALF + DLNS
DER(1) = DEXP(- EXPO) / B(2)
RETURN
END

```

```

SUBROUTINE PCODE(B, P, PRNT, RES, X, Y, I, IB, IP, NDPM)
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION B(1), IB(1), PRNT(1), X(NDPM,1), Y(1)
DIMENSION SA(10,10)
COMMON/LBCOM1/BB(10), A(10), AO(10), ACCURC, DEL, SIZE0, DLNS0,
1 HALF, Z(15), IMAX, NE, IPR(8)
COMMON/TAPES/NI, NO, NP, NTTOC
EXTERNAL EQUA
BB(1) = B(1)
BB(2) = B(2)

C      B(1)          = THE LOGNORMAL MEDIAN
C      B(2)          = THE LOGNORMAL STANDARD DEVIATION
C      B(3)          = THE LINEAR COEFFICIENT
C
IF (I.NE. 1) GO TO 202
A(1) = AO(1) / B(3)
IF (I.EQ. IL) GO TO 152
122 J = 1
S0 = SIZE0
S1 = X(I,1)
IL = I
GO TO 302
152 J = J + 1
GO TO 302
202 IF (I.EQ. IL) GO TO 252
222 J = 1
S0 = S1
S1 = X(I,1)
IL = I
A(1) = SA(1,J)
GO TO 302
252 J = J + 1
A(1) = SA(1,J)
302 UDEL = (S1 - S0) * DEL
CALL KUTTA(S0, S1, A, NE, UDEL, ACCURC, IMAX, EQUA)
SA(1,J) = A(1)
P = A(1) * B(3) + AO(1)
C RES = Y(I) - P
RES = (Y(I) - P) * Z(I)
IF (J.NE. 1) RETURN
PRNT(1) = A(1)
PRNT(2) = X(I,1)
RETURN
END

```

```

SUBROUTINE INPUT(B,PRNT,X,Y,FMT,TITLE,IREAD,NLP,NDPM)
IMPLICIT REAL*8 (A-H, O-Z)
DIMENSION B(1), FMT(1), PRNT(1), TITLE(18,3)
DIMENSION X(NDPM,1), Y(1)
COMMON/LBCOM1/BB(10), YC(10), YCI(10), ACCURC, DEL, SIZE0, DLNSO,
1 HALF, Z(15), IMAX, NE, NEXTRA, IPR(7)
COMMON/TAPES/NI,NO,NTFOC,NP
INTEGER FMT
REAL*4 TITLE

```

THIS PROBLEM IS CONCERNED WITH LOGNORMAL DISTRIBUTION, AS OF
PARTICLE SIZE DISTRIBUTION RESULTING FROM SHEARING NUCLEAR-REACTOR
FUEL PINS OR BUNDLES.

Y(I) = FRACTION OF WEIGHT WITH PARTICLE SIZES LESS THAN
X(I,1) = THE PARTICLE SIZE

THE SOLUTION OF THE PROBLEM REQUIRES THAT WE INTEGRATE THE
LOGNORMAL DISTRIBUTION FROM
SIZE0 = THE SMALLEST PARTICLE SIZE MEASURED
TO

X(I,1) = THE EXPERIMENTAL PARTICLE SIZE IN QUESTION

WE USE DATA ON THE SMALLEST PARTICLE SIZE TO PROVIDE THE INITIAL
ESTIMATE OF THE LOWER RANGE OF THE INTEGRATION.

B(4) = THE FRACTION OF THE TOTAL WEIGHT THAT IS OF A
SIZE SMALLER THAN THE SMALLEST PARTICLE
SIZE MEASURED.

```

READ (NI,9001) (TITLE(I,1), I=1,18)
READ (NI,9001) (TITLE(I,2), I=1,18)
READ (NI,9001) (TITLE(I,3), I=1,18)
READ (NI,9011) ACCURC, DEL, SIZE0, IMAX, NE
READ (NI,FMT) (YCI(I), I=1,10)
WEIGHT = 0.0
I = 0

```

```

101 I = I + 1
READ (NI,FMT) X(100+I,1), X(200+I,1)
IF (X(100+I,1) .LE. 0.0) GO TO 121
WEIGHT = WEIGHT + X(100+I,1)
GO TO 101
121 NDP = I - 1
YY = 0.0
DO 141 I = 1,NDP
Y(I) = YY + X(100+I,1) / WEIGHT
YY = Y(I)
X(I,1) = X(201+I,1)
141 CONTINUE
NDP = NDP - 1

```

X(I,3) = PARTICLE SIZES FOR WHICH WE WISH TO CALCULATE
TABULAR DATA

X(I,4) = FRACTION OF WEIGHT IN PARTICLES SMALLER THAN X(I,3)

IT IS NECESSARY THAT 1 OR MORE VALUES OF X(I,3) BE LESS THAN
SIZE0 AND 1 OR MORE VALUES GREATER THAN SIZE0

```

IF (MYN .EQ. 11897) GO TO 321
MYN = 11897
Z(1) = 1.0
Z(2) = 1.0 / 2.0D0
Z(3) = 1.0 / 3.0D0
Z(4) = 1.0 / 4.0D0
Z(5) = 1.0 / 5.0D0
Z(6) = 1.0 / 6.0D0
Z(7) = 1.0 / 7.0D0
Z(8) = 1.0 / 8.0D0
Z(9) = 1.0 / 9.0D0
Z(10) = 1.0 / 1.0D1
Z(11) = 1.0 / 1.1D1
Z(12) = 1.0 / 1.2D1
Z(15) = 1.0 / DSQRT(2.0D0 * 3.1415926536D0)
HALF = Z(2)
IK = 0
201 IJ = IK + 1
    IK = IJ + 7
    READ (NI,FMT) (X(I,3), I = IJ,IK)
    DO 251 I = IJ,IK
        IF (X(I,3) .LE. 0.0) GO TO 301
251 CONTINUE
    GO TO 201
301 NEXTRA = I - 1
321 IREAD = 0
9001 FORMAT (18A4)
9011 FORMAT (3E10.0, 2I5)
RETURN
END

```

```

SUBROUTINE OUTPUT(A,B,DET,PRNT,SA,SE,X,Y,TITLE,ITCT,K,N,NDPM,NPM)
IMPLICIT REAL*8 (A-H,O-Z)
DIMENSION A(NPM,1),B(1),PRNT(1),SA(1),TITLE(18,3)
DIMENSION X(NDPM,1),Y(1)
DIMENSION SS(10,10)
COMMON/LBCOM1/BB(10),YC(10),YCI(10),ACCURC,DEL,SIZE0,DLNS0,
1 HALF,Z(15),IMAX,NE,NEXTRA,IPR(7)
COMMON/TAPES/NI,NO,NP,NTTDC
REAL*4 TITLE
EXTERNAL EQUA
C IF(K.GT.6) GO TO 81
C M=1
C GO TO 121
C 91 NC=K/6
C J=6*NC
C I=0
C 101 WRITE (NP,901) B(I+1),B(I+2),B(I+3),B(I+4),B(I+5),B(I+6)
C I=I+6
C IF(I.LT.J) GO TO 101
C M=I+1
C 121 WRITE (NP,901) (B(I),I=M,K)
    BB(1) = B(1)
    BB(2) = B(2)
    CONI = Z(15)

```

```

S1 = SIZE0
YC(1) = YCI(1) / B(3)
DO 401 I = 1, NEXTRA
  S0 = S1
  S1 = X(I,3)
  UDEL = (S1 - S0) * DEL
  CALL KUTTA(S0, S1, YC, NE, UDEL, ACCURC, IMAX, EQUA)
  X(I,4) = YC(1)
401 CONTINUE
DO 501 K = 1, NEXTRA
  DLNS = DLOG(X(K,3))
  TERM = (DLNS - B(1)) / B(2)
  EXPO = TERM * TERM * HALF + DLNS
  X(100+K,4) = DEXP(-EXPO) / B(2) * CONI
  X(K+200,4) = X(K,4) * B(3) + YCI(1)
  X(K+300,4) = X(K+200,4) * CONI / B(3)
501 CONTINUE
C
C   T1          = MODE
C   T2          = MEDIAN
C   T3          = MEAN
C
  T1 = DEXP(B(1) - B(2) * B(2))
  T2 = DEXP(B(1))
  T3 = DEXP(B(1) + B(2) * B(2) * HALF)
  WRITE (NO,9201)
  WRITE (NO,9211)
  NX2 = NEXTRA / 2
  NXT = NEXTRA - NX2
  DO 601 K = 1, NX2
    K1 = K + 100
    K2 = K + 200
    K3 = K + 300
    J0 = K + NXT
    J1 = K1 + NXT
    J2 = K2 + NXT
    J3 = K3 + NXT
    WRITE (NO,9221) X(K,3), X(K1,4), X(K2,4), X(K3,4),
1      X(J0,3), X(J1,4), X(J2,4), X(J3,4)
601 CONTINUE
  IF (NXT .LE. NX2) GO TO 611
  WRITE (NO,9231) X(NXT,3), X(NXT+100,4), X(NXT+200,4), X(NXT+300,4)
611 CONTINUE
  WRITE (NO,9251)
  WRITE (NO,9261) T1
  WRITE (NO,9271) T2
  WRITE (NO,9281) T3
901 FORMAT (1P6E12.5)
9201 FORMAT (1H1)
9211 FORMAT (' PARTICLE LOGNORMAL FRACTION OF FRACTION OF
1      PARTICLE LOGNORMAL FRACTION OF FRACTION OF '/'
2      ' SIZE DISTRB. TOTAL DISLODGED
3      SIZE DISTRB. TOTAL DISLODGED '/'
4      ' FUNCTION WEIGHT WITH WEIGHT WITH
5      ' FUNCTION WEIGHT WITH WEIGHT WITH '/'
6      ' SMALLER SMALLER
7      ' SMALLER SPALLER
8      ' MICRON PART. SIZE PART. SIZE
9      MICRON PART. SIZE PART. SIZE '/')

```



```
9221 FORMAT (F10., 1PD14.3,D13.3,D14.3, 0PF17.0, 1PD14.3,D13.3,D14.3)
9231 FORMAT (F10.0, 1PD14.3,D13.3,D14.3)
9251 FORMAT (///)
9261 FORMAT (' THE MODE    =', 1PD10.3, ' MICRONS.' )
9271 FORMAT (' THE MEDIAN =', 1PD10.3, ' MICRONS.' )
9281 FORMAT (' THE MEAN   =', 1PD10.3, ' MICRONS.' )
      RETURN
      END
```

8 2 0 1 0 0 1
1 5 50

1.0 D-06

6.73 1.5

(8P10.0)

PARTICLE SIZE DISTRIBUTION DATA OF R.G.STACY
OCONEE, CYCLE 1, ROD 47-107, PWR, ZIRCALOY-4 CLADDING, 11,000 MWD/MTU
NO2 DISLODGED FROM SEGMENT BBOT WITH 0.5 -INCH CUT

\$	ACCURC	DEL	SIZE0	IMAX	NE							
1.0	D-08	1.0	D-01	0.01	10	1						
\$	YCI(1)	YCI(2)	YCI(3)	YCI(4)	YCI(5)	YCI(6)	YCI(7)	YCI(8)				
1.0	D-09											
\$	YCI(9)	YCI(10)										

0.		
1.1	-	20.
1.0	+	20.
1.1	+	38.
1.6	+	44.
4.0	+	75.
7.1	+	150.
7.5	+	300.
10.0	+	500.
4.3	+	650.
7.6	+	1000.
55.3	+	1400.

1.	2.	4.	6.	8.	10.	15.	20.
25.	30.	35.	40.	45.	50.	60.	70.
80.	90.	100.	120.	140.	160.	180.	200.
250.	300.	350.	400.	450.	500.	550.	600.
700.	800.	900.	1000.	1200.	1400.	1600.	

SEND DATA

8 2 0 1 0 0 1
1 5 50

1.0 D-06

6.73 1.5

(8P10.0)

PARTICLE SIZE DISTRIBUTION DATA OF R.G.STACY
OCONEE, CYCLE 1, ROD 47-107, PWR, ZIRCALOY-4 CLADDING, 11,000 MWD/MTU
NO2 DISLODGED FROM SEGMENT BBOT WITH 2.0 -INCH CUT

\$	ACCURC	DEL	SIZE0	IMAX	NE							
1.0	D-08	1.0	D-01	0.01	10	1						
\$	YCI(1)	YCI(2)	YCI(3)	YCI(4)	YCI(5)	YCI(6)	YCI(7)	YCI(8)				
1.0	D-09											
\$	YCI(9)	YCI(10)										

0.		
0.6	-	20.
0.4	+	20.
0.3	+	38.
0.5	+	44.
1.6	+	75.
2.4	+	150.
2.6	+	300.
3.4	+	500.
1.2	+	650.
2.5	+	1000.
10.1	+	1400.

SEND DATA

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