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U. S. Atomic Energy Commission
Technical Information
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Subject: AT(11-1)-3045, Task 3, Fast Reactor Fuel Element Development

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PELLET SELECTION TO MINIMIZE SMEAR DENSITY
VARIATION WITHIN THE FUEL ELEMENT

TOPICAL REPORT

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BY J.H. Kahn / amh
DATE 2/3/72

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PELLET SELECTION TO MINIMIZE SMEAR DENSITY VARIATION WITHIN THE FUEL ELEMENT

1.0 SUMMARY

A Fortran IV computer program was written to make calculations for more than 8000 fuel pellets. The information was needed for smear density control of pellets selected for fuel pin loading for irradiation testing. For each pellet the output lists included pellet density, smear density, diameter, and length; data were sorted and listed in ascending order for each characteristic in order to simplify handling. For pellet batches, the means, standard deviations, and listings for easy construction of population histograms were available as output.

The frequency distributions were used to select individual pellets for loading into cladding tubing. The scheme described was based on minimizing pellet density variations from the top to the bottom of each pellet stack, as well as minimizing variations between the pellet stacks from any batch.

2.0 INTRODUCTION

Three irradiation programs (WSA-1, -2, -3) have been completed, representing 75 fuel pins fabricated from stainless steel tubing containing $(U_{0.75}Pu_{0.25})O_2$ cylindrical pellets. For each pin fabrication campaign there was a design requirement that allocation of the void space and fuel volume within the cladding tube be closely controlled. The control of smear density required that the dimensions and geometric density of each fuel pellet used be known.

For the WSA-3 experiment, more than 5000 pellets were evaluated in order to select those needed for pin fabrication. The many computations generated indicated that computer data handling was a necessity. The Fortran IV program that developed for doing the arithmetic produced all of the expected benefits of rapid turnover of data, freedom from computational error, and convenient, condensed data listings.

The purpose of this report is to show, for the WSA-3 experiment, how and what pellet data were treated, how the data can be most conveniently presented and used, how pellets were handled within the glove box, and a rationale for individual pellet selection.

It is not a purpose of this report to discuss reasons for the observed differences among the types of fuel pellets or the technical aspects of pellet fabrication. It remains for the pellet fabricators to use information here as an aid to interpret whatever fabrication procedures they may have employed.

3.0 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 The PELPAR Program

The PELPAR program written in Fortran IV produces seven output sheets displaying the following information for any population of sintered pellets.

1. A summary listing for each pellet in the grouping under these headings: Pellet No., Weight, Diameter, Length, Density, % T. D., and Smear Density.
2. Pellet number and corresponding % T.D. For each pellet in ascending order from the lowest to highest value.
3. Same as (2), except Weight is the variable.
4. Same as (2), except Diameter is the variable.
5. Same as (2), except Length is the variable.
6. Same as (2), except % Theoretical Smear Density is the variable.
7. A summary of means and standard deviations for all variables.

Input needed for each batch is: oxygen to metal ratio (O/M) and the inside diameter of the particular pieces of tubing used for loading pellets of that grouping. The O/M ratio is needed because the program makes density corrections corresponding to oxygen content. The tubing diameter is needed because it is a variable affecting smear density calculations.

Input needed for each pellet is: identity number, weight, diameter, and length. This information must be keypunched on a card for each pellet. All measurements are made to four significant figures.

Since pellets are often weighed in the finished condition with the edges rounded by abrasion or chamfered by a lip on the punch faces, an empirical factor is installed in the program to correct for this weight loss. Thus, calculations are based on a perfect right circular cylinder.

3.2 Pellet Batches

The product of a high-temperature sintering run is considered to be a batch of pellets. About 400 pellets in the sintering boat was the maximum number for any batch run. Rejection of pellets to visual standards after grinding generally reduced the number available for evaluation by 10% or more. For the WSA-3 campaign, a total of 18 batches (plus two centerless reground groups) numbering more than 5000 pellets were analyzed using the computer program. Twelve batches which were selected for fuel pin fabrication are presented in Table 1. Of the 3614 pellets in these batches, 54 ± 1 pellet per tube (or 2430 pellets) were required for the 45 fuel pins made for the

Table 1. WSA-3 Fuel Pellet Parameters and Allocation								
Pin Group No.	Batch No.	No. of Pins	Mean Values/Standard Deviation				Pellets Measured	Pellets Loaded
			% T.D.	Weight (g)	Diameter (in.)	Length (in.)		
<u>High Density Pellets</u>								
1	34-2	5	95.78 0.41	1.216 0.011	0.1912 0.0000	0.2464 0.0023	345	270
1	40-1	5	95.89 0.26	1.241 0.006	0.1913 0.0000	0.2503 0.0012	300	270
1	40-2	1	95.80	1.292	0.1953	0.2510	360	270
2		4	0.28	0.009	0.0000	0.0017		
2	36-1	4	95.06 0.36	1.270 0.012	0.1952 0.0003	0.2488 0.0020	304	216
2	36-2	5	95.00 0.73	1.270 0.017	0.1951 0.0000	0.2492 0.0027	346	270
<u>Low Density Pellets</u>								
3	41-2	7	91.27 0.71	1.197 0.021	0.1934 0.0000	0.2486 0.0033	436	378
3	42-3	1	91.60 0.87	1.219 0.039	0.1941 0.0000	0.2505 0.0063	121	54
3	42-4	1	93.02 1.07	1.198 0.017	0.1938 0.0000	0.2438 0.0018	346	54
3	42-5	2	91.41 0.96	1.190 0.012	0.1941 0.0000	0.2455 0.0018	180	108
4	37-1	2	90.25 0.60	1.244 0.013	0.1974 0.0000	0.2512 0.0022	192	108
4	39-5	3	89.17 1.43	1.231 0.022	0.1969 0.0000	0.2525 0.0024	312	162
4	41-1	5	89.49 0.68	1.221 0.018	0.1973 0.0000	0.2491 0.0024	372	270
		45					3,614	2,430

WSA-3 irradiation experiment. High density pellets (for 24 fuel pins) and low density pellets (for 21 pins) were made. Pellets were centerless ground to two different diameters for each density level. Thus, four unique pellet groups were produced.

With the aid of the "ascending-order-of-variable" computer listings, it was easy to construct conventional frequency distributions. The variable of main interest is percent of theoretical density, i.e.,

$$\% \text{ T.D.} = 100 \left[\frac{\text{pellet density}}{\text{theoretical density of } (U_{0.75}Pu_{0.25})O_2 \text{ adjusted for O/M ratio and U enrichment}} \right].$$

Examples of total population pellet density histograms are shown in Figure 1 for the normal distribution of the largest pellet batch (41-2) and for a bimodal distribution in Figure 2. These are typical of the working histograms drawn for every pellet batch or grouping.

Smoothed histograms for the five low density batches are presented in Figure 3. The two batches from which only one pin each was made are not included for simplification. Also, the data have been transformed to relative frequencies so that the ordinate represents percent of the total population for any increment of the discrete histogram. The effect of population size on the representation is thus eliminated. Thus, batches showing the highest mode peak values and minimum variance about the mean are truly represented as more concentrated than other batches. Smoothed histograms for the five high density batches are presented in Figure 4. Finally, cumulative distributions for the low and high density batches are shown in Figures 5 and 6. Percentages of pellets up to any limit or within any interval can be read directly from these charts.

The greater variance of the low density batches is apparent if the calculated standard deviation for each batch is plotted against its mean density as shown in Figure 7. The lower line drawn indicates that slightly greater variance might be expected at lower densities because of the contribution of the greater proportion of voidage within the pellet. The upper line slope indicates that an equilibrium condition of the material may not have been achieved during sintering. Under equilibrium fabrication conditions, a uniformly low variance would be expected at all practical density levels. At any rate, plotting standard deviations as above appears to be an informative way of interpreting density variations among pellet batches.

3.3 Pellet Selection

The WSA-3 irradiation experiment was designed to closely control deployment of the void volume within the fuel pin. This imposed precise control of the smear density; i.e., the quantity of fuel within the confines of any given portion of the cladding tube. The requirements were:

Figure 1. Density Histogram for Pellet Batch 41-2

Figure 2. Density Histogram for Pellet Batch 36-2

Figure 3. Relative Frequency Distribution of Pellet Densities for Low-Density Batches

Figure 4. Relative Frequency Distribution of Pellet Densities for High-Density Batches

Figure 5. Cumulative Frequency Distributions for Low-Density Pellet Batches

Figure 6. Cumulative Frequency Distributions for High Density Pellet Batches

Figure 7. Standard Deviation from Mean Density for all Pellet Batches

Figure 8. Group I Density Relationship

1. Each pellet used must be measured and certain data generated.
2. Tolerance control:
 - a. Pellet density: $\pm 1\%$ T.D.
 - b. Smear density: $\pm 1\%$ T.D. for pin Group II
 $\pm 0.75\%$ T.D. for Groups I, III, IV
 - c. Pellet diameter: ± 0.0005 inch
 - d. Tubing ID: ± 0.0005 inch
3. Minimize smear density variation pin-to-pin for each pellet batch.
4. Minimize smear density variation batch-to-batch for each pin group.

In order to meet these requirements, a frequency diagram of the density parameter was prepared for each batch of pellets, and the number within the tolerance limits was determined. If a sufficient number of pellets were available for four pins, the four pellets at the median of the distribution were assigned to the top position of the four pellet stacks. Next, four pellets alternately on either side of these were assigned and so forth until all pellets were assigned by working away from the median and toward the tolerance limits. Thus, four sub-batch frequency distributions similar to each other and to the original batch were obtained.

The scheme for loading a pin was as follows: pellets 1 and 54 (the two tail positions of a sub-batch) are inserted first and are at the bottom of the fuel stack; pellets 2 and 53 are next and so forth until the pellet of median density is loaded at the top of the column. Therefore, the average of any two adjacent pellets is similar to the median value of density. Since pellets are about 0.25-inch long, each 0.50 inch of fuel (two neighbor pellets) has a similar average density. Such arrangements were used in loading all 45 pins for the experiment.

Pellets were allocated so as to minimize smear density variations from pin to pin as well as in each pin itself. For the final requirement, it will be shown how variations were minimized for the two, three, or four batches constituting each pin grouping. Figures 8 through 11 show the ranges of values when comparing pellet densities to their corresponding smear densities for the four pin groups. For simplicity, only one pin loading was selected to represent each fuel batch. Boundary lines have been drawn around a two-sigma total of the points. Thus, the scatter of both pellet and smear density is defined. All of these envelopes are shown in Figure 12, together with the target range of values finally set for the experiment. The average densities for each pin have been listed in Table 2.

3.4 Glove Box Activities

Of the glove boxes in the Plutonium Fuels Development Laboratory (PFDL), one box (#11) has been assigned exclusively for pellet handling and loading. The purpose of this section is to describe the activities of fuel pin

Figure 9. Group II Density Relationship

Figure 10. Group III Density Relationship

Figure 11. Group IV Density Relationship

Figure 12. Density Relationship for all Fuel Pins

Table 2. Average Densities for Pellets in Each Fuel Pin

Pin No.	Batch No.	% T. D.		Pin No.	Batch No.	% T. D.	
		Pellet	Smear			Pellet	Smear
1	36-1	95.11	90.10	24	39-5	90.11	87.21
2	41-2	91.39	85.68	25	41-2	91.37	85.81
3	36-1	95.05	90.15				
4	40-1	95.89	87.54	26	36-2	95.24	90.42
5	41-1	89.69	87.06	27	39-5	90.10	87.27
				28	41-2	91.37	85.64
6	36-1	95.05	90.18	29	34-2	95.79	87.69
7	41-2	91.40	85.83	30	36-2	95.27	90.51
8	36-1	95.03	90.08				
9	40-1	95.89	87.37	31	41-2	91.38	85.81
10	40-1	95.87	87.98	32	36-2	95.25	90.42
				33	40-2	95.78	90.90
11	41-1	89.71	87.07	34	42-3	91.66	86.00
12	40-2	95.22	90.60	35	40-2	95.84	91.53
13	41-2	91.41	85.85				
14	41-1	89.70	87.07	36	42-5	91.44	86.14
15	41-1	89.68	87.16	37	39-5	90.07	87.34
				38	42-5	91.43	85.97
16	41-2	91.41	85.85	39	42-4	91.85	86.35
17	40-1	95.90	87.54	40	37-1	89.97	87.52
18	40-1	95.90	87.87				
19	36-2	95.22	90.78	41	37-1	89.96	87.52
20	34-2	95.78	87.69	42	34-2	95.76	87.34
				43	40-2	95.83	87.23
21	34-2	95.79	87.32	44	36-2	95.81	91.63
22	34-2	95.78	87.77	45	40-2	95.81	91.17
23	41-1	89.72	87.42				

fabrication. The fundamental point is that 100% inspection and measurement of pellets is not overly time consuming, especially if the importance of rigorous control of fuel distribution in a specimen intended for costly irradiation testing is considered.

Once a batch of pellets is posted in the glove box, it is laid out in parallel V-grooves for visual inspection in preparation for measurement. Ordinarily there are 60 pellets per groove. Diameter measurements are read to the nearest 0.0001 inch with a Supermike held in a clamp. Experience has shown that the diameter of centerless ground pellets 0.25 inch long can be measured accurately with one reading. Length is measured to the nearest 0.0005 inch with either a pedestal dial gage or conventional micrometers. Weights are made on a direct reading balance to the nearest 0.001 gram. One technician makes measurements while a second records the information directly on computer coding forms. A batch of 400 pellets can be measured and calculated within two shifts. Each grooveful of pellets is then pushed into a close-fitting storage tube and plastic caps are placed on the ends. On the computer printouts each pellet is now identified by physical location by a four-digit number: the first two digits identify the storage tube number and the second two identify location in the tube.

After the pellet loading sequence has been established, the classified pellets are again laid out in V-grooves from the storage tubes. As each pellet is selected by its location and placed in the loading tube, it is replaced in the groove position by a white ceramic pellet. Using this technique inventory accountability has been found nearly fool-proof. The key-punched cards for fuel pellet batches are also sorted in a similar manner and rerun so that all information pertaining to each pin is produced separately.

The loading tube in which the pellets are placed to form the stack is so constructed that no mixing of pellets can occur. Further, the "udder-bag" loading technique is used in which the loading tube inside the box butts up against the open end of the fuel tube that is held external to the glove box; a plastic nipple on the udder bag joins the tubes and provides a leak-tight seal. Actual loading occurs when a vibratory feeder device is actuated which gently moves the stack of pellets along the loading tube and into the fuel tube. After withdrawing the loading tube dielectrically sealing the nipple and cutting the plastic between seals, the loaded tube is removed for further processing.

4.0 CONCLUSIONS

Computerized data handling was considered a necessity for the density, standard deviation, and data sorting calculations for the more than 8000 mixed-oxide fuel pellets that have been measured.

The Fortran IV program produced the expected benefits of rapid data turnover, convenient permanent documentation, freedom from computational error, and efficient inventory control.

The objective of the measurement program was to select pellets for controlled fuel loading in each of the 45 pins fabricated; i.e., a known fuel smear density within the active portion of each fuel pin. The design objective of $\pm 1.0\%$ T.D. variation for pellet and smear densities was achieved.

The 100% measurement and data generation effort is not excessively time consuming and is worth the benefit of closer experiment control.