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Evaluation of Gravimetric and Volumetric Dispensers of Particles of Nuclear Material

C. K. Bayne
P. Angelini

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C. K. Bayne* and P. Angelini

ABSTRACT

Theoretical and experimental studies compared the abilities of volumetric and gravimetric dispensers to dispense accurately fissile and fertiel fuel particles. Such devices are being developed for the fabrication of sphere-pac fuel rods for high-temperature gas-cooled light water and fast breeder reactors. The theoretical examination suggests that, although the fuel particles are dispensed more accurately by the gravimetric dispenser, the amount of nuclear material in the fuel particles dispensed by the two methods is not significantly different. The experimental results demonstrated that the volumetric dispenser can dispense both fuel particles and nuclear materials that meet standards for fabricating fuel rods. Performance of the more complex gravimetric dispenser was not significantly better than that of the simple yet accurate volumetric dispenser.

INTRODUCTION

Several processes require accurate dispensing of nuclear materials in the form of coated particles of uranium and thorium compounds. For example, accurate amounts of uranium and thorium must be dispensed into High-Temperature Gas-Cooled Reactor (HTGR) fuel rods in the form of fissile and fertile particles. Other applications include accurately dispensing nuclear materials (1) in fuel rod production for light water and fast breeder reactors and (2) for nuclear waste disposal.

Two methods for dispensing particles are available: volumetric and gravimetric (Fig. 1). The volumetric method dispenses 100% of the particles by volume, whereas the gravimetric method dispenses a fraction of the particles by volume and the remainder by weight. The volumetric

*Computer Sciences Division.

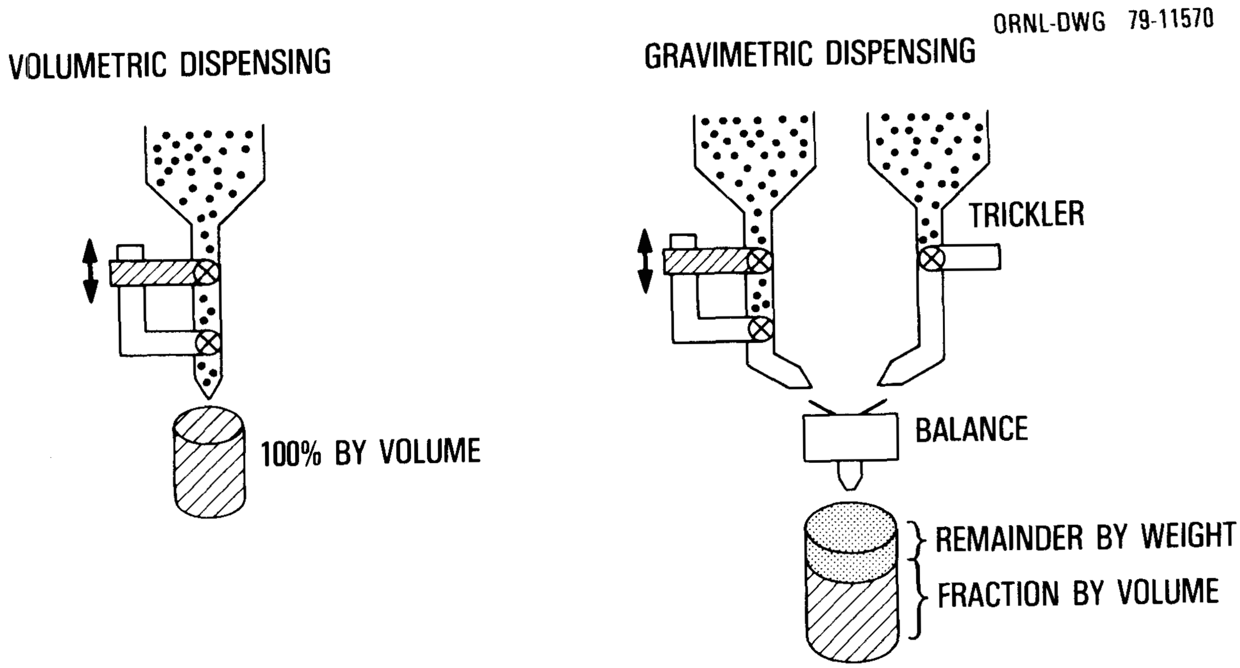

Fig. 1. The volumetric method dispenses 100% of the particles by volume, whereas the gravimetric method dispenses a fraction by volume and the remainder by weight.

method dispenses particles from a hopper into a particle-holding tube, which has its volume controlled by a variable pinch valve. The volume in the chamber is calibrated to dispense the target weight of the total particles. When the chamber is full and closed at the top by the pinch valve, the particles are released into a fuel rod container.

The gravimetric method dispenses a large fraction of the particles by volume onto a balance, which determines the weight required to bring the total particle weight up to the target value. A trickler device adds the remaining amount of particles onto the balance, and the particles are released into a fuel rod container. Ideally, the gravimetric method dispenses particles with greater weight precision than does the volumetric method but requires a more complex apparatus. Dispensing a precise quantity of particles does not necessarily imply that a precise quantity of nuclear material is also dispensed because of variations in the particle kernels and their coatings. The proper comparison of volumetric with gravimetric methods is the comparison of their abilities to dispense precise amounts of nuclear materials rather than precise weights of particles.

Experiments to compare volumetric with gravimetric methods were performed by using two volumetric dispensers having design differences in their particle-holding tubes and pinch valves. These design variations produced slight differences in the precision of the quantities dispensed.

To examine the properties of volumetric and gravimetric dispensers, we conducted both theoretical and experimental studies, which are reported in the following chronology: results of a theoretical study on the effects of variations in the fabrication of a coated particle on total particle weight, a comparison experiment of an ideal gravimetric dispenser by using laboratory equipment with a volumetric dispenser, comparison of a production gravimetric dispenser with a volumetric dispenser, and descriptions of a series of experiments that examine the long-term drift behavior and the operating characteristics of volumetric dispensers.

THEORETICAL CONSIDERATIONS

An HTGR particle consists of a kernel of nuclear material coated with layers of carbonaceous material. During the fabrication of a particle the diameter and the coating thicknesses of the kernel vary about their mean values. Using mean values and standard deviations estimated from previous data, the expected weights of the kernel and each coating as well as the variation in the weight of each particle can be calculated. The derivation of the theoretically expected weights and variances are based on the following assumptions.

1. The kernel and its coatings form concentric spheres.
2. The coating thicknesses are independent of each other and of the kernel diameter.
3. The kernel diameter and coating thicknesses are normally distributed about their respective means.
4. The kernel density and the coating densities are constants.

For a particle with n coatings, these assumptions are symbolically represented by

D_0 = kernel diameter, $D_0 \approx N(\mu_0, \sigma_0^2)$;

t_i = coating thickness, $i = 1,2,\ldots,n$; $t_i \sim N(\mu_i, \sigma_i^2)$; i.e., the t_i are normally distributes with means μ_i and variances σ_i^2;

ρ_0 = kernel density;

ρ_i = ith coating density;

W_0 = weight of kernel;

W_i = ith coating weight.

The diameter of the particle after the ith coating is $D_i = D_{i-1} + 2t_i$. The particle diameter D_i is also normally distributed with a mean and a variance of

$$U_i = \mu_0 + 2 \sum_{j=1}^{i} \mu_j \ , \tag{1}$$

$$S_i^2 = \sigma_0^2 + 4 \sum_{j=1}^{i} \sigma_j^2 \ . \tag{2}$$

The total weight W_t of a particle is given by the volume of each component multiplied by its density:

$$W_t = \sum_{i=0}^{n} W_i \tag{3}$$

or

$$W_t = (\pi/6)\rho_0 D_0^3 + \sum_{i=1}^{n} (\pi/6)\rho_i (D_i^3 - D_{i-1}^3) \ . \tag{4}$$

The expected value of the total weight is the sum of the expected values of the kernel weight and of each coating weight.

$$E\left(W_t\right) = (\pi/6)\rho_0 E\left(D_0^3\right) + \sum_{i=1}^{n} (\pi/6)\rho_i \left[E\left(D_i^3\right) - E\left(D_{i-1}^3\right)\right] . \tag{5}$$

Using the formulas for the third moment of a normal random variable, the expected value of the total weight is

$$E(W_t) = (\pi/6)\rho_0(3\mu_0\sigma_0^2 + \sigma_0^3)$$

$$+ (\pi/6) \sum_{i=1}^{n} \rho_i (3U_i S_i^2 + U_i^3 - 3U_{i-1} S_{i-1}^2 - U_{i-1}^3) . \tag{6}$$

The variance of the total weight involves both the variances of each diameter and the covariances between the diameters:

$$\mathrm{VAR}(W_t) = (\pi/6)^2 \rho_0^2 \mathrm{VAR}(D_0^3) + (\pi/6)^2 \sum_{i=1}^{n} \rho_i^2 [\mathrm{VAR}(D_i^3)$$

$$+ \mathrm{VAR}(D_{i-1}^3) - 2\mathrm{COV}(D_i^3, D_{i-1}^3)] . \tag{7}$$

Each of the variances and covariances can be expressed as a function of the means and standard deviations of the kernel diameter, particle diameter, and coating thicknesses:

$$\mathrm{VAR}(D_0^3) = 15\sigma_0^6 + 36\mu_0^2\sigma_0^4 + 9\mu_0^4\sigma_0^2 , \tag{8}$$

$$\mathrm{VAR}(D_i^3) = 15S_i^6 + 36U_i^2 S_i^4 + 9U_i^4 S_i^2 , \tag{9}$$

$$\mathrm{cov}(D_i^3, D_{i-1}^3) = 15S_{i-1}^6 + 45U_{i-1}^2 S_{i-1}^4 + 15U_{i-1}^4 S_{i-1}^2 + U_{i-1}^6$$

$$+ 6(15U_{i-1}S_{i-1}^4 + 10U_{i-1}^3 S_{i-1}^2 + U_{i-1}^5)\mu_i$$

$$+ 12(3S_{i-1}^4 + 6U_{i-1}^2 S_{i-1}^2 + U_{i-1}^4)(\mu_i^2 + \sigma_i^2)$$

$$+ 8(3U_{i-1}S_{i-1}^2 + U_{i-1}^3)(\mu_i^3 + 3\mu_i\sigma_i^2)$$

$$- (3U_{i-1}S_{i-1}^2 + U_{i-1}^3)(3U_i S_i^2 + U_i^3) \quad . \tag{10}$$

The expected value and variance formulas are applied to the data for fissile and fertile particles in Table A-1 in the Appendix. These data are used to calculate the estimated means and variances of the kernel weight and coating weights of triso-fissile and biso-fertile particles illustrated in Fig. 2. A triso-coated particle has three types of coatings [carbon-buffer, low-temperature isotropic carbon (LTI), and silicon carbide], and a biso-coated particle has two types of coatings (carbon buffer and LTI). The expected value results are given in Fig. 3, and the variance results, in Fig. 4. Figures 3 and 4 show the contribution of each particle component to the total expected weight and total variance, respectively. The importance of these two figures is that, although the kernel contributes significantly to the total expected particle weight (23.7% for a fissile particle and 61.8% for a fertile particle), the kernel contributes an insignificant amount to the total variance of the particle weight (1.1% for a fissile particle and 6.3% for a fertile particle). These theoretical results suggest that the major contribution to particle weight variance is by the coating weight variation rather than by the kernel weight variation.

Although the ideal gravimetric method may be able to dispense particles with better weight precision than can the volumetric method, this

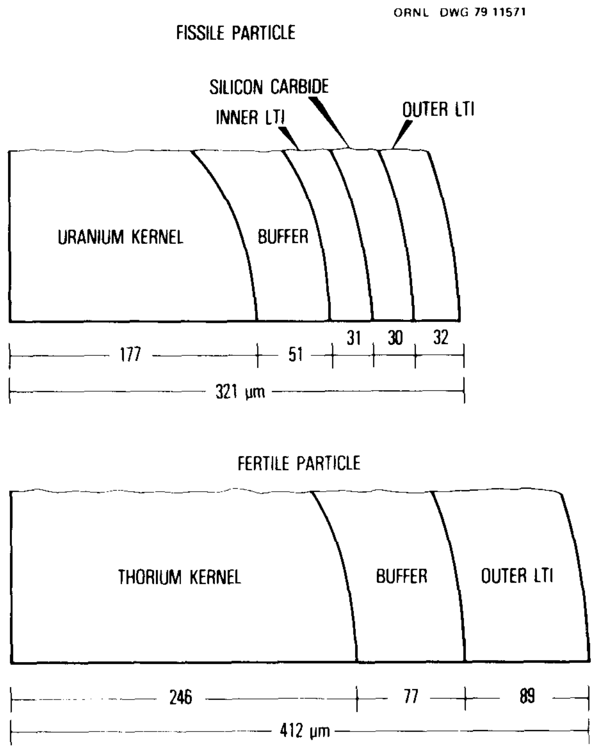

Fig. 2. Fissile and fertile components of High-Temperature Gas-Cooled Reactor (HTGR) fuel particles.

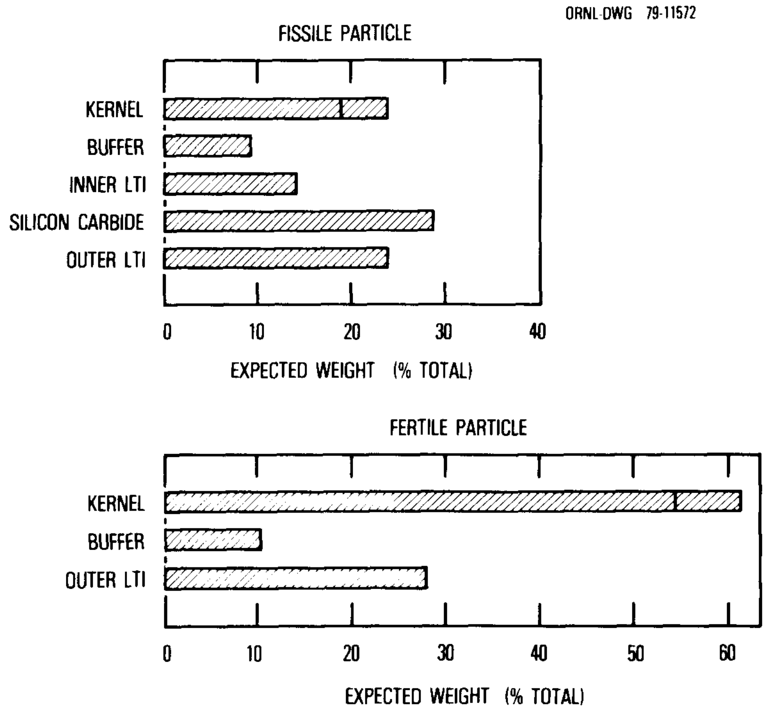

Fig. 3. Percentage of each particle component's contribution to the total expected particle weight.

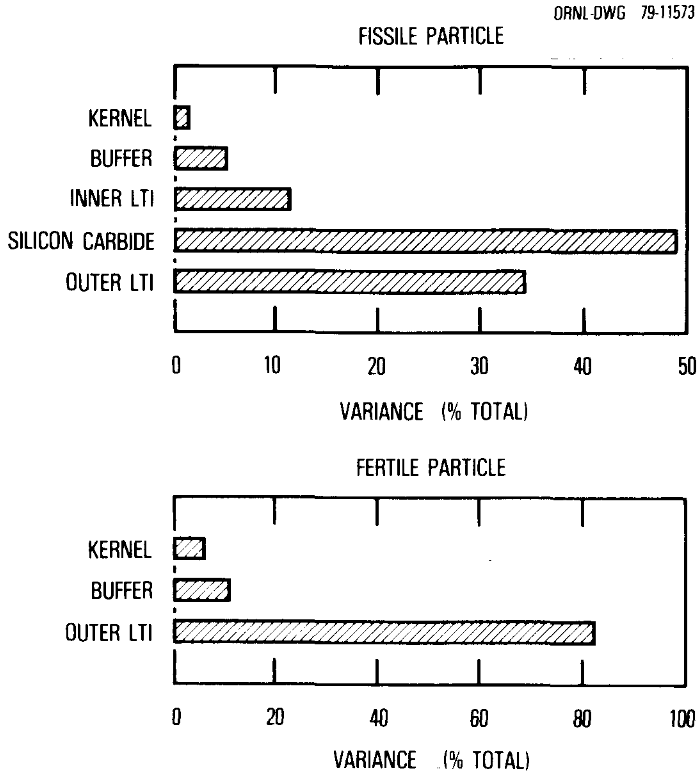

Fig. 4. Percentage of each particle component's contribution to the variance of the total particle weight.

study suggests that the amount of nuclear material dispensed is not significantly different. To investigate this possibility, an experiment was designed to compare both the particle weights and the amount of nuclear material dispensed by an ideal gravimetric dispenser with the results from a volumetric dispenser.

COMPARISON OF IDEAL DISPENSERS

We used the elastomer tube volumetric dispenser shown in Fig. 5 in this set of experiments. The particle-holding tube was constructed of elastomer material, and two valves were mounted on the holding tube to determine the desired volume of particles to be dispensed. The bottom valve was a stationary ball-type valve. The upper valve was a clamp-type pinch valve that could be positioned at any point along the elastomer holding tube to regulate the dispensed particle volume.

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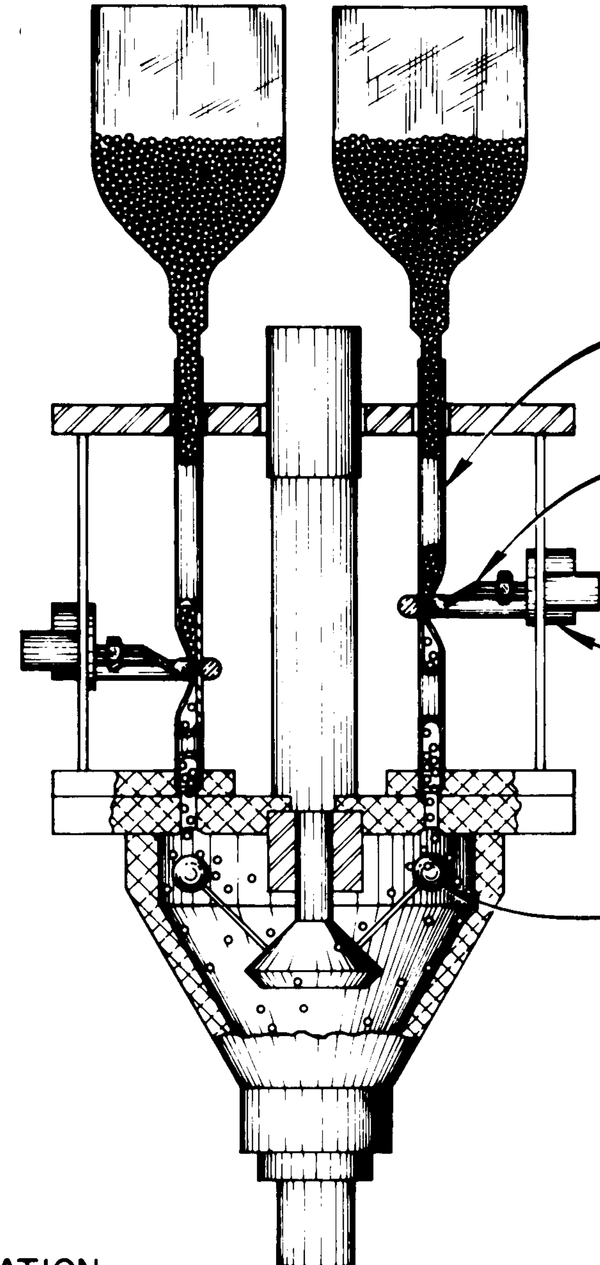

OPERATION

(1) CLOSE PLUG VALVES, OPEN PINCH VALVES TO FILL DISPENSER.

(2) CLOSE PINCH VALVES TO DETERMINE CALIBRATED VOLUMES.

(3) OPEN PLUG VALVES TO DUMP PARTICLES.

Fig. 5. Elastomer tube volumetric dispenser.

An ideal gravimetric dispenser was modeled by dispensing 90% of the total particle weight by the elastomer tube volumetric dispenser and adding the remaining weight manually. This procedure eliminated any variation caused by the automatic trickler device that is normally used to add the remaining weight. To compare the ideal gravimetric dispenser with the volumetric dispenser, 30 samples each of fissile and fertile particles were dispensed by both methods. Each method was to dispense samples with a target weight of 2 g for fissile particles and 6 g for fertile particles. The actual weights of the fissile and fertile samples and their uranium and thorium assay weights were determined. These data are tabulated in Tables A-2 and A-3 in the Appendix. One outlier sample each was not used for the volumetrically and gravimetrically dispensed fissile particles and for the gravimetrically dispensed fertile particles. Summary statistics for the data are also given in Tables A-2 and A-3 and are displayed as box plots[1] in Figs. 6 and 7. The box plots illustrate the data with five statistics: the minimum and maximum values, the upper and lower quartiles (which form the top and bottom of the box), and the median, represented by a dash line. In all cases the medians coincide closely with the means, indicating that all the data varied symmetrically about their means.

The standard deviations of the fissile particle weights are almost identical for both the volumetric and ideal gravimetric dispenser. In addition, good agreement exists between the standard deviations of the uranium assay weights for the two methods. The variance of the uranium assay weights represents 6% of the variance of the fissile particles, which agrees well with the theoretical study in the previous section. The results from the experimental fissile particle data indicate that both the volumetric and ideal gravimetric methods dispense comparable amounts of particle and uranium weights.

The experimental fertile particle data do not show good agreement between the two dispensing methods. The standard deviation of the volumetrically dispensed particle weights (35 mg) is 4.7 times the standard deviation of the ideal gravimetrically dispensed particle weights (7.5 mg). Comparison of the thorium assay weights of the two methods shows a standard deviation for the volumetric method (19.6 mg) to be

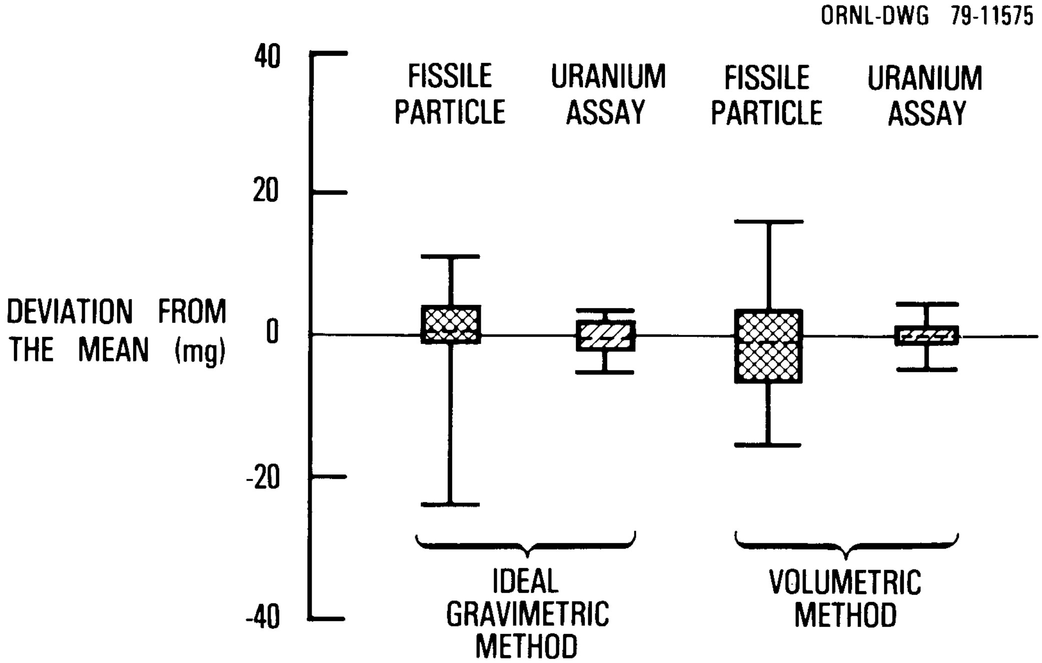

Fig. 6. Box plots of fissile data where the box contains the middle 50% of the data and dotted lines are the medians.

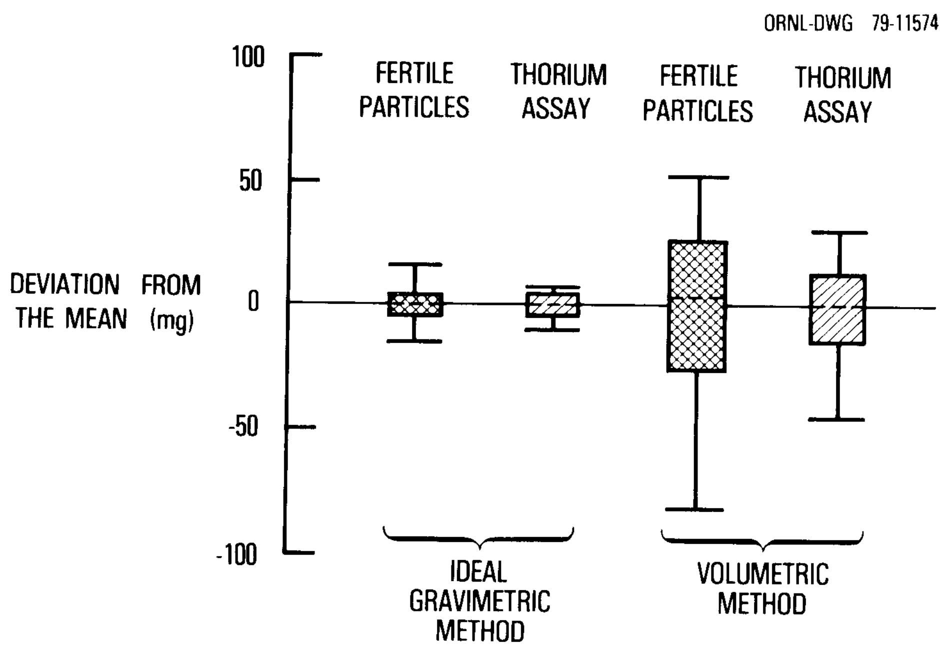

Fig. 7. Box plots of fertile data where the box contains the middle 50% of the data and the dotted lines are the medians.

3.9 times the standard deviation for the ideal gravimetric method (5 mg). For both the particle weights and the uranium assay weights, the volumetric method had a larger variation than did the ideal gravimetric method. The variation of the fertile particle weights for the volumetric method represents a *relative standard deviation* of 0.6%, which is comparable to the *relative standard deviation* of 0.5% for the fissile particle weights. This variation is well within the standards[2] for the fabrication of fuel rods. The variation of the volumetric method for dispensing fertile particle weights is therefore larger than is the variation for the ideal gravimetric method but is well within the standards for fabricating fuel rods. The contribution of the thorium assay weight variance is 31.4% of the total weight variance for the volumetrically dispensed fertile particles and 44.4% of the total weight variance for the ideal gravimetrically dispensed fertile particles. These percentages do not agree with the theoretical percentage of 6.3. However, for the ideal gravimetric case, a 6.3 theoretical percentage would be difficult to detect because of the small absolute size of the variation in the measurements and the detection limits of the chemical thorium assay method.[3]

This experiment demonstrated that the elastomer tube volumetric dispenser can dispense both fuel particles and nuclear materials that meet the standards for fabricating fuel rods. Comparing the particle weights and nuclear materials assays of the volumetric dispenser with an ideal gravimetric dispenser indicates good agreement for fissile particles but large absolute variation for fertile particles. These results are discussed further in the following section describing a comparison experiment that used a production gravimetric dispenser rather than the ideal gravimetric dispenser.

COMPARISON OF PRODUCTION DISPENSERS

An automated gravimetric particle-dispensing system was used to compare the performance of the volumetric and gravimetric methods for dispensing fertile particles. This particle-dispensing system has been used by the General Atomic Company in the manufacture of HTGR fuel rods.

The particle-dispensing system was operated in either a volumetric or a gravimetric mode. The automated gravimetric particle-dispensing system normally operates by volumetrically dispensing a large fraction of the particles onto a balance, which determines the weight required to bring the total particle weight up to the target value. A trickler device calibrated at a constant feed rate is operated for the time required to dispense the final weight onto the balance.

The basic design of the volumetric dispenser used in this system is shown in Fig. 8. The device utilizes a metallic telescoping particle-holding tube and two valves. The bottom valve is a stationary metallic slide valve, and the upper pinch valve is fixed to the telescoping holding tube. The pinch valve uses air pressure on an elastomer insert to stop the particle flow. The volume of the particles is determined by regulating the length of the telescoping holding tube.

All the experimental runs were made in the same afternoon. The hopper level was filled such that the particle level in the hopper did not change appreciably during the runs. Each experimental run consisted of dispensing fertile particles by either of the two methods to get a total net weight. The performance of each method was based on 20 samples run at a low net weight (4.25 g) and 20 samples run at a high net weight (7.75 g).

The volumetric dispenser was calibrated so that the volume dispensed was equal to 100% of the target value. During this experiment the dispenser was calibrated to dispense an amount close (within 15 to 35 mg) to the net weight; an exact calibration would have unnecessarily delayed the experiment. The final weights were recorded as number of milligrams above or below the target net weight. Therefore, the final weights are only relative weights and are not exactly centered on the net weight levels given above.

The gravimetric dispenser first dispenses $\alpha\%$ ($0 < \alpha\% < 100\%$) of the target net weight by the volumetric method, and this amount is represented by the coarse weight. The dispensed particles were weighed to determine the mass needed to bring the weight of the particles up to the target net weight. The dispenser trickled in enough particles until the net weight was 100% of the target net weight. Both the coarse weights (volumetric method) and the final weights were recorded as the number of milligrams

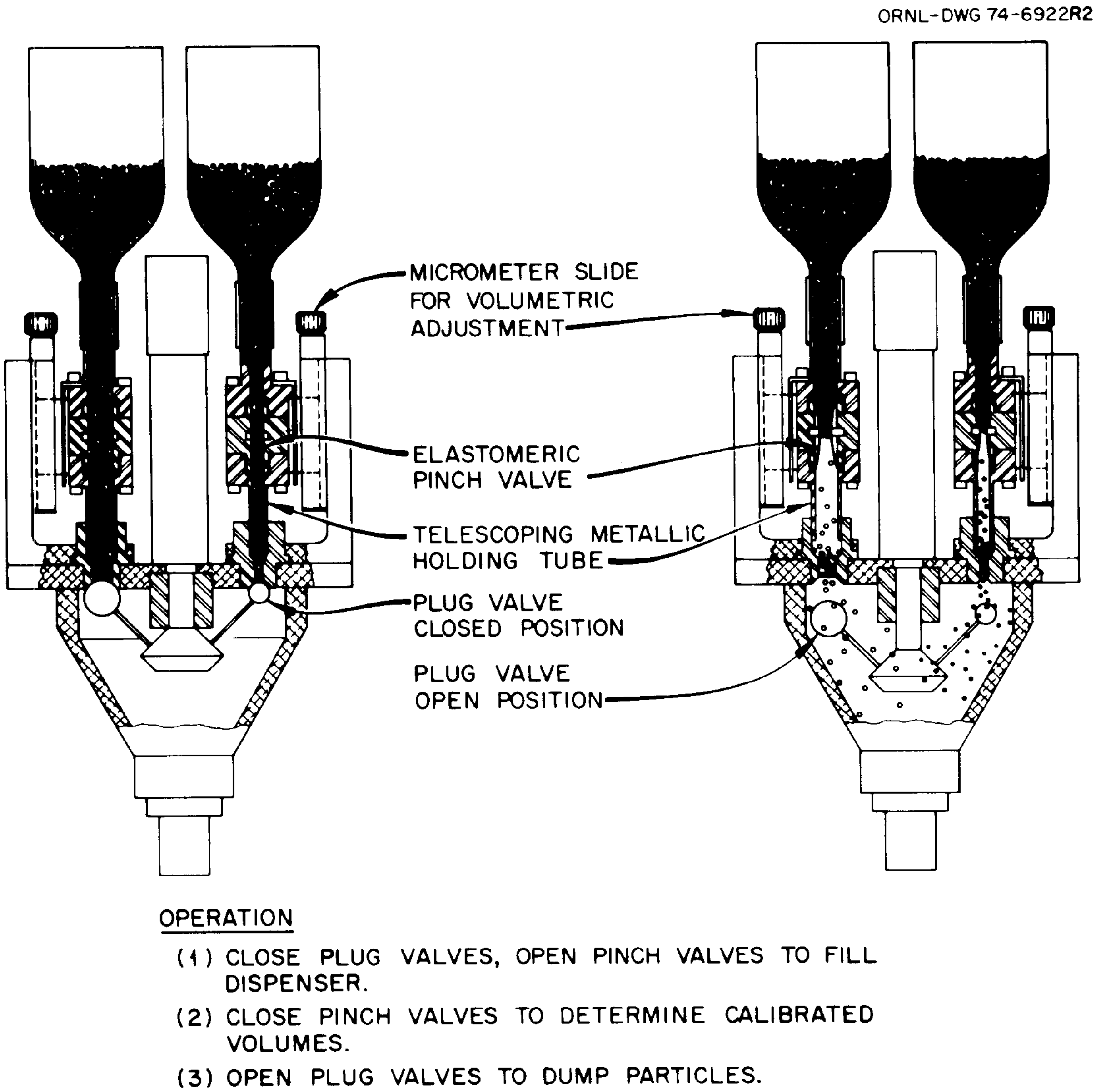

Fig. 8. Volumetric dispenser with a metallic telescoping holding tube.

above or below the target net weight. For the gravimetric method the coarse weights are only relative weights of α% of the target net weights; the final weights should all be zero.

The data from the experiment are tabulated in Table A-4 in the Appendix, and summary statistics of the coarse and final weights are given in Table 1.

Table 1. Mean and standard deviations of the final weights and coarse weights of the particle-dispensing experiment[a]

Weights		Gravimetric, mg		Volumetric, mg	
		High net weight	Low net Weight	High net weight	Low net weight
Final	Mean	11.15	−11.85	34.85	18.00
	Standard deviation	28.56	11.41	16.01	11.34
Coarse	Mean	−21.85	−94.55		
	Standard deviation	15.80	11.46		

[a]Positive and negative values refer to the number of milligrams above or below the target net weight.

Data Analysis

Table 1 shows that the standard deviations of the low-net-weight gravimetric runs and the two volumetric runs are in the same range with values of 11.41, 16.01, and 11.34 mg. In addition, the two volumetric coarse weights for the gravimetric method have standard deviations of 15.80 and 11.46 mg. This similarity of standard deviation values indicates that the weight of all the particles dispensed by the five discharges have the same spread. Only the high-net-weight gravimetric method has a standard deviation out of the range of the other five values, with a standard deviation 1.8 to 2.5 times larger than any of the other five values.

To compare the data for the final net weights for the two gravimetric runs and the two volumetric runs, the final net weights are standardized so that all four runs have a mean of zero. The final weights are standardized by

$$\text{standardized final weights} = \text{final weights} - \text{mean}$$

and are plotted as box plots in Fig. 9.

Figure 9 shows the box plot for the high-net-weight gravimetric method to be quite different from those for the other three runs. The high-net-weight gravimetric method has a much larger spread of data than do any of the other runs, as shown by the length of its box, as well as being skewed, because the median is well below the zero value. The plots for the other three runs show boxes of similar size and median values very close to zero, indicating that the final weights of the three are symmetrically distributed about their mean value.

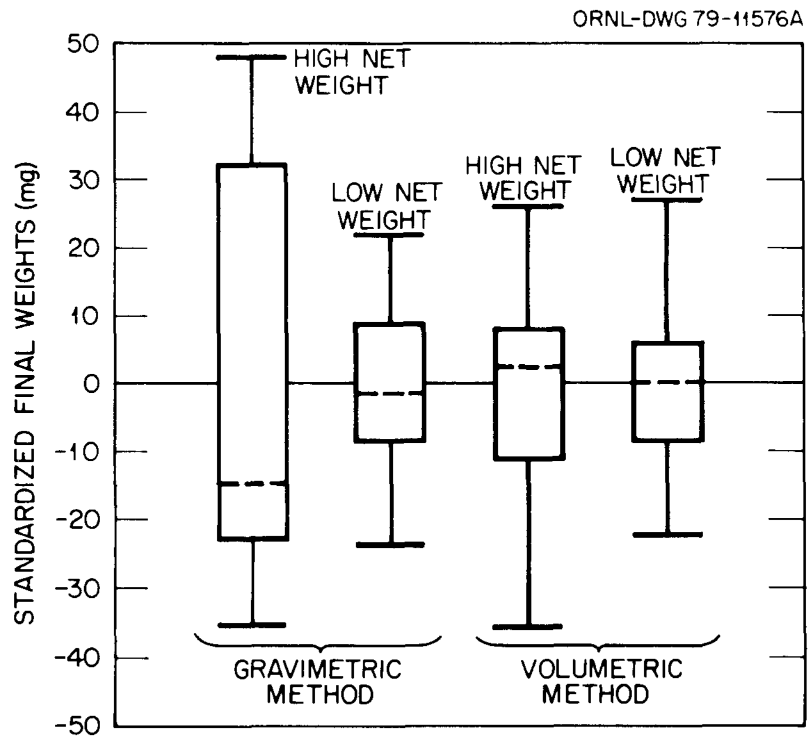

Fig. 9. Box plots of the standardized final weights of the four particle-dispensing runs.

To compare further the low-net-weight gravimetric run with the two volumetric runs, the empirical cumulative distribution function for the standardized final weights of the three runs is plotted in Fig. 10. The maximum vertical distance among the three empirical distribution functions occurs at a standardized final weight value of 1, and this value (0.25) can be used for the Birbaum-Hall test[4] to test the null hypothesis that the three distributions are identical against the alternative hypothesis that at least two of the distributions are different. Because the maximum vertical distance is well below the maximum critical value of 0.40 for the 10% significance level, the distributions of the final weights for the low-net-weight gravimetric run, the low-net-weight volumetric run, and the high-net-weight volumetric run are not shown to be different. In addition, the Shapiro-Wilk[5] test for normality has the value $W = 0.95$ for the low-net-weight gravimetric run and the value $W = 0.96$ for the two volumetric runs, which are greater than the critical value of $W = 0.92$ at 10% significance level. Therefore, these data do not indicate nonnormal distribution of the final weights for these three runs.

To examine the difference between the high- and low-net-weight gravimetric runs, the weights of the particles trickled to obtain the final net weights are plotted against the coarse weights in Fig. 11. An ideal plot would have the data on a decreasing 45° line from the upper left-hand corner to the lower right-hand corner. However, Fig. 11 does not show the ideal case. For the high-net-weight gravimetric run, the coarse weights range from −60 to −1 mg below the target value, but the amount trickled to obtain the target value is approximately a constant 79 mg for −60 mg ⩽ coarse weight ⩽ −25 mg and a constant 2 mg for −25 mg < coarse weight ⩽ 0. For the low-net-weight gravimetric run, the amount of trickled particles is approximately a constant 87 mg (i.e., ignoring the two values at coarse weights −68 and −72 mg) for −110 mg ⩽ coarse weight ⩽ −81 mg. Combining these two results shows that the gravimetric method trickles a fairly constant amount of particles (about 84 mg) if the coarse weight is more than 25 mg below the target value and trickles almost no particles if the coarse weight is less than 25 mg below the target value. The addition of the trickler device does

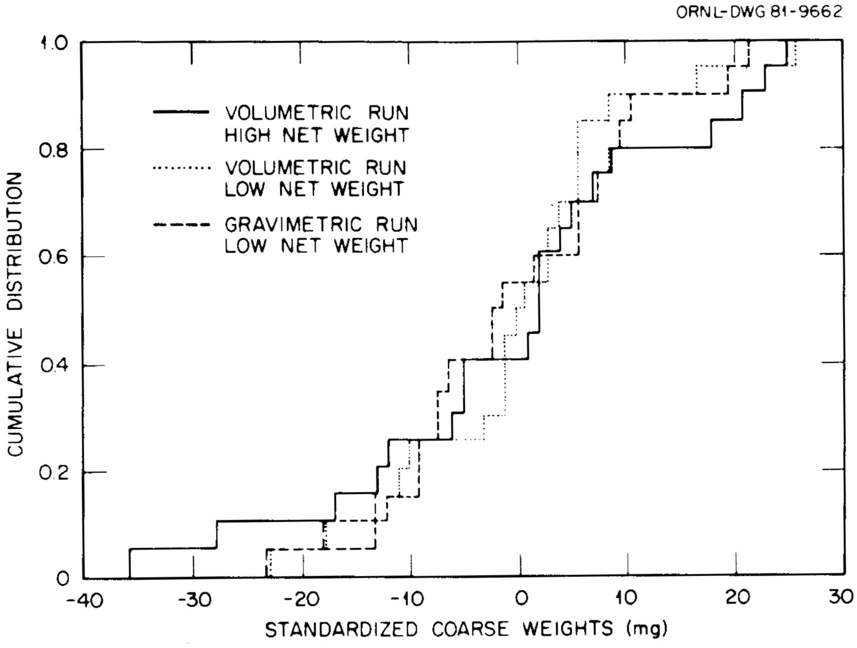

Fig. 10. Empirical cumulative distribution functions for the standardized final weights of the low-net-weight gravimetric run (dashed line), the low-net-weight volumetric run (dotted line), and the high-net-weight volumetric run (solid line).

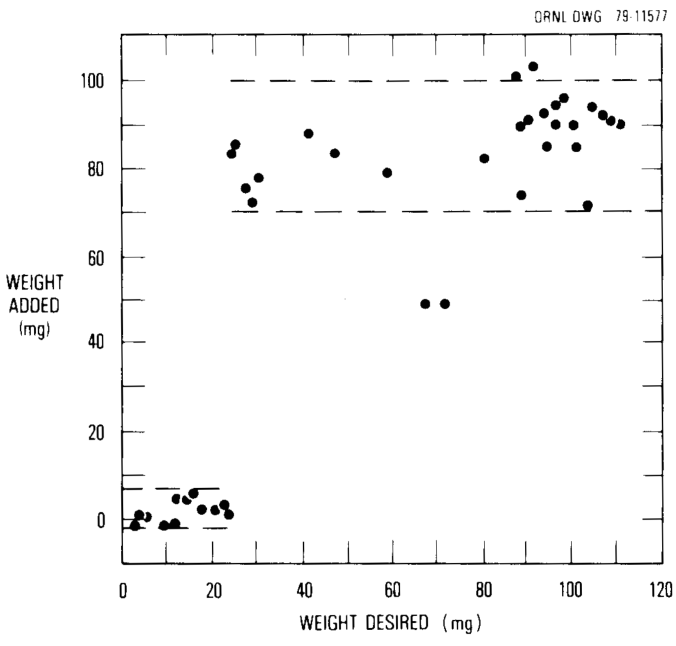

Fig. 11. Weight added by trickler device versus coarse weight for low-net-weight gravimetric run (open circle) and high-net-weight gravimetric run (closed circle).

not improve on the volumetric method. In fact, for the high-net-weight run, the trickler device actually gives worse results than would be expected from using the volumetric method. For the low-net-weight gravimetric run, a constant amount of particles was added to the volumetric coarse weights by the trickler device, which would make the standard deviation of the coarse weights (11.46) and the final weights (11.41) about the same value. Adding a constant amount of particles to the volumetric coarse weights also explains why the distribution of the standardized final weights for the low-net-weight run is the same as the distributions of the standardized final weights for the two volumetric runs because all three runs are essentially volumetric runs that are shifted to different locations. These runs do show that whether the net weight is the low value or the high value does not influence the final weight distribution.

To confirm that the behavior of the gravimetric method is a result of the trickler device, the standardized coarse weights are examined in the box plots in Fig. 12. These two plots show that the coarse weights for the gravimetric runs are symmetrical, with about the same spread. The empirical cumulative distribution functions for the standardized coarse weights are given in Fig. 13. The maximum vertical distance between the two distributions occurs at a standardized coarse weight of 5.7 mg and has a value of 0.20. To test that the two distributions are the same by using the Smirnov[4] two-sample test, the maximum vertical distance is compared with the 10% critical value of 0.35. Because the maximum vertical distance is less than the critical value, no difference is detectable between the distributions at the 10% significance level. The Shapiro-Wilk test for normality has the value of $W = 0.96$ for the high-net-weight gravimetric run and $W = 0.94$ for the low-net-weight gravimetric run. Because both values are greater than the 10% significance value $W = 0.92$, these data do not indicate any nonnormality for the volumetric coarse weights. The difference between the two gravimetric runs is therefore a result of the behavior of the trickler device.

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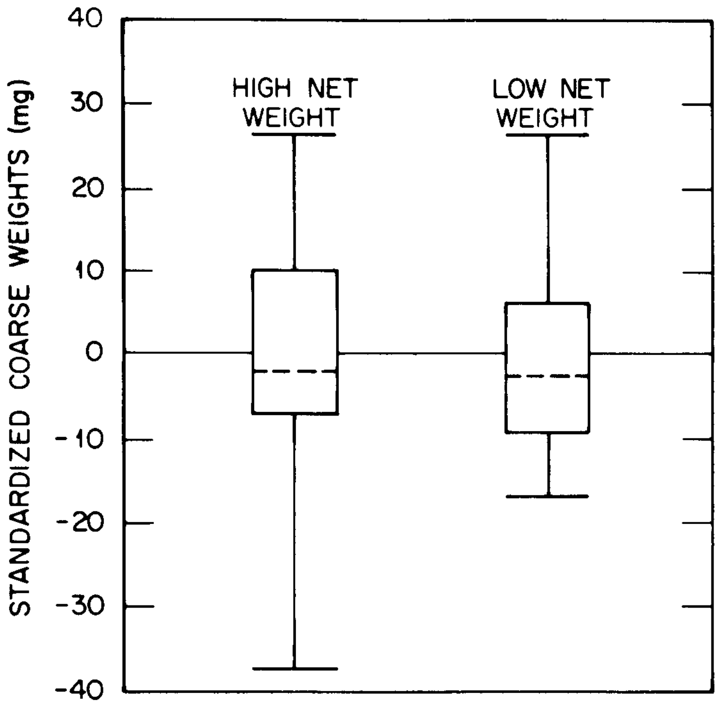

Fig. 12. Box plots for standardized coarse weights.

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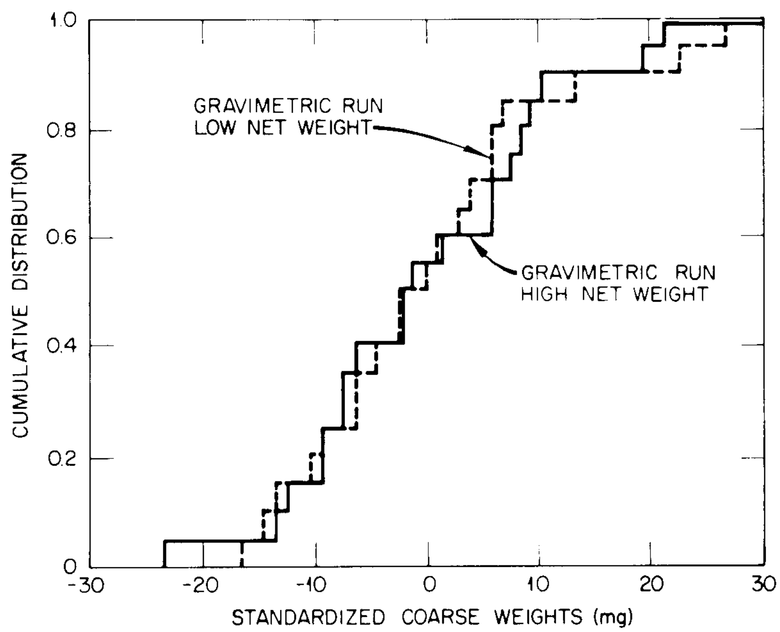

Fig. 13. Empirical cumulative distribution function for the standardized coarse weights of the low-net-weight gravimetric run (dashed line) and the high-net-weight gravimetric run (solid line).

Conclusions

This experiment to characterize the volumetric and gravimetric methods on General Atomic Company's automatic particle dispensing system leads to the following conclusions.

1. The high- and low-net-weight levels affect neither the distribution of the final weights of the two volumetric runs nor the coarse weights of the two gravimetric runs.

2. The weight of the particles from the volumetric method of dispensing particles has a normal distribution about the target value, with an estimated standard deviation of 13.8 mg (estimated from the pooled standard deviations of the two volumetric runs and the two coarse weight runs).

3. The trickler device used for the gravimetric method is not sensitive enough to improve on the volumetric method. The trickler device appears to add a constant amount (~84 mg) of particles when the amount required is in the range of 25 to 110 mg and does not add particles if less than 25 mg is required.

DRIFT BEHAVIOR OF THE VOLUMETRIC DISPENSER

An experiment was conducted to characterize the long-term behavior of volumetrically dispensed fuel particles. The automatic dispensing system was used to dispense 520 charges of each of three types of fuel material (fissile, fertile, and shim) at either a low net weight or a high net weight. The two different runs for each of the three fuel materials were replicated for a total of 12 experimental runs. The hopper of the dispenser was filled with enough particles that the hopper level remained approximately constant during each run. To avoid particles settling in the hopper, once each run was started, it was continued without breaks until completion. The 12 experimental runs listed in Table 2 are identified by the run number and can be divided into set 1 (runs 1 through 6) and set 2 (runs 7 through 12). The first set of runs represents the low and high net weights for the three particle types. The second set of runs is a replicate of the first set except that the

Table 2. Long-term drift experiment

Run	Material	Net weight of dispensed particles (g)	Number of dispensed charges
1	Fissile	0.75	520
2	Fissile	3.25	520
3	Fertile	4.25	520
4	Fertile	7.75	520
5	Shim	1.00	520
6	Shim	5.00	520
7	Fissile	3.25	520
8	Fissile	0.75	520
9	Fertile	7.75	520
10	Fertile	4.25	520
11	Shim	5.00	520
12	Shim	1.00	520

high-net-weight runs are listed before the low-net-weight runs. Each set of runs was performed in random order to minimize the effect of correlation between runs.

Each experimental run consisted of 520 charges dispensed by the volumetric dispensing method at a fixed net weight. The actual weight of each dispensed charge was measured, and the difference between the actual weight and the fixed net weight was recorded. The 6240 data points were tabulated on a computer tape described in Table A-5 in the Appendix.

Summary statistics for the 12 experimental runs are given in Table 3. This table shows that the repeatability of each of four runs on any one of the three particle types is fairly constant. For example, the ranges of the standard deviations are (1) 4.01 to 4.81 for fissile triso-coated particles, (2) 10.74 to 14.31 for fertile biso-coated particles, and (3) 29.29 to 33.69 for carbon shim particles. No trends are apparent that the standard deviations increase or decrease from low- to high-net-weight runs. The large standard deviations for the shim particle runs are caused

Table 3. Summary statistics for weight differences from the long-term drift experiment

Particle type	Fissile				Fertile				Shim			
Net weight	Low (0.75 g)		High (3.75 g)		Low (4.25 g)		High (7.75 g)		Low (1.00 g)		High (5.00 g)	
Run Number	1	8	2	7	3	10	4	9	5	12	6	11
Number of charges	520	520	520	520	520	520	520	520	520	520	520	520
Mean	13.20	11.51	10.03	10.19	24.74	11.44	29.65	17.70	0.13	3.56	–18.77	–24.74
Standard error	0.21	0.18	0.21	0.21	0.61	0.47	0.63	0.61	1.39	1.36	1.48	1.28
Standard deviation	4.81	4.00	4.69	4.80	14.00	10.74	14.31	13.88	31.78	31.03	33.69	29.29
Minimum value	–2.00	–2.00	–5.00	–5.00	–23.00	–23.00	–12.00	–21.00	–120.00	–125.00	–143.00	–155.00
Maximum value	25.00	27.00	28.00	26.00	65.00	55.00	72.00	60.00	48.00	45.00	30.00	16.00

by the abnormally large (between 10 and 15%) shim weights are observed in each of the four runs. These large shim weights were caused by the tendency of the shim particles to plug the dispensing nozzle, which can be corrected by using a larger diameter nozzle. A histogram of the weight differences for each of the four shim runs was examined to eliminate those values, which appeared to be outliers. The range of standard deviations for the shim data without the outliers is reduced to 12.30 to 14.47. The modified shim data were used for the analysis that follows.

Data Analysis

To examine the drift behavior of the dispensing system, a linear regression of weight differences as a function of the sequence number was fitted to the data by the least squares method. The intercept and slope estimates of these 12 lines are given in Table 4, which shows eight of the slopes as being different from zero at the 5% significance level. All the regression lines are poor models for predicting weight differences, with the best model accounting for only 23% of the total variation between the observed values and the mean value. However, if the weight differences increased as estimated by the slopes in Table 4, the number of charges needed to reach 1% of the net weight from the origin would be a minimum of 309 charges for low-net-weight shim run 5 and a maximum of 45,588 charges for the high-net-weight fertile run 4. None of the runs went beyond practical limits until a substantial number of charges were dispensed.

The actual behavior of the weight differences does not increase purely as a linear function of sequence numbers but varies sinusoidally, with slight increases in sequence numbers. To display this characteristic behavior, the moving average of the weight differences was plotted against the sequence numbers (Fig. 14) for the two low-net-weight fissile particle runs. The moving average over 12 charges characterized the weight differences much better than did the moving average over 4 charges but did not appear to be much different from the moving average over 20 charges. Therefore, the moving averages over 12 charges are used to display the behavior of the weight differences for the 12 experimental runs in

Table 4. Intercept and slope values for a linear relation between weight difference and sequence number

Particle type	Fissile				Fertile				Shim			
Net weight	Low (0.75 g)		High (3.75 g)		Low (4.25 g)		High (7.75 g)		Low (1.00 g)		High (5.00 g)	
Run number	1	8	2	7	3	10	4	9	5	12	6	11
Number of charges	520	520	520	520	520	520	520	520	469	443	441	471
Intercept	9.78	11.20	7.70	7.23	13.10	10.16	29.21	15.85	0.78	17.04	–8.10	–24.02
Intercept standard error	0.39	0.35	0.40	0.39	1.08	0.94	1.26	1.22	1.28	1.19	1.15	1.27
Slope	0.0131	0.0012	0.0090	0.0114	0.0447	0.0049	0.0017	0.0071	0.0324	–0.0092	0.0080	0.0285
Slope standard error	0.0013	0.0012	0.0013	0.0013	0.0036	0.0031	0.0042	0.0040	0.0042	0.0040	0.0039	0.0042
Probability of a non-significant slope	0.0001	0.30	0.0001	0.0001	0.0001	0.12	0.69	0.08	0.0001	0.02	0.04	0.0001

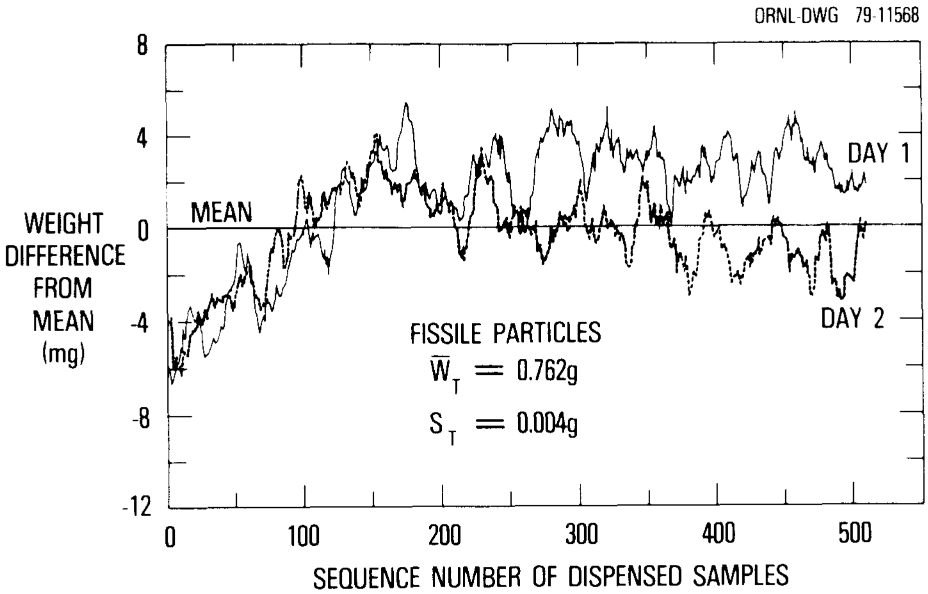

Fig. 14. Moving average over 12 charges for the two low net fissile particle runs.

Figs. A-1 through A-6 in the Appendix. Each figure is a plot of the moving average of the weight differences versus sequence number for the two runs having the same type of particle and net weight.

The two fissile particle runs at low net weight are similar, with an increase from about 6 to 15 mg in the first 150 sequences. The weight differences are fairly constant over the remaining runs. The two high-net-weight runs are also similar, with an increase from 6 to about 14 mg over the total number of sequence numbers. The fertile particle runs at the low net weight behave in the same manner for the first 100 sequences, then diverge and run parallel about 20 mg apart for the remaining charges. The two fertile particle runs at the high net weight are not similar. Both the low- and high-net-weight runs for shim particles are similar, with the weight differences varying slightly around a constant level.

In all the figures, the scale of the weight difference is in milligrams, and some weight differences may be large because of the scale. None of the figures show the weight differences to be large enough to exceed practical limitations. During the actual process of fuel rod fabrication the weight of the fuel particles dispensed could be controlled by use of moving average control chart plots.[6,7]

Conclusions

The long-term drift experiment indicated that General Atomic Company's automatic volumetric dispensing system gives repeatable results with little or no drift behavior. The drift behavior is small enough that corrections need to be made only after a large number of particles have been dispensed, which can be accomplished by use of moving average control chart plots. The data for shim particles show a need to modify slightly the dispensing nozzle to prevent plugging by the shim particles.

OPERATING CHARACTERISTICS OF THE VOLUMETRIC DISPENSER

Because the HTGR fuel rods should be as uniform as possible, a study was made on how different operating conditions affected the operation of the elastomer tube volumetric dispenser. The main concern was whether or not the amount of fuel particles would change if the particle-dispensing machine was operated at different times.

The mass and volume measurements of Biso-coated fertile particles, uncoated ThO_2 kernels, and H-451A shim particles were individually examined to determine the effects of process variables on the elastomer tube volumetric dispensing machine. In each experiment, the particles of one of the three types were loaded into the dispensing machine hopper, and the hopper level was maintained at either a high or a low level. A pinch valve on the machine was set to dispense a fixed quantity of particles. The valve was opened and closed five consecutive times, and the volume and mass of the dispensed particles were measured after each opening. The pinch valve setting was changed to a new level, and five additional consecutive measurements were taken and repeated for five different pinch valve settings. The five repeated measurements at each setting were used to estimate the variance of the experimental random error. This estimate was very small because of the consecutive manner of taking the measurements.

While the same hopper level was maintained, the five consecutive volume and mass measurements were made at the five different pinch valve settings on three different occasions. The experiment was repeated, using a different hopper level.

The variables that were controlled for each of the three different volumetric dispensing experiments were

Controlled variable	Symbol	Level
Hopper level	*H*	Low and high
Run order	*R*	1, 2, and 3
Pinch value setting (cm)	*S*	2, 4, 6, 8, and 10

The three controlled variables are said to be nested because all the measurements at each level of a controlled variable were made while the level of the previous controlled variables remained fixed. Therefore, the run order is nested in hopper level because the measurements of all three run order levels were made at a fixed hopper level before changing to a different hopper level. Similarly, the pinch valve setting is nested in both the run order and the hopper level.

The data collected for the fertile particles, the ThO_2 kernels, and the H-451A shim particles are tabulated in Tables A-6, A-7, and A-8, respectively. In each experiment, 150 data points were measured, but the following point was eliminated for the fertile particle experiment because it had much larger mass and volume measurements than the other four repeated points.

Hopper level	Run order	Pinch valve setting (cm)	Mass of particles (g)	Volume of particles (cm^3)
Full	3	10	12.672	6.000

The reason for the higher values was the long inoperative time period between these and the previous measurements.

We made an initial examination by tabulating the means of the data for several combinations of the levels of the controlled variables. In Table 5 the data were averaged over the hopper levels and pinch valve settings for each run order. Table 5 shows small differences among the means of the measurements for the three runs. In fact, the differences

Table 5. Means and standard deviations (in parentheses) of the dispensed-particle data for each level of run order

Particle type	Measurement	Run 1	Run 2	Run 3
Fertile	Mass (g)	8.544 (2.639)	8.531 (2.611)	8.474 (2.581)
	Volume (cm^3)	4.039 (1.254)	4.040 (1.243)	3.996 (1.233)
Kernel	Mass (g)	19.490 (7.233)	19.489 (7.231)	19.529 (7.261)
	Volume (cm^3)	3.226 (1.223)	3.225 (1.217)	3.239 (1.222)
Shim	Mass (g)	3.101 (1.164)	3.102 (1.149)	3.099 (1.169)
	Volume (cm^3)	2.886 (1.092)	2.893 (1.081)	2.908 (1.117)

among the three means occur in the second or third decimal place. The large standard deviations for the measurements in each run are caused by averaging over the levels of the other two controlled variables.

The means and standard deviations for each hopper level averaged over the run orders and pinch valve settings are given in Table 6. Again the differences between the means for low- and full-hopper-level measurements occur in the second decimal place. The large standard deviations for the measurements in each level and in each level of run order are primarily the results of averaging overall pinch valve settings. Obviously, the larger the pinch valve setting is, the more particles are dispensed.

The increases in the mass and volume measurements with the increases in pinch valve settings are shown in Figs. 15 and 16 by plotting the means of the measurements at each pinch valve setting for the fertile, kernel, and shim particles. The standard deviations of the mass measurements at each pinch valve setting range from 0.048 to 0.094, 0.026 to 0.058, and 0.025 to 0.049 for the fertile, kernel, and shim particles, respectively.

Table 6. Means and standard deviations (in parentheses) of dispensed-particle data for each hopper level

Particle type	Measurement	Low hopper level	Full hopper level
Fertile	Mass (g)	8.500 (2.582)	8.533 (2.622)
	Volume (cm^3)	4.036 (1.237)	4.014 (1.242)
Kernel	Mass (g)	19.517 (7.221)	19.487 (7.213)
	Volume (cm^3)	3.230 (1.220)	3.230 (1.213)
Shim	Mass (g)	3.082 (1.149)	3.120 (1.164)
	Volume (cm^3)	2.890 (1.094)	2.900 (1.091)

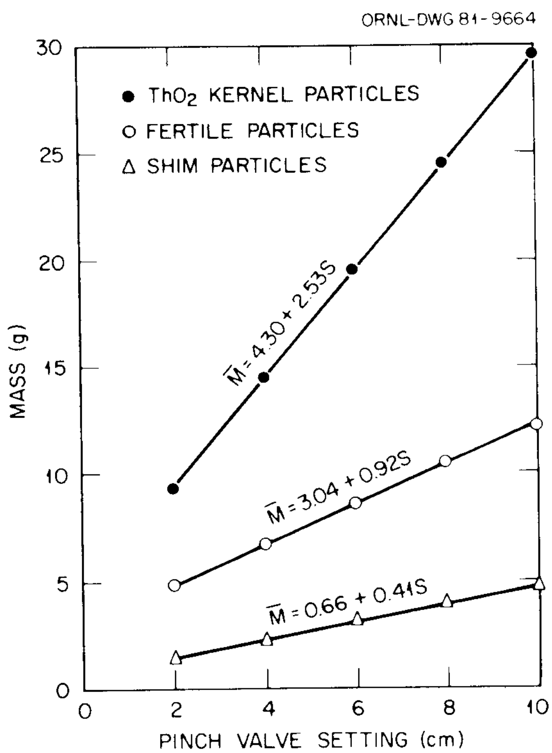

Fig. 15. Means of the mass measurements M at each pinch valve setting S.

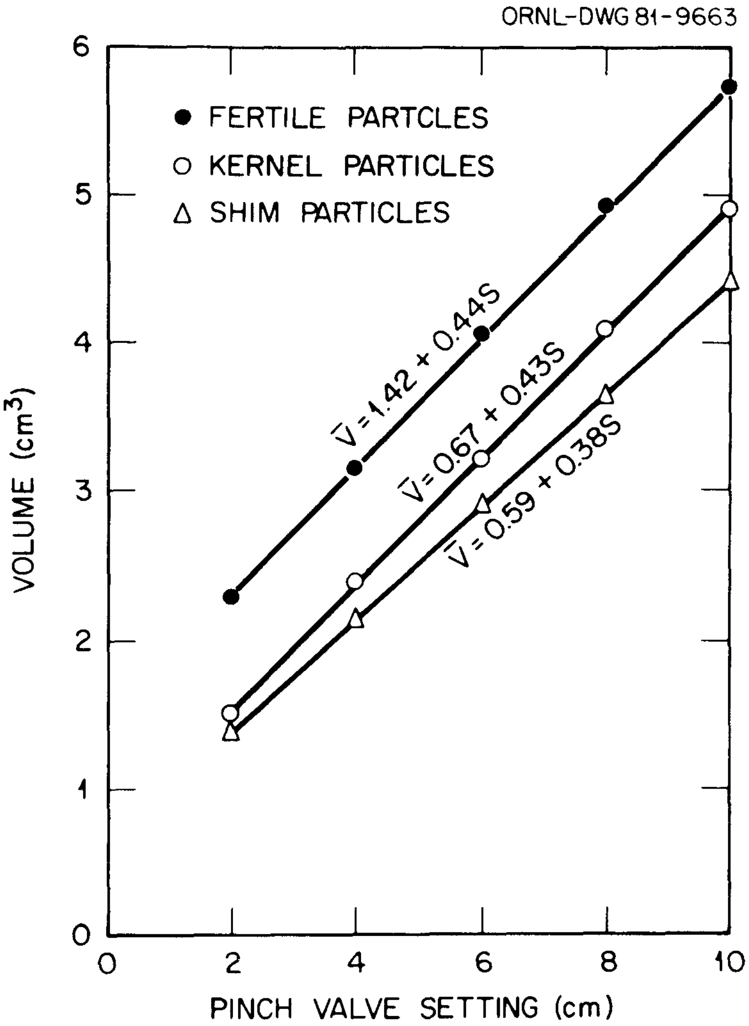

Fig. 16. Means of volume measurements V at each pinch valve setting S.

These standard deviations are small compared with the standard deviations among run order and between hopper level, which indicates that the pinch valve settings account for most of the variation in the mass measurements.

The ranges over pinch valve settings for the volume measurements are 0.027 to 0.037, 0.000 to 0.029, and 0.026 to 0.050 for the fertile, kernel, and shim articles, respectively. Again these small standard deviations indicate that the pinch valve settings account for most of the variation in the volume measurements. Neither the standard deviations for the mass measurements nor those for the volume measurements indicate any heterogeneity of error variance.

Data Analysis

To analyze the data for the effects of the controlled variables, the measurement responses are modeled as linear functions of pinch valve settings. The intercept and the slope of the linear model are indexed to show the effects of hopper level and run order. Let y_{ijkh} represent the response, either mass or volume, for the hth, h = 1, 2, 3, 4, 5; repeated measurement of the kth, k = 1, 2, 3, 4, 5; pinch value setting nested in the jth, j = 1, 2, 3; run order nested in the ith, i = 1, 2; hopper level. The analysis of variance (ANOVA) model used to study the variation in the response resulting from the different controlled variables is

$$y_{ijkh} = u + H_i + (RH)_{ij} + \beta_{ij}S_k + (\text{RANDOM ERROR})_{ijkh} \text{ .}$$

This linear model has the intercept term as a sum of an overall mean u, a hopper level effect H_i, and a run order effect nested within hopper level $(RH)_{ij}$. The slope β_{ij} is indexed by the hopper level effect and the run order effect nested within hopper level. To estimate the slope and intercept terms, the least squares method is used. This method estimates the terms in the ANOVA model to minimize the sum of squared errors SSE:

$$\text{SSE} = \sum_{i,j,k,h} (\text{RANDOM ERROR})^2_{ijkh} \text{ .}$$

If the RANDOM ERROR variables are assumed to be independent and are identically distributed as a normal distribution with mean zero and constant variance σ^2, the effects of the controlled variables can be statistically tested by using standard ANOVA methods.[8] The amount of the total variation accounted for by the ANOVA model is more than 99.9% in each case. By using the SSE and the associated degrees of freedom (d.f.) (d.f. = number of data points — number of estimated parameters), the variance term of the RANDOM ERROR variables σ^2 can be estimated by

$$\sigma^2 = SSE/d.f. \; .$$

These estimates are given in Table 7. The variance estimates are very small; therefore, even small differences among the levels of an effect will be significant when they are compared with the estimated RANDOM ERROR variance. The estimated RANDOM ERROR variances are small because of the consecutive manner in which the five measurements were made at each pinch valve setting.

Table 7. Estimates of the variance of the RANDOM ERROR

	Fertile particles	Kernel particles	Shim particles
Mass measurement	3.25×10^{-3}	1.29×10^{-3}	0.77×10^{-3}
Volume measurement	1.49×10^{-3}	0.62×10^{-3}	0.85×10^{-3}

To examine the effects of hopper level and run order on the slope of the ANOVA model, the SSEs for ANOVA models with three different slopes are calculated, whereas the intercept terms remain the same in each model. Model 1 has the slope with no index β and represents a constant slope for each hopper level and run order. Model 2 has the slope index only by hopper level β_i and represents a slope that is different for each hopper level but is constant over the three run orders nested within the hopper level. Model 3 is the ANOVA model with slope β_{ij} that changes for each hopper level and run order. Using these three models, the following hypotheses can be tested with the *F*-statistic:[9]

Model 1 versus Model 2 — no significant effect from hopper level on the slope and

Model 2 versus Model 3 — no significant effect from run order within each hopper level on the slope.

The calculated *F*-values for these two hypotheses are given in Table 8 with the corresponding probabilities of getting the calculated *F*-value, assuming that the hypotheses are true. If the probability of a calculated *F*-value's occurring is less than 0.05, the slopes are significantly different at the 5% significance level.

Table 8. *F*-values for the effect of hopper level and run order on the slope of pinch valve setting with corresponding probabilities (in parentheses) of getting the calculated *F*-value, assuming no effects

Particle type	Measurement	Hypothesis: Effect from hopper level	Hypothesis: Effect from run order
		$\beta_1 = \beta_2 = \beta$	$\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ and $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$
Fertile	Mass	36.12 (<0.001)	2.57 (0.04)
	Volume	4.57 (0.03)	0.96 (0.43)
Kernel	Mass	1.90 (0.17)	6.19 (<0.001)
	Volume	2.80 (0.10)	0.36 (0.84)
Shim	Mass	10.10 (0.002)	4.05 (0.004)
	Volume	0.28 (0.60)	9.92 (<0.001)

The estimated value of the slopes for models 1, 2, and 3 are given in Table 9 for the mass measurements and in Table 10 for the volume measurements. The maximum absolute difference between the estimated slopes for the two different hopper levels is only 0.0203 for the fertile mass measurements. But this difference is highly significant, $F(1,141) = 36.12$, because of the small estimated random error variance. The hopper level is a significant effect at the 5% level on the slopes of the pinch valve settings for the fertile and shim mass measurements and the volume

Table 9. Slope estimates for models 1, 2, and 3 for mass measurements

Particle type	Slope estimates	Slope estimate: Low hopper level, Run order 1	2	3	Full hopper level, Run order 1	2	3	Standard error of estimates
Fertile	β_{ij}	0.9161	0.9003	0.9036	0.9311	0.9261	0.9236	0.0040
	β_i		0.9067			0.9270		0.0024
	β			0.9167				0.0019
Kernel	β_{ij}	2.5312	2.5346	2.5421	2.5315	2.5268	2.5405	0.0025
	β_i		2.5360			2.5329		0.0016
	β			2.5345				0.0011
Shim	β_{ij}	0.4048	0.3985	0.4068	0.4098	0.4048	0.4115	0.0020
	β_i		0.4087			0.4034		0.0012
	β			0.4061				0.0009

Table 10. Slope estimates for models 1, 2, and 3 for volume measurements

Particle type	Slope estimates	Slope estimate: Low hopper level, Run order 1	2	3	Full hopper level, Run order 1	2	3	Standard error of estimates
Fertile	β_{ij}	0.4382	0.4310	0.4330	0.4390	0.4385	0.4391	0.0027
	β_i		0.4341			0.4389		0.0016
	β			0.4364				0.0009
Kernel	β_{ij}	0.4290	0.4270	0.4290	0.4270	0.4250	0.4260	0.0018
	β_i		0.4283			0.4260		0.0010
	β			0.4272				0.0007
Shim	β_{ij}	0.3830	0.3783	0.3910	0.3808	0.3780	0.3905	0.0021
	β_i		0.3841			0.3831		0.0013
	β			0.3836				0.0009

measurements for fertile particles. No hopper level effect on the slopes is evident for either of the two kernel measurements or for the shim volume measurements.

The effect of run order within each hopper level is significant at the 5% level on the slopes of the pinch valve settings for the mass measurements of all three particle types and the volume measurements of the shim particles. The slopes for the volume measurements of the fertile particles and kernel particles are not affected by different run orders.

The slopes of the pinch valve settings for the kernel volume measurements affected neither by the different hopper levels nor by the different run order within hopper levels. The remaining slopes are affected by either the different hopper levels or the different run order within the hopper level.

To test the effects of hopper level and run order within hopper level on the intercept, the effects must be defined in terms of functions that can be estimated from the data. The hopper level effect is defined as the overall difference between the full and low hopper level plus the average difference of the sum of the effects of the full and low hopper level for each run order. This effect is expressed in terms of the model parameters as

$$\text{HOPPER LEVEL EFFECT} = (H_2 - H_1) + 1/3[(RH)_{11} - (RH)_{21} + (RH)_{12} - (RH)_{22} + (RH)_{13} - (RH)_{23}] \;.$$

The hypothesis that is tested is H_0: HOPPER LEVEL EFFECT = 0. The F-values for this hypothesis and the corresponding probabilities of getting the calculated F-values, assuming the hypothesis is true, are given in Table 11. For the two fertile measurements, the hopper level does not show a significant effect at the 5% significance level. However, the F-values are large enough that the hopper level effect would be a significant effect at the 10% significance level. For the two measurements for the kernel and shim particles, the F-values are small enough that the hopper level effect is not significant either at the 5 or 10% significance level.

Table 11. F-values for H_0: HOPPER LEVEL EFFECT = 0 with corresponding probabilities (in parentheses) of getting the calculated F-values, assuming the hypothesis is true

Measurement	F-value		
	Fertile particle	Kernel particle	Shim particle
Mass	3.22 (0.08)	0.76 (0.38)	0.38 (0.52)
Volume	3.47 (0.06)	2.16 (0.14)	2.13 (0.15)

To test the effect of the run order on the intercept, the differences between run orders at each level of the hopper level variable are simultaneously tested to be zero. In terms of the parameters of the ANOVA model, the run order effect hypothesis is

$$H_0: \left.\begin{matrix} (RH)_{11} - (RH)_{12} \\ (RH)_{12} - (RH)_{13} \\ (RH)_{21} - (RH)_{22} \\ (RH)_{22} - (RH)_{23} \end{matrix}\right\} = 0$$

The F-values for this hypothesis with corresponding probabilities of getting the calculated F-value, assuming the hypothesis is true, are tabulated in Table 12. From Table 12, the run order effect on the intercept is seen not to be significant for the two measurements for fertile particles and kernels at the 5% significance level. The run order effect on the intercept of the two shim particle measurements, however, is highly significant.

A summary of the analysis of the effects of the controlled variables is given in Table 13.

The ANOVA model for the volume measurements for the kernels is not affected by the hopper level or by the run order within each hopper level. The other five ANOVA models have either the intercept or the slope affected by the hopper level or the run order within the hopper

Table 12. *F*-Values for H_0: RUN ORDER EFFECT = 0 with corresponding probabilities (in parentheses) of getting the calculated *F*-Value, assuming the hypothesis is true

Measurement	*F*-value		
	Fertile particle	Kernel particle	Shim particle
Mass	1.84 (0.13)	2.20 (0.07)	4.19 (0.002)
Volume	0.73 (0.57)	0.56 (0.69)	5.69 (0.001)

Table 13. Summary of the significant controlled variables on the intercept and slope of the ANOVA model at the 5% significance level

Particle type	Measurement	Intercept		Slope	
		Hopper level	Run order	Hopper level	run order
Fertile	Mass	No	No	Yes	Yes
	Volume	No	No	Yes	No
Kernel	Mass	No	No	No	Yes
	Volume	No	No	No	No
Shim	Mass	No	Yes	Yes	Yes
	Volume	No	Yes	No	Yes

level. Some of the effects are small in absolute value but are significant because of the small estimated variance of the experimental error. This estimated error is based on the five consecutive measurements and represents the error of reproducing the mass and volume measurements by consecutively opening and closing a valve. Because the estimated error variance was considered to be an underestimate of the experimental error, the data were analyzed again by the same methods, using the average values of each of the five consecutive measurements. A summary of the analysis in Table 14, using the means of the five measurements, shows that none of the intercepts of the six ANOVA models are affected by either hopper level

Table 14. Summary of the analysis on the means of the repeated observations (significant controlled variables at the 5% significance level)

Particle type	Measurement	Intercept		Slope	
		Hopper level	Run order	Hopper level	run order
Fertile	Mass	No	No	Yes	No
	Volume	No	No	No	No
Kernel	Mass	No	No	No	Yes
	Volume	No	No	No	No
Shim	Mass	No	No	No	No
	Volume	No	No	No	Yes

or by run order within hopper level. The hopper level effect is only significant at the 5% level for the slope of the mass measurements for fertile particles, and the run order effect is significant for the mass measurement of the kernel particles and the volume measurement of the shim particles. The three ANOVA models for fertile volume measurements, kernel volume measurements, and shim mass measurements are not affected by either the hopper level or run order within the hopper level.

Conclusions

Mass measurements and volume measurements of fertile, kernel, and shim particles were analyzed to determine the effect of hopper level and run order on the operation of a fuel particle-dispensing machine. Except for the volume measurements of the kernel particles, the hopper level and run order were shown to have significant effects at the 5% level on either the intercept or slope terms of the linear ANOVA model used to describe the data. These significant effects result from comparing the variations of the intercept and slope terms resulting from the two variables with the error variances estimated from consecutive repeated measurements. The error variances are considered to be underestimated, and these underestimations may have caused some false significant effects.

A subsequent analysis by use of error variances estimated from the means of the repeated observations shows that hopper level and run order do not affect the intercept terms and are only significant effects at the 5% level on the slopes for three cases. The hopper level affected the slope for the fertile mass measurements, and the run order affected both the slopes for kernel mass measurements and the shim volume measurements.

SUMMARY

The gravimetric method should repeatedly dispense coated particles of nuclear material to an exact predetermied weight. The repeated use of the volumetric method will dispense coated particles of nuclear material having an average weight that is centered on a predetermined weight, but the particle weights will vary as a result of the calibration of dispensed volume with the weight. Although the exact weight of particles can be dispensed by the gravimetric method, the amount of nuclear material dispensed will vary from fabrication variations. A theoretical study shows that kernel weight represents only a small portion of the total particle variation. This study suggests that, although the ideal gravimetric method may be able to dispense particles with better weight precision than the volumetric method, the amount of nuclear material dispensed by the two methods should be comparable.

This hypothesis was tested by using both an ideal gravimetric dispenser and a production gravimetric dispenser. The variation comparisons with an ideal gravimetric dispenser showed good agreement for both particle weights and nuclear material assays for fissile particles but showed large differences in the variation of particle weights and nuclear material assays for fertile particles. A closer examination of the dispensing of fertile particles was then made using an automatic particle dispenser. This experiment showed that the volumetric dispenser could accurately dispense fertile particles but that the gravimetric trickler device caused a bias in dispensing fertile particles. The ideal and production gravimetric experiments indicated that the volumetric dispenser could perform as well as the gravimetric devices for dispensing particles of coated nuclear material.

Drift and operating characteristic experiments were conducted to characterize the performance and operating parameters of the volumetric dispenser. The long-term drift experiment showed that an automatic volumetric dispensing system gives repeatable results with little or no drift. The experiment to determine the effects of hopper level and run order on the elastomer tube volumetric dispenser showed that hopper level does affect the dispensing of fertile particles and that run order affects the dispensing of both fertile kernels and shim particles.

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APPENDIX

Table A-1. Characteristics of particles used to calculate estimated means and estimated variances of kernel and coating weights

Properties	A-615 Triso-coated fissile particles		Biso-coated fertile particles	
	Mean	Standard deviation	Mean	Standard deviation
Kernel diameter, µm	354.1	15.7	491.2	12.6
Kernel density, g/cm^3	3.076		9.950	
Buffer thickness, µm	51.0	12.3	77.4	12.2
Buffer density, g/cm^3	1.040		1.277	
Inner LTI coat, µm	30.7	3.3		
Inner LTI density, g/cm^3	1.857			
Silicon carbide coat, µm	29.5	1.5		
Silicon carbide density, g/cm^3	3.200			
Outer LTI coat, µm	32.4	4.2	88.9	7.7
Outer LTI density, μ/gm^3	1.910		1.842	

Table A-2. Fissile particle data for comparison of ideal gravimetric and volumetric dispensers

	Ideal gravimetric dispenser data		Volumetric dispenser data	
	Particle weight (g)	Uranium assay (g)	Particle (g)	Uranium (g)
	2.0055	0.3817	1.9872	0.3833
	2.0064	0.3830	1.9978	0.3862
	2.0042	0.3847	2.0113	0.3844
	2.0044	0.3799	1.9931	0.3832
	1.9995	0.3832	2.0122	0.3849
	1.9668	0.3815	1.9976	0.3845
	1.9784	0.3830	2.0069	0.3841
	1.9896	0.3860	2.0163	0.3879
	2.0061	0.3840	2.0024	0.3799
	1.9991	0.3835	1.9987	0.3821
	2.0064	0.3859	1.9929	0.3829
	2.0078	0.3853	2.0033	0.3872
	1.9995	0.3814	1.9994	0.3832
	2.0077	0.3856	2.0128	0.3872
	2.0068	0.3861	1.9847	0.3844
	2.0030	0.3867	2.0143	0.3855
	2.0039	0.3877	1.9936	0.3842
	2.0042	0.3857	1.9960	0.3834
	2.0105	0.3838	1.9882	0.3852
	2.0055	0.3875	1.9917	0.3831
	2.0029	0.3826	1.9945	0.3802
	1.9889	0.3823	2.0099	0.3881
	2.0063	0.3822	1.9993	0.3845
	2.0022	0.3843	2.0037	0.3845
	2.0043	0.3849	1.9867	0.3846
	2.0025	0.3792	1.9876	0.3832
	2.0034	0.3841	1.9969	0.3801
	2.0027	0.3809	2.0023	0.3818
	2.0180	0.3824	2.0141	0.3898
Number	29	29	29	29
Mean	2.0016	0.3838	1.9998	0.3843
Standard deviation	0.0098	0.0022	0.0093	0.0024

Table A-3. Fertile particle data for comparison of ideal gravimetric and volumetric dispensers

	Ideal gravimetric dispenser data		Volumetric dispenser data	
	Particle weight (g)	Uranium assay (g)	Particle (g)	Uranium (g)
	6.0022	3.30438	5.9989	3.30411
	5.9988	3.29506	5.9656	3.28232
	6.0183	3.30877	5.9775	3.29058
	6.0134	3.31255	5.9408	3.27177
	6.0200	3.31149	5.9252	3.25982
	6.0133	3.31132	6.0229	3.31378
	6.0089	3.30851	5.9830	3.29339
	6.0121	3.30710	5.9835	3.29576
	6.0099	3.30077	5.9527	3.27590
	6.0143	3.30780	6.0206	3.31536
	6.0002	3.30253	6.0301	3.31712
	6.0095	3.29831	6.0370	3.32169
	6.0066	3.30279	6.0016	3.30517
	6.0094	3.30965	5.9990	3.30279
	6.0073	3.30209	6.0025	3.30552
	6.0190	3.30895	6.0524	3.32907
	6.0197	3.30815	6.0349	3.32389
	6.0162	3.30798	5.9773	3.29383
	6.0078	3.30332	6.0229	3.32055
	6.0181	3.30710	6.0474	3.33241
	6.0204	3.30736	6.0406	3.32731
	6.0318	3.30068	6.0567	3.33645
	6.0211	3.30332	6.0020	3.30605
	6.0241	3.30253	6.0148	3.31387
	6.0241	3.30253	5.9832	3.29594
	6.0201	3.29866	6.0109	3.30851
	6.0170	3.29866	6.0364	3.32195
	6.0136	3.29304	6.0509	3.33215
	6.0146	3.29902	6.0604	3.33891
			6.0220	3.31316
Number	29	29	30	30
Mean	6.0142	3.3043	6.0085	3.3083
Standard deviation	0.0075	0.0050	0.0350	0.0196

Table A-4. Experimental data from particle dispensing experiment

	Run time			Recorded weight, mg	
		Volumetric run — low net weight			
Date	Hour	Min	Sec	Coarse	Final
61478	13	32	40	.	5
61478	13	32	48	.	18
61478	13	32	56	.	19
61478	13	33	4	.	24
61478	13	33	12	.	7
61478	13	33	20	.	17
61478	13	33	28	.	17
61478	13	33	36	.	44
61478	13	33	44	.	21
61478	13	33	52	.	-5
61478	13	34	1	.	21
61478	13	34	9	.	35
61478	13	34	17	.	24
61478	13	34	25	.	8
61478	13	34	33	.	22
61478	13	34	41	.	24
61478	13	34	49	.	17
61478	13	34	57	.	15
61478	13	35	5	.	0
61478	13	35	13	.	27
		Volumetric run — high net weight			
Date	Hour	Min	Sec	Coarse	Final
61478	14	27	39	.	7
61478	14	27	47	.	22
61478	14	27	55	.	56
61478	14	28	3	.	42
61478	14	28	11	.	58
61478	14	28	19	.	36
61478	14	28	27	.	40
61478	14	28	36	.	30
61478	14	28	44	.	44
61478	14	28	52	.	-1
61478	14	29	0	.	23
61478	14	29	8	.	18
61478	14	29	16	.	37
61478	14	29	24	.	39
61478	14	29	32	.	30
61478	14	29	40	.	29
61478	14	29	48	.	37
61478	14	29	57	.	53
61478	14	30	5	.	60
61478	14	30	13	.	37

Table A-4. (continued)

	Run time			Recorded weight, mg	
Gravimetric run — low net weight					
Date	Hour	Min	Sec	Coarse	Final
61478	16	53	45	-88	10
61478	16	53	59	-97	-6
61478	16	54	14	-99	-6
61478	16	54	28	-94	-4
61478	16	54	42	-92	8
61478	16	54	56	-111	-24
61478	16	55	10	-109	-21
61478	16	55	24	-101	-19
61478	16	55	38	-108	-19
61478	16	55	52	-101	-14
61478	16	56	7	-97	-10
61478	16	56	21	-105	-14
61478	16	56	35	-91	-3
61478	16	56	49	-81	-1
61478	16	57	3	-89	-2
61478	16	57	17	-95	-13
61478	16	57	31	-72	-25
61478	16	57	46	-68	-21
61478	16	58	0	-104	-35
61478	16	58	14	-89	-18
Gravimetric run — high net weight					
Date	Hour	Min	Sec	Coarse	Final
61478	15	40	4	-29	42
61478	15	40	18	-12	-7
61478	15	40	32	-21	-19
61478	15	40	46	-60	17
61478	15	41	0	-3	-4
61478	15	41	14	-31	46
61478	15	41	28	-48	34
61478	15	41	43	-24	-23
61478	15	41	57	4	5
61478	15	42	11	-28	46
61478	15	42	25	-16	-10
61478	15	42	39	-12	-12
61478	15	42	53	-42	44
61478	15	43	7	-1	0
61478	15	43	21	-25	57
61478	15	43	35	-6	-5
61478	15	43	50	-23	-19
61478	15	44	4	-26	58
61478	15	44	18	-19	-17
61478	15	44	32	-15	-10

The 6420 data points have been tabulated on tape number X22251. The data on the tape are in the following format:

Table A-5. Description of the data for the characterization of drift behavior of the volumetric dispenser experiment

Variable	Column
Run number	Col. 1–3 (right adjusted)
Particle type	Col. 5–11 (left adjusted) fissile, fertile, or shim
Net weight level	Col. 13–16 (left adjusted) high or low
Order of run	Col. 19–20 (right adjusted)
Date	Col. 22–27 month, day, and year
Hour	Col. 29–30
Minute	Col. 32–33
Second	Col. 35–36
Weight difference	Col. 39–42 (right adjusted), milligrams
Charge sequence number	Col. 78–80

The data tape can be read in a program by adding the following cards to the back of the program:

```
JOB CARDS
PROGRAM

END
/*
//GO.FT01F001 DD UNIT=TAPE9,DISP=(OLD,PASS),VOL=SER=X22251
//   LABEL=(1,SL),DSN=CKBDATA,
//   DCB=(RECFM=FB,LRECL=80,BLKSIZE=8000)
//
```

Table A-6. Mass and volume (cm^3) measurements for dispensed fertile particles

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	1	2	4.735	2.300
FULL	1	2	4.729	2.250
FULL	1	2	4.797	2.300
FULL	1	2	4.812	2.250
FULL	1	2	4.829	2.300
FULL	1	4	6.731	3.150
FULL	1	4	6.705	3.100
FULL	1	4	6.726	3.150
FULL	1	4	6.775	3.150
FULL	1	4	6.759	3.150
FULL	1	6	8.569	4.050
FULL	1	6	8.602	4.050
FULL	1	6	8.582	4.050
FULL	1	6	8.525	4.025
FULL	1	6	8.560	4.000
FULL	1	8	10.430	4.900
FULL	1	8	10.461	4.950
FULL	1	8	10.485	4.950
FULL	1	8	10.505	4.950
FULL	1	8	10.476	4.950
FULL	1	10	12.228	5.750
FULL	1	10	12.240	5.800
FULL	1	10	12.216	5.800
FULL	1	10	12.200	5.750
FULL	1	10	12.242	5.750
FULL	2	2	4.881	2.300
FULL	2	2	4.899	2.300
FULL	2	2	4.886	2.300
FULL	2	2	4.875	2.300
FULL	2	2	4.892	2.300
FULL	2	4	6.729	3.150
FULL	2	4	6.687	3.100
FULL	2	4	6.737	3.150
FULL	2	4	6.714	3.150
FULL	2	4	6.739	3.150
FULL	2	6	8.563	4.150
FULL	2	6	8.556	4.100
FULL	2	6	8.574	4.050
FULL	2	6	8.586	4.050
FULL	2	6	8.636	4.050
FULL	2	8	10.549	5.000
FULL	2	8	10.549	5.000
FULL	2	8	10.515	4.950
FULL	2	8	10.566	5.000
FULL	2	8	10.551	5.000
FULL	2	10	12.191	5.750
FULL	2	10	12.238	5.750
FULL	2	10	12.244	5.750
FULL	2	10	12.317	5.800
FULL	2	10	12.186	5.750
FULL	3	2	4.838	2.250

Table A-6. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	3	2	4.863	2.250
FULL	3	2	4.890	2.250
FULL	3	2	4.890	2.300
FULL	3	2	4.867	2.250
FULL	3	4	6.766	3.150
FULL	3	4	6.748	3.150
FULL	3	4	6.765	3.150
FULL	3	4	6.712	3.150
FULL	3	4	6.787	3.150
FULL	3	6	8.624	4.050
FULL	3	6	8.640	4.050
FULL	3	6	8.627	4.050
FULL	3	6	8.626	4.050
FULL	3	6	8.617	4.000
FULL	3	8	10.542	4.900
FULL	3	8	10.485	4.900
FULL	3	8	10.517	4.900
FULL	3	8	10.484	4.900
FULL	3	8	10.515	4.900
FULL	3	10	12.157	5.800
FULL	3	10	12.248	5.800
FULL	3	10	12.208	5.750
FULL	3	10	12.238	5.750
LOW	1	2	4.815	2.250
LOW	1	2	4.842	2.300
LOW	1	2	4.827	2.250
LOW	1	2	4.805	2.250
LOW	1	2	4.856	2.300
LOW	1	4	6.705	3.200
LOW	1	4	6.710	3.200
LOW	1	4	6.806	3.250
LOW	1	4	6.648	3.150
LOW	1	4	6.711	3.200
LOW	1	6	8.536	4.000
LOW	1	6	8.517	4.000
LOW	1	6	8.582	4.050
LOW	1	6	8.610	4.100
LOW	1	6	8.500	4.000
LOW	1	8	10.459	4.950
LOW	1	8	10.410	4.900
LOW	1	8	10.421	5.000
LOW	1	8	10.440	4.975
LOW	1	8	10.427	4.900
LOW	1	10	12.123	5.800
LOW	1	10	12.108	5.800
LOW	1	10	12.135	5.750
LOW	1	10	12.132	5.750
LOW	1	10	12.166	5.800
LOW	2	2	4.836	2.300
LOW	2	2	4.851	2.300
LOW	2	2	4.797	2.275

Table A-6. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
LOW	2	2	4.827	2.300
LOW	2	2	4.837	2.300
LOW	2	4	6.688	3.150
LOW	2	4	6.661	3.125
LOW	2	4	6.692	3.150
LOW	2	4	6.673	3.125
LOW	2	4	6.708	3.150
LOW	2	6	8.457	4.100
LOW	2	6	8.485	4.050
LOW	2	6	8.462	4.000
LOW	2	6	8.493	4.050
LOW	2	6	8.522	4.050
LOW	2	8	10.344	4.950
LOW	2	8	10.287	4.900
LOW	2	8	10.320	4.900
LOW	2	8	10.337	4.950
LOW	2	8	10.354	4.950
LOW	2	10	12.007	5.700
LOW	2	10	12.056	5.750
LOW	2	10	11.996	5.700
LOW	2	10	11.994	5.700
LOW	2	10	12.000	5.700
LOW	3	2	4.873	2.300
LOW	3	2	4.817	2.250
LOW	3	2	4.971	2.350
LOW	3	2	4.835	2.250
LOW	3	2	4.827	2.300
LOW	3	4	6.649	3.200
LOW	3	4	6.701	3.150
LOW	3	4	6.660	3.150
LOW	3	4	6.727	3.175
LOW	3	4	6.665	3.100
LOW	3	6	8.569	4.100
LOW	3	6	8.489	4.050
LOW	3	6	8.548	4.100
LOW	3	6	8.557	4.100
LOW	3	6	8.546	4.050
LOW	3	8	10.386	4.950
LOW	3	8	10.369	4.975
LOW	3	8	10.373	4.900
LOW	3	8	10.360	4.950
LOW	3	8	10.361	4.950
LOW	3	10	11.995	5.725
LOW	3	10	12.037	5.700
LOW	3	10	12.063	5.725
LOW	3	10	12.083	5.750
LOW	3	10	12.101	5.725

Table A-7. Mass and volume (cm^3) measurements for dispensed ThO_2 kernel particles

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	1	2	9.293	1.50
FULL	1	2	9.294	1.50
FULL	1	2	9.297	1.50
FULL	1	2	9.298	1.50
FULL	1	2	9.274	1.50
FULL	1	4	14.396	2.40
FULL	1	4	14.431	2.40
FULL	1	4	14.428	2.40
FULL	1	4	14.409	2.40
FULL	1	4	14.448	2.40
FULL	1	6	19.525	3.20
FULL	1	6	19.495	3.20
FULL	1	6	19.530	3.20
FULL	1	6	19.483	3.20
FULL	1	6	19.498	3.20
FULL	1	8	24.547	4.10
FULL	1	8	24.518	4.10
FULL	1	8	24.523	4.10
FULL	1	8	24.500	4.10
FULL	1	8	24.547	4.10
FULL	1	10	29.573	4.90
FULL	1	10	29.567	4.90
FULL	1	10	29.548	4.90
FULL	1	10	29.551	5.00
FULL	1	10	29.528	4.90
FULL	2	2	9.361	1.50
FULL	2	2	9.333	1.50
FULL	2	2	9.352	1.50
FULL	2	2	9.331	1.50
FULL	2	2	9.345	1.50
FULL	2	4	14.465	2.40
FULL	2	4	14.444	2.40
FULL	2	4	14.428	2.40
FULL	2	4	14.446	2.40
FULL	2	4	14.433	2.40
FULL	2	6	19.536	3.25
FULL	2	6	19.497	3.25
FULL	2	6	19.485	3.25
FULL	2	6	19.499	3.20
FULL	2	6	19.455	3.20
FULL	2	8	24.534	4.10
FULL	2	8	24.497	4.10
FULL	2	8	24.480	4.10
FULL	2	8	24.538	4.10
FULL	2	8	24.519	4.10
FULL	2	10	29.561	4.90
FULL	2	10	29.612	4.90
FULL	2	10	29.566	4.90
FULL	2	10	29.577	4.90
FULL	2	10	29.571	4.90
FULL	3	2	9.326	1.50
FULL	3	2	9.332	1.60
FULL	3	2	9.333	1.50

Table A-7. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	3	2	9.340	1.50
FULL	3	2	9.351	1.50
FULL	3	4	14.474	2.40
FULL	3	4	14.482	2.40
FULL	3	4	14.470	2.40
FULL	3	4	14.432	2.40
FULL	3	4	14.436	2.40
FULL	3	6	19.595	3.25
FULL	3	6	19.592	3.25
FULL	3	6	19.556	3.25
FULL	3	6	19.541	3.25
FULL	3	6	19.551	3.25
FULL	3	8	24.620	4.10
FULL	3	8	24.617	4.10
FULL	3	8	24.629	4.10
FULL	3	8	24.563	4.10
FULL	3	8	24.589	4.10
FULL	3	10	29.672	4.95
FULL	3	10	29.701	4.95
FULL	3	10	29.667	4.90
FULL	3	10	29.644	4.90
FULL	3	10	29.663	4.95
LOW	1	2	9.380	1.50
LOW	1	2	9.361	1.50
LOW	1	2	9.370	1.50
LOW	1	2	9.373	1.50
LOW	1	2	9.361	1.50
LOW	1	4	14.501	2.40
LOW	1	4	14.511	2.40
LOW	1	4	14.464	2.40
LOW	1	4	14.490	2.40
LOW	1	4	14.467	2.40
LOW	1	6	19.536	3.20
LOW	1	6	19.514	3.20
LOW	1	6	19.535	3.20
LOW	1	6	19.489	3.20
LOW	1	6	19.520	3.20
LOW	1	8	24.616	4.10
LOW	1	8	24.595	4.10
LOW	1	8	24.590	4.10
LOW	1	8	24.579	4.10
LOW	1	8	24.604	4.10
LOW	1	10	29.614	4.95
LOW	1	10	29.636	4.95
LOW	1	10	29.642	4.95
LOW	1	10	29.658	4.95
LOW	1	10	29.580	4.90
LOW	2	2	9.339	1.50
LOW	2	2	9.326	1.50
LOW	2	2	9.316	1.50
LOW	2	2	9.324	1.50
LOW	2	2	9.334	1.50
LOW	2	4	14.478	2.40

Table A-7. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
LOW	2	4	14.477	2.40
LOW	2	4	14.441	2.40
LOW	2	4	14.470	2.40
LOW	2	4	14.466	2.40
LOW	2	6	19.534	3.20
LOW	2	6	19.514	3.20
LOW	2	6	19.487	3.20
LOW	2	6	19.528	3.20
LOW	2	6	19.512	3.20
LOW	2	8	24.602	4.10
LOW	2	8	24.609	4.10
LOW	2	8	24.612	4.10
LOW	2	8	24.565	4.10
LOW	2	8	24.569	4.10
LOW	2	10	29.465	4.95
LOW	2	10	29.598	4.90
LOW	2	10	29.707	4.95
LOW	2	10	29.622	4.90
LOW	2	10	29.665	4.90
LOW	3	2	9.318	1.50
LOW	3	2	9.361	1.50
LOW	3	2	9.336	1.50
LOW	3	2	9.335	1.50
LOW	3	2	9.346	1.50
LOW	3	4	14.473	2.40
LOW	3	4	14.447	2.40
LOW	3	4	14.433	2.40
LOW	3	4	14.453	2.40
LOW	3	4	14.459	2.40
LOW	3	6	19.583	3.25
LOW	3	6	19.544	3.25
LOW	3	6	19.521	3.25
LOW	3	6	19.567	3.25
LOW	3	6	19.539	3.25
LOW	3	8	24.630	4.10
LOW	3	8	24.623	4.10
LOW	3	8	24.687	4.10
LOW	3	8	24.655	4.10
LOW	3	8	24.632	4.10
LOW	3	10	29.698	4.95
LOW	3	10	29.683	4.95
LOW	3	10	29.653	4.95
LOW	3	10	29.637	4.90
LOW	3	10	29.649	4.95

Table A-8. Mass and volume (cm^3) measurements for dispensed H-451 shim particles

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	1	2	1.390	1.300
FULL	1	2	1.405	1.300
FULL	1	2	1.481	1.400
FULL	1	2	1.429	1.350
FULL	1	2	1.458	1.350
FULL	1	4	2.327	2.150
FULL	1	4	2.323	2.150
FULL	1	4	2.315	2.125
FULL	1	4	2.365	2.200
FULL	1	4	2.329	2.150
FULL	1	6	3.089	2.850
FULL	1	6	3.131	2.900
FULL	1	6	3.132	2.900
FULL	1	6	3.108	2.850
FULL	1	6	3.117	2.900
FULL	1	8	3.917	3.700
FULL	1	8	3.954	3.700
FULL	1	8	3.924	3.650
FULL	1	8	3.978	3.700
FULL	1	8	3.977	3.700
FULL	1	10	4.717	4.350
FULL	1	10	4.712	4.400
FULL	1	10	4.679	4.350
FULL	1	10	4.817	4.450
FULL	1	10	4.683	4.350
FULL	2	2	1.487	1.350
FULL	2	2	1.505	1.400
FULL	2	2	1.490	1.400
FULL	2	2	1.490	1.400
FULL	2	2	1.490	1.400
FULL	2	4	2.349	2.150
FULL	2	4	2.370	2.150
FULL	2	4	2.345	2.150
FULL	2	4	2.342	2.150
FULL	2	4	2.340	2.200
FULL	2	6	3.154	2.900
FULL	2	6	3.169	2.900
FULL	2	6	3.149	2.900
FULL	2	6	3.169	2.950
FULL	2	6	3.145	2.900
FULL	2	8	3.956	3.700
FULL	2	8	3.966	3.700
FULL	2	8	3.940	3.650
FULL	2	8	3.910	3.600
FULL	2	8	3.948	3.650
FULL	2	10	4.745	4.450
FULL	2	10	4.735	4.400
FULL	2	10	4.749	4.400
FULL	2	10	4.731	4.400
FULL	2	10	4.755	4.450
FULL	3	2	1.459	1.350

Table A-8. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
FULL	3	2	1.468	1.350
FULL	3	2	1.438	1.350
FULL	3	2	1.464	1.350
FULL	3	2	1.460	1.350
FULL	3	4	2.299	2.100
FULL	3	4	2.293	2.100
FULL	3	4	2.260	2.100
FULL	3	4	2.321	2.150
FULL	3	4	2.309	2.150
FULL	3	6	3.134	2.900
FULL	3	6	3.129	2.900
FULL	3	6	3.106	2.875
FULL	3	6	3.117	2.875
FULL	3	6	3.115	2.875
FULL	3	8	3.941	3.700
FULL	3	8	3.943	3.700
FULL	3	8	3.940	3.700
FULL	3	8	3.939	3.700
FULL	3	8	3.945	3.700
FULL	3	10	4.765	4.450
FULL	3	10	4.736	4.450
FULL	3	10	4.758	4.475
FULL	3	10	4.741	4.450
FULL	3	10	4.753	4.500
LOW	1	2	1.460	1.350
LOW	1	2	1.484	1.375
LOW	1	2	1.486	1.375
LOW	1	2	1.458	1.350
LOW	1	2	1.472	1.350
LOW	1	4	2.293	2.100
LOW	1	4	2.294	2.100
LOW	1	4	2.300	2.100
LOW	1	4	2.289	2.100
LOW	1	4	2.292	2.150
LOW	1	6	3.109	2.900
LOW	1	6	3.123	2.900
LOW	1	6	3.063	2.850
LOW	1	6	3.053	2.850
LOW	1	6	3.092	2.900
LOW	1	8	3.848	3.650
LOW	1	8	3.861	3.600
LOW	1	8	3.919	3.650
LOW	1	8	3.908	3.650
LOW	1	8	3.889	3.600
LOW	1	10	4.730	4.450
LOW	1	10	4.752	4.450
LOW	1	10	4.693	4.400
LOW	1	10	4.728	4.400
LOW	1	10	4.720	4.450
LOW	2	2	1.445	1.350
LOW	2	2	1.452	1.350

Table A-8. (continued)

Hopper level	Run order	Pinch valve setting (cm)	Mass (g)	Volume (cm^3)
LOW	2	2	1.444	1.350
LOW	2	2	1.450	1.350
LOW	2	2	1.440	1.350
LOW	2	4	2.278	2.100
LOW	2	4	2.260	2.100
LOW	2	4	2.268	2.100
LOW	2	4	2.289	2.125
LOW	2	4	2.291	2.125
LOW	2	6	3.096	2.950
LOW	2	6	3.109	2.900
LOW	2	6	3.082	2.900
LOW	2	6	3.089	2.950
LOW	2	6	3.081	2.900
LOW	2	8	3.912	3.650
LOW	2	8	3.863	3.625
LOW	2	8	3.877	3.625
LOW	2	8	3.892	3.625
LOW	2	8	3.921	3.650
LOW	2	10	4.642	4.400
LOW	2	10	4.609	4.375
LOW	2	10	4.623	4.375
LOW	2	10	4.611	4.350
LOW	2	10	4.634	4.350
LOW	3	2	1.461	1.375
LOW	3	2	1.463	1.350
LOW	3	2	1.435	1.325
LOW	3	2	1.477	1.375
LOW	3	2	1.467	1.375
LOW	3	4	2.284	2.100
LOW	3	4	2.273	2.150
LOW	3	4	2.257	2.100
LOW	3	4	2.284	2.150
LOW	3	4	2.278	2.100
LOW	3	6	3.064	2.900
LOW	3	6	3.074	2.900
LOW	3	6	3.076	2.900
LOW	3	6	3.094	2.925
LOW	3	6	3.080	2.900
LOW	3	8	3.862	3.700
LOW	3	8	3.925	3.700
LOW	3	8	3.901	3.700
LOW	3	8	3.874	3.650
LOW	3	8	3.918	3.700
LOW	3	10	4.739	4.525
LOW	3	10	4.707	4.450
LOW	3	10	4.700	4.500
LOW	3	10	4.702	4.450
LOW	3	10	4.744	4.500

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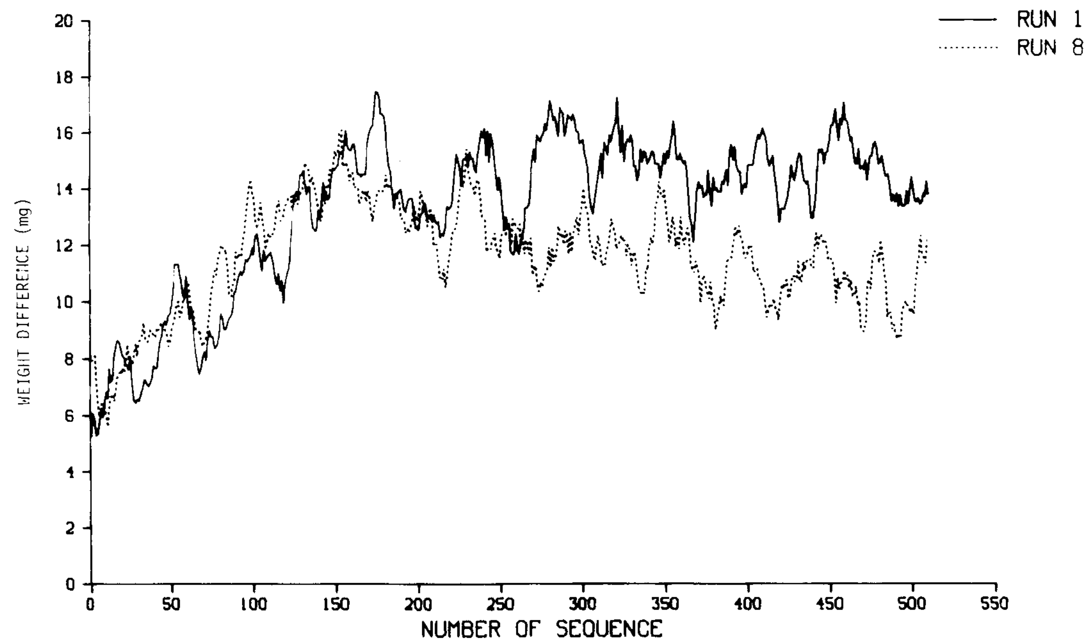

Fig. A-1. Moving average of weight differences over 12 low-net-weight fissile particles.

ORNL-DWG 81-4356

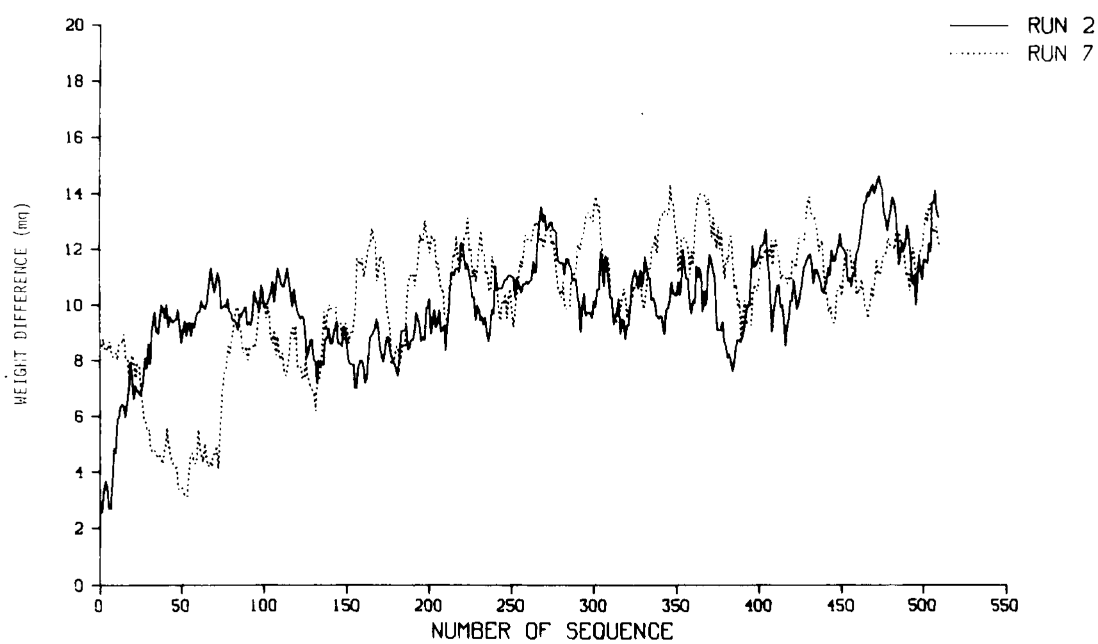

Fig. A-2. Moving average of weight differences over 12 high-net-weight fissile particles.

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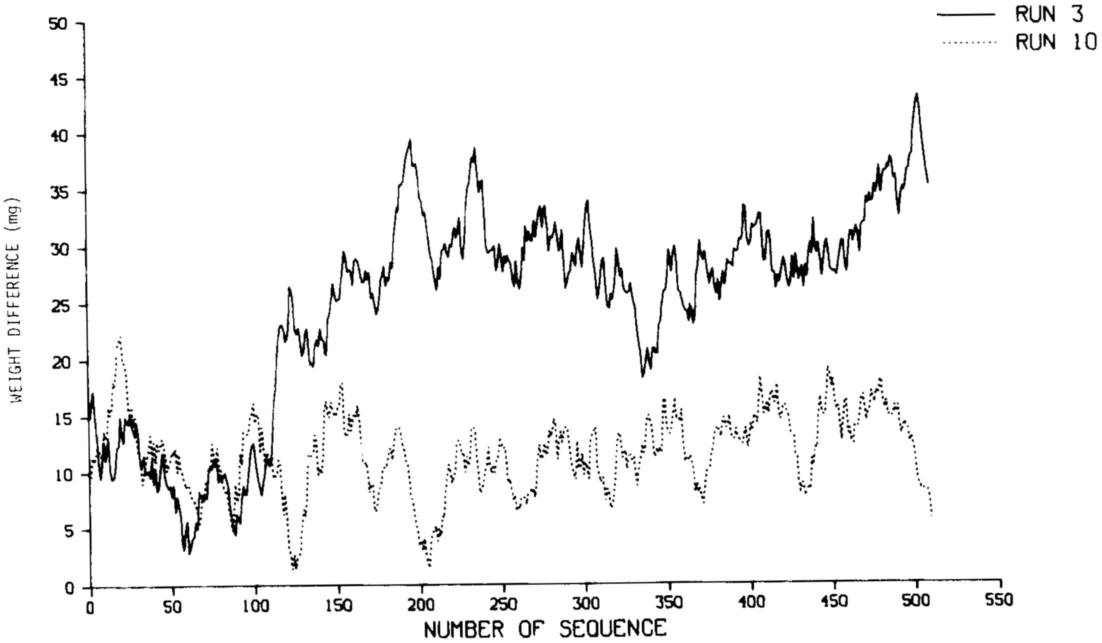

Fig. A-3. Moving average of weight differences over 12 low-net-weight fertile particles.

ORNL-DWG 81-4358

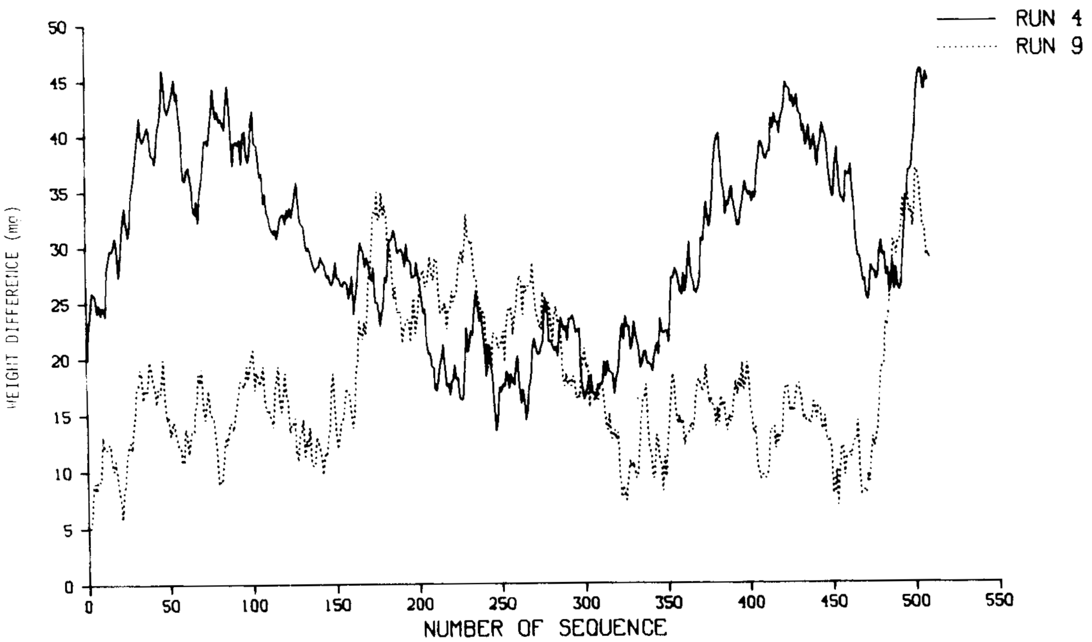

Fig. A-4. Moving average of weight differences over 12 high-net-weight fertile particles.

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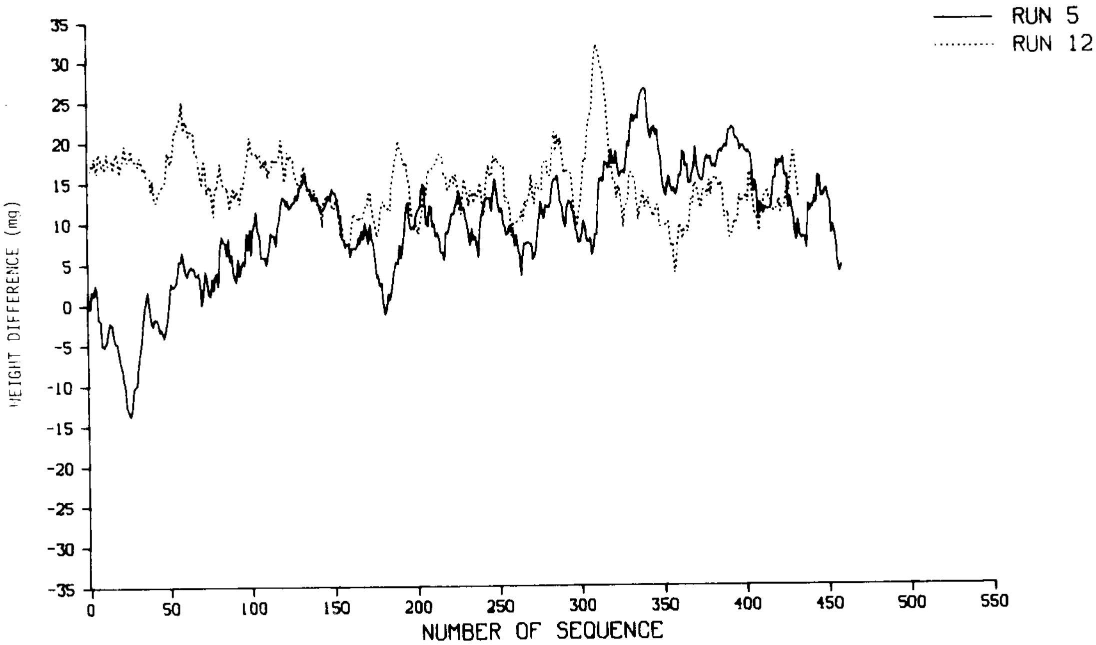

Fig. A-5. Moving average of weight differences over 12 low-net-weight shim particles.

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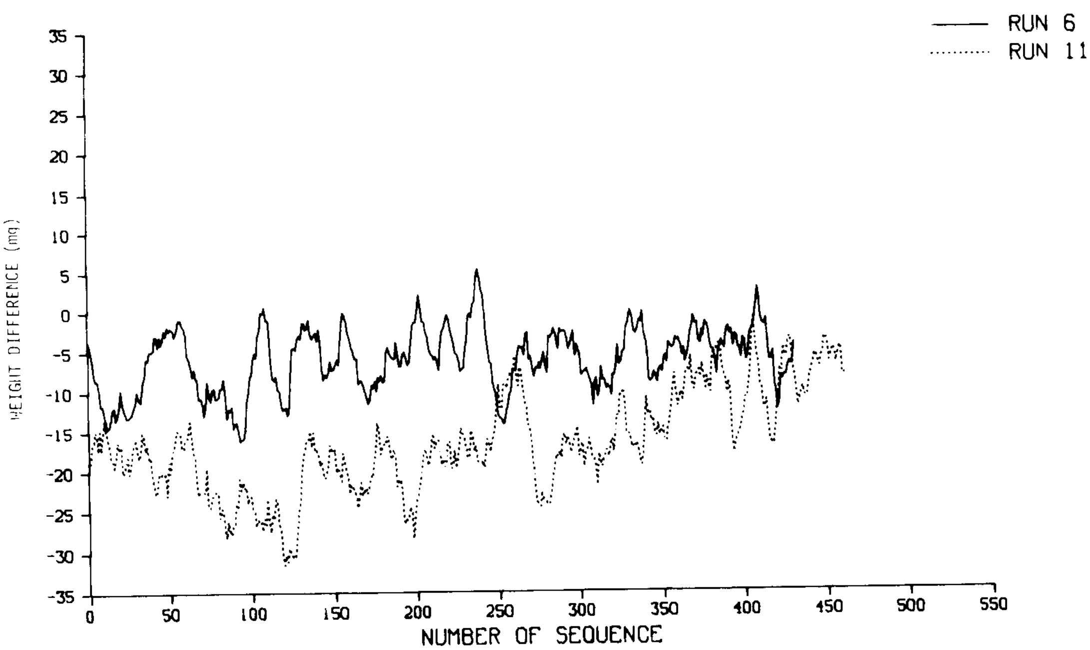

Fig. A-6. Moving average of weight differences over 12 high-net-weight shim particles.

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