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LOGARITHMIC CALCULATIONS OF LINEAL DENSITY OF DATA OUTPUT OF THE MULE

by

M. A. Winkler

ABSTRACT

An alternative method of making calculations of Rover fuel element lineal densities from the data output of the Mass per Unit Length Evaluation (MULE) inspection system is described. The method consists of using a logarithmic relationship between the lineal density and gamma-ray absorption. The method provides an accurate calculation of the absolute lineal density of fuel elements and also increases the accuracy of lineal density change measurements. In addition, the calibration procedure is greatly simplified. The accuracy of the MULE inspection is increased to better than 0.1% of the element lineal density.

I. INTRODUCTION

The Mass per Unit Length Evaluation (MULE) inspection has become a production-type inspection on Rover fuel elements. The inspection is used to determine protective coating profiles as well as corrosion profiles for postmortem analysis. Evaluation of the absolute lineal density profile can be done easily with the proposed method.

The MULE system consists of a depleted uranium shielded housing containing a 400-Ci ^{60}Co source, collimators, and ionization chamber detector. The output from the detector is digitized and the data are punched on IBM cards for analysis. This analysis is done on a Control Data Corporation 6600 computer.

A scanning mechanism is used to move the fuel element through the gamma beam. The element is passed through the beam in 1-in. increments and a 3-sec. count is made on each increment. The element is inspected at each stage of coating, starting at the machined (uncoated) state; thus, changes occurring at each stage can be evaluated.

II. DISCUSSION

In the course of a normal MULE inspection, we wish to determine a change in mass per unit length between different manufacturing processes of the fuel elements. This is done by inspecting a fuel element and making the calculations to determine the mass per unit length in two different conditions. The difference between corresponding readings on a given segment then gives the change that occurred. If the sum of the changes that are calculated is compared with the change in weight of the element, agreement is within a few percent.

A disadvantage to the above approach is that a calibration must be made for each loading of ^{235}U , UC-ZrC-C, and the material being changed; e.g., Zr added during coating or carbon lost during test. The calibration must be repeated for each different MULE system used in the inspections.

The calibration is also based on simulation of the material changed. The calibration for a ZrC coating is simulated with pure Zr foils inserted in the element bores.

For HGT, the material loss is simulated using carbon fibers placed in Nb tubes which are then placed in the bores.

Presently, the mass per unit length of elements inspected on the MULE system is calculated using a linear approximation to the exponential absorption curve. That is, a series of standards having different lineal densities are placed in the γ beam, and the corresponding count rate determined, then the difference in mass per unit length (Δm_j) between successive standards is determined along with the corresponding count rate change (ΔC_j). From this, an average value is determined. This is expressed as,

$$\left(\frac{\Delta m}{\Delta C}\right) = \frac{1}{n} \sum_{j=1}^n \frac{\Delta m_j}{\Delta C_j} \quad (1)$$

This quantity is used in the following equation to determine an unknown mass per inspected unit length,

$$\rho_j = \rho_0 + (C_0 - C_j) \left(\frac{\Delta m}{\Delta C}\right) \quad (2)$$

where,

ρ_j = mass per unit length of increment j ,

ρ_0 = mass per unit length of standard piece,

C_0 = count rate corresponding to standard, and

C_j = count rate corresponding to increment j .

A desirable approach to the calibration would be to use the material which caused the change (either deposition or corrosion). R. Christian, LASL Group N-1, suggested using the weights of the elements and making a calibration based on them. This possibility is investigated herein.

The absorption of a gamma beam can be described using the familiar Beer's Law relation,

$$I = I_0 e^{-\mu m} \quad (3)$$

where,

I = intensity of the transmitted beam,

I_0 = unattenuated beam intensity,

μ = mass absorption coefficient, and

m = mass of material in beam.

This would be the relation describing the MULE if the element attenuated the full beam. However, the MULE is designed so

that some of the beam passes around the sides of the element, thus modifying the relation so that a constant is added to the above equation, i.e.,

$$I = I_0 e^{-\mu \rho} + C \quad (4)$$

Here, μ is a hybrid absorption coefficient (Eq. 3) and ρ is the mass per unit length denoted lineal density. The constant C is considered a hybrid coefficient because it is composed of the combined coefficients of uranium, carbon, and coating material, the proportions of which vary with the loading of the element. In order to establish the appropriateness of this method, it was necessary to estimate the effects of C on the calculations. A straightforward method to measure C is not available. However, estimate of C based on the geometrical configuration of the system can be made. The element is guided through a 1-in.-square cross-section beam. The amount of the beam passing around the edges and its ultimate effects are based on the beam geometry, the detector response, and the material surrounding the element. The material geometry is such that, with an element in the beam, and considering the aluminum sleeve inside the surrounding steel tubing, the beam intensity is uniform across the opening. The detector response is also uniform in the lateral direction. The source geometry is such that some fall-off is present near the edges of the beam. These considerations, along with the element width, provide an estimate of about 10% of the beam intensity, I_0 , leaking around the edges of the element, i.e., leakage equals about $0.1 I_0$.

To study the effects of this leakage on the calculation of the lineal density (ρ) of the elements, a calculation was made using the idealized formula (Eq. 3), and estimating I_0 and μ from previous calculations. The values of I corresponding to a large range of ρ were found. New values of I were then found by adding $0.1 I_0$ to each. These values were then used in the suggested approach to the calculation with the calculation for μ' based on ρ equal to 18.5, 19.0, 19.5, 20.0, 20.5,

21.0, 22.0, and 22.5. These values of ρ cover the lineal density range in the normal inspections of fuel elements. The results of the calculation are shown in Table 1.

Table 1 shows that the lineal density calculations agree to within 0.01 in the range from 12 to 26. This indicates that the approximation to the idealized formula used in the calculation is valid over an adequate range for our purposes.

The relation $I = I_0 e^{-\mu \rho}$ can now be used to make calculations provided we do not diverge too far from the applicable region of the curve. In other words, if we take the natural logarithm $\ln I = \ln I_0 - \mu \rho$, the equation is applicable providing we remain in the linear portion of the curve. To locate a desired position on the curve, immediately before inspection a standard piece of element of the same composition as the one to be inspected can be placed in the beam. The standard piece is short (~4 in.) and uniform, and its lineal density, ρ_0 , is found by weighing. After inspecting the element, the relation,

$$\rho_j = \rho_0 + \frac{1}{\mu} \ln \frac{C_j}{C_0} \quad (5)$$

is used to calculate ρ_j , the unknown lineal density of increment j along the element. C_0 is the count rate corresponding to ρ_0 . In order to use Eq. (5), the value of μ must be found by the following method: In successive increments along the element we have

$$\begin{aligned} \rho_1 &= \rho_0 + \frac{1}{\mu} \ln \frac{C_1}{C_0} \\ \rho_2 &= \rho_0 + \frac{1}{\mu} \ln \frac{C_2}{C_0} \\ &\vdots \\ \rho_j &= \rho_0 + \frac{1}{\mu} \ln \frac{C_j}{C_0} \end{aligned} \quad (6)$$

Now, summing,

$$\begin{aligned} \Sigma \rho_j &= \Sigma \rho_0 + \frac{1}{\mu} \Sigma \ln \frac{C_j}{C_0} \\ &= N \rho_0 + \frac{1}{\mu} \Sigma \ln \frac{C_j}{C_0} \end{aligned}$$

or,

$$\mu = \frac{\Sigma \ln \frac{C_j}{C_0}}{\Sigma \rho_j - N \rho_0}, \quad (7)$$

and $\Sigma \rho_j$ = total weight of the element, which is readily found by weighing. Thus, Eq. (5) can be used to calculate all of the linear densities along the element, and the absolute value of each increment in the element can be found.

In the normal use of the MULE, a change in lineal density for each increment along the element is desired. The above method is not suitable for this determination because the change of lineal density is either an added coating or a selected (normally graphite) loss, i.e., there is not a uniform material change. In other words, a change in the hybrid absorption coefficient occurs. The preinspection calculation involves the equation,

$$I_j = I_0 e^{-\mu \rho_j} \quad (8)$$

whereas the post-inspection calculation equation can be written,

$$I'_j = I_0 e^{-(\mu \rho_j + \mu' \Delta \rho_j)} \quad (9)$$

where I'_j corresponds to the post-inspection measurement. If the incremental lineal densities are compared by dividing Eq. (8) by Eq. (9), we find,

$$\ln \frac{I_j}{I'_j} = \mu' \Delta \rho_j. \quad (10)$$

Again summing, and solving for μ' ,

$$\mu' = \frac{\Sigma \ln \frac{I_j}{I'_j}}{\Sigma \Delta \rho_j} = \frac{\Sigma \ln \frac{I_j}{I'_j}}{\Delta \text{ wt}} \quad (11)$$

where $\Delta \text{ wt}$ is the weighed value of the total change in weight. Thus, the incremental mass gain or loss is found using only the mass change over the length inspected - a readily-available value.

The inspection for reactor postmortem elements is usually done on a different MULE system than was used in the pre-assembly inspection. This will introduce an added factor in the mass loss calculations because each MULE will be slightly different in its geometry, causing the values for I_0 and μ to be different in each MULE system. This necessitates a means of conversion between the MULE systems.

Let the pre-assembly inspection be done on MULE system #1 and the postmortem inspection be done on MULE system #2, the relations for each being, using Eq. (5),

$$\rho_j - \rho_0 = \frac{1}{\mu} \ln \frac{C_0}{C_j} \text{ MULE system \#1} \quad (12)$$

$$\rho'_j - \rho_0 = \frac{1}{\nu} \ln \frac{D_0}{D_j} \text{ MULE system \#2.} \quad (13)$$

In the calibration process, an element and standard piece of given loading is run on both MULES which, for the increment j , $\rho_j = \rho'_j$. Thus, by combining,

$$\nu = \mu \frac{\ln \frac{D_0}{D_j}}{\ln \frac{C_0}{C_j}}. \quad (14)$$

This gives the desired relationship of the two systems. A series of elements are inspected on both systems to find this relationship as a function of load. Once this is established, an element of the same loading whose ρ_j values are calculated from the MULE No. 1 system can be converted to the count rate on the MULE No. 2 system using Eq. (8) in the form,

$$D_{j\#2} = I_{0\#2} e^{-\nu \rho_{j\#1}}, \quad (15)$$

where $I_{0\#2}$ is the unattenuated beam on system No. 2. The incremental mass loss is then calculated using Eq. (6) in the form,

$$\ln \frac{D_j}{I_j} = \mu' \Delta \rho_j, \quad (16)$$

where μ' is found in the usual manner.

Several elements have been inspected and the above methods applied. In measurements of absolute lineal densities, comparisons were made between the new method and the calibration method now being used. The comparisons show very close agreement, i.e., within statistical accuracy (Fig. 1). Also, the difference calculations based on this method agreed well with the measured values for added material. The measured values were obtained by adding tubes in the bores and doing the inspection. The lineal density of the added material was found by weighing and by comparison with

the measured values. Figure 2 is an example of the results of this method.

In the postmortem inspection of fuel elements, some elements are received broken or corroded through. The proposed method of analysis is dependent on making correct count rate measurement along the total length of the element. If the element is parted, a spurious reading will result because of the separation of the pieces while being scanned. It is proposed that the method is sufficiently accurate that each segment can be inspected separately if the exact location of the segment is known. This can be done by adding the results of the measurement of the absolute lineal density made when the element was uncoated with the values of the coating measurements. This sum gives the absolute lineal density of each segment before the reactor is run. Thus, the mass loss can be determined with the above method for any segment as long as its exact location in the element is known.

Figure 3 shows the results of the MULE lineal density calculation plotted over the weighed values. The element is one that had been hot gas corrosion tested and experienced relatively little mass loss. After the MULE inspection was completed, the element was cut into 2-in. segments and the average lineal density of each measured. The results agree to within 0.02 g/in., which is within the statistical accuracy of the MULE measurements.

Several programs for calculating the lineal density and lineal density changes have been written for the Digital Equipment Corporation PDP-9 computer. The input data are taken on punched cards in the same manner now being used in the MULE program. Several elements which had been previously inspected have been used in the calculations. The results of these calculations show very good agreement in profile with the linear calculations, and the absolute density measurements are more realistic because the sum of the values agrees with the total measured values.

Some of the advantages of using this method of calculation are:

1. Calibration, as previously done, of the MULE for various loadings is not necessary.
2. The absolute lineal density is readily measured for homogeneous materials, and is more accurate than the present method.
3. Calibration is done on the actual material and geometry rather than on a simulated material.
4. Remnants of fuel elements can be accurately inspected providing the position of the segments can be accurately identified.

There are some disadvantages, some of which are:

1. Extrapolation of the lineal density or density changes is necessary for the first and last 1/2 in. increments because they are not inspected.
2. If a break occurs, interpolation is necessary across the break.

III. CONCLUSION

This alternate method of lineal density calculations on MULE data is a more accurate approach to the fuel element density measurements. The method offers a simpler calibration procedure which eliminates inherent errors. The weighed values which are necessary in the calculations are routinely done, hence, no additional operations are required.

RELATED REFERENCES

LA-3710 - Nondestructive Incremental Mass Measurements of Rover Fuel Elements.

LA-4105 - Improved Method of Fuel Element Incremental Mass Measurements.

TABLE 1

ρ (lineal density)	I (counts per 3 secs)	I + 20000	ρ'
0	20.000	225000	0.090
2	202960	222960	1.928
4	200941	220941	3.943
6	198941	218941	5.957
8	196962	216962	7.969
10	195002	215002	9.979
12	193062	213062	11.987
14	191141	211141	13.993
16	189239	209239	15.997
18	187356	207356	18.000
20	185492	205492	20.000
22	183646	203646	21.999
24	181819	201819	23.996
26	180010	200010	25.990
28	178218	198218	27.984
30	176445	196445	29.974
35	172089	192089	34.941
40	167840	187840	39.896
50	158654	178654	49.766
75	140894	160894	74.197

Table 1. Column 4 is the result of modifying the count rate to simulate the effects of the gamma beam streaming around the edges of the element segment.

Fig. 1. Comparison of the linear and logarithmic calculations made on a fuel element.

Fig. 2. Results of the MULE inspection compared with weighed values of material added to the bores of an element.

Fig. 3. Comparison of MULE results with 2-in. segment weights of a fuel element.