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16 October 1965

Westinghouse Astronuclear Laboratory

**EVALUATION OF THE FUEL ELEMENT BETA
BACKSCATTER NONDESTRUCTIVE TEST SYSTEM**

(Title Unclassified)

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BACKSCATTER NONDESTRUCTIVE TEST SYSTEM

(Title Unclassified)

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Quality Control

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by authority of

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TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
	SUMMARY	ix
1	PRINCIPLES OF OPERATION	1-1
1.1	Basic Operating Principles	1-1
1.2	System Linearity	1-9
2	CALIBRATION STANDARDS	2-1
2.1	Applications	2-1
2.2	Fabrication of Calibration Standards	2-4
2.3	Standards Correlation with Other Facilities	2-6
3	BETA BACKSCATTER PROBE	3-1
3.1	Characteristics of Probe	3-1
3.2	Problem Areas	3-2
3.3	Probe Fabrication	3-3
3.4	Probe Response Versus Fuel Element Loading	3-5
3.5	Probe Response Versus Niobium Thickness	3-7
3.6	Beta Probe Correlation Studies (Astrofuel Probe Versus LASL Probe Installed in LASL System)	3-7
3.6.1	Probe Response Versus Thickness	3-7
3.6.2	Probe Response Versus Bore Diameter	3-10
3.6.3	Relative Axial Sensitivity - LASL Versus Astrofuel Probes	3-10
3.6.4	Summary of Probe Correlation Studies	3-10
4	BETA BACKSCATTER SYSTEM APPLICATION	4-1
4.1	Mode No. 1	4-1
4.2	Mode No. 2	4-2
4.3	Mode No. 3	4-2
5	EQUIPMENT PRECISION	5-1
6	BETA BACKSCATTER CORRELATION WITH LASL AND OAK RIDGE (Y-12)	6-1

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LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1-1	Automated Beta Backscatter System	1-3
1-2	Schematic of Backscattering Method	1-4
1-3	Curves Representing NbC(Z_1) Thickness Determination	1-5
1-4	Functional Block Diagram of Beta Backscatter System (Automated)	1-6
1-5	Linearity of Attenuator Control in Beta Backscatter System with Input Constant	1-8
1-6	Linearity of Response of Beta Backscatter System, with PM Tube Simulated and System Gain Constant	1-10
2-1	Correlation of Metallographic and Beta Backscatter Results in Checking NbC Coating Thickness Using 1.235 Conversion Factor	2-3
2-2	Beta Backscatter Standard Element Drawing	2-5
2-3	Comparison of Responses of Four Standards from the Code 5 Fuel Loadings	2-8
3-1	Typical Beta Backscatter Scintillation Probe Fabrication Drawing	3-4
3-2	Beta Backscatter Probe Response to Changes in Fuel Element Loading	3-6
3-3	Beta Backscatter Probe Response to Variations in Niobium Foil Thickness	3-8
3-4	Comparison of Astrofuel and LASL Probe Calibrations in the LASL Beta Backscatter System	3-9
3-5	Responses of Astrofuel and LASL Probes Respectively to Variation of Bore Diameter	3-11
3-6	Relative Axial Sensitivities of LASL and Astrofuel Probes	3-12

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LIST OF TABLES

<u>Table</u>		<u>Page</u>
2-1	Beta Backscatter System (BBS) Comparison (Astrofuel and LASL) on Astrofuel-Built Element Standards Tested at LASL	2-9
3-1	Source Strengths Before and After Encapsulation, Stainless Steel Source Capsule Versus Aluminum Source Capsule	3-2
6-1	Comparison of Astrofuel to LASL and Y-12 Beta Backscatter Results of NbC Thickness from Fourteen Interchanged Elements	6-2

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SUMMARY

This report documents the evaluation of the beta backscatter nondestructive test system recently installed at the Westinghouse Astrofuel Facility (WAFF), Cheswick, Pennsylvania. The purpose of this test system is to determine the coating thickness of niobium carbide coated NERVA fuel elements.

This evaluation was extremely useful in developing operating and control procedures which achieved a high degree of consistency in the testing of NERVA fuel elements. A statistical analysis* of beta backscatter data taken as part of this evaluation indicates excellent precision capability for the equipment. Correlation of beta backscatter data with the results of metallographic examinations has established a high degree of confidence in the results provided by this test system.

The way in which the niobium carbide protective coating conforms to the applicable drawings and specifications is a determining factor in the acceptance or rejection of fuel elements. This test system is used both as a process control check and as an acceptance test for the coated element. Another important application for the beta backscatter data is to correct the fuel element as-coated uranium loading for the attenuation of the 185 kev uranium gamma rays by the niobium content of the coating.

The major backscatter problems recognized at Astrofuel are those associated with maintaining system calibration to assure consistent data at all times and to maintain a high level of precision and reliability of the system. Also of importance is the need to optimize the form of the expression for the reduction of the output of the equipment to niobium carbide coating thickness.

*WANL-TME-1244 Results of Beta Backscatter Data Evaluation, August 1965

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SECTION 1

PRINCIPLES OF OPERATION

1.1 BASIC OPERATING PRINCIPLES

The continuous spectrum from beta decay of strontium 90 is used in the reflection or backscattering test system to measure the thickness of the niobium carbide coating on NERVA fuel elements. Figure 1-1 shows the test system components. Figure 1-2 shows the method of backscattering utilized at Astrofuel. The beta particles are continuously emitted from the strontium 90 source. Beta particles in a quantity directly proportional to the thickness of the coating are reflected or backscattered to the scintillator (scintillation crystal). The scintillation crystal is a luminescent material (NE-103 plastic) with a fluorescence efficiency in the order of 5 to 10 percent, depending upon the particle energies. The shield between the scintillator and the strontium 90 source is provided to prevent primary bombardment of the scintillator.

The significant observation in figure 1-3 is that Z_1 (atomic weight of NbC) reflects or backscatters more particles per unit weight than Z_3 (atomic weight of fueled graphite). Curve 2 was superimposed upon Curve 1 to illustrate the effect of adding NbC coating to the graphite.

The energy absorbed by the scintillator is converted to photons. The photons are transmitted to the photomultiplier tube (PM tube) cathode through the quartz light guide. The efficiency of the photon transmission depends upon the:

- 1) Transparency of the scintillation crystal

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- 2) Surface cleanliness of the quartz light guide
- 3) Optical coupling at the interfaces
- 4) Ability to maintain a fixed geometry in the probe once the geometry has been established.

The photons are absorbed in the PM tube cathode. This cathode converts the photons to electrons (with an efficiency usually not exceeding a few percent) and the dynodes or remainder of the stages in the PM tube multiply these electrons to provide for an amplification of the order of 10^6 . The PM tube anode collects the electrons.

There are two basic techniques for utilizing the electrons collected on the PM tube anode. The first, the one used on early systems at Astrofuel, is to place the anode above or below ground potential, develop the multiplied electrons into pulses, and then count the pulses.

The second technique, the approach used with the present automated equipment, is to connect the anode directly to an operational amplifier input summing point which is at zero potential. This technique utilizes the PM tube as a current generator, and the operational amplifier monitors or senses any change in the current generated.

The automated beta backscatter system is defined as a current integrating device. Figure 1-4 is a functional block diagram of the system. As mentioned earlier, the scintillator output is a quantum light or photon energy related to the niobium carbide thickness being observed. As this thickness increases, the photon output increases. The photons bombard the light-sensitive PM tube cathode. The PM tube cathode converts the photons to electron energy and thus functions as a current generator. The current output of the PM tube is related to the thickness of the coating being measured.

During normal operation, a specific range of operating voltages is applied to the photomultiplier tube. The minimum value of the range is selected so as to ensure that the potential between dynode No. 9 and the anode is in the flat response region of the curve. The maximum value is selected so as to ensure that the applied voltage is less than the peak rating of the tube. The normal range of operating voltages is 795 to 1150 volts DC.

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Figure 1-1. Automated Beta Backscatter System

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Figure 1-2. Schematic of Backscattering Method

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Figure 1-3. Curves Representing NbC (Z_1) Thickness Determination

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Figure 1-4. Functional Block Diagram Beta Backscatter System (Automated)

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Problems encountered during operation and equipment startup have been attributed to PM tube cathode fatigue or to the cold cathode effect. It has been found that it is necessary to hand-select these 1P21 tubes, with a resulting high rejection rate. However, once an acceptable tube is found it will last almost indefinitely. In any case, an eight hour startup stabilization period is required after turn-on of the system.

The output of the PM tube is applied to the summing point of the current integrator (operational amplifier). The operational amplifier integrates the current at the summing point and develops an output voltage related to the thickness being measured. The amplifier gain is ten with a frequency response from DC to 100 cycles per second. Examination of the amplifier disclosed excellent linearity characteristics. No difficulty was encountered with drift, probably because of the high percentage of solid state circuitry.

The voltage output of the operational amplifier is applied to an attenuator control, which is regulated to maintain a constant system gain. Typically, this control is adjusted from 25 to 100 percent of full scale. A linearity evaluation was performed on the control using a constant input, and it was found to be linear over the complete range. (See figure 1-5.) The output of the attenuator control is applied to a voltage-to-frequency converter.

The voltage-to-frequency converter is a linear device which will produce frequencies from zero to 10,000 cycles per second for DC inputs from zero to one volt. Its output is a range of pulses whose frequency is related to the thickness being measured. The converter's linearity, response, accuracy and stability were found to be exceptionally good. However, stability and linearity can only be maintained by a good preventive maintenance program; the unit must be calibrated at daily intervals and checked out at least weekly.

The output pulses of the converter are applied to a scaler or counter. The counter will accumulate (count) the pulses over a four second time interval. The scaler-timer combination is acceptable when evaluated for linearity. However, the use of the 60 cps line as a time base is one of the major factors limiting system precision. A repeatability study utilizing a constant simulated input revealed as much uncertainty in the output counts as is indicated typically in normal thickness measurements. There is no cause for concern with

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Figure 1-5. Linearity of Attenuator Control in Beta Backscatter System with Input Constant

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the pulse counting system because of the high count-rate. However, the current averaging system reflects 10 counts per 0.1 mil typically at the 2 mil region of a given calibration curve, thus demanding a highly stable scintillation system.

At the end of the four-second interval the scanner will scan (read out) the decades on the counter into the card punch machine. This machine will punch a card containing the integrated count-rate over a four-second interval which is related to the thickness being measured. Finally, the data cards are submitted to the computer and compared with data cards exhibiting count-rates for known thicknesses in calibration standards. The data is reduced to thickness values and displayed in a printout for distribution.

1.2 SYSTEM LINEARITY

The system's signal-conditioning circuitry was evaluated for linear response by simulating the current-generating photomultiplier tube (PM tube). The linearity was evaluated for the full range of current normally encountered during testing plus or minus 20 percent. The current through the summing point was varied by means of a 10-turn Dekapot. The system gain was held constant during this evaluation. Figure 1-6 illustrates the excellent linear response with negligible point scatter caused by the scintillation counter modules in the system.

Figure 1-6 could also be used to evaluate system resolution. It can be determined from this figure that a one nanoampere change in current reflects a 300 count change in the scintillation counter.

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Figure 1-6. Linearity of Response of Beta Backscatter System, with PM Tube Simulated and System Gain Constant

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SECTION 2

CALIBRATION STANDARDS

2.1 APPLICATIONS

The beta backscatter test system is basically a comparison gage. Initially a series of measurements are made on known thicknesses of niobium foil containing various uranium loadings. Then a series of measurements are made on the niobium carbide coatings in NERVA fuel elements. The readings on the known thicknesses of niobium foil are converted to niobium carbide thicknesses by means of an empirical formula. The two series of measurements are compared and the system is standardized accordingly.

Obviously, the validity of the beta backscatter data depends upon the method with which the test system is standardized. With this in mind, a great deal of effort was expended both on the development of standards and on the techniques used to convert the equipment outputs to niobium carbide coating thicknesses. The technique used to develop the standards will be discussed in the following subsection, 2.2. Prior to the installation of the present automated equipment, the conversion factor $NbC = Nb (1.235)$ was used for the conversion of Nb thicknesses to NbC thicknesses. The 1.235 conversion factor was derived as follows:

$$\begin{aligned}\frac{NbC \text{ thickness}}{Nb \text{ thickness}} &= \frac{NbC \text{ molecular wt} / NbC \text{ density}}{Nb \text{ molecular wt} / Nb \text{ density}} \\ &= \frac{NbC \text{ molecular wt} \times Nb \text{ density}}{Nb \text{ molecular wt} \times NbC \text{ density}} \\ &= \frac{104.9 \times 8.5}{92.9 \times 7.8} = 1.235\end{aligned}$$

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The statistical analysis of the automated beta backscatter system data, as reported in WANL-TME-1244*, concluded that the factor 1.235 was invalid for thicknesses greater than 1.2 mils. Metallographic results were consistently higher than the converted beta backscatter results for thicknesses of 1.2 mils or greater. The divergence increases as the thickness increases. Significantly the LASL (Los Alamos Scientific Laboratory) experimental results reflect the divergence at a thickness of 2.0 mils. This difference will be discussed later when a probe interchange program with LASL is described. Figure 2-1 illustrates the divergence encountered when correlating metallographic results with beta backscatter results utilizing the 1.235 conversion factor. The statistical analysis concluded that a relationship of the form

$$NbC = a + b(Nb) + c(Nb)^2$$

should convert the beta backscatter measurements well enough to have a satisfactory agreement between metallographic results and the beta backscatter results.

Four Astrofuel code 9 elements were each measured 13 times on the beta backscatter system. The coating thickness profiles represented a range of thicknesses of niobium carbide from 0.1 to 2.6 mils. The four elements were then sectioned and measured metallographically for a total of 192 measurements. The standard least squares method was used to estimate the coefficients in the above expression utilizing the 192 comparisons. From these data the following empirical relationship was obtained:

$$NbC = 0.225 + 0.697(Nb) + 0.445(Nb)^2$$

Follow up correlations between metallographic results and beta backscatter results using the above expression reflect no significant differences up to NbC thicknesses of 3 mils. No thicknesses greater than 3 mils have as yet been encountered so no correlations were necessary in this area.

*WANL-TME-1244, Results of Beta Backscatter Data Evaluation, August 1965.

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Figure 2-1. Correlation of Metallographic and Beta Backscatter Results in Checking NbC Coating Thickness Using 1.235 Conversion Factor

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2.2 FABRICATION OF CALIBRATION STANDARDS

A group of 30 beta backscatter element standards were fabricated prior to starting the system evaluation. Two of the 30 were unfueled elements; the remaining 28 consisted of four sets of seven elements each representing the seven fuel element loadings used at Astrofuel. One of the unfueled standards was retained at Astrofuel; the other was sent to LASL. Of the four sets of fueled elements two sets were retained at Astrofuel, one was sent to WANL Large, and the fourth to LASL for use in a system correlation study.

Figure 2-2 is the drawing used in fabricating the standards. Special emphasis was placed on the selection of raw material. The niobium foil was purchased in large enough quantities to assure that all standards would be made from the same lot of material and there would be enough left over for future rework and repairs. The technique used for the fabrication process consists of the following steps:

- 1) Select one as-leached element from each of the seven nominal fuel loadings. Verify that the element selected is representative of the loading category. The non-fueled standards were fabricated for experimental evaluation only.
- 2) Machine the elements in 10-inch lengths as indicated in figure 2-2.
- 3) Purchase niobium foil of 99.8 percent minimum purity in 50 square inch sheets.
- 4) Measure the foil sheets at a minimum of 25 points per sheet and record the thicknesses. The foil is measured with a supermicrometer at a 1/2 pound pressure with an accuracy of 50 millionths of an inch.
- 5) Cut the foil to size using the special shearing fixture built for this application. The foil is cut to two-inch lengths with the width equal to pi times the reaming bore diameter. (See step 7 for the reaming operation.)
- 6) Using the supermicrometer, measure each piece of foil and identify it by number; record the respective thickness readings. This step provides for thickness traceability and permits selecting only identical thicknesses for fabrication. Any variations due to high or low spots in the foil are thus eliminated.
- 7) Ream the element channels an amount equal to the thickness of the foil which will be installed. The intention here is to simulate as closely as possible the innerface recession of the NbC coating of the channel.

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Figure 2-2. Beta Backscatter Standard Element Drawing

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8) Bend the pieces of foil over a mandrel, along the axis. Do not wrap the foil in a spiral configuration.

9) Install the foil pieces in the channels as indicated in figure 2-2. The foil must be worked for a butt fit, i.e., no overlaps or gaps are permissible. The foil seam must be aligned with the "D" face of the element within plus or minus five degrees. The seam is oriented to a fixed position in all standards so that the beta probe can be installed with a window landing or portion of the stainless steel tubing over the seam. This is explained in more detail in the discussion on the beta probe. The foil installations are selected so that any given installed thickness is within 50 percent of the average of the foil thicknesses in the adjacent six channels. This minimizes the effect of error introduced by the adjacent channels. The data readout reflects ascending thickness values, since the probe carriage indexes from channels 1 to 3, then from 7 to 4, then from 8 to 12, then from 16 to 13, and so on. The last 1/8 inch of foil is wetted with Eastman 910 cement before final positioning.

10) Inspect the standards to verify that the requirements of step 7 have been met. Use drill blanks for this measurement.

11) Evaluate each standard on the beta backscatter system. A correlation is performed among the four standards for a given fuel loading. Any standard that does not conform to the group is reworked until all four readings are comparable.

The results of the correlation study performed on four (4) standards from the code 5 fuel loadings are indicated in figure 2-3. No more scatter is indicated than would be expected if a single standard were checked four times. The other six fuel code groups reflected similar readings.

2.3 STANDARDS CORRELATION WITH OTHER FACILITIES

A complete set of Astrofuel built beta backscatter calibration standards were shipped to LASL for a comparison study. Table 2-1 indicates the results of this study. No attempt was made to round off the data. The LASL indicated thicknesses are in NbC as converted by $\text{NbC} = 1.235(\text{Nb})$, the conversion factor used by LASL. The data reflects some scatter, but not an excessive amount considering that the technique used could induce a few tenths error. The most significant observation is that there is a bias indicated. In all cases, when a deviation exists the LASL indicated thickness is greater.

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Another significant fact here is that the Astrofuel indicated thicknesses given in table 2-1 are the values from the supermicrometer procedure mentioned earlier, not the beta backscatter system. The deviations are most pronounced at the greater foil thickness regions. The system evaluation performed on the beta backscatter measurements at Astrofuel was characterized by the same deviations at niobium carbide thicknesses greater than 2.1 mils. This is described in more detail under the probe discussion in Section 3.

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Figure 2-3. Comparison of Responses of Four Standards from the Code 5 Fuel Loadings

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NIOBIUM THICKNESS-MILS

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TABLE 2-1

BETA BACKSCATTER SYSTEM (BBS) COMPARISON (ASTROFUEL AND LASL) ON
ASTROFUEL-BUILT ELEMENT STANDARDS TESTED AT LASL

Astrofuel Standard Number	Astrofuel Measured Coating Thickness By Supermicrometer * (mils, NbC)	LASL Measured Coating Thickness By BBS* (mils, NbC)	Difference in Coating Thickness, LASL-Astrofuel (mils, NbC)
T07	0.0	0.1	0.1
	0.6	0.7	0.1
	1.6	1.6	0.0
	2.1	2.1	0.0
	2.6	2.7	0.1
	3.1	3.2	0.1
	3.9	4.2	0.3
AL39	0.0	0.0	0.0
	0.6	0.6	0.0
	1.6	1.7	0.1
	2.1	2.3	0.2
	2.6	2.8	0.2
	3.1	3.5	0.4
	3.9	4.1	0.2
AL49	0.0	0.0	0.0
	0.6	0.6	0.0
	1.6	1.6	0.0
	2.1	2.2	0.1
	2.6	2.8	0.2
	3.1	3.2	0.1
	3.9	3.9	0.0

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TABLE 2-1 (Continued)

Astrofuel Standard Number	Astrofuel Measured Coating Thickness By Supermicrometer * (mils, NbC)	LASL Measured Coating Thickness By BBS* (mils, NbC)	Difference in Coating Thickness LASL-Astrofuel (mils, NbC)
AL59	0.0	0.0	0.0
	0.6	0.7	0.1
	1.6	1.6	0.0
	2.1	2.4	0.3
	2.6	3.0	0.4
	3.1	3.2	0.1
	3.9	4.0	0.1
AL69	0.0	0.0	0.0
	0.6	0.7	0.1
	1.6	1.7	0.1
	2.1	2.1	0.0
	2.6	2.8	0.2
	3.1	3.4	0.3
	3.9	4.0	0.1
AL79	0.0	0.0	0.0
	0.6	0.7	0.1
	1.6	1.7	0.1
	2.1	2.2	0.1
	2.6	2.9	0.3
	3.1	3.2	0.1
	3.9	4.0	0.1
AL89	0.0	0.0	0.0
	0.6	0.6	0.0
	1.6	1.6	0.0

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TABLE 2-1 (Continued)

Astrofuel Standard Number	Astrofuel Measured Coating Thickness By Supermicrometer* (mils, NbC)	LASL Measured Coating Thickness By BBS* (mils, NbC)	Difference in Coating Thickness LASL-Astrofuel (mils, NbC)
AL99	2.1	2.2	0.1
	2.6	2.9	0.3
	3.1	3.3	0.2
	3.9	4.2	0.3
	0.0	0.0	0.0
	0.6	0.6	0.0
	1.6	1.8	0.2
	2.1	2.3	0.2
	2.6	2.9	0.3
	3.1	3.4	0.3
	3.9	4.4	0.5

*Both Astrofuel and LASL used the following conversion formula: $NbC = 1.235 (Nb)$.
Astrofuel obtained its measurement of Nb by means of a supermicrometer, whereas
LASL measured Nb with its beta backscatter system (BBS).

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SECTION 3

BETA BACKSCATTER PROBE

3.1 CHARACTERISTICS OF PROBE

The scintillation probe assembly is the most critical component of the automated beta backscatter system. System output fluctuations due to the random nature of radioactive disintegrations may be related to the actual variation in the scintillation detector response. Any change in the probe geometry will result in a change in detector response. The probe efficiency is almost entirely determined by the kind of detector used. However, the degree of collimation designed into the probe can improve the effective efficiency. Collimation is defined as the means of directing the beta rays to the scintillation crystal. Collimation is a very important factor because it provides a method of achieving greater sensitivity to thickness changes. It is extremely difficult to produce probe assemblies having the same degree of collimation; therefore, probe sensitivity will vary from probe to probe. Astrofuel selects probes based on the slope of a best-fit exponential curve showing the probe's response to a range of known foil thicknesses. The typical response at a one mil thickness of niobium foil is 200 counts/4 seconds/0.1 mil.

Another important factor in producing probe assemblies is the aluminum foil wrap placed over the scintillation detector-quartz light guide interface for light-shielding purposes. The integrity of this light shield determines the ability of the probe to reject the unwanted effects of extraneous light. However, the addition of this aluminum foil wrap affects the response of the detector, making this step in the fabrication an extremely critical one. The absorption of the continuous spectrum of beta rays may be approximately characterized by the exponential relation,

$$I = I_0 e^{-\mu x}$$

where I_0 represents the initial response (i.e., response before addition of aluminum foil wrap) of the scintillation detector to the radiation. The response is reduced to 1 by applying

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a factor based on the aluminum foil wrap thickness, x , and the linear absorption coefficient, μ . Experimental data and normal probe evaluations have proven this absorption characteristic to be fact. Astrofuel minimizes this absorption effect by applying the same amount of aluminum foil (two wraps of 0.5 mil foil) with each fabrication. A significant observation is that an aluminum source capsule is a factor of two more affected by the addition of aluminum foil than is a stainless steel source capsule.

The attenuation of the encapsulated source strength due to absorption by the capsule itself is a factor of two greater for a stainless steel capsule than for the Astrofuel aluminum capsule, as is shown in table 3-1. The stainless steel source capsule is used in the automated beta backscatter system.

TABLE 3-1

SOURCE STRENGTHS BEFORE AND AFTER ENCAPSULATION,
STAINLESS STEEL SOURCE CAPSULE VERSUS ALUMINUM SOURCE CAPSULE

STAINLESS STEEL SOURCE CAPSULE:	MILLICURIES
Source Strength Before Encapsulation	15 to 20
Source Strength After Encapsulation	4 to 8
ALUMINUM SOURCE CAPSULE:	MILLICURIES
Source Strength Before Encapsulation	5
Source Strength After Encapsulation	3.5

3.2 PROBLEM AREAS

The major problem associated with the beta probe is that of fabrication control. The design requirements for the probe must be met at each stage of fabrication to ensure the achievement of optimum response and sensitivity. Astrofuel has expended considerable effort in developing good fabrication control.

In addition, control methods have been written into operating procedures for the detection of defective probes so that they can be corrected in the shortest possible time.

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The most significant problem associated with the operation of probes is the radiation browning of the tip end of the quartz light guide at the scintillation detector-quartz interface. The browning results in a linear decay in system gain at the rate of 2.5 (at best) to 3.5 percent per day. This decay in gain causes a linear decay in the overall probe response to a range of measured thicknesses. The browning attenuates the photons at the quartz-detector interface; the degree of attenuation increases as the browning increases. The decay in system gain is compensated for by increasing the photomultiplier dynode voltage.

This dynode voltage is increased to a point high enough to accomplish the amount of gain needed but not high enough to cause an intolerable increase in statistical fluctuations in the PM tube output. * An absolute voltage limit is the peak voltage rating of the PM tube, but there would be an intolerable increase in statistical fluctuations in the PM tube output well before reaching this peak voltage rating.

A limited experimental program consisting of decreasing the net dose rate realized at the quartz tip without changing the probe design has had no significant effect. Astrofuel has purchased research time at the Westinghouse Research Laboratory in an effort to improve the radiation resistance of the probe. When the study is complete, a supplement to this report will be issued documenting the results. Until the radiation resistance can be improved, Astrofuel is limiting the beta probes to two weeks of service to maintain maximum reliability and optimum precision. A recent study verified that there is no significant change in probe response over a three week period when dynode voltage compensation is used.

3.3 PROBE FABRICATION

Figure 3-1 illustrates a beta scintillation probe fabrication typical of the probe installed in the automated system. Note the relative positions of the beta source, detector primary beta shield, the scintillation detector and the quartz light guide; the location of the geometry for these positions is very critical. The detector primary beta shield measures 0.040 inch in length. The essential steps in probe fabrication at Astrofuel are the following:

*Experimental data shows that increasing the voltage on the dynodes in a PM tube causes an increase in the statistical fluctuations of the tube output.

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Figure 3-1. Typical Beta Backscatter Scintillation Probe Fabrication Drawing

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- 1) Clean interior of the stainless steel hypodermic tubing using acetone as the flushing agent.
- 2) Cut the quartz to length (requires a square cut at the ends); then polish both ends to obtain a number 4 finish quality.
- 3) Completely clean the exterior surface of the quartz light guide using acetone. (Handle quartz with gloved hands after cleaning.)
- 4) Inspect scintillation detector to verify that both ends are cut square.
- 5) Cut 0.0005 inch thick aluminum foil to $3/4$ inch long by $1/4$ inch wide.
- 6) Wrap foil over quartz guide approximately $1/4$ inch from end.
- 7) Apply optical coupling grease to end of quartz nearest foil. Apply grease so as to obtain a build-up of a few mils on the end face.
- 8) Slide foil slightly beyond end of quartz.
- 9) Insert the scintillation detector against end of quartz guide. Verify that a good optical-mechanical coupling is made.
- 10) Slide foil $1/16$ inch beyond scintillator.
- 11) Tuck foil down over the end of the scintillation detector.
- 12) Insert the quartz-detector assembly into the tubing through the source end.
- 13) Install probe less beta source in the system carriage.
- 14) Install beta source into probe under surveillance of Industrial Hygiene personnel.
- 15) Evaluate probe.
- 16) If probe does not meet established requirements, disassemble and repeat steps 1 through 15.

3.4 PROBE RESPONSE VERSUS FUEL ELEMENT LOADING

Figure 3-2 illustrates the beta probe response to changes in fuel element loading in the absence of coating. Observe that the response is not exponential. The Z of the element increases with the addition of fuel; therefore, the absorption rate should be approximately exponential. However, saturation is reached due to the mechanisms involved and no significant change is realized for a change in loading at the two highest points on the curve.

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Figure 3-2. Beta Backscatter Probe Response to Changes in Fuel Element Loading

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3.5 PROBE RESPONSE VERSUS NIOBIUM THICKNESS

Figure 3-3 shows the beta backscatter probe response to variations in niobium foil thickness. It is a plot of a complete set of beta backscatter standards consisting of the seven nominal fuel loadings fabricated at Astrofuel plus a non-fueled standard for reference purposes. Observe the linear response up to and including the 1.7 mil niobium thickness, which when converted to NbC equals approximately 2.5 mils NbC. Observe the discontinuity from 1.7 mil to 2.1 mil niobium foil thickness. Observe also that the family of loadings approaches the same saturation points at the high end of the range. Spectral studies are in progress at Astrofuel in an effort to define this second order effect. When these studies are complete, a supplement to this report will be issued to document the results. The statistical analysis performed on a series of probe calibrations reflects an increase in statistical count fluctuations above the 1.7 to 2.1 mil region of figure 3-3. Based on this increase in count fluctuations, the statements on precision in Section 5 are restricted to 2.0 mils niobium and lower. The beta system output data uncertainty, due either to instrumentation or the inherent statistical fluctuations of radiation flux in the detector, limits the precision of the system. Therefore, this beta system evaluation and data analysis was primarily directed at defining the equipment precision. As reported in Section 5, Equipment Precision, the accuracy and or precision of the Astrofuel beta backscatter system is certainly adequate. Also, as stated in paragraph 2.1, direct correlations have been made with metallography over a niobium carbide coat thickness range of 0.5 to 3.0 mils with no significant differences.

3.6 BETA PROBE CORRELATION STUDIES (ASTROFUEL PROBE VERSUS LASL PROBE INSTALLED IN LASL SYSTEM)

3.6.1 Probe Response Versus Thickness

Figure 3-4 illustrates a calibration data comparison between the Y-12 designed probe used at Astrofuel and the LASL designed probe. This correlation was performed at LASL in the LASL beta backscatter system. The fuel element standard used was the Astrofuel built code 9 fuel loading standard. The slopes of the two curves are somewhat similar; however, at the non-coated and low thickness end of the response curve, the LASL

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3-8

Figure 3-3. Beta Backscatter Probe Response to Variations in Niobium Foil Thickness

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Figure 3-4. Comparison of Astrofuel and LASL Probe Calibrations in the LASL Beta Backscatter System

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probe exhibits a greater sensitivity to thickness changes and a lesser sensitivity to fuel loadings. The significant fact here is that the LASL source capsule is aluminum and at a significantly lower intensity than the stainless steel Astrofuel capsule. The spectral study of the Astrofuel sources should define the different responses.

3.6.2 Probe Response Versus Bore Diameter

Figure 3-5 exhibits the response of the LASL and Astrofuel probes respectively to bore diameter variation. This diameter effect was measured in a brass block. The two probes showed opposite responses. This inversion is probably due to the difference in design of the collimator and probe windows.

3.6.3 Relative Axial Sensitivity - LASL Versus Astrofuel Probes

Figure 3-6 illustrates another difference in response by the two probe designs. Their relative axial sensitivities were measured using test pieces made of 0.018 inch thick lead sheet mounted in lucite with a 0.100 inch diameter hole bored through each at a 90 degree angle to the lead.

3.6.4 Summary of Probe Correlation Studies

These correlation studies on the two probe designs show a similarity in performance. However, differences due to the geometry are apparent. One possible consequence of these differences was exhibited in the data correlation of 14 fuel elements. At the start of these correlation studies, Astrofuel was utilizing the same Nb-to-NbC conversion factor as LASL. A data review reflected to 0.4 mil deviation at a thickness of 2.3 mils NbC. (The Astrofuel system indicated 1.9 mils.) Immediately after the preliminary data reduction using the 1.235 conversion factor, the Astrofuel analysis of metallography versus beta backscatter was completed. The data was recalculated using the new Astrofuel data conversion equation given in Section 2, Calibration Standards. The results using the revised conversion formula were correlated with LASL, and no significant differences were found.

Figure 3-5. Responses of Astrofuel and LASL Probes Respectively to Variation of Bore Diameter

SECTION 4

BETA BACKSCATTER SYSTEM APPLICATION

The automated beta backscatter system has two basic modes of operation with a third mode intermixing with the two basic modes. Any operating mode is easily selected by a function switch on the control panel. The systems have been modified to facilitate selecting preprogramed levels down the fuel element for spot-checking coat thicknesses. A spot-check is a measurement taken with the carriage stopped for the time interval of the measurement (4 seconds). Fuel element coating runs or batches are evaluated to the specification coating profile requirements by obtaining a dynamic profile. Dynamic profiles are obtained by continuously moving the beta probe down a selected element channel, accumulating counts over a predetermined length (3 inches), and displaying the total counts on an IBM 026 punch card record after a 4-second time interval. The profile measurement commences at 3 inches from the serial numbered end of the element and a total of 16 increments are measured down to the 51-inch level of the element. Two spot-checks are obtained as the probe exits the element. The following is a brief description of the automated operating modes.

4.1 MODE NO. 1

- (a) Full length channel profile plus two spot-checks in any combination of 1 through 19 channels.
- (b) One spot-check taken concurrently with the profile at either 51 inches from the serial numbered end or 1 inch from the serial numbered end. The location of this spot-check is selectable by the equipment setup technician as specified in the system operating procedure.

(c) A second spot-check taken concurrently with the profile at either 18 inches or 10 inches from the serial numbered end. The location of this spot-check is selectable by the equipment setup technician, as specified by the equipment operating procedure.

4.2 MODE NO. 2

- (a) Spot-check mode of operation.
- (b) All 19 channels or any combination of channels at either 18 inches or 10 inches from the serial numbered end of the element.
- (c) The location of this spot-check is selectable by the equipment setup technician as specified by the equipment operating procedure.

4.3 MODE NO. 3

- (a) Single spot-check in all 18 channels with a full-length channel profile in a predetermined channel, and two spot-checks in the profiled channel.
- (b) One spot-check is taken in the profiled channel at either 51 inches or 1 inch from the serial numbered end of the fuel element. The spot-check is selected as indicated above.
- (c) A second spot-check is taken in the profiled channel at either 18 inches or 10 inches from the serial numbered end of the element. The location of this spot-check is selected by the equipment setup technician and is compatible with the individual spot-checks in the other 18 channels.

SECTION 5

EQUIPMENT PRECISION

A total of 13 repetitive runs were made on each of four code 9 elements. The systems were calibrated repetitively against a single standard conforming to the configuration shown in figure 2-2. The raw data counts from the 13 repetitive runs were converted to niobium carbide thickness.

An analysis* of the data revealed that the precision of the system varies with the thickness being observed. The standard deviation at an indicated thickness of 0.5 mil is ± 0.02 mil and at an indicated thickness of 2.0 mil is ± 0.06 mil. Approximately 95 percent of the time, repetitive measurements made at the same location, in the same channel, will repeat within 0.24 mil at an indicated thickness of 2.0 mils. Also, about 95 percent of the time, repetitive measurements made at the same location in the same channel will repeat within 0.08 mil at an indicated thickness of 0.5 mil.

*WANL-TME-1244, Results of Beta Backscatter Data Evaluation, August 1965.

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SECTION 6

BETA BACKSCATTER CORRELATION WITH LASL AND Y-12 (OAK RIDGE)

A total of 14 fuel elements representing two each of the seven nominal fuel loadings manufactured by Astrofuel were sent to LASL and Oak Ridge. This exchange was an effort to compare all the nondestructive test systems and techniques of which beta backscatter is a part. Each of the three facilities used its existing production standards for calibration. Each also used its own expression for the reduction of equipment output to NbC thickness. Significantly, no two of the three facilities use the same expression for data reduction.

Table 6-1 is a listing of the data from the three facilities. The correlations were made using Astrofuel as a reference for a total of 2660 readings between Astrofuel and LASL, and 2660 readings between Astrofuel and Y-12. A highly significant observation can be made on the accumulative total at the end of the table. Specifically, the comparison of the two different probe designs used by the three facilities and the three different data conversion techniques reflects precision that is within the expected deviations of the Astrofuel single equipment precision. The 14 element exchange verified that the LASL, Y-12 and Astrofuel beta backscatter systems are compatible. A program is underway to assure that this compatibility is maintained.

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TABLE 6-1

COMPARISON OF ASTROFUEL TO LASL AND Y-12 BETA BACKSCATTER RESULTS OF
NbC THICKNESS FROM FOURTEEN INTERCHANGED ELEMENTS

Element Serial Number	Correlated to Astrofuel ≤ 0.1 mil	Correlated to Astrofuel ≤ 0.2 mil	Correlated to Astrofuel ≤ 0.3 mil	Correlated to Astrofuel ≤ 0.4 mil	Correlated to Astrofuel > 0.4 mil	Remarks
99-17364						
LASL	137	44	9	0	0	
Y-12	141	37	12	0	0	
99-17673						
LASL	147	36	7	0	0	
Y-12	132	48	9	1	0	
89-16701						
LASL	144	31	12	3	0	
Y-12	176	9	3	0	0	
89-16717						
LASL	137	18	23	12	0	
Y-12	187	3	0	0	0	
79-15327						
LASL	171	18	1	0	0	
Y-12	188	2	0	0	0	
79-15406						
LASL	166	23	1	0	0	
Y-12	178	12	0	0	0	
69-15051						
LASL	174	16	0	0	0	
Y-12	149	39	2	0	0	

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Element Serial Number	TABLE 6-1 (Continued)					Remarks
	≤ 0.1 mil	≤ 0.2 mil	≤ 0.3 mil	≤ 0.4 mil	> 0.4 mil	
69-15065						
LASL	157	33	0	0	0	
Y-12	84	92	14	0	0	
59-17747						
LASL	163	27	0	0	0	> 0.4 = 0.5 at 2.3 mils total
Y-12	104	59	10	10	7	
59-177 48						
LASL	163	24	3	0	0	
Y-12	171	6	12	1	0	
49-17397						
LASL	185	5	0	0	0	
Y-12	157	30	3	0	0	
49-17466						
LASL	164	25	1	0	0	
Y-12	114	61	15	0	0	
39-17133						
LASL	188	2	0	0	0	
Y-12	180	10	0	0	0	
39-17135						
LASL	178	12	0	0	0	
Y-12	<u>190</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	
TOTALS:						
LASL	2274	314	57	15	0	= 2660
Y-12	2151	408	80	12	7	= 2660
Accumulative Totals & Summary:						
LASL	2274/ 85.5%	2588/ 97.3%	2645/ 99.4%	2660/ 100%	---	
Y-12	2151/ 80.9%	2559/ 96.2%	2639/ 99.2%	2651/ 99.7%	2660/ 100%	

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