LA-5260-T

THESIS

New Techniques in Precision Gamma Scanning

Application to Fast-Breeder Reactor Fuel Pins

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

MASTER

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$7.60; Microfiche \$0.95

LA-5260-T

Thesis

UC 4, 80

ISSUED: July 1973

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New Techniques in Precision Gamma Scanning

Application to Fast-Breeder Reactor Fuel Pins

by

J. R. Phillips

This report is derived from a dissertation submitted to the Chemistry Department of The University of New Mexico in partial fulfillment of requirements for the Degree of Doctor of Philosophy

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TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	xi
ABSTRACT	xiii
CHAPTER	
1. INTRODUCTION	1
2. PRECISION GAMMA SCANNING SYSTEM	5
Scanning Mechanism	5
Collimators	16
Calibration of Individual Collimators	29
Calibration of Collimator Assembly	32
Anticoincidence Detector Assembly	44
Detector Assembly Calibration	50
Ge(Li) Detector	50
NaI(Tl) Anticoincidence Annulus	57
Electronics and Data Acquisition System	60
3. RESULTS AND DISCUSSION	70
Gross Gamma Scanning	70
Multispectral Scanning	74
Two-Dimensional Scanning	81
Detection of Cladding Failure	93
Distributions of ^{134}Cs and ^{137}Cs	97
Quantitative Gamma Scanning	114
Burnup Determination	133
Other Applications of Gamma Scanning	142
4. CONCLUSIONS	144
APPENDIX	
I. COLLUM COMPUTER CODE	146
Program Listing	148
II. SURFACE RESPONSE FUNCTIONS	156

TABLE OF CONTENTS - continued

III. QUADET	164
Sample Calculation for QUADET	165
Card Input for QUADET	178
Program Listing	181
ACKNOWLEDGMENTS	199
REFERENCES	200

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Block Diagram of Basic Gamma Scanning System.	6
2. Fuel Pin Scanning Mechanism with Five Degrees of Freedom, Capable of Handling Fuel Pins up to 63.0 in. long.	7
3. Absolute Position Shaft Encoder and Stepping Motor of Tilt Motion.	9
4. Comparison of Bow Effect on Axial Gross Gamma Distribution of an Irradiated Fuel Pin (Maximum Centerline Variation: 0.054 in.- Top, 0.286 in.- Bottom).	12
5. Bow Correction Adapter with Fuel Pin in Scanning Position.	14
6. Precision Scanning Mechanism in Gamma Hot Cell with Fuel Pin in Scanning Position.	17
7. Primary Collimator and Two Secondary Beam-Scraping Collimators with Inner and Outer Collimator Holders.	18
8. Assembled Primary and First Beam-Scraping Collimators in Hot Cell Wall.	19
9. Betatron Radiograph of Primary Collimator Showing Presence of Voids.	21
10. Betatron Radiograph of Acceptable Primary Collimator.	23
11. Effect of Beam-Scraping Collimator on Gamma-Ray Beam.	24
12. Scanning Geometry of Primary and Secondary Collimators with Film Calibration Positions: A and B.	25
13. Betatron Radiograph of Secondary Collimator Showing Presence of Voids.	27

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
14. Betatron Radiograph of Acceptable Secondary Collimator.	28
15. Probe Configuration for Relative Slit Measurements.	30
16. Relative Slit Heights (in.) as a Function of Precise Probe Position.	31
17. Calculated Projection of Gamma-Ray Beam Image on the Surface of Ge(Li) Detector for 0.025 in. Effective Slit.	34
18. Calibration Plot of Intensity Versus Exposure of Film for Collimator Calibration.	38
19. Theoretical Normalized Intensity as a Function of Vertical Image Position with Experimental Values at 37.000-in. Position.	40
20. Theoretical Normalized Intensity as a Function of Vertical Image Position with Experimental Values at 68.375-in. Position.	41
21. Theoretical Normalized Intensity as a Function of Horizontal Image Position with Experimental Values at 37.000-in. Position.	45
22. Theoretical Normalized Intensity as a Function of Horizontal Image Position with Experimental Values at 68.375-in. Position.	46
23. High-Resolution Ge(Li) Detector with NaI(Tl) Anticoincidence Annulus.	48
24. Detector Assembly in Scanning Position in Front of Gamma Hot Cell.	49
25. Absolute Efficiency Curve as a Function of Gamma Photon Energy.	51
26. Contour Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.	54
27. Density Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.	55
28. Isometric Projection Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.	56

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
29. Maximum Surface Response Ratio as a Function of Gamma Photon Energy.	58
30. Block Diagram of Detector Assembly, Daisy Chain, and Pulse Height Analyzer.	61
31. Block Diagram Showing the Interrelationship of the Pulse Height Analyzer, Digital Computer, and Magnetic Tape Units.	64
32. Data Format for IBM Compatible Magnetic Tape.	67
33. Computer-Controlled Data Acquisition Unit with Magnetic Tape Storage.	69
34. Axial Gross Gamma Distribution of a Mixed Uranium-Plutonium Oxide Fuel Pin. (Pin A)	71
35. Axial Gross Gamma Distribution of a Mixed Uranium-Plutonium Oxide Fuel Pin. (Pin B)	73
36. Rhodium-106 Isotopic Distribution as a Function of Axial Position for Pin A.	75
37. Cesium-137 Isotopic Distribution as a Function of Axial Position for Pin A Showing Concentrations in Interpellet Gaps.	76
38. Axial Isotopic Distributions of ^{106}Rh , ^{137}Cs , ^{95}Zr , and ^{54}Mn for Pin B between 16.00 and 18.00 in.	78
39. Axial Isotopic Distributions of ^{106}Rh , ^{137}Cs , ^{95}Zr , and ^{54}Mn for Pin B between 20.50 and 22.50 in.	79
40. Diametral Isotopic Distributions of ^{106}Rh , ^{137}Cs , and ^{95}Zr for Pin B at 22.00 in. Axial Position.	80
41. Photograph of Thin Cross Section (0.050 in.) Prepared (As Ground) for Two-Dimensional Scanning.	82
42. Density Plot of ^{106}Rh Two-Dimensional Radial Distribution.	83

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
43.	Density Plot of ^{137}Cs Two-Dimensional Radial Distribution.	84
44.	Isometric Projection of ^{137}Cs Isotopic Radial Distribution.	86
45.	Density Plot of ^{144}Pr Two-Dimensional Radial Distribution.	87
46.	Isometric Projection of ^{144}Pr Isotopic Radial Distribution.	88
47.	Diametral ^{106}Rh Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).	89
48.	Diametral ^{137}Cs Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).	90
49.	Diametral ^{95}Zr Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).	91
50.	Isometric Projection of ^{95}Zr from Unfolded Diametral Scans Showing in Fig. 49.	92
51.	Cesium-137 and ^{60}Co Axial Distributions of a Failed Doubly Encapsulated Fuel Pin.	96
52.	Axial Gross Gamma Distribution of a Mixed Oxide Fuel Pin. (Pin C)	100
53.	Axial Gross Gamma Distribution of a Mixed Oxide Fuel Pin. (Pin D)	101
54.	Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin C.	103
55.	Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin D.	104
56.	Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin E.	105
57.	Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin F.	106

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
58. Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin G.	107
59. Cobalt-60 Axial Isotopic Distribution over the UO_2 Axial Blanket of Pin G.	111
60. Rhodium-106 Axial Isotopic Distribution for Section A in QUADET Test before Sample Was Removed.	118
61. Cesium-137 Axial Isotopic Distribution for Section A in QUADET Test Before Sample Was Removed.	119
62. Rhodium-106 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement.	120
63. Cesium-137 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement.	121
64. Rhodium-106 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement after Sampling of Section A.	122
65. Cesium-137 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement after Sampling of Section A.	123
66. Rhodium-106 Axial Isotopic Distribution for Section A in QUADET Test after Sample Was Removed.	127
67. Cesium-137 Axial Isotopic Distribution for Section A in QUADET Test after Sample Was Removed.	128
68. Axial Isotopic Distribution of ^{106}Rh for Differential Burnup Profile Calculations.	136
69. Axial Isotopic Distribution of ^{144}Pr for Differential Burnup Profile Calculations.	137
70. Axial Isotopic Distribution of ^{137}Cs Showing Migration to Interpellet Gaps and to Two Axial Locations (19.00 and 25.00 in.).	138

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
71. Differential Burnup Profiles of Uranium and Plutonium	140
72. Contour Plot of Surface Response Function for 60-keV Gamma Photons of ^{241}Am .	157
73. Contour Plot of Surface Response Function for 511-keV Gamma Photons of ^{22}Na .	158
74. Contour Plot of Surface Response Function for 835-keV Gamma Photons of ^{54}Mn .	159
75. Contour Plot of Surface Response Function for 898-keV Gamma Photons of ^{88}Y .	160
76. Contour Plot of Surface Response Function for 1173-keV Gamma Photons of ^{60}Co .	161
77. Contour Plot of Surface Response Function for 1275-keV Gamma Photons of ^{22}Na .	162
78. Contour Plot of Surface Response Function for 1332-keV Gamma Photons of ^{60}Co .	163
79. Cross Section of Source Used in Quantitative Determination of ^{106}Rh and ^{137}Cs .	166
80. Radial Isotopic Distribution of ^{137}Cs .	170
81. Radial Isotopic Distribution of ^{106}Rh .	171
82. Slit Volume and Step Volume Segment of Cylindrical Source.	173
83. Relationship of Source Factor to Relative Centerline Position for ^{137}Cs and ^{106}Rh Radial Distributions.	176

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Maximum Variation of Centerline	13
II	Seidel Values as a Function of Exposure Time	37
III	P(3) Values of Experimental Images as a Function of Exposure Time for the 37.00-in. Position	42
IV	P(3) Values of Experimental Images as a Function of Exposure Time for the 68.375-in. Position	43
V	Absolute Efficiencies for Detector #441	52
VI	Surface Responses as a Function of Gamma Photon Energy	59
VII	Comparison of Gamma Scanning and Mass Spectrometric Analysis	95
VIII	Densities, O/M Ratios, and Fuel Material	99
IX	Relationship of Oxygen Content to ^{134}Cs Deposition	109
X	Comparison of ^{106}Rh and ^{137}Cs Scanning Results for Section I	124
XI	Comparison of ^{106}Rh and ^{137}Cs Scanning Results for Section A	126
XII	Quantity of Isotope Removed for Radiochemical Analysis	129
XIII	Gamma Scanning and Radiochemical Assay Results	130
XIV	Determination of Absolute Burnup Using QUADET	141
XV	Fuel Composition	167
XVI	Multiplication Factor of Net Full-Energy Peak Areas	175

NEW TECHNIQUES IN PRECISION GAMMA SCANNING
APPLICATION TO FAST-BREEDER REACTOR FUEL PINS

by

J. R. PHILLIPS

ABSTRACT

A new precision gamma scanning system is described. The system is designed for the thorough, detailed, nondestructive characterization of irradiated fast reactor fuel pins. Gamma scanning data are given for failed fuel pins, transfer mechanisms of fission products, quantitative isotopic scanning, and differential burnup profiles.

The system consists of a scanning mechanism for the precise positioning (± 0.001 in.) of the irradiated fuel pin, high density tungsten alloy collimators for defining the volume segment from which the gamma-ray spectra are collected, a large high-resolution anticoincidence detector assembly for resolving complex gamma-ray spectra, and a computer controlled data acquisition unit with magnetic tape storage for processing and storing the gamma-ray spectra.

The complete calibration of the gamma scanning system is presented. This includes the calibration of the effective collimating slit aperture, and the determination of the surface response matrices for the Ge(Li) detector as a function of gamma photon energy.

The gamma scanning system is utilized for the characterization of irradiated fuel pins to determine physical dimensions, specific fission product distributions, fuel cladding

failure of doubly encapsulated fuel pins, fast and thermal neutron flux profiles, and relative and absolute burnup profiles. The transfer mechanisms of ^{134}Cs and ^{137}Cs are investigated, showing the selective deposition of cesium on fuel pellets with high oxygen content. The determination of the differential burnup profiles of ^{235}U and ^{239}Pu mixed-oxide fuel materials is presented. The nondestructive quantitative determination of specific fission products by gamma scanning of irradiated materials is compared to destructive radiochemical assay. These gamma scanning results indicate that the method can be applied to the precise quantitative determination of specific fission products.

A computer code, COLLUM, is described for the determination of the effective slit aperture of complex rectangular collimating slit assemblies. The quantitative determination of specific fission products is accomplished by applying a second computer code, QUADET, which allows the calculational simulation of the source response of cylindrical fuel pins.

The integration of the scanning mechanism, collimators, detector assembly, and data acquisition unit has resulted in a completely automated gamma scanning system. The new non-destructive techniques have been applied to the examination of over a hundred irradiated fast reactor fuel pins.

CHAPTER 1

INTRODUCTION

The Federal Power Commission has projected that the United States will require an additional 1,600 million kilowatts of generating power during the next 30 years. Added to the present capacity of 300 million kilowatts, the present fossil fuel resources will be rapidly depleted. Seaborg has suggested that finite reserves of coal, oil, and gas should be utilized as sources of organic molecules rather than as sources of energy.¹ Fast breeder reactors offer an alternate method of producing economical electrical power, by producing more nuclear fuel than they consume. The Atomic Energy Commission has estimated that \$200 billion (in 1970 dollars) would be saved in the next 50 years in the cost of electrical power, if the schedule for introducing fast breeder reactors is maintained. The first breeder power plant is planned to be operational by 1984.

The fast breeder reactor transforms fertile isotopes (^{232}Th and ^{238}U) into fissionable isotopes (^{233}U and ^{239}Pu) permitting the utilization of vast quantities of low-grade thorium and uranium ores. There are two basic concepts being pursued: liquid metal cooled fast breeder reactors and gas-cooled fast breeder reactors. The major effort has

been in the research and development of the Liquid Metal Fast Breeder Reactor (LMFBR), with a substantially smaller effort being expended in the gas-cooled fast breeder program. The LMFBR would be fueled with mixed uranium (^{238}U) and plutonium (^{239}Pu), with more ^{239}Pu being produced from the transmutation of ^{238}U , than is consumed in the fissioning process.

Many experimental test assemblies are presently being irradiated under conditions similar to those expected in the first LMFBR power plants to evaluate the chemical and physical properties of the fuel and other components. These test assembly experiments provide the information base for future designs and operation plans.

The chemical characterization of experimental fuel materials is an important part of this program. New analytical methods are being developed to complement the classical chemical methods in this application. Gamma scanning is a relatively new method now being applied to the determination of the spatial distribution of fission and activation products within experimental fuel pins in the evaluation of prospective fuel materials.

Rasmussen and coworkers suggested the nondestructive measurement of the burnup of fuel elements using a bent-crystal spectrometer.² This method was limited to the measurement of gamma rays in the 100-300 keV range. These gamma rays are significantly absorbed in the fuel material, resulting in appreciable errors. A magnetic Compton spec-

trometer has been applied to the examination of higher energy (1-4 MeV) gamma rays for scanning irradiated fuel elements.^{3,4}

Sodium iodide scintillation crystals have been used in gamma-ray spectrometers for gamma scanning.⁵⁻⁸ Diggle and Blackadder used a sodium iodide scintillation spectrometer for the measurement of the variation in the activity of selected fission products along the length of irradiated fuel pins.^{6,7} Data from NaI(Tl) detector systems were difficult to analyze and interpret due to the inherently poor resolution of the detector. However, the applicability of gamma scanning was illustrated by the determination of burnup profiles and certain fission product distributions.

The introduction of high resolution germanium semiconductor detectors resulted in the increased application of the nondestructive examination of irradiated fuel pins.⁹⁻¹⁴ Precision gamma scanning was used not only for the determination of gross gamma activity distributions and burnup profiles, but for fission product distributions and radial isotopic distributions.¹⁵⁻²⁷

A new gamma scanning system for the examination of irradiated fuel pins is described in this paper. The system consists of a scanning mechanism, collimating slits, detector assembly and automated data acquisition unit. Each of the four components and their respective calibration will be discussed in the next chapter. Computational methods have been developed for the complete evaluation of the precision collimators. The surface responses as a function of precise

position and gamma-ray energy have been determined for the Ge(Li) detectors used in this investigation.

The calibrated system has been applied to the diametral and axial scanning of irradiated fuel pins, as well as two dimensional scanning. Gamma scanning methods have been developed for the nondestructive investigation of the fuel cladding integrity of doubly encapsulated fuel pins. The transfer mechanism of the ^{134}Cs and ^{137}Cs precursors have been investigated. The practicality of using gamma scanning for quantitative analysis of fission products without the necessity of maintaining a large inventory of standards was examined. Also, the differential burnup profiles for uranium and plutonium were determined.

Gamma scanning has been shown to be one of the most powerful methods for the nondestructive examination of irradiated fuel pins. Comparable data can only be obtained by the destructive sampling of the fuel specimen and subsequent chemical analysis. Gamma scanning is not limited by the problems of selecting a representative sample because the entire specimen is examined. Being a nondestructive analysis, the fuel pins integrity is maintained permitting additional analyses to be performed as required.

Because of its many advantages, gamma scanning has become an integral part of the nondestructive examination of irradiated fuel pins. All of the hundreds of irradiated fuel pins examined at the Los Alamos Scientific Laboratory are gamma scanned prior to disassembling for destructive examination.

CHAPTER 2

PRECISION GAMMA SCANNING SYSTEM

The precision gamma scanning system consisted of essentially four separate parts: a scanning mechanism for the precise positioning of the irradiated fuel pin, a set of high-density collimators for the precise definition of the volume segment from which the gamma-ray spectra were collected, a high-resolution anticoincidence detector assembly, and an automated data acquisition unit with magnetic tape storage.²⁸⁻⁴⁰ (Fig. 1)

Scanning Mechanism

The scanning mechanism shown in Fig. 2 had five degrees of movement: X, Y, Z, tilt, and rotation. Each motion was controlled by precision stepping motors coupled to absolute position shaft encoders with binary-coded-decimal readout. The individual degrees of movement: X, Y, Z, and tilt, were positioned with a precision of ± 0.001 in., while the rotation motion was set with a precision of ± 1.8 degrees. The scanning mechanism accommodated fuel pins 23.0 to 63.0 in. long and up to 3.0 in. in diameter.

The accuracy of the Z-motion was ± 0.002 in. over 63.0 in. of travel, Y-motion was ± 0.002 in. over 32.0 in., and X-motion

Fig. 1. Block Diagram of Basic Gamma Scanning System.

SCANNING MECHANISM

Fig. 2. Fuel Pin Scanning Mechanism with Five Degrees of Freedom, Capable of Handling Fuel Pins up to 63.0 in. long.

was ± 0.0005 in. over 6.0 in. The precision ball screws had a 0.200-in. pitch resulting in 5 revolutions per inch of travel. The ball screws were attached to Slo-Syn precision stepping motors having 200 steps per revolution. The absolute position of each motion was obtained from bi-directional position shaft encoders with binary-coded-decimal readout from 00.000 in. to 99.999 in. The shaft encoders, as well as the bifilar stepping motors, had 200 divisions per revolution and therefore were attached directly to the stepping motor shafts. Because of space limitations in the hot cell, the Z-shaft encoder was attached directly to the stepping motor shaft, and the X, Y, tilt, and rotation encoders were coupled to their motors through spring-loaded anti-backlash gears.

The X, Y, tilt, and rotation encoders were placed alongside their respective stepping motors to provide additional physical support. The mounting is shown in the Fig. 3 for the tilt motion. The encoder gear was split with the two halves being pre-loaded with two springs. This reduced the effect of backlash, and eliminated play between the encoder and motor gears.

The shaft encoders and stepping motors were precisely phased to ensure that each step of the motor corresponded to an incremental step in the shaft encoder. The correct phasing was accomplished by applying power to the motor to guarantee that the motor was positioned in the middle of a rotational step. The least significant digit of the binary-

Fig. 5. Absolute Position Shaft Encoder and Stepping Motor of Tilt Motion

coded-decimal encoder was centered on the corresponding stepping motor position. Then the encoder shaft was locked in place with two set screws. The absolute zero position of each motion was arbitrarily set at the minimum physical limit.

The principal motions, X and Z, used for diametral and axial gross gamma scanning and multispectral scanning, were controlled by programmable scan controllers. The scan controllers operated via closed-loop feedback to ensure that the irradiated fuel pin was correctly positioned. The absolute position of the shaft encoder was monitored and compared to the desired position. If the two positions were not identical, the stepping motor was pulsed and the absolute position encoder was interrogated after a 100 msec delay. This process was repeated until the sample was correctly positioned, thus ensuring that the data were collected at the desired locations. The 100 msec delay was necessary to allow the physical oscillations of the stepping motor about its final position, (20 msec), and the mechanical resonance of the scanning mechanism to be eliminated before the shaft encoder reading was taken. The specific time delay was dependent upon the stepping motor, the physical dampening, and the mechanical resonance of the mechanism. A spring-loaded Teflon dampening device was added to the Z-motion.

The X and Z scan controllers had a selectable backlash takeup. As the direction of the motion of a precision ball screw was changed, there was a finite amount of wrap-up over the ball screw length. The selectable backlash takeup was

hardwired and was selected as 0.010 in., 0.020 in., 0.040 in., or 0.080 in. with a jumper plug. This additional feature allowed X, Z, and XZ scans to be performed with the highest degree of accuracy (± 0.001 in.). The Y, tilt, and rotation motions were controlled by Slo-Syn precision stepping motors by preset indexers with the absolute positions being monitored with BCD shaft encoders. Any two of the five separate motions could have been controlled with the programmable scan controllers.

A mechanical adapter was incorporated in the scanning mechanism to ensure the correct positioning of irregular fuel pins exhibiting bow or twist. The specific source response of a fuel pin was dependent upon its position with respect to the centerline of the rectangular collimating slit. This effect will be discussed in detail in the section on the computer codes. A typical example of the effect of bow or twist is shown in Fig. 4. The gross gamma activity was presented as a function of axial position for the same fuel pin at two different rotations, 22.5° and 112.5° .

The two axial distributions were significantly different and could lead to significant error if the presence of twist were not ascertained. The enriched fuel column, 13.370 ± 0.010 in. long, was scanned diametrically at the top, middle, and bottom to determine the variations of the fuel pin centerline as a function of rotational position. (Table I)

The necessary adapter for correcting this problem is shown in Fig. 5. The adapter consisted of three rollers in

Fig. 4. Comparison of Bow Effect on Axial Cross Gamma Distribution of an Irradiated Fuel Pin (Maximum Centerline Variation: 0.054 in. - Top, 0.286 in. - Bottom).

TABLE J
MAXIMUM VARIATION OF CENTERLINE

<u>Rotational Position</u>	<u>Deviation of Centerline</u>
0.0°	0.114 in.
22.5°	0.054 in.
45.0°	0.069 in.
67.5°	0.180 in.
90.0°	0.258 in.
112.5°	0.286 in.
135.0°	0.279 in.
157.5°	0.240 in.
180.0°	0.145 in.

Fig. 5. Bow Correction Adapter with Fuel Pin in Scanning Position.

a triangular arrangement. Two of the rollers were stationary and restricted the movement of the bowed pin in the X-direction, while the third roller was spring-loaded and compensated for changes in the fuel diameter. The centerline of the adapter coincided with the centerline of the collimating slit. Each fuel pin was placed in the scanning mechanism so that one end was held by the adapter and the other end of the fuel pin was rigidly fixed in the scanning mechanism. As a bowed or twisted fuel pin was moved vertically, the volume defined by the collimating slit remained centered with respect to the slit. The adapter reduced the "bow or twist effect" upon the sample activity and improved the reliability of the gamma scanning results.

The bow adapter was moved back and locked in place to allow the bow or twist of the fuel pin to be measured by holding the pin rigidly at both ends and scanning diametrically at specific axial positions. By determining the differences in the centerlines, it was possible to determine the fuel pin's centerline in the XY plane.

The scanning mechanism was designed without any structural material in line with the collimating slit and the fuel pin. This design reduced the occurrence of backscatter peaks from the Compton scattering which might either have been mistaken for, or interfered with the full-energy peaks.

The scanning mechanism was placed in a 6- by 6-ft hot cell with 34.75-in.-thick walls that allowed the examination of irradiated fuel pins with up to 10 kilocuries of 1 MeV

gamma rays. (Fig. 6)

The scanning mechanism was securely anchored to the cell floor with four 0.5-in. bolts to minimize vibration effects. The irradiated pins were loaded remotely using the two Master-Slave manipulators shown in Fig. 6.

Collimators

The gamma scanning system required precise collimation of the gamma-ray beam to obtain the spatial distributions of the gamma-ray emitting isotopes. The collimator arrangement consisted of three separate collimators: a primary collimator which precisely defined the specific volume segment examined, and two beam-scraping collimators which shielded the anticoincidence annulus from the gamma-ray beam. (Fig. 1)

The collimators and the collimating assembly are shown in Fig. 7. Three primary collimators were constructed. Each of the three slits was 0.500 in. wide, 8.125 in. long, while they differed in height: 0.004 in., 0.010 in., and 0.020 in. high. They were constructed of a high-density tungsten-copper alloy insert surrounded with low activity lead. (Fig. 8) The primary slits were constructed of high-density material (17.72 g/cm^3) with a linear gamma attenuation coefficient 1.45 times as large as the lead used for the beam-scraping collimators.

Each primary collimating slit was fabricated from two pieces of tungsten-copper alloy which had been radiographed using a 22 MeV Betatron to ensure uniform density and the

Fig. 6. Precision Scanning Mechanism in Gamma Hot Cell with Fuel Pin in Scanning Position.

Fig. 7. Primary Collimator and Two Secondary Beam-Scraping Collimators with Inner and Outer Collimator Holders.

Fig. 8. Assembled Primary and First Beam-Scraping Collimators in Hot Cell Wall.

absence of voids. The two pieces were precisely machined, fastened together with two steel clamps, placed in a mold casing, and molten lead poured around the insert. The alignment of the insert was maintained with 0.375-in. steel end plates on the collimator casing. The molten lead was slowly cooled to avoid density variations of the lead; should the lead density be nonuniform the collimation effects would be more difficult to predict.⁴¹ Finally, the completed primary collimators were radiographed to determine if significant voids existed.⁴²

The Betatron radiograph of the 0.004-in. slit at 0° is shown in Fig. 9. The tungsten insert was clearly visible as the lighter region in the radiograph. The outer surface of the tungsten insert was stepped to eliminate the possibility of gamma rays streaming through the crack between the tungsten and lead. The two steel clamps were evident as the dark bands around the insert. Also, the three dark spots separated by 120° and located about 1.5 in. from both ends, resulted from three rods extending into the lead from the outer steel casing. These rods maintained the alignment of the slit with respect to the collimator holders. The radiograph showed irregular dark images which revealed the presence of extensive voids. This radiograph showed that the lead had been allowed to cool too rapidly forming the voids described above. The 0.004-in. primary collimator was repoured with the cool-down procedure modified to slow the lead solidification process. The improvements obtained can be seen in the

Fig. 9. Betatron Radiograph of Primary Collimator Showing Presence of Voids.

next Betatron radiograph for the 0° orientation. (Fig. 10)

The first and second beam-scraping collimators were fabricated of low activity lead. The necessity of the beam-scraping collimators can be seen in Fig. 11, with a projection on the XY plane of a primary collimator and one beam-scraping collimator. The detector system will be discussed in detail in the following section. Briefly, it consisted of the principal Ge(Li) detector surrounded by an anticoincidence NaI(Tl) annulus. For reasons to be discussed in the next section, the NaI(Tl) anticoincidence annulus was shielded from the gamma-ray beam. The beam-scraping collimators restrict the beam's divergence to the surface of the Ge(Li) detector.

The beam-scraping collimators were rectangular slits, with the first beam-scraping collimator being 6.250 in. long and located 8.875 in. from the primary collimator which was 8.125 in. long. The second beam-scraping collimator, 7.875 in. long, was located 21.000 in. behind the first beam-scraping collimator and 44.250 in. from the front surface of the primary collimator. The first beam scraper was 0.750 in. wide and 0.032 in., 0.079 in., and 0.126 in. high for the 0.004-in., 0.010-in., and 0.020-in. primary collimators, respectively. (Fig. 12) The second beam scraper was 0.750 in. wide, 0.500 in. high, and 7.875 in. long.

The lead secondary collimators were fabricated by placing a shim of the desired rectangular dimensions coated with a releasing compound in the collimator mold and pouring lead

Fig. 10. Betatron Radiograph of Acceptable Primary Collimator.

Fig. 11. Effect of Beam-Scraping Collimator on Gamma-Ray Beam.

Fig. 12. Scanning Geometry of Primary and Secondary Collimators with Film Calibration Positions: A and B.

around the shim. The shim's alignment was maintained by attaching both ends to a tensile test machine and applying a pulling force while the lead was poured and cooled around the shim. As in the case of the primary collimators, the lead was cooled in programmed steps to ensure an uniform pour. Once the lead had cooled, the tensile test machine was used to withdraw the shim from the lead by releasing one end and slowly pulling the shim through the lead.⁴¹ The rectangular slits were cleaned of extraneous pieces of lead and subsequently radiographed.

The betatron radiograph of the 0.126 in. beam-scraping collimator with several significant voids is shown in Fig. 13. The collimator was melted and repoured resulting in the final radiograph shown in Fig. 14. All of the collimators fabricated were examined in the same manner for voids and anomalies, and were repoured until no such voids were apparent.

The primary and the first secondary collimator were mounted directly in the hot cell wall in a collimator holder which allowed the independent rotational movement of each collimator. The holders were interchangeable permitting the easy changing of collimators. With a separate set of holders for each of the three rectangular slit collimators, they needed only to be aligned once. The collimating slit alignment was checked every six months as a periodic calibration for quality assurance.

The collimator holders were stepped to shield the detector from the streaming of gamma rays between the holder and cell

Fig. 13. Betatron Radiograph of Secondary Collimator Showing Presence of Voids.

Fig. 14. Betatron Radiograph of Acceptable Secondary Collimator.

wall. (Fig. 8) The holder extended into the hot cell 2.5 in. permitting an irradiated sample held in the scanning mechanism to be positioned as close as possible to the front of the primary collimating slit. A 0.0625-in. quartz window, 3 in. in diameter, covered the holder extension to prevent the radioactive contamination of the primary collimating slit if a fuel capsule had inadvertently ruptured.

Calibration of Individual Collimators

The individual collimators were examined by 22 MeV radiography for the detection of voids as described above. Each collimator passing the radiography inspection was inspected by physical dimensioning to a precision of ± 0.00020 in. at selected points inside the collimating slit. This was accomplished by passing a thin wire through the slit on which a precisely measured probe was placed as shown in Fig. 15. The slit and wire were aligned to be parallel and the wire and probe were held stationary while the collimator was moved in the X-direction. The position of the wire was recorded when the probe made electrical contact with the edge of the collimating slit.

The measurements of the height of the 0.020-in. collimating slit at 1.000-in. intervals at the left, center, and right are shown in Fig. 16. The measurements were precise but the absolute accuracy may have been biased by the method of measurement. As mentioned above the probe's position was recorded when electrical contact was made. In the lead

Fig. 15. Probe Configuration for Relative Slit Measurements.

Fig. 16. Relative Slit Heights (in.) as a Function of Precise Probe Positions.

collimators an oxide film covered the inside surface of the collimating slit which acted as an insulator. It was not known what pressure, if any, was required to force the probe through the oxide layer to make electrical contact. Any force would cause the wire to be displaced, resulting in the possibility of errors in the absolute measurements.

All the measurements were made with the collimator being moved in the same direction, to eliminate the wrap-up error in the gauging machine. Consequently the positions of one side were obtained by measuring the position when electrical contact was interrupted, and the other side when electrical contact was initiated. If the oxide layer were assumed to be uniform, the numbers obtained from such measurements can be used to determine the relative changes in the slit height as a function of precise position. All of the collimators were inspected using this method of measurement.

Calibration of Collimator Assembly

The alignment of the collimating slits was necessary to ensure that the volume segment of the pin, viewed by the detector assembly, was precisely defined. As the fuel sample was positioned by the scanning mechanism and the results correlated as a function of precise position, the collimators were aligned with respect to the scanning mechanism motions. The two principal methods of scanning required the alignment of the slits vertically as well as horizontally.

The actual alignment procedure consisted of inserting a

shim into the collimating slit and using an insulated needle attached horizontally or vertically to the scanning mechanism. In the horizontal aligning procedure the needle was placed vertically on the scanning mechanism. The needle was moved vertically until electrical contact was made to one side of the shim. The position was recorded to ± 0.0005 in. The needle was lowered, moved horizontally to the other edge of the shim and moved vertically until electrical continuity was established. The two vertical positions should agree within ± 0.0005 in. if the slit were horizontally aligned with the vertical motion. The process was repeated for the vertical alignment. The primary collimating slits were therefore precisely aligned (± 0.0005 in.) with respect to the scanning mechanism.

The two secondary beam-scraping collimators were aligned with respect to the primary collimating slit. The primary collimator and the first beam-scraping collimator were locked into place in the collimator holder using set screws located at 120° intervals.

The effect of the collimator arrangement on the volume segment was calculated for various collimators using the COLLIM computer code. The detailed description of the code is in Appendix I. The code calculates the collimator effect of an uniform source which is assumed to be planar in the XZ plane.⁴³ Typical calculated results are shown in Fig. 17 for a 0.025-in.-high, 0.500-in.-wide, and 8.125-in.-long primary collimator and two beam scraping collimators for the

Fig. 17. Calculated Projection of Gamma-Ray Beam Image on the Surface of Ge(Li) Detector for 0.025 in. Effective Slit.

scanning geometry of our scanning system. The data were presented in a density plot as a function of gamma ray intensity with respect to position. The circle represented the outer circumferences of the Ge(Li) crystal. The beam-image only covered a fraction of the crystal. This effect was especially important when the relative efficiency of the detector as a function of crystal surface position was considered. Note that the intensity of the gamma ray beam over the illuminated surface area was nonuniform, varying from a maximum at the center to a minimum of zero at different distances in the X and Y directions. The area and relative intensity of the rectangular image was a function of the primary collimator and beam scraping collimators and varied with each collimator configuration.

The effective collimating slit aperture was defined as the collimation of the gamma-ray beam as viewed from the surface of the detector. The effective slit aperture was not identical to the measured slit, but generally larger. For example, for the 0.020-in. collimator described above, the average measured collimator height was 0.0197 in. However, the effective slit height was determined to be 0.025 in., by measuring the collimated beam divergence at various distances from the primary collimator.

To measure the effective slit height x-ray film was exposed to the gamma ray beam at positions A and B shown in Fig. 12, and the height and width of the resulting image was measured by densitometry. Six types of standard film: Profes-

sional Copy, Royal Pan, Fine Grain, ERTA PAN, PAN-X, and High Resolution, and Type A x-ray film were tested as possible recording films before deciding to use Kodak Blue Brand x-ray film. The first five gave uninterpretable images and the High Resolution film with its extremely slow film speed gave no image at all. Type A film exposure, also, resulted in a blank film.

The densities of the film images were measured as a function of precise positions, the densities were converted to Seidel values, transformed to intensities, and the intensities were plotted as a function of precise position.⁴⁴ The x-ray film was calibrated to determine the linearity of intensity as a function of exposure time. To accomplish the calibration an uniform radioactive source was positioned to cover totally the primary collimating slit, and 4 exposures for various time periods at the same position were made. The film was placed in Position A at 37.0 for 6-, 16½-, 17½-, and 18-hr. exposures. The results of the Seidel values with respect to intensities and their respective standard deviations are presented in Table II and plotted in Fig. 18. The Seidel function, $[\log (10^D) - 1]$, was linear at lower density values and the four points were fitted with a linear least squares function. The data approximated a straight line, indicating that the film response was linear.

The theoretical intensity distributions as a function of positions were calculated using the COLLUM computer code, mentioned above and described in Appendix I. The experimental

Table II

Seidel Values as a Function of Exposure Time

<u>Time</u>	<u>Seidel Value</u>
6.00 h	0.164 $\pm$ 0.017
16.25 h	0.436 $\pm$ 0.016
17.25 h	0.509 $\pm$ 0.018
18.00 h	0.532 $\pm$ 0.025

Fig. 18. Calibration Plot of Intensity Versus Exposure of Film for Collimator Calibration.

results for the four exposures are plotted in Fig. 19 for the 37.0 in. position. Similar results are also presented in Fig. 20 for the films exposed at 68.375 in. This position corresponded to the surface of the Ge(Li) detector.

The theoretically calculated distributions for the 0.025-in. effective slit were superimposed on the experimental curves. Both the calculated and experimental data were fitted using a least squares routine to a Gaussian function plus a background contributing term,

$$F(x) = \frac{P(1)}{P(3) \sqrt{2\pi}} \cdot \exp \left[-\frac{1}{2} \left| \frac{P(2) - x}{P(3)} \right|^2 \right] + P(4) \quad (1)$$

where $P(1)$, $P(2)$, $P(3)$, and $P(4)$ were allowed to change.⁴⁵ $P(3)$ was the square root of the variance, or the standard deviation and was a measure of the width of the normal distribution function. The $P(3)$ values for the four different exposures are presented in Table III, with the $P(3)$ values for the calculated distributions at the 37.0-in. position. Similar results are shown in Table IV for the two 24-h exposures at the 68.375-in. position. This position corresponded to the surface of the Ge(Li) detector.

The $P(3)$ values were based on the function of a Gaussian plus a background, however, the calculated distributions had zero backgrounds. Therefore, the $P(3)$ values had to be corrected for the effect of the nonzero backgrounds for comparison with the theoretical values. The corrected values were determined by measuring the widths of the distributions at

Fig. 19. Theoretical Normalized Intensity as a Function of Vertical Image Position with Experimental Values at 37.000-in. Position.

Fig. 20. Theoretical Normalized Intensity as a Function of Vertical Image Position with Experimental Values at 68.375-in. Position.

Table III

P(3) Values of Experimental Images as a Function
of Exposure Time for the 37.000-in. Position

<u>Exposure-Time</u>	<u>P(3) $\pm \sigma$</u>	<u>Corrected M/e</u>
6 h	1.289 $\pm$ 0.070 (3)*	3.61
16½ h	1.205 $\pm$ 0.023 (3)	3.43
17½ h	1.207 $\pm$ 0.012 (3)	3.43
18 h	1.298 $\pm$ 0.002 (3)	<u>3.65</u>
		3.51 mean

P(3) Values of Theoretical Image as a Function
of Slit Height for the 37.000 in. Position

<u>Theoretical Slit</u>		
0.020 in.	1.095	2.67
0.022 in.	1.123	2.90
0.024 in.	1.294	3.27
0.025 in.	1.311	3.48
0.026 in.	1.433	3.54

* The numbers in parenthesis represent the number of measurements in each set of values.

Table IV

P(3) Values of Experimental Images as a Function
of Exposure Time for the 68.375-in. Position

<u>Exposure-Time</u>	<u>P(3) $\pm \sigma$</u>	<u>Corrected M/e</u>
24 h	2.459 $\pm$ 0.027 (3)*	6.21
24 h	2.403 $\pm$ 0.163 (3)	<u>6.30</u>
		6.25 mean

P(3) Values of Theoretical Image as a Function
of Slit Height for the 68.375-in. Position

<u>Theoretical Slit</u>		
0.022	2.109	5.46
0.024	2.311	6.07
0.025	2.431	6.20
0.026	2.526	6.47

* The numbers in parenthesis represent the number of measurements in each set of values.

comparable heights on the plots. The widths were measured at the maximum height divided by e (2.718) or M/e .

The results in Table III and IV indicated that the effective collimating slit height was 0.025 in. The experimentally determined M/e values for the 37.0-in. and 68.375-in. positions of 3.51 and 6.25 mm, respectively, corresponded to the values for the theoretical 0.025-in. slit of 3.48 and 6.20 mm, respectively.

The effective collimation in the X-direction was determined by the second beam-scraping collimator located in the detector shield assembly. The effective slit width for the collimating arrangement was determined in a similar manner as described above. The results for the 37.0-in. and 68.375-in. positions are shown in Figs. 21 and 22 with the corresponding theoretical points. The theoretical values were determined by fitting the calculated values from COLLUM with a six degree polynomial.

Anticoincidence Detector Assembly

The detector assembly consisted of a large, high-resolution Ge(Li) detector surrounded by an 8 in. by 12 in., NaI(Tl) anticoincidence annulus encased in a low gamma activity lead cask. The basic detector arrangement can be seen in Fig. 23. The 50-cm³ closed-end coaxial Ge(Li) detector had a resolution of less than 2.7 keV for the 1332.5 keV full-energy peak of ⁶⁰Co. The energy conversion processes within Ge(Li) detectors have been adequately described in the literature.⁴⁶

Fig. 21. Theoretical Normalized Intensity as a Function of Horizontal Image Position with Experimental Values at 37.000-in. Position.

Fig. 22. Theoretical Normalized Intensity as a Function of Horizontal Image Position with Experimental Values at 68.375-in. Position.

The NaI(Tl) anticoincidence annulus allowed the collection of spectra with a peak-to-Compton ratio of at least 100:1 for routine analyses. A gamma photon striking the Ge(Li) detector and being scattered into the NaI(Tl) annulus was rejected by the pulse height analyzer. (Gamma Photon A in Fig. 23) The only gamma photons processed by the pulse height analyzer were those that deposited their total energy in the Ge(Li) detector, Gamma Photon B, or those that interacted with the Ge(Li) detector with a small angle scatter and passed through the unshielded end of the annulus. (Gamma Photon C)

The anticoincidence mode of data collection improved the resolution of the full-energy peaks, especially those that would normally lie on high Compton backgrounds. The precision for the determination of net full-energy peak areas was improved by increasing the relative peak-to-background ratio.

The detector assembly was mounted in a yoke which was moved using four synchronized stepping motors coupled to an absolute position shaft encoder. The detector assembly in its scanning position is shown in Fig. 24. The positioning mechanism ensured the precise alignment of the entire assembly with the collimating slits. The vertical motion of the assembly was controlled with a precision of ± 0.001 in. The detector assembly holder was mounted on a track parallel to the face of the hot cell to permit it to be moved when changing the collimator holders in the wall. The horizontal

Fig. 23. High-Resolution Ge(Li) Detector with NaI(Tl) Anticoincidence Annulus.

Fig. 24. Detector Assembly in Scanning Position in Front of Gamma Hot Cell.

position was controlled by a micrometer mounted on the base plate of the track to guarantee reproducible positioning of the entire mechanism. The need for precise positioning of the detector assembly will be discussed in the next section on the detector assembly calibration.

Detector Assembly Calibration

This section will be divided into two sections, one for the Ge(Li) detector and one for the NaI(Tl) anticoincidence annulus.

Ge(Li) Detector

The Ge(Li) detector had a 50-cm^3 nominal active volume, with a coaxial, closed-end drift configuration. The detector was 41.8 mm in diameter, 40.7 mm long with an average drift depth of 16.5 mm. The detector was mounted in an elongated cryostat with a 0.010-in. end cap.

The absolute efficiency of the Ge(Li) detector was determined using two sets of certified International Atomic Energy Agency (IAEA) gamma standards (#216 and #217). The efficiency curve shown in Fig. 25 was obtained using these standards. The specific gamma standards used and their absolute efficiencies are listed in Table V.

These efficiency values represent the average efficiencies over the entire surface of the detector and represent the integral of specific point efficiencies over the surface. As shown in the section on calibration of collimators, only

Fig. 25. Absolute Efficiency Curve as a Function of Gamma Photon Energy.

Table V

Absolute Efficiencies For Detector #441

Isotope	Energy-keV	% Absolute Efficiency	
		Std #216*	Std #217*
²⁴¹ Am	59.543	16.62 ± 0.32	17.32 ± 0.33
⁵⁷ Co	121.97	54.25 ± 1.22	54.60 ± 1.23
⁵⁷ Co	136.33	49.69 ± 5.71	48.35 ± 5.55
²² Na	511.006	15.37 ± 0.15	15.20 ± 0.15
¹³⁷ Cs	661.635	11.61 ± 0.17	11.67 ± 0.17
⁵⁴ Mn	834.81	9.14 ± 0.11	9.04 ± 0.11
⁸⁸ Y	898.04	8.56 ± 0.21	8.72 ± 0.20
⁶⁰ Co	1173.23	6.44 ± 0.06	6.48 ± 0.06
⁶⁰ Co	1332.49	5.70 ± 0.05	5.79 ± 0.05
⁸⁸ Y	1836.13	4.08 ± 0.11	4.01 ± 0.11

* Refer to IAEA certified source standards.

a small rectangular surface area of the detector was exposed to the gamma-ray beam. (Fig. 17) Therefore it was necessary to determine the point-by-point efficiencies over the detectors surface.

This was accomplished by exposing precise positions on the detector surface to a collimated beam of gamma rays of various energies and recording the resulting spectra.⁴⁷ The net areas of the full-energy peaks were determined by spectral unfolding and plotted as density plots, isometric projections, and contour plots. Typical results for the efficiency mapping of the collimated 661.6-keV gamma ray of ^{137}Cs are shown in Figs. 26, 27, and 28. Similar results for ^{241}Am (59.5 keV), ^{22}Na (511 keV), ^{54}Mn (834.5 keV), ^{88}Y (898 keV), ^{60}Co (1173 keV), ^{22}Na (1275 keV), and ^{60}Co (1332.5 keV) are presented as contour plots in Appendix II.

The relative efficiencies were recorded every 0.100 in. in the X and Z directions, resulting in a 21 x 21 matrix of gamma-ray spectra. The contour lines represent 10% steps in the relative net full-energy peak areas: G = 90%, F = 80%, E = 70%, D = 60%, C = 50%, B = 40%, and A = 30% of the maximum peak area. The ^{137}Cs efficiency mapping showed the effect of the p-type core surrounded by the Li-compensated layer.

The absolute efficiency of each point was calculated from the absolute average efficiencies for the entire surface area given in Table V. Therefore it was possible to calculate the efficiency of the detector to any collimated

Fig. 26. Contour Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.

Fig. 27. Density Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.

Fig. 28. Isometric Projection Plot of Surface Response Function for 661.6-keV ^{137}Cs Gamma Photons.

gamma-ray beam.

The relative efficiencies over the detector's surface varied as a function of gamma-ray energy and had to be considered when comparing the isotopic activities of different gamma rays. To illustrate this point, the ratio of the maximum in the outer region to the minimum in the center was plotted as a function of gamma-ray energy in Fig. 29. As can be seen from this plot and Table VI, the ratios varied from 1.01 to 2.39.

The shape of the undrifted p-type core was determined nondestructively as the net full-energy peak areas were proportional to the depth of the intrinsic region.⁴⁷ The position of the p-core was calculated by scanning the detector at different angles with a collimated gamma-ray beam.

NaI(Tl) Anticoincidence Annulus

The NaI(Tl) anticoincidence annulus crystal was 8.0 in. in diameter and 12.0 in. in length.³⁵ The crystal had a pulse height resolution of at least 25% with a ^{137}Cs source for any axial source position. The crystal was split in two halves along the length axis with each section isolated from the other. Each half of the NaI(Tl) crystal had three photomultiplier tubes with magnetic shields and voltage dividers. The three photomultiplier tubes on each section had to be electronically matched so that the same response was obtained from the same gamma photon interacting at different locations in the crystal. Gain and threshold parameters for each photo-

Fig. 29. Maximum Surface Response Ratio as a Function of Gamma Photon Energy.

Table VI

Surface Responses as a Function of Gamma Photon Energy

Isotope	Energy(keV)	<u>Net Counts</u>		Ratio(Max/Min)
		Maximum	Minimum	
^{241}Am	59.543	5553	5475	1.014 ± 0.02
^{22}Na	511.006	20958	8960	2.340 ± 0.03
^{137}Cs	661.635	13855	6073	2.280 ± 0.04
^{54}Mn	834.81	4825	2413	2.000 ± 0.05
^{88}Y	898.04	498	208	2.390 ± 0.20
^{60}Co	1173.23	13501	8149	1.660 ± 0.02
^{22}Na	1275.0	9954	6051	1.650 ± 0.03
^{60}Co	1332.49	13340	8468	1.580 ± 0.02
^{88}Y	1836.13	412	257	1.600 ± 0.13

multiplier were determined experimentally using a ^{60}Co gamma source and matching spectra.

The Ge(Li) detector was inserted into the 2.5-in. annular hole of the NaI(Tl) crystal. This detector arrangement allowed the system to be operated in anticoincidence, coincidence and triple coincidence modes of data collection. The NaI(Tl) crystal was encased in a protective aluminum can and the entire detector system was surrounded by 6.0 in. of low gamma activity lead, except for the end of the assembly facing the hot cell wall, which had 8.0 in. of lead.

Electronics and Data Acquisition System

The basic data acquisition unit was a Nuclear Data 50/50 pulse height analyzer with a PDP-8L computer, IBM-compatible magnetic tape unit, and associated daisy chain units.⁴⁸ Complete gamma-ray spectra with up to 4096 channels were accumulated at each programmed position along the major axis or across the diameter of the irradiated fuel pin, the data analyzed and written on magnetic tape, and the scanning mechanism was moved to the next position where the data cycle was again initiated.

The daisy chain contained a time-of-day clock, two programmable scan controllers with positive feedback, three parallel-to-serial converters, a nuclear counter, six scalars, and eight data modules. (Fig. 30) The daisy chain arrangement contained up to 22 separate units in any sequence, which were interrogated by the PDP-8L computer and reset or pulsed

Fig. 30. Block Diagram of Detector Assembly, Daisy Chain, and Pulse Height Analyzer.

at the completion of a data cycle.

The time-of-day (TOD) clock was a 24-hour clock, with the time being presented in a 6-digit display. The TOD was recorded at the completion of the accumulation of the gamma-ray spectra, permitting decay time corrections to be applied when examining isotopes with relative short half-lives.

The two programmable scan controllers controlled the X and Z motions of the scanning mechanism as discussed in the section on the scanning mechanism. The scan controllers were operated individually for one dimensional scanning in the X or Z direction, or together for a two dimensional scan in the XZ-plane. The scan controllers were also used for the Y, tilt, and rotation motions by switching the encoder cables and motor power cables. There were three sets of thumb-wheel switches on the front of the scan controllers for setting in the lower limit and upper limit within 0.001 in. of the scanning motion, and the incremental stepsize to multiples of 0.001 in.

The absolute positions of the X and Z motions were displayed in a 5-digit Nixie tube display. The absolute positions were scanned at the end of a spectra and stored in the computer memory, and the particular motion was incremented and checked with feedback until the scanner was correctly positioned.

The three parallel-to-serial converters were attached to the Y, tilt, and rotation shaft encoders. The five digit position of each encoder was converted to serial bits and

stored in the computer memory. The nuclear counter was used as a preset scaler or a timer to record the clock time required to collect any specific spectra.

The six scalers recorded the total pulses from the Ge(Li) detector, the NaI(Tl) crystal, and the spectra number. The eight data modules were used to input digital data, such as, sample number, date, starting and stopping positions, number of spectra to be recorded, and count time. The data were stored in the computer memory as were the scaler readouts.

At the completion of data collection the time-of-day, scan controllers, parallel-to-serial converters, nuclear counter, scalers, and data modules were read into the computer memory and then written onto magnetic tape to provide a permanent record of the parameters. This allowed the experimenter to reconstruct the scanning parameters when analyzing the data.

The daisy chain units and associated electronics shown in Figs. 30 and 31 were located in an air-conditioned equipment trailer. The temperature had to be maintained at a constant level, because a five-degree temperature shift could result in up to a 25-channel shift in the pulse height analyzer. The twenty-five channel shift was only 0.61% of the total 4096 channels, which appeared to be insignificantly small; however when the full-energy, gamma-ray peak was only 10-15 channels wide, a 25-channel shift was about twice the peak width.

Fig. 31. Block Diagram Showing the Interrelationship of the Pulse Height Analyzer, Digital Computer, and Magnetic Tape Units.

The Ge(Li) signal passed through a preamplifier into a high-stability spectroscopy amplifier where the pulses were shaped. Next was a pile-up rejector and baseline restorer which were essential when analyzing samples with very high count rates. The signal entered the pulse height analyzer through a gated input. The input was gated in anticoincidence to the NaI(Tl) crystal signal. Gamma rays which interacted only with the Ge(Li) detector were converted to digital form through a 100-MHz 8192-channel analog-to-digital converter and stored in the 4096, 24-bit-word memory of the analyzer.

The gamma-ray spectra were accumulated for a predetermined time interval, which was either real or clock time. The digital computer then interrogated the daisy chain units and stored the information in a 53-word (24 bits/word) array. The net full-energy areas of up to 30 gamma-ray peaks were determined automatically using a first-order background subtraction method. The net areas were determined by summing the total counts in the channels between two preset limits around the full-energy peak and subtracting an average background. The average background was calculated by adding the counts in the lower limit channel and upper limit channel, dividing by two, and multiplying by the numbers of channels separating the limits.

The net areas were stored with the daisy chain data and written on magnetic tape in a central processor record (CP) followed by the full, 4096-channel, gamma-ray spectra in

the storage and display record (S&D) in the tape format shown in Fig. 32.

This process was repeated until the specified number of spectra had been accumulated for the scan. The computer then rewound the magnetic tape and searched each central processor record for the times-of-day, stored each time-of-day in the storage and display memory, and wrote all of the times-of-day in the first collected values (CV_1) record on the magnetic tape. The values for the Z and X encoder readouts were similarly collected and written in the second (CV_2) and third (CV_3) collected values records. The net full-energy peak areas of the specified gamma rays were collected and stored in records CV_4 through CV_{n+3} , where n was the number of peaks to be integrated.

The collected records consisted of the times-of-day, the Z and X positions, and the selected net areas of each spectra. The net areas represented the isotopic distributions of the gamma-emitting fission and activation products, and were available for the immediate examination, permitting additional data to be collected over regions of interest. The maximum amount of data was permanently stored on magnetic tape, and was available for more detailed analyses, such as spectral unfolding.⁴⁹

Data were stored on cartridge tapes as well as IBM-compatible magnetic tapes. The cartridge tapes were primarily used for program storage, requiring about 5 seconds to load the 4096-word computer memory with a new program.

MAGNETIC TAPE FORMAT

CV_N

Collected Values

Collected values for the time of day, x-position, z-position and up to 30 net areas

CP

Central Processor

Tag word
Time of day
5 encoder readouts X, Y, Z, tilt, & rotation
Scalers, data modules
Net area of up to 30 full energy peaks

S&D

Storage and Display

Complete spectra of up to 4096 channels

BOT BEGINNING OF TAPE
FM FILE MARK
CV COLLECTED VALUES
CP CENTRAL PROCESSOR
S&D STORAGE & DISPLAY

Fig. 32. Data Format for IBM-Compatible Magnetic Tape.

Programs and data were read in and read out via the teletype unit, however, this process required an excessive amount of time.

The entire system was controlled via the teletype with a conversational language. Once the scan had been initiated, the operations were controlled by the digital computer, thereby freeing the operator to perform other duties. The completely automated system allowed the data collection 24 hours a day, hence, tripling the data output over a manually-operated system. The reliability of the data was significantly improved by eliminating the possibility of human error. The entire data acquisition system and associated electronics are shown in Fig. 33.

Fig. 33. Computer-Controlled Data Acquisition Unit with Magnetic Tape Storage.

CHAPTER 3

RESULTS AND DISCUSSION

The precision gamma scanning system provided a nondestructive analytical technique for the characterization of a variety of irradiated fuel materials. Irradiated uranium-plutonium oxide and uranium-plutonium carbide fuel pins with burnups ranging from 0.3 to 10.0 atom-percent were examined. Complete gamma-ray spectra were measured at precise intervals, and the relative isotopic distributions of fission and activation products were then determined as a function of precise position. These data provided information about fuel column dimensions, fission and activation product distributions, fuel cladding failures, migration mechanisms for specific fission products, radial isotopic distributions, relative burnup profiles, and quantitative determination of fission products.

Gross Gamma Scanning

The irradiated fuel pins were first scanned in the gross gamma mode of data collection, in which the gross gamma activities were determined along a dimensional axis. A typical axial gross gamma scan of a mixed uranium-plutonium oxide fuel pin ($U_{.75}Pu_{.25}O_2$) (Pin A) is shown in Fig. 34. In this figure the top of the fuel was located at 22.96 in. and the

Fig. 34. Axial Gross Gamma Distribution of a Mixed Uranium-Plutonium Oxide Fuel Pin. (Pin A)

bottom at 37.24 in., with a corresponding fuel column length of 14.28 ± 0.010 in. The scan region between 2.8 in. and 16.7 in. shows the gas plenum region of the 316L stainless steel clad fuel pin. A 6.25-in., natural- UO_2 , axial blanket was located between the gas plenum and the enriched fuel column. The high gross gamma activity between the pellets suggested that significant fission product migration occurred within the fuel matrix.

Another example of a gross gamma scan for a mixed uranium-plutonium oxide fuel pin (Pin B) is shown in Fig. 35. The construction of this pin was similar to that described for Pin A (Fig. 34). The enriched fuel column, indicated by the high gamma activity, extended from 13.18 in. to 27.46 in., a length of 13.28 ± 0.010 in. In this scan, two anomalous regions, one between 16.00 and 18.00 in. and one between 20.50 and 22.50 in., were evident. These areas will be discussed in more detail later.

The gross gamma scan of an uniformly dense fuel material should have followed a symmetrical cosine curve reflecting the axial flux distribution in the reactor core. Any deviation from the smooth curve can be explained by fuel inhomogeneity, differing fuel densities or enrichments, fragmented pellets, or redistribution of fuel and fission products. Gross gamma scanning provided a relatively rapid (1h) and accurate (± 0.010 in.) nondestructive measurement of the fuel column length as well as a method for detection of abnormalities in the fuel pin.

Fig. 35. Axial Gross Gamma Distribution of a Mixed Uranium-Plutonium Oxide Fuel Pin. (Pin B)

Multispectral Scanning

In the multispectral mode of data collection, complete gamma-ray spectra were accumulated at specified intervals along the length or across the diameter of the fuel pin. The net areas of the resulting full-energy gamma-ray peaks were determined using a least squares fitting routine of Gaussian and exponential functions.⁴⁹ The entire fuel column of Pin A was scanned in the multispectral mode of data collection at 0.020-in. increments to determine the specific fission product distributions.^{35,48}

The multispectral scan provided distributions of 10 fission and activation products over the fuel region of Pin A (Fig. 34). The ^{106}Rh isotopic distribution over the fuel region (Fig. 36) was relatively uniform. Similar distribution data resulted for the isotopic distributions of ^{103}Ru , ^{144}Pr , ^{95}Zr , and ^{95}Nb . These results indicated that none of these isotopes had caused the spikes found in the gross gamma activity. The ^{137}Cs isotopic distribution, however, indicated that ^{137}Cs was the principal gamma-emitting isotope concentrating in the interpellet gaps. (Fig. 37)

The two anomalous regions of Pin B (Fig. 35) were scanned at 0.010-in. intervals to determine the principal fission or activation products contributing to the anomalous gross gamma distribution. The resulting data are shown in Figs. 38 and 39. Here the computed net areas of the three fission products ^{106}Rh , ^{137}Cs , and ^{95}Zr and one activation product,

Fig. 36. Rhodium-106 Isotopic Distribution as a Function of Axial Position for Pin A.

Fig. 37. Cesium-137 Isotopic Distribution as a Function of Axial Position for Pin A Showing Concentrations in Interpellet Gaps.

^{54}Mn are shown in Fig. 38 as a function of axial position for the first region. The same four isotopic distributions are shown in Fig. 39 for the second region (between 20.50 and 22.50 in.).

The ^{54}Mn distribution resulted from the fast neutron activation of the ^{54}Fe in the stainless steel via an (n,p) threshold reaction. The ^{54}Mn distribution indicated that the observed anomalies were not caused by the activation of the stainless steel structural material. The ^{95}Zr isotopic distributions were uniform in both regions and indicated that the fuel matrix was homogeneous and of uniform fuel density and enrichment. Cesium-137 was usually mobile and concentrated in the cooler interpellet gaps, however, these scans showed uniform axial distributions for this isotope. The two sets of isotopic distributions indicated that the anomalies in the axial gross gamma scan (Fig. 35) were caused by the axial relocation of the ^{106}Rh isotope.

The isotopic distributions of the three fission products, ^{106}Rh , ^{137}Cs , and ^{95}Zr were plotted as a function of diametral position for the second anomalous region to determine the radial location of the ^{106}Rh (Fig. 40). The diametral position of the fuel material was determined from the ^{95}Zr isotopic distribution. The ^{137}Cs isotope had migrated radially, depositing in the cooler outer regions of the fuel pellets, with ^{106}Rh concentrating near the fuel column central void, resulting in the higher activity near the center of the material.

Fig. 38. Axial Isotopic Distributions of ^{106}Rh , ^{137}Cs , ^{95}Zr , and ^{54}Mn for Pin B between 16.00 and 18.00.

Fig. 39. Axial Isotopic Distributions of ^{106}Rh , ^{137}Cs , ^{95}Zr , and ^{54}Mn for Pin B between 20.50 and 22.50 in.

Fig. 40. Diametral Isotopic Distributions of ^{106}Rh , ^{137}Cs , and ^{95}Zr for Pin B at 22.00 in. Axial Position.

Two-Dimensional Scanning

The two-dimensional multispectral gamma scanning techniques were developed to complement one-dimensional gamma scanning and micro-sampling coupled with chemical analysis.⁶¹⁻⁶⁴ In this experimental mode, a thin disc of the fuel matrix was prepared by repetitively impregnating the fuel material with epoxy resin and grinding the section to a 0.050-in. thickness. Complete gamma-ray spectra were collected at selected grid points using a gold-tantalum conical collimator.⁶⁴ The net peak areas of fission and activation products were determined in each spectra, and the results were presented as isometric projections, density plots, or contour plots.⁶³

The thin fuel section of a mixed uranium-plutonium oxide pin, shown in Fig. 41 as a ground surface (not polished), was scanned at every 0.010-in. interval in the XY plane to determine the radial distributions of the specific fission products. The collected gamma-ray spectra were unfolded and the radial distributions for ^{106}Rh , ^{134}Cs , ^{137}Cs , and ^{144}Pr were determined. The two-dimensional distribution of ^{106}Rh is shown in Fig. 42 as a density plot. These data show that the ^{106}Rh has concentrated around the central void and along the columnar grain boundaries. The ^{134}Cs and ^{137}Cs radial distributions were nearly identical within experimental errors; therefore only the ^{137}Cs density plot is presented (Fig. 43). The ^{137}Cs has migrated radially to the cooler regions of the fuel

Fig. 41. Photograph of Thin Cross Section (0.050 in.)
Prepared (As Ground) for Two-Dimensional Scanning.

Fig. 42. Density Plot of ^{106}Rh Two-Dimensional Radial Distribution.

Fig. 43. Density Plot of ^{137}Cs Two-Dimensional Radial Distribution.

section. These results are also presented as an isometric projection in Fig. 44. The radial distributions of ^{144}Pr are presented as a density plot (Fig. 45) and as an isometric projection (Fig. 46). The ^{144}Pr isotope was in equilibrium with its parent ^{144}Ce and exhibited an uniform distribution.

The two-dimensional radial distributions of fission products were also determined over a specific fuel section without having to first section the sample.⁶⁵ This process completely eliminated the preparatory steps described above. The fuel column section was scanned diametrically at one or more different angular orientations of the fuel capsule and then the data were unfolded to obtain isotopic distributions. The results of this nondestructive technique have compared very favorably to results from more classical methods.⁶⁵

The calculated two-dimensional isotopic distributions of ^{106}Rh , ^{137}Cs , and ^{95}Zr fission products along with a typical diametral scan are shown in Figs. 47, 48, and 49 for a low burnup oxide fuel pin. The diametral scans in the top section of these figures represented one of the two scans used as input data to determine the density plots in the lower half of the figures. The ^{106}Rh had migrated radially depositing along the columnar grain boundary and the ^{137}Cs isotope had undergone significant radial migration concentrating in a layer on the outer surface of the fuel material. The ^{95}Zr had remained uniformly distributed in the fuel material with the presence of the central void clearly shown in the isometric projection in Fig. 50. This method of nondestructive

Fig. 44. Isometric Projection of ^{137}Cs Isotopic Radial Distribution.

Fig. 45. Density Plot of ^{144}Pr Two-Dimensional Radial Distribution.

Fig. 46. Isometric Projection of ^{144}Pr Isotopic Distribution.

Fig. 47. Diametral ^{106}Rh Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).

Fig. 48. Diametral ^{137}Cs Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).

Fig. 49. Diametral ^{95}Zr Isotopic Distribution (Top) and the Unfolded Two-Dimensional Radial Distribution (Bottom).

Fig. 50. Isometric Projection of ^{95}Zr from Unfolded Diametral Scans Shown in Fig. 49.

analysis permitted the periodic determination of isotopic distributions during a long term reactor irradiation. The fuel pin could be withdrawn for periodic evaluation and re-inserted into the core for additional irradiation.

Detection of Cladding Failure

A nondestructive technique utilizing precision gamma scanning has been developed for detecting fuel cladding failure in doubly encapsulated fast reactor fuel elements.⁶⁶ Detection of fission products, in particular ^{137}Cs , outside the actual fuel pin envelope was used to indicate the failure. The method was tested by the examination of eleven mixed uranium-plutonium carbide and two mixed uranium-plutonium oxide fuel pins. Gamma scanning indicated that six of the thirteen fuel elements had failed. These results were confirmed by mass spectrometric analysis of the cover gases in the outer encapsulation.

In this method, the gas plenum region of the doubly encapsulated fuel element was scanned axially in the multi-spectral mode. The axial distributions of fission products and activation products were determined as a function of precise position. The ^{137}Cs isotope was selected as the monitor because of its relatively long half-life (30.0y), reasonably high fission yield ($6.60 \pm 0.10\%$ for Pu and $6.21 \pm 0.10\%$ for U) for a fast spectrum, and easily resolvable gamma-ray spectrum.

The gamma scanning results for cladding failure and the cover gas analysis were compared in Table VII. The results obtained from a failed fuel element are shown in Fig. 51. Here the axial distributions of ^{137}Cs and ^{60}Co over the region of the capsule end plug of a mixed uranium-plutonium carbide pin are plotted. The relative positions of the structural material of the capsule were indicated by the relative gamma activity of the ^{60}Co activation product. The ^{137}Cs had deposited on the inner surface and along the side of the capsule end plug, 7.75 in. above the cladding. These spatial distributions clearly indicated that the cladding failed, permitting fission products, in particular ^{137}Cs , to escape from the fuel pin envelope. The cover gas was found later to contain 4.61% krypton and 29.0% xenon, thus confirming that the inner cladding had been breached.

This technique may be used for the interim examination to screen experimental fuel elements and to assess the condition of the fuel pin cladding. If ^{137}Cs were found outside the fuel cladding, the fuel pin has been breached, and it may not be advisable to return the pin to the reactor. The experience to date indicated that positive detection of ^{137}Cs outside the fuel pin cladding was always confirmed by the presence of fission gases in this same space. This latter condition had been routinely associated with cracks or pinholes in the fuel cladding.⁶⁶

This method has shown itself as an effective, nondestructive, screening process for detecting failed inner

Table VII

Comparison of Gamma Scanning and Mass Spectrometric Analysis

Fuel	Number of Elements	Fission Gas in Cover Gas, Atom %		¹³⁷ Cs Detected Outside Fuel Cladding
		Krypton	Xenon	
(U. ₈ Pu. ₂)O ₂	1	0.00	0.00	not detected
(U. ₈ Pu. ₂)O ₂	1	9.31	65.00	detected
(U. ₈ Pu. ₂)C	5	1.76-5.46	11.80-34.70	detected
(U. ₈ Pu. ₂)C	5	0.00	0.00	not detected
(U. ₈ Pu. ₂)C	1	0.003*	0.016*	not detected

* Represent the present lower limits of detection for gamma scanning.

Fig. 51. Cesium-137 and ^{60}Co Axial Isotopic Distributions of a Failed Doubly Encapsulated Fuel Pin.

cladding in encapsulated fast reactor fuel pins. An adaptation of this method has been added to the interim examination of experimental fuel elements at the Hot Fuels Examination Facility in Idaho.⁶⁷

Distributions of ^{134}Cs and ^{137}Cs in Oxide Fuels

The axial distributions of ^{134}Cs and ^{137}Cs in the axial blanket column of mixed uranium-plutonium oxide fuel pins showed that the migration mechanism of their precursors were significantly different.

Cesium can seriously affect the fuel material and structural properties of stainless steel cladding in fast reactor fuel pins.^{68, 69} This volatile fission product has been observed in the reaction layers, in the attacked grain boundaries of the cladding, and on the cladding where it concentrated at pellet-pellet interfaces.^{68, 69} The interaction of cesium with the fuel matrix was important in oxide fuel swelling, and fuel-cladding interactions generally were greater in areas having higher cesium concentrations.⁷⁰ The effects of cesium on cladding attack and fuel swelling appeared to be dependent upon the oxygen potential of the system.

Differences in the relative concentrations of ^{134}Cs and ^{137}Cs were found as a function of axial position in the study of cesium distributions. This was especially evident for measurements of the two cesium isotopes in the natural- UO_2 axial blankets of five uranium-plutonium oxide fuel pins.

Evidence was obtained that cesium concentrated selectively on some of the UO_2 pellets and that the ^{134}Cs and ^{137}Cs distributions were significantly different. To determine the effect of the pellet oxygen content on cesium distributions, selected UO_2 pellets were destructively analyzed for their total oxygen contents.

The five fuel pins were similar to Pins A and B described in the Multispectral Scanning section. Each of the five fuel pins contained a short UO_2 insulator pellet, a 14.2 in. mixed $(\text{U}_{.8}\text{Pu}_{.2})\text{O}_2$ fuel column, and a 6.25-in., natural- UO_2 , upper, axial blanket column. The upper end of the pellet column was held in place by means of an extensometer spring and spacer tube. A gas plenum, about 14.0 in. long was located above the axial blanket column. Three different types of fuel pellets were used for the fabrication of the five pins: master mix, mechanically blended, and coprecipitated material. Each fuel column contained two of the three types; one type in the top half and another type in the bottom half. The oxygen-to-metal atom ratios (O/M) varied from 1.94 to 2.00 and the theoretical densities varied from 82.38% to 90.45%. The materials used in the pins designated as C, D, E, F, and G are summarized in Table VIII.

Gross gamma scans were obtained on each of the fuel pins to determine anomalous regions and relative gross gamma activity as a function of discrete axial position. The gross gamma scans of fuel Pins C and D (Fig. 52 and 53) showed abnormally high gross gamma activity over the axial UO_2 blanket

Table VIII

Densities, O/M Ratios, and Fuel Material

Pin	Section	O/M	%Theo. Density	Fuel Material
C	Top	1.94	82.38	coprecipitated
	Bottom	1.96	82.85	mechanically blended
D	Top	2.00	83.55	mechanically blended
	Bottom	1.99	82.40	coprecipitated
E	Top	1.97	90.31	master mix
	Bottom	1.96	90.13	mechanically blended
F	Top	1.97	89.90	mechanically blended
	Bottom	1.99	90.45	master mix
G	Top	2.00	89.59	mechanically blended
	Bottom	2.00	88.02	master mix

Fig. 52. Axial Gross Gamma Distribution of a Mixed Oxide Fuel Pin. (Pin C)

Fig. 53. Axial Gross Gamma Distribution of a Mixed Oxide Fuel Pin. (Pin D)

columns. The two blanket columns were removed from the pins and sealed in an inert atmosphere when the fuel pins were disassembled. The two, UO_2 , blanket columns and the three blanket columns of Pins E, F, and G were also scanned in the multispectral mode of data collection to identify the principal isotopes causing these high gross gamma activities.

The net areas of the full-energy peaks of ^{134}Cs and ^{137}Cs are plotted as a function of axial position for Pins C, D, E, F, and G (Figs. 54-58). The complete gamma-ray spectra indicated that the two cesium isotopes were the dominant gamma-emitting isotopes in the UO_2 blanket regions. The ^{134}Cs activity generally increased as the distance from the enriched fuel column increased. The dashed lines have been drawn to accentuate this general trend. In Pin C (Fig. 54) the ^{137}Cs activity decreased as the distance from the fuel column increased. This behavior was just the opposite to that found for the ^{134}Cs isotope.

The ^{137}Cs distribution in Pin D (Fig. 55) indicated that this isotope has undergone very little migration into the UO_2 blanket column. A slight increase in the activity around 16.0 in. indicated that ^{137}Cs has migrated only to the first two pellets in the blanket column.

It was obvious that the two isotopes collected preferentially on specific UO_2 pellets. Selected UO_2 pellets from Pins C and D were examined to determine if their total oxygen contents differed. The samples were reduced at 2000° to 2200°C with carbon to quantitatively convert the oxygen to carbon

Fig. 54. Cesium-134 and ¹³⁷Cs Axial Isotopic Distributions over the UO₂ Axial Blanket of Pin C.

Fig. 55. Cesium-134 and ^{137}Cs Axial Isotopic Distributions over UO_2 Axial Blanket of Pin D.

Fig. 56. Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin E.

Fig. 57. Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin F.

Fig. 58. Cesium-134 and ^{137}Cs Axial Isotopic Distributions over the UO_2 Axial Blanket of Pin G.

monoxide and carbon dioxide which were measured gravimetrically.⁷¹ Pellets 2, 4, and 5 from Pin C were combined as one sample as were pellets 3 and 7. The total oxygen content of pellets 2, 4, and 5 was slightly higher than that of pellets 3 and 7. The results indicated that the amount of cesium absorbed on a UO_2 pellet might be related to the oxygen contents of the individual pellets. Subsequently three samples of two pellets each from Pin C and three samples from Pin D were analyzed for total oxygen content. Conditions to avoid oxygen contamination of these pellets were carefully maintained. The results for the latter samples are given in Table IX.

It was concluded that the amount of ^{134}Cs adsorbed on the natural- UO_2 blanket pellets was a direct function of the total oxygen content of the pellet. The ^{137}Cs distribution in Pin C (Fig. 54) was also directly related to the total oxygen content of the UO_2 blanket pellets.

The ^{134}Cs and ^{137}Cs distributions for fuel Pins E, F, and G are shown in Fig. 56, 57, and 58, respectively. The top section of the natural- UO_2 blanket region was shown in each figure. The two isotopes exhibited distinctively different distributions. The ^{137}Cs distribution was related to the positions of the UO_2 blanket pellets, while the ^{134}Cs isotope concentrated at specific locations in the blanket region.

Since the ^{134}Cs isotopes were produced from the thermal neutron-capture reaction of ^{133}Cs , the ^{134}Cs distribution was dependent upon the variations in the neutron flux profile. The thermal neutron flux profile was related to the ^{60}Co activ-

Table IX

Relationship of Oxygen Content to ^{134}Cs Deposition

Fuel Pin	Sample	Pellet Numbers	Oxygen, Wt. %	^{134}Cs Activity*
C	1	16, 17	11.87 ± 0.03	High
	2	21, 22	11.64 ± 0.03	Low
	3	23, 25	11.81 ± 0.03	High
D	4	1, 2	11.72 ± 0.03	Low
	5	4, 7	11.89 ± 0.03	High
	6	5, 6	11.73 ± 0.03	Low

* High refers to pellets having more than three times the activity of the lower activity pellets.

ity, and the fast neutron flux profile was related to the distribution of the threshold monitor, ^{54}Mn . The ^{60}Co and ^{54}Mn were neutron activation products of the stainless steel cladding, therefore the relative neutron flux profiles were determined by plotting their isotopic distributions. The distributions were relatively smooth over the scanned regions indicating the absence of any significant flux perturbations that would have caused the resulting ^{134}Cs distributions. The higher ^{60}Co activity in Pin G around 17.0 in. (Fig. 59) was due to a short stainless steel spacer located between the top UO_2 blanket pellet and the second UO_2 blanket pellet. The effect of the spacer can be seen in the ^{137}Cs distributions for Pins E, F, and G (Fig. 56, 57 and 58, respectively). The smooth neutron flux profiles showed that the significantly different distributions of the two cesium isotopes were not the result of flux variations.

The precursors of ^{134}Cs and ^{137}Cs were then considered in seeking an explanation for their different distributions. The two cesium isotopes result from the beta decay of precursor fission products in the following ways:

^{134}Cs :

^{137}Cs :

For the ^{134}Cs isotopic distributions the net areas of three gamma-ray peaks (566, 604.6, and 795.8 keV) were cal-

Fig. 59. Cobalt-60 Axial Isotopic Distribution over the UO_2 Axial Blanket of Pin G.

culated and plotted. Only the gamma-ray peak at 661.6 keV was plotted for ^{137}Cs .

A possible explanation for the two distinct cesium distributions was formulated based on the half-lives of their precursors. Consideration of the short half-lives of the precursors of ^{137}Cs and the ^{137}Cs isotopic distribution of Pin C (Fig. 54) led to the conclusion that either cesium or a cesium complex was the principal migrating species for ^{137}Cs and not one of its precursors. Once the cesium has moved from the enriched fuel column, it preferentially adsorbed on the natural- UO_2 blanket pellets with high oxygen contents. The average oxygen-to-metal ratio of the enriched fuel material in fuel Pin C was 1.95. The O/M atom ratio for the fuel column in fuel Pin D was significantly higher, 1.99. The oxygen content of fuel in Pin D may have been sufficiently high to permit the ^{137}Cs to form an oxide and remain in the enriched fuel column as was indicated by the very low activity of ^{137}Cs in the UO_2 blanket shown in Fig. 55. The O/M atom ratios in fuel Pins E, F, and G (1.97, 1.98, and 2.00, respectively) also were relatively higher than the 1.95 O/M ratio of fuel Pin C. It was concluded that the ^{137}Cs , generated from the fissioning process, remained within the fuel matrix of pins with O/M ratios greater than 1.95. The respective ^{137}Cs isotopic distributions (Figs. 56, 57, and 58) of the blanket regions showed relatively smooth distributions, indicating that the ^{137}Cs activity present was due to the fissions in the natural- UO_2 pellets.

The ^{134}Cs isotopic distribution resulted from a more complicated process. The two ^{134}Cs precursors, ^{133}I and ^{133}Xe have half-lives of 21h and 5.27d, respectively. The long half-lives of ^{133}I and ^{133}Xe , relative to the ^{137}Cs precursors, would permit the diffusion of these species from the enriched fuel matrix and subsequent movement into the inert gas phase in the plenum. The ^{133}Xe decayed by beta emission to ^{133}Cs which was adsorbed on the surface of the UO_2 pellets; the ^{133}Cs was then neutron activated to ^{134}Cs which was measured by gamma scanning. The ^{134}Cs concentration would therefore be expected to be higher at the gas plenum end of the UO_2 blanket and decrease toward the enriched fuel column. This general trend was observed for Pins A and B (Fig. 54 and 55). Variations in the total oxygen content of the individual UO_2 blanket pellets would perturb the general trend.

The theoretical densities of fuel Pins E, F, and G were higher than the densities of Pins C and D (Table VIII). These higher densities retarded the migration of ^{133}I and ^{133}Xe . The ^{134}Cs distributions of fuel Pins E, F, and G (Figs. 56, 57, and 58, respectively) were significantly different from the corresponding ^{137}Cs distributions. The localized concentration of the ^{134}Cs isotope was evident in all three plots. General trends in the ^{134}Cs activity, similar to those of Pins C and D, were found in fuel Pins F and G (Figs. 57 and 58). Only a short region of the axial blanket of Pin E was scanned, eliminating the possibility of determining any significant trend in the ^{134}Cs activity.

The isotopic distributions of the two cesium isotopes, ^{134}Cs and ^{137}Cs , indicated that their distributions were related to the half-lives of their I and Xe precursors. The ^{137}Cs isotope migrated as the metal, iodide, or other compound form, while the final distribution of the ^{134}Cs was a result of the migration of either the ^{133}I or the ^{133}Xe precursor which deposits as ^{133}Cs on the UO_2 blanket pellets with high oxygen content. The examination of six samples from the blanket regions of two fuel pins indicated that both cesium isotopes preferentially concentrated on the pellets having oxygen contents above 11.80% as compared to pellets with 11.73% or less.

The movement of ^{137}Cs from the enriched fuel region was retarded by high oxygen-to-metal ratios in the fuel. Fuel matrices with higher densities reduced the probability that the relatively long-lived precursors of ^{134}Cs would escape and migrate to the axial UO_2 blanket regions. These suggested mass transfer mechanisms for ^{134}Cs and ^{137}Cs provided a self-consistent explanation for their respective isotopic distributions for this set of fuel pins. It would be difficult to arrive at a single set of transfer mechanisms for all types of fuel pins.

Quantitative Gamma Scanning

Gamma scanning provided the only nondestructive method for the quantitative determination of fission and activation products as a function of precise (± 0.010 -in.) position in an

irradiated fuel pin. Quantitative gamma scanning was applied to the determination of absolute burnup profiles, mass transfer mechanisms of fission products, and total amounts of fission products present in an irradiated pin. The problem of selecting a representative sample was eliminated because the entire sample was examined.

Many types of fuel materials including oxides, carbides, nitrides and metallic alloys of uranium and plutonium have been scanned. These fuel pins represented a wide variety of fuel burnups, fuel densities, and operating conditions which influenced the radial and axial isotopic distributions of each fission product. Therefore, a complete set of standards for single fission product would have consisted of an individual standard for each fission material, fuel density, burnup value, cladding material, power density, and radial and axial isotopic distribution. Hundreds of standards would have been required for each fission product quantitatively determined.

An alternate approach to maintaining a very large inventory of standards was to calibrate completely the gamma scanning system and to calculate the quantity of a fission product from the number of full-energy gamma photons collected within a specified time interval. The calibration process included the scanning mechanism, effective collimating slit apertures, and the specific detector efficiencies. Each of these calibration processes was discussed in the Experimental section.

A computer code, QUADET, was developed to calculate the

effects of the scanning geometry, the source distribution, the shielding materials, and surface responses of the Ge(Li) detector. The code was used to simulate various source geometries and their effects upon the net areas of the full-energy peaks. A detailed description of the code and a typical example utilizing the code are presented in Appendix III.

The precise calibration of the scanning mechanism and the effective collimating slit aperture has been described. The particular source geometries of the fission products were determined nondestructively using the TWODIM computer code, which calculated the radial isotopic distributions.⁶⁵ These data, plus the fuel composition, fuel density, cladding material and density, capsule material and density, and the scanning geometry were required as code input parameters. The code provided a calculational mockup of the experimental configuration and calculated the source attenuation, solid angle effects, and collimation effects. The resulting source activities as a function of position on the detector's surface were combined with the surface response functions of the Ge(Li) detector. The final source-geometry multiplication factor related the net full-energy peak areas to the number of fission product atoms present within the volume segment of the fuel pin.

This quantitative method has been compared with the destructive radiochemical analysis of low burnup samples. The initial sample examined consisted of two sections of a mixed uranium-plutonium oxide fuel pin. (Section A was 5.220 in.

long and Section I was 5.020 in. long.) The two sections were axially scanned twice to determine the precision of the gamma scanning results. The axial isotopic distributions of ^{106}Rh (622 keV) and ^{137}Cs (662 keV) were determined using spectral unfolding.⁴⁹ The isotopic distributions of ^{106}Rh and ^{137}Cs for Section A are presented in Figs. 60 and 61. Similar results are shown in Figs. 62 and 63 for Section I. The ^{106}Rh axial isotopic distributions for both sections (Figs. 60 and 62) were relatively uniform, while the ^{137}Cs axial distributions (Figs. 61 and 63) showed significant axial migration. In these scans complete gamma-ray spectra were collected for 480 sec real-time at every 0.020-in. interval.

A 0.635-in. section was removed from Section A for the destructive radiochemical analysis of ^{106}Rh and ^{137}Cs . The remainder of Section A was sealed in an inert atmosphere and again scanned to determine the precise amount removed for analysis. Section I was again scanned to provide an internal standard for comparison with the previous scanning results. The ^{106}Rh and ^{137}Cs axial distributions of this scan for Section I are shown in Figs. 64 and 65, respectively. The comparison of these results (Figs. 64 and 65) with the previous scanning results (Figs. 62 and 63) illustrated the reproducibility of the respective scans. A detailed comparison of the three scans for Section I are presented in Table X.

As was shown in Table X, the precision of the ^{137}Cs determinations was 1.3 relative percent and the precision for ^{106}Rh was 2.6 relative percent. A similar comparison of the

Fig. 60. Rhodium-106 Axial Isotopic Distribution for Section A in QUADET Test before Sample Was Removed.

Fig. 61. Cesium-137 Axial Isotopic Distribution for Section A in QUADET Test Before Sample Was Removed.

Fig. 62. Rhodium-106 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement.

Fig. 63. Cesium-137 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement.

Fig. 64. Rhodium-106 Axial Isotopic Distribution for Section I in QUADET Test for Reproducibility of Measurement after Sampling of Section A.

Fig. 65. Cesium-137 Axial Isotopic Distribution for Section 1 in QUADET Test for Reproducibility of Measurement after Sampling of Section A.

Table X

Comparison of ^{106}Rh and ^{137}Cs Scanning Results for Section I

	Net Peak Areas		
	^{106}Rh	^{137}Cs	Length
Scan #1	$502,853 \pm 30,116^*$	$770,896 \pm 17,183^*$	5.020 ± 0.010 in.
Scan #2	$462,361 \pm 15,732$	$759,913 \pm 17,280$	5.020 ± 0.010 in.
Scan #3	<u>$477,719 \pm 16,451$</u>	<u>$776,534 \pm 16,779$</u>	<u>5.020 ± 0.010 in.</u>
	$480,978 \pm 12,584$	$769,114 \pm 9,862$	5.020 ± 0.010 in.

Amount Present**

Scan #1	283.5 ± 17.0 μg	2216.4 ± 49.4 μg
Scan #2	260.7 ± 8.9 μg	2184.8 ± 49.7 μg
Scan #3	<u>269.4 ± 9.3 μg</u>	<u>2232.6 ± 48.2 μg</u>
	271.2 ± 7.1 μg	2211.3 ± 28.4 μg

* The $\pm$ values are estimates of the standard deviations for each measurement.

** Computed using the QUADET computer code.

gamma scanning results for Section A are presented in Table XI. The axial distributions of ^{106}Rh and ^{137}Cs for Section A, after the radiochemical sample was removed, are presented in Figs. 66 and 67. The precision of the ^{137}Cs measurements (1.8%) was a factor of two lower than the ^{106}Rh measurements (4.4%) for Section A. The overall precision of the gamma scanning results for the two sections was 1.5% for the ^{137}Cs and 3.3% for the ^{106}Rh .

The quantities of ^{106}Rh and ^{137}Cs in the radiochemical sample were determined from the gamma scanning results by measuring the length of fuel column removed and computing the specific activities from Scans #1 and #2. The results are summarized in Table XII.

The radiochemical sample (4.5 g, including fuel and cladding) was dissolved in an acid solution. The insoluble residue was transferred to a thick-walled fused-silica tube and dissolved using the sealed-tube method.⁷³ The two solutions were combined and duplicate weighed aliquots were analyzed by gamma-ray spectrometry for ^{106}Rh and ^{137}Cs . The comparisons of the quantitative results for the two methods are presented in Table XIII.

The ^{137}Cs results for gamma scanning and radiochemical analysis compared very favorably, with the radiochemical results being 4.4 to 5.8% lower. The radiochemical results for ^{106}Rh were 39% lower than the gamma scanning results. The difference in the ^{106}Rh measurements corresponded to 16.9 μg . The quantitative determination of ^{106}Rh has been

Table XI

Comparison of ^{106}Rh and ^{137}Cs Scanning Results for Section A

Before Sampling	Net Peak Areas		
	^{106}Rh	^{137}Cs	Length
Scan #1	<u>549,918 ± 32,847*</u>	<u>857,762 ± 20,424*</u>	5.220 ± 0.010 in.
Scan #2	<u>549,099 ± 36,023</u>	<u>850,053 ± 23,074</u>	<u>5.210 ± 0.010 in.</u>
	549,509 ± 24,375	853,908 ± 15,407	5.215 ± 0.010 in.
After Sampling			
Scan #3	<u>456,097 ± 17,194*</u>	<u>766,780 ± 18,971*</u>	<u>4.580 ± 0.010 in.</u>
Difference	93,412 ± 29,829	87,128 ± 24,439	0.635 ± 0.010 in.

Amount Present**		
Before Sampling		
Scan #1	310.1 ± 18.5 μg	2466.2 ± 58.7 μg
Scan #2	<u>309.1 ± 20.3 μg</u>	<u>2444.0 ± 66.3 μg</u>
	309.6 ± 13.7 μg	2455.1 ± 44.3 μg
After Sampling		
Scan #3	<u>257.2 ± 9.7 μg</u>	<u>2204.6 ± 54.5 μg</u>
Difference	52.7 ± 16.8 μg	250.5 ± 70.3 μg

* The ± values are estimates of the standard deviation of each measurement.

** Computed using the QUADET computer code.

Fig. 66. Rhodium-106 Axial Isotopic Distribution for Section A in QUADET Test after Radiochemical Sample Was Removed.

Fig. 67. Cesium-137 Axial Isotopic Distribution for Section A in QUADET Test After Radiochemical Sample Was Removed.

Table XII

Quantity of Isotope Removed for Radiochemical Analysis

	Net Peak Areas	
	<u>^{106}Rh</u>	<u>^{137}Cs</u>
Scan #1	$74,373 \pm 4,284^*$	$105,844 \pm 2,641$
Scan #2	<u>$77,580 \pm 6,158$</u>	<u>$104,191 \pm 5,128$</u>
Average	$75,978 \pm 3,751$	$105,018 \pm 2,884$

	Amount Present**	
Scan #1	$41.9 \pm 2.4 \text{ } \mu\text{g}$	$304.3 \pm 7.6 \text{ } \mu\text{g}$
Scan #2	<u>$43.7 \pm 3.3 \text{ } \mu\text{g}$</u>	<u>$299.6 \pm 14.7 \text{ } \mu\text{g}$</u>
Average	$42.8 \pm 2.1 \text{ } \mu\text{g}$	$301.9 \pm 8.3 \text{ } \mu\text{g}$

* The $\pm$ values are estimates of the standard deviations for each measurement.

** Computed using the QUADET computer code, total quantity in radiochemical sample.

Table XIII

Gamma Scanning and Radiochemical Assay Results

Atoms Present

<u>^{137}Cs</u>	<u>Gamma Scanning</u>	<u>Radiochemical Analysis</u>	
Sample #1	$1.340 \pm .030 \times 10^{18*}$	$1.253 \pm .003 \times 10^{18**}$	$1.272 \pm .003 \times 10^{18} ***$
Sample #2	$1.320 \pm .060 \times 10^{18}$	$1.252 \pm .003 \times 10^{18}$	$1.272 \pm .003 \times 10^{18}$
	$1.330 \pm .030 \times 10^{18}$	$1.253 \pm .002 \times 10^{18}$	$1.272 \pm .003 \times 10^{18}$
<u>^{106}Rh</u>			
Sample #1	$2.380 \pm .130 \times 10^{17}$	$1.404 \pm .006 \times 10^{17}$	
Sample #2	$2.480 \pm .200 \times 10^{17}$	$1.531 \pm .008 \times 10^{17}$	
	$2.430 \pm .120 \times 10^{17}$	$1.467 \pm .005 \times 10^{17}$	

Amount Present

<u>^{137}Cs</u>			
Sample #1	$304.7 \pm 6.8 \text{ } \mu\text{g}$	$285.0 \pm 0.7 \text{ } \mu\text{g}$	$289.3 \pm 0.7 \text{ } \mu\text{g}$
Sample #2	$300.3 \pm 13.6 \text{ } \mu\text{g}$	$284.8 \pm 0.7 \text{ } \mu\text{g}$	$289.3 \pm 0.5 \text{ } \mu\text{g}$
	$302.5 \pm 6.8 \text{ } \mu\text{g}$	$284.9 \pm 0.5 \text{ } \mu\text{g}$	$289.3 \pm 0.5 \text{ } \mu\text{g}$

*

**

The $\pm$ values are estimates of the standard deviations for each measurement.
 Based on efficiency calibration using ^{228}Th standard.
 Based on standard ^{137}Cs source.

Table XIII (cont.)

Gamma Scanning and Radiochemical Assay Results

Atoms Present

<u>^{106}Rh</u>	<u>Gamma Scanning</u>	<u>Radiochemical Analysis</u>
Sample #1	$41.9 \pm 2.3 \mu\text{g}^*$	$24.7 \pm 0.1 \mu\text{g}^{**}$
Sample #2	<u>$43.6 \pm 3.5 \mu\text{g}$</u>	<u>$26.9 \pm 0.1 \mu\text{g}$</u>
	$42.8 \pm 2.1 \mu\text{g}$	$25.8 \pm 0.1 \mu\text{g}$

* The $\pm$ values are estimates of the standard deviations for each measurement.

** Based on efficiency calibration using ^{228}Th standard.

rarely attempted because the dissolution of fuel materials often resulted in important losses of its parent, ^{106}Ru . The ^{106}Rh ($t_{1/2} = 30$ s) was in secular equilibrium with its parent ^{106}Ru ($t_{1/2} = 367$ d). In this particular case the ruthenium may have existed as suspended particles in the acid solution and adsorbed onto the glass surface when the solutions were transferred to the storage container prior to the radiochemical analysis.⁴⁶ The gamma scanning results for ^{106}Rh (42.8 ± 2.1 μg) compared favorably with the calculated results (39.6 μg) obtained from the nominal burnup values (0.35%). The cesium isotope was very soluble in the acid solution and was quantitatively transferred to the storage containers.

The experimental results indicated that gamma scanning can be used for the quantitative nondestructive determination of specific fission products in irradiated fuel pins. The above results emphasized the problems associated with the destructive sectioning and chemical analysis: the problem of obtaining a representative sample, the quantitative transfer of the sample, the complete dissolution of the sample, and the radiochemical or wet chemical analysis.

This gamma scanning technique provided a nondestructive method for the determination of specific gamma-emitting fission products in the irradiated fuel pin. The integrity of the fuel pin was maintained throughout the analysis. The entire sample was scanned, eliminating the problems associated with obtaining a representative sample. The results presented in the Multispectral Scanning section indicated that

^{137}Cs , ^{134}Cs , and ^{106}Rh fission products can undergo significant migration. Many other isotopes, such as, ^{140}Ba , ^{95}Nb , ^{141}Ce , ^{144}Ce , ^{131}I , ^{125}Sb , and ^{103}Rh can also migrate under special conditions within fuel materials. As can be seen by the number of migrating isotopes listed above, precision gamma scanning provided the only nondestructive method for the quantitative determination of these isotopes.

Burnup Determination

Burnup is a measure of the depletion of fissionable material within an irradiated fuel pin. The degree of burnup can be determined by calorimetry and integrated neutron flux dosimetry when lower accuracy ($\pm 5\%$) is permissible.⁷⁴ Mass spectrometric analysis provides the most accurate method ($\pm 1\%$) but requires the destructive sampling of the fuel pin. It also only provides an accurate burnup value for a precise position for the entire fuel column.

Gamma scanning can provide a nondestructive method for correlating mass spectrometric results to the burnup along the column. The relative isotopic distribution of a fission product can be used to obtain the relative burnup profile.⁷⁵⁻¹¹⁹ The fission products selected must satisfy six conditions to be applicable:

1. Long half-life relative to irradiation period.
2. High fission yields for the fissionable material.
3. Non-migrating at the fuel's operating temperature.
4. Easily resolvable gamma-ray spectra.
5. Small neutron-capture cross-section.
6. Negligible formation of the isotope from adjacent isotopes.

Possible monitor fission products include: ^{95}Zr ($t_{1/2}=65\text{d}$), ^{103}Ru ($t_{1/2}=39.5\text{d}$), ^{106}Ru ($t_{1/2}=367\text{d}$), ^{134}Cs ($t_{1/2}=2.05\text{y}$), ^{137}Cs ($t_{1/2}=30.0\text{y}$), ^{140}Ba ($t_{1/2}=12.8\text{d}$), ^{141}Ce ($t_{1/2}=32.5\text{d}$), and ^{144}Ce ($t_{1/2}=284\text{d}$). As the irradiation exposure of experimental fuel pins varies from 6 months to 3 years, with decaying times ranging up to a couple years, only five of the above isotopes would appear to be applicable, based on half-lives: ^{95}Zr , ^{106}Ru , ^{134}Cs , ^{137}Cs , and ^{144}Ce .

The ^{95}Zr isotope with a half-life of 65d was applicable only to the determination of burnup in recently irradiated fuels. Zirconium probably did not undergo migration within the fuel matrix and had two resolvable gamma rays: 724 keV and 756 keV. The 756 keV peak was near the 765 keV peak of ^{95}Nb ($t_{1/2}=35\text{d}$), the daughter of ^{95}Zr . To obtain the highest degree of precision, spectral unfolding has to be used to separate these two peaks in the determination of net areas.

The relative distribution of ^{106}Ru was determined by scanning for its daughter ^{106}Rh ($t_{1/2}=30\text{s}$) which was in secular equilibrium with ^{106}Ru ($t_{1/2}=367\text{d}$). The daughter, ^{106}Rh , has an easily resolvable gamma spectra with gamma peaks at 512 keV and 622 keV. However, the ^{106}Rh isotopic distributions showed substantial migration, radially as well as axially, as was described in the Multispectral Scanning section. Therefore ^{106}Ru can only be used under specific conditions, where the isotope has not undergone significant axial migration. The fission yields of ^{106}Ru for uranium and plutonium vary by a factor of 11 and the ^{106}Rh distribution can be related to the

differential burnup of uranium and plutonium.

From the known migration properties (page 97) of ^{134}Cs and ^{137}Cs , it was evident that these two isotopes would definitely not be applicable for burnup profile monitors. However, they do have long half-lives and easily resolvable gamma-ray spectra. Cesium-137 has been used as a burnup monitor for fuels in which it had not migrated.^{91,93,94,99}

Cerium-144 has a relatively long half-life of 285 d and its daughter, ^{144}Pr , has a gamma-ray spectra with peaks at 695, 1487, and 2186 keV. Cerium may migrate radially, but it probably does not migrate axially to any significant degree.^{103,106} Therefore, ^{144}Ce satisfied the six criteria of a burnup monitor, and ^{106}Ru satisfied some of the criteria.

The burnup profile of a mixed uranium-plutonium oxide fuel pin with a nominal burnup of 6.5 atom percent was scanned in the multispectral mode of data collection to obtain the ^{106}Ru and ^{144}Ce axial distributions. The respective results are presented in Figs. 68, 69, and 70 for the ^{106}Rh , ^{144}Pr , and ^{137}Cs distributions, respectively. The ^{137}Cs distribution (Fig. 70) emphasized the conclusion that the isotope cannot provide the accurate burnup profile of a pin. The axial distributions of ^{106}Rh and ^{144}Pr were relatively uniform. There was no evidence of any axial migration of ^{106}Rh within the fuel material, therefore, both isotopes, ^{106}Rh and ^{144}Pr , represented the axial burnup profile.

As was mentioned above, the fission yields of ^{106}Rh for uranium ($0.44 \pm 0.05\%$) and plutonium ($4.7 \pm 0.5\%$) vary by an

Fig. 68. Axial Isotopic Distribution of ^{106}Rh for Differential Burnup Profile Calculations.

Fig. 69. Axial Isotopic Distribution of ^{144}Pr for Differential Burnup Profile Calculations.

Fig. 70. Axial Isotopic Distribution of ^{137}Cs Showing Migration to Interpocket Gaps and to Two Axial Locations (19.00 and 25.00 in.).

order of magnitude. The fission yields of ^{144}Ce for uranium and plutonium are approximately equal. Therefore it was possible to obtain two simultaneous equations, with the appropriate decay corrections and calculate the relative burnup profiles of uranium and plutonium.¹¹⁹ The results are presented in Fig. 71 with the results normalized to the 6.5 atom-percent burnup. The heavy atoms appear to have similar burnup profiles for this particular sample, however in cases where the uranium and plutonium have undergone significant segregation, gamma scanning provided relative burnup profiles.

The absolute burnup can be calculated if the total amount of a specific fission product were known by the following equation:

$$\text{Absolute Burnup} = \frac{N_1}{N_2 \cdot \epsilon \cdot \text{FY} \cdot \text{BR}} \quad (2)$$

- N_1 = counts in the specific fission product full energy peak (corrected for decay)
- N_2 = total number of fissionable atoms present
- ϵ = efficiency of counting system
- FY = fission yield of specific fission product
- BR = branching ratio of gamma ray (decay scheme)

The total number of fission product atoms was determined using the QUADET computer program described in Appendix III. In the section on the Quantitative Gamma Scanning of fission products, the total counts of ^{137}Cs and ^{106}Ru atoms were calculated for the two sections of a low burnup sample. The nominal burnup of the fuel pin was 0.35 atom-percent. The results for the two sections are tabulated in Table XIV.

Gamma scanning methods were used to determine the rela-

Fig. 71. Differential Burnup Profiles of Uranium and Plutonium

Table XIV

Determination of Absolute Burnup Using QUADET

	<u>Section A</u>	<u>Section I</u>
^{137}Cs atoms	1.08×10^{19}	9.71×10^{18}
^{106}Ru atoms	1.76×10^{18}	1.54×10^{18}
Total fission- able atoms	4.76×10^{22}	4.58×10^{22}
Burnup*		
^{137}Cs	$0.35 \pm 0.02\%$	$0.33 \pm 0.02\%$
^{106}Ru	$0.34 \pm 0.03\%$	$0.31 \pm 0.03\%$

* Average burnup for each section, based on respective fission yields.

tive burnup profile of an irradiated fuel pin. Additional information concerning the relative burnup of uranium and plutonium was obtained by using two isotopes, in this case, ^{106}Ru and ^{144}Ce . Therefore, it was possible to determine the absolute burnup of a pin by the quantitative determination of fission products. Additional samples are being prepared to permit a statistical evaluation of the accuracy of the gamma scanning methods.

Other Applications of Gamma Scanning

(1) Smeared Densities

The relative density of a fuel column can be determined by measuring the attenuation of specific gamma rays.¹²⁰ This requires the precise alignment of the source, the fuel pin, and the collimation assembly to obtain meaningful results. An alternate method is presently being investigated to determine the relative smeared densities along the major axis of a fuel pin.

Preliminary calculations indicate that this can be accomplished by comparing the respective attenuations of several gamma rays emitted by the same fission product. In this method the fuel pin itself is used as the source, thereby eliminating the problems of alignment. This method can possibly be extended to determine the absolute smeared densities as a function of precise position along the axis or across the diameter of the pin. Two isotopes presently being considered are ^{106}Rh (512, 622, 1050, and 1560 keV) and ^{144}Pr (695, 1487,

and 2186 keV).

(2) Three-Dimensional Profiles

The three-dimensional profile of an irradiated fuel pin can be calculated by scanning at 0° and 90° . By scanning the pin at several Z-positions, the three-dimensional projection of the pin can be determined, indicating the presence of preferential cladding swelling or contraction as a function of rotational position. Gamma scanning could be applied to studying directional neutron fluence and structural changes in an operating reactor.

CHAPTER 4

CONCLUSIONS

A new gamma scanning system has been described which represents the state-of-the-art for the thorough, detailed, nondestructive examination of fast reactor fuel pins. The system has been applied to the characterization of irradiated fuel pins resulting in information about fuel dimensions, fission product distributions, fast and thermal neutron flux profiles, relative burnup profiles, and fuel cladding failures.

A nondestructive method utilizing precision gamma scanning for the detection of fuel cladding failures in doubly encapsulated fuel pins was described. Thirteen mixed uranium-plutonium fuel pins have been examined. Gamma scanning indicated that six of the thirteen fuel pins had failed. These results were confirmed by mass spectrometric analysis of the gases in the outer encapsulation which were found to contain 11.7 to 65.0% xenon and 1.76 to 9.31% krypton.

The precision gamma scanning system was used for the investigation of the mass transfer mechanisms of ^{134}Cs and ^{137}Cs in irradiated fuel pins. The two isotopes were found to adsorb preferentially on fuel pellets having relatively higher oxygen contents. The isotopic distributions of the

two cesium isotopes were also related to the half-lives of their precursors.

The quantitative determinations ($\pm 5\%$) of specific fission products in a low burnup (0.35%) fuel pin were described. Quantitative gamma scanning required the complete calibration of the system, including the effective collimating slits, the surface response functions of the Ge(Li) detector, and the total geometrical efficiency.

The absolute burnup profiles were determined from the quantitative gamma scanning results at 0.010-in. intervals. The burnup profile of a mixed uranium-plutonium oxide fuel pin was separated into two components, The uranium burnup and the plutonium burnup, using the relative fission yields of two isotopes, ^{106}Rh and ^{144}Pr .

The gamma scanning system provided a vast amount of information about the physical and chemical properties of the irradiated fuel pins. No other nondestructive or destructive method of analysis could provide comparable information in the time required for gamma scanning. Gamma scanning will become an even more valuable analytical technique as additional applications are investigated and proven.

APPENDIX I

COLLUM Computer Code

The COLLUM computer code permitted the calculation of the geometrical projection of a collimated gamma-ray beam onto a planar surface. The code calculated the effect of up to ten rectangular collimating slits on the divergence of the gamma-ray beam. The gamma-ray beam was separated into two components, the umbra and the penumbra, permitting the investigation of the two effects on the resulting image.

The basic assumptions of the code were: the collimating material was black, there were no contributions from gamma-ray penetrations of the collimating material, there was no coherent scattering of gamma photons by the slit walls, and the source was assumed to be uniform and planar, extending in the X and Z directions sufficiently to cover completely the collimating slit.

The particular collimator arrangements to which the code had been applied have supported these assumptions, as evidenced by the comparisons of experimental collimation images and calculated distributions. (Figs. 19, 20, 21, and 22) The input data consisted of collimator parameters, such as, heights, widths, and lengths of the rectangular

slits, the collimators positions with respect to the source, and the projection surface (detector surface). The collimating slits did not have to be parallel to the major axis, the sides could have been parallel, or sloped inwardly or outwardly. The resulting gamma-ray beam image was represented by a 64 by 64 matrix with the intensities of the specified points. The data were plotted as a projection onto the detector surface by using special plotting routines.⁶⁵ This allowed the visual inspection of the beam image and its relation to the detector's surface, as shown in Fig. 17.

The computer code could be used to examine the collimation effects of any rectangular slit arrangement for a particular geometrical configuration. The code was used extensively in the design of the collimating system and in the evaluation of the final collimators. A listing of the computer code is given in Control Data Corporation FORTRAN IV, the plotting routines have been described in a previous publication.⁶⁵

	PROGRAM COLLUM (INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT,TAPE7)	COL	
	DIMENSION XBSC(10), YBSC(10), ZBSC(10), YBSLOC(10), SHAPE(10), XAN	COL	1
1	GLE(10), ZANGLE(10), XPI(65), ZP(65), XAB(1650), XCD(1650), ZAD(165	COL	2
2	0), ZBC(1650), Z(65,65), ZZ(65,65), TITLE(8)	COL	3
	DIMENSION XM(10), ZM(10)	COL	4
	COMMON /W1/ TITLE,LL,XS,DELX,ZS,DELZ,Z,DIADET	COL	5
	DATA PENUM,UMBRA,TOTAL/5HPENUM,5HUMBRA 5HTOTAL/	COL	6
	EQUIVALENCE (Z(1,1),ZZ(1,1))	COL	7
C		COL	8
C	***** DEFINITION OF VARIABLES *****	COL	9
C		COL	10
C	CARD NO.	COL	11
C	1 *PNORUM*	COL	12
C	DETERMINES WHETHER THE UMBRA, PENUMBRA, OR TOTAL RESPONSE IS TO	COL	13
C	PNORUM MAY BE SET TO UMBRA,PENUMBRA, OR TOTAL	COL	14
C	BE CALCULATED BY THE CODE	COL	15
C	2 *TITLE*	COL	16
C	TITLE OF COLLIMATING SYSTEM BEING INVESTIGATED MAY BE UP TO	COL	17
C	80 CHARACTERS LONG	COL	18
C	3 *XC,YC,ZC,YD,YS,ANGX,ANGZ*	COL	19
C	PARAMETERS OF PRIMARY COLLIMATOR, SOURCE, AND DETECTOR	COL	20
C	XC WIDTH OF PRIMARY COLLIMATOR IN INCHES	COL	21
C	YC LENGTH OF PRIMARY COLLIMATOR IN INCHES	COL	22
C	ZC HEIGHT OF PRIMARY COLLIMATOR IN INCHES	COL	23
C	YD DISTANCE FROM SURFACE OF PRIMARY COLLIMATOR TO	COL	24
C	DETECTORS SURFACE IN INCHES	COL	25
C	YS DISTANCE THE UNIFORM SOURCE IS IN FRONT OF THE	COL	26
C	PRIMARY COLLIMATOR IN INCHES	COL	27
C	ANGX SLOPE OF PRIMARY COLLIMATOR IN THE X DIRECTION OF THE	COL	28
C	YZ PLANE GIVEN IN DEGREES	COL	29
C	ANGZ SLOPE OF PRIMARY COLLIMATOR IN THE Z DIRECTION OF THE	COL	30
C	XY PLANE GIVEN IN DEGREES	COL	31
C	A POSITIVE ANGLE INDICATES THAT THE SLIT BECOMES WIDER AS	COL	32
C	DISTANCE FROM THE SOURCE INCREASES	COL	33
C	4 *STEPX,STEPZ*	COL	34
C	STEP SIZE SEPARATING POINTS AT WHICH RESPONSE IS CALCULATED	COL	35
C	STEPX SPACING IN THE X-DIRECTION	COL	36
C	STEPZ SPACING IN THE Z-DIRECTION	COL	37
C	STEPX AND STEPZ MAY HAVE ANY VALUES AND DO NOT HAVE TO BE EQUAL	COL	38
C	5 *XSTART,ZSTART,DIADET*	COL	39
C	DEFINITION OF AREA IN WHICH COLLIMATOR RESPONSE IS CALCULATED	COL	40
C	XSTART THE AREA OF CALCULATED RESPONSE IS - XSTART TO XSTART	COL	41
C	IN STEPS EQUAL TO XSTART/32.0	COL	42
C	ZSTART THE AREA OF CALCULATED RESPONSE IS - ZSTART TO ZSTART	COL	43
C	IN STEPS EQUAL TO ZSTART/32.0	COL	44
C	THE VALUES OF XSTART AND ZSTART ARE NOT RESTRICTED	COL	45
C	6 *NBSC*	COL	46
C	NUMBER OF BEAM SCRAPING COLLIMATORS TO BE CONSIDERED,	COL	47
C	LIMITED TO BEING EQUAL TO OR LESS THAN 10	COL	48
C	7 *XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(I)*	COL	49
C	XBSC(I) WIDTH OF BEAM SCRAPING COLLIMATOR I	COL	50
C	YBSC(I) LENGTH OF BEAM SCRAPING COLLIMATOR I	COL	51
C	ZBSC(I) HEIGHT OF BEAM SCRAPING COLLIMATOR I	COL	52
C	YBSLOC(I) DISTANCE FROM THE FRONT OF THE PRIMARY COLLIMATOR TO	COL	53
C	TO THE BACK OF THE BEAM SCRAPING COLLIMATOR I	COL	54

C	8	"DIADET"	COL 55
C		DIADET DIAMETER OF THE GE(LI) DETECTOR, VALUE USED IN PLOT	COL 56
C		XANGLE(I) SLOPE IN X-DIRECTION OF THE YZ PLANE GIVEN IN DEGREES	COL 57
C		ZANGLE(I) SLOPE IN Z-DIRECTION OF THE XY PLANE GIVEN IN DEGREES	COL 58
C		.....	COL 59
C			COL 60
C		READ (1,115)PNORUM	COL 61
		READ (1,140)(ITITLE(L),L=1,8)	COL 62
		READ (1,145)XC,YC,ZC,YD,YS,ANGX,ANGZ	COL 63
		READ (1,145)STEPX,STEPZ	COL 64
		READ (1,145)XSTART,ZSTART,DIADET	COL 65
		READ (1,200)NBSC	COL 66
		IF (NBSC.EQ.0) GO TO 5	COL 67
		READ (1,135)((XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(I)	COL 68
1		),SHAPE(I)),I=1,NBSC)	COL 69
5		CONTINUE	COL 70
		READ (1,145)DIADET	COL 71
		IF (PNORUM.EQ.UMBRA) WRITE (2,120)	COL 72
		IF (PNORUM.EQ.PENUM) WRITE (2,125)	COL 73
		IF (PNORUM.EQ.TOTAL) WRITE (2,130)	COL 74
		WRITE (2,150)XC,ZC,YC	COL 75
		WRITE (2,155)ANGX,ANGZ	COL 76
		WRITE (2,160)STEPX,STEPZ	COL 77
		WRITE (2,165)YD	COL 78
		WRITE (2,170)YS	COL 79
		IF (YS.EQ.0.0) WRITE (2,175)	COL 80
		IF (YS.LE.0.0) PNORUM=UMBRA	COL 81
		IF (YS.LT.0.0) WRITE (2,180)	COL 82
		XR=XC/2.0	COL 83
		XL=-XR	COL 84
		ZT=ZC/2.0	COL 85
		ZMIN=(ZC*(YC+YS)/(YC-ZC))/YS	COL 86
		XMIN=(XC*(YC+YS)/(YC-XC))/YS	COL 87
		ZB=-ZT	COL 88
C			COL 89
C		 VARIABLES USED IN CALCULATIONS	COL 90
C			COL 91
C			COL 92
C	XSP	X-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	COL 93
C		DETECTORS SURFACE IS DETERMINED	COL 94
C	YSP	Y-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	COL 95
C		DETECTORS SURFACE IS DETERMINED	COL 96
C	ZSP	Z-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	COL 97
C		DETECTORS SURFACE IS DETERMINED	COL 98
C	XAB	THE MINIMUM X VALUE ON THE DETECTORS SURFACE VIEWED	COL 99
C		FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	COL 100
C	XCD	THE MAXIMUM X VALUE ON THE DETECTORS SURFACE VIEWED	COL 101
C		FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	COL 102
C	ZAD	THE MINIMUM Z VALUE ON THE DETECTORS SURFACE VIEWED	COL 103
C		FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	COL 104
C	ZBC	THE MAXIMUM Z VALUE ON THE DETECTORS SURFACE VIEWED	COL 105
C		FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	COL 106
C	XMIN	MINIMUM X-POSITION ON THE PLANAR SOURCE	COL 107
C	ZMIN	MINIMUM Z-POSITION ON THE PLANAR SOURCE	COL 108
C			COL 109

C	XABBSC	XAB-BEAM-SCRAPING-COLLIMATOR	COL	110
C	XCDBSC	XCD-BEAM-SCRAPING-COLLIMATOR	COL	111
C	ZADBSC	ZAD-BEAM-SCRAPING-COLLIMATOR	COL	112
C	ZBCBSC	ZBC-BEAM-SCRAPING-COLLIMATOR	COL	113
C			COL	114
C	XABBSC,XCDBSC,ZADBSC, AND ZBCBSC DEFINE THE SURFACE AREA OF THE		COL	115
C	DETECTOR SEEN THROUGH THE BEAM-SCRAPING COLLIMATORS FROM THE		COL	116
C	POINT (XSP,YSP,ZSP) ON THE SOURCE		COL	117
C	.....		COL	118
C			COL	119
	IF (NBSC.EQ.0) GO TO 10		COL	120
	WRITE (2,185)NBSC		COL	121
	WRITE (2,190)((XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(		COL	122
1	I)),I=1,NBSC)		COL	123
10	CONTINUE		COL	124
	WRITE (2,195)		COL	125
C			COL	126
C	.....		COL	127
C			COL	128
C	CALCULATES THE LIMITS OF THE PENUMBRA ON THE SOURCE		COL	129
C			COL	130
C	XSPM	X-SOURCE-PENUMBRA-MAXIMUM	COL	131
C	ZSPM	Z-SOURCE-PENUMBRA-MAXIMUM	COL	132
C	XSLP	X-SOURCE-LEFT-PENUMBRA	COL	133
C	XSRP	X-SOURCE-RIGHT-PENUMBRA	COL	134
C	ZSTP	Z-SOURCE-TOP-PENUMBRA	COL	135
C	ZSBP	Z-SOURCE-BOTTOM-PENUMBRA	COL	136
C			COL	137
C	.....		COL	138
C			COL	139
	IF (NBSC.EQ.0) GO TO 25		COL	140
	DO 15 J=1,NBSC		COL	141
	XANGLE(J)=(XANGLE(J)*3.1415927)/180.0		COL	142
	ZANGLE(J)=(ZANGLE(J)*3.1415927)/180.0		COL	143
	XM(J)=((XBSC(J)/2.0)+TAN(XANGLE(J))*YBSC(J)+XC/2.0)/(YBSLOC(J))		COL	144
	XMF=(XBSC(J)/2.0+XC/2.0)/(YBSLOC(J)-YBSC(J))		COL	145
	IF (XMF.LT.XM(J)) XM(J)=XMF		COL	146
	ZM(J)=((ZBSC(J)/2.0)+TAN(ZANGLE(J))*YBSC(J)+ZC/2.0)/(YBSLOC(J))		COL	147
	ZMF=(ZBSC(J)/2.0+ZC/2.0)/(YBSLOC(J)-YBSC(J))		COL	148
	IF (ZMF.LT.ZM(J)) ZM(J)=ZMF		COL	149
15	CONTINUE		COL	150
	DO 20 JJ=1,NBSC		COL	151
	IF (XM(JJ).LT.XMIN) XMIN=XM(JJ)		COL	152
	IF (ZM(JJ).LT.ZMIN) ZMIN=ZM(JJ)		COL	153
20	CONTINUE		COL	154
	XSPM=(XMIN*YS)		COL	155
	ZSPM=(ZMIN*YS)		COL	156
25	CONTINUE		COL	157
	XSLP=XL-XSPM		COL	158
	XSRP=XR+XSPM		COL	159
	ZSTP=ZT+ZSPM		COL	160
	ZSBP=ZB-ZSPM		COL	161
C			COL	162
			COL	163

C	.....	COL 164
C		COL 165
C	<i>CALCULATES PENUMBRA AND UMBRA AREA ON THE SURFACE OF THE SOURCE</i>	COL 166
C	.....	COL 167
C		COL 168
C		COL 169
	PNAREA=(XSRP-XSLP)*(ZSTP-ZSBP)	COL 170
	WRITE (2,205)XSLP,XSRP,ZSTP,ZSBP	COL 171
	XUMBRA=XC*ZC	COL 172
	XPENUM=PNAREA-XUMBRA	COL 173
	WRITE (2,210)PNAREA,XPENUM,XUMBRA	COL 174
C	.....	COL 175
C		COL 176
C		COL 177
C	<i>DETERMINES THE NUMBER OF STEPS AND STEPSIZE TO BE CONSIDERED</i>	COL 178
C	<i>ACROSS THE SURFACE OF THE SOURCE</i>	COL 179
C	<i>THE STEP SIZE IS ADJUSTED TO AN INTEGRAL MULTIPLE OF THE TOTAL</i>	COL 180
C	<i>DISTANCE ACROSS THE SOURCE</i>	COL 181
C		COL 182
C	<i>IXS TOTAL NUMBER OF X POINTS AT WHICH XAB, XCD, ZAD, AND</i>	COL 183
C	<i>ZBC ARE CALCULATED</i>	COL 184
C	<i>IZS TOTAL NUMBER OF Z POINTS AT WHICH XAB, XCD, ZAD, AND</i>	COL 185
C	<i>ZBC ARE CALCULATED</i>	COL 186
C	<i>IXS*IZS TOTAL NUMBER OF POINTS CONSIDERED</i>	COL 187
C	.....	COL 188
C		COL 189
	IF (PNORUM.EQ.UMBRA) GO TO 30	COL 190
	ISTEPX=(XSRP-XSLP)/STEPX+0.5	COL 191
	ISTEPZ=(ZSTP-ZSBP)/STEPZ+0.5	COL 192
	STEPX=(XSRP-XSLP)/ISTEPX	COL 193
	STEPZ=(ZSTP-ZSBP)/ISTEPZ	COL 194
	IXS=(XSRP-XSLP)/STEPX+1.5	COL 195
	IZS=(ZSTP-ZSBP)/STEPZ+1.5	COL 196
	GO TO 35	COL 197
	CONTINUE	COL 198
30	IXS=(XR-XL)/STEPX+1.5	COL 199
	IZS=(ZT-ZB)/STEPZ+1.5	COL 200
	ISTEPX=IXS-1	COL 201
	ISTEPZ=IZS-1	COL 202
35	CONTINUE	COL 203
	WRITE (2,215)ISTEPX,ISTEPZ,STEPX,STEPZ,IXS,IZS	COL 204
	K=0	COL 205
	ANGX=(ANGX*3.1415927)/180.0	COL 206
	ANGZ=(ANGZ*3.1415927)/180.0	COL 207
	IF (PNORUM.EQ.UMBRA) XLS=XL	COL 208
	IF (PNORUM.EQ.UMBRA) ZBS=ZB	COL 209
	IF (PNORUM.EQ.TOTAL) XLS=XSLP	COL 210
	IF (PNORUM.EQ.TOTAL) ZBS=ZSBP	COL 211
	IF (PNORUM.EQ.PRNUM) XLS=XSLP	COL 212
	IF (PNORUM.EQ.PENUM) ZBS=ZSBP	COL 213
	DO 70 I=1,IZS	COL 214
	DO 65 J=1,IXS	COL 215
	K=K+1	COL 216
	XSP=XLS+(J-1)*STEPX	COL 217
		COL 218

	ZSP=ZBS+ (I- 1)*STEPZ	COL 219
	IF (XSP. LE. XR. AND. XSP. GE. XL. AND. ZSP. LE. ZT. AND. ZSP. GE. ZB) GO TO 40	COL 220
	GO TO 45	COL 221
40	CONTINUE	COL 222
	IF (PNORUM. EQ. PENUM) GO TO 65	COL 223
	XCD(K)=XSP+ (XR+ YC*TAN(ANGX)- XSP)*(YS+ YD)/(YS+ YC)	COL 224
	XAB(K)=XSP+ (XL- YC*TAN(ANGX)- XSP)*(YS+ YD)/(YS+ YC)	COL 225
	ZAD(K)=ZSP+ (ZB- YC*TAN(ANGZ)- ZSP)*(YS+ YD)/(YS+ YC)	COL 226
	ZBC(K)=ZSP+ (ZT+ YC*TAN(ANGZ)- ZSP)*(YS+ YD)/(YS+ YC)	COL 227
	GO TO 50	COL 228
45	CONTINUE	COL 229
	IF (PNORUM. EQ. UMBRA) GO TO 50	COL 230
	IF (YS. EQ. 0. 0) GO TO 50	COL 231
	XAB(K)=(XL- XSP)*(YS+ YD)/YS+ XSP	COL 232
	XAB1=(XL- XSP- YC*TAN(ANGX))*(YS+ YD)/(YS+ YC)+ XSP	COL 233
	IF (XAB1. GT. XAB(K)) XAB(K)=XAB1	COL 234
	XCD(K)=(XR- XSP+ YC*TAN(ANGX))*(YS+ YD)/(YS+ YC)+ XSP	COL 235
	XCD1=(XR- XSP)*(YS+ YD)/YS+ XSP	COL 236
	IF (XCD1. LT. XCD(K)) XCD(K)=XCD1	COL 237
	ZAD(K)=(ZB- ZSP)*(YS+ YD)/YS+ ZSP	COL 238
	ZAD1=(ZB- ZSP- YC*TAN(ANGZ))*(YS+ YD)/(YS+ YC)+ ZSP	COL 239
	IF (ZAD1. GT. ZAD(K)) ZAD(K)=ZAD1	COL 240
	ZBC(K)=(ZT- ZSP+ YC*TAN(ANGZ))*(YS+ YD)/(YS+ YC)+ ZSP	COL 241
	ZBC1=(ZT- ZSP)*(YS+ YD)/YS+ ZSP	COL 242
	IF (ZBC1. LT. ZBC(K)) ZBC(K)=ZBC1	COL 243
50	CONTINUE	COL 244
C		COL 245
C	*****	COL 246
C		COL 247
C	THIS SECTION DEALS WITH THE EFFECT OF BEAM SCRAPING COLLIMATORS	COL 248
C	ON THE GAMMA BEAM	COL 249
C	THE BEAM SCRAPING COLLIMATORS MUST BE SLITS, MAY EITHER BE	COL 250
C	POSITIVELY OR NEGATIVELY SLOPED	COL 251
C	THE VALUES XAB,XCD,ZAD,ZBC DEFINE THE RECTANGULAR LIMITS ON THE	COL 252
C	DETECTORS SURFACE WITH RESPECT TO A POINT LOCATED IN THE SOURCE	COL 253
C	AT (XSP,YSP,ZSP)	COL 254
C	EACH BEAM SCRAPING COLLIMATOR IS CHECKED TO DETERMINE IF THE	COL 255
C	FRONT OR THE BACK OF THE SLIT DEFINES THE GAMMA BEAM	COL 256
C	ZBC1,ZAD1,XAB1,XCD1 - FRONT END TOWARDS THE SOURCE	COL 257
C	ZBC2,ZAD2,XAB2,XCD2 - BACK END TOWARDS THE DETECTOR	COL 258
C	*****	COL 259
C		COL 260
C		COL 261
	IF (NBSC. EQ. 0) GO TO 60	COL 262
	DO 55 II=1,NBSC	COL 263
	ZAD1=ZSP+ (- ZBSC(II)/2. 0- ZSP)*(YS+ YD)/(YBSLOC(II)+ YS- YBSC(II))	COL 264
1	ZAD2=ZSP+ (- ZBSC(II)/2. 0- YBSC(II)*TAN(ZANGLE(II))- ZSP)*(YS+ YD)/(YBS	COL 265
	LOC(II)+ YS)	COL 266
	ZADBSC=ZAD1	COL 267
	IF (ZADBSC. LT. ZAD2) ZADBSC=ZAD2	COL 268
	ZBC2=ZSP+ (ZBSC(II)/2. 0- ZSP)*(YS+ YD)/(YBSLOC(II)+ YS- YBSC(II))	COL 269
1	ZBC1=ZSP+ (ZBSC(II)/2. 0+ YBSC(II)*TAN(ZANGLE(II))- ZSP)*(YS+ YD)/(YBSL	COL 270
	OC(II)+ YS)	COL 271
	ZBCBSC=ZBC1	COL 272
	IF (ZBCBSC. GT. ZBC2) ZBCBSC=ZBC2	COL 273

	IF (ZADBSC.GT.ZAD(K)) ZAD(K)=ZADBSC	COL 274
	IF (ZBCBSC.LT.ZBC(K)) ZBC(K)=ZBCBSC	COL 275
	XAB1=XSP+ (-XBSC(III)/2.0-XSP)*(YS+YD)/(YBSLOC(III)+YS-YBSC(III))	COL 276
	XAB2=XSP+ (-XBSC(III)/2.0-YBSC(III)*TAN(XANGLE(III))-XSP)*(YS+YD)/(YBS	COL 277
1	LOC(III)+YS)	COL 278
	XABBSC=XAB1	COL 279
	IF (XABBSC.LT.XAB2) XABBSC=XAB2	COL 280
	XCD1=XSP+ (XBSC(III)/2.0-XSP)*(YS+YD)/(YBSLOC(III)+YS-YBSC(III))	COL 281
	XCD2=XSP+ (XBSC(III)/2.0+YBSC(III)*TAN(XANGLE(III))-XSP)*(YS+YD)/(YBSL	COL 282
1	OC(III)+YS)	COL 283
	XCOBSC=XCD1	COL 284
	IF (XCOBSC.GT.XCD2) XCOBSC=XCD2	COL 285
	IF (XABBSC.GT.XAB(K)) XAB(K)=XABBSC	COL 286
	IF (XCOBSC.LT.XCD(K)) XCD(K)=XCOBSC	COL 287
55	CONTINUE	COL 288
60	CONTINUE	COL 289
65	CONTINUE	COL 290
70	CONTINUE	COL 291
C		COL 292
C	.....	COL 293
C		COL 294
C	XRD X-RIGHT-DETECTOR MAXIMUM POINT IN POSITIVE X DIRECT.	COL 295
C	XLD X-RIGHT-DETECTOR MINIMUM POINT IN POSITIVE X DIRECT.	COL 296
C	ZTD Z-TOP-DETECTOR MAXIMUM POINT IN POSITIVE Z DIRECT.	COL 297
C	ZBD Z-BOTTOM-DETECTOR MINIMUM POINT IN NEGATIVE Z DIREC.	COL 298
C		COL 299
C	.....	COL 300
C		COL 301
	DELX=-.2.0*XSTART/63.0	COL 302
	DELZ=-.2.0*ZSTART/63.0	COL 303
	XS=XSTART	COL 304
	ZS=ZSTART	COL 305
	LL=32	COL 306
	DO 75 I=1,64	COL 307
	XP(I)=XS+ (I-1)*DELX	COL 308
	ZP(I)=ZS+ (I-1)*DELZ	COL 309
75	CONTINUE	COL 310
	WRITE (2,220)	COL 311
	WRITE (2,225)(XP(J),J=1,64)	COL 312
	WRITE (2,230)	COL 313
	WRITE (2,225)(ZP(I),I=1,64)	COL 314
C		COL 315
C	.....	COL 316
C		COL 317
C	XD,ZD SPECIFY POSITION ON THE SURFACE OF THE DETECTOR	COL 318
C	IF (XD,ZD) LIE WITHIN XAB, XCD, ZAD, AND ZBC Z(N,M)	COL 319
C	IS INCREMENTED BY 1	COL 320
C	Z(N,M) INTENSITY FUNCTION AT POINT (XD,ZD)	COL 321
C		COL 322
C	THE SPACING BETWEEN SUBSEQUENT (XD,ZD) IS DEPENDENT UPON	COL 323
C	XSTART AND ZSTART ON THE INPUT CARDS	COL 324
C	THE RESULTS ARE PRINTED OUT IN A 64X64 MATRIX AND A SUBROUTINE	COL 325
C	WRIT2P IS CALLED TO WRITE THE RESULTS ONTO MAGNETIC TAPE	COL 326
C		COL 327
C	.....	COL 328

C		COL 329
	DO 90 N=1,32	COL 330
	DO 85 M=1,32	COL 331
	DO 80 J=1,K	COL 332
	ICH=0	COL 333
	XD=XP(M)	COL 334
	ZD=ZP(N)	COL 335
	IF (XD.GE.XAB(J)) ICH=ICH+ 1	COL 336
	IF (XD.LE.XCD(J)) ICH=ICH+ 1	COL 337
	IF (ZD.LE.ZBC(J)) ICH=ICH+ 1	COL 338
	IF (ZD.GE.ZAD(J)) ICH=ICH+ 1	COL 339
	IF (ICH.EQ.4) Z(IN,M)=Z(IN,M)+ 1	COL 340
80	CONTINUE	COL 341
	Z(65-N,M)=Z(N,M)	COL 342
	Z(N,65-M)=Z(N,M)	COL 343
	Z(65-N,65-M)=Z(N,M)	COL 344
85	CONTINUE	COL 345
90	CONTINUE	COL 346
	J1=1	COL 347
	J16=16	COL 348
	J17=17	COL 349
	J32=32	COL 350
	J33=33	COL 351
	J48=48	COL 352
	J49=49	COL 353
	J64=64	COL 354
	WRITE (2,235)J1,J16	COL 355
	DO 95 I=1,64	COL 356
	WRITE (2,240)(ZZ(I,J),J=J1,J16)	COL 357
95	CONTINUE	COL 358
	WRITE (2,235)J17,J32	COL 359
	DO 100 I=1,64	COL 360
	WRITE (2,240)(ZZ(I,J),J=J17,J32)	COL 361
100	CONTINUE	COL 362
	WRITE (2,235)J33,J48	COL 363
	DO 105 I=1,64	COL 364
	WRITE (2,240)(ZZ(I,J),J=J33,J48)	COL 365
105	CONTINUE	COL 366
	WRITE (2,235)J49,J64	COL 367
	DO 110 I=1,64	COL 368
	WRITE (2,240)(ZZ(I,J),J=J49,J64)	COL 369
110	CONTINUE	COL 370
	CALL WRIT2P	COL 371
	STOP	COL 372
C		COL 373
C		COL 374
115	FORMAT (A5)	COL 375
120	FORMAT (1H1,///,30X,73H+++++ UMBRA RESPONSE FOR THE	COL 376
1	DETECTOR +++++ ,//)	COL 377
125	FORMAT (1H1,///,30X,75H+++++ PENUMBRA RESPONSE FOR	COL 378
1	THE DETECTOR +++++ ,///)	COL 379
130	FORMAT (1H1,///,30X,75H+++++ TOTAL RESPONSE FOR	COL 380
1	THE DETECTOR +++++ ,///)	COL 381
135	FORMAT (7F10.4)	COL 382
140	FORMAT (8A10)	COL 383
145	FORMAT (7F10.3)	COL 384

150	FORMAT (///,25H THE COLLIMATING SLIT IS ,F6.4,13H INCHES) BY ,F6.	COL	385
1	4,14H INCHES) AND ,F6.4,12H INCHES LONG)	COL	386
155	FORMAT (/,35H THE PRIMARY COLLIMATOR IS TAPERED ,F5.2,32H DEGREE S	COL	387
1	IN THE X-DIRECTION AND,F5.2,27H DEGREES IN THE Z-DIRECTION)	COL	388
160	FORMAT (5X,/,8H STEPX =,F10.6,10X,7HSTEPZ =,F10.6)	COL	389
165	FORMAT (/,17H THE DETECTOR IS ,F7.4,38H INCHES FROM THE END OF THE	COL	390
1	COLLIMATOR)	COL	391
170	FORMAT (/,15H THE SOURCE IS ,F7.4,31H FROM THE END OF THE COLLIMAT	COL	392
1	OR,///)	COL	393
175	FORMAT (////,10X,78H YS = 0.0, SOURCE ASSUMED TO BE AT THE FRONT	COL	394
1	SURFACE OF THE PRIMARY COLLIMATOR,///)	COL	395
180	FORMAT (////,10X,68H YS .LT. 0.0, THE SOURCE ASSUMED TO BE INSIDE	COL	396
1	THE PRIMARY COLLIMATOR,////)	COL	397
'85	FORMAT (10X,///,11H THERE ARE ,I3,28H BEAM SCRAPERS IN THE SYSTEM)	COL	398
40	FORMAT (///,5X,18H THE COLLIMATOR IS ,F6.3,13H INCHES WIDE ,F6.3,13H	COL	399
1	INCHES LONG ,F6.3,28H INCHES HIGH AND IS LOCATED ,F7.3,33H INCHES	COL	400
2	FROM THE FRONT COLLIMATOR,/,36H WITH A SLOPE IN THE X-DIRECTION O	COL	401
3	F ,F5.2,23H DEGREES AND A SLOPE OF,F5.2,19H IN THE Z-DIRECTION)	COL	402
195	FORMAT (//)	COL	403
200	FORMAT (I6)	COL	404
205	FORMAT (/,32H THE PENUMBRA AREA EXTENDS FROM ,F6.4,4H TO ,F6.4,19H	COL	405
1	IN THE X DIRECTION,/,10H AND FROM ,F6.4,4H TO ,F6.4,43H IN THE Z	COL	406
2	DIRECTION ON THE DETECTORS SURFACE)	COL	407
210	FORMAT (///,5X,12HTOTAL AREA =,F10.5,5X,15HPENUMBRA AREA =,F10.5,5X	COL	408
1	,12HUMBRA AREA =,F10.5,///)	COL	409
215	FORMAT (5X,8HISTEPX =,I4,5X,8HISTEPZ =,I4,5X,7HSTEPX =,F6.4,5X,7HS	COL	410
1	TEPZ =,F6.4,5X,5HIXS =,I4,5X,5HIZS =,I4)	COL	411
220	FORMAT (///,10X,113H THE FOLLOWING ARE THE X COORDINATES FOR THE G	COL	412
1	RID OVER THE DETECTOR AT WHICH THE INTENSITIES ARE TO BE DETERMINE	COL	413
2	D,///)	COL	414
225	FORMAT (10(2X,F10.5))	COL	415
230	FORMAT (///,10X,113H THE FOLLOWING ARE THE Z COORDINATES FOR THE G	COL	416
1	RID OVER THE DETECTOR AT WHICH THE INTENSITIES ARE TO BE DETERMINE	COL	417
2	D,///)	COL	418
235	FORMAT (1H1,/,8H COLUMN ,I3,16H THROUGH COLUMN ,I3)	COL	419
240	FORMAT (I6(1X,F7.0))	COL	420
	END	COL	421

APPENDIX II

SURFACE RESPONSE FUNCTIONS

The surface response functions are plotted for the following gamma photon energies: 59.5, 511, 834.5, 898, 1173, 1275, and 1332 keV in Figs. 72-78. The contour lines represent 10% steps in the relative net full-energy peak areas: G = 90%, F = 80%, E = 70%, D = 60%, C = 50%, B = 40%, and A = 30% of the maximum peak areas. The effect of the p-type core was evident in all of the surface response functions, except for the 59.5 keV function which appears to have been completely absorbed in the detector's outer layer.

These surface response functions were used in the QUADDET computer code to represent the Ge(Li) detector efficiency as a function of gamma photon energy and precise surface position. Each Ge(Li) detector will have an unique set of surface response functions.

Fig. 72. Contour Plot of Surface Response Function for 60-keV Gamma Photons of ^{241}Am .

Fig. 73. Contour Plot of Surface Response Function for 511-keV Gamma Photons of ^{22}Na .

Fig. 74. Contour Plot of Surface Response Function for 835-keV Gamma Photons of ^{54}Mn .

Fig. 75. Contour Plot of Surface Response Function for 898-keV Gamma Photons of ^{88}Y .

Fig. 76. Contour Plot of Surface Response Function for 1173-keV Gamma Photons of ^{60}Co .

Fig. 77. Contour Plot of Surface Response Function for 1275-keV Gamma Photons of ^{22}Na .

Fig. 78. Contour Plot of Surface Response Function for 1332-keV Gamma Photons of ^{60}Co .

APPENDIX III

QUADET

The QUADET computer code determined the quantities of fission products or activation products in cylindrical sources from precision gamma scanning. The code calculated the influences of the source geometry, the scanning geometry, the detector response, and decay parameters. The results of the code were used for the quantitative determinations described in the Results and Discussion section.

The code consisted of a main program, QUADET, and four subprograms, SOURCE, SOLANG, SOURIN, and DETEFF. The main program, QUADET, computed the effect of up to ten rectangular collimating slits on the gamma-ray beam, acted as a data manager for the input, and calculated the decay-time corrected multiplication factors. The subroutine, SOURCE, computed the isotopic source distributions from the calculated TWODIM values by randomly distributing a variable number of points (XSAP,YSAP,ZSAP) under the constraints of the specific isotopic distribution.⁶⁵ SOLANG computed the solid angle for each point selected in SOURCE. The specific detector efficiency as a function of precise surface position was obtained from DETEFF using the surface response matrices given in Appendix II.

The attenuation factor for each point was calculated through the respective absorption materials and the specific detector efficiency was determined in the source intensity program, SOURIN. The total attenuation factor for the effective collimating slit or incremental scanning step was calculated and combined with the other parameters, resulting in a factor by which the total net area of the full-energy peak was multiplied to obtain the quantity of the specific isotope present.

Sample Calculation for the Quantitative Determination of ^{137}Cs and ^{106}Rh in a Mixed Uranium-Plutonium Oxide Fuel Pin

The scanning geometry was shown in Fig. 12 with the cylindrical source (fuel pin), the three collimating slits, and the high resolution detector. The fuel pin was a mixed uranium-plutonium oxide irradiated in Experimental Breeder Reactor II in 1971. A cross-section of the sample with all of the structural material is presented in Fig. 79. The necessary information for the fuel material is tabulated in Table XV.

The fuel diameter was nominally 0.190 in. The fuel was thermally bonded to the 316L stainless steel cladding with He and Xe. The cladding was 0.015-in. thick. The 304 stainless steel capsule with 0.035-in. thick walls had an outer diameter of 0.500 in. The entire assembly was encased in a 304 stainless steel alpha container. The enriched fuel column which was originally 13.470 ± 0.010 -in. long was sectioned into nine sections, with Section A (5.215 ± 0.010 in.) and Section

Fuel Pin Cross Section

Fig. 79. Cross Section of Source Used in Quantitative Determination of ^{106}Rh and ^{137}Cs .

Table XV

Fuel Composition*

Composition:

U	75% (80% ^{235}U)
Pu	25% (12% ^{240}Pu)
O/M	1.96

Density:

90.6% of Theoretical Density
or 9.89 g/cm³

* Obtained from Fuel Fabrication Data.

I (5.020 ± 0.010 in.) being sealed in an inert atmosphere for gamma scanning analysis. The other seven samples were used for destructive analyses. Both sections, A and I, were scanned twice in the multispectral mode of data collection, to obtain data regarding the system's reproducibility. A sample was removed from Section A and radiochemically analyzed for specific fission products. The comparison of the results were presented in the results and discussion section. The method of calculation will be presented as an example of the QUADDET computer code.

The surface response for the gamma ray of interest as a function of XZ position on the detectors surface was calculated in the DETEFF subroutine. The input data consisted of a 21 x 21 response matrix, the average surface efficiency, and the detector surface dimensions. A two-dimensional bi-cubic spline function was fitted to the data, permitting the specific efficiency to be determined at any surface position. This was essential in the computation of the average efficiency for a specific source image. As shown in Fig. 17, only a relatively small area of the detector was exposed to the source gamma rays. The surface response function was centered in the three-dimensional coordinate system at (0, Y, Z) where Y was the distance between the surface of the source and the surface of the detector.

The source was approximated by selecting a large number of random samples under certain restrictions with the SOURCE subroutine. There were two basic restrictions: (1) the

sample points (XSAP, YSAP, ZSAP) were only selected from the set of sample points that were within the volume segment contributing to the source image, and (2) the points were weighted by the radial distribution of the specified fission product. The radial distribution of a fission product was determined nondestructively using the TWODIM computer code as described in the Results and Discussion.⁶⁵ The radial distribution of ^{137}Cs and ^{106}Rh were presented in Figs. 80 and 81, respectively. The normalized maximum of ^{137}Cs occurred at 0.090 in. and ^{106}Rh at 0.060 in. The final radial distribution of the randomly selected sample points approximated the distributions shown in Fig. 80 and 81 for ^{137}Cs and ^{106}Rh , respectively.

The solid angle of each sample point was computed in SOLANGE. The effect of the collimating slits was included to obtain the solid angle of the source image on the detector surface.

The intensity factor of each point was computed in SOURIN subroutine by tracing 100 gamma paths from a single point to 100 randomly distributed points on the surface of the detector. The 100 factors were averaged to obtain one source intensity factor $S(J)$ for each point. The subroutine calculated the source self-attenuation, cladding attenuation, capsule and bonding attenuation, and other attenuation factors for each path and these factors were multiplied by the specific detector efficiency determined from the bi-cubic spline function. The resulting factor, $S(J)$, was the factor by which each

Fig. 80. Radial Isotopic Distribution of ^{137}Cs .

Fig. 81. Radial Isotopic Distribution of ^{106}Rh .

gamma ray detected (net area of the full-energy peak) was divided to determine the actual source strength. This process was repeated for each sample point selected in the SOURCE program.

Any cylindrical source could be simulated in this manner resulting in a set of source intensity factors, $S(J)$, where each $S(J)$ represented the attenuation effects, the solid angle effects, and the specific detector efficiency. These values could be manipulated to determine the total $S(J)$ value for the volume segment of the source being examined. The code calculated two factors, one for the effective slit size and one for the scanning stepsize.

The average source intensity factor was computed in the following manner for the step and slit volume segments:

$$\bar{S}_{ns1} = \sum_{i=1}^{ns1} \frac{S_i(J)}{ns1}$$

where i denoted the indices of the points that were within the slit volume. $ns1$ was the total number of points

$$\bar{S}_{nst} = \sum_{j=1}^{nst} \frac{S_j(J)}{nst}$$

where j denoted the indices of the points that were within the step volume. nst was the total number of points.

The $S_i(J)$ and $S_j(J)$ values were previously weighted in the SOURIN subprogram by the restrictions placed on the randomly selected points.

The experimental configuration for this example is shown in Fig. 82. The stepsize was smaller than the effective slit size for this particular case. The $\bar{S}_{ns1}$ and $\bar{S}_{nst}$ values for

Fig. 82. Slit Volume and Step Volume Segment of Cylindrical Source.

^{106}Rh and ^{137}Cs are presented in Table XVI with their respective half-life and branching ratio corrections.

The above values were used to calculate the quantities of ^{137}Cs and ^{106}Rh in a sample destructively analyzed by radiochemistry. The results compared very favorable for ^{137}Cs (2.4% difference). The discrepancy of the ^{106}Rh results between the two methods was due to the incomplete dissolution of the sample as explained in a previous chapter.

The code was also used to evaluate the effect of a bow in the fuel pin on the quantitative results. Fig. 83 showed the effect of moving the sample centerline from the centerline of the collimating slit for the ^{137}Cs and ^{106}Rh source functions. The ^{137}Cs geometry attenuation factor varied between 1.2 and 1.3×10^{-7} for a fuel pin bow ranging from 0.000 to 0.060 in. The ^{106}Rh geometry attenuation factors were similar to the ^{137}Cs factors, except that the ^{106}Rh factor was a maximum at 0.070 in. off centerline, where ^{137}Cs was a maximum at 0.040 in. This again illustrated the importance of the scanning mechanism adapter in maintaining the correct alignment of the fuel pin and collimating slit.

The number of sample points required for a particular fuel pin was dependent upon the fission product distribution. In this particular example the ^{137}Cs multiplication factor converged in 700 randomly selected points, and ^{106}Rh in 500 points. Convergence was assumed if the factor did not vary more than 0.1% for 100 consecutive points.

The QUADET computer code permitted the quantitative

Table XVI

Multiplication Factor of Net Full-Energy Peak Areas

	Atoms of Fission Product	
	<u>^{106}Rh</u>	<u>^{137}Cs</u>
Slit Volume	$4.125 \times 10^{12} \cdot \text{NA}^*$	$1.617 \times 10^{13} \cdot \text{NA}^*$
Step Volume	$3.204 \times 10^{12} \cdot \text{NA}$	$1.264 \times 10^{13} \cdot \text{NA}$

* NA was equal to the net area of the specific gamma peak, for ^{106}Rh (622 keV) and for ^{137}Cs (662 keV).

Fig. 83. Relationship of Source Factor to Relative Centerline Position for ^{137}Cs and ^{106}Rh Radial Distributions.

determination of a fission product as a function of axial position. This was possible due to the complete calibration of the gamma scanning system. It was not necessary to have a set of standards for every fuel pin examined; this removed the major problem of quantitative gamma scanning.

Since the total number of atoms of a migrating fission product can be determined in the entire sample, there are no problems associated with the selection of a representative sample. The method is applicable to the study of mass transfer of fission and activation products within the fuel material. A fuel pin can be irradiated for a period, examined by non-destructive gamma scanning, and reinserted into the reactor for additional exposure. In this manner, the behavior of fission products can be monitored as a function of irradiation history.

CARD INPUT FOR QUADET COMPUTER CODE

The card format and input is described for the data deck. The data deck structure in the comment cards at the beginning of the code differs slightly from the following correct sequence.

Card No.

- 1 PNORUM (A5)
 Control card for determining the effects of the umbra or penumbra.
 TOTAL Total source response is calculated.
 UMBRA Only the umbra component is calculated.
 PENUM Only the penumbra component is calculated.
- 2 TITLE (8A10)
 Title card may contain up to 80 alpha-numeric characters.
- 3 XC,YC,ZC,YD,YS,ANGX,ANGZ (7F10.3)
 Parameters of the primary collimator and source position.
 XC Width of the primary collimating slit.
 YC Length of the primary collimating slit.
 ZC Height of the primary collimating slit.
 YD Distance from the front of the primary collimating slit to the detector' surface.
 YS Distance of the source centerline from the primary collimator.
 ANGX Slope of the primary collimator in the X-direction of the YZ plane in degrees.
 ANGZ Slope of the primary collimator in the Z-direction of the XY plane in degrees.
- 4 NBSC (I6)
 Number of beam-scraping collimators in the collimation assembly.
- 5 XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),
 ZANGLE(I) (7F10.3)
 Parameters of the beam-scraping collimators.

XBSC(I) Width of the Ith beam-scraper.
 YBSC(I) Length of the Ith beam-scraper.
 ZBSC(I) Height of the Ith beam-scraper.
 YBSLOC(I) Position of the beam-scraper in the
 Y-direction from the front of the
 primary collimator.
 XANGLE(I) Slope of the Ith collimator in the
 X-direction.
 ZANGLE(I) Slope of the Ith collimator in the
 Z-direction.

6 SLIT,STPZ (2F10.3)
 SLIT The effective height of the primary colli-
 mating slit.
 STPZ The step length in the Z-direction at
 which complete spectra are collected.

7 RADIUS,DIADET (2F10.3)
 RADIUS Radius of the fuel material, assuming
 a cylindrical source configuration.
 DIADET Diameter of the Ge(Li) detector

8 CNTTME,T12,BRATIO (3F10.3)
 CNTTME Real time interval for which the spectra
 are collected, in seconds.
 T12 Half-life of the isotope being deter-
 mined, in seconds.
 BRATIO Branching ration of the full-energy
 peak, determined from the decay scheme.

9 NMAX (I6)
 Number of randomly selected points in
 the source to simulate the distribution.

10 CYLIND (A6)
 CYLIND Indicates that a cylindrical source
 configuration is assumed.

11 NOM (I6)
 Number of shielding materials through which
 the gamma photon's attenuation is calculated.

12 TYPE(J),RADMAT(J),RHO(J),XATT(J) (A10,3E12.5)
 Parameters of the attenuation materials.
 TYPE(J) Type of Jth material.
 RADMAT(J) Radius of the Jth material.
 RHO(J) Density of the Jth material.
 XATT(J) Mass attenuation coefficient of the
 Jth material.

- 13 TITLE (8A10)
 Title for detector and gamma photons used
 in the surface response function.
- 14 DETRAD, GAMEFF, STEPX, STEPZ (4F12.2)
 DETRAD Detector radius in inches.
 GAMEFF Absolute average efficiency for specific
 gamma energy.
 STEPX Positions in X-direction at which surface
 response was experimentally determined.
 STEPZ Positions in Z-direction at which surface
 response was experimentally determined.
- 15 The specific relative efficiencies as a function
 of precise positions. For this example, a 21x21
 matrix of values was stored into the EFF(I,J) array.

*DECK, QUADET		
PROGRAM COLLUM (INPUT,OUTPUT,TAPE1=INPUT,TAPE2=OUTPUT,TAPE7,TAPE20	QUA	
1)	QUA	1
DIMENSION XBSC(10), YBSC(10), ZBSC(10), YBSLOC(10), SHAPE(10), XAN	QUA	2
1 GLE(10), ZANGLE(10), TITLE(8)	QUA	3
DIMENSION XM(10), ZM(10)	QUA	4
COMMON /W2/ S(701),XSAP(701),YSAP(701),ZSAP(701),SOMEGA(701)	QUA	5
COMMON /W3/ XAB(701),XCD(701),ZBC(701),ZAD(701)	QUA	6
COMMON /W4/ ATTEN(701)	QUA	7
COMMON /W13/ XSLP,XSRP,ZSTP,ZSBP,XMIN,ZMIN	QUA	8
DATA PENUM,UMBRA,TOTAL/5HPENUM,5HUMBRA,5HTOTAL/	QUA	9
C	QUA	10
C ***** DEFINITION OF VARIABLES *****	QUA	11
C	QUA	12
C CARD NO.	QUA	13
C 1 *PNORUM*	QUA	14
C DETERMINES WHETHER THE UMBRA, PENUMBRA, OR TOTAL RESPONSE IS TO	QUA	15
C PNORUM MAY BE SET TO UMBRA,PENUMBRA, OR TOTAL	QUA	16
C BE CALCULATED BY THE CODE	QUA	17
C 2 *TITLE*	QUA	18
C TITLE OF COLLIMATING SYSTEM BEING INVESTIGATED MAY BE UP TO	QUA	19
C 80 CHARACTERS LONG	QUA	20
C 3 *XC,YC,ZC,YD,YS,ANGX,ANGZ*	QUA	21
C PARAMETERS OF PRIMARY COLLIMATOR, SOURCE, AND DETECTOR	QUA	22
C XC WIDTH OF PRIMARY COLLIMATOR IN INCHES	QUA	23
C YC LENGTH OF PRIMARY COLLIMATOR IN INCHES	QUA	24
C ZC HEIGHT OF PRIMARY COLLIMATOR IN INCHES	QUA	25
C YD DISTANCE FROM SURFACE OF PRIMARY COLLIMATOR TO	QUA	26
C DETECTORS SURFACE IN INCHES	QUA	27
C YS DISTANCE THE UNIFORM SOURCE IS IN FRONT OF THE	QUA	28
C PRIMARY COLLIMATOR IN INCHES	QUA	29
C ANGX SLOPE OF PRIMARY COLLIMATOR IN THE X DIRECTION OF THE	QUA	30
C YZ PLANE GIVEN IN DEGREES	QUA	31
C ANGZ SLOPE OF PRIMARY COLLIMATOR IN THE Z DIRECTION OF THE	QUA	32
C XY PLANE GIVEN IN DEGREES	QUA	33
C A POSITIVE ANGLE INDICATES THAT THE SLIT BECOMES WIDER AS	QUA	34
C DISTANCE FROM THE SOURCE INCREASES	QUA	35
C 4 *STEPX,STEPZ*	QUA	36
C STEP SIZE SEPARATING POINTS AT WHICH RESPONSE IS CALCULATED	QUA	37
C STEPX SPACING IN THE X-DIRECTION	QUA	38
C STEPZ SPACING IN THE Z-DIRECTION	QUA	39
C STEPX AND STEPZ MAY HAVE ANY VALUES AND DO NOT HAVE TO BE EQUAL	QUA	40
C 5 *XSTART,ZSTART,DIADET*	QUA	41
C DEFINITION OF AREA IN WHICH COLLIMATOR RESPONSE IS CALCULATED	QUA	42
C XSTART THE AREA OF CALCULATED RESPONSE IS - XSTART TO XSTART	QUA	43
C IN STEPS EQUAL TO XSTART/32.0	QUA	44
C ZSTART THE AREA OF CALCULATED RESPONSE IS - ZSTART TO ZSTART	QUA	45
C IN STEPS EQUAL TO ZSTART/32.0	QUA	46
C THE VALUES OF XSTART AND ZSTART ARE NOT RESTRICTED	QUA	47
C 6 *NBSC*	QUA	48
C NUMBER OF BEAM SCRAPING COLLIMATORS TO BE CONSIDERED,	QUA	49
C LIMITED TO BEING EQUAL TO OR LESS THAN 10	QUA	50
C 7 *XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(I)*	QUA	51
C XBSC(I) WIDTH OF BEAM SCRAPING COLLIMATOR I	QUA	52
C YBSC(I) LENGTH OF BEAM SCRAPING COLLIMATOR I	QUA	53
C ZBSC(I) HEIGHT OF BEAM SCRAPING COLLIMATOR I	QUA	54

C	YBSLOC(I) DISTANCE FROM THE FRONT OF THE PRIMARY COLLIMATOR TO	QUA	55
C	TO THE BACK OF THE BEAM SCRAPING COLLIMATOR I	QUA	56
C	XANGLE(I) SLOPE IN X-DIRECTION OF THE YZ PLANE GIVEN IN DEGREES	QUA	57
C	ZANGLE(I) SLOPE IN Z-DIRECTION OF THE XY PLANE GIVEN IN DEGREES	QUA	58
C	8 *SLIT,STPZ*	QUA	59
C	SLIT THE EFFECTIVE SLIT HEIGHT FOR THE PARTICULAR COLLIMA	QUA	60
C	STPZ THE STEPSIZE FOR THE SCAN	QUA	61
C	9 *RADIUS*	QUA	62
C	RADIUS OF THE CYLINDRICAL SOURCE	QUA	63
C	10 *CNTTME,T12,BRATIO*	QUA	64
C	CNTTME THE REAL COUNT TIME FOR EACH SPECTRA	QUA	65
C	T12 HALF-LIFE OF THE FISSION PRODUCT	QUA	66
C	BRATIO BRANCHING RATIO OF SPECIFIC GAMMA PHOTON MEASURED	QUA	67
C		QUA	68
C	*****	QUA	69
C		QUA	70
	READ (1,110)PNORUM	QUA	71
	READ (1,125)((TITLE(L)),L=1,8)	QUA	72
	READ (1,130)XC,ZC,YD,YS,ANGX,ANGZ	QUA	73
	READ (1,180)NBSC	QUA	74
	IF (NBSC.EQ.0) GO TO 5	QUA	75
	READ (1,120)((XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(I	QUA	76
1	),SHAPE(I)),I=1,NBSC)	QUA	77
5	CONTINUE	QUA	78
	READ (1,130)SLIT,STPZ	QUA	79
	READ (1,130)RADIUS,DIADET	QUA	80
	READ (1,75)CNTTME,T12,BRATIO	QUA	81
	READ (1,70)NMAX	QUA	82
	IF (PNORUM.EQ.TOTAL) WRITE (2,115)	QUA	83
	WRITE (2,135)XC,ZC,YC	QUA	84
	WRITE (2,140)ANGX,ANGZ	QUA	85
	WRITE (2,145)YD	QUA	86
	WRITE (2,150)YS	QUA	87
	IF (YS.EQ.0.0) WRITE (2,155)	QUA	88
	IF (YS.LT.0.0) WRITE (2,160)	QUA	89
	XR=XC/2.0	QUA	90
	XL=-XR	QUA	91
	ZT=ZC/2.0	QUA	92
	ZB=-ZT	QUA	93
	XMIN=(XC*(YC+YS)/(YC-XC))/YS	QUA	94
	ZMIN=(ZC*(YC+YS)/(YC-ZC))/YS	QUA	95
C		QUA	96
C	***** VARIABLES USED IN CALCULATIONS *****	QUA	97
C		QUA	98
C	XSP X-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	QUA	99
C	DETECTORS SURFACE IS DETERMINED	QUA	100
C	YSP Y-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	QUA	101
C	DETECTORS SURFACE IS DETERMINED	QUA	102
C	ZSP Z-COORDINATE ON THE SOURCE FROM WHICH THE AREA ON THE	QUA	103
C	DETECTORS SURFACE IS DETERMINED	QUA	104
C	XAB THE MINIMUM X VALUE ON THE DETECTORS SURFACE VIEWED	QUA	105
C	FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	QUA	106
C	XCD THE MAXIMUM X VALUE ON THE DETECTORS SURFACE VIEWED	QUA	107
C	FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	QUA	108
C	ZAD THE MINIMUM Z VALUE ON THE DETECTORS SURFACE VIEWED	QUA	109
C	FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	QUA	110
C	ZBC THE MAXIMUM Z VALUE ON THE DETECTORS SURFACE VIEWED	QUA	111

C		FROM THE POINT (XSP,YSP,ZSP) ON THE SOURCE	QUA 112
C			QUA 113
C	XABBSC	XAB-BEAM-SCRAPING-COLLIMATOR	QUA 114
C	XCDBSC	XCD-BEAM-SCRAPING-COLLIMATOR	QUA 115
C	ZADBSC	ZAD-BEAM-SCRAPING-COLLIMATOR	QUA 116
C	ZBCBSC	ZBC-BEAM-SCRAPING-COLLIMATOR	QUA 117
C			QUA 118
C	XABBSC,XCDBSC,ZADBSC, AND ZBCBSC	DEFINE THE SURFACE AREA OF THE	QUA 119
C	DETECTOR SEEN THROUGH THE BEAM-SCRAPING COLLIMATORS FROM THE		QUA 120
C	POINT (XSP,YSP,ZSP) ON THE SOURCE		QUA 121
C			QUA 122
C	*****		QUA 123
C			QUA 124
	IF (NBSC.EQ.0) GO TO 10		QUA 125
	WRITE (2,165)NBSC		QUA 126
1	WRITE (2,170)((XBSC(I),YBSC(I),ZBSC(I),YBSLOC(I),XANGLE(I),ZANGLE(I)),I=1,NBSC)		QUA 127
	CONTINUE		QUA 128
10	WRITE (2,175)		QUA 129
C			QUA 130
C	*****		QUA 131
C			QUA 132
C			QUA 133
C	CALCULATES THE LIMITS OF THE PENUMBRA ON THE SOURCE		QUA 134
C			QUA 135
C	XSPM	X-SOURCE-PENUMBRA-MAXIMUM	QUA 136
C	ZSPM	Z-SOURCE-PENUMBRA-MAXIMUM	QUA 137
C	XSLP	X-SOURCE-LEFT-PENUMBRA	QUA 138
C	XSRP	X-SOURCE-RIGHT-PENUMBRA	QUA 139
C	ZSTP	Z-SOURCE-TOP-PENUMBRA	QUA 140
C	ZSBP	Z-SOURCE-BOTTOM-PENUMBRA	QUA 141
C			QUA 142
C	*****		QUA 143
C			QUA 144
	IF (NBSC.EQ.0) GO TO 25		QUA 145
	DO 15 J=1,NBSC		QUA 146
	IF (YBSLOC(J).GT.YD) WRITE (2,80)		QUA 147
	XANGLE(J)=(XANGLE(J)*3.1415927)/180.0		QUA 148
	ZANGLE(J)=(ZANGLE(J)*3.1415927)/180.0		QUA 149
	XM(J)=((XBSC(J)/2.0)+TAN(XANGLE(J))*YBSC(J)+XC/2.0)/(YBSLOC(J))		QUA 150
	XMF=(XBSC(J)/2.0+XC/2.0)/(YBSLOC(J)-YBSC(J))		QUA 151
	IF (XMF.LT.XM(J)) XM(J)=XMF		QUA 152
	ZM(J)=((ZBSC(J)/2.0)+TAN(ZANGLE(J))*YBSC(J)+ZC/2.0)/(YBSLOC(J))		QUA 153
	ZMF=(ZBSC(J)/2.0+ZC/2.0)/(YBSLOC(J)-YBSC(J))		QUA 154
	IF (ZMF.LT.ZM(J)) ZM(J)=ZMF		QUA 155
15	CONTINUE		QUA 156
C	ZMIN	THE MINIMUM SLOPE IN THE Z-DIRECTION WHICH PASSES THR	QUA 157
C		THE PRIMARY AND SECONDARY COLLIMATORS	QUA 158
C	XMIN	THE MINIMUM SLOPE IN THE X-DIRECTION WHICH PASSES THR	QUA 159
C		THE PRIMARY AND SECONDARY COLLIMATORS	QUA 160
	DO 20 JJ=1,NBSC		QUA 161
	IF (XM(JJ).LT.XMIN) XMIN=XM(JJ)		QUA 162
	IF (ZM(JJ).LT.ZMIN) ZMIN=ZM(JJ)		QUA 163
20	CONTINUE		QUA 164

	XSPM=(XMIN*YS)	QUA 165
	ZSPM=(ZMIN*YS)	QUA 166
25	CONTINUE	QUA 167
	XSLP=XL- XSPM	QUA 168
	XSRP=XR+ XSPM	QUA 169
	ZSTP=ZT+ ZSPM	QUA 170
	ZSBP=ZB- ZSPM	QUA 171
	K=0	QUA 172
	ANGX=(ANGX*3. 1415927)/180. 0	QUA 173
	ANGZ=(ANGZ*3. 1415927)/180. 0	QUA 174
	NPS=NMAX	QUA 175
	CALL SOURCE (XSLP,XSRP,ZSTP,ZSBP,RADIUS,CONFIG,XMIN,ZMIN,YS,NPS,NM	QUA 176
1	AX)	QUA 177
	DO 55 I=1,NPS	QUA 178
	K=K+ 1	QUA 179
	ICK1=0	QUA 180
	IF (XSAP(K). LE. XR) ICK1=ICK1+ 1	QUA 181
	IF (XSAP(K). GE. XL) ICK1=ICK1+ 1	QUA 182
	IF (ZSAP(K). LE. ZT) ICK1=ICK1+ 1	QUA 183
	IF (ZSAP(K). GE. ZB) ICK1=ICK1+ 1	QUA 184
	IF (ICK1. EQ. 4) GO TO 30	QUA 185
	GO TO 35	QUA 186
30	CONTINUE	QUA 187
	XCD(K)=(XSAP(K)+(XR+ YC*TAN(ANGX)- XSAP(K))/(YS+ YD- YSAP(K)))/(YS+ YC- YS	QUA 188
1	AP(K))	QUA 189
	XAB(K)=(XSAP(K)+(XL- YC*TAN(ANGX)- XSAP(K))/(YS+ YD- YSAP(K)))/(YS+ YC- YS	QUA 190
1	AP(K))	QUA 191
	ZAD(K)=(ZSAP(K)+(ZB- YC*TAN(ANGZ)- ZSAP(K))/(YS+ YD- YSAP(K)))/(YS+ YC- YS	QUA 192
1	AP(K))	QUA 193
	ZBC(K)=(ZSAP(K)+(ZT+ YC*TAN(ANGZ)- ZSAP(K))/(YS+ YD- YSAP(K)))/(YS+ YC- YS	QUA 194
1	AP(K))	QUA 195
	GO TO 40	QUA 196
35	CONTINUE	QUA 197
	IF (YS. EQ. 0. 0) GO TO 40	QUA 198
	XAB(K)=(XL- XSAP(K))/(YS+ YD- YSAP(K))+ XSAP(K)	QUA 199
	XAB1=(XL- XSAP(K)- YC*TAN(ANGX))/(YS+ YD- YSAP(K))+ XSA	QUA 200
1	P(K)	QUA 201
	IF (XAB1. GT. XAB(K)) XAB(K)=XAB1	QUA 202
	XCD(K)=(XR- XSAP(K)+ YC*TAN(ANGX))/(YS+ YD- YSAP(K))+ X	QUA 203
1	SAP(K)	QUA 204
	XCD1=(XR- XSAP(K))/(YS+ YD- YSAP(K))+ XSAP(K)	QUA 205
	IF (XCD1. LT. XCD(K)) XCD(K)=XCD1	QUA 206
	ZAD(K)=(ZB- ZSAP(K))/(YS+ YD- YSAP(K))+ ZSAP(K)	QUA 207
	ZAD1=(ZB- ZSAP(K)- YC*TAN(ANGZ))/(YS+ YD- YSAP(K))+ ZSA	QUA 208
1	PI(K)	QUA 209
	IF (ZAD1. GT. ZAD(K)) ZAD(K)=ZAD1	QUA 210
	ZBC(K)=(ZT- ZSAP(K)+ YC*TAN(ANGZ))/(YS+ YD- YSAP(K))+ Z	QUA 211
1	SAP(K)	QUA 212
	ZBC1=(ZT- ZSAP(K))/(YS+ YD- YSAP(K))+ ZSAP(K)	QUA 213
	IF (ZBC1. LT. ZBC(K)) ZBC(K)=ZBC1	QUA 214
40	CONTINUE	QUA 215
C		QUA 216
C	.....	QUA 217
C		QUA 218
C	THIS SECTION DEALS WITH THE EFFECT OF BEAM SCRAPING COLLIMATORS	QUA 219

C	ON THE GAMMA BEAM	QUA	220
C	THE BEAM SCRAPING COLLIMATORS MUST BE SLITS, MAY EITHER BE	QUA	221
C	POSITIVELY OR NEGATIVELY SLOPED	QUA	222
C	THE VALUES XAB,XCD,ZAD,ZBC DEFINE THE RECTANGULAR LIMITS ON THE	QUA	223
C	DETECTORS SURFACE WITH RESPECT TO A POINT LOCATED IN THE SOURCE	QUA	224
C	AT (XSP,YSP,ZSP)	QUA	225
C	EACH BEAM SCRAPING COLLIMATOR IS CHECKED TO DETERMINE IF THE	QUA	226
C	FRONT OR THE BACK OF THE SLIT DEFINES THE GAMMA BEAM	QUA	227
C	ZBC1,ZAD1,XAB1,XCD1 - FRONT END TOWARDS THE SOURCE	QUA	228
C	ZBC2,ZAD2,XAB2,XCD2 - BACK END TOWARDS THE DETECTOR	QUA	229
C		QUA	230
C	*****	QUA	231
C		QUA	232
	IF (NBSC.EQ.0) GO TO 50	QUA	233
	DO 45 II=1,NBSC	QUA	234
	ZAD1=ZSAP(K)+ (- ZBSC(II)/2.0- ZSAP(K))*(YS+ YD- YSAP(K))/(YBSLOC(II)+ Y	QUA	235
1	S- YSAP(K)- YBSC(II))	QUA	236
	ZAD2=ZSAP(K)+ (- ZBSC(II)/2.0- YBSC(II))*TAN(ZANGLE(II))- ZSAP(K))*(YS+	QUA	237
1	YD- YSAP(K))/(YBSLOC(II)+ YS- YSAP(K))	QUA	238
	ZADBSC=ZAD1	QUA	239
	IF (ZADBSC.LT. ZAD2) ZADBSC=ZAD2	QUA	240
	ZBC1=ZSAP(K)+ (ZBSC(II)/2.0+ YBSC(II))*TAN(ZANGLE(II))- ZSAP(K))*(YS+ Y	QUA	241
1	D- YSAP(K))/(YBSLOC(II)+ YS- YSAP(K))	QUA	242
	ZBC2=ZSAP(K)+ (ZBSC(II)/2.0- ZSAP(K))*(YS+ YD- YSAP(K))/(YBSLOC(II)+ YS	QUA	243
1	- YSAP(K)- YBSC(II))	QUA	244
	ZBCBSC=ZBC1	QUA	245
	IF (ZBCBSC.GT. ZBC2) ZBCBSC=ZBC2	QUA	246
	IF (ZADBSC.GT. ZAD(K)) ZAD(K)=ZADBSC	QUA	247
	IF (ZBCBSC.LT. ZBC(K)) ZBC(K)=ZBCBSC	QUA	248
	XAB1=XSAP(K)+ (- XBSC(II)/2.0- XSAP(K))*(YS+ YD- YSAP(K))/(YBSLOC(II)+ Y	QUA	249
1	S- YSAP(K)- YBSC(II))	QUA	250
	XAB2=XSAP(K)+ (- XBSC(II)/2.0- YBSC(II))*TAN(XANGLE(II))- XSAP(K))*(YS+	QUA	251
1	YD- YSAP(K))/(YBSLOC(II)- YSAP(K)+ YS)	QUA	252
	XABBSC=XAB1	QUA	253
	IF (XABBSC.LT. XAB2) XABBSC=XAB2	QUA	254
	XCD1=XSAP(K)+ (XBSC(II)/2.0- XSAP(K))*(YS+ YD- YSAP(K))/(YBSLOC(II)+ YS	QUA	255
1	- YSAP(K)- YBSC(II))	QUA	256
	XCD2=XSAP(K)+ (XBSC(II)/2.0+ YBSC(II))*TAN(XANGLE(II))- XSAP(K))*(YS+ Y	QUA	257
1	D- YSAP(K))/(YBSLOC(II)+ YS- YSAP(K))	QUA	258
	XCDBSC=XCD1	QUA	259
	IF (XCDBSC.GT. XCD2) XCDBSC=XCD2	QUA	260
	IF (XABBSC.GT. XAB(K)) XAB(K)=XABBSC	QUA	261
	IF (XCDBSC.LT. XCD(K)) XCD(K)=XCDBSC	QUA	262
45	CONTINUE	QUA	263
50	CONTINUE	QUA	264
55	CONTINUE	QUA	265
C		QUA	266
C	*****	QUA	267
C		QUA	268
C	RETURNED WITH A S(I) VALUE- FACTOR FOR EACH POINT PICKED IN	QUA	269
C	SOURCE TO THE MIDPOINT OF (XAB,XCD,ZBC,ZAD)	QUA	270
C		QUA	271
C	*****	QUA	272
C		QUA	273
	NPS=K	QUA	274

	CALL SOURIN (NPS,YS,YD,YC)	QUA 275
	STOTAL=0.0	QUA 276
	DO 60 NP=1,NPS	QUA 277
	STOTAL=STOTAL+ S(NP)	QUA 278
60	CONTINUE	QUA 279
	SFACTOR=STOTAL/FLOAT(NPS)	QUA 280
C		QUA 281
C	.....	QUA 282
C		QUA 283
C	SFACTOR THE FACTOR BY WHICH THE SOURCE HAS BEEN REDUCED	QUA 284
C	IN INTENSITY	QUA 285
C	TO OBTAIN THE NUMBER OF ATOMS THAT DECAYED DURING THE	QUA 286
C	TIME, MULTIPLE THE COUNTS(NET AREA) BY 1/SFACTOR	QUA 287
C	XNUM THE FACTOR TO MULTIPLE THE COUNTS BY TO OBTAIN THE	QUA 288
C	ACTUAL NUMBER OF ATOMS IN THE SAMPLE SEGMENT	QUA 289
C	.....	QUA 290
C		QUA 291
C		QUA 292
	SSTEP=0.0	QUA 293
	SSLIT=0.0	QUA 294
	SLIT=ZC	QUA 295
	NOSL=0	QUA 296
	CNTS=1.0	QUA 297
	NOSTP=0	QUA 298
	XCNTS=(CNTS*T12)/(0.693*CNTTME*BRATIO)	QUA 299
C		QUA 300
C	.....	QUA 301
C		QUA 302
C	COMPUTES THE AVERAGE ATTENUATION FACTOR FOR THE SLIT AND STEP	QUA 303
C	.....	QUA 304
C		QUA 305
C		QUA 306
	DO 65 I=1,NPS	QUA 307
	IF ((SLIT/2.0).GT.ABS(ZSAP(I))) SSLIT=SSLIT+ S(I)	QUA 308
	IF ((SLIT/2.0).GT.ABS(ZSAP(I))) NOSL=NOSL+ 1	QUA 309
	IF ((STPZ/2.0).GT.ABS(ZSAP(I))) SSTPZ=SSTPZ+ S(I)	QUA 310
	IF ((STPZ/2.0).GT.ABS(ZSAP(I))) NOSTP=NOSTP+ 1	QUA 311
65	CONTINUE	QUA 312
	SLAVE=SSLIT/NOSL	QUA 313
	STAVE=SSTPZ/NOSTP	QUA 314
	SLCNTS=XCNTS*(SSLIT/STOTAL)/SLAVE	QUA 315
	STPCNT=XCNTS*(SSTPZ/STOTAL)/STAVE	QUA 316
	WRITE (2,85)NMAX	QUA 317
	WRITE (2,90)CNTTME,T12,BRATIO	QUA 318
	WRITE (2,95)SLIT,STPZ	QUA 319
	WRITE (2,100)	QUA 320
	WRITE (2,105)SLCNTS,STPCNT	QUA 321
	STOP	QUA 322
C		QUA 323
C		QUA 324
70	FORMAT (I6)	QUA 325
75	FORMAT (5F12.5)	QUA 326
80	FORMAT (10X,26H BEAM SCRAPING COLLIMATOR ,12,26H EXTENDS INTO THE	QUA 327
1	DETECTOR)	QUA 328
85	FORMAT (1H1,///,10X,I6,35H SOURCE POINTS USED IN CALCULATIONS)	QUA 329

90	FORMAT (//,10X,27H THE SOURCE WAS COUNTED FOR ,F8.4,8H SECONDS,/,10	QUA	330
1	X,26H THE ISOTOPE HALF-LIFE IS =,1PE12.5,8H SECONDS,/,10X,37H THE GA	QUA	331
2	MMA PHOTON BRANCHING RATIO IS =,E12.3)		
95	FORMAT (//,10X,20H THE SLIT HEIGHT IS =,F8.4,7H INCH ,/,10X,16H THE	QUA	333
1	STEPSIZE IS ,F8.4,5H INCH)	QUA	334
100	FORMAT (///,10X,98H THE NET FULL-ENERGY PEAK AREA IS MULTIPLIED BY	QUA	335
1	THE FOLLOWING FACTORS TO OBTAIN THE NUMBER OF ATOMS)	QUA	336
105	FORMAT (/////10X,24H ATOMS IN SLIT VOLUME = ,1PE12.5,/,10X,28H A	QUA	337
1	TOMS IN THE STEP VOLUME = ,E12.5)	QUA	338
110	FORMAT (A5)	QUA	339
115	FORMAT (1H1,///,30X,75H+++++ TOTAL RESPONSE FOR	QUA	340
1	THE DETECTOR +++++,///)	QUA	341
120	FORMAT (7F10.4)	QUA	342
125	FORMAT (8A10)	QUA	343
130	FORMAT (7F10.3)	QUA	344
135	FORMAT (///,25H THE COLLIMATING SLIT IS ,F6.4,13H INCH(ES) BY ,F6.	QUA	345
1	4,14H INCH(ES) AND ,F6.4,12H INCHES LONG)	QUA	346
140	FORMAT (5X,/,34H THE PRIMARY COLLIMATOR IS TAPERED ,F5.2,32H DEGREE	QUA	347
1	S IN THE X-DIRECTION AND ,F5.2,27H DEGREES IN THE Z-DIRECTION)	QUA	348
145	FORMAT (/,17H THE DETECTOR IS ,F7.4,38H INCHES FROM THE END OF THE	QUA	349
1	COLLIMATOR)	QUA	350
150	FORMAT (/,15H THE SOURCE IS ,F7.4,31H FROM THE END OF THE COLLIMAT	QUA	351
1	OR,///)	QUA	352
155	FORMAT (/////10X,78H YS = 0.0, SOURCE ASSUMED TO BE AT THE FRONT	QUA	353
1	SURFACE OF THE PRIMARY COLLIMATOR,///)	QUA	354
160	FORMAT (/////10X,68H YS .LT. 0.0, THE SOURCE ASSUMED TO BE INSIDE	QUA	355
1	THE PRIMARY COLLIMATOR,///)	QUA	356
165	FORMAT (10X,///,11H THERE ARE ,I3,28H BEAM SCRAPERS IN THE SYSTEM)	QUA	357
170	FORMAT (//,5X,18H THE COLLIMATOR IS ,F6.3,13H INCHES WIDE ,F6.3,13H	QUA	358
1	INCHES LONG ,F6.3,28H INCHES HIGH AND IS LOCATED ,F7.3,33H INCHES	QUA	359
2	FROM THE FRONT COLLIMATOR,/,36H WITH A SLOPE IN THE X-DIRECTION O	QUA	360
3	F ,F5.2,23H DEGREES AND A SLOPE OF ,F5.2,19H IN THE Z-DIRECTION)	QUA	361
175	FORMAT (//)	QUA	362
180	FORMAT (I6)	QUA	363
	END	QUA	364

1	SUBROUTINE SOURCE (XSAP,XSRP,ZSTP,ZSBP,RADIUS,CONFIG,XMIN,ZMIN,YS,	SCRE	
	NPS,NMAX)	SCRE	1
	COMMON /W2/ S(701),XSAP(701),YSAP(701),ZSAP(701),SOMEGA(701)	SCRE	2
	COMMON /W3/ XAB(701),XCD(701),ZBC(701),ZAD(701)	SCRE	3
	COMMON /W4/ ATTEN(701)	SCRE	4
	COMMON /W6/ RADMAT(10),RHO(10),XATT(10),TYPE(10),SF(10)	SCRE	5
	COMMON /W12/ NOM	SCRE	6
	DATA CYLIND,DISK,PLANE,SPHER/6HCYLIND,6HDISK ,6HPLANE ,6HSPHERE/	SCRE	7
	READ (1,40)CONFIG	SCRE	8
	IF (CONFIG.EQ.CYLIND) WRITE (2,45)	SCRE	9
	IF (CONFIG.EQ.DISK) WRITE (2,50)	SCRE	10
	IF (CONFIG.EQ.PLANE) WRITE (2,55)	SCRE	11
	IF (CONFIG.EQ.SPHER) WRITE (2,60)	SCRE	12
	*****	SCRE	13
	*****	SCRE	14
	*****	SCRE	15
	CHECKS FOR SOURCE GEOMETRY PLANAR,SPHERICAL, DISC, CYLINDRICAL	SCRE	16
	AND DETERMINES THE COORDINATES OF NPS POINTS IN SOURCE	SCRE	17
	XSAP X- SOURCE- LEFT- PENUMBRA AT (X,0,Z)	SCRE	18
	XSRP X- SOURCE- RIGHT- PENUMBRA AT (X,0,Z)	SCRE	19
	ZSTP Z- SOURCE- TOP- PENUMBRA AT (X,0,Z)	SCRE	20
	ZSBP Z- SOURCE- BOTTOM- PENUMBRA AT (X,0,Z)	SCRE	21
	XSAP(K) X- SOLID- ANGLE- POINT AT WHICH SOLID ANGLE IS COMPUTED	SCRE	22
	YSAP(K) Y- SOLID- ANGLE- POINT AT WHICH SOLID ANGLE IS COMPUTED	SCRE	23
	ZSAP(K) Z- SOLID- ANGLE- POINT AT WHICH SOLID ANGLE IS COMPUTED	SCRE	24
	RADIUS OF CYLINDER, SPHERE, OR DISC SOURCE	SCRE	25
	CONFIG SPECIFIC CONFIGURATION WHICH PLACES RESTRICTIONS ON	SCRE	26
	(XSAP(K),YSAP(K),ZSAP(K))	SCRE	27
	XMIN THE SLOPE IN THE X- DIRECTION FROM THE FRONT OF THE	SCRE	28
	PRIMARY COLLIMATOR TO THE SURFACE OF THE DETECTOR	SCRE	29
	ZMIN THE SLOPE IN THE Z- DIRECTION FROM THE FRONT OF THE	SCRE	30
	PRIMARY COLLIMATOR TO THE SURFACE OF THE DETECTOR	SCRE	31
	FRSAP FACTOR FOR NONUNIFORM RADIAL DISTRIBUTIONS	SCRE	32
	*****	SCRE	33
	COMPUTATION ASSUMES THAT THE MINIMUM SOURCE- COLLIMATOR DISTANCE	SCRE	34
	SELECTS RANDOM X POSITION IN THE CIRCLE (X**2 + Y**2) = RADIUS**2	SCRE	35
	CLACULATES THE CORRESPONDING Y VALUE, THEN SELECTS Z- POSITION	SCRE	36
	RANDOMLY BETWEEN THE UPPER AND LOWER PENUMBRA LIMITS	SCRE	37
	ASSUME THAT THE RADIAL DISTRIBUTION OF THE GAMMA EMTITTING	SCRE	38
	ISOTOPE IS NONUNIFORM	SCRE	39
	THE ISOTOPIC DISTRIBUTION IS ASSUMED TO BE RADIALY SYMMETRIC,	SCRE	40
	HENCE THE DISTRIBUTION MAY BE EXPRESSED AS A NORMALIZED	SCRE	41
	ANALYTICAL FUNCTION OF RADIAL POSITION	SCRE	42
	RANDOMLY SELECT A (XSAP,YSAP) POINT IN THE TWO DIMENSIONAL DISC	SCRE	43
	WITH THE GIVEN RADIUS	SCRE	44
	COMPUTE RSAP = SQRT(XSAP**2 + YSAP**2), DETERMINE VALUE OF	SCRE	45
	NORMALIZED ANALYTICAL FUNCTION AT RSAP, COMPARE F(RSAP) WITH	SCRE	46
	RANDOM NUMBER, IF F(RSAP) GT RANDOM(X) RETAIN THE POINT, BUT	SCRE	47
	IF RANDOM(X) GT F(RSAP) REJECT THE POINT (XSAP,YSAP) AND SELECT	SCRE	48
	ANOTHER SET OF COORDINATES	SCRE	49
	RADMAT(I) THICKNESS OF THE ITH MATERIAL	SCRE	50
	RHO(I) DENSITY OF ITH MATERIAL IN G/CC	SCRE	51
	XATT(I) MASS ATTENUATION COEFFICIENT OF ITH MATERIAL CM**2/G	SCRE	52
	NOM NUMBER OF MATERIALS THROUGH WHICH THE GAMMA- RAY	SCRE	53
	ATTENUATION IS TO BE CALCULATED	SCRE	54

C	READS THE INNER RADIUS,THICKNESS,DENSITY, AND ATTENUATION	SCRE 55
C	FACTOR FOR EACH MATERIAL	SCRE 56
C	*****	SCRE 57
C		SCRE 58
C		SCRE 59
	IF (CONFIG.NE.CYLIND) GO TO 30	SCRE 60
	READ (1,65)NOM	SCRE 61
	READ (1,70)(TYPE(I),RADMAT(I),RHO(I),XATT(I),I=1,NOM)	SCRE 62
	WRITE (2,80)NOM	SCRE 63
	WRITE (2,75)(I,TYPE(I),RADMAT(I),RHO(I),XATT(I),I=1,NOM)	SCRE 64
C	*****	SCRE 65
C		SCRE 66
C		SCRE 67
C	RADMAX IS THE RADIAL POSITION WHERE THE ISOTOPIC DISTRIBUTION	SCRE 68
C	IS A MAXIMUM	SCRE 69
C	CSFUNX FUNCTION OF RADIAL DISTRIBUTION AT MAXIMUM	SCRE 70
C	CSFUN VALUE OF RADIAL DISTRIBUTION AT SPECIFIC POSITION AT	SCRE 71
C	RCHK	SCRE 72
C	*****	SCRE 73
C		SCRE 74
	RADMAX=0.060	SCRE 75
	CSFUNX=-.129044.59624*RADMAX**4+24853.21604*RADMAX**3-2304.00151*RA	SCRE 76
1	DMAX**2+119.69214*RADMAX+0.30136	SCRE 77
	THKCLD=0.0	SCRE 78
	NOM1=NOM-1	SCRE 79
	DO 5 I=2,NOM1	SCRE 80
	THKCLD=THKCLD+RADMAT(I)	SCRE 81
5	CONTINUE	SCRE 82
	K=0	SCRE 83
10	CONTINUE	SCRE 84
	IF (K.GE.NMAX) GO TO 25	SCRE 85
	K=K+1	SCRE 86
	YSAP(K)=-(2.*RADIUS*RANDOM(X))-THKCLD	SCRE 87
	XSAP(K)=RANDOM(Y)*RADIUS	SCRE 88
	IF (RANDOM(W).LT.0.5) XSAP(K)=-XSAP(K)	SCRE 89
	RCHK=SQRT((ABS(XSAP(K)))**2.+(ABS(YSAP(K)+RADIUS+THKCLD))**2.)	SCRE 90
	IF (RCHK.GT.RADIUS) GO TO 15	SCRE 91
	CSFUN=-.129044.59624*RCHK**4+24853.21604*RCHK**3-2304.00151*RCHK**2	SCRE 92
1	+119.69214*RCHK+0.30136	SCRE 93
	FRSAP=CSFUN/CSFUNX	SCRE 94
	IF (FRSAP.GE.RANDOM(Z)) GO TO 20	SCRE 95
15	CONTINUE	SCRE 96
	K=K-1	SCRE 97
	GO TO 10	SCRE 98
C	*****	SCRE 99
C		SCRE 100
C		SCRE 101
C	IF THE RANDOMLY CHOSEN (XSAP,YSAP) POINT PASSES THE RESTRICTION	SCRE 102
C	OF THE RADIAL DISTRIBUTION, IT IS LIKEWISE CHECKED FOR THE	SCRE 103
C	Z- COORDINATE	SCRE 104
C	*****	SCRE 105
C		SCRE 106
C		SCRE 107
C		SCRE 108
C	COMPUTES UPPER AND LOWER LIMITS OF LINE NORMAL TO X-Y PLANE AT	SCRE 109

C	(XSAP(K),YSAP(K)) WITH RESPECT TO COLLIMATOR APERTURE	SCRE 110
C	ZLENG EQUALS THE LENGTH OF Z LINE	SCRE 111
20	ZLENG=(ZSTP- ZSBP)+ 2. 0*((2. 0*(RADIUS+ THKCLD))*ZMIN/YS)	SCRE 112
	ZSAP(K)=(RANDOM(X)*ZLENG)- ZLENG/2. 0	SCRE 113
	ZPOS=((ZSTP- ZSBP+ 2*(ABS(YSAP(K))*ZMIN/YS)))/2. 0	SCRE 114
	IF (ABS(ZSAP(K)). GT. ZPOS) K=K- 1	SCRE 115
	GO TO 10	SCRE 116
25	CONTINUE	SCRE 117
	GO TO 35	SCRE 118
30	CONTINUE	SCRE 119
	WRITE (2,85)	SCRE 120
35	RETURN	SCRE 121
C		SCRE 122
40	FORMAT (A6)	SCRE 123
45	FORMAT (1H1,///,25X,34H CYLINDRICAL SOURCE CONFIGURATION ,//)	SCRE 124
50	FORMAT (1H1,///,25X,27H DISK SOURCE CONFIGURATION ,//)	SCRE 125
55	FORMAT (1H1,///,25X,29H PLANAR SOURCE CONFIGURATION ,//)	SCRE 126
60	FORMAT (1H1,///,25X,32H SPHERICAL SOURCE CONFIGURATION ,//)	SCRE 127
65	FORMAT (I6)	SCRE 128
70	FORMAT (A10,2X,3E12. 5)	SCRE 129
75	FORMAT (5X,12,5X,7H TYPE = ,A10,5X,9HRADIUS = ,1PE12. 5,5X,10HDENSIT	SCRE 130
1	Y = ,E12. 5,5X,30HMASS ATTENUATION COEFFICIENT =,E12. 5)	SCRE 131
80	FORMAT (///,10X,11H THERE ARE ,12,79H TYPES OF MATERIAL THROUGH WH	SCRE 132
1	ICH THE GAMMA- RAY ATTENUATION IS TO BE DETERMINED ,//)	SCRE 133
85	FORMAT (///,1H0,10X,102H THE SOURCE GEOMETRY IS NOT CYLINDRICAL AND	SCRE 134
1	THEREFORE CANNOT BE CALCULATED WITH THIS VERSION OF COLLIM)	SCRE 135
	END	SCRE 136

	SUBROUTINE SOLANG (YS,YD,NPS)	SOLA	
	COMMON /W2/ S(701),XSAP(701),YSAP(701),ZSAP(701),SOMEGA(701)	SOLA	1
	COMMON /W3/ XAB(701),XCD(701),ZBC(701),ZAD(701)	SOLA	2
	COMMON /W4/ ATEN(701)	SOLA	3
	COMMON /W13/ XSLP,XSRP,ZSTP,ZSBP,XMIN,ZMIN	SOLA	4
C		SOLA	5
C	*****	SOLA	6
C		SOLA	7
C	COMPUTES THE SOLID ANGLE FOR NPS RECTANGLES ON THE	SOLA	8
C	SURFACE FOR EACH (XSAP,YSAP,ZSAP)	SOLA	9
C	ZADP1 FACTOR TO ACCOUNT FOR ALGEBRAIC SIGN	SOLA	10
C	ZBCP1 FACTOR TO ACCOUNT FOR ALGEBRAIC SIGN	SOLA	11
C	XABP1 FACTOR TO ACCOUNT FOR ALGEBRAIC SIGN	SOLA	12
C	XCDP1 FACTOR TO ACCOUNT FOR ALGEBRAIC SIGN	SOLA	13
C	PD DISTANCE FROM POINT (XSAP,YSAP,ZSAP) TO RECTANGLE	SOLA	14
C	XAB,XCD,ZAD,ZBC ON DETECTOR SURFACE	SOLA	15
C	YSAP(I) HAS TO BE POSITIVE TO BE TAKEN TO A POWER	SOLA	16
C	THE CORRECT VALUE IS SAVED IN YSAVE	SOLA	17
C	SOMEGA(I) SOLID ANGLE OF POINT (XSAP,YSAP,ZSAP), NORMALIZED	SOLA	18
C	AS FUNCTION OF AREA	SOLA	19
C	S(I) SOURCE STRENGTH AT (XSAP,YSAP,ZSAP)	SOLA	20
C	SOMEGA IS THE SOLID ANGLE FRACTION FOR EACH NPS POINTS,	SOLA	21
C	MULTIPLYING BY S GIVES THE NUMBER OF PHOTONS STRIKING THE	SOLA	22
C	RECTANGULAR AREA, DIVIDE BY AREA TO OBTAIN PHOTON INTENSITY PER	SOLA	23
C	PER UNIT AREA	SOLA	24
C		SOLA	25
C	*****	SOLA	26
C		SOLA	27
	DO 5 I=1,NPS	SOLA	28
	IF ((XCD(I)-XAB(I)).LE.0.00010) SOMEGA(I)=0.0	SOLA	29
	IF ((XCD(I)-XAB(I)).LE.0.0001) GO TO 5	SOLA	30
	IF ((ZBC(I)-ZAD(I)).LE.0.0001) SOMEGA(I)=0.0	SOLA	31
	IF ((ZBC(I)-ZAD(I)).LE.0.0001) GO TO 5	SOLA	32
	S(I)=1.0	SOLA	33
	YSAVE=YSAP(I)	SOLA	34
	PD=YS+YD-YSAP(I)	SOLA	35
	ZADP=(ZAD(I)-ZSAP(I))	SOLA	36
	XCDP=(XCD(I)-XSAP(I))	SOLA	37
	XABP=(XAB(I)-XSAP(I))	SOLA	38
	ZBCP=(ZBC(I)-ZSAP(I))	SOLA	39
	XABP1=1.0	SOLA	40
	XCDP1=1.0	SOLA	41
	ZADP1=1.0	SOLA	42
	ZBCP1=1.0	SOLA	43
	IF (ZADP.LT.0.0) ZADP1=-1.0	SOLA	44
	IF (ZBCP.LT.0.0) ZBCP1=-1.0	SOLA	45
	IF (XABP.LT.0.0) XABP1=-1.0	SOLA	46
	IF (XCDP.LT.0.0) XCDP1=-1.0	SOLA	47
	ZADP=ABS(ZADP)	SOLA	48
	ZBCP=ABS(ZBCP)	SOLA	49
	XABP=ABS(XABP)	SOLA	50
	XCDP=ABS(XCDP)	SOLA	51
	YSAP(I)=ABS(YSAP(I))	SOLA	52
	SOMEGA(I)=ATAN((XCDP*ZBCP)/(PD*SQRT(XCDP**2.+ZBCP**2.+PD**2.)))*ZBC	SOLA	53
1	P1*XCDP1)-ATAN((XABP*ZBCP)/(PD*SQRT(XABP**2.+ZBCP**2.+PD**2.)))*XAB	SOLA	54

2	P1*ZBCP1)- ATAN((XCDP*ZADP)/(PD*SQRT(XCDP**2. + ZADP**2. + PD**2.))*XCD	SOLA	55
3	P1*ZADP1)+ ATAN((XABP*ZADP)/(PD*SQRT(XABP**2. + ZADP**2. + PD**2.))*XAB	SOLA	56
4	P1*ZADP1)	SOLA	57
	YSAP(I)=YSAVE	SOLA	58
	SOMEGA(I)=SOMEGA(I)/(4. 0*3. 1415927)	SOLA	59
5	CONTINUE	SOLA	60
	RETURN	SOLA	61
	END	SOLA	62

	SUBROUTINE SOURIN (NPS,YS,YD)	SRIN	1
	COMMON /W2/ S(701),XSAP(701),YSAP(701),ZSAP(701),SOMEGA(701)	SRIN	2
	COMMON /W3/ XAB(701),XCD(701),ZBC(701),ZAD(701)	SRIN	3
	COMMON /W4/ ATTEN(701)	SRIN	4
1	COMMON /W5/ EFF(21,21),Z(21),X(21),FX(21,21),FZ(21,21),FXZ(21,21),	SRIN	5
	T1(21),T2(21),T3(21),IBD(6)	SRIN	6
	COMMON /W6/ RADMAT(10),RHO(10),XATT(10),TYPE(10),SF(10)	SRIN	7
	COMMON /W7/ DETRAD,STEPX,STEPZ,GAMEFF,AVEFF	SRIN	8
	COMMON /W8/ IOP(2),TAB(3),XD(110),ZD(110)	SRIN	9
	COMMON /W9/ ICENT,JCENT	SRIN	10
	COMMON /W12/ NOM	SRIN	11
C	*****	SRIN	12
C		SRIN	13
C	COMPUTES THE SOURCE STRENGTH OF EACH (XSAP,YSAP,ZSAP) CONSIDER	SRIN	14
C	THE ATTENUATION OF THE SOURCE, BONDING, CLADDING AND OTHER MATE	SRIN	15
C	BETWEEN THE ORIGINATING POINT AND THE MIDPOINT OF THE RECTANGLE	SRIN	16
C	XAB,XCD,ZBC,ZAD	SRIN	17
C		SRIN	18
C	COMPUTES THE MIDPOINT OF XAB,XCD,ZBC,ZAD	SRIN	19
C	RADMAT(I) THICKNESS OF THE ITH MATERIAL	SRIN	20
C	RHO(I) DENSITY OF ITH MATERIAL IN G/CC	SRIN	21
C	XATT(I) MASS ATTENUATION COEFFICIENT OF ITH MATERIAL CM**2/G	SRIN	22
C	DETEFF DETERMINES THE 2-DIMENSIONAL BI-CUBIC SPLINE FUNCTION	SRIN	23
C	OVER THE SURFACE OF THE DETECTOR	SRIN	24
C	ZFACT IS THE FACTOR TO MULTIPLE PATH LENGTH THROUGH THE	SRIN	25
C	MATERIAL TO ACCOUNT FOR Z VECTOR COMPONENT	SRIN	26
C	*****	SRIN	27
C		SRIN	28
C	CALL SOLANG (YS,YD,NPS)	SRIN	29
	CALL DETEFF	SRIN	30
	SCENT=0.0	SRIN	31
	NOM1=NOM-1	SRIN	32
	DO 5 I=1,NOM1	SRIN	33
	SCENT=SCENT- RADMAT(I)	SRIN	34
5	CONTINUE	SRIN	35
	DO 30 J=1,NPS	SRIN	36
	SAVE=0.0	SRIN	37
		SRIN	38
C	*****	SRIN	39
C		SRIN	40
C	CALCULATES THE GAMMA PHOTON PATHS OF 100 PHOTON AT EACH	SRIN	41
C	(XSAP,YSAP,ZSAP) TO THE SURFACE OF THE DETECTOR AND CALCULATES	SRIN	42
C	THE AVERAGE	SRIN	43
C		SRIN	44
C	*****	SRIN	45
C		SRIN	46
C		SRIN	47
	DO 25 I=1,100	SRIN	48
	ZMIDP=(ZBC(J)- ZAD(J))*RANDOM(X)+ ZAD(J)	SRIN	49
	XMIDP=(XCD(J)- XAB(J))*RANDOM(Y)+ XAB(J)	SRIN	50
	YMIDP=YD+ YS	SRIN	51
	DIST=SQRT((ABS(XMIDP- XSAP(J)))**2. + (ABS(YMIDP- YSAP(J)))**2. + (ABS(Z	SRIN	52
1	MIDP- ZSAP(J)))**2.)	SRIN	53
	YDET=YS+ YD- YSAP(J)	SRIN	54

	ZFACT=DIST/YDET	SRIN	55
	R1=0.0	SRIN	56
	DO 15 K=1,NOM	SRIN	57
	RAD=0.0	SRIN	58
	DO 10 II=1,K	SRIN	59
	RAD=RADMAT(II)+ RAD	SRIN	60
10	CONTINUE	SRIN	61
	C12=((XMIDP- XSAP(J))*(XMIDP- XSAP(J)))/((YMIDP- YSAP(J))*(YMIDP- YSAP(J)))	SRIN	62
1	A=C12+ 1.0	SRIN	63
	B=2.0*(SQRT(C12))*XSAP(J)- 2.0*YSAP(J)*C12- 2.0*SCENT	SRIN	64
	C=C12*YSAP(J)**2+ XSAP(J)**2+ SCENT**2- RAD**2- 2.0*(SQRT(C12))*XSAP(J)*YSAP(J)	SRIN	65
1	YY=(- B+ SQRT(ABS(B*B- 4.0*A*C)))/(2.0*A)	SRIN	66
	XX=(YY- YSAP(J))*SQRT(C12)+ XSAP(J)	SRIN	67
	R1=SQRT((YSAP(J)- YY)*(YSAP(J)- YY)+ (XSAP(J)- XX)*(XSAP(J)- XX))*ZFACT	SRIN	68
1	- R1	SRIN	69
	R11=R1*2.54	SRIN	70
	SF(K)=1/(EXP(XATT(K)*RHO(K)*R11))	SRIN	71
15	CONTINUE	SRIN	72
	ATTEN(J)=1.0	SRIN	73
	DO 20 KK=1,NOM	SRIN	74
	ATTEN(J)=ATTEN(J)*SF(KK)	SRIN	75
20	CONTINUE	SRIN	76
	S(J)=(SOMEGA(J)*ATTEN(J))	SRIN	77
	MAXZ=21	SRIN	78
	PTEFF=SPL2D2(XMIDP,ZMIDP,21,Z,21,X,EFF,FX,FZ,FXZ,MAXZ,0,0)	SRIN	79
	RLIMIT=SQRT(XMIDP**2+ ZMIDP**2)	SRIN	80
	IF (RLIMIT.GT.DETRAD) PTEFF=0.0	SRIN	81
	IF (PTEFF.LT.0.0) PTEFF=0.0	SRIN	82
	PTEFF=(PTEFF*GAMEFF)/AVEFF	SRIN	83
	S(J)=S(J)*PTEFF	SRIN	84
	SAVE=S(J)/100. + SAVE	SRIN	85
25	CONTINUE	SRIN	86
	S(J)=SAVE	SRIN	87
30	CONTINUE	SRIN	88
	RETURN	SRIN	89
C		SRIN	90
	END	SRIN	91
		SRIN	92
		SRIN	93

	SUBROUTINE DETEFF	DTEF	1
	COMMON /W8/ IOP(2),TAB(3),XD(110),ZD(110)	DTEF	2
	COMMON /W9/ ICENT,JCENT	DTEF	3
	DIMENSION XS(21), ZS(21)	DTEF	4
	DIMENSION W(21), XFUN(110), ZFUN(110), TITLE(8)	DTEF	5
	COMMON /W5/ EFF(21,21),Z(21),X(21),FX(21,21),FZ(21,21),FXZ(21,21),	DTEF	6
1	T1(21),T2(21),T3(21),IBD(6)	DTEF	7
	COMMON /W7/ DETRAD,STEPX,STEPZ,GAMEFF,AVEFF	DTEF	8
	COMMON /W11/ ZZ(21,21)	DTEF	9
C		DTEF	10
C	*****	DTEF	11
C		DTEF	12
C	READS IN SURFACE RESPONSE EFFICIENCIES FOR SPECIFIC GAMMA AND CRYSTALS	DTEF	13
C	COMPUTES AVERAGE EFFICIENCY FOR EACH RECTANGLE	DTEF	14
C	STARTX STARTING POSITION FOR X VECTOR	DTEF	15
C	STARTZ STARTING POSITION FOR Z VECTOR	DTEF	16
C	DESTEPX STEP SIZE DISTANCE BETWEEN GRID POINTS OF SURFACE RES	DTEF	17
C	DESTEPZ STEP SIZE DISTANCE BETWEEN GRID POINTS OF SURFACE RES	DTEF	18
C	SPLINE INTERPOLATION TO OBTAIN A 41 BY 41 MATRIX	DTEF	19
C	DETRAD DETECTOR RADIUS	DTEF	20
C	GAMEFF ABSOLUTE EFFICIENCY FOR SPECIFIC GAMMA RAY	DTEF	21
C	READ IN THE EFFICIENCY DATA FOR EACH POINT IN I X J MATRIX	DTEF	22
C		DTEF	23
C	*****	DTEF	24
	READ (1,100)TITLE	DTEF	25
	WRITE (2,105)TITLE	DTEF	26
	READ (1,155)DETRAD,GAMEFF,STEPX,STEPZ	DTEF	27
	WRITE (2,110)DETRAD,GAMEFF	DTEF	28
	WRITE (2,115)STEPX,STEPZ	DTEF	29
	DO 10 I=1,21	DTEF	30
	DO 5 J=1,21	DTEF	31
	READ (1,120)EFF(I,J)	DTEF	32
	ZZ(I,J)=EFF(I,J)	DTEF	33
5	CONTINUE	DTEF	34
10	CONTINUE	DTEF	35
	WRITE (2,125)	DTEF	36
C		DTEF	37
C	*****	DTEF	38
C		DTEF	39
C	THE RELATIVE EFFICIENCIES ARE READ IN TO EFF ARRAY WHERE I IS	DTEF	40
C	THE ROW INDICE AND J IS THE COLUMN INDICE	DTEF	41
C	THE FIRST VALUE IS READ FOR THE LOWER LEFTHAND SIDE, ALONG THE	DTEF	42
C	ROW(LEFT TO RIGHT)	DTEF	43
C		DTEF	44
C	*****	DTEF	45
C		DTEF	46
	DO 15 I=1,21	DTEF	47
	WRITE (2,130)(EFF(22-I,J),J=1,21)	DTEF	48
15	CONTINUE	DTEF	49
	IOP(1)=5	DTEF	50
	IOP(2)=5	DTEF	51
	DO 20 I=1,21	DTEF	52
	XS(I)= 1. 0+ (I- 1)*0. 100	DTEF	53
	ZS(I)= 1. 0+ (I- 1)*0. 100	DTEF	54

20	CONTINUE	DTEF 55
C	.....	DTEF 56
C		DTEF 57
C		DTEF 58
C	THE 21 POINTS ARE EXPANDED TO 101 POINTS BY 1-D SPLINE INTER-	DTEF 59
C	POLATION ALONG THE X AND A GRID LINES PARALLEL TO THE X AND Z,	DTEF 60
C	AXES, RESPECTIVELY.	DTEF 61
C	THE TWO CENTER GRID LINES ARE USED TO DETERMINE THE CENTER OF	DTEF 62
C	THE SURFACE RESPONSE FUNCTION WITH RESPECT TO THE COLLIMATING S	DTEF 63
C	DETERMINE THE CENTER INDICES BY MINIMIZING THE DIFFERENCES BETW	DTEF 64
C	THE TWO SIDES	DTEF 65
C	ICENT THE CENTER INDICE FOR THE X-DIRECTION	DTEF 66
C	JCENT THE CENTER INDICE FOR THE Z-DIRECTION	DTEF 67
C	X(ICENT) THE CENTER POSITON ON THE X-AXEIS	DTEF 68
C	Z(JCENT) THE CENTER IN	DTEF 69
C	Z(JCENT) THE CENTER POSITION ON THE Z-AXIS	DTEF 70
C	SET UP NEW MATRIX OF RELATIVE EFFICIENCIES AROUND THE NEW	DTEF 71
C	COORDINATE SYSTEM CENTERED AT X(ICENT),Z(JCENT)	DTEF 72
C	RESTRICTS VALUES TO LIE ON THE SURFACE OF THE CRYSTAL	DTEF 73
C	.....	DTEF 74
C		DTEF 75
C		DTEF 76
	DO 25 K=1,21	DTEF 77
	W(K)=0.0	DTEF 78
	Z(K)=EFF(K,10)	DTEF 79
	X(K)=EFF(10,K)	DTEF 80
25	CONTINUE	DTEF 81
	CALL SPL1D1 (21,XS,X,W,IOP,1,T1,T2,T3)	DTEF 82
	DO 30 I=1,101	DTEF 83
	XD(I)=- 1.00+ (I- 1)*0.020	DTEF 84
	CALL SPL1D2 (21,XS,X,W,1,XD(I),TAB)	DTEF 85
	XFUN(I)=ABS(TAB(1))	DTEF 86
30	CONTINUE	DTEF 87
	CALL SPL1D1 (21,ZS,Z,W,IOP,1,T1,T2,T3)	DTEF 88
	DO 35 I=1,101	DTEF 89
	ZD(I)=- 1.00+ (I- 1)*0.020	DTEF 90
	CALL SPL1D2 (21,ZS,Z,W,1,ZD(I),TAB)	DTEF 91
	ZFUN(I)=ABS(TAB(1))	DTEF 92
35	CONTINUE	DTEF 93
C	.....	DTEF 94
C		DTEF 95
C		DTEF 96
C	DETERMINE THE CENTER OF I AND J INDICES BY MINIMIZING THE	DTEF 97
C	DIFFERENCE BETWEEN THE TWO SIDES	DTEF 98
C	.....	DTEF 99
C		DTEF 100
C		DTEF 101
	M=101	DTEF 102
	ASUM=1.0E+ 220	DTEF 103
	M4=M/4	DTEF 104
	M41=M4- 1	DTEF 105
	M34=(M*3)/4	DTEF 106
	DO 45 I=M4,M34	DTEF 107
	BUM=0.0	DTEF 108
	DO 40 K=1,M41	DTEF 109

	BUM=BUM+(XFUN(I,K)-XFUN(I+K))**2	DTEF 110
40	CONTINUE	DTEF 111
	IF (ASUM.LT.BUM) GO TO 45	DTEF 112
	ASUM=BUM	DTEF 113
	ICENT=I	DTEF 114
45	CONTINUE	DTEF 115
	ASUM=1.0E+220	DTEF 116
	DO 55 J=M4,M34	DTEF 117
	BUM=0.0	DTEF 118
	DO 50 K=1,M41	DTEF 119
	BUM=BUM+(ZFUN(J,K)-ZFUN(J+K))**2	DTEF 120
50	CONTINUE	DTEF 121
	IF (ASUM.LT.BUM) GO TO 55	DTEF 122
	ASUM=BUM	DTEF 123
	JCENT=J	DTEF 124
55	CONTINUE	DTEF 125
C		DTEF 126
C	.....	DTEF 127
C		DTEF 128
C	SET UP MATRIX AROUND CENTERED INDICES	DTEF 129
C		DTEF 130
C	.....	DTEF 131
C		DTEF 132
	WRITE (2,135)ICENT,JCENT	DTEF 133
	WRITE (2,140)XD(ICENT),ZD(JCENT)	DTEF 134
	DO 60 II=1,21	DTEF 135
	X(II)=1.00+(II-1)*STEPX-XD(ICENT)	DTEF 136
	Z(II)=1.00+(II-1)*STEPZ-ZD(JCENT)	DTEF 137
60	CONTINUE	DTEF 138
	DO 70 I=1,21	DTEF 139
	DO 65 J=1,21	DTEF 140
	EFF(I,J)=ZZ(J,I)	DTEF 141
65	CONTINUE	DTEF 142
70	CONTINUE	DTEF 143
	EFFMAX=0.0	DTEF 144
	EFFTOT=0.0	DTEF 145
	DO 80 I=1,21	DTEF 146
	DO 75 J=1,21	DTEF 147
	RLIMIT=SQRT(X(J)**2+Z(I)**2)	DTEF 148
	IF (RLIMIT.GT.DETRAD) EFF(J,I)=0.0	DTEF 149
	IF (EFF(I,J).GE.EFFMAX) EFFMAX=EFF(I,J)	DTEF 150
	EFFTOT=EFFTOT+EFF(I,J)	DTEF 151
75	CONTINUE	DTEF 152
80	CONTINUE	DTEF 153
C		DTEF 154
C	.....	DTEF 155
C		DTEF 156
C	THE FIRST EFF VALUE IS FROM THE LOWER LEFTHAND SIDE OF THE	DTEF 157
C	SURFACE RESPONSE GRID	DTEF 158
C	Z(J,I) = EFF(I,J) IS NEEDED TO REVERSE THE INDICES, LATER	DTEF 159
C	EFF(I,J) = Z(I,J) BECAUSE SOME IDOIT IN SPL2D1 SET EFF(I,J) EQU	DTEF 160
C	TO THE FUNCTION AT X(J),Z(I)	DTEF 161
C	EFFTOT IS EQUIVALENT TO SOME AVERAGE EFFICIENCY FOR A GAMMA RAY	DTEF 162
C	AVEFF EFFICIENCY FOR PARTICULAR GAMMA RAY	DTEF 163
C		DTEF 164

C	.....	DTEF 165
C	DETRAD=3.1415927*DETRAD*DETRAD	DTEF 166
	AVEFF=(EFFTOT/DETRAD)*STEPX*STEPZ	DTEF 167
	EMAX=(GAMEFF*EFFMAX)/AVEFF	DTEF 168
	WRITE (2,145)EMAX	DTEF 170
C	SUBSTITUTE THE ACTUAL EFFICIENCIES FOR THE RELATIVE CNTS	DTEF 171
	NBRX=21	DTEF 172
	NBRZ=21	DTEF 173
	MAXZ=21	DTEF 174
C	EFF(I,J) IS A TWO DIMENSIONAL TABLE OF VALUES AT (X(I),Z(I))	DTEF 175
	IBD(1)=4	DTEF 176
	IBD(2)=4	DTEF 177
	IBD(3)=4	DTEF 178
	IBD(4)=4	DTEF 179
	IBD(5)=4	DTEF 180
	IBD(6)=4	DTEF 181
	CALL SPL2D1 (NBRX,Z,NBRZ,X,EFF,FX,FZ,FXZ,MAXZ,IBD,T1,T2,T3)	DTEF 182
	DO 90 J=1,21	DTEF 183
	DO 85 I=1,21	DTEF 184
	XMIDP=.1.00+(J-.1)*STEPX	DTEF 185
	ZMIDP=.1.0+(I-.1)*STEPZ	DTEF 186
	PTEFF=SPL2D2(XMIDP,ZMIDP,21,Z,21,X,EFF,FX,FZ,FXZ,MAXZ,0,0)	DTEF 187
	RLIMIT=SQRT(XMIDP**2+ZMIDP**2)	DTEF 188
	IF (RLIMIT.GT.DETRAD) PTEFF=0.0	DTEF 189
	ZZ(I,J)=PTEFF	DTEF 190
85	CONTINUE	DTEF 191
90	CONTINUE	DTEF 192
	DO 95 I=1,21	DTEF 193
	WRITE (2,150)(ZZ(22-I,J),J=1,21)	DTEF 194
95	CONTINUE	DTEF 195
	RETURN	DTEF 196
C		DTEF 197
100	FORMAT (8A10)	DTEF 198
105	FORMAT (11H1,/,8A10,/,/,)	DTEF 199
110	FORMAT (5X,17HDETECTOR RADIUS =,F7.4,/,5X,28HABSOLUTE GAMMA EFFIC	DTEF 200
1	ENCY =,F7.4)	DTEF 201
115	FORMAT (5X,39HRELATIVE EFFICIENCY MEASURED AT STEPX =,F6.4,10HAND	DTEF 202
1	STEPZ ,F6.4)	DTEF 203
120	FORMAT (21X,E20.7)	DTEF 204
125	FORMAT (/,/,10X,75H THE RELATIVE EFFICIENCIES USED FOR THE DETERMIN	DTEF 205
1	ATION OF 2-D SPLINE SURFACE ,/,/,)	DTEF 206
130	FORMAT (5X,21F6.0,/,)	DTEF 207
135	FORMAT (11H1,/,9X,27HTHE CENTER INDICE FOR X IS ,I6,/,8X,28H THE	DTEF 208
1	CENTER INDICE FOR Z IS ,I6)	DTEF 209
140	FORMAT (/,10X,40H THE CENTERED SURFACE IS LOCATED AT X =,F8.4,2X,	DTEF 210
1	5H Z =,F8.4,/,)	DTEF 211
145	FORMAT (/,10X,49HMAXIMUM EFFICIENCY OF SURFACE RESPONSE FUNCTION =	DTEF 212
1	,F7.4,/,)	DTEF 213
150	FORMAT (5X,21F6.0,/,)	DTEF 214
155	FORMAT (6F12.2)	DTEF 215
	END	DTEF 217

ACKNOWLEDGMENTS

I am very grateful for the assistance and encouragement of Dr. G. R. Waterbury, CMB-1 Group Leader, and Dr. N. E. Vanderborgh, UNM Chemistry Department. They offered many useful suggestions during the research and preparation of the dissertation.

I would like to acknowledge the assistance of the professional staff of Groups CMB-1, CMB-14, CMB-11, A-1, and M-1. In particular I would like to thank J. R. Netuschil, J. N. Quintana, and G. H. Mottaz for their assistance in collecting and processing the gamma scanning data. J. B. Deal did an excellent job maintaining and modifying the data acquisition system. The Hot Cell Group under the supervision of J. W. Schulte was very helpful in the fabrication of the scanning equipment and in the preparation of samples.

The encouragement and assistance of Dr. B. K. Barnes is gratefully acknowledged. I would also like to thank Dr. D. M. Holm for sharing his previous experiences. I would like to thank J. E. Phillips for preparing many of the figures and typing the manuscript. Her patience and encouragement contributed to the successful completion of the research dissertation.

This work was performed at the Los Alamos Scientific Laboratory for the Reactor Development and Technology Branch of the U. S. Atomic Energy Commission.

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