GAMMA SCANNER
FOR NITR II FUEL PLATES

by
DONALD EDWARD LAUGHLIN
S.B., Lowell Technological Institute
1973

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF
SCIENCE
at the
MASSACHUSETTS INSTITUTE OF
TECHNOLOGY
August, 1974

Signature of Author

Nuclear Engineering Department
August 12, 1974

Certified by

Thesis Supervisor

Accepted by

Chairman, Department Committee
on Graduate Students

SEP 13 1974
ABSTRACT

GAMMA SCANNER FOR MITR II FUEL PLATES
by
Donald Edward Labbe

A gamma scanner is designed and constructed for a pre-start-up relative power distribution measurement of the MITR II core. The design problems of resolution, gamma ray leakage through shielding, and backscattered radiation are investigated.

A computer code is developed which corrects the data for background, decay, and activity of previous irradiations to yield the relative power distribution of the fuel plate. The code also corrects for area averaging effects by fitting the power distribution output of every three point sequence into quadratic equations. New values for the relative power distribution are calculated. Maxima and minima values are located and calculated.

A discussion of errors involved in the experiment and analysis is presented. Fluctuations in background due to backscattering and counting statistics are the main sources of experimental error. However, the major potential source of error is the analysis of the power spike at the hot end of the fuel plate. Many measurements are required to evaluate the power spike accurately.
ACKNOWLEDGEMENTS

The assistance of Professor David D. Lanning, Assistant Professor James W. Gosnell, and Glenn G. Lucas was fundamental to the development of this thesis. Their ideas helped to identify the problems and broaden the scope.

Special thanks to Paula Labbe, my wife, for her patience and understanding throughout the year. Paula's typing of the manuscript is appreciated.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>3</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>4</td>
</tr>
<tr>
<td>List of Figures</td>
<td>6</td>
</tr>
<tr>
<td>List of Tables</td>
<td>8</td>
</tr>
<tr>
<td>Chapter 1. Introduction</td>
<td>9</td>
</tr>
<tr>
<td>1.1 Foreward</td>
<td>9</td>
</tr>
<tr>
<td>1.2 Objective</td>
<td>9</td>
</tr>
<tr>
<td>Chapter 2. Gamma Scanner</td>
<td>12</td>
</tr>
<tr>
<td>2.1 General Description</td>
<td>12</td>
</tr>
<tr>
<td>2.2 Collimator</td>
<td>13</td>
</tr>
<tr>
<td>2.3 Backscattering Radiation</td>
<td>25</td>
</tr>
<tr>
<td>Fuel Plate Movement</td>
<td>30</td>
</tr>
<tr>
<td>Detector Electronics</td>
<td>34</td>
</tr>
<tr>
<td>Integrated Design</td>
<td>35</td>
</tr>
<tr>
<td>Experimental Procedure</td>
<td>39</td>
</tr>
<tr>
<td>Chapter 3. Computer Code GAMSCAN</td>
<td>48</td>
</tr>
<tr>
<td>3.1 General Description</td>
<td>48</td>
</tr>
<tr>
<td>3.2 Decay Corrections</td>
<td>48</td>
</tr>
<tr>
<td>3.3 Area Averaging Corrections</td>
<td>56</td>
</tr>
<tr>
<td>3.4 Sources of Error</td>
<td>60</td>
</tr>
<tr>
<td>Chapter 4. Summary</td>
<td>66</td>
</tr>
<tr>
<td>4.1 Gamma Scanner</td>
<td>66</td>
</tr>
<tr>
<td>4.2 The Experiment</td>
<td>72</td>
</tr>
<tr>
<td>4.3 Data</td>
<td>73</td>
</tr>
<tr>
<td>4.4 Computer Code</td>
<td>73</td>
</tr>
<tr>
<td>Appendix A.</td>
<td>Collimator Leakage Calculations</td>
</tr>
<tr>
<td>Appendix B.</td>
<td>Shield Leakage</td>
</tr>
<tr>
<td>Appendix C.</td>
<td>Detection Rate of Collimated Gamma Rays</td>
</tr>
<tr>
<td>Appendix D.</td>
<td>Count Rate</td>
</tr>
<tr>
<td>Appendix E.</td>
<td>Leakage Contributing to Backscatter Activity</td>
</tr>
<tr>
<td>E.1</td>
<td>Leakage Through a Two Inch Lead and One Inch Steel Backscatter Shield</td>
</tr>
<tr>
<td>E.2</td>
<td>Leakage Through a Six Inch Backscatter Shield</td>
</tr>
<tr>
<td>Appendix F.</td>
<td>Compton Scattered Gamma Rays</td>
</tr>
<tr>
<td>Appendix G.</td>
<td>Dose Calculations</td>
</tr>
<tr>
<td>G.1</td>
<td>Dose from Unshielded Fuel Element</td>
</tr>
<tr>
<td>G.2</td>
<td>Shield Dose</td>
</tr>
<tr>
<td>Appendix H.</td>
<td>Counting Statistics</td>
</tr>
<tr>
<td>Appendix I.</td>
<td>Computer Code GAMSUAN</td>
</tr>
<tr>
<td>Appendix J.</td>
<td>Data Format</td>
</tr>
<tr>
<td>Appendix K.</td>
<td>References</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.1</td>
<td>Radial Section of MITR-11 Core</td>
</tr>
<tr>
<td>1.2</td>
<td>Vertical Power Density Distribution</td>
</tr>
<tr>
<td>2.1</td>
<td>Slotted Lead Brick</td>
</tr>
<tr>
<td>2.2</td>
<td>Collimator Brick Overlap</td>
</tr>
<tr>
<td>2.3</td>
<td>Collimator Leakage and Effective Viewing Area for A</td>
</tr>
<tr>
<td>2.6</td>
<td>Machined Lead Bricks on Lathe Cross Beams</td>
</tr>
<tr>
<td>2.7</td>
<td>Side Shielding</td>
</tr>
<tr>
<td>2.8</td>
<td>Fuel Support Plate</td>
</tr>
<tr>
<td>2.9</td>
<td>Collimator Insert</td>
</tr>
<tr>
<td>2.10</td>
<td>Ba-133 Energy Spectrum</td>
</tr>
<tr>
<td>2.11</td>
<td>Cr-51 Energy Spectrum</td>
</tr>
<tr>
<td>2.12</td>
<td>Collimator Section of Gamma Scanner</td>
</tr>
<tr>
<td>2.13</td>
<td>Side View of Collimator</td>
</tr>
<tr>
<td>2.14</td>
<td>Gamma Scanner</td>
</tr>
<tr>
<td>3.1</td>
<td>Ten Minute Irradiation Decay Curve</td>
</tr>
<tr>
<td>3.2</td>
<td>Power Spike</td>
</tr>
<tr>
<td>4.1</td>
<td>Gamma Scanner</td>
</tr>
<tr>
<td>4.2</td>
<td>Machined Lead Bricks on Lathe Cross Beams</td>
</tr>
<tr>
<td>4.3</td>
<td>Side Shielding</td>
</tr>
<tr>
<td>A.1</td>
<td>Geometries of Collimators A, B, C</td>
</tr>
<tr>
<td>A.2</td>
<td>Leakage of A from 0.125&quot; Edge</td>
</tr>
<tr>
<td>A.3</td>
<td>Leakage of A from 0.500&quot; Edge</td>
</tr>
<tr>
<td>A.4</td>
<td>Leakage of B from 0.125&quot; Edge</td>
</tr>
<tr>
<td>A.5</td>
<td>Leakage of B from 0.500&quot; Edge</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>B.1</td>
<td>Geometry of Greatest Shield Leakage</td>
</tr>
<tr>
<td>F.1</td>
<td>Geometry of Detection System</td>
</tr>
<tr>
<td>Table No.</td>
<td>Table Title</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>2.1</td>
<td>Collimator Dimensions</td>
</tr>
<tr>
<td>2.2</td>
<td>Collimator Leakage</td>
</tr>
<tr>
<td>2.3</td>
<td>Expected Count Rates of Collimators A,B, and C at Four Longitudinal Positions</td>
</tr>
<tr>
<td>2.4</td>
<td>Leakage Data for Collimator B</td>
</tr>
<tr>
<td>2.5</td>
<td>Reproducibility of Position</td>
</tr>
<tr>
<td>2.6</td>
<td>Suggested Scanning Points</td>
</tr>
<tr>
<td>4.1</td>
<td>Collimator Parameters</td>
</tr>
<tr>
<td>B.1</td>
<td>Gamma Energy Spectrum, 1-Hour Irradiation, 2-Hour Decay, Reactor Power - 1 Watt</td>
</tr>
<tr>
<td>B.2</td>
<td>Efficiencies of 2x2 NaI Crystal</td>
</tr>
<tr>
<td>B.3</td>
<td>Leakage Parameters 12&quot; Pb Shield</td>
</tr>
<tr>
<td>D.1</td>
<td>Expected Count Rate of Collimator B at Four Longitudinal Locations</td>
</tr>
<tr>
<td>E.1</td>
<td>Leakage Parameters of One Inch Steel Plus Two Inch Lead Backscatter Shield</td>
</tr>
<tr>
<td>E.2</td>
<td>Leakage Parameters for Six Inch Backscatter Shield</td>
</tr>
<tr>
<td>G.1</td>
<td>Parameter for Unshielded Dose Calculation</td>
</tr>
</tbody>
</table>
Chapter I
INTRODUCTION

1.1 FOREWORD

The present redesign of the MIT reactor will increase the thermal fluxes available to experimental facilities by nearly a factor of three. The compact highly enriched core is cooled by H2O and moderated by D2O. Fixed neutron absorbers suppress the thermal flux in the upper half of the core. Thermal neutron access to the core is limited to the base of the core. Hence, the base region will have the highest thermal fluxes and power peaking (I, Addae, P30). Figure I.1 shows the positions of the fuel elements, absorbers, and shim rods (I, Addae, P179).

Computer predictions for the core power distribution are shown in figure I.2 (I, Addae, P172). The core temperature distribution can be calculated from the computer prediction of the power distribution. Temperature limits of the fuel and coolant must not be exceeded during full power operation of the core.

1.2 OBJECTIVE

The purpose of this thesis is to provide an experimental device and a method of analysis to determine the power density distribution during low power start up testing. This information will be used to estimate full power temperature distribution in the fuel.
Fig. 1.1

RADIAL SECTION OF MITR-II CORE
Fig. 1.2

VERTICAL POWER DENSITY DISTRIBUTION

LIGHT WATER TANK

HEAVY WATER TANK

POWER DENSITY DISTRIBUTION \(10^{12}\text{FISSIONS/CM}^3\text{-SEC}\)
2.1 GENERAL DESCRIPTION

The purpose of the gamma scanner is to count the fission product gamma rays emitted from a specified volume of the fuel plate. Gamma rays from the remainder of the fuel plate must be shielded. Comparison of the count rates from different volumes of the fuel plate will show the relative power distribution.

The collimator will allow gamma rays emitted from a specified volume of the fuel plate access to the detector. A rectangular shaped hole extending through twelve inches of lead has been determined to be a sufficient collimator.

The remainder of the fuel plate is shielded from the detector by a minimum of twelve inches of lead. The shielding and collimator are mounted on an eight foot lathe bed.

To cut down on the amount of backscattered radiation reaching the detector and to decrease the dose rate to the operator, two to six inches of lead lie around the sides and bottom of the fuel plate.

Movement of the fuel plate under the collimator is controlled by the lathe table. The longitudinal and transverse motion of the table will position any specified area of the fuel plate under the collimator.

The electronics and detection system consists of a NaI (Tl) crystal and photomultiplier mounted above the collimator and coupled to a single channel analyzer. Drift of the electronics
during counting will be checked by a standard source.

2.2 COLLIMATOR

The total fuel plate activity is limited by the acceptable power level of the core during start up tests and dose to personnel during handling procedures. The count rate of the detector is determined by the activity of the fuel plate and the area under the collimator. To limit area averaging effects, the power density change over the area should be minimized. Since longitudinal changes in the power density are expected to be much greater than transverse changes, a rectangular slot collimator has been selected.

To minimize the cost of making a rectangular slot in a lead brick, the slot is end milled from the 8 inch by 2 inch face of an 8 inch by 4 inch by 2 inch lead brick. Figure 2.1 is a sketch of the machined lead brick. A twelve inch collimator is formed by stacking six machined lead bricks with the slots lined up.

Streaming of gamma rays along the edges of the lead bricks is virtually eliminated by placing the collimator bricks on opposite sides and overlapping as shown in figure 2.2.

To select the best type of collimator for the gamma scanner, the merits of three designs will be compared. Collimator A is a twelve inch collimator with a uniform cross sectional area of one-sixteenth square inch. The slot is 0.5 inch wide and 0.125 inch deep. This type of collimator was used by Battelle-Northwest for the Phoenix Fuel critical experiments (3, Davis, P.19).
Fig. 2.1

SLOTTED LEAD BRICK

SCALE $\frac{1}{2}'' = 1''$
Fig. 2.2

COLLIMATOR BRICK OVERLAP

SCALE $\frac{1}{2}'' = 1''$
Collimator B is a twelve inch collimator with a lower six inch section and three upper two inch sections. The first six inches has a uniform cross sectional area formed by a slot 0.50 inch wide and 0.125 inch deep. The slot of the next three sections is made increasingly larger. Gamma rays passing through the first six inches of the collimator are allowed unshielded access to the detector. The first two inch section has a slot 0.833 inch wide and 0.208 inch deep. The next two inch section has a slot width of 1.167 inches and depth of 0.291 inch. The top section has a slot width of 1.500 inches and depth of 0.375 inch. The primary advantage of the collimator B over collimator A is the four-fold increase in geometric efficiency.

To reduce area averaging effects a third collimator was designed using a smaller width. Collimator C is also twelve inches long with a six inch section and three upper two inch sections. The slot for the first six inches is 0.250 inch wide and 0.125 inch deep. Area averaging effects are cut in half, since the viewing area is one half that of the previous collimators. To increase the geometric efficiency, the design technique used in collimator B is employed. The slot width for the first two inch section is 0.417 inch and the depth is 0.208 inch. The next two inch section has a slot width of 0.583 inch and depth of 0.291 inch. The last two inch section has a slot width of 0.75 inch and depth of 0.375 inch. The number of gamma rays passing through this collimator is essentially the same as collimator A, but the viewing area has been
<table>
<thead>
<tr>
<th>Height</th>
<th>A Width</th>
<th>A Depth</th>
<th>B Width</th>
<th>B Depth</th>
<th>C Width</th>
<th>C Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6in</td>
<td>0.500</td>
<td>0.125</td>
<td>0.500</td>
<td>0.125</td>
<td>0.250</td>
<td>0.125</td>
</tr>
<tr>
<td>6in-8in</td>
<td>0.500</td>
<td>0.125</td>
<td>0.833</td>
<td>0.208</td>
<td>0.417</td>
<td>0.208</td>
</tr>
<tr>
<td>8in-10in</td>
<td>0.500</td>
<td>0.125</td>
<td>1.167</td>
<td>0.291</td>
<td>0.583</td>
<td>0.291</td>
</tr>
<tr>
<td>10in-12in</td>
<td>0.500</td>
<td>0.125</td>
<td>1.500</td>
<td>0.375</td>
<td>0.750</td>
<td>0.375</td>
</tr>
</tbody>
</table>
cut in half. Table 2.1 lists the collimator dimensions for comparison.

The main objective of the gamma scanning experiment is to determine the power peaking factors and their positions on the fuel plate. The following five factors will determine the accuracy of the measurements:

1) leaking around the collimator,
2) leakage through the shield,
3) counting statistics,
4) backscattered radiation reaching the detector, and
5) errors introduced by area averaging effects.

The first three factors determine the best collimator. The fourth factor will be discussed in the backscattering section. Factor five will be discussed in the computer code section 3.3.

To simplify calculations of leakage, the power distribution in the fuel plate may be approximated. Since most of the power is produced in the bottom half of the fuel plate, assume the power distribution can be represented by a uniform plane source eleven inches long.

Using the above assumption, collimator A has a collimator leakage of 4.4% from the one-eighth inch edges and 1.2% from the half inch edges. Refer to Appendix A for the calculations of collimator leakage. Most of this leakage comes from the area just outside the collimator viewing area. For example, 90% of the collimator leakage from the 0.125 inch edges comes from the area which lies 0.050 inch from the edges. Figure 2.3 illustrates the collimator leakage for A.
Fig. 2.3

COLLIMATOR LEAKAGE &

EFFECTIVE VIEWING

AREA FOR A

SCALE 6"=1"
The sum of the edge leakages is 11.2%. This leakage effect represents about 10% of the total counts.

Table 2.2 lists the leakage from each edge for collimators A, B and C. Also the distance from each edge which determines the area that produces 90% of the collimator leakage is given.

Collimator B has twice the collimator leakage of A. This leakage decreases the resolution of the scanner, or effectively increases the viewing area of the collimator by 20%.

Collimator C has slightly more collimator leakage than A. However, the viewing area is half that of A, thus the resolution is better by nearly a factor of two.

A more significant type of leakage is the shielding leakage. Since shielding leakage is not localized, the counting rate of the whole fuel plate can be influenced by one hot spot. To obtain an accurate measurement of the relative power distribution, the shielding leakage must be kept to a minimum.

The shielding leakage is the same for all three collimators, because each lead shield is twelve inches thick. However, the fraction of the counting rate due to shielding leakage is a factor of four greater for collimators A and B.

To calculate the shielding leakage the following textbook information was used:

1. The fission product gamma energy distribution for a one hour irradiation period and two hour decay period.
## Table 2.2

Collimator Leakage

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Edge Length (in)</th>
<th>Leakage</th>
<th>90% distance (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.125</td>
<td>4.4%</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>1.2%</td>
<td>0.020</td>
</tr>
<tr>
<td>B</td>
<td>0.125</td>
<td>8.5%</td>
<td>0.120</td>
</tr>
<tr>
<td></td>
<td>0.500</td>
<td>2.4%</td>
<td>0.030</td>
</tr>
<tr>
<td>C</td>
<td>0.125</td>
<td>4.4%</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>2.4%</td>
<td>0.030</td>
</tr>
</tbody>
</table>
2. NaI(Tl) detector efficiency at different energies.

3. Leakage and build up factor formulas for a uniform line source.

The calculated leakage of a twelve inch lead shield is $1.51 \times 10^{-8}\%$ of the total activity of the line source. Refer to appendix B for shield leakage calculations.

The detection rate of collimators A and C is $1.98 \times 10^{-5}\%$ of the total activity. Refer to Appendix C for detection rate calculations. The shield leakage is less than 0.1\% of the detected collimator gamma rays. Hot spot activity will not significantly effect the count rate of the remainder of the plate.

Collimator B decreases the shielding leakage to less than 0.025\% of the selected collimated gamma rays, because of the factor of four increase in count rate. However, the reduction in shielding leakage is not significant.

Obtaining significant counting statistics is a potential problem of the experimental set up. The measured background in the room is 300 counts per minute. There will also be an increase in background due to backscattered radiation discussed in section 2.3. Areas of the fuel plate which have low activity will require very long counting periods to produce significant data. Fluctuation of background with time will distort the results.
Increasing the count rate from the fuel plate decreases the distortion caused by background fluctuations. Collimator B will give the most reliable counting statistics, for it has a geometric counting efficiency four times greater than collimators A and C.

Table 2.3 lists the expected count rates of collimators A, B, and C at four longitudinal positions of the fuel plate. L is the distance from the cool end of the fuel plate in inches. \( f_L \) is the approximate fraction of the average power density at position L. An 0.5 hour irradiation at 100 watts total core power is assumed. Refer to Appendix D for calculations.

After long decay periods the activity of the cool end of the fuel plate will be difficult to measure with accuracy. Measurements obtained with collimator B will be far more accurate than those obtained from collimators A or C.

To determine which collimator is best, compare the errors introduced by collimator leakage and poor counting measurements. Collimator leakage effectively increases the area averaging effects. From the radiographs of the fuel plates, the fuel meat thickness is nearly constant. Since the flux distribution is smooth, the power density distribution should follow a smooth curve as shown in figure 1.2. If the smooth curve distribution is maintained, the computer code described in section 3.3 will correct the distribution for area averaging effects.

Poor counting measurements due to background fluctuations can not be corrected by calculational schemes. The errors can be reduced by going to higher count rates. Background is a large
Table 2.3

Expected Count Rates of Collimators A, B and C at Four Longitudinal Positions

<table>
<thead>
<tr>
<th>L (in)</th>
<th>$f_L$</th>
<th>A &amp; C</th>
<th>B</th>
<th>A &amp; C</th>
<th>B</th>
<th>A &amp; C</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.07</td>
<td>74</td>
<td>295</td>
<td>44</td>
<td>179</td>
<td>29</td>
<td>115</td>
</tr>
<tr>
<td>7</td>
<td>0.17</td>
<td>179</td>
<td>717</td>
<td>109</td>
<td>436</td>
<td>70</td>
<td>279</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>1054</td>
<td>4217</td>
<td>641</td>
<td>2564</td>
<td>411</td>
<td>1624</td>
</tr>
<tr>
<td>22</td>
<td>3.4</td>
<td>3584</td>
<td>14337</td>
<td>2179</td>
<td>8717</td>
<td>1396</td>
<td>5583</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L (in)</th>
<th>$f_L$</th>
<th>A &amp; C</th>
<th>B</th>
<th>A &amp; C</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.07</td>
<td>22</td>
<td>86</td>
<td>17</td>
<td>69</td>
</tr>
<tr>
<td>7</td>
<td>0.17</td>
<td>52</td>
<td>209</td>
<td>42</td>
<td>166</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>307</td>
<td>1229</td>
<td>245</td>
<td>979</td>
</tr>
<tr>
<td>22</td>
<td>3.4</td>
<td>1045</td>
<td>4179</td>
<td>832</td>
<td>3327</td>
</tr>
</tbody>
</table>
fraction of the count rate over the entire fuel plate. A reduction in this fraction will produce more accurate results.

By using the above criteria, collimator B was selected. Table 2.4 lists the leakage data for collimator B.

2.3 BACKSCATTERING RADIATION

Gamma rays leaking out of the bottom and sides of the lathe bed may be backscattered into the detector. Since only a small fraction of the fuel plate activity reaches the detector through the collimator, $7.92 \times 10^{-5}$, the amount of backscattered radiation producing counts must be kept low. These two techniques are used:

1) Shield all sides of the fuel plate.

2) Since backscattered radiation is predominately of low energy, discriminate against low energy radiation in the single channel analyzer.

The bottom of the fuel plate is shielded by one inch of steel and two inches of lead. The lead is machined to fit the lathe bed cross beams as shown in figure 2.6.

The activity per unit area 12 inches below the center of the fuel plate is $1.11 \times 10^{-5} \Gamma_T$ per square inch, where $\Gamma_T$ is the total fuel plate activity. More lead would provide better shielding, but mounting the lead would be very difficult. Refer to Appendix E.1 for backscatter shielding calculations.

The sides of the fuel plate are shielded with 6 inches of lead. The lead is mounted on 33 inch high tables placed next to the lathe as shown in figure 2.7. The lead is stacked 8 inches high and 6 inches wide for the entire length of the gamma scanner.
Table 2.4

Leakage Data for Collimator B

<table>
<thead>
<tr>
<th>LEAKAGE TYPE</th>
<th>EDGE LENGTH</th>
<th>LEAKAGE</th>
<th>90% DISTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collimator</td>
<td>0.125 in</td>
<td>8.5%</td>
<td>0.12 in</td>
</tr>
<tr>
<td></td>
<td>0.500 in</td>
<td>2.4%</td>
<td>0.03 in</td>
</tr>
<tr>
<td>Shielding</td>
<td>------</td>
<td>0.025%</td>
<td>------</td>
</tr>
</tbody>
</table>
Fig. 2.6

MACHINED LEAD BRICKS ON LATHE CROSS BEAMS

SCALE $\frac{1}{8}'' = 1''$
Each table will support nearly 1000 pounds of lead.

The activity per unit area penetrating the 6 inch shield at a distance of one foot from the center of the fuel plate is $1.75 \times 10^{-7}$ $\gamma_T$ per square inch. Refer to Appendix E.2 for calculations.

The geometry of the detector-collimator set up provides more than 6 inches shielding between gamma rays compton scattered in the 6 inch backscatter shield and the detector. The gamma rays must scatter more than 90° to reach the detector. For a single scattering of 90° the maximum gamma ray energy is 0.51 Mev. Multiple scattering at smaller angles will result in a higher backscatter gamma ray energy. Refer to Appendix F for illustrative calculations. The probability of penetration of low energy gamma rays through a lead shield 6 inches or more thick is very low. Hence, radiation backscattered from the 6 inch backscatter shield will not produce significant counts.

Radiation passing through the 6 inch backscatter shield and scattering back from a distant object must pass through four more inches of lead to reach the detector. Since scattering at large angles reduces the gamma ray energy to low levels, the probability of passing through the shield is again very low. The leakage through the backscatter shield is $1.75 \times 10^{-7}$ $\gamma_T$ per square inch at 12 inches. Coupled with the probability of the gamma ray scattering at the proper angle from a distant object and penetrating through the four inch shield around the detector, very little backscattered radiation will reach the detector in this way.
by setting the lower level discriminator at 0.30 Mev, backscattered radiation below this energy will not register counts.

The main source of backscattered radiation is the base of the gamma scanner. The leakage through the one inch steel and two inch lead shield is a factor of 64 greater than the leakage through the side backscatter shield. The cement floor under the scanner will serve as a backscatterer. The geometry of the problem is shown in Appendix F.

The minimum number of scatterings required to reach the detector with an energy greater than 0.30 Mev is four. Each of these scatterings must be at an angle $51^\circ \pm 3^\circ$. Multiple scatterings of higher order have larger angle tolerances. However, the probability of multiple scatterings grow smaller.

Combining the four inch lead shield around the detector and the requirement for multiple scatterings, the total probability of count production is very low. Hence, it is assumed that the count rate will not be affected by the backscattered radiation emitted from the bottom of the scanner.

Backscattered radiation reaching the detector through the collimator is the last backscattering problem considered. Radiation from the fuel plate will be scattered by the shielding below it. Some of this radiation will travel through the collimator and into the detector. There is no way to eliminate this leakage. Therefore it must be included in the background. The procedure for determining the background is shown in section 2.7.

2.4 FUEL PLATE MOVEMENT

The lathe controls the position of the fuel plate under the
collimator very precisely. A long steel plate, 0.250 inch thick and 3.0 inch wide, is secured to the lathe table. The plate can travel transversely and longitudinally in the 0.5 inch high, 6.5 inch wide tunnel under the shielding. The longitudinal and transverse motion of the lathe table is measurable to 0.001 inch. By laying the fuel plate on the steel plate, any point on the fuel plate can be placed under the collimator.

The steel plate shown in figure 2.8 is formed by welding four pieces. The long 48 inch x 30 inch piece will hold the uranium fuel plate. The other three pieces secure the long leg to the lathe table. Two bolts protruding from the lathe table can be used to further secure the plate.

The fuel plate is mounted on the last two foot section of the steel plate. To fix the position of the fuel plate, a wire taped to the steel plate borders all sides of the plate.

To fill the 4.5 inch gap in the lathe bed, two steel bars are inserted. One is 48 inches by 4 inches by 1 inch and the other 48 inches by 0.5 inch by 1 inch. The bars and lathe bed provide a smooth surface over which the steel plate rides. Surface sticking should be eliminated by placing graphite lubricant between the steel plate and its riding surface.

To test the reproducibility of the fuel plate position, a Cs-137 source was placed on an aluminum plate fixed to the table. Because of the flexibility of the long aluminum plate sticking of the plate was visually observed. To reduce transverse sticking problems, the fuel plate was pulled and pushed longitudinally. The results of the test are shown in Table 2.5. Even with the
Fig. 2.8

FUEL SUPPORT PLATE

TOP VIEW

WIRE TAPED TO SURFACE

FRONT VIEW

SCALE $\frac{1}{8}'' = 1''$
Table 2.5
Reproducibility of position

<table>
<thead>
<tr>
<th>Longitudinal distance (in)</th>
<th>Transverse distance (in)</th>
<th>Counts (cpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.333</td>
<td>0</td>
<td>1018</td>
</tr>
<tr>
<td>-0.167</td>
<td>0</td>
<td>14914</td>
</tr>
<tr>
<td>+0.000</td>
<td>0</td>
<td>14289</td>
</tr>
<tr>
<td>+0.167</td>
<td>0</td>
<td>565</td>
</tr>
<tr>
<td>+0.333</td>
<td>0</td>
<td>509</td>
</tr>
<tr>
<td>+0.500</td>
<td>0</td>
<td>464</td>
</tr>
<tr>
<td>+0.667</td>
<td>0</td>
<td>471</td>
</tr>
<tr>
<td>+0.500</td>
<td>0</td>
<td>522</td>
</tr>
<tr>
<td>+0.333</td>
<td>0</td>
<td>541</td>
</tr>
<tr>
<td>+0.167</td>
<td>0</td>
<td>606</td>
</tr>
<tr>
<td>+0.000</td>
<td>0</td>
<td>13472</td>
</tr>
<tr>
<td>-0.167</td>
<td>0</td>
<td>14736</td>
</tr>
<tr>
<td>-0.333</td>
<td>0</td>
<td>1094</td>
</tr>
<tr>
<td>+0.000</td>
<td>0</td>
<td>14191</td>
</tr>
<tr>
<td>0</td>
<td>-0.5</td>
<td>560</td>
</tr>
<tr>
<td>0</td>
<td>-0.375</td>
<td>3829</td>
</tr>
<tr>
<td>0</td>
<td>-0.250</td>
<td>12070</td>
</tr>
<tr>
<td>0</td>
<td>-0.125</td>
<td>12765</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
<td>13431</td>
</tr>
<tr>
<td>0</td>
<td>0.125</td>
<td>13602</td>
</tr>
<tr>
<td>0</td>
<td>0.250</td>
<td>870</td>
</tr>
<tr>
<td>0</td>
<td>0.250</td>
<td>719</td>
</tr>
<tr>
<td>0</td>
<td>0.125</td>
<td>13342</td>
</tr>
<tr>
<td>0</td>
<td>0.000</td>
<td>13203</td>
</tr>
<tr>
<td>0</td>
<td>-0.125</td>
<td>12757</td>
</tr>
<tr>
<td>0</td>
<td>-0.250</td>
<td>10972</td>
</tr>
<tr>
<td>0</td>
<td>-0.375</td>
<td>1834</td>
</tr>
</tbody>
</table>
transverse sticking problem the reproducibility of the position is good.

Since the distance measurements on the lathe are relative measurements, a reference point must be established. The corner of the fuel meat farthest from the movement controls of the lathe table has been arbitrarily chosen. This is called the left lower corner in the computer program.

Using the radiograph as a guide, approach the longitudinal edge of the fuel meat. When the count rate increases by 8.5% of the expected count rate, the edge is 0.250 inch from the center of the collimator. The 8.5% value corresponds to the previously calculated collimator leakage.

To locate the transverse edge, approach the edge until the count rate increases by 2.4% of the expected count rate. The transverse edge is 0.0625 inch from the center of the collimator. The intersection of the two edges is the corner of the fuel meat. To simplify this procedure, the fuel plate with the straightest transverse edge should be used.

2.5 DETECTOR ELECTRONICS

The following components make up the simple detection system:

1) 2 inch diameter x 2 inch high NaI(Tl) crystal,
2) Phototube and pre Amp,
3) Amp B set at 1/8 course gain and one fine gain,
4) Single channel Analyzer 413 with 10 volt window setting,
5) Scalar B,
6) High voltage supply set at 1000V.
The lower level setting of the single channel analyzer is
set to discriminate energy pulses corresponding to gamma ray
energies less than 0.30 Mev. This cut off point was selected
because most of the backscattered radiation is below this energy
(3, Davis P.19). Refer to Appendix F for illustrative calculations.

To correct for the energy drift of the detector electronics,
a standard source should be counted at intervals during the
experiment. A collimator insert which can be placed next to the
detector in a reproducible geometry will contain the source.
Figure 2.9 is a sketch of the collimator insert and its position
relative to the detector.

Ba-133 and Cr-51 have decay features suitable for energy
drift detection. The 0.3 Mev point is part way up the major
decay peak. Set the window on the single channel analyzer at
0.20V. If the energy drift is downward, the count rate will
decrease. If the energy drift is upward, the count rate will
increase. Figure 2.10 and 2.11 give the decay spectrum of these
two isotopes. A 100 to 200 μCi source of either sample will be
suitable.

The amount of drift decreases with running time of the system.
By warming up the equipment for a few days, the drift should be
minor and may not require correction. Experiments indicate a
drift of 0.025 Mev below 0.3 Mev will decrease the count rate
by 5%.

2.6 INTEGRATED DESIGN

The integrated design incorporates the previous features:
Fig. 2.9

COLLIMATOR INSERT

NaI

Pb

COLLIMATOR INSERT

Pb

END VIEW

COLLIMATOR INSERT

FRONT VIEW

SCALE $\frac{1}{8}" = 1"
Fig. 2.11
Cr-51 ENERGY SPECTRUM

Kev
1) collimator,
2) shielding,
3) fuel plate movement,
4) collimator insert for energy drift correction,
5) back scattering shield.

Collimator B of section 2.2 is the center of the scanner. A minimum of ten inches of lead shielding bricks are stacked above the hot side of the fuel plate, six inches above the cool side. The shield length is 48 inches and the width is 8 inches. Figure 2.12 is a sketch of the collimator section of the gamma scanner. Figure 2.13 is a side view of the collimator.

The fuel plate moves in a tunnel under the shielding. It rests on a steel plate fixed to the movable lathe table. By moving the lathe table longitudinally or transversely any point on the on the 23 inch by 2.6 inch fuel plate can be placed under the collimator hole.

Energy drift from the 0.30 Mev cut off will be detected by a standard source in the collimator insert. Figure 2.14 is a sketch of the gamma scanner without the backscatter shield.

The backscatter shield effectively encloses the fuel plate in a lead box. Most of the gamma rays which leak out and backscatter to the detector will have energy less than 0.30 Mev. The overall count rate should be changed very little by backscattered radiation.

2.7 EXPERIMENTAL PROCEDURE

Producing enough activity in the fuel plate for counting purposes require a total core power of 100 watts for an 0.5
Fig. 2.12

COLLIMATOR SECTION OF GAMMA SCANNER

SCALE $\frac{1}{2}''=1''$
Fig. 2.13
SIDE VIEW OF COLLIMATOR

COLLIMATOR

NaI

COLLIMATOR INSERT

SCALE $\frac{1}{4}"=1"$
hour operation period. The count rates at several decay times is shown in Table 2.3.

A neutron detector may be used to determine the core power level. Placing the detector in a position where the flux has been accurately predicted will increase the reliability of the measurement.

Relating the power levels of succeeding irradiations is necessary for the computer code calculations. Shifting the fuel distribution causes shim rod movement. The flux change due to the new geometry may affect the reading of the neutron detector. The reading will not be an accurate measure of the core power level.

A gamma ray detector may be used to relate the power levels of succeeding irradiations. Shifts in the flux distribution will not affect the reading. A beamport would be a suitable location for the detector.

As a check of the measured power levels, a foil will be irradiated each period at the same location. This location should have a flux distribution fairly independent of fuel reshuffling and control blade movements. After each irradiation, the foil will be counted in the collimator insert.

The fuel element will have a dose rate of approximately 5.8 K per hour at 12 inches. Refer to Appendix G.1 for calculations. The dose rate from the unshielded fuel plate is 380 mK per hour at one foot.

The fuel plate will be moved to the gamma scanner in a shielded container. All handling of the fuel plate should be done at the top or cool end of the fuel plate. The fuel plate
will be placed in the gamma scanner, hot end first. The dose to the operator from the leakage through the bottom of the gamma scanner is less than 10 mr/hr. Refer to Appendix G.2 for calculations.

Before scanning any points, the increase in background due to backscattering must be determined. Using the radiograph as a guide, move the transverse edge of the fuel meat to about 0.5 inch from the collimator. The increase in background count is due to scattering of gamma rays up through the collimator. The amount of backscattering will change with time and position. The background may be approximated in the following way. For each transverse scan, the background activity on each side of the fuel plate should be measured. Two suitable Y-coordinates are -0.5 inch and +2.9 inches. This gives a measure of the longitudinal change in background. The transverse change in background may be approximated by scanning just beyond the hot edge of the plate. A suitable X-coordinate is -0.250 inch. Subtract the value of the natural background from the above longitudinal and transverse measurements. These values represent the background due to backscattering. Normalize the transverse backscattering background to the point (-0.25, -0.5). The background at each point, (X,Y), can be estimated as twice the product of the normalized factor at Y and the backscattering background at X plus the natural background. Table 2.6 lists suggested points for scanning.

Some of the points place fuel meat under only 25% or 50% of the collimator. The counts due to the direct collimated
Table 2.6
Suggested Scanning Points

<table>
<thead>
<tr>
<th>No.(J)</th>
<th>X(in)</th>
<th>Y(in)</th>
<th>No.(J)</th>
<th>X(in)</th>
<th>Y(in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bkg</td>
<td>No Plate</td>
<td></td>
<td>Bkg</td>
<td>0.8</td>
<td>-0.5</td>
</tr>
<tr>
<td>1-Foil</td>
<td>10</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Bkg</td>
<td>0</td>
<td>0.25</td>
<td>3</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.60</td>
<td>4</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>1.0</td>
<td>5</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.4</td>
<td>6</td>
<td>0.8</td>
<td>1.4</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>1.8</td>
<td>7</td>
<td>0.8</td>
<td>1.8</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>2.15</td>
<td>8</td>
<td>0.8</td>
<td>2.15</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>2.4</td>
<td>9</td>
<td>0.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Bkg</td>
<td>0</td>
<td>2.9</td>
<td>Bkg</td>
<td>0.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.0625</td>
<td>2.9</td>
<td>10</td>
<td>1.4</td>
<td>2.9</td>
</tr>
<tr>
<td>11</td>
<td>0.0625</td>
<td>2.4</td>
<td>11</td>
<td>1.4</td>
<td>2.4</td>
</tr>
<tr>
<td>12</td>
<td>0.0625</td>
<td>2.15</td>
<td>12</td>
<td>1.4</td>
<td>2.15</td>
</tr>
<tr>
<td>13</td>
<td>0.0625</td>
<td>1.8</td>
<td>13</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>14</td>
<td>0.0625</td>
<td>1.4</td>
<td>14</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>15</td>
<td>0.0625</td>
<td>1.0</td>
<td>15</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>16</td>
<td>0.0625</td>
<td>0.60</td>
<td>16</td>
<td>1.4</td>
<td>0.6</td>
</tr>
<tr>
<td>17</td>
<td>0.0625</td>
<td>0.25</td>
<td>17</td>
<td>1.4</td>
<td>0.25</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.0625</td>
<td>0.0</td>
<td>Bkg</td>
<td>1.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.125</td>
<td>-0.5</td>
<td>18</td>
<td>2</td>
<td>-0.5</td>
</tr>
<tr>
<td>19</td>
<td>0.125</td>
<td>0.0</td>
<td>19</td>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>20</td>
<td>0.125</td>
<td>0.25</td>
<td>20</td>
<td>2</td>
<td>0.25</td>
</tr>
<tr>
<td>21</td>
<td>0.125</td>
<td>0.60</td>
<td>21</td>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>22</td>
<td>0.125</td>
<td>1.0</td>
<td>22</td>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>23</td>
<td>0.125</td>
<td>1.4</td>
<td>23</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td>24</td>
<td>0.125</td>
<td>1.8</td>
<td>24</td>
<td>2</td>
<td>1.8</td>
</tr>
<tr>
<td>25</td>
<td>0.125</td>
<td>2.15</td>
<td>25</td>
<td>2</td>
<td>2.15</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.125</td>
<td>2.4</td>
<td>Bkg</td>
<td>2</td>
<td>2.4</td>
</tr>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.4</td>
<td>2.9</td>
<td>Bkg</td>
<td>3</td>
<td>2.9</td>
</tr>
<tr>
<td>26</td>
<td>0.4</td>
<td>2.4</td>
<td>26</td>
<td>3</td>
<td>2.4</td>
</tr>
<tr>
<td>27</td>
<td>0.4</td>
<td>2.15</td>
<td>27</td>
<td>3</td>
<td>2.15</td>
</tr>
<tr>
<td>28</td>
<td>0.4</td>
<td>1.8</td>
<td>28</td>
<td>3</td>
<td>1.8</td>
</tr>
<tr>
<td>29</td>
<td>0.4</td>
<td>1.4</td>
<td>29</td>
<td>3</td>
<td>1.4</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>1.0</td>
<td>30</td>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>31</td>
<td>0.4</td>
<td>0.6</td>
<td>31</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>32</td>
<td>0.4</td>
<td>0.25</td>
<td>32</td>
<td>3</td>
<td>0.25</td>
</tr>
<tr>
<td>33</td>
<td>0.4</td>
<td>0.0</td>
<td>33</td>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>Bkg</td>
<td>0.4</td>
<td>-0.5</td>
<td>Bkg</td>
<td>3</td>
<td>-0.5</td>
</tr>
<tr>
<td>No. (J)</td>
<td>X (in)</td>
<td>Y (in)</td>
<td>No. (J)</td>
<td>X (in)</td>
<td>Y (in)</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Bkg</td>
<td>5</td>
<td>-0.5</td>
<td>Bkg</td>
<td>-0.25</td>
<td>-0.5</td>
</tr>
<tr>
<td>66</td>
<td>5</td>
<td>0.0</td>
<td>Skg</td>
<td>-0.25</td>
<td>0.0</td>
</tr>
<tr>
<td>67</td>
<td>5</td>
<td>0.25</td>
<td>Bkg</td>
<td>-0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>68</td>
<td>5</td>
<td>0.6</td>
<td>Bkg</td>
<td>-0.25</td>
<td>1.0</td>
</tr>
<tr>
<td>69</td>
<td>5</td>
<td>1.0</td>
<td>Bkg</td>
<td>-0.25</td>
<td>1.4</td>
</tr>
<tr>
<td>70</td>
<td>5</td>
<td>1.4</td>
<td>Skg</td>
<td>-0.25</td>
<td>1.8</td>
</tr>
<tr>
<td>71</td>
<td>5</td>
<td>1.8</td>
<td>Bkg</td>
<td>-0.25</td>
<td>2.15</td>
</tr>
<tr>
<td>72</td>
<td>5</td>
<td>2.15</td>
<td>Bkg</td>
<td>-0.25</td>
<td>2.15</td>
</tr>
<tr>
<td>73</td>
<td>5</td>
<td>2.9</td>
<td>Bkg</td>
<td>-0.25</td>
<td>2.9</td>
</tr>
<tr>
<td>Sta</td>
<td>--</td>
<td>--</td>
<td>Bkg</td>
<td>10</td>
<td>2.9</td>
</tr>
<tr>
<td>74</td>
<td>10</td>
<td>2.4</td>
<td>75</td>
<td>10</td>
<td>2.15</td>
</tr>
<tr>
<td>76</td>
<td>10</td>
<td>1.80</td>
<td>77</td>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td>78</td>
<td>10</td>
<td>1.0</td>
<td>79</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>0.25</td>
<td>81</td>
<td>10</td>
<td>0.0</td>
</tr>
<tr>
<td>Bkg</td>
<td>10</td>
<td>-0.5</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>82</td>
<td>15</td>
<td>-0.5</td>
<td>Bkg</td>
<td>15</td>
<td>0.0</td>
</tr>
<tr>
<td>83</td>
<td>15</td>
<td>0.0</td>
<td>84</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>85</td>
<td>15</td>
<td>0.6</td>
<td>86</td>
<td>15</td>
<td>1.0</td>
</tr>
<tr>
<td>87</td>
<td>15</td>
<td>1.4</td>
<td>88</td>
<td>15</td>
<td>1.8</td>
</tr>
<tr>
<td>89</td>
<td>15</td>
<td>2.15</td>
<td>89</td>
<td>15</td>
<td>2.4</td>
</tr>
<tr>
<td>Bkg</td>
<td>15</td>
<td>2.9</td>
<td>Sta</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>90</td>
<td>20</td>
<td>2.9</td>
<td>Bkg</td>
<td>20</td>
<td>2.4</td>
</tr>
<tr>
<td>91</td>
<td>20</td>
<td>2.15</td>
<td>92</td>
<td>20</td>
<td>1.8</td>
</tr>
<tr>
<td>93</td>
<td>20</td>
<td>1.4</td>
<td>94</td>
<td>20</td>
<td>1.0</td>
</tr>
<tr>
<td>95</td>
<td>20</td>
<td>0.6</td>
<td>96</td>
<td>20</td>
<td>0.25</td>
</tr>
<tr>
<td>97</td>
<td>20</td>
<td>0.0</td>
<td>Bkg</td>
<td>20</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
gamma rays should be increased by a factor of four and two, respectively. Direct collimated gamma rays excludes backscattered radiation and natural background.

Accurate measurements of the peaking factors also depends on the counting statistics. At the hot end of the fuel plate, the total counts should be greater than 5000. There is 95% certainty that the count is within ± 2.7% of the true count rate. Refer to Appendix H for calculations.

At the cool end of the plate, the count rate will be much lower. A total count of 2000 will provide 95% certainty that the count is ± 4.4% of the true count rate. The decreased accuracy is permissible, because the average power of the lower fuel plate is all that is required.
Chapter 3

COMPUTER CODE GAMSCAN

3.1 GENERAL DESCRIPTION

The analysis of the experimental data is complicated. The fission product decay rate depends upon the duration and power level of the irradiation period and upon the history of previous irradiations. Correcting the data for decay by hand calculations would be a tedious project. Therefore, a short program was written to perform the calculations.

The first half of the program corrects for background, decay and the activity of the previous irradiations.

The last half corrects for averaging effects across both the width and length of the collimator slot. The correction is based on the assumption that the second derivative of the power density distribution between three points is a constant.

3.2 DECAY CORRECTIONS

To find the decay curve of fission product gamma rays, three irradiations were performed. The irradiation periods were 10 minutes, 30 minutes, and 60 minutes. Counting measurements were made after a 2 hour decay period.

The decay curves of the three irradiation periods are simply related. The 60 minute irradiation period can be treated like six irradiations of 10 minutes each. For example, the count rate at 2 hours of decay of a 60 minute irradiation is the sum of the 10 minute irradiation count rates at the following six decay times:
1) 2.833 hours  
2) 2.667 hours  
3) 2.500 hours  
4) 2.333 hours  
5) 2.167 hours  
6) 2.000 hours  

Likewise the count rate for a thirty minute irradiation is the sum of the 10 minute irradiation count rates of three decay times, 10 minutes apart. Or, another example is a two hour decay following a 30 minute irradiation period which gives a count rate equal to the sum of the 10 minute irradiation count rates at decay times 2.000 hours, 2.167 hours, and 2.333 hours.

During the start up test, the power level of the core will not be constant. The irradiation period may be divided into 10 minute periods. The power level for each 10 minute period will be the average over the period. This approximation is better than a simple average over the entire irradiation period. Dividing the period into 10 minute intervals also allows the operator to change the power level of the core at 10 minute intervals.

The information required for the power level measurement of each irradiation (K) is the following:

1) the number of irradiation, NO,  
2) an arbitrary reference power level, eg. 100, A,  
3) the number of 10 minute intervals the fuel plate i: _rradiated, LI (K),  
4) the power level of each 10 minute interval for 10 intervals, P(K,I).
Calculations of the decay require the following experimental data:

1) the number of points scanned in the irradiation, \( WP(K) \),
2) the average background, \( B(K) \),
3) the time between the irradiations, \( DT(K) \),
4) the longitudinal and transverse position of the \( J \)th point located directly under the center of the collimator, \( X(K,J) \) and \( Y(K,J) \), respectively,
5) the time between the start of the \( K \)th irradiation and the middle of the counting period of the \( J \)th point, \( TI(K,J) \),
6) the counts of the \( J \)th point, \( C(K,J) \), and
7) the width of the slot which is 0.500 for this collimator, \( WIDTH(K,J) \).

The significance of each piece of data is further explained here. The maximum number of irradiations is set at 5. If more irradiation are performed the DIMENSION and EQUIVALENCE statements must be changed.

The reference power level, \( A \), is any convenient non-zero measure of the power. For example, if the power measuring system registers 2.6 at a core power of 100 watts, the value of \( A \) could be set at 2.6.

The desired irradiation period is 30 minutes, however circumstances may increase or decrease the irradiation period. For example, a scram may occur five minutes after the beginning of the irradiation. In thirty minutes the reactor may be brought up to power with the irradiation continuing for thirty
minutes more. The average power of each period can be fed in, \( P(K,I) \). The code requires that a value for the power be fed in for all ten intervals (0.0 is a good value). To increase the accuracy of averaging the power over 10 minute intervals, the power level should be kept constant over the interval. The rise up to power and fall from power should be as rapid as possible, approaching a rectangular power shape over the entire radiation period.

The number of irradiation intervals, \( LI(K) \), is simply a counting scheme used by the code to eliminate extra steps.

The code requires the same points to be scanned after each irradiation. The order of points must be preserved. Calculating the activity due to previous irradiations at any point, \((X(K,J),Y(K,J))\), requires values for the counts at that point from all previous irradiations. The counting subscript \( J \) is used for associating points from different irradiations. Each value \( J \) corresponds to a particular \( X \) coordinate and \( Y \) coordinate. Thus, the order of scanning points must be kept the same for each irradiation experiment. The number of points, \( MP(K) \), is limited to 100 by the DIMENSION and EQUIVALENCE statements.

The average background, \( B(K) \), may not be useful. Since the background changes with time and position, the counts will have to be corrected for background before being put into the computer. Section 2.7 describes a method for correcting the background.
The time between the starts of irradiation periods, DT(K), is given in decimal minutes as are all time measurements. Since the first irradiation has no preceding irradiation, DT(1) must be given the value 0.0. DT(2) is the time between irradiations one and two. DT(3) is the time between irradiations two and three, and so on.

Measurements of position on the lathe are relative. A reference point must be established. Let the corner of the fuel meat farthest from the controls of the lathe be assigned an X and Y value of 0.0. Section 2.4 describes the procedure for locating the corner of the fuel. The longitudinal edge is designated the +X axis. The +Y axis is directed in the transverse direction across the fuel plate, originating at point (0,0,0).

The correction for area averaging effects requires the points, (X,Y), to lie in straight lines. Therefore, it is advisable to scan transversely at the same set of coordinates changing the X coordinate after each transverse scan. Table 2.6 suggests a possible scanning sequence.

The time, TI(K,J), between the start of the Kth irradiation and the middle of the counting period of the Jth point is given in decimal minutes. TI(K,J), is the sum of the decay time and the time duration of the irradiation period.

The count, C(K,J), is the experimental count of the Jth point adjusted for background.
The width of the slot, WIDTH \((K, J)\) was written into the code to adjust for variable collimator size. For collimator \(B\), the width is 0.500 inch.

Figure 3.1 shows the decay curve of a 10 minute irradiation. The activity at a decay time of two hours is assigned the value 1.0. The activity at other decay times is normalized to the two hour decay. The fraction of the activity at time \(t\) relative to a two hour decay can be read off the figure. By using linear point interpolation between selected points on the graph, the fraction of the activity present at a time \(t\) is calculated.

Normalizing a count taken at time \(t\) back to the reference time is accomplished by dividing the count by the fraction of activity at time \(t\).

Since the irradiation period is divided into \(N\) 10 minute intervals, the decay correcting factor is a sum of \(N\) fractions of decay weighted by the \(N\) power measurements, or

\[
C = (\text{Count} - \text{Background}) \sum_{i=1}^{N} \frac{P_i}{A f_i}, \quad (3.1)
\]

where

\(C\) is the count corrected for decay,
\(P_i\) is the power level of the \(i\)th 10 minute period,
\(A\) is the reference power level,
\(f_i\) is the fraction of activity present at time \(t_i\),
\(t_i\) is the decay time from the \(i\)th irradiation interval to the middle of the counting period,
Figure 3.1

Ten Minute Irradiation Decay Curve

Relative Activity

Time (hrs)
\( n \) is the number of 10 minute irradiation intervals.

The activity of previous irradiations must be subtracted from the count data before the decay corrections can be made. The decay time of previous irradiations is the sum of the time between irradiations and the decay time from the last irradiation. A value of the fraction of remaining activity corresponds to the decay time of each of the previous irradiations. The activity due to previous activities can be calculated as follows

\[
S_n = \sum_{n=1}^{n-1} (\text{Counts}_n - \text{background}_n) \sum_{i=1}^{n} \frac{P_{n,i}}{A} f_{n-k,i},
\]

(3.2)

where

- \( S_n \) is the activity due to all irradiations previous to irradiation \( n \),
- \( \text{Counts}_k \) is the counts of the Kth irradiation,
- \( \text{background}_k \) is the background for the Kth irradiation,
- \( P_{K,i} \) is the power level of the ith interval of the Kth irradiation,
- \( A \) is the reference power level,
- \( f_{K-k,i} \) is the fraction of the activity present at time \( t_{K-k,i} \),
- \( t_{K-k,i} \) is the sum of the decay time of the Kth irradiation and the difference in time between the starts of the Kth irradiation and the Kth irradiation,
\( n \) is the number of the last irradiation,

\( n_k \) is the number of 10 minute irradiation intervals in the \( k \)th irradiation.

The corrected count is found by subtracting all activity due to previous irradiations and adjusting for the decay, or

\[
\text{CC}_n = (\text{Count}_n - \text{background}_n - \beta_n) \sum_{i=1}^{n_k} \frac{r_{n,i}}{\alpha n_i, i},
\]

(3.3)

where

\( \text{CC}_n \) is the corrected count of irradiation \( n \).

By this calculation scheme each point is assigned a new count corrected for background, activity of previous irradiations, and decay.

3.3 Area Averaging Corrections

The corrected count at each set of coordinates does not represent the true relative power distribution. To obtain sufficient count data, a one-sixteenth square inch area is scanned. The count is an area integral of the activity. The point by point change in activity is indistinguishable. This integration effect is called area averaging effects.

The power distribution in the fuel plate can be represented
by an nth order polynomial in \( x \) and \( y \). The polynomial can be approximated by quadratic functions. The cubic and higher order terms are neglected. Hence, the error of the approximation is of order \( \lambda^3 \). As the distance \( \lambda \) goes smaller and smaller the error will decrease.

Three integrals of the quadratic equation are required to determine the equation. The procedure for calculating the constants in the longitudinal direction is the following:

\[
\mathcal{C}_1 = \int_{a - 1/16}^{a + 1/16} (Ax^2 + bx + D) \, dx ,
\]  
\[
\mathcal{C}_2 = \int_{b - 1/16}^{b + 1/16} (x^2 + cx + D) \, dx ,
\]  
\[
\mathcal{C}_3 = \int_{d - 1/16}^{d + 1/16} (Ax^2 + dx + D) \, dx ,
\]  

where

\( \mathcal{C}_1, \mathcal{C}_2, \) and \( \mathcal{C}_3 \) are the corrected counts at position \( a, b, \) and \( d \), respectively.

The integration limits are determined by the slot width of 1/8 inch.

The value of the constants are determined by integrating the above equations. The values of \( A, B, \) and \( D \) are given as:
A = \left[ \frac{4C_2}{a} - \frac{(a-d) C_2 - (b-a) C_3}{a-b-d} \right] \frac{1}{b-d}, \quad (3.7)

B = \frac{8}{b-d} \left[ C_2 - C_3 - \frac{A}{16} (b^2 - d^2) \right], \quad (3.8)

D = 8 \left[ C_3 - \frac{b d}{8} - A \left( \frac{d^2}{16} + 0.00008 \right) \right]. \quad (3.9)

In the transverse, $Y$, direction the integration limits are changed. The width of the slot is $0.5$ inches. The new constants are given as:

$$E = \frac{1}{4} A, \quad (3.10)$$

$$F = \frac{2}{b-d} \left[ C_2 - C_3 - \frac{E}{4} (b^2 - d^2) \right], \quad (3.11)$$

$$G = 2 \left[ C_3 - \frac{Fd}{2} - \frac{E}{4} (d^2 + 0.02083) \right], \quad (3.12)$$

where the quadratic equation is given by,

$$f(x) = \frac{Ex^2}{2} + Fx + G.$$  

The highest accuracy is maintained by calculating a quadratic equation for every three point sequence. Consider the first three point sequence in the transverse direction. A quadratic equation is determined from the corrected counts corresponding to the three points. The equation is evaluated at the three points in the following way:
\[ L = E \cdot a^{2/2} + Fa + G, \quad (3.14) \]
\[ M = E \cdot b^{2/2} + Fb + G, \quad (3.15) \]
\[ N = E \cdot d^{2/2} + Fd + G, \quad (3.16) \]

where

\[ L, M, \text{ and } N \text{ are the values of the function at } a, \]
\[ b, \text{ and } d \text{ respectively (Y direction)}. \]

If a maximum or minimum exists on the segment formed by the points, its value is recorded. The maximum or minimum is found by setting the derivative of the quadratic equation equal to zero and solving for the position of the maximum, that is,

\[ Z = - \frac{F}{E}, \quad (E.17) \]

where

\[ Z \text{ is the transverse position of the maximum or minimum}. \]

The value of the maximum or minimum, \( Q \), is given by:

\[ Q = + \frac{p^2}{2E} + G. \quad (E.18) \]

The program proceeds to the next three point sequence formed by the second and third points of the first sequence and the next point in line. Again, the quadratic equation is calculated. However, only the last two points are evaluated.
The first point was previously evaluated by an equation determined from data on both sides of the point. The accuracy of the quadratic equation is lower, if the data lies on one side of the point.

The program proceeds through every three point sequence in the Y direction. It calculates new values for each of the J points and any maxima or minima lying within each three point sequence.

New values are determined for the J points in the X direction by the same technique. Any maxima or minima lying within each three point sequence are located and evaluated.

Let the relative power distribution calculated from the application of quadratic equation in the longitudinal direction be designated \( P_X \), that in the transverse direction, \( P_Y \). The ratio between \( P_X \) and the relative power distribution determined by the corrected counts is the relative change at every point. Call the relative change \( R \). The product of the relative change \( R \) and \( P_Y \) represents double corrected values for each point J.

The computer output lists the corrected counts calculated in Part 1, and the Y corrected, X corrected and doubly corrected values, calculated in Part 2. The corrected counts of Part 1 are normalized to the lowest value. The outputs of part two are not normalized and cannot be directly compared. Results from each irradiation are normalized to the first irradiation. The corresponding outputs can be directly compared.

3.4 SOURCES OF ERROR

The main sources of error in this experiment are the following:
1) Area averaging effects which disguise the true power density distribution at the hot edge of the fuel,

2) Errors made by estimating the background due to backscattering, and

3) Statistical counting errors determined by the number of counts at each point.

The largest potential source of error is a result of the area averaging effect. The hot edge of the fuel plate is expected to have a spiked shape power distribution. The determination of the peak of the spike is a difficult procedure. Since the count is the average power distribution over the area, the peak is not evaluated.

The following scheme will estimate the value of the peak. It is assumed that the edges of the fuel meat are parallel to the edges of the collimator. Figure 3.2 illustrates a spike shaped power distribution. If the slope of the spike can be determined, the peak can be evaluated. Consider counting measurements made at the edge of the fuel meat. When the edge of the collimator extends beyond the edge of the fuel meat, the count must be increased to compensate for the smaller fuel area under the collimator. The count rate should be increased by a factor equal to the ratio of the collimator area to the fuel meat area under the collimator. This count data should be fed into the computer. The computer CORCOU output will list the data corrected for decay, background and the activity of previous irradiations. Another correction must be made on the adjusted output, that is the output corresponding to the data
Fig. 3.2

POWER SPIKE

RELATIVE POWER

X(in)
taken without the fuel meat under the entire collimator. Call
the position of the unadjusted output nearest the hot edge
position A, and the position of the nearest adjusted output
position B. To correct the output of B, use the following
procedure. Subtract the output of position A from the output
of position B. Multiply the remainder by the ratio of the
collimator area to the fuel meat area under the collimator, at B.
Add to this the output of A. This corrects the output at B.
Now, find the slope between A and B and compare it to the slope
between A and the previous unadjusted point. If the slopes are
the same, the peak can simply be evaluated by the equation,

\[ P = mx + b, \]

where

\[ P \]  is the peak relative value of the power density,
\[ m \]  is the slope,
\[ x \]  is the distance from the peak to B,
\[ b \]  is the relative power density at B.

If the slopes are not the same, assume the same rate of change
in slope from B to 0.0. The peak can be estimated as,

\[ P = \left( \frac{M_B - M_A}{B - A} \right) \frac{x^2}{2} + M_B x + b, \]

where

\[ M_B \]  is the slope from B to A,
$\hat{N}_A$ is the slope from A to the previous point.

The accuracy of these methods is inversely proportional to the slope from b to a. The larger the slope, the greater the chance of error.

To check the approximation another point C, closer to the fuel meat edge may be scanned. Following the same procedure, the peak power density can be estimated. If the estimates agree, then the results should be correct. The difference the estimates is an indication of the accuracy of the method.

The power distribution along the remainder of the plate should be well represented by the corrected count results, COXCOU. The correction for area averaging effects is not necessarily a better representation of the power distribution. Since the spacing in the longitudinal direction is rather large, the assumption that the power distribution can be represented by a quadratic equation is not very good. However, the spacing in the Y-direction is much smaller. The width of the slot is 0.5 inches in the Y-direction. If the spacing is less than the slot width, the area correction in the Y-direction is a better representation of the power distribution than the COXCOU results. The location and values of the maxima and minima are useful for locating peaking points.

The background due to backscattering can not be measured at each point. Therefore, a background estimation scheme was derived in section 2.7. The scheme assumes that the transverse change in backscatter background at any longitudinal location is proportional to the transverse change measured at an X value
of -0.25 inch. The scheme has good merit if the relative transverse power distribution in the fuel plate is independent of longitudinal position. The natural background component of the background has an accurately measured count rate and will not give any significant error. The backscattered component of the background should be propertional to the average activity of the plate in the vicinity of the collimator. Gamma rays emitted near the collimator will have the greatest chance of scattering up it. When the count rate is high, the backscatter component of the background should be proportionately high. At the cool end of the plate the backscatter component of the background should be proportionately low. Estimating the backscatter background by the scheme developed in section 2.7 should reduce the backscatter error to less than 2%.

The statistical errors can be controlled by the operator. At the cool end of the fuel plate fuel plate long counting periods may be required for good statistics. For a total count of 5000 there is 95% certainty that the error is less than \( \pm 2.15\% \). At the cooler end of the fuel plate a total count of 2000 may be acceptable. There is 95% certainty that the error is less than 4.38\%. 
Chapter 4

SUMMARY

4.1 GAMMA SCANNER

The gamma scanner is designed to count fission product gamma rays emitted from a specified volume of the fuel plate. It consists of lead shielding, a collimator slot cut through the shielding, a gamma ray detection system, and a lathe used to move the fuel plate under the collimator.

The collimator is twelve inches high with a nonuniform cross sectional area. Leakage around the edges of the collimator effectively increases the viewing area of the collimator by 20%. Table 4.1 lists the essential parameters of the collimator.

The lead shielding is twelve inches thick. The leakage of fuel plate radiation through the shield is less than 0.25%. Therefore, leakage of gamma rays through the shield will not distort the count rate.

To prevent high background due to backscattering, the fuel plate is effectively encased in a lead box. Two inches of lead plus an inch of steel shield the base of the fuel plate. The leakage through this shield must be scattered a minimum of four times to reach the detector with an energy greater than 0.30 MeV. The lower level of the discriminator is set at 0.30 MeV. Thus, all gamma rays with energy less than 0.30 MeV are not counted. Six inches of lead lie on the sides of the fuel plate. The backscattering radiation reaching the detector after passing through this shield is also very low. To cut down on natural background and backscatter background four inches of lead surrounds the detector. These shields should essentially eliminate all exterior effects of backscattered radiation.
### Table 4.1
Collimator Parameters

<table>
<thead>
<tr>
<th>Portion of Height</th>
<th>Width of Slot (in)</th>
<th>Depth of Slot (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0&quot;-6&quot;</td>
<td>0.5</td>
<td>0.125</td>
</tr>
<tr>
<td>6&quot;-8&quot;</td>
<td>0.833</td>
<td>0.205</td>
</tr>
<tr>
<td>8&quot;-10&quot;</td>
<td>1.167</td>
<td>0.291</td>
</tr>
<tr>
<td>10&quot;-12&quot;</td>
<td>1.5</td>
<td>0.375</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Edge Length (in)</th>
<th>Leakage %</th>
<th>90% Distance (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>8.5</td>
<td>0.120</td>
</tr>
<tr>
<td>0.5</td>
<td>2.4</td>
<td>0.030</td>
</tr>
</tbody>
</table>
The natural background level should be cut down to about 300 counts per minute.

The main effect of the backscattered radiation is the distortion of the count rate by radiation scattered up through the collimator. To calculate the amount of radiation scattered up through the collimator a scheme of longitudinal and transverse background measurements has been devised. The backscatter background at each point is estimated as twice the product of the longitudinal backscatter background and a normalized transverse backscatter background. The error in the count due to backscattering should be reduced to less than 2% after subtraction of the estimated background.

The simple electronics and detection system consists of a NaI(Tl) crystal coupled to a single channel analyzer. To correct energy drift of the lower level discriminator a standard source will be positioned in the collimator insert. The collimator insert is a simple block of steel which can be placed next to the detector in a reproducible geometry.

Movement of the fuel plate under the collimator is controlled by the movement of the lathe table. The uranium fuel plate is mounted on the end of the steel plate. The lathe table movements in the transverse and longitudinal directions will position the fuel plate under the collimator.

Figure 4.1 is a sketch of the gamma scanner without the backscatter shield. The base backscatter shield is shown in figure 4.2. The side backscatter shield is shown in figure 4.3.
Fig. 4.1

COLLIMATOR SECTION OF GAMMA SCANNER

COLLIMATOR

SCALE $\frac{1}{2}''=1''$
Fig. 4.2

MACHINED LEAD BRICKS ON LATHE CROSSBEAMS

SCALE $\frac{1}{6}'' = 1''$
4.2 THE EXPERIMENT

To produce the proper level of activity in the fuel plate, the core should be operated for 30 minutes at a total core power of 100 watts. After a two hour decay the plate should be placed in the scanner. The unshielded dose rate from the fuel plate is 388 mR per hour at 12 inches. Once inside the scanner, the dose is cut to less than 10 mR per hour at 12 inches.

The corner of the fuel meat farthest from the controls is the reference point (o.o). This point is located by finding the transverse and longitudinal edges. The edge is located just before a sudden sharp increase in the count rate. The increase in count rate at the edge is a small fraction of the count rate of the fuel meat. The fraction is determined by the collimator leakage.

Once the origin (o.o) is established, the scanning can begin. Transverse scans at selected longitudinal locations will give data leading to a relative power density distribution. Background measurements should be included with each transverse scan. The radiation scattered up the collimator should be subtracted from the count rate, to remove backscattering distortions.

Since the peak power is expected to be at the base of the fuel plate, many transverse scans should be made at the hot end of the fuel plate. The highest activity occurs at the beginning of the scanning period. Good counting statistics are easily obtained with high activity. Therefore, the hot end of the fuel plate should be scanned first.
4.3 DATA

Table 4.2 lists the data required from the scan experiment. Appendix 1 contains a printout of the computer code GAMSCAN and sample data.

Before the data can be entered into the computer program the following conditions must be met.

1) Only 5 irradiations and 100 scanning points are allowed by the DIMENSION AND EQUIVALENCE STATEMENTS.

2) The same points must be scanned in each irradiation.

3) The points scanned must be placed in the same order for each irradiation.

4) The reference power level must be a non-zero number in the same units as the measured power level.

5) Measured core power levels must be given for 10 intervals.

6) All distance measurements shall be in inches.

7) All time data shall be in minutes.

8) The counts must be corrected for backscatter.

9) All count data shall be in counts per minute.

10) The first point is assigned the position (10.10) and corresponds to the foil activity.

11) To utilize the area averaging correction of the code all points must lie in a rectangular grid.

4.4 COMPUTER CODE

Corrections for background, decay and activity of previous irradiations are made in the code. The corrected counts are called CORCOU (K,J). Decay corrections utilize an experimental decay curve.
The code also corrects for area averaging in the longitudinal and transverse directions. The correction is based on the assumption that the relative power density can be represented by a quadratic equation over three points.

Calculations of the power spike at the hot end of the fuel plate will have to be done by hand. By manipulating the count data at the hot end, the slope of the spike can be approximated, and the value of the spike can then be established. The power distribution of the remainder of the fuel plate is well represented by the Y-corrected data or the COMPO (K,J) values.
Appendix A

COLLIMATOR LEAKAGE CALCULATIONS

The geometries of collimators A, B and C are shown in figure A.1.

The leakage, $Q$, reaching the detector is a function of both $x$ and $0$, or

$$Q = \int \int e^{-ux/cos\theta} \, d\theta \, dx. \tag{A.1}$$

Substituting the limits for collimator A, $0$ is given by:

$$Q_A = \int \int_{x=0}^{L} e^{-ux/cos\theta} \, d\theta \, dx. \tag{A.2}$$

The value $x$ is proportional to $r$, or

$$x=r \cos \theta = \sqrt{x^2 + y^2} \cos \theta. \tag{A.3}$$

Thus, the leakage, $Q_A$ is given by:

$$Q_A = \int \int_{x=0}^{L} e^{-u \sqrt{x^2 + y^2}} \, dy \, dx, \tag{A.4}$$
Fig. A.1

GEOMETRIES OF COLLIMATORS A, B, & C

COLLIMATORS B & C

COLLIMATOR A
\[ Q_A = \int_{x=0}^{L} u \left( e^{-u \sqrt{x^2 + (12)^2}} - e^{-u x \sqrt{1 + \frac{12}{L+x}}} \right) \, dx, \quad (A.5) \]

or \[ Q_A = \int_{x=0}^{L} -u f(x) \, dx. \quad (A.6) \]

The integration is most easily done by graphing.

Figure A.2 is a plot of \( f(x) \) for an \( L \) of 0.500 inch. The area under the curve is 0.0220, or

\[ Q_A = \int_0^{0.0220} u f(x) \, dx, \quad (A.7) \]

\[ Q_A = 2.009 \times 0.0220 = 0.044. \quad (A.8) \]

Thus, the leakage from the 0.125 inch edge of collimator A is 4.4%. Also, 90% of the area under the curve lies between 0 and 0.050 inch.

Figure A.3 is a graph of \( f(x) \) for an \( L \) of 0.125 inch. The leakage from the 0.500 inch edge is expressed as the following:

\[ Q_A = 2.009(0.0059) = 0.012. \quad (A.9) \]

Ninety percent of the area under the curve lies between 0 and 0.002 inch.
FIG. A.2

LEAKAGE OF A FROM 0.125" EDGE

f(x)

1.0

0.5

x (in)

0.0

0.1

0.2

0.3

0.4

0.5

0.6
Substituting the limits into the leakage equation of collimator \( B \), \( Q_B \) is given by:

\[
Q_B = \int_{0}^{2L} \int_{0}^{6} e^{-u \sqrt{x^2 + y^2}} dy \, dx, \quad (A.10)
\]

\[
Q_B = \int_{0}^{2L} -u(e^{-u \sqrt{x^2 + 6^2}} - e^{-ux \sqrt{1 + \frac{12}{2L+x}}}) dx, \quad (A.11)
\]

or \( Q_B = \int_{0}^{2L} -u(f(x)) \, dx \). \quad (A.12)

Figure A.4 is a plot of \( f(x) \) for an \( L \) of 0.500 inch. The leakage \( Q_B \) is 8.5% for the 0.125 inch edge. Ninety percent of the area under the curve lies between 0 and 0.120 inch.

Figure A.5 is a plot of \( f(x) \) for an \( L \) of 0.125 inch. The leakage \( Q_B \) is 2.3% for the 0.500 inch edge. Ninety percent of the area under the curve lies between 0 and 0.030 inch.

The leakage from the 0.250 inch edge of collimator \( C \) is the same as the leakage from the 0.500 inch edge of collimator \( A \), or

\[
Q_C = 4.4\%, \ 0.125 \text{ inch edge.} \quad (A.13)
\]

The leakage from the 0.125 inch edge of collimator \( A \), or

\[
Q_C = 2.3\%, \ 0.25 \text{ inch edge.} \quad (A.14)
\]
Fig. A.4

LEAKAGE OF B FROM 0.125" EDGE

f(x)

1.0

0.5

0.05

0.10

0.15

x(in)

81
Fig. A.5

LEAKAGE OF B FROM 0.500" EDGE
Appendix B

SHIELD LEAKAGE

The following information is required for the shield leakage calculation:

1) The fission product gamma energy spectrum for a one hour irradiation and two hour decay is listed in Table B.1 (2, Blizzard, P.29).

2) The NaI(Tl) detector efficiencies for the gamma energy spectrum is listed in Table B.2 (8, Siegbaum, P. 289-291).

3) Leakage and build up factor formulas are given (7, Rockwell, P. 348).

4) Values of the leakage parameters $\mu(E)$, $F(b_n,0)$, $\alpha_n$, and $A_n$ are given (7, Rockwell, P. 385-449).

To find the leakage at $P$, assume the fuel plate can be represented by a uniform line source eleven inches long. Figure B.1 illustrates the geometry which would produce the greatest leakage. The leakage from a line source is given by the equation (7, Rockwell, P.348),

$$Q_P = A_1 F(b_1, \Theta) + A_2 F(b_2, \Theta) \frac{S_L(E)}{2\pi a}, \quad (B.1)$$

where

- $A_n$ are energy dependent build up factors,
- $\Theta$ is the angle $\text{OPR}$,
- $b_n = (1 + \alpha_n) \mu x$,
- $x$ is the lead thickness,
Fig. B.1

GEOMETRY OF GREATEST SHIELD LEAKAGE

FUEL PLATE

11"

Pb SHIELD

a=12"

SCALE $\frac{1}{4}"=1"$
Table B.1

Gamma Energy Spectrum

1-hr Irradiation, 2-hr Decay, Reactor Power=1 Watt

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Decay Rate (Mev/sec\cdot watt x10^{-8})</th>
<th>Average Energy (MeV)</th>
<th>Decay Rate (sec^{-1} x10^{-8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.4</td>
<td>2.7</td>
<td>0.25</td>
<td>11</td>
</tr>
<tr>
<td>0.4-0.9</td>
<td>13.0</td>
<td>0.65</td>
<td>20</td>
</tr>
<tr>
<td>0.9-1.35</td>
<td>5.1</td>
<td>1.125</td>
<td>4.5</td>
</tr>
<tr>
<td>1.35-1.8</td>
<td>8.0</td>
<td>1.575</td>
<td>5.1</td>
</tr>
<tr>
<td>1.8-2.2</td>
<td>4.2</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>2.2-2.60</td>
<td>3.3</td>
<td>2.4</td>
<td>1.4</td>
</tr>
<tr>
<td>2.6-</td>
<td>0.90</td>
<td>3.5</td>
<td>0.26</td>
</tr>
<tr>
<td>Total</td>
<td>37.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_n$ (MeV)</td>
<td>(2x2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.20</td>
<td>96.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.30</td>
<td>87.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>80.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>70.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>66.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.70</td>
<td>63.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>60.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.90</td>
<td>58.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>56.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.50</td>
<td>50.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>46.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td>43.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td>42.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td>42.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\( \mu \) is the linear absorption coefficient,
\( \alpha_n \) are energy dependent build up factors,
\( F(b_n, \theta) = \int_0^\theta e^{-b \sec \theta} d\theta \),
\( S_L(E) \) is the source strength of the line source
\( (\text{cm}^{-1}\text{sec}^{-1}) \) at energy \( E \),
a is the distance from 0 to \( P \).

Table B.3 lists the volumes of \( \eta \), energy, \( \mu x \), \( \alpha_n \), \( A_n \) and \( F(b_n, \theta) \) for \( n \) equal to one and two. To be conservative, the value of \( \mu \) corresponding to the highest energy of the energy group was selected.

The fraction of each energy group which passes through the shield can be calculated. Weighting these results with the fraction of the spectrum in each energy group (\( f_i \)) and the detector efficiency for the energy group (\( \eta_i \)), the detected leakage can be calculated as follows:

\[
Q = Q_P A_P = \sum_{i=1}^{7} f_i \eta_i A_i F(b_1, \theta) + A_2 F(b_2, \theta) \frac{S_L A_P}{2 \| a} .
\]

\( (B.2) \)

Substituting the values for \( A_n \) and \( F(b_n, \theta) \) gives,

\[
Q = 3.98 \times 10^{-8} \frac{S_L A_P}{2 \| a} ,
\]

\( (B.3) \)

where

\[
S_L = \frac{\text{Total plate activity}}{\text{length}} = \frac{1}{12 \text{ in}} ,
\]
<table>
<thead>
<tr>
<th>Det</th>
<th>ux</th>
<th>1</th>
<th>2</th>
<th>A₁</th>
<th>A₂</th>
<th>F(b₁,0)</th>
<th>F(b₂,0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>82.7</td>
<td>-0.0125</td>
<td>0.14</td>
<td>2.2</td>
<td>-1.2</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>0.58</td>
<td>27.6</td>
<td>-0.035</td>
<td>0.14</td>
<td>2.6</td>
<td>-1.6</td>
<td>6.2x10⁻¹³</td>
<td>4.4x10⁻¹⁵</td>
</tr>
<tr>
<td>0.52</td>
<td>19.6</td>
<td>-0.043</td>
<td>0.14</td>
<td>2.75</td>
<td>-1.75</td>
<td>1.9x10⁻⁹</td>
<td>5.0x10⁻¹¹</td>
</tr>
<tr>
<td>0.47</td>
<td>16.2</td>
<td>-0.055</td>
<td>0.139</td>
<td>2.72</td>
<td>-1.72</td>
<td>7.0x10⁻⁸</td>
<td>2.6x10⁻⁹</td>
</tr>
<tr>
<td>0.45</td>
<td>15.0</td>
<td>-0.06</td>
<td>0.137</td>
<td>2.60</td>
<td>-1.60</td>
<td>2.3x10⁻⁷</td>
<td>1.1x10⁻⁸</td>
</tr>
<tr>
<td>0.44</td>
<td>14.5</td>
<td>-0.07</td>
<td>0.135</td>
<td>2.30</td>
<td>-1.30</td>
<td>4.3x10⁻⁷</td>
<td>2.1x10⁻⁸</td>
</tr>
<tr>
<td>0.43</td>
<td>14.1</td>
<td>-0.09</td>
<td>0.130</td>
<td>1.80</td>
<td>-0.80</td>
<td>8.3x10⁻⁷</td>
<td>3.5x10⁻⁸</td>
</tr>
</tbody>
</table>
a = 12 inches,

\( A_p = \text{Cross sectional area of the detector}, \)

\( A_p \approx \pi (1 \text{ in})^2 = 3.14 \text{ in}^2. \)

The leakage through the shielding is given by:

\[ Q = 1.51 \times 10^{-10} \Gamma. \]  \hspace{1cm} (B.4)
Appendix C

DETECTION RATE OF COLLIMATED GAMMA RAYS

The detection rate is proportional to the following:

1) total activity of the plate, $\Gamma$,
2) fraction of the plate under the collimator, $A/A_T$,
3) geometric efficiency, $A/\pi r^2$,
4) the sum over all groups of the products of the fraction of the gamma energy spectrum in group $i$ and the detector efficiency in group $i$, $\sum_i \eta_i f_i$

or

$$\text{Detection Rate} = \Gamma \left( \frac{A}{A_T} \right) \left( \frac{A}{\pi r^2} \right) \sum_{i=1}^{7} \eta_i f_i.$$  \hfill (C.1)

Since most of the power is produced in the lower half of the fuel plate; assume that the plate is a uniform plate source eleven inches long and 2.4 inches wide. This assumption is consistent with the uniform line source assumption of Appendix B. Since the assumptions are consistent, the results of Appendices A, B, C and D can be directly compared.

Thus the detection rate of collimator B is given by:

$$\text{Detection Rate}_B = \Gamma \left( \frac{\frac{3}{2} \times 1/8}{11 \times 2.4} \right) \left( \frac{\frac{3}{2} \times 1/6}{\pi \times (6)^2} \right) \sum_{i=1}^{7} f_i \eta_i, \hfill (C.2)$$

$$\text{Detection Rate}_B = 7.92 \times 10^{-7} \Gamma, \hfill (C.3)$$

The detection rate of collimator A and C is a factor of four lower than B, because of the decrease in geometric efficiency.
Detection Rate_{A+C} = \frac{1}{4} \quad \text{Detection Rate}_B = 1.98 \times 10^{-7} \text{T} \quad (C.4)
Appendix D

COUNT RATE

The count rate can be calculated using experimental data. From foil irradiation data, the power level of the foil is given by (6, Glasstone, p. 89):

\[ P_f = 8.3 \times 10^{10} g \sigma_f \phi \text{ watts}, \]  \hspace{1cm} (D.1)

where

- \( P_f \) is the power in watts of the foil,
- \( g \) is the mass in grams of U-235,
- \( \sigma_f \) is the fission cross section in \( \text{cm}^2 \),
- \( \phi \) is the flux in \( \text{neutrons/cm}^2\text{-sec} \).

The experimental values are

\[ g = 0.00106 \text{ grams}, \]
\[ \sigma_f = 0.8862 \text{ f.o}, \]
\[ \sigma_{fo} = 577 \times 10^{-24} \text{ cm}^2, \]
\[ \phi = 2.5 \times 10^9 \text{ n/cm}^2\text{-sec}. \]

The power is given by:

\[ P = 1.12 \times 10^{-4} \text{ watt} \]  \hspace{1cm} (D.2)

The power generated in an average fuel plate is the total
power of the core divided by the number of fuel plates. The desired power level of the core is 100 watts. For a viewing area of 0.0625 square inch the power is given by:

\[ P_p = 100 \times \frac{0.0625}{27 \times 15 \times 22 \times 2.405} \text{ watts}, \quad (D.3) \]

where

27 is the number of fuel elements,
15 is the number of fuel plates per element,
22 x 2.405 is the area of the fuel meat in square inches.

The average power produced by the area under the collimator is given by:

\[ P_p = 2.92 \times 10^{-4} \text{ watts}, \quad (D.4) \]

The count rate from foil, \( C_f \), is proportional to the power level of the foil during irradiation, \( P_f \), the geometric efficiency of the counting set up, \( \eta_f \), and a function of time, \( f(t) \), incorporating the duration of the irradiation period and the decay time, or

\[ C_f \propto P_f \eta_f f(t). \quad (D.5) \]

In the same manner the count rate from the 0.0625 square inch viewing area of the fuel plate can be expressed as:
\[ C_p \propto P_p \eta_p f(t). \quad (D.6) \]

For irradiations of the same duration and decays of the same length, the ratio of the count rates can be expressed as

\[ \frac{C_p}{C_f} = \frac{P_p}{P_f} \frac{\eta_p}{\eta_f} , \quad (D.7) \]

where

\[ \eta_f = 0.004031 , \]
\[ \eta_p = 0.0001382 , \]

or

\[ \frac{C_p}{C_f} = 0.0894. \quad (D.8) \]

Therefore, the fuel plate viewing area count rate is 8.94\% of the foil count rate.

The power density is much greater at the base of the fuel plate than at the top (see figure 1.2). The activity of the base of the fuel plate is a factor of 3.4 greater than the average activity of 2.9 x 10^{12} fission/cm^2-sec (full power). Near the top of the fuel plate, the activity decreases to 5\% of the average activity. The viewing area count rate can be expressed by:
\[ C_p = 0.0894 \, f_L C_f \]

where

\( f_L \) is the fraction of the average activity produced at position \( L \).

To find the expected count rates the data from an 0.5 hour foil irradiation is used. The value of \( f_L \) is approximated from figure 1.2. Table D.1 lists the count data for collimator B. The count data for collimators A and C will be a factor of four lower than for collimator B.
Table D.1
Expected Count Rate of Collimator B
at Four Longitudinal Locations

<table>
<thead>
<tr>
<th>Decay Time (hrs)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foil Counts</td>
<td>47168</td>
<td>28679</td>
<td>18376</td>
<td>13750</td>
<td>10947</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>L (in)</th>
<th>$f_L$</th>
<th>Plate Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.07</td>
<td>295 179 115 86 69</td>
</tr>
<tr>
<td>7</td>
<td>0.</td>
<td>717 436 279 209 166</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>4217 2564 1642 1229 979</td>
</tr>
<tr>
<td>22</td>
<td>3.4</td>
<td>14337 8717 5583 4179 3327</td>
</tr>
</tbody>
</table>
Appendix E

LEAKAGE CONTRIBUTING TO BACKSCATTER ACTIVITY

Section E.1

LEAKAGE THROUGH TWO INCH LEAD AND ONE INCH STEEL BACKSCATTER SHIELD

This calculation is very similar to the Shield Leakage Calculation. The major difference is the use of the dose build up factors rather than the energy build up factors (7, Rockwell, p. 422). The difference is in the use of the dose and energy build up factors is small.

The gamma leakage flux, \( \phi_P \), at 12 inches from the fuel plate can be expressed as

\[
\phi_P = \sum_{i=1}^{7} f_i \left[ A_1 F(b_1, \Theta) + A_2 F(b_2, \Theta) \right] \frac{F}{2 \pi a L}, \quad (E.1)
\]

where all the parameters have been defined in Appendix B.

Table E.1 lists the values of the leakage parameters. Note that the linear absorption coefficient of iron and lead have been combined into one average coefficient. The simple formula governing this average is

\[
\mu_{XT} = \mu_{Fe} x_{Fe} + \mu_{Pb} x_{Pb}. \quad (E.2)
\]

Carring out the calculations, the resultant gamma flux at \( P \), \( \phi_P \), is \( 1.11 \times 10^{-5} \) T per square inch.
Table E.1
Leakage Parameters of One Inch Steel
Plus Two Inch Lead Backscatter Shield

<table>
<thead>
<tr>
<th>En</th>
<th>ux</th>
<th>1</th>
<th>2</th>
<th>A₁</th>
<th>A₂</th>
<th>F(b₁,0)</th>
<th>F(b₂,0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>15.6</td>
<td>-0.0125</td>
<td>0.30</td>
<td>1.50</td>
<td>-0.5</td>
<td>5.8x10⁻⁸</td>
<td>3.7x10⁻¹⁰</td>
</tr>
<tr>
<td>0.9</td>
<td>5.83</td>
<td>-0.035</td>
<td>0.20</td>
<td>2.20</td>
<td>-1.2</td>
<td>1.4x10⁻³</td>
<td>3.5x10⁻⁴</td>
</tr>
<tr>
<td>1.35</td>
<td>4.25</td>
<td>-0.05</td>
<td>0.13</td>
<td>2.70</td>
<td>-1.7</td>
<td>7.6x10⁻³</td>
<td>3.4x10⁻³</td>
</tr>
<tr>
<td>1.8</td>
<td>3.54</td>
<td>-0.068</td>
<td>0.11</td>
<td>2.67</td>
<td>-1.67</td>
<td>1.6x10⁻²</td>
<td>8.3x10⁻³</td>
</tr>
<tr>
<td>2.2</td>
<td>3.29</td>
<td>-0.075</td>
<td>0.10</td>
<td>2.55</td>
<td>-1.55</td>
<td>2.1x10⁻²</td>
<td>1.15x10⁻²</td>
</tr>
<tr>
<td>2.6</td>
<td>3.15</td>
<td>-0.0875</td>
<td>0.0081</td>
<td>2.3</td>
<td>-1.3</td>
<td>2.5x10⁻²</td>
<td>1.4x10⁻²</td>
</tr>
<tr>
<td>3.5</td>
<td>3.031</td>
<td>-0.112</td>
<td>0.067</td>
<td>1.8</td>
<td>-0.8</td>
<td>3.0x10⁻²</td>
<td>1.7x10⁻²</td>
</tr>
</tbody>
</table>
Section E.2

LEAKAGE THROUGH SIX INCH BACKSCATTERING SHIELD

The gamma flux at a point \( P \) can again be expressed as

\[
Q_P = \sum_{i=1}^{7} f_i \left[ A, F(b_1, \Theta) + A_2 F(b_2, \Theta) \right] \frac{t}{2\pi aL},
\]

(E.3)

where all the parameters have been defined in Appendix B.

Table E.2 lists the values of the leakage parameters for the six inch lead shield. From these values \( Q_P \) is expressed as

\[
Q_P = 1.75 \times 10^{-7} \sqrt{T}.
\]

(E.4)
Table E.2
Leakage Parameters for Six Inch Backscatter Shield

<table>
<thead>
<tr>
<th>En</th>
<th>ux</th>
<th>1</th>
<th>2</th>
<th>A₁</th>
<th>A₂</th>
<th>F(b₁,0)</th>
<th>F(b₂₀)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>41.3</td>
<td>-0.0125</td>
<td>0.30</td>
<td>1.50</td>
<td>-0.5</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>0.9</td>
<td>13.8</td>
<td>-0.035</td>
<td>0.20</td>
<td>2.20</td>
<td>-1.2</td>
<td>5.2x10⁻⁷</td>
<td>1.8x10⁻⁸</td>
</tr>
<tr>
<td>1.35</td>
<td>9.82</td>
<td>-0.05</td>
<td>0.13</td>
<td>2.70</td>
<td>-1.7</td>
<td>5.4x10⁻⁵</td>
<td>5.6x10⁻⁶</td>
</tr>
<tr>
<td>1.8</td>
<td>8.09</td>
<td>-0.068</td>
<td>0.11</td>
<td>2.67</td>
<td>-1.67</td>
<td>2.0x10⁻⁴</td>
<td>4.5x10⁻⁵</td>
</tr>
<tr>
<td>2.2</td>
<td>7.49</td>
<td>-0.075</td>
<td>0.10</td>
<td>2.55</td>
<td>-1.55</td>
<td>3.7x10⁻⁴</td>
<td>9.6x10⁻⁵</td>
</tr>
<tr>
<td>2.6</td>
<td>7.23</td>
<td>-0.0875</td>
<td>0.0875</td>
<td>2.3</td>
<td>-1.3</td>
<td>5.4x10⁻⁴</td>
<td>1.4x10⁻⁴</td>
</tr>
<tr>
<td>3.5</td>
<td>7.06</td>
<td>-0.112</td>
<td>0.067</td>
<td>1.8</td>
<td>-0.8</td>
<td>7.4x10⁻⁴</td>
<td>2.1x10⁻⁴</td>
</tr>
</tbody>
</table>
Appendix F

COMPTON SCATTERED GAMMA RAYS

The equation governing the energy of a compton scattered gamma ray is

\[
hV' = \frac{E_0}{1 - \cos \theta} + \frac{E_0}{hV} \tag{F.1}
\]

where

\(E_0\) is rest mass energy of the electron, 0.51 Mev,
\(\theta\) is the scattering angle of the gamma ray,
\(hV\) is the initial gamma ray energy, and
\(hV'\) is the final gamma ray energy (5, Evans, P.675).

From observation the maximum energy of a gamma ray scattered 180° is 0.255 Mev. The maximum energy for a 90° scattering is 0.51 Mev.

The geometry of the detection system is shown in figure F.1. The angles shown are the minimum angles through which the gamma ray must be scattered to reach the detector.

The scattering angle for the doubly scattered gamma ray is 106.5°. Assuming the initial energy of the gamma ray is 3.0 Mev, the final energy is expressed as

\[
hV'' = \frac{0.51}{1 + \cos 106.5° + \frac{0.51}{hV'}} \tag{F.2}
\]
where
\[ hV' = \frac{0.51}{1 + \cos 106.5^\circ + \frac{0.51}{3.0}}. \]  

(F.3)

The final gamma ray energy is 0.186 Mev.

For triple scattering, the minimum angle is 67^\circ. The final gamma ray energy \( hV''' \) is 0.250 Mev.

The threshold energy of 0.30 Mev is exceeded when four scatterings each at an angle of 51^\circ \pm 3^\circ occur. The final energy of four 51^\circ scatterings is 0.312 Mev.

The leakage of the backscattered radiation can be illustrated by calculating the attenuation of low energy gamma rays by a four inch shield. The leakage from a point source without build up is expressed as

\[ Q = Q_0 e^{-ux}. \]  

(F.4)

For gamma rays of energy 0.5 Mev the leakage is

\[ \frac{Q}{Q_0} = e^{-17.22}, \]  

(F.5)

\[ \frac{Q}{Q_0} = 3.39 \times 10^{-8}. \]  

(F.6)

Leakage for gamma rays of energy 1.0 Mev is

\[ \frac{Q}{Q_0} = e^{-7.69}, \]  

(F.7)

\[ \frac{Q}{Q_0} = 4.55 \times 10^{-4}. \]  

(F.8)
Appendix G

DOSE CALCULATIONS

Section G.1

DOSE FROM UNSHIELDED FUEL ELEMENT

The dose rate from the unshielded fuel plate can be expressed as

\[ \text{Dose}_p = \sum_{i=1}^{7} f_i D_i / 2 \pi a L, \]  \hspace{1cm} (G.1)

where

\[ \Gamma_T \] is the total activity of the fuel plate,
\[ f_i \] is the energy distribution of Table B.1,
\[ D_i \] is the dose due to 1 photon/cm² sec at energy \[ E_i(\gamma, \text{Rockwell, P.19}) \],
\[ a \] is the distance to point P, and
\[ L \] is the length of the line source.

Table G.1 lists the parameters for the dose calculation.
For a one hour irradiation at 100 watts total core power the dose from the fuel plate at 12 inches is 388 mR/hr. A fuel element has 15 fuel plates. The dose from a fuel element is 5.82 R/hr.
Table G.1
Parameters for Unshielded Dose Calculation

<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>$D_i \times 10^{-6}$ (R/hr)</th>
<th>$f_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.82</td>
<td>0.248</td>
</tr>
<tr>
<td>0.9</td>
<td>1.75</td>
<td>0.451</td>
</tr>
<tr>
<td>1.35</td>
<td>2.4</td>
<td>0.102</td>
</tr>
<tr>
<td>1.8</td>
<td>3.0</td>
<td>0.115</td>
</tr>
<tr>
<td>2.2</td>
<td>3.5</td>
<td>0.0474</td>
</tr>
<tr>
<td>2.6</td>
<td>3.9</td>
<td>0.0316</td>
</tr>
<tr>
<td>3.5</td>
<td>5.7</td>
<td>0.00587</td>
</tr>
</tbody>
</table>
Section G.2

SHIELD DOSE

The dose due to the leakage of radiation through the base of the gamma scanner is calculated as

\[
Dose_p = \int_T \sum_{i=1}^{?} f_i D_i \cdot A \cdot F(b_1, \theta) + A_2 \cdot F(b_2, \theta) \cdot \frac{1}{2\pi} aL,
\]

\[\text{(G.2)}\]

where

\[f_i \text{ and } d_i \text{ are given in Table G.1 and the leakage parameters are given in Table E.1.}\]

The dose one foot from the bottom of the fuel plate is 10mr/hr.
Appendix H

COUNTING STATISTICS

The error in counting statistics is related to the total number of counts. The 95% confidence errors are tabulated (4, Chase, P. 85)

For 2000 counts there is 95% confidence that the counts are within ± 4.4% of the true value. The error is reduced to 2.7% for 5000 counts.
Appendix I

COMPUTER CODE GAMSCAN
C GAMSCAN
C CODE ANALYZING DATA FROM GAMMA SCANS OF MITR2 FUEL PLATES
C EACH J CORRESPONDS TO A PARTICULAR X AND Y FOR EACH RUN(K) USE THE SAME
C POINTS (X,Y) IN THE SAME ORDER (J)
C PART 1.
C CORRECTION FOR BACKGROUND AND ACTIVITY OF PREVIOUS IRRADIATIONS
C REAL MULT, MUL, NEW, NEWX, NEWY
C DIMENSION MP(5), LI(5), EI(5), DT(5), P(5,10), X(5,100), Y(5,100),
C CTI(5,100), C(5,100), DELT(5,5), T(5,5,10), MULT(5,100),
C CSUBT(5,100), MUL(5,100), CORCOU(5,100), RATIO(5,100),
C WIDTH(5,100), AR(100,30), BR(100,30), N2(100,100), Z(100,30),
C Q(100,30), NEW(100,30), U1(300G), NEWY(300G), U2(3000), V1(3000),
C NEWX(300G), V2(3000), ORDER(3000), U3(300G), CA(30)
C EQUIVALENCE(T(1,1,1), N2(1,1), (T(1,1,1,5), BR(1,1),
C 1(T(1,1,21,6), Z(1,1)), (T(1,1,41,7)), Q(1,1)), (T(1,1,61,8), NEW(1,1)),
C 2(T(1,1,81,9), U1(1)), (AR(1,1), T(1,1), (AR(1,6), MULT(1,1)),
C 3(AR(1,1), SUBT(1,1)), (AR(1,16), MUL(1,1)), (AR(1,21), CORCOU(1,1)),
C 4(Z(1,1), ORDER(1))
C NO IS THE NUMBER OF TIMES THE FUEL PLATE IS IRRADIATED
C A IS AN ARBITRARY REFERENCE POWER LEVEL, E.G., 100 WATTS
C READ(5,10) NO, A
C 10 FORMAT(12,F7.2)
C MP(K) IS THE NUMBER OF POINTS SCANNED IN THE KTH IRRADIATION
C LI(K) IS THE NUMBER OF 10 MINUTE INTERVALS THE FUEL PLATE IS IRRADIATED
C B(K) IS THE AVERAGE BACKGROUND FOR THE KTH SCAN
C DT(K) IS THE TIME BETWEEN IRRADIATIONS, E.G., DT(3) IS THE TIME BETWEEN
C THE STARTS OF IRRADIATIONS 2 AND 3
C P(K,1) IS THE POWER LEVEL OF THE ITH 10 MINUTE IRRADIATION INTERVAL OF
C THE KTH IRRADIATION, E.G., P(1,2) = 75 WATTS (USE SAME UNITS AS A)
C INDICATE THE POWER LEVEL FOR 10 INTERVALS
C READ(5,20) (MP(K), LI(K), B(K), DT(K), (P(K,1), I=1,10), K=1,NO)
C 20 FORMAT(213,F7.1/UCF.3)
C X(K,J) IS THE DISTANCE ALONG THE LENGTH FROM THE LEFT LOWER CORNER OF THE
C FUEL PLATE TO THE JTH POINT CF THE KTH IRRADIATION IN INCHES
C Y(K,J) IS THE DISTANCE ALONG THE WIDTH FROM THE LEFT LOWER CORNER
C TI(K,J) IS THE TIME BETWEEN THE START OF THE KTH IRRADIATION AND THE
C MIDDLE OF THE COUNTING OF THE JTH POINT
C C(K, J) IS THE CUMULATIVE COUNTS/MINUTE RECORDED AT POINT J FOR THE KTH IRRADIATION
DO 32 K=1, N
N=MP(K)
READ(5, 30) (X(K, J), Y(K, J), TI(K, J), C(K, J), WIDTH(K, J), J=1, N)
30 FORMAT(2F7.3, 2F8.2, F8.3)
32 CONTINUE
C DELT(L, K) IS THE TIME DIFFERENCE BETWEEN THE STARTS OF IRRADIATIONS L AND K
DO 35 L=1, N
35 DELT(L, L)=C.0
L1=NO-1
DO 40 L=1, L1
L2=L+1
DO 40 K=L2, NO
M=K-1
40 DELT(L, K)=DELT(L, M)+DT(K)
DO 100 L=1, N
DO 100 K=L, NO
N=MP(K)
DO 100 J=1, N
K=10.0
N1=LI(K)
DO 100 I=1, N1
C T(L, K, J, I) IS THE DIFFERENCE IN TIME BETWEEN THE SCAN OF THE JTH POINT OF THE
C KTH IRRADIATION AND THE JTH 10 MINUTE IRRADIATION INTERVAL OF THE RTH
C IRRADIATION
T(L, K, J, I)=DELT(L, K)+TI(K, J)-R
R=R+10.0
S=T(L, K, J, I)
IF (S.GT.130.0) GO TO 41
IF (S.LE.115.0) U=1.1817+0.08*(115.0-S)/5.0
IF (S.GT.115.0 .AND. S.LE.120.0) U=1.045+0.0772*(120.0-S)/5.0
IF (S.GT.120.0 .AND. S.LE.125.0) U=1.0474+0.0571*(125.0-S)/5.0
IF (S.GT.125.0 .AND. S.LE.130.0) U=1.0+0.0474*(130.0-S)/5.0
41 IF (S.GT.130.0) GO TO 42
IF (S.LE.130.0) GO TO 100
IF (S.GT.130.0 .AND. S.LE.140.0) U=0.38366+0.11634*(140.0-S)/10.0

110
IF (SGT.140.0).AND.SLE.150.0)U=0.79472+0.08984*(150.0-S)/10.0
IF (SGT.150.0.AND.SLE.180.0)U=0.61252+0.18220*(180.0-S)/30.0
IF (SGT.180.0.AND.SLE.190.0)U=0.5592+0.05332*(190.0-S)/10.0

42 IF (SGT.285.0)GO TO 43
IF (SLE.190.0)GO TO 100
IF (SGT.190.0.AND.SLE.210.0)U=0.47671+0.0825*(210.0-S)/20.0
IF (SGT.210.0.AND.SLE.241.0)U=0.39403+0.0827*(241.0-S)/31.0
IF (SGT.241.0.AND.SLE.261.0)U=0.34452+0.04951*(261.0-S)/20.0
IF (SGT.261.0.AND.SLE.285.0)U=0.30186+0.04266*(285.0-S)/24.0

43 IF (SGT.440.0)GO TO 44
IF (SLE.285.0)GO TO 100
IF (SGT.285.0.AND.SLE.330.0)U=0.24824+0.05362*(330.0-S)/45.0
IF (SGT.330.0.AND.SLE.360.0)U=0.21712+0.03112*(360.0-S)/30.0
IF (SGT.360.0.AND.SLE.380.0)U=0.20225+0.01487*(380.0-S)/20.0
IF (SGT.380.0.AND.SLE.440.0)U=0.16830+0.03395*(440.0-S)/60.0

44 IF (SGT.680.0)GO TO 45
IF (SLE.440.0)GO TO 100
IF (SGT.440.0.AND.SLE.500.0)U=0.15137+0.01693*(500.0-S)/60.0
IF (SGT.500.0.AND.SLE.560.0)U=0.13556+0.01781*(560.0-S)/60.0
IF (SGT.560.0.AND.SLE.620.0)U=0.12456+0.0169*(620.0-S)/60.0
IF (SGT.620.0.AND.SLE.680.0)U=0.11429+0.01027*(680.0-S)/60.0

45 IF (SGT.1540.0)GO TO 46
IF (SLE.680.0)GO TO 100
IF (SGT.680.0.AND.SLE.740.0)U=0.10734+0.00695*(740.0-S)/60.0
IF (SGT.740.0.AND.SLE.1340.0)U=0.06350+0.04384*(1340.0-S)/600.0
IF (SGT.1340.0.AND.SLE.1580.0)U=0.0499+0.0136*(1580.0-S)/240.0
IF (SGT.1580.0.AND.SLE.1940.0)U=0.04119+0.00871*(1940.0-S)/360.0

46 IF (SLE.1940.0)GC 100
IF (SGT.1940.0.AND.SLE.2850.0)U=0.01859+0.0044*(3254.0-S)/449.0
IF (SGT.3254.0.AND.SLE.4286.0)U=0.0136+0.00499*(4286.0-S)/1032.0
IF (SGT.4286.0.AND.SLE.5880.0)U=0.0078+0.00577*(5880.0-S)/1594.0
IF (SGT.5880.0.AND.SLE.7260.0)U=0.00616+0.00167*(7260.0-S)/1380.0
IF (SGT.7260.0)U=0.00431+0.00185*(10140.0-S)/2890.0

100 T(L,K,J,I)=U
C MULT(N,J) IS THE DECAY FACTOR FOR THE NTH IRRADIATION
C SUBT(K,J) IS THE ACTIVITY DUE TO PREVIOUS IRRADIATIONS AND WILL BE SUBTRACTED
\( n = \text{MP}(1) \)

DO 105 \( j = 1, n \)

105 \( \text{SUBT}(1, j) = c \cdot 0 \)

DO 140 \( k = 1, n_0 \)

\( n_3 = \text{MP}(k) \)

DO 140 \( j = 1, n_3 \)

\( k_a = k - 1 \)

IF(\( k_a \).EQ.0) GO TO 125

\( \text{SUBT}(k, j) = 0 \)

DO 120 \( m = 1, k_a \)

\( n = k - m \)

\( \text{MULT}(n, j) = 0 \cdot 0 \)

\( n_{99} = \text{LI}(n) \)

DO 110 \( i = 1, n_{99} \)

110 \( \text{MULT}(n, j) = \text{MULT}(n, j) + P(n, i) / A \cdot T(n, k, j, i) \)

120 \( \text{SUBT}(k, j) = (C(n, j) - P(n)) \cdot \text{MULT}(n, j) + \text{SUBT}(k, j) \)

C \( \text{MULT}(k, j) \) IS THE DECAY FACTOR FOR THE \( k \)TH IRRADIATION

C \( \text{CORCUM}(k, j) \) IS THE CORRECTED COUNTS PER MINUTE FOR THE \( j \)TH POINT

125 \( \text{MULT}(k, j) = 0 \cdot 0 \)

\( n_4 = \text{LI}(k) \)

DO 130 \( i = 1, n_4 \)

130 \( \text{MULT}(k, j) = \text{MULT}(k, j) + P(k, i) / A \cdot T(k, k, j, i) \)

140 \( \text{CORCUM}(k, j) = (C(k, j) - P(k) - \text{SLBT}(k, j)) \cdot \text{MULT}(k, j) \)

C PRINT OUT MEASURED POWER LEVEL AND FOIL ACTIVITY FOR COMPARISON

WRITE(*,145)

145 FORMAT(1H1)

WRITE(*,150)(C(k, i), i=1, 10), \( \text{CORCUM}(k, 1) / k = 1, n_0 \)

150 FORMAT(25HCM, MEASURED POWER LEVELS \( k = 12 / 1 H, f 7.2, 9 F 8.3 / /

C (14H FOIL ACTIVITY // 1 X, F8.2) \)

C COR1 IS THE SMALLEST CORCUM(1, J) - FIRST IRRADIATION

COR1 = 99999.0

\( n_5 = \text{MP}(1) \)

DO 152 \( j = 1, n_5 \)

IF(\( \text{CORCUM}(1, j) \leq \text{COR1} \)) COR1 = \( \text{CORCUM}(1, j) \)

152 CONTINUE

DD 155 \( k = 1, n_0 \)
N6=MF(K)
DO 155 J=1,N6
155 RATIO(K,J)=CORCOU(K,J)/CJR1
C PRINT OUT THE CORRECTED DATA POINTS
DO 156 K=1,N
N7=MF(K)
WRITE(6,160)(K,J,X(K,J),Y(K,J),RATIO(K,J),WIDTH(K,J),J=1,N7)
160 FORMAT(1H1,'CORRECTED DATA POINTS',/1H,'K','X(K,J)',4X,'Y(K,J)',4X,'RATIO(K,J)',4X,'WIDTH(K,J)',/1H,'2X,212,3X,13,3X,7.3,3X,7.3,4X,8.1,6X,F8.3')
156 CONTINUE
C PART 2
C CORRECTING POINTS FOR AREA AVERAGING EFFECTS ASSUMING A SMOOTH POWER
C DENSITY DISTRIBUTION
191 K=1
192 K3=0
193 J=1
L1=1
IF(K3.EQ.1)GO TO 157
WRITE(6,155)
195 FORMAT(1H1,'CORRECTED IN Y DIRECTION',/1H,'K',8X,'X',10X,'Y',9X,'NEW',15X,'MAX CR MIN')
GO TO 200
157 WRITE(6,198)
198 FORMAT(1H1,'CORRECTED IN X DIRECTION',/1H,'K',8X,'X',10X,'Y',15X,'NEW',15X,'X',4X,'MAX CR MIN')
200 K3=K3+1
M1=MF(K)
DO 204 I=1,M1
DO 204 N=1,M1
204 N2(N,I)=0
202 L=J+1
203 I=2
205 IF(X(K,J),NF,X(K,L))GC TO 210
AR(J,1)=Y(K,J)
AR(J,I)=Y(K,L)
N2(J,I) = L
BR(J,I) = RATIO(K,J)
BR(J,I) = RATIO(K,L)
I = I + 1
L = L + 1
IF(L .LE. M1) GO TO 205
IF(I .LE. 3) GO TO 300
N3 = I - 2
N1 = N3 + 1
DO 212 N = 1, N3
IP1 = N + 1
DO 212 M = IP1, N1
IF(AR(J,N) .LE. AR(J,M)) GC TC 212
TEM = AR(J,N)
AR(J,N) = AR(J,M)
AR(J,M) = TEM
TEM = BR(J,N)
BR(J,N) = BR(J,M)
PR(J,M) = TEM
212 CONTINUE
DO 215 N = 1, N1
Z(J,N) = 0.0
Q(J,N) = 0.0
215 NEW(J,N) = Q(J,N)
N = 1
CA(N) = 4.0*(BR(J,N) - ((AR(J,N) - AR(J,N+1)) + AR(J,N+1) - AR(J,N+2)) / (AR(J,N+1) - AR(J,N+2))) / (AR(J,N) = (AR(J,N) - AR(J,N+1) - AR(J,N+2)) / (AR(J,N) = (AR(J,N) - AR(J,N+1) - AR(J,N+2)) + AR(J,N+1))
IF(K3 . EQ. 2) GO TO 232
IF(WIDTH(K,J) . NE. 0.5) GO TO 230
CA(N+1) = 2.0*(BR(J,N+1) - BR(J,N+2) - CA(N) / 4.0*(((AR(J,N+1))**2 - 1(AR(J,N+2))**2)) / (AR(J,N+1) - AR(J,N+2))
CA(N+2) = 2.0*(PR(J,N+2) - CA(N) / 4.0*(((AR(J,N+2))**2 + 0.02083 - ICA(N+1) / 2.0*AR(J,N+2))
230 IF(WIDTH(K,J) . NE. 0.125) GO TO 235
232 CA(N) = 4*CA(N)
CA(N+1) = 8.0*(BR(J,N+1)-BR(J,N+2)-CA(N)) / 16.0*((AR(J,N+1))*2-1*(AR(J,N+2)))*2 / AR(J,N+1)-AR(J,N+2))
CA(N+2) = 8.0*(BR(J,N+2)-CA(N)) *((AR(J,N+2))*2 / 16.0*0.00308)/
1CA(N+1)*AR(J,N+2)/8.0

235 IF (NEW(J,N) .NE. 0.0) GO TO 240
NEW(J,N) = CA(N) * (AR(J,N))*2 / 2.0*CA(N+1) *AR(J,N) + CA(N+2)

240 NEW(J,N+1) = CA(N) *(AR(J,N+1))*2 / 2.0*CA(N+1) *AR(J,N+1) + CA(N+2)
NEW(J,N+2) = CA(N) *(AR(J,N+2))*2 / 2.0*CA(N+1) *AR(J,N+2) + CA(N+2)
Z(J,N) = -CA(N+1)/CA(N)
IF (Z(J,N) .LE. AR(J,N+2) .AND. Z(J,N) .GE. AR(J,N)) Q(J,N) = -(CA(N+1))
C/CA(N)*CA(N+1)/2.0 + CA(N+2)
N=N+1
IF ((N+2) .LE. N1) GO TO 220
IF (K3 .EQ. 2) GO TO 243
WRITE(6, 245) (K, X(K, J), AR(J, I), NEW(J, I), Z(J, I), Q(J, I), I=1, N1)
GO TO 244
243 WRITE(6, 245) (K, AR(J, I), X(K, J), NEW(J, I), Z(J, I), Q(J, I), I=1, N1)
CONTINUE
244 FORMAT(5X, I2, 4X, F8.3, 3X, F8.3, 3X, F8.3, 3X, F8.3, 3X, F8.3)
IF (K3 .EQ. 2) GO TO 275
IF (L1 .EQ. 1) GO TO 250
L=L2
GO TO 260
250 L=1
260 DO 270 I=1, N1
U1(L)=AR(J, I)
U3(L)=BR(J, I)
NEWY(L)=NEW(J, I)
U2(L)=X(K, J)
L=L+1
270 L2=L
GO TO 300
275 IF (L1 .EQ. 1) GO TO 28C
L=L3
GO TO 285
280 L=1
285 DO 290 I=1,N1
     V1(L)=AR(J,I)
     NEWX(L)=NEW(J,I)
     V2(L)=X(K,J)
     L=L+1
290  L3=L
300  J=J+1
     L1=L1+1
     M=1
305  N=1
310  IF (J.EQ.N2(M,N)) GO TO 300
     N=N+1
     IF (N.LE.M) GO TO 310
     M=M+1
     IF (M.LE.M1) GO TO 305
     IF (J.LE.M) GO TO 202
     IF (K3.NE.1) GO TO 330
     DO 320 J=1,M1
     TEMP=X(K,J)
     X(K,J)=Y(K,J)
320  Y(K,J)=TEMP
     GO TO 193
330  CONTINUE
     L4=L2-1
     L5=L3-1
     DO 335 I=1,L4
335  CRDER(I)=C(I)
     DO 340 I=1,L4
     DO 340 J=1,L5
     IF (U1(I).EQ.V2(J).AND.U2(I).EQ.V1(J).AND.CRDER(I)=(NEWY(I)*NEWX(J))/
          103(I))
     CONTINUE
     WRITE(6,350)(U2(I),U1(I),CRDER(I),I=1,L4)
350  FORMAT(LH1,6X,'DOUBLE CORRECTED VALUES',/,'7X','X','6X','Y','4X,
     1'CORRECT',//(4X,F8.3,2X,F8.3,2X,F8.3))
     K=K+1
IF (K LE NC) GO TO 192
STOP
END
Appendix J

DATA FORMAT
Appendix K
REFERENCES


