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Vol. 1

ANALYSIS OF AIRBORNE RADIOMETRIC DATA

VOLUME 1

EVALUATION OF THE DELPHI/MAZAS
COMPUTER CODE

FINAL REPORT

by

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1. INTRODUCTION	1
1.1 Airborne Data	2
1.2 Analysis of Airborne Data	5
1.3 Time Filters.	7
1.4 DELPHI.	8
1.5 Summary of Volume 1	8
1.6 Summary of Conclusions.	9
2. DESCRIPTION OF THE DELPHI/MAZAS COMPUTER CODE	11
2.1 Design Goals.	11
2.2 Philosophy.	13
2.3 Mathematical Description.	16
2.4 Response Functions.	33
2.5 Generation of Simulated Data.	45
2.6 Window Method	54
3. MAZAS/DELPHI PERFORMANCE	57
3.1 History of Tests/Modifications to Code	58
3.2 Tests Using Simulated Data.	59
3.3 Conclusions from Analysis of Simulated Data.	75
3.4 Analysis of the Lake Mead Test Range Data.	79
3.5 Analysis of Slaton Test Range Data. . .	98
4. CONCLUSIONS AND FUTURE IMPROVEMENTS/ DEVELOPMENTS	101
4.1 Conclusions	101
4.2 Recommendations for Future Work . . .	102

Table of Contents (Continued)

<u>Section</u>	<u>Page</u>
5. REFERENCES	107
APPENDIX 1 GAMMA-RAY DATA.	A1

FIGURES

<u>Figure</u>		<u>Page</u>
1	Relative Intensities of Gamma Rays from the Decay of ^{232}Th and ^{226}Ra	35
2	Comparison of the Third Exponential Integral E_3 and Approximation	39
3	Examples of the Calculated $11\frac{1}{2}" \times 4"$ NaI(Tl) Detector Response (Dots) for Groups of Closely Spaced Gamma Rays	41
4	Calculated Current of Scattered Photons from Monoenergetic Uniformly Distributed Sources of Radiation in Seawater	43
5	Estimated Continuum Gamma-Ray Spectra for Ground Sources of Potassium, Thorium, and Uranium.	46
6	Calculated $11\frac{1}{2}" \times 4"$ NaI(Tl) Detector Responses to the Estimated Continuum Gamma-Ray Spectra for Potassium, Uranium, and Thorium.	47
7	Shape of the Step Change Introduced into the Discrete Gamma-Ray Intensities used for Data Simulation	49
8	Summations of 30 Seconds of Simulated Data	52
9	Comparison of Single-Second Window Method and MAZAS Analyses of Constant Simulated Data.	61
10	Comparison of Input Intensities and Average Values Obtained from MAZAS for Six-Second Sums of Constant Simulated Data vs. Energy	63
11	Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Potassium Component	64
12	Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Uranium Component	65

List of Figures (continued)

<u>Figure</u>		<u>Page</u>
13	Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Thorium Concentration	66
14	Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Continuum-to-Discrete Ratio	69
15	Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Constant Data.	70
16	Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Increase in Potassium Concentration	71
17	Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Increase in Uranium Concentration.	72
18	Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Increase in Thorium Concentration.	73
19	DELPHI Time Filter of MAZAS Analysis of Simulated Data	74
20	Comparison of Sums of Lake Mead Test Range Data Taken Over Land and the MAZAS Fits for Different Aircraft Elevations.	80
21	Example of Single-Second of Data Obtained at a 400-ft. Elevation Over the Lake Mead Test Range and the MAZAS Fit.	81
22	Comparison of Single-Second Window Method and MAZAS Analyses of 200-ft. Elevation Data Obtained at the Lake Mead Test Range	82
23	Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 200-ft. Lake Mead Test Range Data.	83

List of Figures (continued)

<u>Figure</u>		<u>Page</u>
24	Comparison of Single-Second Window Method and MAZAS Analyses of 400-ft. Data Obtained at Lake Mead Test Range	84
25	Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 400-ft. Data Obtained at Lake Mead Test Range	85
26	Comparison of Single-Second Window Method and MAZAS Analyses of 600-ft. Data Obtained at Lake Mead Test Range	86
27	Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 600-ft. Data Obtained at Lake Mead Test Range	87
28	Comparison of Single-Second Window Method and MAZAS Analyses of 800-ft. Data Obtained at Lake Mead Test Range.	88
29	Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 800-ft. Data Obtained at Lake Mead Test Range	89
30	Comparison of Single-Second Window Method and MAZAS Analyses of 1000-ft. Data Obtained at Lake Mead Test Range.	90
31	Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 1000-ft. Data Obtained at Lake Mead Test Range	91
32	Comparison of Height Corrected Average Window and MAZAS Results of the Lake Mead Test Range Data as a Function of Elevation	94
33	MAZAS Results for Summed 1000-ft. Elevation Data.	97

List of Figures (continued)

<u>Figure</u>		<u>Page</u>
34	Comparison of Single-Second Window Method and MAZAS Analyses of Fairly Constant Portion of Slaton Test Line Data at 400-ft. Elevation	99
35	Comparison of DELPHI Time Filter Applied to Uranium Analysis Using the Window Method and MAZAS Analyses for the Slaton Test Line Data	100

1. INTRODUCTION

The need for an accurate determination of the uranium resources in the United States has resulted in the Department of Energy's establishment of the National Uranium Resource Evaluation Program. As part of this program, aerial radiometric surveys are being conducted throughout the United States. These surveys are typically conducted by fixed-wing aircraft carrying arrays of NaI(Tl) detectors which measure the gamma radiation emerging from the naturally occurring radioisotopes. Since the energies of the gamma rays from ^{40}K and the decay chains following ^{238}U and ^{232}Th are different, one can infer the relative contributions of each by measuring the energy spectrum of the gamma radiation.

This report is comprised of four volumes and describes efforts made by Science Applications, Inc., under contract to Bendix Field Engineering Corp., to increase and improve the information extracted from these airborne radiometric surveys. Volume 1 of this report is devoted to the description of the DELPHI/MAZAS code which has been developed by SAI as the major task of this contract effort. DELPHI/MAZAS is designed to extract the maximum information from the airborne radiometric data. Volume 2 contains instructions and a listing of the DELPHI/MAZAS code. Volume 3 is a collection of three topical reports: 1) Calculations of the effects of groundcover and overburden on the gamma-ray spectra reaching the airborne detectors, 2) a description of the effectiveness of the code MAZNAI in the deconvolution of very poor statistical NaI(Tl) gamma-ray spectral data, and 3) the nonlinear response of NaI(Tl) to gamma rays. The final volume contains a listing of the MAZNAI code.

This introduction discusses the problems inherent

in airborne radiometric data, gives a general outline of the MAZAS approach to the analysis of such data, and summarizes the results of tests that have been conducted on the code to date.

1.1 AIRBORNE DATA

The data generated by an airborne gamma-ray detector is typically collected in one-second intervals. (At a speed of 150 miles per hour, an aircraft will cover more than 200 ft. each second.) In order to achieve reasonable spatial resolution with statistical precision, the detectors must be large, i.e. have high detection efficiencies. To obtain the efficiency requirements, arrays of large NaI(Tl) detectors are typically employed. However, the energy resolution of NaI(Tl) detectors is poor, meaning that the resulting pulse height spectrum is badly smeared in relationship to the true energy spectrum of the incident gamma radiation. As an added complicating factor, the energy spectrum of gamma radiation incident on the detector contains both discrete and continuum gamma-ray components. The method used to process this data should be able to separate these components.

1.1.1 Sources of Gamma Radiation

The gamma radiation incident on an airborne detector comes from

- Discrete (monoenergetic) gamma-rays from naturally occurring radioisotopes
- Continuum gamma radiation

Typically, it is the discrete portion of the spectrum that is of most interest.

Sources of Discrete Gamma Radiation: The discrete gamma radiation observed in radiometric surveys comes primarily from the naturally occurring radioisotopes ^{40}K and the daughters of ^{238}U and ^{232}Th . The decay of ^{40}K produces

a single monoenergetic gamma ray of 1.461 MeV. The daughters of ^{238}U (primarily ^{214}Pb and ^{214}Bi) give rise to many gamma rays whose energies extend from less than 100 keV to over 3 MeV. The daughters of ^{232}Th (principally ^{228}Ac , ^{212}Pb , and ^{208}Tl) also produce many gamma rays extending in energy up to the 2.614 MeV ^{208}Tl line. In addition to these gamma rays, one also observes discrete gamma radiation from positron annihilation (0.511 MeV), ^{137}Cs (0.611 MeV) from old fallout, cosmic ray neutron capture by hydrogen (2.22 MeV), and $^{234}\text{Pa}^m$, an early daughter of ^{238}U .

The primary source of ^{40}K radiation is the ground with traces of ^{40}K in the NaI(Tl) detection system itself. The source of the radiation from ^{232}Th daughters is also primarily from the ground, although there may be traces of the daughters of ^{220}Rn (half-life = 55 sec.) in the atmosphere caused by the emanation of the gaseous ^{220}Rn from the ground.

The source of the ^{214}Bi and ^{214}Pb gamma rays can be from both the ground and the air, since their precursor, gaseous ^{222}Rn (half-life = 3.8 d) has a fair chance of emanating from the ground. The airborne source of these gamma rays is large, often times contributing more signal than the ground. Also it can be highly variable, depending on atmospheric conditions which can cause more or less emanation from the ground and can disperse or concentrate the radon.

Airborne radon is a major problem in radiometric surveys whose primary goal is the evaluation of ground uranium concentration.

Sources of Continuum Gamma Radiation: In addition to the discrete gamma radiation reaching the detector, the incident gamma-ray spectrum will contain a large amount of continuum radiation. A part of this continuum comes from cosmic ray bombardment of the upper atmosphere, which produces a rather smooth distribution of gamma rays as a function

of energy. The second and most important source of continuum gamma radiation is from Compton scattering of discrete gamma radiation either within the ground or while passing through the air.

1.1.2 Detector Response to Gamma Radiation

The NaI(Tl) detectors used in airborne surveys produce a signal approximately proportional to the energy of secondary electrons produced by the incident gamma ray. The incident gamma ray can interact with electrons in three ways: photoelectric absorption, Compton scattering, and pair production (if the energy of the photon is above 1.022 MeV). In photoelectric absorption, all of the gamma-ray energy is transferred to an electron. In Compton scattering, the photon scatters off an electron, transferring only part of its energy to the electron. The scattered photon can interact again in the detector or escape from it. Pair production results in the production of an electron-positron pair that share the energy of the incident photon, minus the rest mass of the pair (1.022 MeV). The positron will annihilate, creating two 0.511 MeV photons. Either, or both of these photons can escape from the detector. In each case, the energetic electrons (and positrons) transfer their energy to the NaI(Tl) crystal which produces a light pulse approximately proportional to the energy deposited by the electrons.

These interactions give rise to the detector response, which includes a photopeak corresponding to the gamma ray transferring all of its energy to the detector, a Compton distribution corresponding to only part of the gamma-ray energy being transferred to the detector, and escape peaks arising from the escape from the detector of one or both of the annihilation gamma rays. This energy deposition is smeared by the detector resolution, giving rise to broad peaks.

1.1.3 Counting Statistics

In order to maximize spatial resolution in airborne surveys, it is desirable to collect the data over as short a period of time as possible. This results in spectra which have rather large statistical fluctuations. Each datum in the spectrum is associated with its expectation value by a distribution given by Poisson statistics. For small numbers the scatter of the data from these expectation values can be relatively large, leading to large uncertainties.

1.2 ANALYSIS OF AIRBORNE DATA

1.2.1 Window Method

The goal of the data analysis code for airborne radiometric data must be to provide a rapid determination of the ground concentrations of potassium, uranium, and thorium. Present analysis methods typically use a "window" approach. Energy windows are set around the 2.614 MeV peak from ^{208}Tl (Th chain), the 1.461 MeV peak from ^{40}K , and the 1.764 MeV peak from ^{214}Bi (U chain). The counts in each of these windows are summed. The levels of potassium, uranium, and thorium as indicated by these windows are adjusted by several empirical parameters. These include:

1. Stripping ratios which attempt to correct for the influence each of the decay chains has on the windows of the other decay chains.
2. Removal of the aircraft background contribution from each window.
3. Removal of the cosmic background contribution from each window.
4. An attempt is made to remove the contribution of the airborne daughters of ^{222}Rn from each of the windows.
5. Adjustments which correct for small variations in aircraft altitude and air density (pressure).

The window method is possibly the fastest analysis method available, but it has limitations. First, if the continuum-to-discrete ratio were to change for the Compton scattered part of the continuum (due to such effects as vegetation, overburden), then the stripping ratios should also change. Empirical corrections to the stripping ratios are made for altitude variations, but cannot be made for vegetation or overburden. Second, changes in the concentration of the airborne radon component in the uranium signal cannot be detected using the window method without the use of effective 2π detection systems. Finally, the accuracy of the method for source geometrics other than those used to establish the stripping ratios may be in doubt.

1.2.2 Spectral Unfolding

Spectral unfolding codes such as the code MAZNAI⁽¹⁾ initially assume no information about the incident gamma-ray spectrum and attempt to create an estimate of the spectrum based on the data and the detector response function. These codes are typically iterative, and require fair statistical data and considerable computer time. The use of such codes for the present problem would, first, consume too much computer time, and, second, not necessarily produce the desired results since not all of the desired lines would necessarily be resolved.

Unfolding codes which use catalogs of NaI(Tl) gamma-ray spectra measured for known sources are attractive in the present problem since the number of such sources is small. However, such an approach is untenable for this application since the required catalog of spectra is found to be very geometry dependent. The shape of the discrete component, the shape of the continuum component, and their relative magnitude at the detector are dependent on such experimental parameters as (1) the amount of scattering material between the source and detector, and (2) the source geometry (e.g.,

distributed planar source or distributed volumetric source). These parameters are not controllable in this application; therefore, an appropriate library can not be constructed.

The analysis code, MAZAS, described below has been designed specifically for application to airborne radiometric survey data and eliminates many of the limitations of alternate analysis codes.

1.2.3 MAZAS Approach

The MAZAS approach to spectral unfolding is specifically designed for analysis of airborne radiometric data. The code assumes that energies of incident gamma rays and detector responses to these gamma rays are known. The code also assumes a polynomial representation for expanding the shape of the detected continuum. With these postulates and the fact that intensities of lines in given decay chains, normalized for branching ratios, vary smoothly, the code constructs a solution matrix by Gram-Schmidt orthogonalization. When this matrix operates on data it estimates the intensities of the spectral components. The code was designed to be fast running, with analysis taking less computer time than the actual flight time for data acquisition.

The MAZAS code is potentially a very powerful tool for the analysis of airborne data, since it gives information about the entire energy spectrum of gamma rays for uranium and thorium as well as the continuum components for these decay chains.

1.3 TIME FILTERS

Analysis of single seconds of data using any analysis method is strongly affected by counting statistics. Simple running sum time filters remove some statistical fluctuations

but also blur temporal characteristics. DELPHI (See Section 1.4) contains a unique time filter which suppresses statistical fluctuations while retaining temporal characteristics of the data.

1.4 DELPHI

The code MAZAS and the time filter routine are incorporated into an interactive, English language control program called DELPHI. This program contains modules for

- DATA UNFOLDING using MAZAS
- DATA REDUCTION using the Window Method
- DATA SIMULATION
- RESPONSE FUNCTION SIMULATION
- DATA INPUT
- DATA OUTPUT
- GRAPHICS ROUTINES for DISPLAYING RESULTS
- DATA ANALYSIS for TIME SEQUENCES using RUNNING SUM and FILTER METHODS

A general description of these routines is given in Section 2 of this report. Volume 2 of this report gives operating instructions for DELPHI, examples of graphical output, and a complete listing of the code.

1.5 SUMMARY OF VOLUME 1

Section 2 of this volume contains a description of the code DELPHI/MAZAS, mathematical formulations of the MAZAS and time filter modules, and a description of calculations of discrete and continuum response functions used in the present analysis. Section 2 also discusses the generation of simulated data. Section 3 of this report contains results of tests performed using simulated data and actual flight data obtained over the Lake Mead Test Range and the Slaton Test Line.

Section 4 gives a summary of the results of the tests and an evaluation of the MAZAS results as compared to simple window analysis. It also contains recommendations for improving the ease of operating the code for large amounts of data, improvements that might be made in calculating the continuum response functions, and tests that might be made to improve the precision and sensitivity of the MAZAS analysis.

1.6 SUMMARY OF CONCLUSIONS

The data presented in this report show that, in its present version, MAZAS is

- Consistently more precise for uranium analysis for both simulated and test range data than the window method
- Comparable to the window method in precision for the potassium analysis for both simulated and actual data.
- Less precise than the window method for the analysis of thorium
- Consistently more accurate in the analysis of simulated data for potassium, uranium, and thorium than the window method
- Unaffected by gain drifts up to 11 keV (~ one channel) in 100 seconds of data
- Unaffected by changes in the continuum-to-discrete ratio
- Able to process 100 seconds of airborne data in less than 100 seconds of computer time

The analysis of the Lake Mead Test Range data appears to indicate that the present MAZAS analysis, which measures only the discrete gamma-ray portion of the spectrum, is more sensitive to airborne radon than the window method. This raises the possibility that examination of the variation of the uranium continuum intensity (which is not available at

present) may give considerable information about the ratio of airborne-to-ground based gamma radiation and could possibly limit the necessity for a 2π detection system.

2. DESCRIPTION OF THE DELPHI/MAZAS COMPUTER CODE

2.1 DESIGN GOALS

Some of the problems associated with airborne radiometric survey data were discussed in the introduction. These problems include:

- The incident gamma-ray spectrum is complicated with many discrete-energy gamma rays superimposed on a large continuum background.
- NaI(Tl) detectors used for airborne surveys have fairly poor energy resolution.
- The counting statistics for single seconds of data are poor.
- Airborne sources of radon daughters can contribute significantly to the signal from the uranium decay chain.

In the analysis of aerial data, one wishes to extract ground concentrations of potassium, uranium, and thorium. For both potassium and thorium analyses, one can relate intensities of the discrete spectral components (corrected for elevation) to concentrations of these elements in the ground (in the absence of overburden) since the problem of airborne activity is minimal.

The uranium analysis is considerably more complicated because of the possible presence of airborne activity. There are features of the incident gamma-ray spectra that might provide information on the origin of uranium gamma rays:

- The relative intensities of the discrete gamma rays as a function of energy, since it is expected that the attenuation for ground and air sources will be different.

- The relative magnitude of the continuum-to-discrete ratio for the uranium component, since one expects that the continuum-to-discrete ratio will differ for air and ground sources.

Ideally, the analysis program would both give information about the entire energy spectrum and distinguish between continuum and discrete components of the spectrum. In order to obtain such information from poor resolution, poor statistical data obtained during airborne surveys, one must make maximum use of available information about the incident gamma-ray spectrum, the detector response function, and the nature of the statistical process.

The DELPHI/MAZAS program was written to provide a rapid means of analyzing airborne data with the goal of extracting the maximum possible amount of information. The overall code was designed to:

- Provide ease of interactive communication between operator and computer.
- Provide the capability for analysis of single spectra, sums of many spectra, or analysis of a time series of data.
- Provide the capability of adjusting response functions to handle changes in detector gain.
- Provide the capability of simulating data.
- Provide graphical presentation of input data, analyzed data, and results via a graphics terminal.

The following part of this section will discuss the philosophy and mathematics of the DELPHI/MAZAS code.

2.2 PHILOSOPHY

Although the ultimate function of MAZAS is to produce time-sequences of unfolded potassium, uranium and thorium data, the development of MAZAS has and, we anticipate, will require many peripheral tasks such as input and output, simulation of data, and analysis of unfolded results. Therefore, MAZAS has been built into a larger code system, called DELPHI, containing these capabilities.

DELPHI responds to English language commands communicated to it via an interactive terminal keyboard, based upon vocabulary stored in a data memory file. English was chosen as the command language in order to allow complete flexibility in utilizing capacities which were at the time of the construction of the language processor undetermined in type and extent. English has the advantage of being natural for users, vocabulary and grammar coming to mind with relative ease. (Commands do however, tend to be couched in the form of nuclear jargon.) A typical command sentence would be

DISPLAY THE DISCRETE RESPONSE.

As in conversational English, any sentence can have many related forms. For example, the preceding sentence might be stated alternatively as

DISPLAY K(DISCRETE).

Either of these commands would cause a display in graphical form of the discrete line components of the spectrometer response (discussed in the following section).

In FORTRAN language structure there is minimal use of verbs. For example, to unfold, one might say

CALL UNFOLD,

or,

CALL MAZAS.

Grammatically, the function of the verb is displaced into the noun, which is cumbersome and conversationally unnatural. Rather than

CALL UNFOLD,

the more straightforward English expression or command is

UNFOLD.

This mode of speech is employed by DELPHI.

Commanding an interactive system in this manner places requirements on the structure of the executing software. It has been our experience with DELPHI that these requirements have desirable effects on code architecture. For example, the separation of functions into verb categories (INPUT, OUTPUT, UNFOLD, SIMULATE, etc.) leads logically to the separation of routines into functional modules. This has little advantage on the DEC-10 but would be of considerable advantage on a smaller system in which only part of the program could reside in random access memory at any one time.

In DELPHI there are separate module groups for command processing; for input of data, parameters, vocabulary, etc. into memory; for output of numerical results to graphical displays and other media; for unfolding; for data simulation; for response generation; and for fundamental arithmetic processes involving vectors and matrices. In addition, there is a module for

analysis of MAZAS results. This structure may not be carried over in its entirety to the operating forms of the ultimate MAZAS code for reasons of simplicity.

In addition, the English language form of the command interaction results in commands that are relatively data free. For example, in requesting DELPHI to unfold a given data set, it would not be good English form to explicitly include in the command sentence the actual data values or the values of parameters used in specifying the spectrometer response. Therefore, there must be standardized places for holding standardized types of data parameters. This has led in DELPHI to a relatively uniform and memory efficient manner of storing and accessing data, with DELPHI explicitly recognizing most such areas by name (noun descriptor). In the case of the verb "UNFOLD", a complete command sentence would require the verb to take a noun:

UNFOLD DATA.

However, since DATA is the only possible object of UNFOLD, it may be omitted. This is not the case with other verbs, such as DISPLAY, which can take as its object many nouns or complex noun forms. Some examples:

DISPLAY THE DATA

DISPLAY THE DATA AND THE EXPECTED DATA

DISPLAY THE URANIUM FIT

The latter two commands result in graphics with two graph lines: the first comparing the data to the refolded spectrum; and the second comparing the data to the refolded uranium spectral components.

2.3 MATHEMATICAL DESCRIPTION

2.3.1 MAZAS

MAZAS is based upon statistical properties of the energy spectrum and of the data, including noise effects associated with statistical fluctuations. The approach is a general one, which in principle subsumes the conventional window method. However, we have chosen, as with all previous MAZE codes, to make maximal use of information related to the spectrometer response. For effects independent of noise, the fundamental equation is

$$f(h) = \int_0^{\infty} f(h|E) f(E) dE, \quad (1)$$

where $f(h)$ is the probability of determining a detected event at pulse height h and $f(E)$ is the probability of receiving a gamma ray at energy E . The conditional probability $f(h|E)$ determines the response of the spectrometer system. While this equation is fundamental in a statistical sense, it does assume that each event is independent of all previous events. For count rates observed in aerial data, this condition is well obeyed.

The expected data in any channel i , $\bar{D}_i$, is related to the pulse height probability distribution by the following:

$$\bar{D}_i = NP_i = N \int_{\Delta h_i} f(h) dh, \quad (2)$$

where N is the number of events, P_i the probability of detecting an event in the i -th channel, and Δh_i the i -th channel interval. The energy spectrum is given directly by $f(E)$, but it is sometimes more convenient to express it in terms of a basis of specified energy-dependent functions, in which case the energy spectrum is given by coefficients $\hat{\phi}_\lambda$ according to the following equation:

$$f(E) = \sum_{\lambda} \hat{\phi}_{\lambda} \xi_{\lambda}(E) \quad (3)$$

where $\xi_\lambda(E)$ represents the energy distribution used as the λ -th basis function. For example, the numerous uranium and thorium lines are grouped in narrow energy bins dominated by one or two prominent lines, with each line cluster forming some shape ξ_λ . The continuum shapes are quantified by a variety of smooth or wave-like functions which are described later in the text.

By combining Eq. (2) and Eq. (3) with Eq. (1), we can relate the expected data to the ϕ parameters which are descriptive of the spectrum, in the following form:

$$\bar{D}_i = \sum_{\lambda} K_{i\lambda} (N\hat{\phi}_\lambda) \equiv \sum_{\lambda} K_{i\lambda} \phi_\lambda, \quad (4a)$$

or, more simply in terms of vectors $\bar{D}$ and ϕ and matrix K ,

$$\bar{D} = K \phi, \quad (4b)$$

where $K_{i\lambda}$, the $i\lambda$ -th response matrix component, is given by

$$K_{i\lambda} = \int_{\Delta h_i} dh \int_0^\infty dE f(h|E) \xi_\lambda(E). \quad (5)$$

K_i can also be written in the following form:

$$K_{i\lambda} = \int_{\Delta h_i} f_\lambda(h) dh, \quad (6)$$

where $f_\lambda(h)$ is the λ -th response function. The efficiency of detection can be related by integration to the conditional probability of detection:

$$\epsilon(E) = \int_0^\infty f(h|E) dh. \quad (7)$$

Thus, the conditional probability $f(h|E)$ entirely determines the static characteristics of the spectrometer response.

So far this concerns only the expected values of the data. The actually observed data values can be related to the expected data values by

$$D = \bar{D} + \eta, \quad (8)$$

where η is a stochastic vector whose components can vary positive or negative. Given such a data set, the values of ϕ are not uniquely determined but are distributed according to the probability distribution, $f(\phi|D)$, the conditional probability of ϕ if the given data set D is observed. This probability distribution is difficult to determine directly and must be related to other probability distributions in the following form:

$$f(\phi|D) = \{f(D|\phi)/f(D)\} * f(\phi), \quad (9)$$

where $f(D|\phi)$ is the conditional probability of the data being observed if ϕ is the set of spectral parameters, where $f(D)$ is the a priori distribution of data and where $f(\phi)$ is the a priori distribution of ϕ parameters.

The ideal method of solution would be to use $f(\phi|D)$ in an integral to determine the expectation value of ϕ . In practice this is impossible because of the high dimensionality of the integral. Fortunately, the maximum value of $f(\phi|D)$ lies close to the expectation value and this property can be used to derive an optimization principle in the following form. First, an information function W is defined as

$$W = - \ln f(\phi|D). \quad (10a)$$

All MAZE codes make use of an information function of this form. This information function is the sum of two component information functions, $W_{\text{a posteriori}}$, defined as

$$W_{\text{a posteriori}} = - \ln \{f(D|\phi) / f(D)\}, \quad (10b)$$

and $W_{\text{a priori}}$ defined as

$$W_{\text{a priori}} = - \ln f(\phi). \quad (10c)$$

The relationship between Eq. (9) and Eq. (10) is direct. It is simply more convenient to work in a logarithmic space because of the compressed number scale. The solution spectrum corresponds to the ϕ parameters that minimize the information function W . The a posteriori part of the W function forces ϕ to be such that the refolded data is consistent with the true data. The a priori part of the information function exerts a regularization effect.

The explicit form of the a posteriori information function is

$$W_{\text{a posteriori}} = \frac{1}{2} (D - K\phi)^t G(D - K\phi), \quad (11)$$

where superscript t indicates transpose. This can be interpreted as one-half the length-squared of an estimate of the deviation vector η , with components weighted by a factor G . G is a diagonal matrix whose diagonal elements are equal to the inverse of the expected data values,

$$G_{ij} = \frac{\delta_{ij}}{\bar{D}_i}. \quad (12)$$

In MAZAS, the a priori information function has the form

$$W_{\text{a priori}} = \tau * (W_{\text{a priori}}^U + W_{\text{a priori}}^T) \quad (13)$$

where superscripts U and T denote uranium and thorium, respectively, and where τ is an adjustable normalization factor. The action of the a priori information function is one of regularizing the variation of line strength with energy, and since potassium has only one line represented in the spectrum, it has no corresponding a priori information function. The form of the uranium a priori information function which is used in the present version of MAZAS is:

$$W_{a \text{ priori}}^U = \frac{1}{2} \sum_{\lambda} \left(\frac{\phi_{\lambda}^U - \phi_{\lambda-1}^U}{\ln E_{\lambda} - \ln E_{\lambda-1}} \right)^2 \quad (14)$$

where E_{λ} is representative of the energy in λ energy group. An analogous form is used for thorium. This form should be considered provisional, since we may wish to alter it after analysis of larger volumes of data than have been studied during this phase of development.

$W_{a \text{ priori}}$ may be expressed in the general form

$$W_{a \text{ priori}} = \frac{1}{2} \tau (R\phi)^t (R\phi) \quad (15)$$

where R is a matrix. This general form should hold for all cases anticipated present and future. It is quadratic in ϕ , and in this sense analogous to the a posteriori function, but with equal weighting of all components.

MAZAS differs from MAZNAI in that pure quadratic information functions are used. This approximation gives rise to a solution in the form of a set of linear equations. The solution may be obtained by taking the derivative of the information function with respect to ϕ_{λ} , and may be expressed in the following form:

This equation can be written in symbolic form as

$$D_o = K_o \phi, \quad (17)$$

where D_o is an extended data matrix and K_o is an extended response matrix corresponding to the configuration shown in Eq. (16). In MAZAS Eq. (17) is solved by the method of Gram Schmidt orthogonalization. It works as follows: Suppose we can find a matrix S which orthogonalizes the columns of the extended response matrix. In this case, we can write

$$O_o = K_o S, \quad (18)$$

where O_o represents the resulting orthogonal matrix, a set of column vectors orthogonal to one another with the weighting discussed in the preceeding paragraphs. That is, O_o obeys the orthogonalization equation

$$O_o^t G_o O_o = II, \quad (19)$$

where II is the identity matrix, and where G_o is the G matrix extended by the addition of ones on the diagonal until the dimensionality matches that of the extended data and response matrices.

Define the transpose of an augmented matrix O -tilde as

$$\hat{O}_o^t \equiv S O_o^t G_o. \quad (20)$$

If the non-augmented portion of this transpose is applied to the data, the result is the set of spectral parameters, as may be seen by following Eq. (21a) through Eq. (21e): Eq. (21a) results from applying the left and right sides of Eq. (20) to the data vector,

$$\hat{O}_O^t D = S O_O^t G_O D. \quad (21a)$$

Eq. (21b) follows by noting that the augmented data is formed from the data vector itself by adding zeros, and that zeros multiplicatively have no effect on the result,

$$\hat{O}_O^t D = S O_O^t G_O D_O. \quad (21b)$$

Eq. (21c) follows by substitution of Eq. (17),

$$\hat{O}_O^t D = S O_O^t G_O K_O \phi. \quad (21c)$$

Eq. (21d) follows by substitution of Eq. (18) somewhat rearranged,

$$\hat{O}_O^t D = S O_O^t G_O O_O S^{-1} \phi. \quad (21d)$$

Combining terms on the right side of Eq. (21d) yields the final result,

$$\hat{O}_O^t D = \phi. \quad (21e)$$

The values $\hat{O}^t$ are stored in an area called the O-buffer. Similarly, response matrix values are stored in the K-buffer.

The structure of the response matrix is as follows:

$$K = \begin{bmatrix} K & U & T & L & K & U & T & O \\ C & C & C & A & D & D & D & T \\ O & O & O & G & I & I & I & H \\ N & N & N & U & S & S & S & E \\ T & T & T & E & R & R & R & R \\ I & I & I & R & R & R & R & D \\ N & N & N & E & E & E & E & I \\ U & U & U & P & T & T & T & S \\ U & U & U & O & (1) & (9) & (8) & C \\ M & M & M & L & & & & R \\ (1) & (1) & (1) & Y & & & & E \\ & & & N & & & & T \\ & & & O & & & & E \\ & & & M & & & & (3) \\ & & & I & & & & \\ & & & A & & & & \\ & & & L & & & & \\ & & & S & & & & \\ & & & (8, & & & & \\ & & & 1) & & & & \end{bmatrix} \quad (22)$$

Eq. (22) shows the columns of the response matrix divided into two groups, continuum and discrete. The continuum consists of potassium, uranium and thorium Compton components with discontinuous transitions at the appropriate Compton energies blurred by the spectrometer resolution, followed by Laguerre polynomials which can be superimposed to form arbitrary shapes. The discrete part of the response consists of the potassium, uranium and thorium discrete components followed by other discrete components which are necessary to obtain a reasonable fit of the refolded spectral parameters to the actual data. The numbers in parentheses below each column refer to the dimensionality of each response component. In the case of the Laguerre polynomials, two values are indicated because the number of components is varied during the construction of the O-buffer.

The O-buffer is constructed in three stages. These stages are tabulated as follows:

STAGE	G_{ii}	K(continuum)
1	$1/D_i$	KUT Scattering + Laguerre Basis
2	$1/\sum K_{i\lambda} \phi_\lambda$	KUT Scattering + Laguerre Basis
3	$1/\sum K_{i\lambda} \phi_\lambda$	KUT Scattering + $\sum_{\text{Laguerre Basis}} K_{i\lambda} \phi_\lambda$

During stage one, the G matrix is specified by the actual data values and the full eight-dimensional Laguerre basis is used. In the second stage, an approximate response has been formed, with an approximate O-buffer, and it is therefore possible to estimate the spectral parameters, which can in turn be used to estimate expected data. The inverse of these expected data values are employed as diagonal members of the G-matrix with the Laguerre basis continuing to be used in its full eight-dimensional form. In the third stage, the particular superposition of the Laguerre polynomials which fit the data is substituted for the

eight-dimensional set, compressing it to one dimension. This 0-buffer construction is applicable to a period of one to three hundred seconds, describing average data characteristics during that period. Any one second of data has statistics that are insufficient to determine accurately the proper superposition of the full eight-dimensional Laguerre basis.

2.3.2 Time Filter

The output of MAZAS consists of spectral estimates of the same intervals as the input data, typically one-second. As with the conventional window method, these output values are highly affected by statistical fluctuations, making some form of time filtration essential. The actual variation of potassium, uranium, and thorium concentration is such that there are relatively constant periods during which strong filtration is required and relatively variable periods during which the temporal bandwidth must be widened to accomodate more rapid fluctuations.

This dynamic operation is carried out efficiently in frequency space by the use of Fourier transformations. In the MAZAS time filter, a 42-second window centered at the current second of data is passed along the time sequence, second-by-second, with transformations into frequency space obtained for each window. The values which are used as input for the time-varying structure of potassium, uranium and thorium are weighted superpositions of the ϕ spectral parameters mathematically expressed as

$$\psi^i(t) = \sum_{\lambda} w_{\lambda}^i \phi_{\lambda}; \quad t = 0, 1, \dots, n-1, \quad (23)$$

where superscript i denotes either potassium, uranium or thorium. The w values which optimize these estimates have not been determined to our complete satisfaction. At the present time, we are using 1) for potassium an estimate of the single potassium line strength, 2) for uranium an equal superposition of the six highest

energy uranium lines, and 3) for thorium an equal superposition of the three highest energy thorium lines. It is anticipated that these weighting estimates will be improved after analysis of larger quantities of data.

The transformation of the ψ^i values from time-space into frequency-space is given by the discrete Fourier expansion

$$g^i(v) = \sum_t \psi^i(t) e^{-2\pi i \frac{vt}{n}}; v = 0, 1, \dots, n-1. \quad (24)$$

The number of frequency components is equal to the number of time components which in the present case is 42. From the frequency components, one may return to the ψ^i time components by the inverse transformation equation

$$\psi^i(t) = \frac{1}{n} \sum_v g^i(v) e^{2\pi i \frac{vt}{n}} \quad (25)$$

It follows that there is a cyclic behavior of the $\psi^i(t)$ value "seen" by the Fourier transformation equations such that

$$\psi^i(t+\Delta t) \sim g^i(v) e^{2\pi i \frac{v\Delta t}{n}}, \quad (26)$$

Thus, displacements of time in temporal space give rise to phase shifts in frequency space. Thereby it follows, that

$$\psi^i(t+n) = \psi^i(t), \quad (27)$$

that is, the ψ value displaced in time by 42 seconds is equivalent to the original ψ value, a wraparound effect. Since the

values at the two extremes of the time window can differ significantly, this can be perceived by the filter as a large fluctuation in value corresponding to large high-frequency components, producing spurious artifacts. Therefore, the MAZAS time filter uses a cosine filter instead of a pure Fourier filter.

The cosine filter can be understood intuitively by considering an augmented set of KUT strengths, $\hat{\psi}^i$ which are related to the original ψ 's by the following equation:

(28)

$$\hat{\psi}^i(0) = \psi^i(0)$$

$$\hat{\psi}^i(1) = \psi^i(1)$$

$$\hat{\psi}^i(2) = \psi^i(2)$$

$$\vdots$$

$$\hat{\psi}^i(n-1) = \psi^i(n-1)$$

$$\hat{\psi}^i(n) = \psi^i(n-2)$$

$$\hat{\psi}^i(n+1) = \psi^i(n-3)$$

$$\vdots$$

$$\hat{\psi}^i(2n-5) = \psi^i(3)$$

$$\hat{\psi}^i(2n-4) = \psi^i(2)$$

$$\hat{\psi}^i(2n-3) = \psi^i(1)$$

Note that the values of $\hat{\psi}$ continue for the full 42 seconds and reflect in such a way that they return to the original value at $2n-2$ seconds. Thus, the values wrap around in a continuous fashion (although there may be abrupt transitions in the first derivative).

The corresponding transformation equations are given by

$$\hat{g}^i(v) = \psi^i(0) + (-1)^v \psi^i(n-1) + 2 \sum_{t=1}^{n-2} \psi^i(t) \cos\left(\frac{\pi vt}{n-1}\right), \quad (29)$$

$$\psi^i(t) = \frac{1}{2n} \left\{ \hat{g}^i(0) + (-1)^t \hat{g}^i(n-1) + 2 \sum_{v=1}^{n-2} \hat{g}^i(v) \cos\left(\pi \frac{vt}{n-1}\right) \right\}. \quad (30)$$

Note that unlike the Fourier transformation equation, the cosine transformation is essentially equivalent in both directions.

The amplitudes in frequency space, $\hat{g}(v)$, are real valued and consist of the superposition of signal and statistical fluctuation values expressed as

$$\hat{g}(v) = s(v) + \epsilon(v). \quad (31)$$

It is assumed by virtue of the Central Mean Value Theorem that both signal and fluctuations distribute themselves normally, and by symmetry that their mean values are zero. They may therefore be expressed as

$$f(s) = G_{\sigma_s}(s), \quad (32a)$$

$$f(\epsilon) = G_{\sigma_\epsilon}(\epsilon), \quad (32b)$$

where the G, or gaussian, function has the form

$$G_{\sigma}(x) = \frac{1}{\sqrt{2\pi} \sigma} \exp\left\{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2\right\}. \quad (33)$$

The distribution of $\hat{g}$, if s is held fixed, that is the conditional probability of $\hat{g}$ -if- s , is just the distribution of ϵ , since the variation of $\hat{g}$ in the absence of a variation in s is the statistical fluctuation of the frequency amplitude component. Therefore, this conditional probability has the form of the following Gaussian equation:

$$f(\hat{g}|s) = G_{\sigma_{\epsilon}}(\hat{g}-s) \quad (34)$$

The variation of $\hat{g}$ which is not conditional upon either s or ϵ is given by the combination of the two Gaussian functions representing s and ϵ :

$$f(\hat{g}) = G_{\sqrt{\sigma_s^2 + \sigma_{\epsilon}^2}}(\hat{g}) \quad (35)$$

and is also a Gaussian.

For the purposes of filtration, the most important distribution is the conditional distribution of s -if- $\hat{g}$, since s is the desired unknown to be estimated from the known $\hat{g}$. This is related to the previously described distributions by

$$f(s|\hat{g}) = f(\hat{g}|s) f(s)/f(\hat{g}). \quad (36)$$

Working through the Gaussian forms involved, one arrives at the following Gaussian form for the conditional probability of s -if- $\hat{g}$.

$$f(s|\hat{g}) = G_{\sigma}(s-\bar{s}) \quad (37a)$$

where the average value of the signal given a certain measured $\hat{g}$ is

$$\bar{s}(v) = \frac{\sigma_s^2}{\sigma_s^2 + \sigma_{\epsilon}^2} \hat{g}(v) \quad (37b)$$

and the standard deviation is as given by

$$\sigma = \frac{\sigma_s \sigma_\epsilon}{\sqrt{\sigma_s^2 + \sigma_\epsilon^2}} \quad (37c)$$

It should be apparent by inspecting Eqs. (37a-c) that everything is determined by $\hat{g}$, σ_s , and σ_ϵ .

The form of filter which, on the average, optimizes the distance between the filtered time sequence and the actual time sequence has the following form:

$$F = \frac{\bar{s}^2}{\bar{s}^2 + \bar{\epsilon}^2} \quad (38)$$

This is a standard result in filter theory and will not be derived here. By substituting the values of $\bar{s}$ and $\bar{\epsilon}$, we obtain

$$F = \frac{\hat{g}^2}{\hat{g}^2 + \sigma_\epsilon^2 (\sigma_s^2 + \sigma_\epsilon^2)^2 / \sigma_s^4} \quad (39)$$

The value of $\bar{s}$ was given by Eq. (3/b) and the value of $\bar{\epsilon}^2$ is simply σ_ϵ^2 .

A description of the variables involved in the construction of the filter is given in the following tabular form.

VARIABLE	DATA/MODEL	v-DEPENDENCE
$\hat{g}$	DATA	YES
σ_s	MODEL	YES
σ_ϵ	MODEL	NO

The variable $\hat{g}$ is measured, although it must be obtained indirectly via the cosine transform. It has a frequency dependence as does the standard deviation of the signal. However, the standard deviation of the signal, σ_s , is not measured, but must be represented in some model form. This is true also of the frequency-independent standard deviation of the statistical fluctuations.

The model chosen for σ_s is given as follows:

$$\sigma_s^2(\nu) = K_t^2(\nu) / (\nu^2 + \nu_0^2) \quad (40)$$

It consists of two parts: one of which represents the temporal characteristics of the spectrometer; and the other represents the temporal characteristics of the data. The temporal characteristics of the spectrometer systems are represented by K_t and in the time domain have the form

$$K_t(t) = \frac{e^{-\lambda S} * (.05 + .95 \cos \phi)}{S^2} \quad (41)$$

This consists of three parts: (1) a $(1/\text{distance})^2$ effect, (2) an attenuation effect due to increasing pathlength in air, and (3) a cosine effect related to the angle of the detector plane with respect to the direction of the incoming gamma rays. In Eq. (41), the variable S represents the pathlength, and may be determined from the altitude and speed of the aircraft by

$$S = \left[(\text{altitude})^2 + (\text{speed} * t)^2 \right]^{\frac{1}{2}} \quad (42a)$$

The angle ϕ is determined from the altitude and pathlength by

$$\cos \phi = \text{altitude} / S \quad (42b)$$

The variation with cosine is impure because the detectors have thickness and therefore have significant response even at the 90° angle.

Upon completion of filtration, the resulting frequency components are transformed back into temporal space where they form a 42-second time-sequence.

Only the central 10 seconds of this sequence are used to produce the final data output. The two 16-second intervals adjacent at the beginning and the end of the time sequence are used as buffers to determine the frequency content within the time interval. The ten seconds which are used are weighted more heavily at the center than at the periphery. The purpose of this is not to alter the smoothing effect, but to control sudden fluctuations in the temporal resolution of the processed data which might result from sudden fluctuations in the filter strength. The weights chosen limit the suddenness of these fluctuations.

2.4 RESPONSE FUNCTIONS

The response functions used in the DELPHI/MAZAS code consist of four continuum components and 21 discrete components. However, only a few of the discrete "response functions" correspond to the response of the detector to single, monoenergetic gamma rays. The others correspond to the calculated spectrum the detector would produce if bombarded by groups of gamma rays that are closely spaced in energy from a common decay chain. Three of the continuum responses correspond to estimates of the detector response to Compton-scattered gamma rays from ground sources of potassium, uranium, and thorium. This section will describe the calculation of these response functions.

2.4.1. Discrete Response Functions

The pulse height spectrum $S(\text{Ph})$ which one would obtain from an airborne detector (in the absence of statistics) can be written as:

$$S(\text{Ph}) = \sum_{i=1}^{N_{\gamma}} \phi_D(E_i) R(E_i, \text{Ph}) \epsilon(E_i) + \int dE \phi_c(E) R(E, \text{Ph}) \epsilon(E) \quad (43)$$

where N_{γ} is the number of all of the discrete gamma rays reaching the detector

$\phi_D(E_i)$ is the intensity of the i^{th} discrete gamma ray at the detector

$R(E_i, \text{Ph})$ is the detector response function for monoenergetic gamma rays of energy E_i producing a pulse height Ph

$\epsilon(E)$ is the absolute detector efficiency for gamma rays of energy E

$\phi_c(E)$ is the differential energy spectrum of continuum gamma rays at the detector

The purpose of the analysis of a spectrum is to determine the magnitudes of the discrete gamma-ray intensities ϕ_D .

A basic assumption of the code MAZAS is that the number of discrete lines in the incident spectrum is rather small (the code will allow up to a total of 32 discrete and continuum components). The number of discrete gamma rays resulting from the uranium and thorium decay chains is large, however, with more than 200 individual gamma rays having been resolved in high resolution studies ^(2,3). Figure 1 shows the energy spectrum of discrete gamma rays and their relative intensities from the decay of ^{232}Th and ^{226}Ra (U chain), respectively, with all daughters in secular equilibrium. It seems clear that one will have to include a large number of the lines in the "continuum" if only the response function for the strong lines are used. It should also be clear that this "continuum" will not have a smooth shape in contrast to the continuum caused by Compton scattering or cosmic rays.

It was decided to include all known lines from the decays of U and Th by calculating the detector responses for groups of closely spaced lines from the respective decay chains. Two assumptions are made:

- Secular equilibrium is assumed for the daughters of ^{232}Th and ^{226}Ra . Since most of the strong gamma-ray transitions from ^{226}Ra come from the isotopes ^{214}Pb and ^{214}Bi which have half lives of 27 and 20 minutes, respectively, this should be a good approximation for the U chain. For the ^{232}Th decay chain there can be a separation between the ^{228}Ac lines and those resulting from the isotopes below ^{220}Rn in the chain. This could

Figure 1. Relative Intensities of Gamma Rays from the Decay of ^{232}Th and ^{226}Ra . The energies of the major lines are listed in keV. All daughters are assumed to be in secular equilibrium. The numbers at the top of each graph show the division into groups used in the present study.

be taken into account by making separate lines for the ^{228}Ac decay. This would increase the number of "lines" from 21 to about 30 and was not felt to be important.

- The relative intensities of gamma rays in a single "line" will not change with differing attenuations.

In addition to the ^{40}K , ^{226}Ra and ^{232}Th lines, response functions have been calculated for ^{137}Cs (0.661 MeV), annihilation radiation (0.511 MeV) and ^{234}Pa which corresponds to the first step in the ^{238}U chain. Appendix 1 lists the gamma-ray energies used in the calculation of the detector responses, the source intensities of each gamma ray and the parent isotope (2,3).

The branching ratios given in Appendix 1 correspond to the number of gamma rays originating from the source per 100 decays. The relative number of gamma rays which reach an airborne detector will not correspond to these values, however, since ground and air attenuation will reduce the number of low energy photons relative to the number of high energy photons. This was taken into account in an approximate manner in calculating the detector responses.

The current of unscattered photons from a differential volume of earth which pass through a unit detector area horizontal to the ground surface at an elevation H is given by the equation

$$dJ = \frac{S_v}{4\pi r^2} \cos\theta \exp \left[-(\sigma_a H + \sigma_g Z) / \cos\theta \right]$$

where J is the current of unscattered photons (photons/cm².sec)

S_v is the source strength (photons/cm³.sec)

r is the distance from the volume element dv to the detector (cm)

θ is the angle between the vector $\vec{r}$ and the normal to the detector area (rad)

H is the elevation of the detector above ground level (cm)

Z is the depth of the volume element (cm)

σ_a is the total attenuation coefficient for air (cm^{-1})

σ_g is the total attenuation coefficient for the ground (cm^{-1})

The total current is obtained by integrating over the entire volume source. If one assumes

- a uniform distribution of radioactive material in the ground
- a flat earth
- the quantity Z is much smaller than H

one can express the volume element $d\tau$ as

$$d\tau = 2\pi H^2 \frac{\tan\theta}{\cos^2\theta} d\theta dz$$

and J as

$$J = \int_0^{\pi/2} \frac{\pi/2 S_v}{2} \sin\theta d\theta \int_0^\infty dz \exp \left[-(\sigma_a H + \sigma_g Z)/\cos\theta \right]$$

The integral over dZ can be done at once giving

$$J = \frac{S_v}{2} \int_0^{\pi/2} \frac{\cos\theta \sin\theta}{\sigma_g} d\theta e^{-\sigma_a H/\cos\theta}.$$

Substituting $1/x = \cos\theta$ yields

$$J = \frac{S_v}{2\sigma_g} \int_1^\infty \frac{e^{-\sigma_a Hx}}{x^3} dx$$

This yields the expression

$$J = \frac{S_v E_3(\mu_a \rho_a H)}{2\mu_g \rho_g} \quad (44)$$

where

μ_g and μ_a are the mass attenuation coefficients for gamma rays of energy E in ground and air, respectively.

ρ_g and ρ_a are the densities of the ground and air, respectively.

E_3 is an Exponential Integral of the third kind⁽⁴⁾, namely

$$E_3(\tau) = \int_1^{\infty} \frac{e^{-\tau x} dx}{x^3}.$$

An approximation for $E_3(\tau)$ for values of τ greater than unity is

$$E_3(\tau) \approx 0.32 e^{-1.19\tau} \quad (45)$$

A graph showing this approximation is given in Figure 2.

The discrete response functions used in MAZAS are calculated according to the formula

$$K_I(\text{Ph}) = 0.16 \sum_{i=1}^{M_I} \frac{\epsilon(E_i) B_i(E_i) R(E_i, \text{Ph}) e^{-1.19 \mu_a(E_i) \rho_a H}}{\mu_g(E_i)} \quad (46)$$

with $\epsilon(E_i)$ being the absolute detection efficiency for gamma rays of energy E_i

$B_i(E_i)$ being the number of gamma rays of energy E_i emitted per disintegration (See Appendix 1)

$R(E_i, \text{Ph})$ being the detector response function for gamma rays of Energy E_i

H being taken as 400 feet

ρ_a being the density of air at sea level
($\rho_a = 1.23 \times 10^{-3} \text{ g/cm}^3$)

and the sum extending over a group of gamma rays from a given decay chain. In the present work the values of $\epsilon(E_i)$ and $R(E_i, \text{Ph})$ were taken from Reference 5 which gives the calculated response for an $11\frac{1}{2}'' \times 4''$ NaI(Tl) detector. The resolution in percent as a function of energy used in the present work is

$$\text{RES}(E) = 9.55 \left(\frac{0.661}{E} \right)^{0.38} \quad (47)$$

and is based on an analysis of the Lake Mead Test Range data which is discussed in Section 3.

The responses have been calculated for 248 channels with $E_0 = 0.0867 \text{ MeV}$ and $\Delta E = 0.01165 \text{ MeV/channel}$.

SAI-79DS-42

Figure 2. Comparison of the Third Exponential Integral, E_3 , and the Approximation

The gamma-ray lines were positioned in the 248 channels according to the nonlinear energy prescription given by Heath⁽⁶⁾

$$PH(E) = 1.32 + E \left[97.55 + E * \{ 3.885 + E * [-6.453 + E * (2.481 - E * .3894)] \} \right] \quad (48)$$

and the known pulse heights of the 1.461 MeV and 2.614 MeV lines in the airborne spectrum.

Examples of the detector "responses" used in the present work are shown in Figure 3. The positions and relative intensities of the discrete gamma rays used in calculating these responses are also shown on the figure.

2.4.2 Continuum Response Functions

Continuum gamma radiation arriving at an airborne detector comes from three sources:

- Cosmic radiation
- Compton-scattered radiation
- Bremsstrahlung

The continuum gamma-ray spectrum from cosmic radiation is quite smooth as a function of energy and fairly constant as a function of time and elevation. The shape of the cosmic ray energy spectrum can be well represented by a low order expansion in Laguerre polynomials.

Bremsstrahlung is produced when electrons are stopped. The bremsstrahlung produced by naturally occurring radioisotopes is low in energy and quite weak. The bremsstrahlung continuum should not be important in the analysis of airborne radiometric data.

Figure 3. Examples of the Calculated 11½" x 4" NaI(Tl) Detector Response (dots) for Groups of Closely Spaced Gamma Rays. The lines indicate the relative intensities of the various gamma rays. The energies of the major gamma rays are listed in MeV.

The Compton-scattered continuum is produced by scattering of discrete energy gamma rays as they pass between the source and the airborne detector. The gamma rays resulting from Compton scattering will extend in energy from near zero up to the energy of the source photon. The shape and magnitude of this scattered spectrum will depend on the amount of scattering material between the source and detector.

Some thought was given to including a scattered component for each of the discrete gamma rays since a large portion of the gamma rays from a monoenergetic source in the ground will have undergone Compton scattering before reaching the detector. Since the amount of overburden is unknown, and since the elevation of the detector can vary, the ratio of the continuum to discrete gamma rays can change significantly. For this reason separate continuum components for potassium, uranium, and thorium were calculated.

In addition, the code DELPHI calculates a fourth continuum component based on a Laguerre polynomial expansion corresponding to the rest of the continuum including the cosmic contribution. This shape should be fairly insensitive to changes in the concentrations of potassium, uranium, and thorium on the ground.

The shape of the continuum responses for ground sources of potassium, uranium, and thorium were based on data obtained in another study.⁽⁷⁾ The results of detailed calculations for the transport of gamma radiation from a distributed seawater source were used as approximations for the shapes of the continuum gamma radiation emerging from a ground source. Figure 4 shows the scattered current of photons emerging inward from a uniformly distributed source of photons in seawater.⁽⁷⁾

Figure 4. Calculated Current of Scattered Photons from Monoenergetic Uniformly Distributed Sources of Radiation in Seawater. The numbers give the energies of the source photons.

The calculations were performed using the discrete ordinates gamma-ray transport code ANISN. Since the Compton cross sections are similar for water and earth, and since the results calculated for a 1-D spherical geometry can be transformed directly into the results for a 1-D slab geometry, the results given in Figure 3 should be a reasonable approximation for the differential energy spectrum of the current of photons emerging from a uniformly distributed source of photons in a slab earth geometry.

The results shown in Figure 4 were parameterized as:

$$J_0(E, E_0) \approx 0.9 (1.5 + 21.3 e^{-2.36E} + 400 e^{-15.7E}) \quad (49)$$

$$E \leq E_0$$

$$= 0.0 \quad E > E_0$$

where E_0 is the energy of the source photon

E is the energy of the scattered photons

This parameterization is shown in Figure 3.

The shape of the scattered continuum arriving at an airborne detector for a monoenergetic source was approximated by multiplying the parameterization for the scattered current by an exponential attenuation term:

$$J(E, E_0, H) \approx J_0(E, E_0) e^{-\mu_a(E) \rho_a H} \quad (50)$$

where μ_a , ρ_a , and H are the air mass attenuation coefficient, density, and thickness, respectively. (This approximation does not include "build-up" at the low energies due to the air scattering of photons.)

The detector responses to the continuum gamma rays were calculated as:

$$K_{c_I}(\text{Ph}) = \sum_{i=1} B_i(E_i) \int J(E, E_i, H) R(E, \text{Ph}) dE \quad (51)$$

where the values of $B_i(E_i)$ are given in Appendix 1 and the sum extends over all of the gamma rays from a given elemental decay chain. Figure 5 shows the estimated gamma-ray spectrum and Figure 6 shows the calculated continuum response functions for the ground-based potassium, uranium, and thorium.

2.5 GENERATION OF SIMULATED DATA

An important part of the testing and evaluation of the computer code DELPHI/MAZAS has involved the generation and analysis of simulated data. In the case of real airborne data a number of experimental uncertainties can introduce uncertainties into the comparison of the MAZAS analysis with other methods. First, the true concentrations of potassium, uranium, and thorium on the ground may be unknown or at least uncertain. Second, the effects of ground cover, soil moisture and changing aircraft elevation can introduce uncertainties. Third, the effects of airborne radon and its daughters can make analysis of the uranium component uncertain. Finally, instrumental effects such as analyzer gain shifts can introduce uncertainties. Simulated data, on the other hand, will introduce none of these effects. The input numbers are known and can be shifted at will, the response functions are known, and one can make a direct comparison of accuracy and precision of MAZAS in comparison with other analysis methods.

For these reasons several sets of simulated data were generated to study the ability of MAZAS to calculate the correct results for:

- Static data - no changes in gain or elemental concentrations

Figure 5. Estimated Continuum Gamma-Ray Spectra for Ground Sources of Potassium, Thorium, and Uranium. The major discontinuities (at the energies of the discrete gamma rays) are listed in keV.

Figure 6. Calculated 11½" x 4" NaI(Tl) Detector Responses to the Estimated Continuum Gamma-Ray Spectra for Potassium, Uranium, and Thorium.

- Data in which only one component (K,U or Th) was changed while the other components were left unaltered
- Data in which known gain shifts were introduced
- Data in which the continuum-to-discrete ratio was changed.

Each data set consisted of 100 seconds of simulated data. For the changes in concentration and continuum-to-discrete ratio, the change was introduced gradually according to the formula:

$$\phi_I = \phi_{I_0} \left[1 + (1 + e^{(60-t)/5})^{-1} \right] \quad (52)$$

where ϕ_I is the simulated intensity, ϕ_{I_0} is the nominal intensity, and t is the time in seconds. Figure 7 shows a plot of this function. It was felt that such a functional dependence would give a reasonable test of both MAZAS and the DELPHI time filter.

2.5.1 Simulation of Static Data

An important consideration in the evaluation of the code MAZAS is the ability of the code to produce precise results for the analysis of potassium, uranium, and thorium. To evaluate the precision of the MAZAS analysis a set of data with no changes in the input parameters was generated. The generation of simulated data is straightforward in the DELPHI framework. Each time the code DELPHI/MAZAS unfolds a data set, it solves the equation:

$$\text{DATA}(\text{Ph}) \approx \sum_I \phi_I K_I(\text{Ph}) \quad (53)$$

where $\text{DATA}(\text{Ph})$ is the pulse height spectrum

Figure 7. Shape of the Step Change Introduced into the Discrete Gamma-Ray Intensities used for Data Simulation.

$K_I(\text{Ph})$ are the response function

ϕ_I are the unfolded intensities

The results of the unfolding are the values of ϕ_I . Simulated data can be generated by calculating:

$$D_{\text{Exp}}(\text{Ph}) = \sum \phi_I K_I(\text{Ph}) \quad (54)$$

which is the predicted shape of the spectrum, and then modifying each value of $D_{\text{Exp}}(\text{Ph})$ with a random number generator with a Poisson distribution. This will produce a simulated data set which is very similar to that of the original data $\text{DATA}(\text{Ph})$. Variations in the total number of counts can be simulated easily by modifying all of the values of ϕ_I before the random number generator is used. Variations in the intensities of individual components can also be simulated by changing the appropriate values of ϕ_I in the calculation of $D_{\text{Exp}}(\text{Ph})$.

The static simulated data were generated by unfolding 100 seconds of the 400 feet elevation Lake Mead Test Range data⁽⁸⁾ to generate the values of ϕ_I and normalizing these values to correspond to the number of counts obtained for a single second of data.

2.5.2 Changes in Elemental Concentrations

Changes in the concentrations of potassium, uranium or thorium in the ground will produce changes in both the discrete and continuum gamma-ray components for these elements. Since both the continuum and discrete response functions are included in MAZAS, it is possible to simulate data that includes changes to both. Because of the way MAZAS initiates the unfolding matrix, it is not straight

forward to change both the continuum and discrete intensities by the same amount.

The initiation process used in DELPHI/MAZAS consists of taking the input elemental continuum response functions $K_I^{IN}(Ph)$ which were discussed in Section 2.4 and orthogonalizing them using the Gram-Schmidt process. The orthogonalized continuum responses are calculated from the input responses according to the formulas:

$$K_1 = K_1^{IN} / |K_1^{IN}| \quad (55)$$

$$K_2 = (K_2^{IN} - (K_1 \cdot K_2^{IN}) K_1) / |K_2^{IN} - (K_1 \cdot K_2^{IN}) K_1|$$

etc.

where $K_1, K_2, \dots$ are the orthogonalized continuum response functions and $(K \cdot K^{IN})$ represents a dot product. The values of ϕ_I obtained in MAZAS for the continuum components are for the orthogonalized functions $K_I(Ph)$ and not for the input functions $K_I^{IN}(Ph)$. Since one can only change the value of ϕ_i in DELPHI the corresponding change to the magnitude of the unorthogonalized response function is uncertain.

In the present data simulation the coefficients of the continuum component were increased by an amount obtained from an analysis of the Slaton anomaly data which showed that the coefficient of the orthogonalized "uranium" continuum increased by about one half of the amount of the discrete components at the anomaly. Figure 8 shows examples of the simulated data with changed concentrations. The nominal simulated spectrum (consisting of 30 seconds of summed data) is shown at the top. The next three traces show summations of 30 seconds of data simulated for an increase of a factor of 2 in the potassium concentration, uranium concentration, and thorium concentration, respectively. The bottom portion of this graph shows the predicted continua for these spectra with varied concentrations.

Figure 8. Summations of 30 Seconds of Simulated Data. The top graph shows the nominal spectrum, and the spectra with the potassium, uranium, and thorium each increased by a factor of 2. The bottom graph shows the continua for these modified spectra.

2.5.3 Changes in Continuum to Discrete Ratio

When the aircraft elevation is changed or when overburden covers the source, the main change in the spectral shape is expected to come from a change in the continuum-to-discrete ratio. To simulate the effects of elevation or overburden in an approximate way, the continuum-to-discrete ratio was changed. The discrete component was held constant and all of the continuum components were increased.

2.5.4 Gain Shift Simulation

One of the modules in the code DELPHI allows data to be rebinned from one gain into another gain. This feature of the code was used to simulate gain drifts. Since some of the airborne systems include gain stabilization based on positioning the 2.614 MeV thorium peak at a particular position, the gain shifts used in the data simulation leave the position of the 2.614 MeV thorium peak unchanged. Both the gain and zero of the data are modified so that, during one hundred seconds of data, the energy of the first channel changes linearly with time by up to 24 keV. Three cases were simulated:

- A drift of -11.6 keV for E_0
- A drift of +11.6 keV for E_0
- A drift of +23.2 keV for E_0

where E_0 is the energy of the first channel. Since it is envisioned that the code will be initialized at about 100-second intervals, long term gain shifts can easily be handled. A drift of 24 keV in 100 seconds is considered to be an extreme situation.

2.6

WINDOW METHOD

The evaluation of the MAZAS/DELPHI analysis of airborne data requires some standard method for comparison. The standard used in this work is the simple Window method which employs a single window for each of the potassium, uranium, and thorium analyses. The stripping parameters corrections were obtained from Reference 9 for $11\frac{1}{2}$ " x 4" NaI(Tl) detectors. The correction for cosmic ray background was obtained from data supplied by GEODATA, Inc. for their detectors.⁽⁸⁾ In the present analysis, the corrected window values K, U, and Th are given by the equations:

$$\begin{aligned} K &= (K_o - \beta Th_o - \gamma U_o) e^{-0.0023(H-400)} \\ U &= (U_o - \alpha Th_o) e^{-0.0017(H-400)} \\ Th &= Th_o e^{-0.0017(H-400)} \end{aligned} \quad (56)$$

with K_o , Th_o , and U_o being given by the sums corrected for cosmic radiation

$$\begin{aligned} K_o &= \left[\sum_{1.361 \text{ MeV}}^{1.561 \text{ MeV}} Cts(E) \right] - 0.04668 * Cos \\ U_o &= \left[\sum_{1.665 \text{ MeV}}^{1.865 \text{ MeV}} Cts(E) \right] - 0.04131 * Cos \\ Th_o &= \left[\sum_{2.414 \text{ MeV}}^{2.814 \text{ MeV}} Cts(E) \right] - 0.0498 * Cos \end{aligned} \quad (57)$$

with $Cts(E)$ being the number of counts in the channel with energy E

H being the elevation in feet

Cos being the number of counts above 3 MeV.

The stripping parameters α , β , γ were calculated according to the height-dependent formulas:

$$\begin{aligned}\alpha &= .4 + (H * 0.3048 - 50.) 0.03/75. \\ \beta &= .52 + (H * 0.3048 - 50.) 0.04/75. \\ \gamma &= .91 + (H * 0.3048 - 50.) 0.04/75.\end{aligned}\tag{58}$$

given in Reference 9.

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3. MAZAS/DELPHI PERFORMANCE

The computer code MAZAS/DELPHI was specifically designed to analyze airborne radiometric data. The usefulness of the code to the NURE* program will depend on

- The precision of the results obtained from MAZAS
- The accuracy of those results
- The ability of the code to accurately time filter the unfolded results
- The ability of the code to flag anomolous data such as that produced by overburden and airborne radon.

The tests reported here have been designed mainly to assess the precision and accuracy of the MAZAS results. The time filtering capability of the code will also be considered in comparison to running sum techniques.

The tests include the analysis of simulated and actual data. In the analysis of simulated data the input parameters are known. Both the accuracy and precision of the unfolding can be tested. The accuracy of the analysis of actual flight data are somewhat uncertain because of uncertainties in the actual input parameters. It is not known, for example, how much airborne radon was present during the actual flights.

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3.1 HISTORY OF TESTS/MODIFICATIONS TO CODE

The testing of MAZAS/DELPHI has extended over a considerable period of time. The testing has not been a linear process, however, with some tests leading to substantial modifications in the code. This section will outline the major tests and modifications that have lead to the present version of the code.

In its initial configuration the code used eleven continuum components made up of orthogonalized Laguerre polynomials. The coefficients of all of these components were calculated for each unfolding. The code also contained a parameter TAUD which controlled how strongly the uranium and thorium lines tended toward their group averages. Initial tests using this version of the code showed that the fluctuations in all of the uranium and thorium lines were much larger than the fluctuations seen using the simple window approach.

The cause of these large fluctuations was traced to the high frequency Laguerre polynomials which could overlap strongly with the statistical fluctuations in the data. A parameter TAUC was introduced to control the behavior of these high frequency polynomials. The use of this parameter had the wanted effect of suppressing the fluctuation in the intensities of the discrete lines relative to those observed in the window method. However, the unfolded discrete intensities did not agree with the input values of simulated data.

At this point another problem in the initialization of the program MAZAS was uncovered, and the code was changed substantially. The eleven component Laguerre polynomial fitting of each data point was dropped and instead a single continuum component based on the eleven component Laguerre polynomial fit to a large amount of data was used. The code at this point would fit an individual spectrum with the 21 discrete responses

and a single continuum component. Also, at this time, the parameter TAUC which had previously controlled the behavior of the high frequency Laguerre polynomials was dropped and the parameter TAUD changed so that instead of the uranium and thorium lines each tending toward their group averages, individual lines would tend toward the average of the two adjacent lines.

The results of this code seemed very encouraging. The fluctuations in the unfolded uranium intensities were smaller than those obtained using the window method, the average values of the unfolded intensities agreed well with the input values, the code was flexible enough to handle changes in elevation or overburden and the problems with initialization were gone. A problem arose, however, when the concentration of a single element on the ground changed. Since the continuum is actually comprised of gamma rays from each of the individual elements and the shape of these continuum are different, changes in concentration lead to changes in the shape of the composite continuum. Approximate continuum shapes were calculated for potassium, uranium, and thorium, and these continuum response functions were incorporated into the code so that a change in concentration of one element could lead to changes in both the discrete gamma rays and the continuum for that element.

The results presented here correspond to the tests run after the preceding changes had been made.

3.2 TESTS USING SIMULATED DATA

Tests using simulated data (see Section 2.5) have been run to determine the accuracy and precision of MAZAS. These data are based on average single second count rates and K, U, and Th concentrations that were observed at a 400 ft. elevation over the Lake Mead test range by GEODATA, Inc. using

8 - $11\frac{1}{2}$ x 4" NaI(Tl) detectors. This section describes the results of these tests and presents comparisons of the MAZAS results and the simple window analysis. The results of using running sum analysis are compared to the DELPHI time filtered results.

3.2.1 Analysis of Constant Simulated Data

Figure 9 shows the results of applying the Window method and MAZAS to single seconds of the constant simulated data. The top two graphs show the potassium analysis using the Window method and MAZAS. The results are comparable. The RMS deviation for the Window analysis is 10% while the RMS deviation for the MAZAS analysis is 11%. The next two graphs show the results for the uranium analysis. The MAZAS results correspond to a linear average of the unfolded intensities of the six highest energy uranium lines (0.934 to 2.447 MeV). The RMS deviations of the MAZAS analysis are 30% while the RMS deviations of the Window analysis are 31%. The bottom two figures show the Window and MAZAS results for the thorium analysis. The MAZAS results shown here are an average of the intensities of three highest energy thorium lines (1.246 to 2.614 MeV). In this case the thorium Window analysis is considerably more precise than the MAZAS analysis giving an 11% RMS deviation compared to 15% for the MAZAS analysis.

It should not be surprising that the thorium analysis using MAZAS is not as precise as the Window method. Reference to Figure 8 of Section 2.5.2 will show that a significant portion of the area under the 2.614 MeV thorium peak is predicted as coming from the forward Compton scattered gamma ray continuum associated with the 2.614 MeV gamma ray. This continuum component is counted in the Window analysis while it is not counted in the MAZAS analysis. The statistics associated with the larger subtraction in MAZAS give rise to the larger fluctuations seen in the MAZAS analysis.

Figure 9. Comparison of Single-Second Window Method and MAZAS Analyses of Constant Simulated Data.

The accuracy of the MAZAS results is demonstrated in Figure 10 which shows the average values and RMS deviations of the unfolded intensities of all of the uranium and thorium lines for the analysis of independent seconds of this simulated data using MAZAS. The average values obtained from MAZAS agree well with the input values over the entire energy spectrum. It is seen that the RMS deviations increase significantly at the lower energies for six seconds of data. These data were analyzed using larger integration times, and it was found that the deviations of 0.351 MeV uranium line decreased from 43% for a six-second integration to 20% for an 18-second integration, while the deviations for the 0.609 MeV uranium decreased from 18% to 7%. One can thus expect to obtain fairly accurate information on the shape of the discrete uranium spectrum for integration times of 15 to 20 seconds of data.

3.2.2 Analysis of Simulated Changes in Elemental Concentration

The data simulated for changing elemental concentrations of potassium, uranium, and thorium were discussed in Section 2.5.2. The MAZAS analysis of these data was treated in exactly the same way one would analyze a new data set: First, all 100 seconds of data were read into the code and summed. The code was initialized by adjusting the gain, changing the discrete response, and then inputting this new discrete response function. The single seconds of data were then analyzed. Figures 11 through 13 show a comparison of the MAZAS and Window analysis for single seconds of simulated data. It will be noticed that there appears to be some feedthrough for the Window analysis where an increase in the thorium concentration, for example, produces changes in both the uranium and potassium results. This could be due either to improper stripping ratios or to the way the data has been simulated. It should be stressed, however, that the MAZAS results do not show these effects.

Figure 10. Comparison of Input Intensities and Average Values Obtained from MAZAS for Six-Second Sums of Constant Simulated Data vs. Energy. The flags indicate the RMS deviations for 18 independent analyses.

Figure 11. Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Potassium Component.

Figure 12. Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Uranium Component.

Figure 13. Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Thorium Concentration.

Another point that can be made is that, in both the Window and MAZAS analyses, the deviations increase as the background under the particular component increases. Thus, for the simulated increase in the thorium content a decrease in precision is seen in both the uranium and potassium analyses.

3.2.3 Analysis of Simulated Changes in Continuum-to-Discrete Ratio

An attempt was made to simulate the effects of altitude and/or vegetation and overburden by changing all of the continuum components and leaving all of the discrete components the same. The continuum components were all increased above their nominal values according to equation 52. This change would produce a spectrum similar to that which might have been produced by increasing the concentration of K, U, and Th in the ground by about a factor of 2.7 and then adding one mean free path of scattering/absorbing material such as 5 inches of wood or water over the ground surface. With this change, the intensity of the discrete gamma radiation at the detector would remain unchanged (neglecting energy dependent attenuation coefficients). While the continuum component would increase by roughly a factor of two (based on a rough approximation using dose buildup factors). In a real situation it would be expected that the shape of the continuum would change with the lower energy portion increasing somewhat faster than the high energy portion and that the cosmic continuum would not increase at all. This was neglected in this simulation.

Figure 14 shows the MAZAS and Window Method analyses of these data. It is apparant from the Figures that MAZAS gives the correct result with all of the discrete components remaining constant. The Window method shows significant increases as the continuum is increased. There are no modifications that can be made to the "stripping ratios" that would remove this increase.

Figure 14. Comparison of Single-Second Window Method and MAZAS Analyses of Simulated Data with a Changing Continuum-to-Discrete Ratio.

3.2.4 Simulated Gain Changes

Similar simulated data tests were conducted to determine the sensitivity of MAZAS to gain changes. All of the input parameters in these data were left unchanged. The results of these analyses show that no significant changes are observed in the Window method for gain drifts of up to 23 keV (two channels out of 240 channels) in 100 seconds of data. The MAZAS analysis of these data show that a gain drift of 11 keV (one channel out of 240 channels) in 100 seconds does not deteriorate the performance of MAZAS. Gain drifts of 23 keV (two channels) in 100 seconds will produce adverse effects with the standard deviation for the uranium analysis going from 30% for no gain shift to 37% for a two-channel gain drift.

3.2.5 Comparison of Running Sum Time Filter Vs. DELPHI Time Filter

Figures 15 through 18 show comparisons of the analysis of the simulated data using a five-second running sum filter on both the Window and MAZAS results. In these cases, the top set of graphs on each page shows a comparison of the potassium Window and potassium MAZAS results. The second set of figures compare the window results for uranium with the MAZAS results for a single line (1.764 MeV U) and an average of four uranium lines. (The 1.764-MeV uranium line tends to yield a higher intensity than does the average of the four uranium lines. Figure 10 showed that MAZAS line intensities for uranium and thorium consistently increase with increasing energy for data obtained over land at 400 ft. elevation. Apparently, the initial relative normalizations of the individual uranium and thorium lines did not include sufficient attenuation for the low energy portion of the spectrum.) The bottom figure compares the Window and MAZAS thorium analyses. It is seen from these figures that a five-second running sum reduces the sta-

SAI-78DS-57.1

Figure 15. Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Constant Data.

SAI-78DS-58.1

Figure 16. Comparison of Five-Second Running Sum Time Filter of Window Method and MAZAS Analyses for Simulated Increase in Potassium Concentration.

SAI-78DS-59.1

Figure 17. Comparison of Five-Second Running Sum Filter of Window Method and MAZAS Analyses for Simulated Increase in Uranium Concentration.

SAI-78DS-60.1

Figure 18. Comparison of Five-Second Running Sum Filter of Window Method and MAZAS Analyses for Simulated Increase in Thorium Concentration.

tistical fluctuations seen in the previous figures, but that considerable ripple still exists in the filtered data. Figure 19 shows the results of the DELPHI time filter as applied to the MAZAS results. In all cases very good agreement is obtained between the DELPHI time-filtered results and the input parameters.

3.3 CONCLUSIONS OF ANALYSIS OF SIMULATED DATA

3.3.1 Precision

Table 1 gives a summary of the results of the RMS deviations obtained using MAZAS and the simple Window method on the simulated data. For cases where the concentration is changed, the deviations of the first 40 seconds and last 30 seconds are given. In all cases, the precision of the uranium analysis using MAZAS is equal to or better than the precision obtained from the Window analysis. The precisions obtained from the Window analysis for potassium are slightly better than those obtained from the MAZAS analysis. The precisions obtained from the MAZAS analysis for thorium are consistently worse than those obtained from the Window analysis.

SAI-78DS-61.1

Figure 19. DELPHI Time Filter of MAZAS Analysis of Simulated Data. The potassium results are increased by a factor of 10 and the thorium results increased by a factor of 4 for these graphs.

Table 1. Comparison of the Precision of MAZAS vs. Window Method for Simulated Data. The values listed are the RMS deviations obtained for single-second analysis of the data. For data which has a shift in concentration, two values are given: One measured before the change, the other after the change.

	K WINDOW %	K MAZAS %	II WINDOW %	II MAZAS %	Th WINDOW %	Th MAZAS %
No Change	10.0	11.3	31.0	30.0	11.2	15.6
K*2 Before After	12.2	12.1	33.0	32.	12.2	13.5
	6.0	7.3	34.0	29.	9.4	15.7
U*2 Before After	10.2	9.1	39.	26.	12.	17.
	9.8	13.3	22.	22.	11.	18.
Th*2 Before After	8.3	8.6	29.	26.	10.2	14.1
	12.0	13.5	40.	35.	6.9	9.0
Cont*2 Before After	8.2	8.5	30.	24.	9.7	15.0
	12.2	15.1	29.	25.	8.3	17.3
Gain 1 ch	10.0	10.7	37.5	35.9	11.5	15.2
Gain 2 ch	9.9	10.5	32.	32.	12.1	16.0

3.3.2 Accuracy

Table 2 gives a summary of the accuracy of the results obtained using MAZAS and the Window method on the simulated data. The table gives the ratio of the average value of the parameter before the change is introduced to the average value obtained after the change is introduced. It should be pointed out that only one parameter is varied at a time. For example, when the thorium concentration is varied, one expects a change in the thorium ratio with all of the other ratios remaining unity. This table shows that for all of the tests, MAZAS is clearly superior to the Window method in terms of accuracy. For changes in K, U, and Th concentrations this simply means that the stripping ratios assumed in the present Window Method analyses are improper. The Window Method cannot be expected to correctly handle changes in the continuum to discrete ratio (See Table 2.) In contrast, MAZAS is seen to have handled all of the various changes introduced in the data correctly, giving rise to the expectation that the code will give correct average values of the discrete gamma-ray components when applied to actual data.

3.3.3 DELPHI Time Filter

The time filter incorporated in DELPHI is seen to give very good results when applied to the MAZAS analysis. These time-filtered results correspond very well to the changes introduced in the input parameters. One can thus expect that the MAZAS-DELPHI time-filtered results will correspond closely to the true input time history of discrete gamma radiation arriving at an airborne detector.

Table 2. Comparison of Window and MAZAS Ability to Deal with Shifts in Isotopic Concentration, Vegetation, and Gain Shifts. The numbers correspond to the ratio of the average of the intensity obtained after the change to before the change.

Parameter Varied	K Window	K Mazas	U Window	U Mazas	Th Window	Th Mazas
K*2	1.94	2.02	0.91	0.93	0.99	0.96
U*2	1.10	1.01	2.13	2.10	1.06	1.05
Th*2	1.12	1.02	1.28	1.03	1.88	1.97
Continuum *2						
Overburden*2	1.25	1.01	1.63	1.01	1.30	1.01
Gain (1 ch out of 240 ch)	1.04	1.02	0.90	1.03	1.06	1.04
Gain (2 ch out of 240 ch)	1.04	1.04	0.92	0.85	1.03	1.06

3.4 ANALYSIS OF THE LAKE MEAD TEST RANGE DATA

A portion of the Lake Mead test range data obtained by Geodata, Inc.⁽⁸⁾ using an array of eight 11½" x 4" NaI(Tl) detectors have been analyzed using MAZAS and the simple window method. Seven flight lines have been analyzed including three flight lines at 400 ft, and additional flight lines at 200, 600, 800, and 1000 ft elevations.

3.4.1 Code Initialization

Each flight line consists of about 150 to 180 sec of data and corresponds to the aircraft flying over both land and water. The code MAZAS was initialized for each flight line by summing the data taken over the land, adjusting the gain of the response functions for the particular data set and then reading in these modified response functions. This process sets up the code for the particular data set. Figure 20 shows the data and the MAZAS fits for the various elevations. The values of chi-squared range from 1.3 to 1.8 for these fits.

3.4.2 Analysis

Each second of the flight data was analyzed using both MAZAS and the window method. Figure 21 shows a single second of data obtained at 400 ft and the MAZAS fit. The DELPHI time filter was applied to both the MAZAS and window results. Figures 22 through 31 show the results of the single second analysis and of the DELPHI time filter results for all of the elevations. The figures are arranged in pairs with the first pair giving the results for the 200-ft. elevation, the second pair giving the results for the 400-ft. elevation, etc. The first figure of a pair gives the results of single-second analysis, while the second gives the DELPHI time-filtered results. The graphs are arranged on each figure with potassium results at the top, uranium in the middle, and thorium at the bottom.

Figure 20. Comparison of Sums of Lake Mead Test Range Data Taken Over Land (dots) and the MAZAS Fits (lines) for Different Aircraft Elevations.

Figure 2-1. Example of Single-Second of Data Obtained at a 400-Ft. Elevation Over the Lake Mead Test Range (dots) and the MAZAS Fit (line).

Figure 22. Comparison of Single-Second Window Method and MAZAS Analyses of 200-Ft. Elevation Data Obtained at the Lake Mead Test Range. The graphs are linear with the maximum value normalized to 95% of full scale.

Figure 23. Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 200-Ft. Lake Mead Test Range Data. The graphs are linear with the maximum value normalized to 95% of full scale.

Figure 24. Comparison of Single-Second Window Method and MAZAS Analyses of 400-ft. Data Obtained at Lake Mead Test Range.

Figure 25. Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 400-ft. Data Obtained at Lake Mead Test Range.

Figure 26. Comparison of Single-Second Window Method and MAZAS Analyses of 600-ft. Data Obtained at Lake Mead Test Range.

Figure 27. Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 600-ft. Data Obtained at Lake Mead Test Range.

Figure 28 . Comparison of Single-Second Window Method and MAZAS Analyses of 800-ft. Data Obtained at Lake Mead Test Range.

Figure 29. Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 800-ft. Data Obtained at Lake Mead Test Range.

Figure 30. Comparison of Single-Second Window Method and MAZAS Analyses of 1000-ft. Data Obtained at Lake Mead Test Range.

Figure 31. Comparison of DELPHI Time Filter Applied to Window Method and MAZAS Analyses of 1000-ft. Data Obtained at Lake Mead Test Range.

In each flight line the aircraft passed over both land and water. In the 200 ft. elevation data, the transition from ground to water is very dramatic. At 1000 ft. the transition is not nearly as obvious. Neither the Window Method analysis nor the MAZAS analysis attempt to remove the airborne radon or aircraft background contributions from the data, therefore, the measured concentrations over water would not be expected to decrease to zero.

Precision

The potassium, thorium, and uranium concentrations are known to be fairly constant over the Lake Mead Test Range. The precision of MAZAS can be compared to the precision of the window method since the fluctuations in the single seconds data are large compared with the changes in the concentrations. Table 3 gives the RMS deviations of the potassium, uranium, and thorium intensities obtained over land for the Lake Mead Test Range. It will be seen that, like the analysis of the simulated data, MAZAS gives more precise results for the uranium analysis, comparable results for the potassium analysis, and poorer results for the thorium analysis than the window method.

Accuracy

It is difficult to compare the accuracy of the MAZAS and window analysis for this data since the true input parameters are not known. One striking difference between the window and MAZAS analysis is the variation of the uranium results as a function of elevation and the difference between the ratio of the results over land to those over water.

MAZAS gives a smaller drop when the aircraft passes from land to water than the window method at all elevations and this effect becomes more pronounced as the elevation increases. It would appear from this behavior that MAZAS is indicating considerably more airborne radon than the window method. A further indication of this is given by plotting the analyzed results over land versus the aircraft elevations. Figure 32 shows such a plot. Since the data are all corrected for elevation and providing

Table 3. RMS (%) Deviation from Average Obtained for Lake Mead Test Range for Various Elevations. These data all correspond to data obtained over land.

COMPARISON OF PRECISION LAKE MEAD TEST RANGE DATA

Elevation Records	200 ft 1-30	400 ft 1-80	400 ft 1-50	400 ft 130-180	600 ft 1-75	800 ft 1-80	1000 ft 130-180
U MAZAS	28.2	31.5	35.6	25.0	33.0	35.0	40.0
U Window	29.0	40.0	37.0	45.0	48.0	49.0	53.0
K MAZAS	9.0	13.6	13.2	15.5	16.1	21.0	24.0
K Window	9.5	13.2	12.9	14.1	14.7	19.5	20.0
Th MAZAS	10.8	15.8	15.7	14.8	20.7	25.0	25.0
Th Window	8.8	13.5	11.6	12.2	17.0	20.0	19.0

Figure 32. Comparison of Altitude Corrected Average Window and MAZAS Results of the Lake Mead Test Range Data as a Function of Elevation.

there are no large scale inhomogenities in ground concentrations, one would expect a ground source of radiation to produce a constant value versus height. Both the Window and MAZAS analyses of the potassium and thorium components are rather flat, indicating a predominantly ground source of radiation. (It appears that the elevation corrections for the MAZAS results need to be increased slightly.) The Window and MAZAS analyses of the uranium differ significantly, however, with the MAZAS results increasing by a factor of two in going from 200 to 1000 ft. The uranium Window analysis shows some decrease up to 600 ft. and then a 30-40% increase up to 1000 ft. Again, it appears that the MAZAS analysis is indicating considerably more airborne activity than the Window analysis.

A possible explanation of the above results is that both analyses are correct and that MAZAS and the Window are measuring slightly different quantities. The analysis of the simulated data showed that MAZAS gave correct results for the discrete portion of the spectrum while the Window method was sensitive to changes in the continuum. It is to be expected that radiation from the ground arriving at the detector will contain a considerably stronger continuum component than radiation from airborne sources. If the Window method is measuring part of the uranium continuum, then the ratio of ground based signal to the airborne signal in the Window analysis may be larger than for the MAZAS analysis which, at present, only considers the discrete gamma-ray component. Also, the MAZAS results shown for uranium are the averages of the six highest energy uranium lines (0.934 to 2.447 MeV). It was noticed that the shape of the uranium line intensity versus energy changed after the aircraft passed over land to over water. The average intensities of the lowest energy lines changed less than the intensities of the highest energy lines in this transition. This is constant with the fact that low energy gamma rays from airborne radon will be relatively more abundant than the higher energy gamma rays from

radon associated with ground sources. The averaging of several lines thus makes the present MAZAS analysis more sensitive to airborne radon than the use of just the highest energy line. If this is indeed the case, then MAZAS can offer considerably more information than the Window method since all individual discrete components and continuum components can be obtained.

To investigate the possible effects of continuum influencing the Window results, the various components of the fit to the 1000 ft. data were investigated. Figure 33 shows the sum of the 1000 ft. data over land and the MAZAS fit, the predicted continuum, the predicted thorium component, and the predicted uranium component. From these data one can estimate that about 20% of the uranium Window count rate is attributable to the uranium continuum. This would explain many of the inconsistencies observed in the comparison of results of the MAZAS and Window method for 1) different elevations and 2) transitions from over land to over water. Clearly these effects will have to be investigated further.

Figure 33. MAZAS Results for Summed 1000-ft. Elevation Data. The graphs show the data and the MAZAS fit, the data and the predicted continuum, the data and the predicted uranium component and the data and the predicted thorium component.

3.5 ANALYSIS OF SLATON TEST RANGE DATA

Three hundred seconds of data obtained at a nominal elevation of 400 ft. along the Slaton test line have been analyzed. Figure 34 shows single second analysis using MAZAS and the Window method over a fairly constant portion of the flight line. Like the simulated data and the Lake Mead test range data, the uranium analysis using MAZAS is more precise than the Window method having an RMS deviation of 24% compared with a 28% deviation for the Window method. The deviation for the potassium MAZAS and Window analysis are 19% and 18%, respectively, while the thorium MAZAS analysis is considerably poorer than the Window analysis having a 26% RMS deviation as compared to the Window value of 17%. Figure 35 shows a comparison of the DELPHI time filtered uranium analysis over the anomaly using MAZAS and the Window analysis. The shapes are very similar except that the MAZAS results give a smaller increase than the Window analysis. The speculation made in the preceeding section that the MAZAS analysis measures only the discrete portion of the spectrum while the Window analysis includes some continuum from the ground would explain this difference.

Figure 34. Comparison of Single-Second Window Method and MAZAS Analyses of Fairly Constant Portion of Slaton Test Line Data at 400-ft. Elevation.

Figure 35. Comparison of DELPHI Time Filter Applied to Uranium Analysis Using the Window Method and MAZAS Analyses for the Slaton Test Line Data.

4. CONCLUSIONS AND FUTURE IMPROVEMENTS/DEVELOPMENTS

4.1 CONCLUSIONS

The present testing and evaluation of the code MAZAS/DELPHI has lead to the following conclusions:

- The precision of MAZAS is:
 - Better than the Window method for the analysis of uranium
 - Comparable to the Window method for the analysis of potassium
 - Worse than the Window method for the analysis of thorium.
- The accuracy of MAZAS is consistently better than the Window method when used on simulated data.
- The accuracy of the average values of the individual gamma-ray intensities obtained with MAZAS is good over the entire energy spectrum for the uranium and thorium spectra. The precision of the intensities of the low energy lines is poor unless 15-20 sec integration times are used.
- The results of the analysis of actual flight data for potassium and thorium are very similar for MAZAS and the Window method.
- The results of the analysis of actual flight data for uranium using MAZAS and the Window method appear to be different. MAZAS, which measures an average of several discrete gamma-ray components, seems to indicate considerably more airborne radon than the Window method. It is suspected that the Window method is measuring a combination of discrete and continuum components and that this is resulting in analyses that are inconsistent with MAZAS.
- The DELPHI time filter appears to work exceedingly well on simulated data. The accuracy of the method on actual flight data is uncertain.

4.2 RECOMMENDATIONS FOR FUTURE WORK

This testing and evaluation have also lead to some recommendations and suggestions for future work on the development of the MAZAS/DELPHI code.

4.2.1 Generation of Response Functions in DELPHI

The response functions now used in DELPHI were calculated on the Berkeley CDC-7600 computer using subroutines in the code MAZNAI. If these response functions are to be changed for any reason, such as changed detector resolution, the calculations have to be redone on the CDC-7600 computer, transferred into the DEC-10 working area and then written into a form compatible with the DELPHI input format. DELPHI should include the capability of calculating detector responses given the parameters for the response function.

4.2.2 Calculation of Continuum Gamma-Ray Shapes

In addition to the modifications to the basic code DELPHI/MAZAS noted above, calculation of the continuum gamma-ray spectra should be made using a realistic gamma-ray transport code such as ANISN or MORSE. These calculations should include:

- Calculations of the scattered gamma-ray spectra at various elevations above a uniformly distributed ground source of radiation.
- Calculations of the scattered spectra for various thickness of overburden.
- Calculation of the scattered spectra for airborne radon.

The inclusion of such scattered spectral shapes into the code would be a significant improvement over the estimates of the scattered components used in the present study.

4.2.3 Ability to Extract Continuum Intensities

At present the unfolded intensities of the continuum components correspond to orthogonalized response functions. The numbers necessary to convert these to intensities for unorthogonalized response functions are calculated in the code but discarded. The code needs to be modified so that the intensities of the unorthogonalized response functions can be extracted.

4.2.4 Analysis of Additional Simulated and Actual Flight Data

The data analysis presented in this report on the simulated data gives the indication that the MAZAS code is calculating the quantities it is designed to calculate. The analysis of the airborne flight data raises some question concerning the comparison of the MAZAS and window uranium analysis. Additional simulated data and actual flight data should be analyzed to determine the origin of the differences. Also, methods of using the information contained in the uranium and thorium continua intensities should be investigated to see if more sensitive analyses can be obtained from the MAZAS analysis of airborne data.

4.2.5 Extraction of Slope Parameters

The code now calculates the intensities of all of the various lines for the thorium and uranium spectra. Only a few of the intensities are used, however. One needs to be able to extract a slope parameter for the determination of the shape of the discrete spectra. This could indicate the presence of vegetation effects or overburden and airborne random. Thus, it may be possible to correct for these using the 4π data itself. Since all of the lines from a given element are correlated in both energy and time the application of a two-dimensional time/energy filter would give a time averaged slope parameter.

4.2.6 Extraction of Additional Information

From the analyses of the test and simulated data discussed above, it should be possible to determine how much information concerning vegetation effects, overburden and airborne radon can be extracted from the MAZAS analysis of airborne data. The code should be modified so this information is automatically produced. A determination should also be made of what information is required and how this information can be employed by contractors.

4.2.7 Modification of Code to Handle Large Amounts of Data

As the code is now structured, the analysis of sizable amounts of data would be time-consuming. The data are read from tape and converted to DEC-10 compatible files. These files are then converted to a form which is read by DELPHI.

In executing DELPHI one must go through the following command structure to obtain a single second analysis of a new data set:

```
READ "DATA" FROM RECORD 1-100
ADJUST THE GAIN
CHANGE K
READ "DATA" FROM RECORD 1 TO RECORD 100
INPUT K (DISCRETE)
SET MAZAS
SET SUM TO 1
SURVEY DATA FROM RECORD 1 TO 100
```

This process must be repeated for the second 100 seconds of data, and so forth. The code should have a module so that an entire data tape of many thousands of seconds of data can be analyzed using a single command.

This new capability should be exercised on a complete quadrangle of data. This will provide the background experience with the code necessary to devise and recommend proper analysis procedures and data presentations.

4.2.8 Reconfiguration of DELPHI/MAZAS for Production Analysis of Data

Based on the experience gained in the above analysis, the code should be reconfigured in a manner appropriate for subcontractor use for the routine analysis of airborne radiometric data.

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5. REFERENCES

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APPENDIX 1

GAMMA RAY ENERGIES, BRANCHING RATIOS
AND PARENT ISOTOPES USED IN CALCULATING
RESPONSE FUNCTIONS FOR MAZAS

APPENDIX 1 - Gamma Ray Energies, Branching Ratios and
Parent Isotopes Used in Calculating
Response Functions for MAZAS.

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
1	1.461	10.1	1.461 K	^{40}K
2			0.351 U	
	0.4057	0.19		^{211}Pb
	0.3960	0.033		^{214}Bi
	0.3880	0.61		^{214}Bi
	0.3860	0.56		-
	0.3519	40.0		^{214}Pb
	0.3471	0.061		-
	0.336	0.106		-
	0.3236	0.055		^{223}Ra
	0.3141	0.158		^{214}Pb
	0.3044	0.14		^{214}Pb
3			0.609 U	
	0.6654	1.58		^{214}Bi
	0.6492	0.061		-
	0.6394	0.032		-
	0.6331	0.066		-
	0.6157	0.101		-
	0.6093	46.9		^{214}Bi
	0.5801	0.39		^{214}Bi
	0.5728	0.091		^{214}Bi
	0.5434	0.083		^{214}Pb
	0.5369	0.074		-
	0.5336	0.173		^{214}Pb

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
3 (cont'd)	0.5115	0.37		^{214}Pb
	0.4870	0.46		^{214}Pb
	0.4804	0.40		^{214}Pb
	0.474	0.131		^{214}Pb
	0.4697	0.145		^{214}Bi
	0.4618	0.281		^{214}Bi
	0.4547	0.36		^{214}Bi
4			0.768 U	
	0.7683	4.97		^{214}Bi
	0.7528	0.135		^{214}Bi
	0.7336	0.054		-
	0.7278	0.016		-
	0.7198	0.39		^{214}Bi
	0.7106	0.077		-
	0.7031	0.45		^{214}Bi
	0.6979	0.035		-
	0.6832	0.073		-
5			0.934 U	
	0.964	0.38		^{214}Bi
	0.934	3.19		^{214}Bi
	0.904	0.124		^{214}Pb
	0.839	0.59		^{214}Bi
	0.8323	0.02		^{214}Pb
	0.8261	0.093		-
	0.8311	0.141		^{214}Bi
	0.8151	0.047		-
	0.8061	1.28		^{214}Bi
	0.7997	0.044		^{214}Po
	0.7859	1.09		^{214}Pb

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
6			1.120 U	
	1.1730	0.078		-
	1.1551	1.73		^{214}Bi
	1.1336	0.272		^{214}Bi
	1.1202	15.5		^{214}Bi
	1.1041	0.183		^{214}Bi
	1.0610	0.29		^{214}Bi
	1.0519	0.33		^{214}Bi
	1.0323	0.128		-
7			1.377 U	
	1.4792	0.074		^{214}Bi
	1.4079	2.5		^{214}Bi
	1.4015	1.38		^{214}Bi
	1.3853	0.80		^{214}Bi
	1.3776	4.1		^{214}Bi
	1.3699	0.088		-
	1.3037	0.118		^{214}Bi
	1.2809	1.47		^{214}Bi
	1.2381	6.1		^{214}Bi
	1.2077	0.47		^{214}Bi
8			1.764 U	
	1.896	0.18		^{214}Bi
	1.890	0.084		-
	1.873	0.23		^{214}Bi
	1.847	2.16		^{214}Bi
	1.838	0.37		^{214}Bi
	1.764	16.2		^{214}Bi
	1.729	3.0		^{214}Bi

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
8 (cont'd)	1.6839	0.225		^{214}Bi
	1.6612	1.14		^{214}Bi
	1.5993	0.37		^{214}Bi
	1.5947	0.28		^{214}Bi
	1.5832	0.77		^{214}Bi
	1.5432	0.40		^{214}Bi
	1.5385	0.39		^{214}Bi
	1.5091	2.2		^{214}Bi
9			2.2041 U	
	2.3311	0.26		^{214}Bi
	2.2934	0.34		^{214}Bi
	2.2666	0.019		-
	2.597	0.015		-
	2.2041	5.25		^{214}Bi
	2.1928	0.052		-
	2.1478	0.021		-
	2.1185	1.25		^{214}Bi
	2.1099	0.089		-
	2.0895	0.056		-
	2.0529	0.066		^{214}Bi
	2.0210	0.020		-
	2.0107	0.061		^{214}Bi
10			2.447 U	
	3.0816	0.0038		-
	3.0536	0.022		^{214}Bi
	2.9996	0.009		^{214}Bi
	2.9785	0.015		^{214}Bi
	2.9217	0.016		^{214}Bi

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
10 (Cont'd)	2.8933	0.0056		^{214}Bi
	2.8801	0.010		^{214}Bi
	2.8270	0.004		-
	2.7861	0.006		-
	2.7688	0.026		^{214}Bi
	2.6946	0.033		^{214}Bi
	2.5057	0.005		-
	2.4477	1.62		^{214}Bi
	2.3767	0.12		-
11			0.3387 Th	
	0.3387	11.1		^{228}Ac
	0.3329	0.36		^{228}Ac
	0.3283	3.21		^{228}Ac
	0.3279	0.156		-
	0.3219	0.24		^{228}Ac
	0.3001	3.15		^{212}Pb
	0.2881	0.33		^{212}Pb
	0.2794	0.252		^{228}Ac
	0.2773	2.28		^{208}Tl
	0.2705	3.36		^{228}Ac
	0.2526	0.35		-
12			0.463 Th	
	0.5093	0.48		^{228}Ac
	0.5037	0.12		^{228}Ac
	0.4786	0.24		^{228}Ac
	0.4633	4.44		^{228}Ac
	0.4528	0.38		^{212}Bi
	0.4411	0.12		^{228}Ac
	0.4098	0.12		^{228}Ac
	0.3401	0.48		^{228}Ac

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
13			0.5831 Th	
	0.5831	29.9		$^{208}_{\text{Tl}}$
	0.5711	0.288		$^{228}_{\text{Ac}}$
	0.5626	0.84		$^{228}_{\text{Ac}}$
	0.5497	0.12		$^{220}_{\text{Rn}}$
	0.5464	0.18		$^{228}_{\text{Ac}}$
	0.5221	0.12		$^{228}_{\text{Ac}}$
14			0.7272 Th	
	0.7272	6.62		$^{212}_{\text{Bi}}$
	0.7267	0.80		$^{228}_{\text{Ac}}$
	0.7014	0.12		$^{228}_{\text{Ac}}$
	0.6754	0.13		$^{228}_{\text{Ac}}$
	0.5832	0.13		$^{228}_{\text{Ac}}$
15			0.9112 Th	
	0.9688	15.96		$^{228}_{\text{Ac}}$
	0.9644	4.44		$^{228}_{\text{Ac}}$
	0.9519	0.28		-
	0.9112	26.9		$^{228}_{\text{Ac}}$
	0.8933	0.34		$^{212}_{\text{Bi}}$
	0.8605	4.50		$^{212}_{\text{Bi}}$
	0.8404	1.10		$^{228}_{\text{Ac}}$
	0.8356	1.80		$^{228}_{\text{Ac}}$
	0.8304	0.72		$^{228}_{\text{Ac}}$
	0.7950	4.68		$^{228}_{\text{Ac}}$
	0.7855	1.06		$^{212}_{\text{Bi}}$
	0.7820	7.56		$^{228}_{\text{Ac}}$
	0.7718	1.80		$^{228}_{\text{Ac}}$
	0.7633	0.60		$^{208}_{\text{Tl}}$
	0.7553	0.97		$^{228}_{\text{Ac}}$

APPENDIX - (Continued)

"Line" #	E_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
16			1.246 Th	
	1.287	0.12		^{228}Ac
	1.2469	0.58		^{228}Ac
	1.1535	0.18		^{228}Ac
	1.1104	0.29		^{228}Ac
	1.095	0.12		^{228}Ac
	1.0943	0.15		^{208}Tl
	1.0787	0.54		^{212}Bi
	1.0650	0.13		^{228}Ac
	1.0331	0.20		^{228}Ac
	0.9879	0.19		^{228}Ac
17			1.6307 Th	
	1.6663	0.18		^{228}Ac
	1.6383	0.48		^{228}Ac
	1.6307	1.44		^{228}Ac
	1.6256	0.31		^{228}Ac
	1.6207	1.47		^{212}Bi
	1.6056	0.16		^{228}Ac
	1.5883	3.12		^{228}Ac
	1.580	0.76		^{228}Ac
	1.5571	0.17		^{228}Ac
	1.5017	0.48		^{228}Ac
	1.4962	0.94		^{228}Ac
	1.4592	0.90		^{228}Ac
	1.3596	0.14		^{228}Ac

APPENDIX - (Continued)

"Line" #	I_{γ} (MeV)	I_{γ} ($\gamma/100$ disintegrations)	Name	Parent Isotope
18	2.6145	36.0	2.614 Th	^{208}Tl
19	0.511	1.	0.511 ANN	annihilation
20	0.661	-	0.661 Cs	^{137}Cs
21	0.2583	0.063	1.001 U	^{234}Pa
	0.7428	0.743		^{234}Pa
	0.7500	0.014		^{234}Pa
	0.7665	0.309		^{234}Pa
	0.7863	0.309		^{234}Pa
	1.001	0.83		^{234}Pa
	1.5109	0.014		^{234}Pa