(2)

Feasibility of a Hand-Held Integrating Dosimeter Using a Cadmium Telluride Detector

Final Report to

UNITED STATES AIR FORCE

School of Aerospace Medicine
Brooks Air Force Base
San Antonio, Texas 78235-5301

Work Performed Under Contract Number
F33615-85-C-4532

by

Barry G. Wahlig

SOURCE TECHNOLOGIES, INC.

Quantum Technology Division
830 Franklin Court
Marietta, Georgia 30067

September 1986

NOTICES

This technical report is published as received and has not been edited by the technical editing staff of the Armstrong Laboratory.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement operation, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder or any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The mention of trade names or commercial products in this publication is for illustration purposes and does not constitute endorsement or recommendation for use by the United States Air Force.

This report has been reviewed and is approved for publication.

Government agencies and their contractors registered with the Defense Technical Information Center (DTIC) should direct requests for copies to: DTIC, Cameron Station, Alexandria VA 22304-6145.

Non-Government agencies may purchase copies of this report from: National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield VA 22161.

Kenneth A Hardy

Kenneth A. Hardy
Physicist, Personnel Dosimetry Branch

REPORT DOCUMENTATION PAGE

OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	86SEP26	FINAL 7/31/85 TO 9/31/86

4. TITLE AND SUBTITLE
Feasibility of a Hand-Held Integrating Dosimeter Using a Cadmium Telluride Detector

5. FUNDING NUMBERS
C - F33615-85-C-4532
PE - 65502F
PR - 7757
TA - 04
WU - 46

6. AUTHOR(S)
Wahlig, Barry G.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Source Technologies, Inc.
Quantum Technology Div.
830 Franklin Court
Marietta, GA 30067

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
USAFSAM/RZB
BROOKS AFB, TX 78235-5301

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL-TR-1992-0075

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this contract was to conduct research leading to the development of a real-time, hand-held, integrating dosimeter for the measurement of ionizing radiation doses to the crews of high-altitude aircraft and space flights. The specific method chosen was the use of a cadmium telluride detecor with appropriate circuitry and computer processing to determine the total energy dposited in the detector. The raw spectra from energy deposited in the detector, and the rate of energy disposition. These unmodified results were found to have a strong dose rate dependence above about 1 rad/hr. This dependence was removed through the use of an empirically determined correction based on the dead time of the MCA during spectrum acquisition. With this correction applied to all data the system response was highly linear with respect to dose rate and total dose and showed no energy depencence over the range of gamma ray energies from 186 keV to 1250 deV. The results support the feasibility of the method and suggest that further development would lead to a real-time electronic dosimeter capable of approximately tissue-equivalent response to a wide range of radiation types in mixed fields.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Radiation Dosimeter (U), Integrating Electronic Dosimeter (U), Cadmium-Telluride (CdTe) Dosimeter (U)	81
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

PROJECT SUMMARY

Report Title: Feasibility of a Hand-Held Integrating Dosimeter Using a Cadmium Telluride Detector

Contract No.: F33615-85-C-4532

Purpose: To conduct research leading to the development of a real-time, hand-held, integrating electronic dosimeter for the measurement of ionizing radiation doses to the crews of high-altitude and space flights. The specific method to be explored is the use of a cadmium telluride detector and appropriate circuitry and computer processing to determine the total energy deposited in the detector.

Summary description of the work carried out:
Following appropriate research into previous approaches to and results of the measurement of radiation doses in space, a test system was assembled. This system consisted of commercially-available components: a CdTe detector in wound probe geometry, a charge-sensitive preamplifier, a portable multichannel analyzer (MCA) system, and a portable computer. The computer captured the data generated by the MCA for subsequent processing and analysis. The system was exposed to gamma rays of Ra-226 and Co-60 sources, and tested for linearity in dose rate and total dose responses, and for energy independence.

Findings: The raw spectra from the detector were processed using predetermined energy calibrations to estimate the total energy deposited in the detector, and the rate of energy deposition. These unmodified results were found to have a strong dose rate dependence above about 1 rad/hr. This dependence could be removed through the use of an empirically determined correction based on the dead time of the MCA during spectrum acquisition. With this correction applied to all data, the system response was highly linear with respect to dose rate and total dose, and showed no energy dependence over the range of gamma ray energies from 186 keV to 1250 keV.

Applications:
The results support the feasibility of the method and suggest that further development would lead to a real-time electronic dosimeter capable of approximately tissue-equivalent response to a wide range of radiation types in mixed fields.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1.0
INTRODUCTION

1.1 Statement of the Problem

During high-altitude and space flights, vehicles and their occupants encounter a variety of high-energy particles and radiations to an extent not normally experienced near the earth's surface. As a result of the interactions of this steady stream of high-energy radiations with the vehicle structure, the occupants are showered with a number of kinds of ionizing radiations, including alpha particles, electrons, protons, and photons (in the X-ray and gamma ray energy span).

Electronic dosimeters developed for nuclear reactor applications are not satisfactory for monitoring this radiation because they are sensitive mainly to photons.. This is appropriate at reactors, where photons are the principal type of radiation with sufficient energy to penetrate deeply into the whole body. However, this condition is not true in space, where several types of radiation contribute significantly to the total body dose (see Section 1.2).

Since electronic dosimeters *sensitive* to the whole range of significant radiations are not yet available, a number of other dosimeter types have been used in space. As discussed in Section 1.2, these have ranged from passive dosimeter arrays to electronic instruments. In general, however, the existing dosimeters have not matched the ideal characteristics for a device suitable for use on long missions:

1. Response to all significant radiations. This should definitely include electrons, photons, protons, and alpha particles. It should preferably also include fast neutrons.

2. Full portability within and outside the spacecraft.

3. Real time or near-real time digital presentation of the current dose rate and the accumulated dose.

4. Accurate operation over a wide range of dose rates from near-zero (5 mrad/day = 0.2 mrad/hr) to 100 rad/hr.

5. Accurate operation over a moderate range of accumulated doses, from 1 mrad to 100 rad.

6. Durability sufficient for use in spacecraft (including the STS) and airplanes.

The requirements of durability and portability suggest the use of solid state radiation detectors. This would reduce the size and weight of the power supplies compared to those required to operate gas-filled detectors. Also, it would be clearly preferable to use the minimum number of detectors to cover the range of radiation types and dose rates to be encountered.

The purpose of the research reported here is to devise a method which satisfies the the above requirements, and to develop data to determine the feasibility of the method. It was performed under Contract No. F33615-85-C-4532. This contract was executed following a Source Technologies proposal which responded to Topic No. 208 in the 1985 Defense Department Small Business Innovation Research Program Solicitation, "Development of Hand-Held Integrating Dosimeter."

Section 2.0 describes the basic approach evaluated in the research, which involves the use of a cadmium telluride detector as a spectrometer in the dosimeter. This approach is supported by the introductory material on previous measurements of space flight radiation doses in Section 1.2, and on previous applications of CdTe detectors in Section 1.3.

Sections 3.0 and 4.0 describe the measurements which were made under this contract, and evaluate the performance of the test system. They support the conclusion that the concept is workable. Therefore, Section 5.0 presents a conceptual design for a hand-held version of the test system, and suggests areas of further research which would determine its feasibility definitively, leading up to the development of a practical commercial device.

1.2 Previous Measurements of the Radiation Environment of Space

Any attempt to develop a device to measure radiation doses in space must begin with some knowledge of prior efforts in this field. This section will summarize a representative sample of the published information on the methods and results of previous space radiation dose measurements.

1.2.1 Measurement Methods Used

A very wide variety of methods have been used to measure radiation doses on manned space flights, including both passive detectors (such as TLD's) which provide no external indication during use, and active electronic instruments which can provide real-time readings to the crew. Among the most widely-used are the following:

1. Crystalline TLD's. Several authors report the use of ordinary crystalline thermoluminescent phosphors such as calcium sulfate (Dy and Tm activated), lithium fluoride (both Li-6 and Li-7), and calcium fluoride (Akatov 1980, Benton 1984, Benton 1985). In several cases, they were used in connection with thick plastic stacks, serving both as track etch detectors (see below), and as absorbers to provide sufficient thickness for charged particle equilibrium at the TLD's. Their purpose is invariably to estimate dose due to low-LET (*linear energy transfer*) radiation such as photons and electrons, and they seem to perform with adequate reproducibility and accuracy. However, in no case has provision been made for onboard readout, so that the information they contain is extracted only after the conclusion of the mission.

2. Aluminophosphate glass TLD's. Some Soviet authors report the use of glass TLD's without suggesting any particular advantages for them over the well-established crystalline types . The agreement between the glass and crystalline TLD's was reported to be approximately the same as among the various types of crystalline TLD's (Akatov 1980). Onboard readout in the event of solar flares has been suggested, but apparently not put into practice (Bochvar 1983).

3. Track etch detectors. Both Soviet and American authors report the use of plastic track etch detectors for the estimation of the fluence rate of high-LET particles such as alpha particles, protons, and heavy high-energy nuclei known as HZE particles (Akatov 1980, Benton 1984, Benton 1985). On the American flights, the plastics used have included cellulose nitrate, Lexan polycarbonate, and CR-39. In the particular case of the Spacelab missions, complex stacks known as VFI (Verifi-

cation of Flight Instrumentation) Passive Detectors were developed that included a number of irradiators and absorbers for estimation of the fluence in various parts of the neutron spectrum (Benton 1985). Somewhat less complex stacks of different types have been used on most space shuttle (STS) missions (Benton 1984). Like other types of passive detectors (TLD's and emulsions), track etch detectors have only been read out on the ground.

4. Nuclear emulsions. In at least two cases, track etch detectors have been supplemented by nuclear emulsions, especially for the measurement of proton fluences (Akatov 1980, Benton 1985). Like plastic track detectors, emulsions must have their latent particle tracks developed for examination through the use of liquid baths, and have apparently been read only on the ground.

5. Fixed electronic detectors. Spacelab-1 included an Active Radiation Detector consisting of a tissue-equivalent ionization chamber and two xenon-filled proportional counters (Benton 1985). However, this unit was not used to estimate doses directly, but only to: a) estimate the temporal variation in the total dose that was itself estimated using passive detectors; and b) to indicate which radiation types were primary contributors to dose. A complex electronic instrument based on the principles of microdosimetry and designed to measure dose, dose equivalent, and HZE fluence has been developed but has apparently not yet been used in space (Braby 1984a, Braby 1984b, Braby 1985). Both of these instruments are rather large and heavy, and are not well suited for being moved frequently about the vehicle. For example, the microdosimetry system consists of an electronics enclosure attached to two separate gas-filled detectors (and a battery charger if necessary) for a total size of over 1 cubic foot and a weight of about 40 pounds (Braby 1984a).

6. Hand-held electronic instruments. Reports of hand-held electronic instruments used in space are rather limited. Of direct interest is the Radiation Monitoring Equipment tested on Space Shuttle flights STS-8, -11, -41C, -41D, -41G, and -51A (Cash 1985, Madonna 1984, Madonna 1985). This equipment consists of two instruments developed by EG&G: a Pocket Rem Meter or PRM (including three ionization tubes surrounded by tissue-equivalent plastic) for the determination of proton and neutron doses; and a Hand-Held Gamma-Ray Counter or HRM-III (consisting of a mercuric iodide detector with a 100 keV threshold) which counts photons, but does not estimate dose from them. Both these instruments have proven reasonably rugged and

practical for use for periods on the order of one hour to one day, but neither provides complete dosimetric information.

In short, although a number of approaches have been used for the estimation of radiation doses during space flight, no system has yet been used in space which provides complete dosimetric information in near-real time, and which is also fully portable. Thus, the effort expended in this and parallel research projects may lead to a development which is both novel and useful.

1.2.2 Summary of Previous Dose Measurement Results

The space radiation environment is a most complex one which varies by orders of magnitude as a function of altitude above the Earth, latitude and longitude, time of day, the general level of solar activity, and the number and intensity of solar flares and magnetic storms. The following discussion of measurements of that environment is separated into a description of the origins and types of the radiation, and the degree of personnel exposure which results from it.

1.2.2.1 Types of Radiation in Space

The principal components of the space radiation field are the following (Jordan 1983, Miroshnichenko 1983):

1. Trapped radiation. The Earth's geomagnetic field captures and redirects charged particles approaching the Earth into belts which are farthest from the surface at the equator, and impinge on the Earth at the poles. The majority of this radiation is electrons, although protons also contribute some dose.

2. Solar cosmic radiation. The Sun is a constant source of radiation, mostly protons with energies greater than 1 MeV. The energy range between 20 MeV and 500 MeV is perhaps most critical to personnel and equipment protection.

3. Galactic cosmic radiation. A stream of protons, alpha particles, and other nucleons, with energies up to about 10^{16} MeV, strikes the Earth from deep space. However, these particles are not very effective in imparting dose equivalent: the overall quality factor for HZE particles has been estimated as ~1.5 for near-Earth orbit, and ~5.5 in free space (Benton 1983). The total cosmic radiation (solar plus galactic) varies in magnitude by about a factor of 2 over the solar cycle, being strongest when sunspot activity is minimal.

4. Solar flare radiation. The composition of solar flares is similar to that of galactic cosmic radiation, but is highly variable in magnitude. Variations in solar flares are as yet not reliably predictable.

To these four natural sources may also be added the man-made component due to any nuclear reactors or thermoelectric generators on board the spacecraft. In all cases found in the open literature, the natural contribution was by far the dominant one.

Because the radiation found in space is composed of a variety of particles which come from several sources, a number of parameters influence the degree to which the crew on any particular mission is exposed. The most important influences on the crew dose rate are the following (Benton 1983, Benton 1985, Jordan 1983):

1. Altitude. The strongest influence on the dose is the altitude of the craft above the surface of the Earth. For example, at constant orbital inclination, the dose rate has been shown to multiply by about 200 times as altitude increases from 200 to 800 km.

2. Latitude and longitude. There are two important influences of latitude and longitude at constant altitude. One is the "horns" of the inner electron belt which approach closer to the Earth's surface the closer one is to the poles. The extreme case is a polar orbit in which the maximum time is spent in the most intense portions of the electron belts. The second influence is encounters with the South Atlantic Anomaly, an area near the eastern coast of South America in which electron flux reaches over 1000 times the world average and the proton flux exceeds 10 times the world average at the same altitude. The South Atlantic Anomaly (SAA) is encountered at all orbital inclinations greater than about 25°, and becomes less important beyond about 50° where the inner electron belt begins to be encountered. Therefore, orbital inclination is a weak influence on dose rate, so long as altitude is greater than about 300 km and inclination is greater than about 35°. HZE radiation also becomes more important at the higher inclinations. However, at lower inclinations, geomagnetic shielding removes the influence of galactic cosmic radiation and solar flares almost completely.

3. Solar activity. As mentioned above, solar cosmic radiation from the quiescent Sun varies by about a factor of 2 over the solar cycle. Far more important is the effect of solar flares, especially at higher orbital inclinations where geomagnetic shielding is minimal.

Indeed, in high polar orbits it would be possible for the crew to absorb unacceptable doses from a large flare before mitigating maneuvers could be completed, especially in the case of extravehicular activity (Jordan 1983).

4. Shielding. The amount of material around the crew is a minimal influence on the radiation dose, particularly for the HZE component. For example, inside the film vault on Skylab (up to 50 g/cm^2 in thickness), the HZE fluence was still about one-half what it was outside (Benton 1983). Calculations indicate that spacecraft shielding of up to 10 g/cm^2 reduces the total dose rate by less than a factor of 10 compared to free space (Smirennyy 1983). However, the presence of heavy shielding does have the effect of shifting the spectrum of HZE particles toward lighter masses.

The large number of effects at work have so far exceeded the ability of modelers. It is estimated that models for spectra and intensities are uncertain by approximately factors of 2 for protons, 5 for electrons, and more for neutrons (Benton 1984).

1.2.2.2 Radiation Doses on Previous Missions

Considering the many factors and parameters listed in Section 1.2.2.1, it is perhaps not surprising that it is difficult to make meaningful general statements regarding the dose rates encountered in space. Nevertheless, some idea of the magnitudes involved can be gained from Benton's summary of dose rates on U.S. space missions over the last 20 years, reproduced in Table 1-1 (Benton 1985).

Benton's data show dose rates ranging from about 5 mrad/day to 90 mrad/day in Earth orbit, depending on the orbital altitude and inclination; these doses are about 30% due to low-LET radiation and 70% due to high-LET radiation. As expected, the missions with lower orbital inclinations have the lower dose rates, on the order of 5 to 20 mrad/day in most cases. This in agreement with Salyut-6 estimates, which were in the range of 15 to 31 mrad/day, depending on the location within the station (Akatov 1980). Neutron doses were on the order of 4 to 12 mrem/day on a variety of STS missions (Benton 1985, Cash 1985, Madonna 1984, Madonna 1985). These are certainly manageable dose rates from a dosimeter design point of view.

From a personnel protection point of view, dose rates of 10 to 20 mrem/day are of no great concern, even for very long missions in Earth orbit. However, higher altitudes and inclinations will produce higher dose rates (up to 100

Table 1-1. Dosimetry Data from U.S. Manned Spaceflights

Flight	Duration (hrs/days)	Inclination (deg)	Apogee-Perigee (km)	Average Dose (mrad)	Average dose rate (mrad/day)
Gemini 4	97.3 hrs	32.5	296 - 166	46	11
Gemini 6	25.3 hrs	28.9	311 - 283	25	23
Apollo 7*	260.1 hrs			160	15
Apollo 8	147.0 hrs		lunar orbital flight	160	26
Apollo 9	241.0 hrs			200	20
Apollo 10	192.0 hrs		lunar orbital flight	480	60
Apollo 11	194.0 hrs		lunar orbital flight	180	22
Apollo 12	244.5 hrs		lunar orbital flight	580	57
Apollo 13	142.9 hrs		lunar orbital flight	240	40
Apollo 14	216.0 hrs		lunar orbital flight	1140	127
Apollo 15	295.0 hrs		lunar orbital flight	300	24
Apollo 16	265.8 hrs		lunar orbital flight	510	46
Apollo 17	301.8 hrs		lunar orbital flight	550	44
Skylab 2**	28 days	50	altitude = 435	1596	57 ± 3
Skylab 3	59 days	50	" = 435	3835	65 ± 5
Skylab 4	90 days	50	" = 435	7740	86 ± 9
Apollo-Soyuz Test Project	9 days	50	" = 220	106	12
STS-2†	57.5 hrs	38	" = 240	12.5 ± 1.8	5.2
STS-3	194.5 hrs	38	" = 240	52.5 ± 1.8	6.5
STS-4	169.1 hrs	28.5	" = 297	44.6 ± 1.1	6.3
STS-5	120.0 hrs	28.5	" = 297	27.8 ± 2.5	5.6
STS-6	120.0 hrs	28.5	" = 284	27.3 ± 0.9	5.5
STS-7	143.0 hrs	28.5	" = 297	34.8 ± 2.3	5.8
STS-8	70/75 hrs	28.5	" =297/222	34.8 ± 1.5	5.8
STS-9	240.0 hrs	57	" = 241	101.1 ± 3.1	10.1
STS-9 (SL-1)				100.0 ±10.3	10.0
STS-41B	191.0 hrs	28.5	" = 297	43.6 ± 1.8	5.5
STS-41C	168.0 hrs	28.5	" = 519	403.0 ±12.0	57.6
STS-41D	145.0	28.5	" 297	42.0 ± 2.8	7.0
STS-41G	29/19/148.5	57.0	" 352/274/224	82.4 ± 2.4	10.0
STS-51A	192	28.5	" 324	94.3 ± 4.9	11.8

*Doses quoted for the Apollo flights are skin TLD doses. The doses to the blood-forming organs are approximately 40% lower than the values measured at the body surface.
**Mean thermoluminescent dosimeter (TLD) Skylab dose rates from crew dosimeters.
†STS data is an average of USF TLD-700 (^{7}LiF) readings.

Table reproduced from (Benton 1985).

mrem/day or more). Instantaneous dose rates may be 10 times higher, for example in the SAA. The major concern in the lower inclination and altitude cases would be: a) extra-vehicular activity, especially when suits do not shield out energetic electrons; and b) unpredictable solar flares, which can produce dose rates an order of magnitude above the averages. The question for mission managers becomes how to balance the costs of training and cycling crews with the potential effects of lengthy exposures to moderate dose rates.

1.3 Prior Developments with Cadmium Telluride Detectors

The charge in this project is the development of a solid state electronic integrating dosimeter especially suited to space flights. There are a limited number of potential detectors for such a system, assuming that a semiconductor detector is to be used rather than the bulkier and less stable scintillator detectors. Among the semiconductors, there are the elemental semiconductors germanium and silicon; and the compound semiconductors such as cadmium telluride, mercuric iodide, and gallium arsenide.

A dosimeter must operate at room temperature, which serves to exclude the elemental semiconductors from consideration. They have such small band gaps (0.7 eV for Ge, and 1.1 eV for Si) that their conductivity is excessive at room temperature. The resulting electronic noise in these materials makes it impossible to distinguish between nuclear events and background when they are operated without cooling. Therefore, consideration must be confined to the compounds.

The compound semiconductors share several traits which make them potentially useful for dosimeters. In particular their wider band gaps (1.5 eV or more at room temperature) reduce their conductivity appreciably, but the gap is still narrow enough that a large number of charge carriers are generated and the energy resolution is quite acceptable. Furthermore, they have much higher atomic numbers than do Si and Ge (48 and 52 for CdTe; 80 and 53 for HgI_2) implying much higher detection efficiencies for ionizing radiation of all types.

As laboratory instruments, the compounds offer poorer energy resolution than do the elements, but this is not a serious consideration in a dosimeter where nuclide identification is not required and a wide range of energies is present. The more important practical disadvantage of the compounds is their lesser availability as commercial products, since they have been under serious development for only about 15 years. Indeed it is primarily for the reason of commercial availability that CdTe was selected for investigation in this project: there are several suppliers of CdTe detectors who can offer detectors in a variety of configurations. In addition, as summarized below, there have been a number of interesting devices developed based on CdTe which provide background useful to this research. The remainder of this section is devoted to reviewing that experience.

1.3.1 Basic Physical Parameters

Cadmium Telluride is a detector material which is just beginning to find wide industrial applicability. Its most important physical parameters for use in a dosimeter are shown in Table 1-2 (Ristinen 1981, Bojsen 1984).

The characteristics shown are for typical modern detectors, which are chlorine-doped p-type material, purified by the traveling heater method, and fabricated as surface barrier diode detectors (Wald 1972, Serreze 1974). These detectors are now customarily produced with platinum surface contacts to avoid the polarization problem (see Section 3.2.1), which was quite severe with the MOS structure formerly used for contacts (see e.g., Hodgkinson 1979). They operate at low voltages that are well suited to portable instruments in general, and to high altitude and space flight instruments in particular, for which power supplies need to be light and where electrical arcing must be avoided. A minor disadvantage is the very high light sensitivity of CdTe, which implies that its housing must always be thick enough to be light-tight.

Of particular importance in dosimetry is the radiation ionization energy, which should preferably be as independent as possible of the type and energy of the radiation causing the ionization. The average value of 4.43 eV/electron-hole pair is well established on the basis of alpha particle measurements (e.g., Cornet 1970, Quaranta 1970, Dabrowski 1974, Ristinen 1981). Information of its dependence on radiation type and energy is somewhat harder to locate. However, the pulse height response of CdTe to alpha particles is known to be highly linear (Cornet 1970). The response is also known to be the same and highly linear for protons, deuterons, He-3 nuclei, and alpha particles over the entire energy range of total absorption in the detector; and the response to protons and oxygen nuclei is at least 80% of the response to electrons of the same energies (Ristinen 1981). Klein showed [as cited in Figure 13-22 of (Knoll 1979)] that other semiconductor detectors such as Si, Ge, and CdS each have uniform response to different types of radiation. Finally, Section 3.2.3 shows a very linear pulse height response to gamma rays of different energies for the detector used in this work. Based on all this information, it may reasonably be expected that the response of CdTe as a function of radiation type is uniform, and as a function of energy is highly linear. However, very high mass and energy particles such as fission products can show a significant pulse height defect compared to alpha particles, perhaps due to incomplete charge collection (Bonchetti 1981).

Table 1-2. Characteristics of Typical CdTe Detectors

Intrinsic Material:	
Density	6.06 g/cm^3
Average atomic number	50
Band gap	1.47 eV
Radiation ionization energy	4.43 eV/electron-hole pair
Practical Detectors:	
Size	5 x 5 x 5 mm
Operating voltage	60 - 100 volts
Resistance	$> 10^9$ Ω
Leakage current	< 10 nA

The radiation durability of CdTe is adequate for the purposes of a dosimeter. Tests to over 500 R of integrated exposure to photons showed no change in detector response (Johnson 1981). Fast neutron fluences of about $5 \times 10^5/cm^2$ or fast neutron doses in the range of 50-100 rads in tissue are required to reduce the detector response appreciably (Johnson 1981, Ristinen 1981). Given the reported doses for flights cited above in Section 1.2.2.2, periods on the order of at least one to three years in space under worst average conditions would be required to reach these integrated exposures.

1.3.2 General Applications of Cadmium Telluride Detectors

Because of its gamma ray attenuation properties, CdTe has found application in a number of areas where small size detectors are required, and energy resolution is not of great importance. Many of these applications are clinical, and involve the insertion or implantation of the detector in tissue (e.g., Bojsen 1984, Entine 1985). A related application is the development of a probe for traveling through nuclear plant systems for the spectroscopic determination of nuclides deposited at various points (Jones 1977).

It should also be noted that a CdTe detector system was assembled and ruggedized to serve as a calibrated event counter for use in space reentry vehicles (Lyons 1977). No energy or dosimetry information was extracted from the output.

The applications noted above are not directly related to dosimetry, although they can provide some guidance in detector packaging, handling and testing. However, there have been several dosimetric applications, as noted in the following Section.

1.3.3 Application of Cadmium Telluride to Dosimeters

During the last 8 - 10 years, cadmium telluride detectors have been used in a number of radiation dosimeter designs, some of them quite novel, and certain of them highly miniaturized. Most have operated in the conventional pulse counting mode (e.g., Umbarger 1979, Wolf 1979, Gorev 1981, Johnson 1981, Wolf 1981, McGowan 1982), although some have been based on current measurements from a detector operated in the photovoltaic mode (e.g., Fox 1978, Entine 1981). However, all of these dosimeters are designed to detect only gamma rays by simply counting detector pulses, rather than by extracting any energy information from them. They therefore use approaches which would be unsuitable if applied to mixed fields that include charged particles.

When designing a gamma dosimeter using CdTe, the attenuation properties of the material (see Figure 1-1) are both its greatest advantage and its greatest disadvantage. The extraordinarily high photoelectric interaction cross section, when coupled with CdTe's high density, make it a very efficient gamma ray absorber. However, this also produces a pronounced over-response at low energies when response is measured simply as count rate per unit exposure rate: a typical result is a count rate per unit exposure rate at 85 keV which is 120 times that at 1250 keV (Johnson 1981).

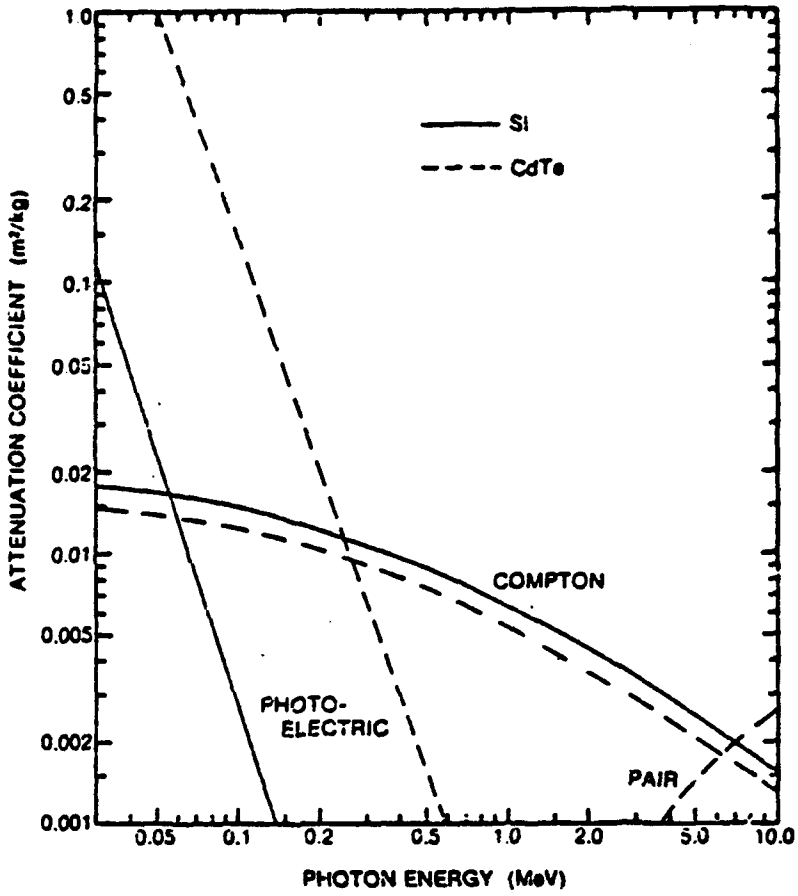
In an unsophisticated pulsed counter of this type, there are really only two workable approaches to reducing this energy dependence, and both have been applied:

1. Energy compensating covers. The approach that has been used with Geiger-Mueller tubes for many years has been to surround the detector with relatively thin metallic covers which selectively attenuate low-energy photons, reducing the response of the detector at low energies. The same method has been extended to CdTe detectors. The covers have been as simple as 3.2 g/cm^2 of lead (Johnson 1981) or 0.4 g/cm^2 of copper (Umbarger 1979), or as complex as 1 g/cm^2 of tin plus 0.2 g/cm^2 of lead (McGowan 1982). This approach can be very effective in flattening the gamma ray response, but is totally unsuited to dosimeters intended to measure charged particles which do not display such a variable response as a function of energy.

2. Energy compensating processes. Given the knowledge of precisely how the count rate sensitivity varies as a function of energy, it is possible to devise pulse processing schemes which weight pulses of different sizes by different factors to flatten the energy response. This results in requiring about 3-5 discriminators to break up the highly-variable portion of the response into regions where the response is more nearly flat (Gorev 1981, McGowan 1982). The multiple-discriminator method is very successful in flattening the response to a few per cent over the range from 50 - 5000 keV, but it is another ad hoc approach suitable only to gamma rays and not to mixed field dosimetry.

In summary, several dosimeters have been developed using CdTe detectors, but none have been based on principles suitable for or readily extendible to dosimetry in mixed fields that include both photons and charged particles.

Figure 1-1. Photon Attenuation Coefficients for CdTe



Reproduced from (McGowan 1982).

SECTION 2.0
DESCRIPTION OF THE PROPOSED METHOD

The method to be evaluated in the present research is based on the realization that the total energy deposited in a CdTe detector is a reasonable surrogate for the energy deposited in a similar volume of tissue. That is, although a CdTe detector will be a more efficient medium for the capture of radiation energy, it will capture the energy according to the same basic mechanisms as would tissue exposed to the same radiation. Therefore, the total energy deposited in a detector will be similar to a tissue dose, perhaps when modified by some factor(s).

This point has been realized before (McGowan 1982), but apparently has not been put into practice. This is because, for a single radiation type such as gamma rays, it is cheaper and simpler to build energy compensation into the hardware than it is to build that compensation into the pulse processing electronics. But when mixed radiation is to be measured, it becomes essential to treat all energy deposition equally, regardless of either the type or energy of the incident radiation.

The approach to be tested is therefore simple in concept, but potentially difficult in practice: to add up the total energy deposited in a CdTe detector, modify that value by factors which do not depend on the type of radiation being absorbed, and use the resulting value as the estimate of absorbed dose in tissue under the same circumstances. This method rests on two principal assumptions:

1. The pulse height out of the detector is a function only of the amount of energy deposited, and not of the radiation type. The evidence on this point was summarized briefly in Section 1.3.1. While it is by no means conclusive, there is a reasonable probability that this assumption will be satisfied.

2. The energy absorbed by the detector is roughly proportional to that absorbed by tissue as a function of radiation energy and type. Clearly this assumption will be satisfied in only a rather gross sense. For example, because of the high atomic number of CdTe compared to tissue, CdTe will be a much more efficient absorber of low-energy gamma rays than is tissue. However, in a mixed radiation field where there are gamma rays of many energies, as well as radiations of other types, it is likely that these differences will compensate for each other to at least some degree.

The practicality of the suggested approach received initial testing in this project through the following steps:

1. A CdTe detector was obtained and integrated into a system capable of measuring its output pulse height spectrum.

2. The detector pulse height output was calibrated with gamma rays over the energy range 80-1300 keV. (It was desired to extend this calibration to as much as 45 MVp X-rays, but the only machines available to the project within its budget and travel constraints were highly pulsed therapeutic devices with peak dose rates far in excess of the ability of the test system's electronics. It was also desired to extend this calibration to other radiation types, especially to electrons and alpha particles, but the end window thickness on the available detector, 70 mg/cm^2 precluded these measurements.)

3. The detector system was irradiated with gamma rays of different energies, and at several dose rates and total doses.

4. Computer software was developed to permit the analysis of the spectra acquired in the irradiations. The software took the energy calibration determined in (2) above and used it to determine the total energy deposition represented by each spectrum, the energy deposition per unit irradiation time, and other relevant parameters.

5. The energy deposition estimates were correlated with the known dosimetric information on the sources used in the irradiations. These correlations were used to study the linearity of the system with respect to the most important potential influences on system output: gamma ray energy, dose rate, and total dose.

The test system and the data acquired from it are described in Section 3.0. The results are analyzed further in Section 4.0.

SECTION 3.0
EXPERIMENTAL MEASUREMENTS

This section describes the equipment and methods used to obtain data in the present research, and presents the data which were actually obtained. The significance of these data is discussed in Section 4.0.

3.1 Equipment

The test system used in the field measurements consisted of the following components:

1. CdTe detector. The detector used was a commercially available unit, purchased from RMD, Inc. (Watertown, Mass.): an octagonal prism of chlorine-doped cadmium telluride approximately 3 mm across x 2 mm thick. The detector was fabricated by RMD in a wound probe geometry which places the detector on the end of a rigid stainless steel stalk 40 mm long and 5 mm in diameter. At the end of the stalk, the detector is covered by an end cap of 0.010" aluminum (density thickness = 70 mg/cm^2). This particular geometry was selected as advantageous for several reasons: a) the detector position within the probe is well defined; b) the detector protrudes from its base far enough to make it easy to hold and mount; and c) if necessary, caps of absorbing material could be readily placed around the detector, surrounding it almost completely. In practice, the detector proved satisfactorily durable and dependable in routine operational testing. A much less expensive geometry and mounting technique could be used in a production device.

   Electronic connections to the detector are made through a single BNC connector which serves as the base for the probe. Some basic tests used to characterize the detector are described in Section 3.2.

2. Preamplifier. The detector preamplifier used was a Canberra Industries (Meriden, Conn.) Model 2003BT, a charge-sensitive FET input device. While this preamplifier is designed for use with silicon detectors rather than CdTe specifically, it had the advantages of smaller size and lower price than the units offered by the detector supplier. With no modifications, it proved adequate for the measurements performed. It is likely that less than optimal resolution was achieved in the measured spectra, since preamplifiers optimized for silicon's pulse shape are known to perform less well with CdTe (deCarolis 1976). However, this was con-

sidered acceptable since resolution is not critical in the dosimeter application.

3. Multichannel analyzer. External pulse processing was provided by a Canberra Industries (Meriden, Conn.) Series 10 multichannel analyzer. This instrument is designed for field use and had the following capabilities relevant to this work: a) extended operation on internal battery power, without need for external batteries or chargers; b) internal high voltage and preamplifier power supplies; c) internal spectroscopy-grade amplifier and analog to digital converter; d) 4096-channel memory, capable of storing up to 8 of the 512-channel spectra used in the measurements; and e) a built-in serial interface for reading out the data for further analysis. While several portable MCA's have similar capabilities, Quantum Technology had previously developed software for acquiring data from the Series 10, which meant that costs to the project could be minimized.

   In the experiments performed, the MCA performed quite satisfactorily in most cases. Specific problems were experienced, however, in two areas. First, although the unit is intended for field use, its internal printed circuit boards occasionally rattle loose during transportation. This results in non-reproducible errors in performance of normal operations such as spectrum acquisition. Reseating of the boards corrects the problems, but it must first be recognized that this is the source of the difficulties. On several occasions, delays of hours or days occurred due to this problem. The boards can be secured more rigidly within the case than is done by the manufacturer, and this is recommended when rough field use is envisioned.

   The second problem encountered is the battery capacity of the unit. In the model used in the present work, the preamplifier power supply can drain the MCA's batteries in a matter of 2-3 hours of continuous use. This necessitated either limiting the length of experiments, or arranging them so that the MCA could be plugged into its charger for the duration. The manufacturer is said to have corrected the problem with the preamplifier power supply in subsequent units.

   The above difficulties aside, the Series 10 MCA proved versatile and easy to use in most cases. The ability to provide reliably the low bias voltage required by the detector (+60 volts) proved especially convenient.

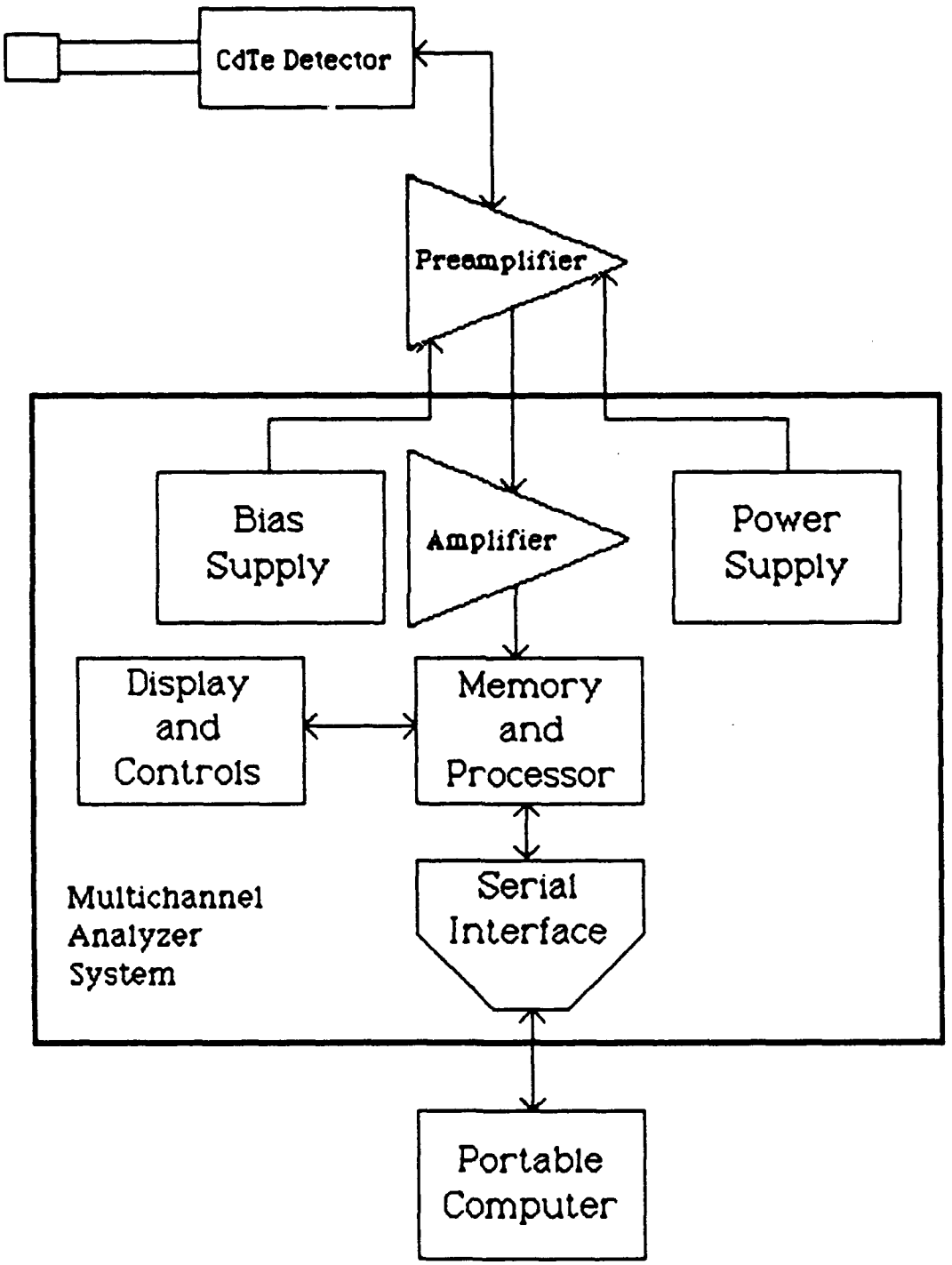
4. Computer. Data acquisition from the MCA was accomplished by a Hewlett-Packard 110 portable computer. This unit was interfaced to the MCA and was used to read out spectra after acquisition. They were then stored on floppy disk for further analysis. The data transfer was accomplished using existing software developed by Quantum Technology for this purpose. The computer was trouble-free in routine operation, and had a sufficiently long battery life that it could be operated continuously during a 16-hour day of measurements with adequate reserve power.

   In principle, it would not always have been necessary to take the computer into the field, since the MCA memory would retain up to 8 spectra. However, more than 8 spectra were frequently obtained in a single series of measurements, and it was also judged more secure to transfer the data from the MCA as soon as possible. Therefore, the computer was always used in the field with the rest of the apparatus.

   A schematic diagram of the electronic detector system is shown in Figure 3-1.

5. Detector mounting stand. It was necessary to hold the detector in reproducible position during irradiations. A wooden stand was built for this purpose which permitted the adjustment of detector height from about 0.1 m to about 1.5 m above the base. Most irradiations were performed with the detector about 1 m above the base. The stand also held the preamplifier in place about 20 cm from the detector, so that the lead from the detector to the preamplifier could be kept shorter than 30 cm as the detector manufacturer recommends.

Figure 3-1. Electronic Detector System



3.2 System Characterization

This section describes the principal measurements used to characterize the basic performance of the detector and its associated electronics. The measurements which pertain specifically to testing the dosimeter method under investigation are presented in Section 3.4.

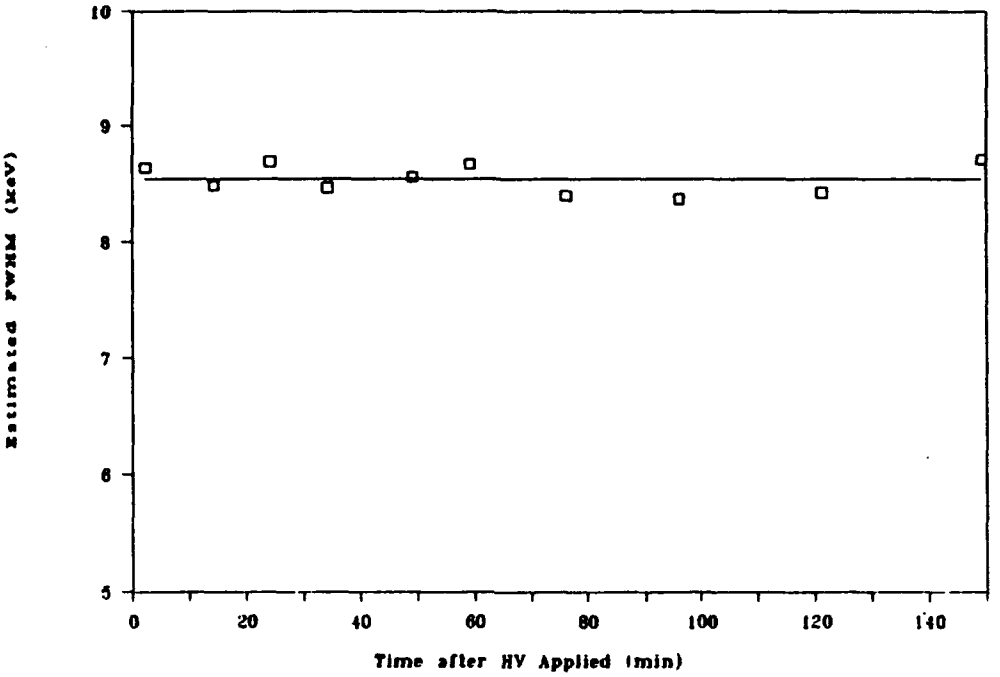
3.2.1 Detector Polarization Tests

Many users have experienced detector polarization with CdTe detectors. Polarization is a buildup of space charge within the active region of the detector which causes a time-dependent decrease in count rate and in charge collection efficiency. [For a particularly serious example see (Hodgkinson 1979).] However other users both early and late in the development of CdTe have experienced no such difficulties (e.g., Serreze 1974, Bojsen 1984).

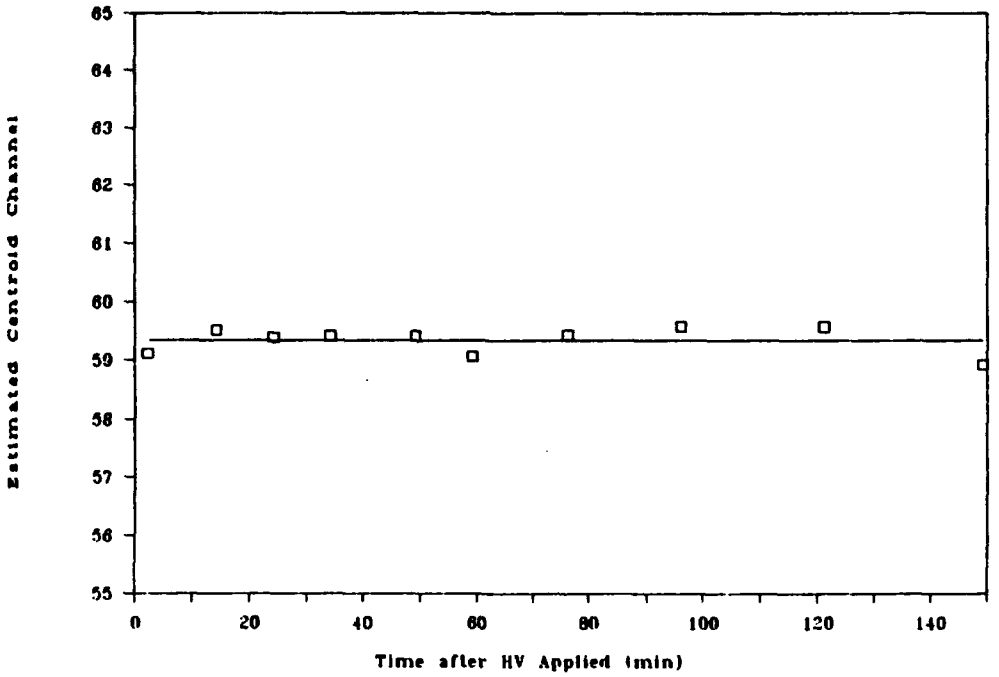
A test was performed using the suggestion of Vidra that the measurement of resolution as a function of time is a good practical indicator of polarization (Vidra 1979). Operating bias was applied to the detector and left on; at intervals between 30 seconds 2.5 hours after the voltage was applied, the resolution of the Cd-109 gamma ray peak was measured in spectra collected for 200 sec. If polarization were significant, the FWHM resolution would be expected to increase with time to a steady level, while the pulse height would decrease measurably.

No such changes were observed: as shown in Figure 3-2, both the centroid channel of the 88 keV gamma peak of Cd-109, and its FWHM, were constant over the period of observation. Therefore, the detector was judged to be free of polarization and was thereafter used with minimal time lag between the application of bias and the beginning of measurements.

Figure 3-2. Detector Polarization Test Results



a. Peak Resolution vs. Time



b. Peak Position vs. Time

3.2.2 Selection of Normal Operating Parameters

Several parameters had to be selected or set to prepare the test system for operation. They were arrived at as follows:

1. Amplifier settings. Amplifier gain settings are discussed in Section 3.2.1.3 as part of the energy calibration process. The MCA's internal amplifier offers only two choices for the pulse shaping speed, fast and slow. Fast (pulse width = 12.5 μsec) was selected for two reasons: a) It is suggested in the literature (Vidra 1979) that short time constants lead to better peak resolution; and b) Shorter time constants produce briefer pulses, which have less tendency to pile up at the high count rates resulting from operation in high dose rate fields. Amplifier polarity was required to be positive, since the preamplifier inverted the negative tail pulses coming from the detector.

2. Bias voltage. The detector was operated at the manufacturer's suggested bias of +60 volts. However, because this level is toward the extreme low end of the capabilities of the MCA's bias supply, the MCA's estimate of the bias level was inaccurate by 1-2 volts. It was necessary to use a digital voltmeter to determine what bias supply setting would result in an actual output bias of +60 volts.

3. ADC settings. The analog to digital converter offers three main settings. The lower level discriminator level (LLD) varied depending on the amplifier gain used for the acquisition of each spectrum, and was chosen to minimize dead time from noise pulses when counting low-level sources. For example, at the normal operating amplifier gain of 375, the LLD was set at 3% of the ADC range; lower gains permitted lower LLD settings, and higher gains required higher LLD settings. The upper level discriminator level (ULD) was held at a constant 110%. The system was operated normally with a conversion gain of 512 channels. This is the minimum available on the MCA, and was selected for two reasons: a) As will be seen below, the resolution of the spectra produced by the system was rather limited, and a higher conversion gain did not seem justified; and b) Lower conversion gains result in shorter conversion times in Wilkinson ADC's (such as that used in the Series 10 MCA), and shorter conversion times would reduce ADC dead time at high count rates.

3.2.3 System Energy Calibration

In order to compute the total energy absorbed in the detector, which is the basis of the method being tested, it is necessary to know the energy value of each channel in the acquired spectrum. This is accomplished through the energy calibration process. Amplifier gain is the primary determinant of the energy calibration, and four different values (33, 100, 375, and 1000) were used in various applications. Therefore four different energy calibrations were derived, as discussed below. (The other determining factors were held constant: ADC offset was 0.0; ADC zero was 0.0; and ADC conversion gain was 512.)

The system was calibrated with gamma rays from nominal 1 μCi sources. However, because the detector was rather small, the peak region count rate from such a source was rather low. This led to long count times to acquire a spectrum with a peak well enough defined to locate reproducibly. In addition, the amplifier gains selected resulted in some operations in which only one or two of the available source energies were within the ADC's window.

For these reasons, it was decided to perform the calibration as a three-step process:

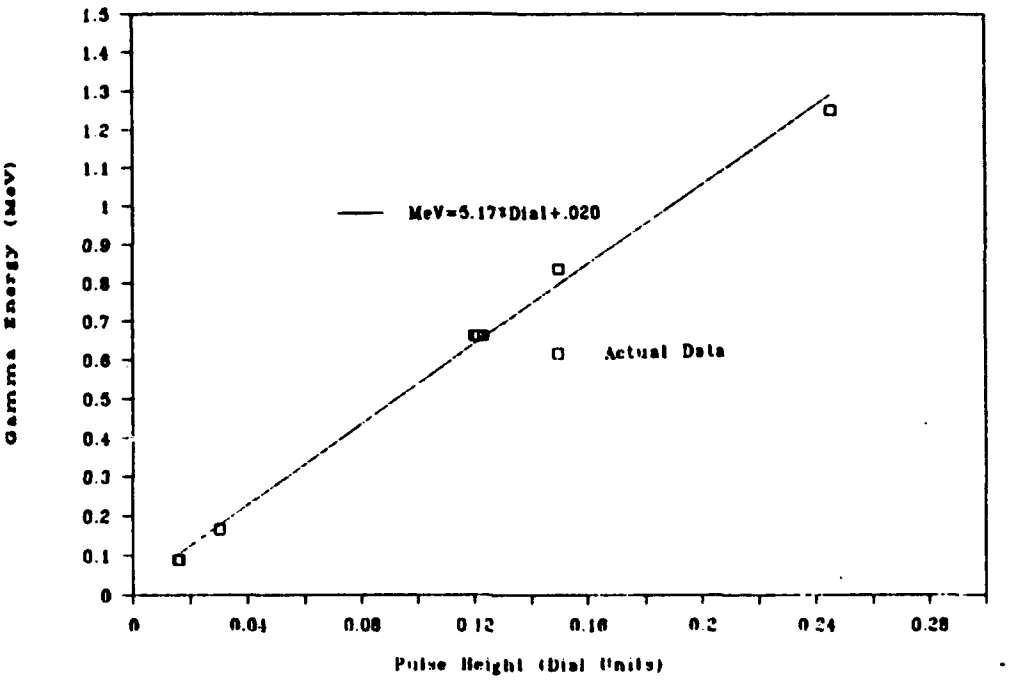
1. A precision pulser (Tennelec Model TC 812) was calibrated for pulse height versus gamma ray energy. This same relationship applies regardless of the amplifier gain used to accumulate any particular spectrum.

2. The pulser was then used to determine the pulse height versus channel relationship. This relationship could be determined quickly for any new amplifier gain selected.

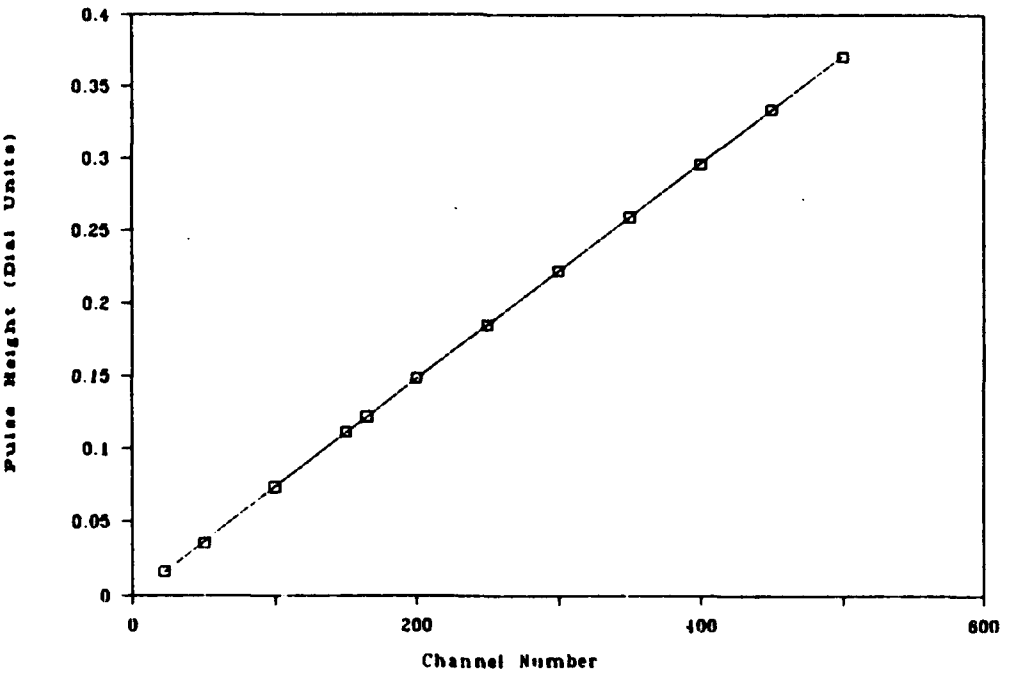
3. The two component functions could then be combined to produce the energy versus channel number relationship for each amplifier gain.

The pulse height versus gamma ray energy data (Figure 3-3.a) were fitted with a linear function, since the data do not suggest any systematic deviation from linearity. (On that graph, multiple points at a single energy represent correlations between gamma energy and pulser pulse height made with different amplifier gains.) As might have been expected of modern electronics, the pulse height versus channel number relationships were all highly linear (see, e.g., Figure 3-3.b). Thus, the overall energy calibration relationships were also linear. For example, the calibration for the most common amplifier gain (375) was:

Figure 3-3. System Energy Calibration



a. Pulse Height versus Energy Relationship



b. Example Pulse Height versus Channel Number Relationship

$$E\ [keV] = 17.25 + 3.8426 * Channel$$

A 512-channel spectrum at this calibration therefore covers the approximate energy range of 21 to 1930 keV. This energy range was satisfactory for most measurements performed in this project.

3.2.4 Daily Performance Checking

Once normal operating parameters had been established for the system, a series of repetitive counts were made to set baseline values for comparison with daily checks. This was done for three parameters: Cs-137 peak counts, Cs-137 total spectrum counts, and total spectrum background. The daily check values were tracked to make certain that the system was operating in a reproducible manner from day to day, and it was found that the system did indeed maintain its stability. For example, the mean of the 10 baseline Cs-137 peak counts was 397 $\pm$ 12 counts in 300 sec.; the mean of the daily check counts was 402 $\pm$ 16 counts.

3.3 Spectrum Analysis Methods

As discussed in Section 2.0, the principle of the method under investigation is to approximate the dose to tissue by computing the total energy deposition in the detector. This is to be accomplished by accumulating a spectrum of counts versus energy, and integrating this spectrum from 0 energy upward. The means by which this was performed for the spectra accumulated in this research are described in this section.

3.3.1 Basic Method

The method under investigation calls for the summation of the energy deposited in the detector. That is, the detector integral response Δ (in keV) is computed as:

$$\Delta = \sum_{Chan=C0}^{Cf} [\ E(Chan) * Counts(Chan)\ ] \qquad (3.3\text{-}1)$$

where:

E is the energy value of channel Chan (in keV), from the energy calibration described in Section 3.2.1.3;

Counts is the number of counts in channel Chan; and

C0,Cf are respectively the beginning and ending channels for the summation. There were a few preliminary test cases when the summation was not made over the entire 512-channel range of the spectrum, but in most cases all 512 channels of data were used.

As discussed above in Section 3.1, a portable computer was used in the field to capture the spectral data from the MCA for further analysis. A BASIC-language program, DOSEANAL (see Appendix B), was then used to perform the energy summation and print the results.

In addition to the integral detector response Δ, DOSEANAL computes and prints other parameters of interest. The most important of these are the following:

1. Detector Response Rate $\dot{\Delta}$

The response rate (in keV/sec) is defined as:

$$\dot{\Delta} = \Delta / t_{eff} \qquad (3.3\text{-}2)$$

where:

t_{eff} is the effective irradiation time. It is equal to the actual irradiation time, minus the ADC dead time recorded by the MCA.

2. Fractional Response

DOSEANAL divides up the integration range (C0 to Cf) into ten equal-sized bins. In addition to reporting the total energy deposition represented by the entire spectrum, it also reports the portion of this which is deposited in each of the ten bins, and the fraction of the total which this represents.

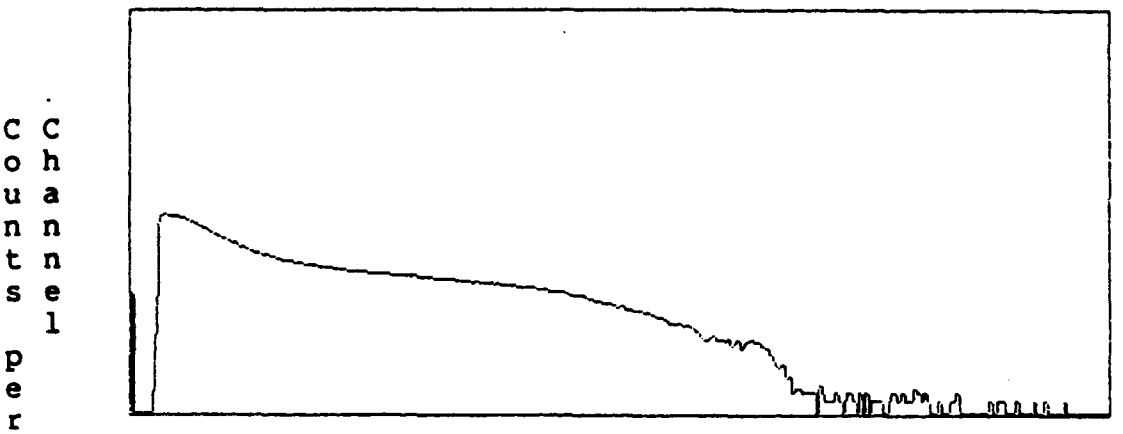
3.3.2 Spectrum Extrapolation

Because of electronic noise, it is not feasible to operate an ADC without a lower level discriminator to screen out the smallest pulses coming from the amplifier. For example, the normal LLD setting used in this work was 3% of the ADC full range. The effect of this LLD is to exclude not only the smallest noise pulses, but also the smallest real detector pulses. The result of this exclusion is that the low-energy end of the spectrum of energy deposition events is omitted from the spectrum recorded by the MCA, and the energy represented by these low-energy events would not be included in the energy integration described in Section 3.3.1. Example spectra are shown in Figure 3-4.

Therefore, DOSEANAL was provided with the ability to handle the low-energy end of the spectrum in five different ways, as follows:

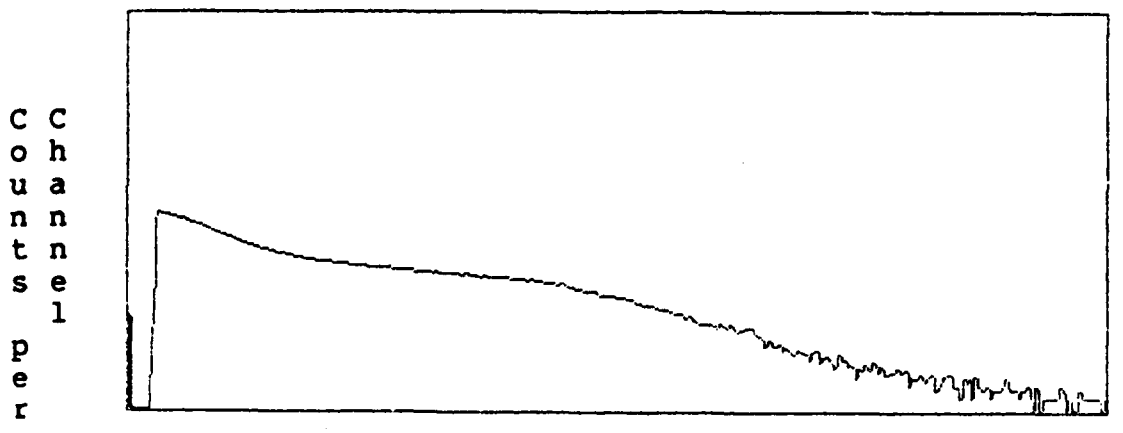
1. No extrapolation. The simplest method of handling the empty channels at the low-energy end of the spectrum is to ignore them, that is to use the spectrum precisely as recorded. This would also be easiest to implement in a real-time dosimeter which would handle each pulse separately, rather than as part of an accumulated spectrum.

Figure 3-4. Example Cobalt-60 Spectra



Channel Number

a. Low Dose Rate Spectrum



Channel Number

b. High Dose Rate Spectrum

2. Flat extrapolation. The next simplest approach is to assume that the spectrum has the same number of counts in each channel below the LLD level. DOSEANAL performs this approximation by finding the lowest channels in which the spectrum reaches full height, averaging the first three such channels, and placing this average number of counts in each channel below the spectrum beginning edge.

3. Linear extrapolation. The low-energy end of the spectrum may also be approximated as a straight line:

$$\text{Counts(Chan)} = a * \text{Chan} + b$$

DOSEANAL finds the slope and intercept of the early full-height part of the spectrum, extrapolates back using this function, and places the resulting number of counts in each channel below the spectrum beginning edge.

4. Semi-log extrapolation. A similar process to the linear extrapolation is used to fit the early channels of the spectrum to an equation of the form:

$$\text{Counts(Chan)} = b * \exp(a * \text{Chan})$$

5. Log-log extrapolation. The same extrapolation method is also extended to a fit of the form:

$$\text{Counts(Chan)} = b * \text{Chan}^a$$

As will be shown below, it became apparent rather quickly that, even for relatively low-energy gamma rays such as those from Ra-226 (186 keV), the amount of energy deposited in the lowest-energy events was an insignificant part of the whole. That is, the difference between the estimates of Δ were very similar regardless of the extrapolation method used, and thus the effort of performing the extrapolation would be unnecessary in a real dosimeter.

3.4 Dosimetric Measurements

Sections 3.1 - 3.3 have discussed the design and preliminary characterization of the test system, as well as the basic methods used to analyze the spectra produced by it. The present section will describe the measurements performed to test the dosimetric method under investigation, and will present the data produced by those measurements. For convenience and clarity in the discussion, the tests are grouped first according to the radionuclide source which they used, and within each source, according to the purpose of the tests. This ordering does not necessarily correspond to the order in which the measurements were actually performed.

3.4.1 Radium-226 Measurements

3.4.1.1 Source Characterization

Low-energy and low dose rate measurements were performed in a large open calibration facility using a 50 mg Ra-226 source owned the Georgia Institute of Technology. Given the specific gamma ray constant of Ra-226 (8.25 R per hr/mCi at 1 cm), this source was useful for dose rates ranging from about 110 mR/hr at 2 feet, to about 1.3 mR/hr at 19 feet.

These values may be converted to dose rates in tissue through the standard stopping power formula (*see, e.g.*, pp. 378-379 in Attix 1968):

$$D_{Tiss}[\text{rad}] = 0.869 * \frac{(\mu_{en} / \rho)_{Tiss}}{(\mu_{en} / \rho)_{Air}} * X\,[R] \qquad (3.4\text{-}1)$$

Using Attix's values (p. 138) for the mass energy absorption coefficients at 186 keV (tissue = striated muscle), this reduces to:

$$D\,[\text{rad}] = 0.953 * X\,[R] \qquad \text{(for Ra-226)}$$

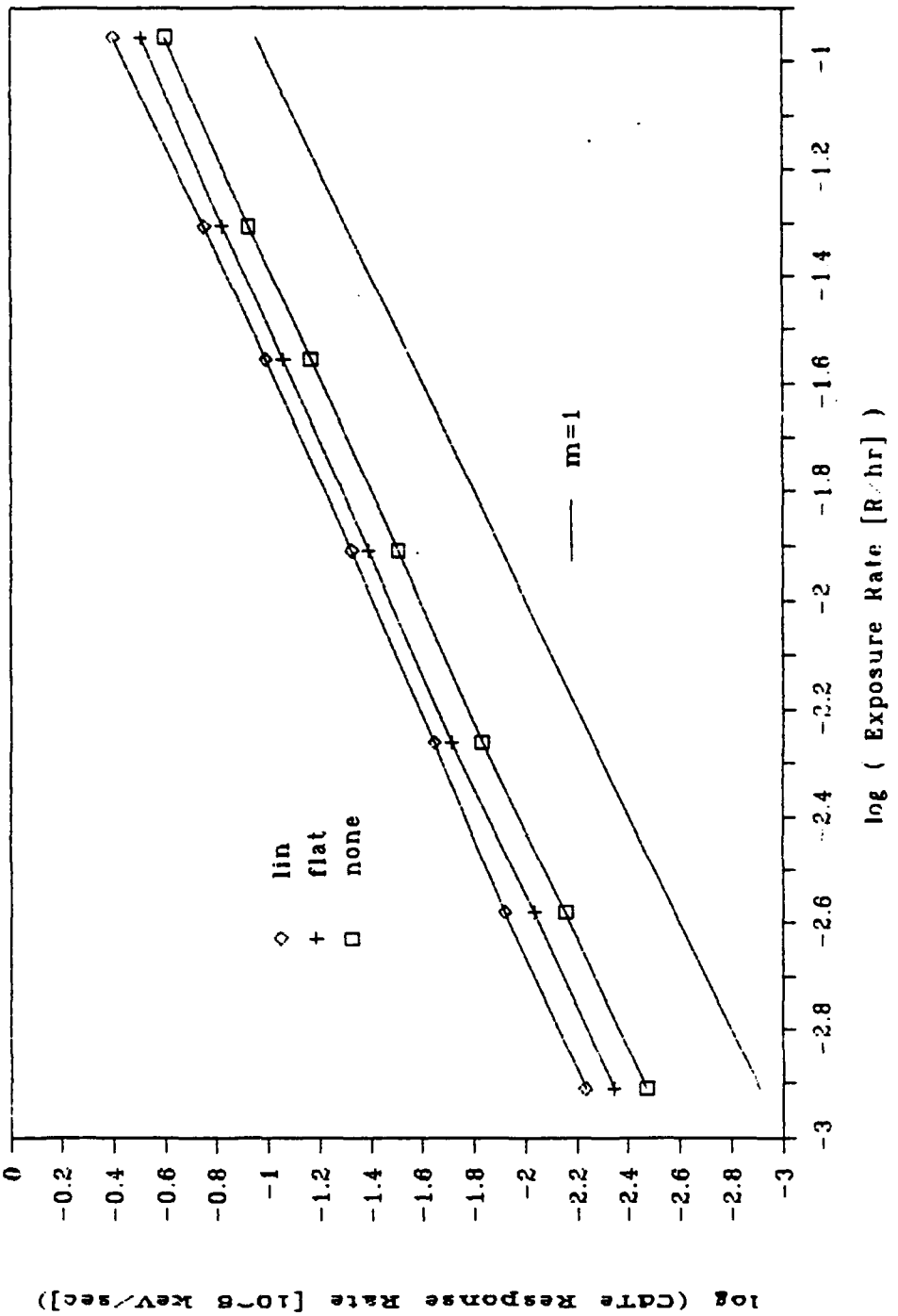
3.4.1.2 Exposure Rate Dependence Measurements

The detector was irradiated at seven distances over the useful range of the radium source, for sufficient times to reach total doses of approximately 1 - 10 mR. The exposure rate for each irradiation was calculated from the known source strength and the inverse square law. The spectra were transferred from the MCA to the computer and saved on disk for the analysis described in Section 3.3 above. The results of this analysis (developed with three of the types of low-channel extrapolation) are shown in Table 3-1 and Figure 3-5.

Table 3-1. Ra-226 Exposure Pate Response Data

Source Distance (ft)	Calculated Exposure Rate (R/hr)	CdTe Response Rate [net of background] (10^6 keV/sec) [with no extrap.]	[with flat extrap.]	[with linear extrap.]
19	0.0012	0.00338	0.00451	0.00585
13	0.0026	0.00698	0.00924	0.0121
9	0.0055	0.0148	0.0194	0.0225
6	0.0123	0.0312	0.0406	0.0472
4	0.0278	0.0676	0.0865	0.101
3	0.0493	0.118	0.150	0.176
2	0.111	0.251	0.309	0.398
Note: Background Response Rate		0.00012	0.00015	0.00019

Figure 3-5. Ra-226 Exposure Rate Response



Two points are outstanding in these data. The first is that the three simplest methods of low-channel spectrum extrapolation produce results that differ from each other by only a few percent. The simplest of these methods (the no extrapolation method) is also the most workable for a real-time dosimeter which would not accumulate a spectrum. Since the results of estimating and including the effects of the low-channel spectrum are small, and since (as will be shown below) omitting the extrapolation still produces acceptable results, no extrapolation was used in developing the results which appear in the remainder of this report.

The second outstanding point is the linearity of the results. The solid line shown on the graph has a slope of 1.0, meaning that it corresponds (on a log-log graph) to an equation of the form:

$$\dot{\Delta} = k * \dot{X}^{+1.0}$$

That is, it implies that exposure rate $\dot{X}$ and response rate $\dot{\Delta}$ are linearly related at these low dose rates. This is of course a highly desirable attribute for any dosimeter. It should be noted that the dead time was minimal in all these irradiations: it ranged from 0% at 1.2 mR/hr to 0.7% at 111 mR/hr.

3.4.2 Cobalt-60 Measurements

3.4.2.1 Source Characterization

Several irradiation tests were performed in a Co-60 irradiator owned by the School of Biology, Georgia Institute of Technology. This facility is a large-volume irradiator in which samples may be exposed to a source of ~60 Ci over distances from about 1 - 50 feet, in a tunnel about 6 feet in diameter. At the time of use, the dose rate in the facility was not well characterized over its entire length, which required that reliable measurements be made before the irradiation results could be interpreted. It seemed likely that scattered radiation would be a significant contributor to the exposure rate.

A Victoreen electrometer (Model 500) was used with a low range R-chamber (Model 550-3, 0-2000 mR) to make the determination of exposure rate as a function of position. This equipment, on loan from the Georgia Power Company, has a calibration traceable to the National Bureau of Standards. The results of the measurements are shown in Figure 3-6, which indicates that the exposure rate from the source displays a $1/r^2$ dependence ($\pm$ 6%) over the entire length of the irradiator. The exposure rates graphed in the Figure were used as the reference values for all irradiations performed in this facility.

The useable range of the Co-60 irradiator was found to be between 460 mR/hr at 45 feet, and 105 R/hr at 3 feet. These exposure rates may be converted to dose rates in tissue using equation (3.4-1) and Attix's values for μ_{en}/ρ. This produces the relationship:

$$D\ [rad] = 0.950 * X\ [R] \qquad \text{(for Co-60)}$$

The useable range of the Co-60 facility was then from approximately 440 mrad/hr at 45 feet, to 100 rad/hr at 3 feet. This maximum dose rate is equal to the upper limit dose rate in which the space dosimeter is required to operate.

3.4.2.2 Exposure Rate Dependence Measurements

By varying the position of the detector down the length of the irradiator, the system was irradiated at twelve different exposure rates. Total exposures ranged from approximately 100 mR to 4.4 R, and because of the higher dose rates, system dead times were appreciable; they ranged from approximately 3.2% at 460 mR/hr to 27% at 100 R/hr. The results of these irradiations are shown in Table 3-2 and Figure 3-7.

Figure 3-6. Exposure Rates in the Co-60 Irradiator

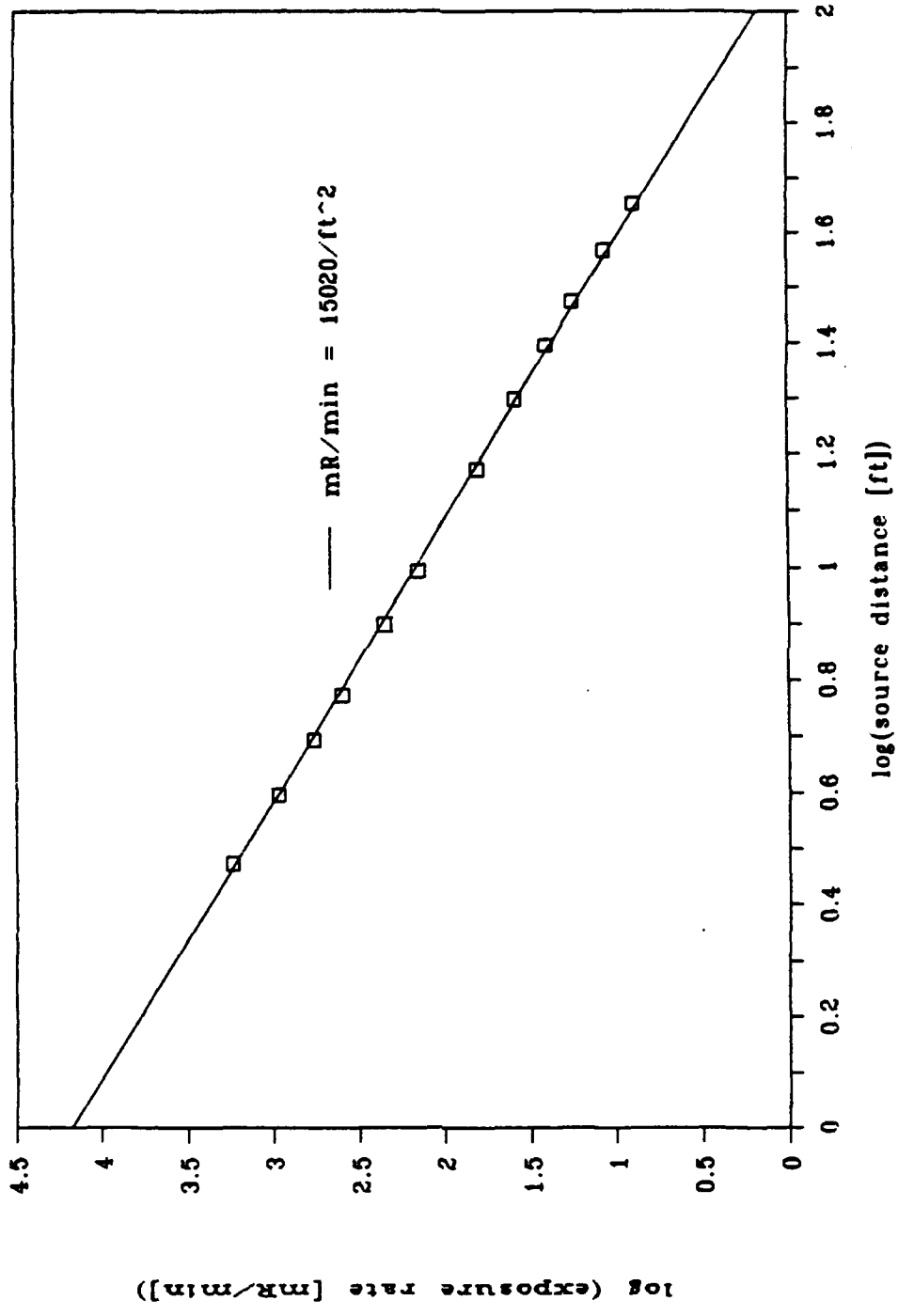
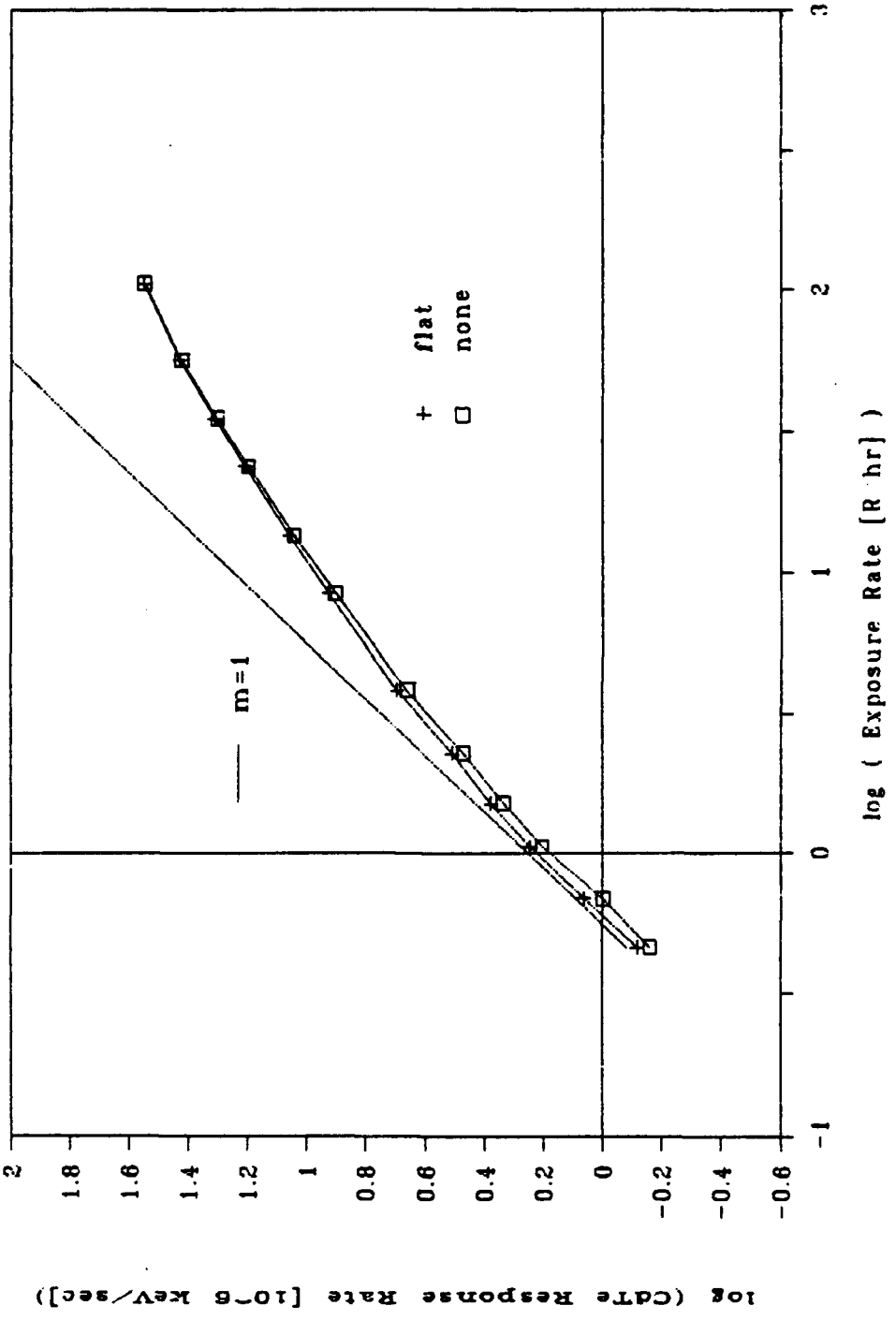


Table 3-2. Co-60 Exposure Rate Response Data

Source Distance (ft)	Measured Exposure Rate (R/hr)	CdTe Response Rate (10^6 keV/sec) [with no extrapolation]	CdTe Response Rate (10^6 keV/sec) [with flat extrapolation]
45	0.463	0.688	0.762
37	0.692	0.996	1.158
30	1.06	1.60	1.75
25	1.51	2.16	2.38
20	2.28	2.94	3.23
15	3.83	4.55	4.95
10	8.46	7.97	8.44
8	13.5	11.0	11.5
6	23.7	15.7	16.2
5	34.9	20.0	20.4
4	56.3	26.6	26.9
3	105.	35.2	35.5

Figure 3-7. Co-60 Exposure Rate Response



As in the case of the Ra-226 data, it is seen that the alternative methods of low-channel extrapolation are virtually equivalent in their final results. This supports the decision to omit spectrum extrapolation in the final results.

However, in marked contrast to the low-exposure rate Ra-226 data, these high-exposure rate Co-60 results deviate appreciably from linearity, as represented by the straight solid line in the figure. This is a common problem with electronic dosimeters, and has been observed in other devices using CdTe (see Section 1.3). It should be noted that this is not simply the result of lost counting time, since the response rate calculation already is based on the MCA live time, as shown in equation 3.3-2. Potential reasons for this deviation, and approaches to correcting for it, are discussed in Section 4.1.2.

3.4.2.3 Cumulative Exposure Dependence Measurements

Besides responding linearly to all dose rates, a dosimeter should respond linearly as a function of cumulative dose. Therefore, the detector was irradiated at a fixed distance (i.e., fixed exposure rate) for varying periods to determine the cumulative exposure response. The detector position chosen for this test was 15 feet from the source (3.83 R/hr), which produced a system dead time of almost exactly 10%. The results of these irradiations are summarized in Table 3-3 and Figure 3-8.

The slope of the solid line on the log-log graph of Figure 3-8 is 1.0, meaning that the total response of the system is linearly related to the total exposure (or total dose):

$$\Delta = k * X^{+1.0}$$

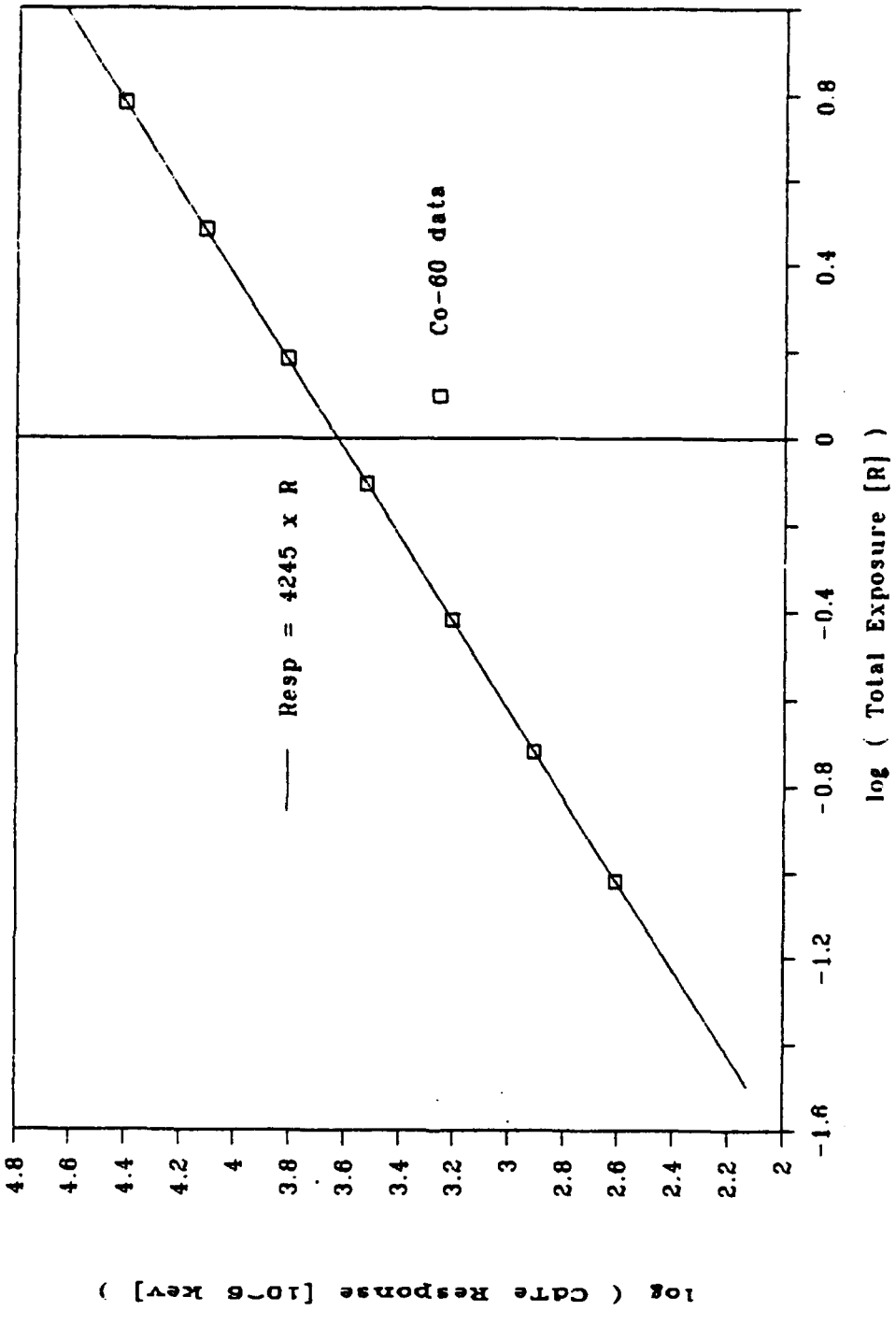
Table 3-3. Cumulative Exposure Response Data

Irradiation Time (sec)	MCA Dead Time (sec)	Live Irradiation Time (sec)	Total Live Exposure (R)	CdTe Response [No Extrap.] (10^6 keV)
100	10	90	0.0957	407
200	20	180	0.192	815
400	40	360	0.383	1630
820	82	738	0.785	3330
1600	160	1440	1.53	6500
3200	322	2878	3.06	13000
6330	638	5692	6.05	25600

Notes:

(1) Exposure Rate at 15 ft. = 63.8 mR/min = 1.063 mR/sec

Figure 3-8. Cumulative Exposure Response



SECTION 4.0
EVALUATION OF RESULTS

4.1 Discussion

Section 3.0 presented the basic data which were collected in this research. The present section will discuss and evaluate those data in terms of their implications for a useful dosimeter.

4.1.1 Energy Response

Data were collected in irradiations by two nuclides, Ra-226 and Co-60, whose average energies per gamma ray are respectively 186 and 1250 keV. The exposure rate response data were presented in Figures 3-5 and 3-7. When the exposure rates are converted to dose in tissue, but not otherwise modified, the composite data appear as shown in Figure 4-1.

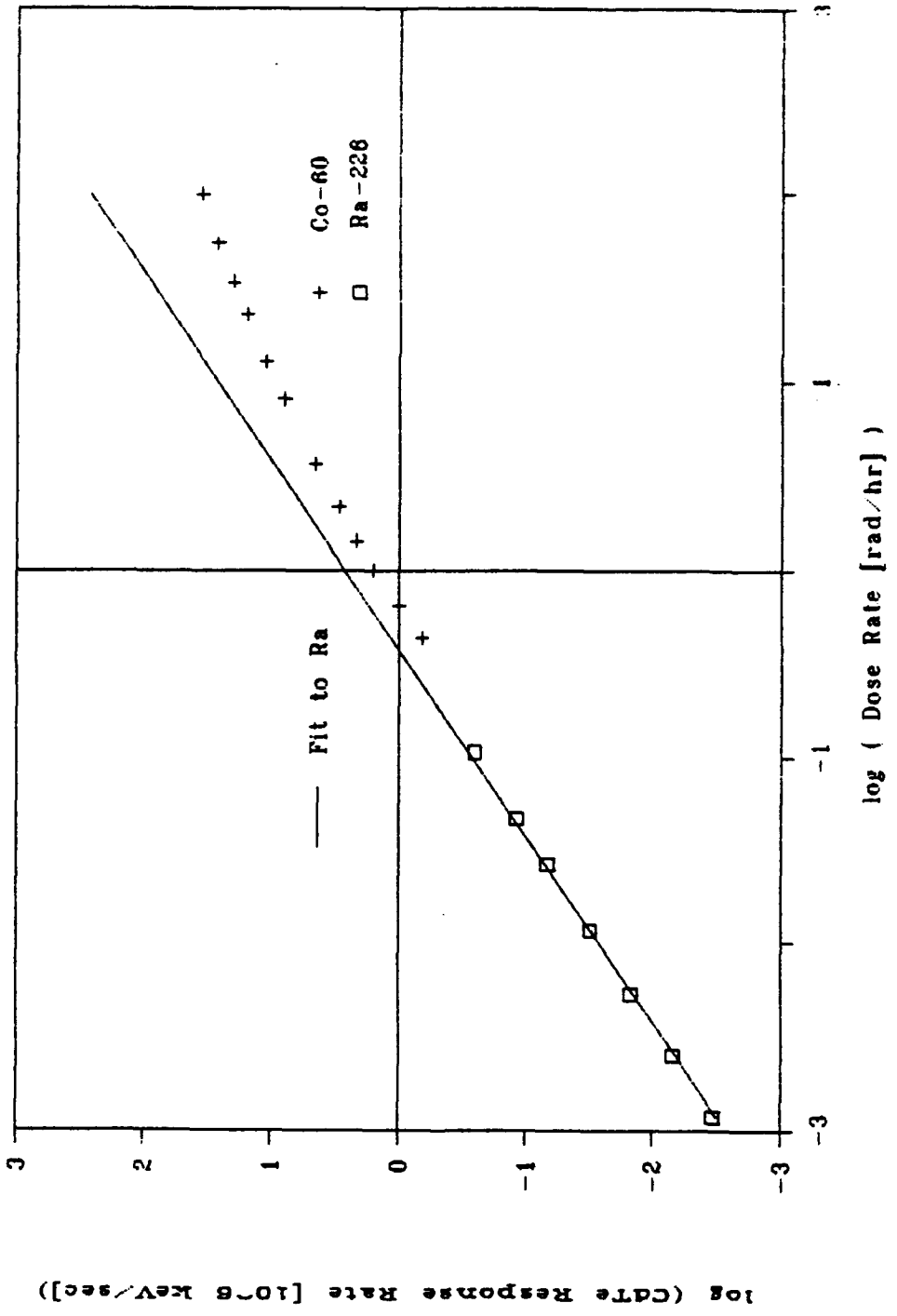
These data suggest a difference in response between the two energies, but on closer examination, the difference appears more likely to be due to dead time effects in the MCA. For example, even within the Ra-226 data there appears to be some decrease in response per unit dose at the higher dose rates. It would have been desirable to establish directly the relative response of the detector at the two energies by making some measurements of both nuclides at the same dose rates, but the relative strengths of the two sources available did not permit this. The further analysis presented in Section 4.1.2 supports the conclusion that the discrepancy between the Ra-226 and Co-60 responses can be accounted for fully by dead time effects.

However, it should be noted that the detector was not tested in the region of highest energy dependence (below 100 keV), and that the presence of the end cap of the detector housing (thickness ≥ 70 mg/cm^2) would tend to flatten the energy response in any event.

4.1.2 Dose Rate Response

Figure 4-1 shows a clear decrease in response for the detector system when it is exposed to high dose rate gamma fields. This is a phenomenon that has been observed by other workers, even when using quite dissimilar CdTe systems (Hodgkinson 1979, Umbarger 1979, Wolf 1979, Johnson 1981). Theoretical factors have been suggested to explain this decrease in terms of changes in the detector sensitive volume, and changes in

Figure 4-1. Unmodified Composite Dose Rate Response



the charge trapping and detrapping behavior of the detector due to the high density of free charge that results from the high rate of ionization within the detector (Hodgkinson 1979). In addition to factors unique to CdTe, amplifiers and ADC's are both known to exhibit downward gain shifts when operating in very high count rate situations.

For all these reasons, it is not surprising to encounter a decrease in system response at high count rates or dose rates. A modifying factor was sought which could be applied to the observed data to remove this deficit in response, with the provision that the modification should be amenable to performance by a system operating in near-real time. Acceptable improvement was achieved by multiplying all detector responses by a modifying factor M defined as:

$$M = \left(\frac{\text{Irradiation Time}}{\text{MCA Live Time}} \right)^n$$

It is clear that a modification of this type becomes larger as dose rate rises, since this results in progressively higher MCA dead time.

No quantitative attempt was made to optimize the exponent n, nor is there any obvious theoretical reason for any particular value. Nevertheless it was found that values in the range of $n \approx 6$ produced modified detector response values which were approximately linear for Co-60. When the modification was applied to all the data for both nuclides, it was found as shown in Table 4-1 and Figure 4-2 that the Co-60 and Ra-226 data agreed not only within themselves, but also with each other. The fitted line shown in the Figure is based on $n = 6.5$ and represents the linear response:

$$\dot{\Delta}\ [10^6\ \text{keV/sec}] = 2.59 * \dot{D}\ [\text{rad/hr}]$$

According to this graph, the response of the system appears to be linear over 5 orders of magnitude in dose rate (0.001 to 100 rad/hr), and uniform over the gamma ray energy range from 180 to 1300 keV. Because the linearity at low dose rates is unmodified by the dead time correction, and since other researchers have observed linear response from CdTe at very low dose rates, it reasonably may be expected that the linear dose rate response would extend downward to zero dose rate. The uniformity of energy response outside of the tested gamma energy range is unknown.

Table 4-1. Modified Composite Ra-226 and Co-60 Response Rate Data

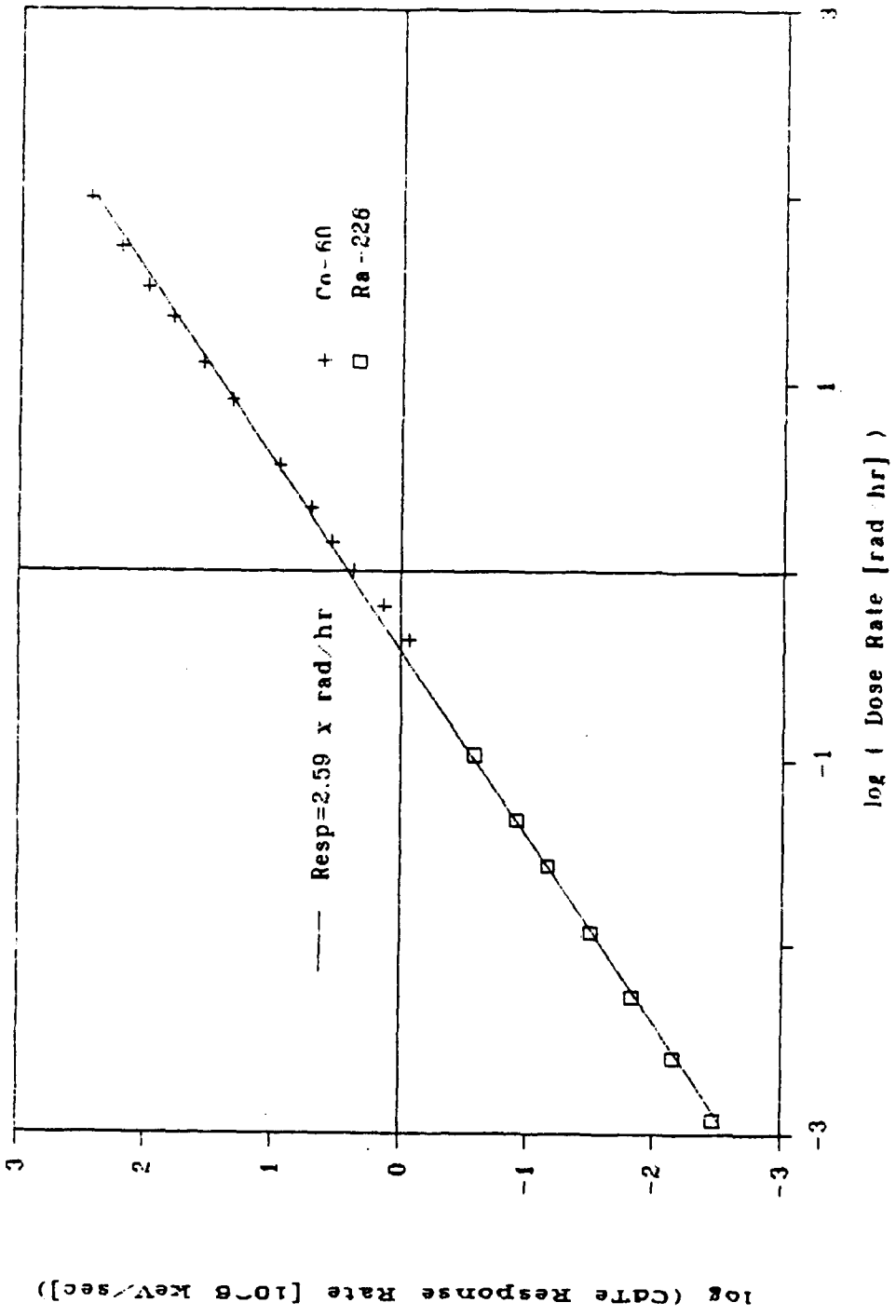
Nuclide	Dose Rate (rad/hr)	CdTe Response Rate (10^6 keV/sec) Unmodified	CdTe Response Rate (10^6 keV/sec) Modified	Time Ratio (1)	Modifying Factor (2)
Ra-226	0.0012	0.0034	0.0034	1.000	1.000
Ra-226	0.0025	0.0070	0.0070	1.000	1.000
Ra-226	0.0052	0.0148	0.0148	1.001	1.005
Ra-226	0.0118	0.0312	0.0314	1.001	1.006
Ra-226	0.0265	0.0676	0.0685	1.002	1.014
Ra-226	0.0471	0.118	0.122	1.004	1.028
Ra-226	0.106	0.251	0.262	1.007	1.044
Co-60	0.439	0.688	0.85	1.033	1.236
Co-60	0.658	0.996	1.36	1.049	1.362
Co-60	1.004	1.60	2.36	1.062	1.478
Co-60	1.43	2.16	3.46	1.075	1.599
Co-60	2.17	2.94	5.10	1.088	1.731
Co-60	3.64	4.55	9.03	1.111	1.982
Co-60	8.03	7.97	21.2	1.163	2.665
Co-60	12.8	11.0	36.1	1.200	3.274
Co-60	22.5	15.7	63.4	1.239	4.037
Co-60	33.1	20.0	101.	1.282	5.028
Co-60	53.4	26.6	163.	1.322	6.123
Co-60	99.3	35.2	280.	1.375	7.942

Notes:

(1) Ratio of (Irradiation time)/(MCA live time)

(2) Factor = Time Ratio ^ 6.5

Figure 4-2. Modified Composite Dose Rate Response



4.1.3 Cumulative Dose Response

The response of the test system as a function of total exposure dose was discussed in Section 3.4.2.3, and graphed in Figure 3-8. The exposure dose values may be converted to absorbed doses in tissue, and the system response values multiplied by the appropriate dead time modification factor (which at a dead time of 10%, for exponent n=6.5, is 1.982), with the results shown in Table 4-2 and Figure 4-3.

Since the cumulative response in exposure units was highly linear, and since all spectra collected at the same dose rate had the same dead time fraction (and therefore the same modifying factor), it was to be expected that the cumulative response in dose units is also highly linear. According to the fit plotted in the graph, the total response Δ is related to the cumulative absorbed dose D by the relationship:

$$\Delta\ [10^6\ \text{keV}] = 8860 * D\ [\text{rad}]$$

This result is consistent with the dose rate response developed in Section 4.1.2. The dose rate response may be expressed as :

$$1\ \frac{\text{rad}}{\text{hr}} = 2.59 \times 10^6\ \frac{\text{keV}}{\text{sec}} = 9.32 \times 10^9\ \frac{\text{eV}}{\text{hr}}$$

or, 1 rad in tissue = 9.32×10^9 eV in the detector.

For comparison, the cumulative dose response may be expressed as:

$$1\ \text{rad} = 8860 \times 10^6\ \text{keV}$$

or, 1 rad in tissue = 8.86×10^9 eV in the detector.

The two values, which are based on data and mathematical fits which are independent, agree with each other to within 5.1%.

Table 4-2. Modified Cumulative Dose Response Data

Irrad. Time (sec)	MCA Dead Time (sec)	Live Irrad. Time (sec)	Total Live Exposure (R)	Total Live Dose (rad)	Total Energy Recorded [No Extrapolation] (10^6 keV)	
					Unmod.	Mod.
100	10	90	0.0957	0.0909	407	807
200	20	180	0.192	0.182	815	1615
400	40	360	0.383	0.364	1630	3230
820	82	738	0.785	0.745	3330	6610
1600	160	1440	1.53	1.45	6500	12900
3200	322	2878	3.06	2.91	13000	25700
6330	638	5692	6.05	5.75	25600	50800

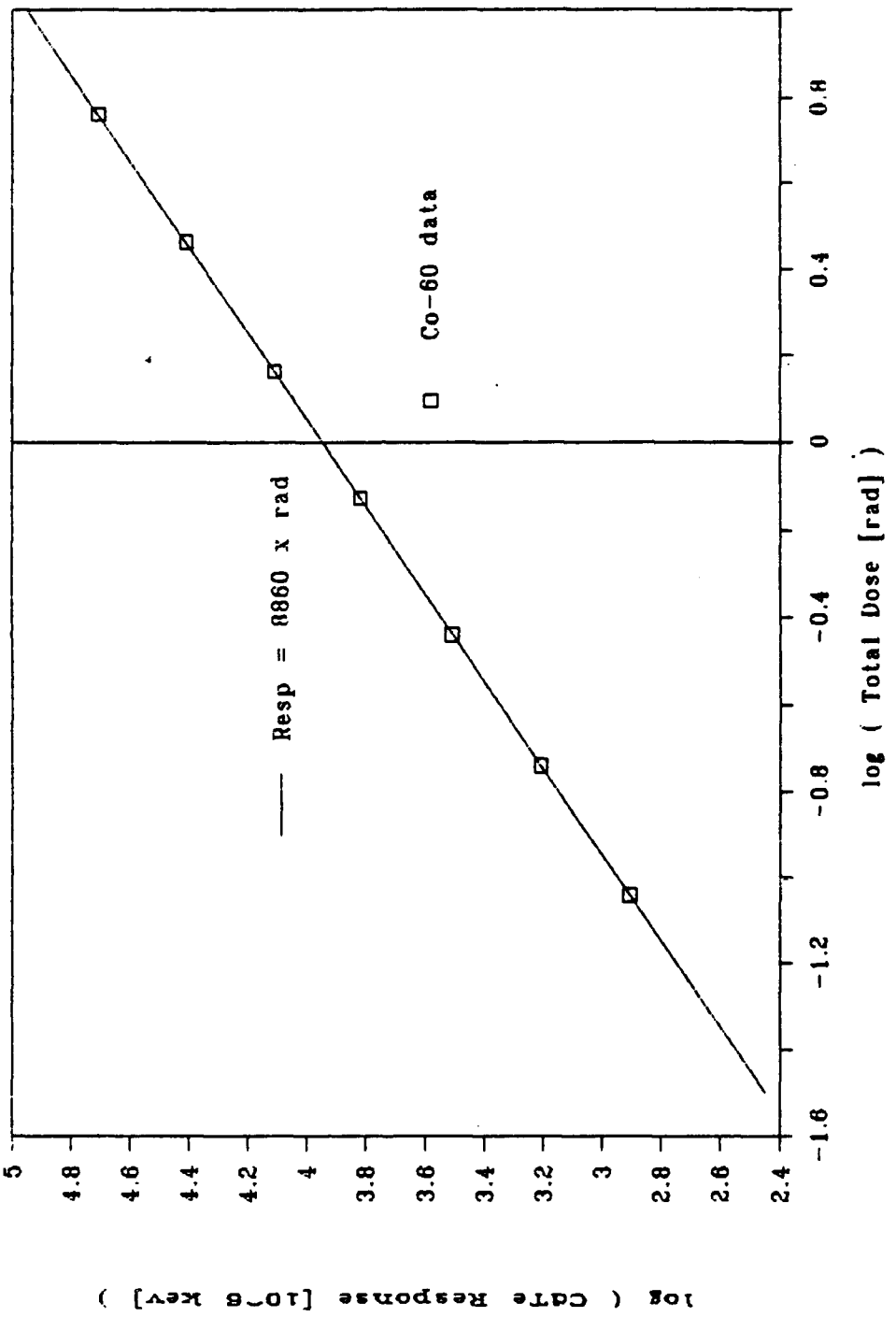
Notes:

(1) Co-60 Dose Conversion Factor = 0.950 rad/R

(2) Exposure Rate at 15 ft. = 63.8 mR/min = 1.063 mR/sec

(3) Dead Time Factor = 1.982

Figure 4-3. Modified Cumulative Dose Response



4.2 Conclusions

Within the constraints of the available calibration sources, the test system was examined exhaustively with respect to energy dependence, and dose rate and dose linearity. The performance in all cases was very good:

1. No energy dependence was found for gamma rays in the range 180 - 1300 keV.

2. The relationship between dose rate and modified system response rate was found to be very linear.

3. The relationship between cumulative dose and total system response was found to be almost perfectly linear.

In short, the system performed as a nearly ideal gamma ray dosimeter over moderate energies when the response was modified to account for effects dependent on system dead time. However, this research provides no information regarding response to other types of radiation, nor response to gamma rays with energies in the tens and hundreds of MeV. Additional research in these areas is recommended in Section 5.2.

SECTION 5.0
SUGGESTED FURTHER DEVELOPMENTS

The success reported in the earlier sections of this report would seem to justify continued development of the spectroscopic dosimeter concept. A conceptual design for such a device is presented in Section 5.1, while the additional steps required to complete testing of the concept and of a prototype dosimeter are outlined in Section 5.2.

5.1 Conceptual Design of a Hand-Held Dosimeter

Since the spectroscopic concept could not be completely tested in the Phase I project, it is difficult to say with great certainty what the design of a prototype dosimeter based on the concept would be. However, a preliminary concept can be outlined, along with some of the design constraints which would apply to the construction of the instrument.

5.1.1 Design Constraints

Some of the principal design constraints on the prototype system may be listed at this stage in the work. This is done below, according to the subsystems which would compose the complete instrument.

5.1.1.1 Radiation Detector

1. Size and shape. The detector size used in this research responded adequately over the range of dose rates required of the dosimeter (~1 mrad/hr to 100 rad/hr). That is, it produced detectable response at low dose rates, without excessive non-linearity at high dose rates. Therefore, a detector on the order of 2-3 mm on a side would be appropriate in the prototype. To make the response as isotropic as possible, the detector should be approximately the same size in all dimensions, but should be of prismatic or cylindrical shape; this is because the unusual field shapes prevailing in spherical detectors constrain the operating voltages and attainable resolution excessively (Vidra 1979).

2. Required resolution. A dosimetric system responding to a range of energies and radiation does not require the same degree of energy resolution as does a detector which will be used for radionuclide identification. However, the underlying concept of the dosimeter is

spectroscopic, so that some degree of accuracy in energy response is called for. Therefore, a moderate spectroscopic grade of CdTe is necessary: resolution on the order of 30-60 keV FWHM for Cs-137 gammas at 662 keV. The detector used in the Phase I research was of this grade.

3. Packaging. The detector needs to respond to all types of radiation, including both charged particles and photons. It should therefore be surrounded by whatever minimal covering is required to protect the electrical connections, and then inserted into a small mass of tissue equivalent plastic to flatten the low-energy gamma response and provide charged particle equilibrium for all radiations. Previous work suggests about 3 mm of plastic for use in space (Braby 1984b, Braby 1985). The detector package should be situated on one end of the dosimeter so that it maximally exposed in all directions. This is important not only in use (because there is no preferred direction for the incident radiation), but also in calibration because air-scattered electrons can be a significant dose contributor (Hankins 1985). Previous experience in building ruggedized CdTe detectors for space use should be considered in designing the package (Lyons 1977).

5.1.1.2 Pulse Processing

1. General Requirements. All circuitry should be designed with low power consumption as a primary consideration because of the need to maximize battery life at low weight. This suggests the use of CMOS technology, LCD display, etc. Previous experience suggests that commercially available circuitry is likely not to have the combination of capabilities required in this particular application, but considerable development work has already been performed for a similar application (Braby 1984a). To the extent possible, commercial circuits should be used, but custom circuit designs probably will be required.

2. Multiple Pulse Trains. Because of the energy range involved, two parallel pulse processing trains are called for. One would cover the upper range of particle energies (such as 4 MeV to 200 MeV), while the other would cover the range below the lower discriminator level of the first (such as 50 keV to 4 MeV). The total response of the instrument would be the sum of the responses of the two trains, which would split the output signal of a single preamplifier.

3. Bias Supply. The bias supply does not need to be a highly capable device since CdTe detectors of the size to be used in the prototype operate at less than 100 volts while drawing nanoamp currents. However, it should be stable, and must be programmable to permit the instrument's microcomputer to set the bias on instrument power-up.

4. Amplifiers. The amplifiers used should be of high quality, but absolute linearity is not vital. Far more important is short pulse shaping time to permit high throughput. They must also be programmable to permit the instrument's microcomputer to set their gain on instrument power-up.

5. ADC's. The ADC's should be designed for maximum speed so as to work well at high dose rates. This suggests the use of successive approximation (or so-called fixed dead time) devices which are considerably faster than the Wilkinson type. Speed would be further improved without loss of dosimetric capability if the ADC's had minimal conversion gain: 256 channels per train would likely be sufficient. The circuit design should also permit the passage of timer pulses to permit dead time determination, since dead time was found to be a major factor in the test system's response.

5.1.1.3 Microcomputer

1. Spectrum Storage. The instrument might operate on either a pulse-by-pulse analysis, or short-term spectrum analysis basis. The advantages of accumulating a short-term spectrum prior to analysis are that it leaves the instrument microcomputer free to perform other functions when analysis is not actually in progress, and that it permits a simple dead time fraction determination. Therefore it seems advisable to store spectra for a short period such as 10 seconds, analyze them, and then update the instrument display. It has been found that buffered direct storage in RAM of the spectral data, rather than passage through the microcomputer on the way to RAM, is workable and fast (Braby 1984a).

2. Analysis Functions. The principal function of the instrument microcomputer will be the integration of spectrum energy in order to determine dose and dose rate. It should do so with a program read from ROM on power-up, using constants read from non-volatile RAM. The storage of constants such as energy calibrations in RAM permits their easy modification during calibration.

3. Control Functions. In addition to reading in spectra from RAM and calculating dose and dose rate, the microcomputer must also control other components in the instrument. This includes setting the bias supply voltage and amplifier gains on power-up, driving the display, and processing interrupts from keys controlling display and operation functions. It must also communicate via a serial interface for sending and receiving data during calibration.

5.1.2 Functional Design

A conceptual design for a prototype instrument which meets the above constraints is presented in Figure 5-1. It consists of the basic components discussed above, plus the additional components such as batteries and power supplies required in any instrument. An external battery charger would probably also be required, due to the power consumption of even the most efficient ADC's and microcomputers.

The instrument would operate normally according to a sequence similar to that shown in Table 5-1. In the calibration mode (as initiated by a panel key) the instrument would operate under the direction of an external computer which would give instructions for data acquisition and transfer through the serial interface. (The exact calibration sequence would depend among other things on the results of the prototype testing discussed in Section 5.2.) Operational constants would also be transferred through the serial interface for storage in the non-volatile RAM.

Figure 5-1. Conceptual Design of a Prototype Instrument

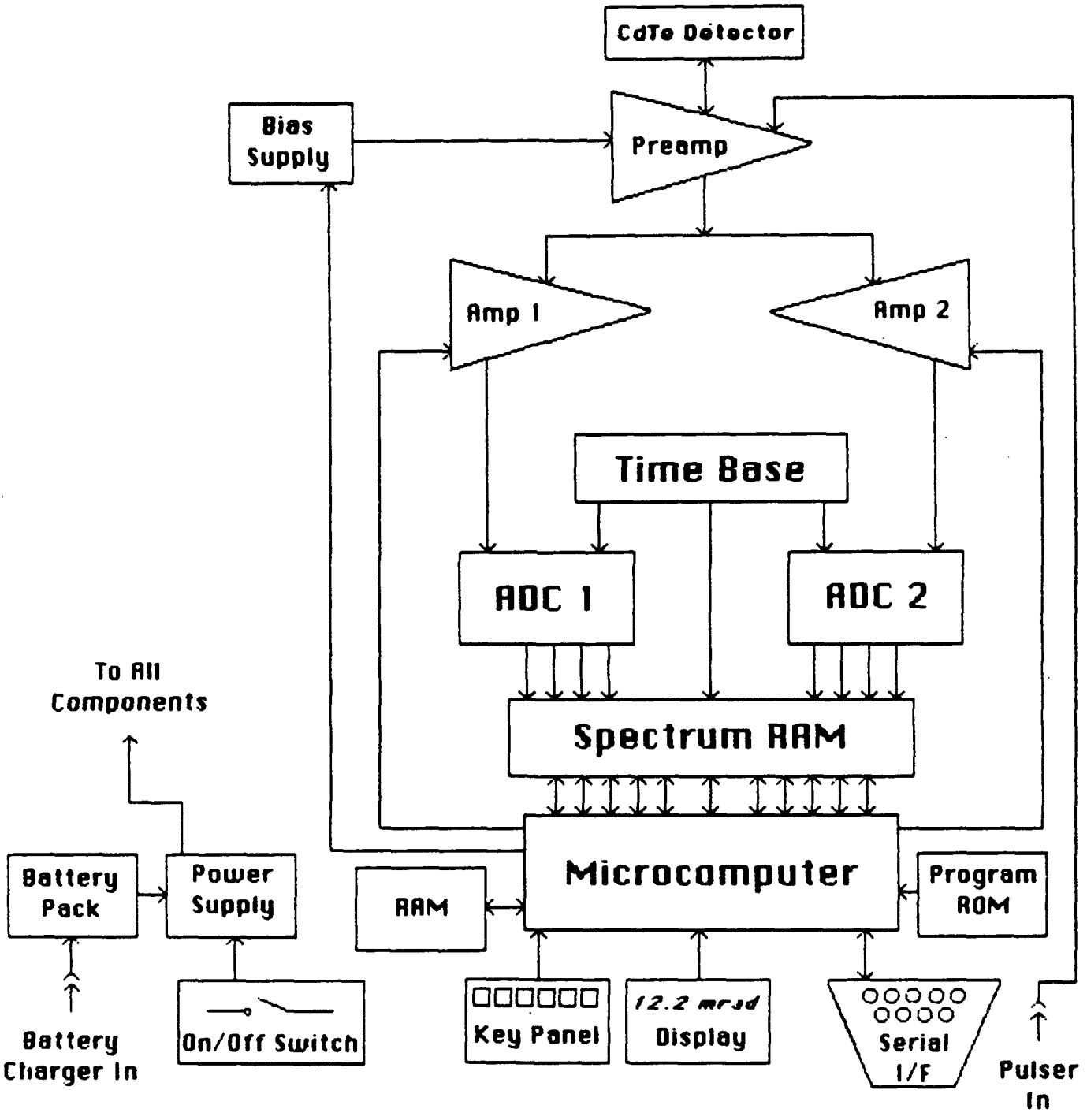


Table 5-1. Conceptual Normal Operation Sequence

Step No.	Operation
1.	On power-up, read ROM, and begin program.
2.	Read non-volatile RAM for constants. Set bias supply voltage and amplifier gains accordingly. Wait 1 - 3 minutes for the system to warm up and stabilize.
3.	Zero out the spectrum RAM.
4.	Allow spectra to continue accumulating in spectrum RAM for a suitable period (say, 10 - 30 seconds). During this period, if key interrupts are sensed, modify the display or perform other functions as called for.
5.	At the end of the predetermined spectrum accumulation period, read in the contents of the spectrum RAM, and zero it out. Allow spectra to accumulate while proceeding to step (6).
6.	Integrate the spectra's total energies using the energy calibration constants stored in RAM. Determine the dead time during each spectrum's accumulation, and perform the dead time correction.
7.	Add the results of the processing of the two spectra. Calculate the dose rate for the period. Update the running registers of total dose and elapsed time.
8.	Update the instrument display. Return to step (4).

5.2 Additional Research Required

A number of technical items would need to be resolved prior to the completion of the development of a commercial instrument. These may be divided into those which should be resolved prior to committing to the design and construction of a prototype, and those which should be tested in the prototype itself.

5.2.1 Pre-Prototype Testing

The Phase I research did not answer all questions regarding the spectroscopic dosimeter principle, in part because of a lack of access to suitable sources of radiation for some tests. The remainder of those issues should be explored before the expensive and lengthy process of prototype design and development is undertaken. They include the following:

1. Response to particles other than photons. A detector with a very thin end window should be tested to determine the energy calibration for important types of charged particles such as electrons, alpha particles, and protons. If the spectroscopic dosimeter principle is to work in practice, energy deposition of a given quantity must lead to the same pulse size regardless of the incident particle type. Thus, if the calibrations do not match initially, ways must be explored for bringing them into agreement. The appropriate thickness of tissue equivalent covering for the detector should also be determined.

2. Response to high-energy photons. Sources of high-energy photons (5 to 100 MV) which operate at reasonably low dose rates (on the order of 1 rad/hr or less) must be located and used to test the system response.

3. Spectrum response combination methods. The conceptual design calls for two parallel pulse processing trains to handle the upper and lower parts of the total energy range of the instrument. Tests should be performed to determine whether the instrument response is the same a) when the incoming pulses are divided into two spectra with the results combined, as it was b) when only one spectrum was used. Some preliminary tests performed in Phase I indicated as much as a 15% discrepancy, indicating that the spectrum division and result combination process needs to be studied thoroughly to be optimized.

5.2.2 Prototype Testing

Once the prototype design and development are undertaken, a number of crucial tests of the complete system will be required. These include the following:

1. Component stability. When prototype circuits are mocked up, they must be tested for long-term stability prior to integration into the completed prototype. Especially important are drift in the power supply, bias supply, and amplifiers. Temperature stability of the bias supply, amplifiers, and ADC's is also a concern, since the dosimeter could conceivably be used both inside and outside spacecraft.

2. Software development. Software (almost certainly in assembly language) to permit the instrument microcomputer to perform its functions must be specified, developed, tested, and installed in ROM.

3. Calibration methods. Energy calibration methods for the assembled prototype need to be developed and tested. Software must be developed for the host computer which would control the dosimeter and process results during calibration. A method for field-testing the energy calibration without external equipment should be developed if possible, and tested.

4. Dosimeter performance testing. The complete unit must be retested to determine its response as a function of dose rate, cumulative dose, particle type, and particle energy. Adjustments to the calibration factors and perhaps the methods are likely to be required.

The prototype developed in this process would be relatively large device using standard integrated circuits and boards. It should be amenable to substantial size reduction through the use of custom integrated circuits and VLSI technology, if the performance of the prototype is adequate.

A program of development similar to the above should assure that the completed commercial device fulfills the needs for a space dosimeter. At the present stage of research, the spectroscopic dosimeter method seems very promising for this purpose.

SECTION 6.0
REFERENCES

The following documents are cited by name in prior sections of this report:

Akatov 1980. Yu. A. Akatov, T. V. Batenchuk, A. M. Borodin, and ten others. "Results of Cosmic Radiation Dose Field Measurements Aboard the 'Salyut-6' Orbital Station." Hungarian Academy of Sci. Rept. KFKI-1980-35.

Attix 1968. F. H. Attix and W. C. Roesch. Radiation Dosimetry. Volume I: Fundamentals. Second Edition. Academic Press, New York.

Becchetti 1981. F. D. Becchetti, R. A. Ristinen, R. J. Peterson, J. J. Hamill, C. E. Thorn, and G. Entine. "Pulse Height Response of Cd-Te to Heavy Ions." IEEE Trans. Nuc. Sci. NS-28, 1546-1547.

Benton 1983. E. V. Benton and R. P. Henke. "Radiation Exposures During Space Flight and Their Measurement." Adv. Space Res. 3, 171-185.

Benton 1984. E. V. Benton. "Summary of Current Radiation Dosimetry Results on Manned Spacecraft." Adv. Space Res. 4, 153-160.

Benton 1985. E. V. Benton, A. L. Frank, T. A. Parnell, J. W. Watts, Jr., and J. C. Gregory. "Radiation Environment of Spacelab-1." Presented at American Inst. of Aero. and Astro. Conference, "AIAA Shuttle Environment and Operations II," Houston, November 1985.

Bochvar 1983. I. V. Bochvar, T. I. Gimadova, and I. B. Keirim-Markus. "Expediency of Using Personal Dosimeters for Effective Doses during Manned Spaceflights." USSR Rept. Space Biol. and Aero. Med. 17, trans. as pp. 98-100 in JPRS Rept. JPRS-83828.

Bojsen 1984. J. Bojsen. "Cadmium Telluride [CdTe(Cl)] Detectors and Their Geometrical Characteristics in Local Disappearance Measurements Using Radionuclides." Nucl. Instrum. and Meth. in Phys. Res. A219, 592-600.

Braby 1984a. L. A. Braby, C. A. Ratcliffe, N. F. Metting, and M. K. Lien. "Develop Real-Time Dosimetry Concepts and Instrumentation for Long-Term Missions." USDOE Rept. PNL-5112.

Braby 1984b. L. A. Braby, C. A. Ratcliffe, and N. F. Metting. "Evaluation of a Portable Microdosimetry System." Rad. Pro. Dosim. 9, 219-221.

Braby 1985. L. A. Braby. "A Portable Dose Equivalent Meter Based on Microdosimetry." Nuc. Instrum. and Meth. in Phys. Res. B10/11, 910-914.

Cash 1985. S. E. Cash, R. G. Madonna, M. R. McClellan, and M. E. Fields. "Results from Radiation Monitoring Equipment Experiments on STS-41C, 41D, 41G, and 51A." USAF AFTAC Rept. AFTAC-TR-85-4.

deCarolis 1976. M. deCarolis, T. Dragnev, and A. Waligura. "IAEA Experience in the Development and Use of CdTe Gamma Spectrometric Systems for Safeguards Applications." IEEE Trans. Nuc. Sci. NS-23, 70-74.

Cornet 1970. A. Cornet, P. Siffert, and A. Coche. "Cadmium Telluride Surface Barrier Detectors." App. Phys. Let. 17, 432-436.

Dabrowski 1974. A. J. Dabrowski, J. Iwanczyk, R. Triboulet. "n-Type Cadmium Telluride Surface-Barrier Nuclear Radiation Detectors." Nucl. Instrum. and Meth. 118, 531-535.

Entine 1981. G. Entine, M. R. Squillante, H. B. Serreze, and E. Clarke. "Fast, High-Flux, Photovoltaic CdTe Detector." IEEE Trans. Nuc. Sci. NS-28, 558-562.

Entine 1985. G. Entine. "Applications of CdTe to Nuclear Medicine." USDOE Rept. DOE/EV/02541.

Fox 1978. R. J. Fox and D. C. Agouridis. "CdTe Photovoltaic Gamma-Ray Dosimeter." Nuc. Instrum. and Meth. 157, 65-69.

Gorev 1981. V. S. Gorev, V. A. Kozhemyakin, O. A. Matveev, M. D. Firsov, A. Kh. Khusainov, and G. I. Shul'govich. "Using Cadmium Telluride Detectors in Gamma-Radiation Dosimetry." Instrum. and Exp. Tech. 24 (1), 60-65.

Hankins 1985. D. E. Hankins. "Effect of Air-Scattered Beta Particles on Instrument and Dosimeter Response." Health Physics 49, 435-441.

Hodgkinson 1979. J. A. Hodgkinson, J. H. Howes, and D. H. J. Totterdell. "Non-Linearity Effects in the Response of Cadmium Telluride Nuclear Radiation Detectors." Nuc. Instrum. and Meth. 164, 469-475.

Johnson 1981. O. E. Johnson. "Radiation and Temperature Tests of Cadmium Telluride Detectors." US Army ERADCOM Rept. DELCS-TR-81-3.

Jones 1977. L. T. Jones. "The Use of Cadmium Telluride Gamma Spectrometers in Monitoring Activity Deposited in Nuclear Power Stations." Rev. Phys. App. 12, 379-384.

Jordan 1983. T. M. Jordan. "Radiation Protection for Manned Space Activities." NASA Rept. JPL 83-26.

Knoll 1979. G. F. Knoll. Radiation Detection and Measurement. Wiley and Sons, New York.

Lyons 1977. R. B. Lyons. "Cadmium Telluride Detector Development and Use in Reentry Vehicle Applications." Rev. Phys. App. 12, 385-389.

McGowan 1982. S. McGowan. "Cadmium Telluride Detectors for Gamma Dose-Rate Meters." Defense Research Establishment Ottawa Rept. DREO-859.

Madonna 1984. R. G. Madonna, R. L. Amico, V. L. Brown, and V. R. Kidd. "Results from Radiation monitoring Equipment Experiment on STS-8." USAF AFTAC Rept. AFTAC-TR-84-4.

Madonna 1985. R. G. Madonna, V. L. Brown, and S. E. Cash. "Results from Radiation Monitoring Equipment Experiment on STS-11." USAF AFTAC Rept. AFTAC-TR-85-2.

Miroshnichenko 1983. L. I. Miroshnichenko. "Solar Cosmic Radiation and Radiation Hazard of Spaceflights." USSR Rept. Space Biol. and Aero. Med. 17, trans. as pp. 7-14 in JPRS Rept. JPRS-83828.

Quaranta 1970. A. A. Quaranta, C. Canali, and G. Ottaviani. "Electron-Hole Pair Ionization Energy in CdTe between 85°K and 350°K." Nuovo Cimento Let. 19, 908-910.

Ristinen 1981. R. A. Ristinen, R. J. Peterson, J. J. Hamill, F. D. Becchetti, and G. Entine. "An Evaluation of CdTe Surface Barrier Diodes as Detectors for Energetic Charged Particles." Nuc. Instrum. and Meth. 188, 445-452.

Serreze 1974. H. B. Serreze, G. Entine, R. O. Bell, and F. V. Wald. "Advances in CdTe Gamma-Ray Detectors." IEEE Trans. Nuc. Sci. NS-21, 404-407.

Smirenyy 1983. L. N. Smirenyy and A. V. Khortsev. "Estimates of Cosmic Ray Doses in Near-Earth Orbits with Apogee up to 1000 km during Period of Solar Inactivity." USSR Rept. Space Biol. and Aero. Med. 17, trans. as pp. 94-97 in JPRS Rept. JPRS-83828.

Umbarger 1979. C. J. Umbarger, M. A. Wolf, and G. Entine. "A Totally New Pocket Radiation Chirper." Health Physics 36, 455-458.

Vidra 1979. M. Vidra. "Optimising the Parameters of Spectrometers with Cadmium-Telluride Detecrtors." Jaderna Energie 25, 446-453. Trans. as British Library Lending Division Rept. RTS-12539.

Wald 1972. F. Wald, R. O. Bell, and A. A. Menna. "Cadmium Telluride Detectors." Isotopes and Rad. Tech. 9, 444-447.

Wolf 1979. M. A. Wolf, C. J. Umbarger, and G. Entine. "Use of a Cadmium Telluride Detector in a New Tiny Personal Radiation Chirper." IEEE Trans. Nuc. Sci. NS-26, 777-779.

Wolf 1981. M. A. Wolf, D. A. Waechter, and C. J. Umbarger. "A New Tiny Computerized Radation Dosimeter." IEEE Trans. Nuc. Sci. NS-29, 773-774.

APPENDIX A
PROGRAM DOSEANAL

A.1 Program Description

Program DOSEANAL is written in BASICA to run on an IBM/PC or lookalike. It reads in spectral data previously stored on disk in a set format, and integrates the total energy deposition represented by the spectrum (see Section 3.3). It prints those results and other parameters of interest on the system printer.

A.2 Testing of the Program

Several tests of the program were performed to make certain that it was performing its functions correctly. For example, spectra as read in and stored by the program were printed out and compared with those originally stored in the MCA. No problems were found.

The principal function of the program, energy deposition integration, was tested by preparing and storing spectra whose counts as a function of channel number were described by simple functions (such as Counts(Chan) = constant, or Counts(Chan) = constant/Chan) so that the integration could be performed analytically for comparison with the values generated by the program. The program agreed with the analytical results within a few percent, which was judged to be due to integer roundoff in the program.

Other functions of the program were tested by similar methods and found to be correct.

A.3 Program Listing

The following pages present the listing of Program DOSEANAL as it was used in the research described in this report.

```
10  REM ***DOSEANAL***  CdTe SPECTRUM ANALYZER  BGW 86/09
/10
20  REM -- from program of 86/09/08
30      OPTION BASE 1
40      DIM SPECTRUM(2048),ENERGY#(5),EFF#(6),FWHM#(5),DATES#(7)
50      DIM BINTOT#(11),EXSPEC(2048),LIM(11,2)
60      REM
70      KEY OFF
80      GOSUB 780:                          'Select File
90      GOSUB 900                           'Read File
100     HEADCHNG%=0:CHNGEVER%=0: LOEXTRAP%=1: HIEXTRAP%=0
110     GOSUB 1310:                         'Header on Screen
120     GOSUB 1500:                         'Edit Header Data
130     IF NEWFILE%=1 THEN GOTO 90
140     IF HEADCHNG%=1 THEN CHNGEVER%=1
150     IF CHNGEVER%=0 THEN GOTO 190
160             IF HEADCHNG%=0 THEN GOTO 180
170             HEADCHNG%=0: GOTO 110
180     GOSUB 1990                          'Store Changed Data
190 REM                                     Set Calculation Parameters
200     Q$="Select BEGINNING Channel for integration."
210       LIN%=5: LO%=1: HI%=NCHANS: OK%=1: GOSUB 3260
220       BEGCHAN%=IN%
230     Q$="Select ENDING Channel for integration."
240       NOCLEAR%=1: LIN%=10: LO%=LOCHAN%: HI%=NCHANS: OK%=LOCHAN%: GOSUB 3260
250       ENDCHAN%=IN%
260     GOSUB 3740                          'Select Extrapolation Mode
270 REM                                     Print Out Header Information
280     GOSUB 1050
290 REM                                     Perform Calculations
300     CLS
310     FOR CASE%=1 TO 5
320       ON CASE% GOTO 330,380,460,540,620
330         TITLE$="No Extrapolation":'                         **Case 1
340             GOSUB 2390
350             LOCHAN%=BEGCHAN%: HICHAN%=ENDCHAN%: GOSUB 2180
360             NOTE$="Spectrum used as collected."
370             GOTO 700
380         TITLE$="Flat Extrapolation at Low E":'              **Case 2
390             IF EXMODE%<2 THEN GOTO 740
400             GOSUB 2390
410             GOSUB 2470:  ' find low edge
420             GOSUB 2550:  ' flatten below low edge
430             LOCHAN%=1: HICHAN%=ENDCHAN%: GOSUB 2180
440             NOTE$="Below Low Edge, spectrum estimated as constant "+STR$(EXV
AL)+" counts."
450             GOTO 700
460         TITLE$="Linear Extrapolation at Low E":'            **Case 3
470             IF EXMODE%<3 THEN GOTO 740
480             GOSUB 2390
490             GOSUB 2470:  ' find low edge
500             GOSUB 2910:  ' linear extrapolation
510             LOCHAN%=1: HICHAN%=ENDCHAN%: GOSUB 2180
520            NOTE$="Below Low Edge, spectrum est. as:  "+STR$(B)+" + "+STR$(M)
+" *Ch"
530             GOTO 700
```

```
540         TITLE$="Semi-log Extrapolation at Low E":'          **Case 4
550             IF EXMODE%<4 THEN GOTO 740
560             GOSUB 2390
570             GOSUB 2470:  ' find low edge
580             GOSUB 3010:  ' semi-log extrapolation
590             LOCHAN%=1: HICHAN%=ENDCHAN%: GOSUB 2180
600            NOTE$="Below Low Edge, spectrum est. as:  "+STR$(B)+" * exp( "+ST
R$(M)+"* Ch )"
610             GOTO 700
620         TITLE$="Log-log Extrapolation at Low E":'           **Case 5
630             IF EXMODE%<4 THEN GOTO 740
640             GOSUB 2390
650             GOSUB 2470:  ' find low edge
660             GOSUB 3130:  ' log-log extrapolation
670             LOCHAN%=1: HICHAN%=ENDCHAN%: GOSUB 2180
680            NOTE$="Below Low Edge, spectrum est. as:  "+STR$(B)+" * ( Ch^ "+S
TR$(M)+" )"
690             GOTO 700
700      CLS: GOSUB 2690:  ' print case results
710       IF LOEXTRAP%=0 THEN GOTO 730
720       NEXT CASE%
730 REM
740 REM
750     GOSUB 3570: '          choose next action
760    CLS: ON WHERE% GOTO 100, 80, 770
770    CLS:KEY ON: END
780 REM ********************************SELECT DATA FILE
790    CLS:LOCATE 3,1:PRINT "                  *** CdTe Spectrum Analysis Program
***"
800    LOCATE 10,1:PRINT "Path to Data File:";
810       LOCATE 10,20:INPUT;"",PATH$
820    LOCATE 12,1:PRINT "Data File Name:";
830      LOCATE 12,20:INPUT;"",FSPEC$
840     LOCATE 20,1:INPUT; "Want to CHANGE? [n]",ANS$
850       IF ANS$="N" OR ANS$="n" OR ANS$="" THEN RETURN
860       IF ANS$="Y" OR ANS$="y" THEN GOTO 800
870       BEEP:CLS:LOCATE 10,1:PRINT "Improper reply. Try again.";
880            FOR J%=1 TO 100:L%=1+1:NEXT J%:GOTO 790
890 REM ************************************************************
900 REM ********************************Read Data File
910    OPEN PATH$+FSPEC$ FOR INPUT AS 1
920     INPUT #1,COMMENT$,DETECTOR,YIELD,TOTCTS,UNITS$
930     INPUT #1,DATES#(1),DATES#(2),DATES#(3),DATES#(4),DATES#(5),DATES#(6)
940     INPUT #1,RADTIM,DEADTIM
950     IF DEADTIM=0 THEN DEADTIM=TCLOCK-TLIVE
960     INPUT #1,ENERGY#(1),ENERGY#(2),ENERGY#(3),ENERGY#(4),ENERGY#(5)
970     INPUT #1,EFF#(1),EFF#(2),EFF#(3),EFF#(4),EFF#(5),EFF#(6)
980     INPUT #1,FWHM#(1),FWHM#(2),FWHM#(3),FWHM#(4),FWHM#(5)
990     INPUT #1,TLIVE,TCLOCK,NCHANS
1000    FOR CH%=1 TO NCHANS: INPUT #1,SPECTRUM(CH%): NEXT CH%
1010    CLOSE #1
1020    IF TOTCTS<100 THEN GOSUB 3660
1030    RETURN
1040 REM ************************************************************
```

```
1050 REM ******************************** Print Header on Printer
1060    LPRINT CHR$(12): LPRINT "                    *** CdTe Spectrum Analysis *
**"
1070    LPRINT:LPRINT:LPRINT
1080    LPRINT "File Name:    ";PATH$+FSPEC$
1090    LPRINT
1100    LPRINT "Comment:      ";COMMENT$
1110    LPRINT
1120    LPRINT USING "&#####.##     &#####.##     &#####.##";"Irrad. : ",RADTIM,
" sec.","Live Irrad.: ",RADTIM-DEADTIM," sec.","Dead : ",DEADTIM," sec."
1130    LPRINT
1140    LPRINT USING "&##.###^^^^           &##.###^^^^";"Total Cts. in Spec.: "
,TOTCTS,"Ave. Cts. per Live Sec.:",TOTCTS/(RADTIM-DEADTIM)
1150    LPRINT
1160    LPRINT STRING$(78,"-")
1170    LPRINT "Energy Calibration:"
1180    LPRINT
1190    LPRINT USING "&##.###^^^^&##.###^^^^&##.###^^^^&##.###^^^^";"E(keV) = ",
ENERGY#(1)," +  ",ENERGY#(2)," *CH +  ",ENERGY#(3)," *CH^2 +  ",ENERGY#(4)," *CH
^3"
1200    LPRINT
1210    LPRINT STRING$(78,"-")
1220    LPRINT
1230    LPRINT "Selected Channel Range:":LPRINT
1240       CH%=BEGCHAN%: GOSUB 2650: BEGEN=EN
1250       CH%=ENDCHAN%: GOSUB 2650: ENDEN=EN
1260    LPRINT USING "&######&##.##^^^^&######&##.##^^^^&";"From Channel ",BEGCHAN%,"
 (= ",BEGEN," keV)      To Channel ",ENDCHAN%,"  (= ",ENDEN," keV)"
1270    LPRINT
1280    LPRINT STRING$(78,"-")
1290    RETURN
1300 REM ********************************* *****************************
1310 REM ******************************** Print Header on Screen
1320    CLS:PRINT "                     *** CdTe Spectrum Analysis ***"
1330    PRINT:PRINT:PRINT
1340    PRINT "File Name:    ";PATH$+FSPEC$
1350    PRINT
1360    PRINT "Comment:      ";COMMENT$
1370    PRINT
1380    PRINT USING "&#####.##        &#####.##     &#####.##";"Irrad. : ",RADTI
M," sec.","Live Irrad.: ",RADTIM-DEADTIM," sec.","Dead : ",DEADTIM," sec."
1390    PRINT
1400    PRINT USING "&##.###^^^^          &##.###^^^^";"Total Cts. in Spec.: ",TOT
CTS,"Ave. Cts. per Live Sec.:",TOTCTS/(RADTIM-DEADTIM)
1410    PRINT
1420    PRINT STRING$(78,"-")
1430    PRINT "Energy Calibration:"
1440    PRINT
1450    PRINT USING "&##.###^^^^&##.###^^^^&##.###^^^^&##.###^^^^";"E(keV) = ",E
NERGY#(1)," +  ",ENERGY#(2)," *CH +  ",ENERGY#(3)," *CH^2 +  ",ENERGY#(4)," *CH^
3"
1460    PRINT
1470    PRINT STRING$(78,"-")
1480    RETURN
1490 REM ************************************************************
```

```
1500 REM ******************************** Edit Header Data
1510    LOCATE 23,1:INPUT; "Do you want to CHANGE ANY DATA?  [n]   ",ANS$
1520      IF ANS$="n" OR ANS$="N" OR ANS$="" THEN RETURN
1530      IF ANS$="Y" OR ANS$="y" THEN GOTO 1570
1540      BEEP:LOCATE 23,1:PRINT "        Improper reply. Try again.        ";
1550           FOR J%=1 TO 100:L%=1+1:NEXT J%:LOCATE 23,1:PRINT STRING$(75," "):GOTO 900
1560    REM                                 'Edit File Specification
1570    NEWFILE%=0
1580    CLS:LOCATE 10,1:PRINT "Enter Path to Data File.  [";PATH$;"]";
1590      LOCATE 10,40:INPUT;"",INPATH$
1600    IF INPATH$="" OR INPATH$=PATH$ THEN GOTO 1620
1610      NEWFILE%=1: PATH$=INPATH$
1620    LOCATE 12,1:PRINT "Enter Data File Name.  [";FSPEC$;"]";
1630      LOCATE 12,40:INPUT;"",INFSPEC$
1640    IF INFSPEC$="" OR INFSPEC$=FSPEC$ THEN GOTO 1660
1650      NEWFILE%=1: FSPEC$=INFSPEC$
1660    IF NEWFILE%=1 THEN RETURN
1670    REM                                 'Edit Comment$
1680    CLS:LOCATE 10,1:PRINT "Enter Comment.  [";COMMENT$;"]";
1690      LOCATE 11,18:INPUT;"",INANS$
1700    IF INANS$="" OR INANS$=COMMENT$ THEN GOTO 1720
1710      HEADCHNG%=1: COMMENT$=INANS$
1720    REM                                 'Edit Irradiation Time
1730    CLS:LOCATE 10,1:PRINT "Enter Length of Irrdn (sec).  [";RADTIM;"]";
1740      LOCATE 10,40:INPUT;"",INANS$:INANS=VAL(INANS$)
1750    IF INANS$="" OR INANS=RADTIM THEN GOTO 1770
1760      HEADCHNG%=1: RADTIM=INANS
1770    REM                                 'Edit Dead Time
1780    CLS:LOCATE 10,1:PRINT "Enter Counting Dead Time (sec).  [";DEADTIM;"]";
1790      LOCATE 10,40:INPUT;"",INANS$:INANS=VAL(INANS$)
1800    IF INANS$="" OR INANS=DEADTIM THEN GOTO 1820
1810      HEADCHNG%=1: DEADTIM=INANS
1820    REM                                 'Edit Energy Calibration
1830    CLS:LOCATE 10,1:PRINT USING "&#.##^^^^&#.##^^^^&#.##^^^^&#.##^^^^&";"Ent
er E Cal Coeffs.  [";ENERGY#(1),",",ENERGY#(2),",",ENERGY#(3),",",ENERGY#(4);"]"

1840      LOCATE 11,5:LINE INPUT;"",INANS$
1850    IF INANS$="" THEN RETURN
1860    FOR K%=1 TO 4
1870      IF K%<4 THEN GOTO 1890
1880      A$=INANS$: GOTO 1920
1890     J%=LEN(INANS$)
1900      L%=INSTR(1,INANS$,",")
1910      A$=LEFT$(INANS$,L%-1)
1920      INEN#=VAL(A$)
1930      INANS$=RIGHT$(INANS$,J%-L%)
1940      IF INEN#=ENERGY#(K%) THEN GOTO 1960
1950      ENERGY#(K%)=INEN#: HEADCHNG%=1
1960      NEXT K%
1970    RETURN
1980 REM ************************************************************
```

```
1990 REM ********************************* Store Revised Data
2000    CLS:LOCATE 10,1:INPUT "Do you want to STORE REVISED DATA?  [y]",ANS$
2010      IF ANS$="n" OR ANS$="N" THEN RETURN
2020      IF ANS$="y" OR ANS$="Y" OR ANS$="" THEN GOTO 2050
2030        BEEP:LOCATE 23,1:PRINT "        Improper reply. Try again.        ";
2040        FOR J%=1 TO 100:L%=1+1:NEXT J%:LOCATE 23,1:PRINT STRING$(75," "):GOTO 20
00
2050    CLS:LOCATE 10,20:PRINT "STORING FILE  ";PATH$+FSPEC$;
2060    OPEN PATH$+FSPEC$ FOR OUTPUT AS 1
2070    WRITE #1,COMMENT$,DETECTOR,YIELD,TOTCTS,UNITS$
2080    WRITE #1,DATES#(1),DATES#(2),DATES#(3),DATES#(4),DATES#(5),DATES#(6)
2090    WRITE #1,RADTIM,DEADTIM
2100    WRITE #1,ENERGY#(1),ENERGY#(2),ENERGY#(3),ENERGY#(4),ENERGY#(5)
2110    WRITE #1,EFF#(1),EFF#(2),EFF#(3),EFF#(4),EFF#(5),EFF#(6)
2120    WRITE #1,FWHM#(1),FWHM#(2),FWHM#(3),FWHM#(4),FWHM#(5)
2130    WRITE #1,TLIVE,TCLOCK,NCHANS
2140    FOR CH%=1 TO NCHANS: WRITE #1,SPECTRUM(CH%): NEXT CH%
2150    CLOSE #1
2160    RETURN
2170 REM ************************************************************
2180 REM ***************************** Total Energy Integration
2190    CHPERBIN%=INT((HICHAN%-LOCHAN%)/10)+1:  CLS
2200    FOR BIN%=1 TO 11
2210      LOCATE 10,23: PRINT "Working on Case # ";CASE%;", Bin # ";BIN%;
2220      BINTOT#(BIN%)=0
2230      FRSTCHAN%=LOCHAN% + (BIN%-1)*CHPERBIN%: LASTCHAN%=LOCHAN%+CHPERBIN%*BI
N%-1
2240            IF FRSTCHAN%>HICHAN% THEN RETURN
2250            IF BIN%=11 THEN LASTCHAN%=HICHAN%
2260            IF LASTCHAN%<FIRSTCHAN% THEN GOTO 2370
2270      CH%=FRSTCHAN%: GOSUB 2650: LIM(BIN%,1)=EN
2280      FOR CH%=FRSTCHAN% TO LASTCHAN%
2290            IF CH%>HICHAN% THEN GOTO 2340
2300            GOSUB 2650
2310            DELEN#=EN*EXSPEC(CH%):  IF DELEN#<0 THEN DELEN#=0
2320            BINTOT#(BIN%)=BINTOT#(BIN%) + DELEN#
2330            NEXT CH%
2340      CH%=CH%-1: GOSUB 2650: LIM(BIN%,2)=EN
2350      IF CH%>HICHAN% THEN RETURN
2360      NEXT BIN%
2370    RETURN
2380 REM ************************************************************
2390 REM ***************************** Load SPECTRUM into EXSPEC
2400    CLS: LOCATE 10,20: PRINT "Setting up Extrapolated Spectrum"
2410    CHF%=2048: IF HIEXTRAP%=1 OR ENDCHAN%>1350 THEN GOTO 2430
2420    CHF%=ENDCHAN%*1.5
2430    FOR IJ%=1 TO CHF%: EXSPEC(IJ%)=SPECTRUM(IJ%): NEXT IJ%
2440    EXSPEC(1)=0:'                    (Correct for time in ch. 1)
2450    RETURN
2460 REM ************************************************************
2470 REM ***************************** Find First Full-Height Channel
2480    FOR CH%=1 TO NCHANS
2490      IF EXSPEC(CH%)>0 THEN GOTO 2520
2500      NEXT CH%
2510    PRINT "*** WARNING!!  NO LOW EDGE FOUND ***": CH%=CH%-5
2520    LOEDGE%=CH%+4
2530    RETURN
2540 REM ************************************************************
```

```
2550 REM ***************************** Flatten EXSPEC below LOEDGE%
2560    EXVAL=0
2570    FOR CH%=LOEDGE% TO LOEDGE%+3
2580      EXVAL=EXVAL+EXSPEC(CH%)
2590      NEXT CH%
2600    EXVAL=INT(EXVAL/4)
2610    FOR CH% =1 TO LOEDGE%-1
2620      EXSPEC(CH%)=EXVAL
2630      NEXT CH%
2640    RETURN
2650 REM ***************************** Convert Channel Number to E(keV)
2660    EN=((ENERGY#(4)*CH% + ENERGY#(3))*CH% + ENERGY#(2))*CH% + ENERGY#(1)
2670    RETURN
2680 REM ************************************************************
2690 REM ***************************** Print Case Results
2700    CLS: LOCATE 10,30: PRINT "Printing Results"
2710 LPRINT:LPRINT:LPRINT
2720    LPRINT "      CASE # ";CASE%;":  ";TITLE$
2730    LPRINT: LPRINT "        NOTE:  ";NOTE$:LPRINT:LPRINT
2740    ETOT#=0: FOR I%=1 TO 11: ETOT#=ETOT#+BINTOT#(I%): NEXT I%
2750    LPRINT "            Energy Range (keV)"
2760    LPRINT "            ------------------       Total Energy       % of"
2770    LPRINT " Bin #     Low            High      Deposited (keV)     Total"
2780    LPRINT " -----  ----------    ----------   ---------------   ---------"
2790    LPRINT
2800    FOR BIN%=1 TO 11
2810      LPRINT USING "  ###    ##.###^^^^     ##.###^^^^      ##.####^^^^      ##.
##^^^^";BIN%,LIM(BIN%,1),LIM(BIN%,2),BINTOT#(BIN%),BINTOT#(BIN%)*100/ETOT#
2820      NEXT BIN%
2830    LPRINT "                                          ---------------"
2840    LPRINT USING "                 &                 ##.####^^^^";"TOTAL",ETOT
#
2850    LPRINT
2860    LPRINT USING "                  &                   ##.####^^^^&";"or",ETO
T#/(RADTIM-DEADTIM)," keV/sec
2870    LPRINT USING "                                                    &";"(liv
e irradiation time)"
2880    LPRINT : LPRINT STRING$(78,"-")
2890    CLS:RETURN
2900 REM ************************************************************
2910 REM ******************************** Linear Back-Extrapolation of EXSPEC
2920    Y1=0: FOR CH%=LOEDGE% TO LOEDGE%+2: Y1=Y1+EXSPEC(CH%): NEXT CH%: Y1=Y1/3
2930    Y2=0: FOR CH%=LOEDGE%+3 TO LOEDGE%+5: Y2=Y2+EXSPEC(CH%): NEXT CH%: Y2=Y2/3
2940    X1=LOEDGE%+1: X2=LOEDGE%+4
2950    M=(Y2-Y1)/(X2-X1): B=Y1-M*X1
2960    FOR CH%=1 TO LOEDGE%-1
2970      EXSPEC(CH%)=M*CH%+B:  IF EXSPEC(CH%)<0 THEN EXSPEC(CH%)=0
2980      NEXT CH%
2990    RETURN
3000 REM ************************************************************
```

```
3010 REM ********************************* Semi-log Back-Extrapolation of EXSPEC
3020    Y1=0: FOR CH%=LOEDGE% TO LOEDGE%+2: Y1=Y1+LOG(EXSPEC(CH%)): NEXT CH%: Y1=Y1/
3
3030    Y2=0: FOR CH%=LOEDGE%+3 TO LOEDGE%+5: Y2=Y2+LOG(EXSPEC(CH%)): NEXT CH%: Y2=Y
2/3
3040    X1=LOEDGE%+1: X2=LOEDGE%+4
3050    M=(Y2-Y1)/(X2-X1)
3060      IF M<>0 THEN B=EXP(Y1)/EXP(M*X1)
3070      IF M=0 THEN B=EXSPEC(LOEDGE%+3)
3080    FOR CH%=1 TO LOEDGE%-1
3090      EXSPEC(CH%)=B*EXP(M*CH%):  IF EXSPEC(CH%)<0 THEN EXSPEC(CH%)=0
3100      NEXT CH%
3110    RETURN
3120 REM ************************************************************
3130 REM ********************************* Log-log Back-Extrapolation of EXSPEC
3140    Y1=0: FOR CH%=LOEDGE% TO LOEDGE%+2: Y1=Y1+LOG(EXSPEC(CH%)): NEXT CH%: Y1=Y1/
3
3150    Y2=0: FOR CH%=LOEDGE%+3 TO LOEDGE%+5: Y2=Y2+LOG(EXSPEC(CH%)): NEXT CH%: Y2=Y
2/3
3160    X1=0: FOR CH%=LOEDGE% TO LOEDGE%+2: X1=X1+LOG(CH%): NEXT CH%: X1=X1/3
3170    X2=0: FOR CH%=LOEDGE%+3 TO LOEDGE%+5: X2=X2+LOG(CH%): NEXT CH%: X2=X2/3
3180    M=(Y2-Y1)/(X2-X1)
3190      IF M<>0 THEN B=EXP(Y1)/((EXP(X1))^M)
3200      IF M=0 THEN B=EXSPEC(LOEDGE%+3)
3210    FOR CH%=1 TO LOEDGE%-1
3220      EXSPEC(CH%)=B*CH%^M:  IF EXSPEC(CH%)<0 THEN EXSPEC(CH%)=0
3230      NEXT CH%
3240    RETURN
3250 REM ************************************************************
3260 REM ***************************Integer Precision Input Routine
3270 REM (OK% is an acceptable out-of-bounds value for a flag)
3280 IF NOCLEAR% <> 1 THEN CLS
3290 IF LIN%<1 OR LIN%>24 THEN LIN%=10
3300 IF COL%<1 OR COL%>79 THEN COL%=1
3310 LOCATE LIN%,COL%: IF Q$<>"" THEN PRINT STRING$(79-COL%," "): PRINT Q$+" ( "
;LO%;" -> ";HI%;" )"
3320 INPUT;"", IN$
3330    IF LEN(IN$)=0 THEN GOTO 3350
3340      IN%=VAL(IN$)
3350    IF IN%>=LO% AND IN%<=HI% THEN GOTO 3400
3360    IF IN%=OK% THEN GOTO 3400
3370      BEEP:LOCATE LIN%,1: PRINT STRING$(78," "):PRINT "*** Response OUT OF R
ANGE.  Try again. ***"
3380      FOR KI%=1 TO  200:KJ%=1+1:NEXT KI%
3390      GOTO 3310
3400 LIN%=0: COL%=0: Q$="": NOCLEAR%=0
3410 RETURN
3420 REM ************************************************************
3430 REM ************************** Answer Yes/No Question
3440 IF NOCLEAR% <> 1 THEN CLS
3450 IF LIN%<1 OR LIN%>24 THEN LIN%=10
3460 LOCATE LIN%,1: PRINT STRING$(78," "): PRINT Q$+" (Y/N)    ["+ANS$+"]"
3470 INPUT;"", IN$
3480    IF LEN(IN$)=0 THEN GOTO 3510
3490    IF IN$="N" OR IN$="n" THEN ANS$="N"
3500    IF IN$="Y" OR IN$="y" THEN ANS$="Y"
3510    IF ANS$="Y" OR ANS$="N" THEN GOTO 3550
3520      BEEP:LOCATE LIN%,1: PRINT STRING$(78," "):PRINT "*** Please answer Yes
 or No.  Try again. ***"
```

```
3530       FOR KI%=1 TO  200:KJ%=1+1:NEXT KI%
3540       GOTO 3460
3550 LIN%=0: COL%=0: Q$="": NOCLEAR%=0: RETURN
3560 REM ************************************************************
3570 REM ***************************** Choose Next Action
3580     CLS: LOCATE 8,1: PRINT "Chobse one of the following:  "
3590     LOCATE 10,5: PRINT "1.  Reanalyze SAME spectrum."
3600     LOCATE 11,5: PRINT "2.  Analyze NEW spectrum."
3610     LOCATE 12,5: PRINT "3.  END program"
3620     NOCLEAR%=1: LIN%=8: COL%=32: LO%=1: HI%=3: OK%=1: Q$="": GOSUB 3260
3630     WHERE%=IN%
3640     RETURN
3650 REM ************************************************************
3660 REM ***************************** Totalize Spectrum Counts
3670     SUM#=0: CLS: LOCATE 10,26: PRINT "Totalizing Spectrum Counts";
3680     FOR CH%=3 TO NCHANS
3690       SUM#=SUM#+SPECTRUM(CH%)
3700       NEXT CH%
3710     TOTCTS=SUM#
3720     CLS: RETURN
3730 REM ************************************************************
3740 REM ***************************** Choose Extrapolation Mode
3750     CLS: LOCATE 8,1: PRINT "What kind(s) of LOW-END EXTRAPOLATION should be used
? "
3760     LOCATE 10,5: PRINT "1.  NO extrapolations."
3770     LOCATE 11,5: PRINT "2.  FLAT only."
3780     LOCATE 12,5: PRINT "3.  FLAT and LINEAR only."
3790     LOCATE 13,5: PRINT "4.  ALL available types."
3800     NOCLEAR%=1: LIN%=8: COL%=65: LO%=1: HI%=4: OK%=1: Q$="": GOSUB 3260
3810     EXMODE%=IN%
3820     RETURN
3830 REM ************************************************************
```

A.4 Example Printout

The following pages present an example printout generated from the analysis of a Co-60 spectrum by DOSEANAL.

*** CdTe Spectrum Analysis ***

File Name: a:\co22.spc

Comment: 400 sec. at 15 ft.

Irrad. : 400.4 sec. Live Irrad.: 360.4 sec. Dead : 40.0 sec.

Total Cts. in Spec.: 6.793E+06 Ave. Cts. per Live Sec.: 1.885E+04

Energy Calibration:

E(keV) = 1.725D+01 + 3.843D+00 *CH + 0.000D+00 *CH^2 + 0.000D+00 *CH^3

Selected Channel Range:

From Channel 1 (= 2.11E+01 keV) To Channel 512 (= 1.98E+03 keV)

CASE # 1 : No Extrapolation

NOTE: Spectrum used as collected.

Bin #	Energy Range (keV) Low	High	Total Energy Deposited (keV)	% of Total
1	2.109E+01	2.171E+02	6.0316D+08	3.71D+01
2	2.209E+02	4.169E+02	3.7692D+08	2.32D+01
3	4.207E+02	6.167E+02	2.4858D+08	1.53D+01
4	6.205E+02	8.165E+02	2.1068D+08	1.29D+01
5	8.204E+02	1.016E+03	1.3389D+08	8.23D+00
6	1.020E+03	1.216E+03	4.1731D+07	2.56D+00
7	1.220E+03	1.416E+03	9.6440D+06	5.93D-01
8	1.420E+03	1.616E+03	1.8570D+06	1.14D-01
9	1.620E+03	1.816E+03	5.9489D+05	3.66D-02
10	1.819E+03	1.985E+03	1.5301D+05	9.40D-03
11	0.000E+00	0.000E+00	0.0000D+00	0.00D+00
	TOTAL		1.6272D+09	
	or		4.5150D+06	keV/sec (live irradiation time)

CASE # 2 : Flat Extrapolation at Low E

NOTE: Below Low Edge, spectrum estimated as constant 180922 counts.

Bin #	Energy Range (keV) Low	High	Total Energy Deposited (keV)	% of Total
1	2.109E+01	2.171E+02	7.3446D+08	4.18D+01
2	2.209E+02	4.169E+02	3.7692D+08	2.14D+01
3	4.207E+02	6.167E+02	2.4858D+08	1.41D+01
4	6.205E+02	8.165E+02	2.1068D+08	1.20D+01
5	8.204E+02	1.016E+03	1.3389D+08	7.61D+00
6	1.020E+03	1.216E+03	4.1731D+07	2.37D+00
7	1.220E+03	1.416E+03	9.6440D+06	5.48D-01
8	1.420E+03	1.616E+03	1.8570D+06	1.06D-01
9	1.620E+03	1.816E+03	5.9489D+05	3.38D-02
10	1.819E+03	1.985E+03	1.5301D+05	8.70D-03
11	0.000E+00	0.000E+00	0.0000D+00	0.00D+00
	TOTAL		1.7585D+09	
	or		4.8793D+06	keV/sec (live irradiation time)

CASE # 3 : Linear Extrapolation at Low E

NOTE: Below Low Edge, spectrum est. as: 183446.3 + -138.7761 *Ch

Bin #	Energy Range (keV) Low	High	Total Energy Deposited (keV)	% of Total
1	2.109E+01	2.171E+02	7.3535D+08	4.18D+01
2	2.209E+02	4.169E+02	3.7692D+08	2.14D+01
3	4.207E+02	6.167E+02	2.4858D+08	1.41D+01
4	6.205E+02	8.165E+02	2.1068D+08	1.20D+01
5	8.204E+02	1.016E+03	1.3389D+08	7.61D+00
6	1.020E+03	1.216E+03	4.1731D+07	2.37D+00
7	1.220E+03	1.416E+03	9.6440D+06	5.48D-01
8	1.420E+03	1.616E+03	1.8570D+06	1.06D-01
9	1.620E+03	1.816E+03	5.9489D+05	3.38D-02
10	1.819E+03	1.985E+03	1.5301D+05	8.70D-03
11	0.000E+00	0.000E+00	0.0000D+00	0.00D+00
	TOTAL		1.7594D+09	
	or		4.8818D+06	keV/sec (live irradiation time)

APPENDIX B
ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of several people outside Source Technologies whose cooperation greatly facilitated the work here reported. These include the following:

Dr. Thomas Tornabeene of the School of Biology, Georgia Institute of Technology, who consented to the use in this research of the cobalt irradiator owned by the School.

Mr. Robert Boyd and Mr. Steven Millspaugh of the Office of Radiological Safety, Georgia Institute of Technology, who provided instruction and supervision in the use of radioactive sources owned by the Institute.

Mr. Michael Nichols and Mr. Donald Philpotts of the Central Laboratory, Georgia Power Company, who provided the electrometer used to measure the cobalt-60 exposure rates, and who shared their data on this source.

The comments provided by Drs. Mahmoud Ghavi and David Walker of Source Technologies proved most helpful in guiding this research and in improving this report.