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**THE MEASUREMENT OF
GAMMA RAY INDUCED HEATING
IN A MIXED NEUTRON AND
GAMMA RAY ENVIRONMENT**

by

Henry K. Chiu

FUSION POWER PROGRAM

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MASTER

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Henry K. Chiu

ABSTRACT

The problem of measuring the gamma heating in a mixed DT neutron and gamma ray environment was explored. A new detector technique was developed to make this measurement. Gamma heating measurements were made in a low-Z assembly irradiated with 14-MeV neutrons and (n,n') gammas produced by a Texas Nuclear Model 9400 neutron generator. Heating measurements were made in the mid-line of the lattice using a proportional counter operating in the Continuously-varied Bias-voltage Acquisition (CBA) mode. The neutron-induced signal was separated from the gamma-induced signal by exploiting the signal rise-time differences inherent to radiations of different linear energy transfer coefficient (LET), which are observable in a proportional counter. The operating limits of this measurement technique were explored by varying the counter position in the low-Z lattice, hence changing the irradiation spectrum observed.

The experiment was modelled numerically to help interpret the measured results. The transport of neutrons and gamma rays in the assembly was modelled using the one-dimensional radiation transport code ANISN/PC. The cross-section set used for these calculations was derived from the ENDF/B-V library using the code MC²-2 for the case of DT neutrons slowing down in a low-Z material. The calculated neutron and gamma spectra in the slab and the relevant mass-stopping powers were used to construct weighting factors which relate the energy deposition in the counter fill-gas to that in the counter wall and in the surrounding material. The gamma energy deposition at various positions in the lattice is estimated by applying these weighting factors to the measured gamma energy deposition in the counter at those locations. The overall utility of this measurement technique for gamma heating in a low-Z structure irradiated by a broad energy range, low fluence mixed radiation field (characteristic of fusion blanket neutronics) was discussed.

1. Introduction

The motivation for measuring the gamma heating in a low fluence, broad energy, mixed gamma and neutron environment and the proposed methodology to conduct this measurement are presented.

1.1 Motivation

One criterion used in material selection for the next generation of fusion test stand is the heating per material per fusion event. Knowledge of the expected gamma heating will allow design engineers to evaluate the heating that a given material will experience in a fusion radiation environment. Satisfactory (experimental error of less than 15%) measured gamma heating data does not currently exist for materials exposed to the fusion radiation sources in the current generation of test stands. At best the fusion-induced heating values for materials are calculated from neutronics transport simulations that model the current generation of fusion test stands. The main obstacle that bars the way for a satisfactory heating measurement is the low radiation flux characteristic of the existing test stands. At the present flux output levels, direct measurement techniques such as calorimetry and laser interferometry cannot distinguish the radiation-induced heating from the heating induced by other factors in the test stand.

Dosimetry techniques such as thermo-luminescent dosimeters (TLDs) and activation foils have been used to conduct heating

measurements in these test stands with limited success. The failure of the TLDs lie in their inability to distinguish the energy weighted importance of neutron induced effects from gamma induced effects. Neutron activation foils cover a limited energy range and require high fluences for good statistics. All dosimetry techniques suffer from the inability to perform a true integrated energy measurement in a mixed radiation field. However, by carefully designing a detector one can create a device that will enable the experimenter to perform signal separation on its output. Having built such a detection system, one must choose to measure either the neutron component or the gamma component of the fusion radiation field. As gamma rays numerically dominate the radiation spectrum, a measurement of the gamma heating in the materials placed in an existing fusion radiation spectrum was believed to be the simpler course. Once the gamma heating for a material has been measured, the total heating for it can be found by consulting design studies for the fraction of energy of a fusion reaction partitioned to gamma rays through the inelastic scattering of the fusion neutrons and then multiply the inverse of this fraction by the measured gamma heating.

1.2 A Brief Review of Recent Attempts at Gamma Heating Measurements

Previous attempts to measure gamma heating in simulated fusion blanket assemblies have met little success.¹ In the low fluence rate regime the traditional macroscopic measurement methodologies (e.g.

calorimetry, thermocouples, thermistors) are not applicable. The well established microscopic methods (thermo-luminescent dosimeters (TLDs), scintillation counters, and proportional counters) exhibit characteristics that limit their use in this measurement.

TLDs are thin film type dosimeters formed from material that fluoresces proportionally to the damage incurred under irradiation, when such materials are annealed after exposure. TLDs are integral dosimeters, and they are excellent for quantifying the number of particles interacting in the TLD material. The advantages that TLDs have over most other dosimeters are that they are physically compact and require no in-situ electronics. However, the TLD material has little capability to distinguish different species of radiation, hence for radiations of different ionizing capacity TLDs do not accurately report the energy deposition.

Scintillation counters can differentiate between different radiations by pulse-shape discrimination of the output. The light pulse output of the scintillator is a function of the exposure rate and energy of the initiating radiation. Operation in a broad energy mixed gamma and neutron field is difficult as there exist some regions in energy ($E < 1$ MeV) where pulse-shape discrimination is not possible.

Proportional counters are differential dosimeters. With a proportional counter one is able to distinguish between different neutral particles by the differences in the signal rise time of the secondary charged particles formed through radiation-material interaction. Generally proportional counters are configured as gas-

filled cavities with walls made of electrically conductive material and filled with a molecular gas. Proportional counters are fragile, physically restrictive and require in-situ electronic support. These characteristics limit the placement of this type of detectors in a complex experimental geometry.

The main difficulties of the heating measurements stem from the broad energy range (0.0-14.8 MeV), the relatively low flux (10^8 particles/cm²-sec), and the ambiguity of separating the neutron effects from the gamma dose measurement. At present the dominant technique for energy characterization is the wide dispersal of thin film TLDs.²⁻⁶ TLDs are very effective for providing energy deposition data in pure gamma or pure neutron fields. They are unfortunately limited to the measurement of integrated dose. In a mixed neutron and gamma field, the effectiveness of TLDs is questionable since the TLD response to neutrons is dependent upon the spectrum. Presently the only method readily available for resolution of radiation in a mixed field is the use of calibrated proportional counters. Proportional counters can be effective at low levels of gamma dose,⁷ and can readily observe the fast pulse-rise events which are characteristic of the nuclear recoils produced by elastic neutron scatter.^{7,8} By extending the observable energy range of the proportional counter and providing a data acquisition routine that records events by energy and differential rise times, one can measure the gamma heating in a low fluence rate, broad energy mixed radiation field with high confidence.

The basis of the present work is a logical continuation and extension of Yule's⁷ and Simons'⁹ efforts to measure gamma heating of structural materials in fast reactor environments. Stainless-steel walled counters were used for that series of experiments. The efforts of Yule and Simons led to the following conclusions on gamma heating measurements. (1) Ideally the walls of the proportional counter should be made of the material of interest (i.e. aluminum walls for measuring dose in an aluminum assembly). (2) The counting method must be calibrated absolutely with respect to energy for the results to be credible. (3) This method must show the ability to separate the neutron induced signals from the gamma induced signals for the results to be credible. (4) Some idea of the electron spectra in the measuring device must be known (as we measure the energy-loss of the gammas' secondary electrons), before the results can be properly interpreted.

A given detector's energy response is characteristic of the material from which it was fabricated. The gamma heating in materials can be found if one makes detectors from each type of material or if one can relate the measured heating in one material to another by considering the underlying physics of the heating processes. The investigation of the underlying physics will provide a better understanding of the process and promises a general method of solution for this problem.

1.3 Statement of Thesis Goals

The goals of this thesis are to: (1) develop a detector technique that is sufficiently sensitive to register the differences between neutron-induced and gamma-induced signals in a low fluence environment, (2) make a measurement over the entire energy range of the radiation environment, (3) develop a method to relate the measured gamma heating in one material to another. It is hoped that by measuring the gamma heating, one will be able to provide valuable engineering criteria for proposed fusion blanket assemblies.

A coupled calculational and experimental program has been designed to address these problems. Techniques to extend the energy range of proportional counters and analysis software for fast neutron signal rejection were developed. An experiment was designed to test these developments in a simulated fusion radiation spectrum. A Texas Nuclear 9400 deuterium-tritium fusion neutron generator was engaged to simulate a fusion radiation environment. The transport and interaction of gamma rays and neutrons in this experiment were calculated with the radiation transport code ANISN/PC to provide a basis for relating the measured heating in the counter material to the heating in the other materials irradiated by the neutron generator. The results of the experiment and the calculations are presented in the following chapters.

2. Theoretical Background

The theoretical basis for the measurement of gamma heating in a mixed gamma and neutron field is presented in this chapter. The interaction mechanisms for gamma rays and neutrons are reviewed to bring the problem into focus. The theory and operation of a proportional counter as a dosimeter as well as the use of $\langle 1/f \rangle$ factors in dosimetry are presented. A discussion is given on the physical mechanisms that permit proportional counters to operate as charged-particle species sensitive detectors and how they apply to this thesis. Finally, the numerical methods used to calculate the $\langle 1/f \rangle$ factors are reviewed.

2.1 A Review of Gamma Ray and Neutron Interaction Mechanisms

The goal of this thesis is the measurement of gamma heating in a mixed gamma and neutron field characteristic of deuterium-tritium (DT) fusion. As such, the production of gamma rays and neutrons by DT fusion is reviewed, then the interaction mechanisms of both gamma rays and neutrons are presented.

The energy released in a DT fusion reaction (17.6 MeV)¹⁰ is partitioned between the daughter products; an alpha particle and a neutron, with the neutron receiving 14.1 MeV of kinetic energy (for reactants at rest). Other neutron energies are possible, and are dependent upon the kinematics of the reaction.¹¹ The neutron interacts with the surrounding material through scattering and

absorption. The by-products of these neutron interactions are charged particles (alphas, protons, and recoil nuclei) and gamma rays. The gamma spectrum arises from inelastic scattering and radiative capture of the fusion neutrons. The gamma population is directly dependent on the neutron population. Gamma rays and neutrons are electro-statically neutral and as such are undetectable in their respective primary forms. However, both gamma rays and neutrons produce charged particles as they interact with matter. These secondary charged particles can be detected through electronic means. A DT neutron will produce many gamma rays through inelastic scattering off of the surrounding materials before capture, and each of these gamma rays will produce electrons through scattering and/or absorption. In fact the gamma induced electron spectrum will numerically dominate the direct neutron generated charged particle spectra.

Gamma rays interact with matter through pair production ($h\nu > 8$ MeV for $Z < 20$), Compton scatter and the photo-electric effect (mainly below 60 keV); all of these reactions lead to the production of energetic electrons. Figure 1 illustrates the regions in which each type of interaction dominates. The two curves in Figure 1 mark the parameter space in which 2 types of gamma interaction have equal importance. From Fig. 1, the dominant interaction for gamma-rays of energy < 7 MeV with materials of $Z < 30$ is Compton scattering.

Fig. 1 Relative importance of the three major gamma interactions with matter. From Evans (1955)¹²

Compton scattering of gamma-rays of energy E_p and an atom (an atom's electrons) produces an electron ejected from the collision with energy K_e and a gamma-ray of energy $E_{p'}$, and it is given by:

$$K_e = E_p - E_{p'} - Q, \quad (2.1)$$

the kinetic energy (K_e) of the electron being the difference between E_p the energy of the unscattered photon, $E_{p'}$ the energy of the scattered photon; and Q , the binding energy of that electron. The degraded gamma-ray will undergo either Compton scattering or be absorbed in the surroundings producing a photo-electron via the photo-electric effect. The initial gamma-ray's energy can be considered deposited in a localized area if the scattered gamma interacts in close proximity to the initial interaction site.

Fig. 2 Total Compton cross-section for producing a free electron. Cember (1983)¹³

According to Fig. 2 as the gamma-ray's energy decreases, the probability of interaction via only the Compton process increases. Summarizing, if a gamma ray interacts in a given test volume of low-Z material (contributes to the gamma heating in that volume), then the most likely interaction mechanism is Compton scattering and the interacting gamma ray will transfer the majority of its energy to secondary electrons. The resultant secondary electron spectrum, indicative of gamma interaction with matter can be readily observed.

The Compton scattering of gamma rays can be treated as the scattering of unpolarized photons off of free electrons. Klein and Nishina^{12,14} have treated this theoretically and their results are applicable for incident gamma rays in the energy range of 100 keV to 7 MeV and for target nuclei of Z less than 30. The Klein-Nishina derived expressions for the average collision cross section, the average scattering cross section, the average absorption cross section, the recoil electron population as a function of electron

energy for an initial photon energy, and the average energy imparted to the recoil electron per incident gamma for Compton scattering are:12,14

for
$$\alpha = \frac{h\nu}{m_e c^2}$$

$$\begin{aligned} e\sigma(\alpha) &= \int_0^\pi \frac{d_e\sigma(\alpha)}{d\Omega} 2\pi \sin\theta d\theta \\ &= 2\pi r_o^2 \left\{ \frac{1+\alpha}{\alpha^2} \left[\left(2\frac{1+\alpha}{1+2\alpha} \right) - \frac{\ln(1+2\alpha)}{\alpha} \right] + \frac{\ln(1+2\alpha)}{2\alpha} - \frac{(1+3\alpha)}{(1+2\alpha)^2} \right\} \\ &\quad \left(\frac{\text{cm}^2}{\text{electron}} \right) \quad (2.2) \end{aligned}$$

is the average collision cross section,

$$\begin{aligned} e\sigma_s(\alpha) &= \int_0^\pi \frac{d_e\sigma_s(\alpha)}{d\Omega} 2\pi \sin\theta d\theta \\ &= \pi r_o^2 \left\{ \frac{\ln(1+2\alpha)}{\alpha^2} + \frac{2(1+\alpha)(2\alpha^2-2\alpha-1)}{\alpha^2(1+2\alpha)^2} + \frac{8\alpha^2}{3(1+2\alpha)^2} \right\} \\ &\quad \left(\frac{\text{cm}^2}{\text{electron}} \right) \quad (2.3) \end{aligned}$$

is the average scattering cross section,

$$e\sigma_a(\alpha) = e\sigma(\alpha) - e\sigma_s(\alpha)$$

$$\begin{aligned}
&= 2\pi r_o^2 \left[\frac{2(1+\alpha)^2}{\alpha^2(1+2\alpha)} - \frac{1+3\alpha}{(1+2\alpha)^2} - \frac{(1+\alpha)(2\alpha^2-2\alpha-1)}{\alpha^2(1+2\alpha)^2} - \frac{4\alpha^2}{3(1+2\alpha)^3} \right. \\
&\quad \left. - \left(\frac{1+\alpha}{\alpha^3} - \frac{1}{2\alpha} + \frac{1}{2\alpha^3} \right) \ln(1+2\alpha) \right] \\
&\quad \left(\frac{\text{cm}^2}{\text{electron}} \right) \quad (2.4)
\end{aligned}$$

is the average absorption cross section,

$$\begin{aligned}
&\frac{d_e \sigma(h\nu_o; T)}{dT} Z \\
&= Z \left\{ \frac{\pi r_o^2}{\alpha^2 m_e c^2} \left[2 + \left(\frac{T}{h\nu_o - T} \right)^2 \left[\frac{1}{\alpha^2} + \frac{h\nu_o - T}{h\nu_o} - \frac{2}{\alpha} \frac{h\nu_o - T}{T} \right] \right] \right\} \\
&\quad \left(\frac{\text{cm}^2}{\text{keV-atom}_Z} \right) \quad (2.5)
\end{aligned}$$

is the expression for the recoil electron number distribution as a function of recoil electron energy, of Compton recoil electrons produced by the interaction of photons of energy $h\nu_o$ and atoms of element Z .

$$T_{av}(\alpha) = h\nu_o \frac{e\sigma_a(\alpha)}{e\sigma(\alpha)} \quad (\text{MeV}) \quad (2.6)$$

is the relationship for the average energy imparted to each struck electron for a gamma ray of energy $h\nu_o$. In the above equations; α is the kinetic energy ($h\nu_o$) of the interacting gamma ray divided by the rest mass energy of an electron, $\frac{d_e \sigma(h\nu_o; T)}{dT} Z$ is the Compton recoil electron distribution vs. electron energy (T) for a Compton scatter between a photon with energy $h\nu_o$ and an atom of element Z , $e\sigma_a(\alpha)$ is

the Compton absorption cross section for a gamma ray of energy ($h\nu_0$), and $T_{av}(\alpha)$ is the average fraction of the gamma ray's kinetic energy imparted to a free electron in a given Compton interaction. From these equations the average kinetic energy released in a given material (KERMA) by gamma rays of energy E via Compton scattering can be found by substituting the appropriate values into:

$$KERMA(E_i, X) = \Gamma(E_i, X) * T_{av}(\alpha), \quad (2.7)$$

where $\Gamma(E_i, X)$ is the number of gamma rays of energy E_i at position (X). The Compton recoil electron spectrum for a gamma ray of energy E_i is $N(E_i, T, X)$, and it is given by:

$$N(E_i, T, X) = \Gamma(E_i, X) \frac{d_e \sigma(E_i; T)}{dT} \quad (2.8)$$

Neutrons of all energies interact with matter through three types of interactions, and a given neutron can undergo a host of such interactions before final capture. The three interaction processes of the neutron are: (1) elastic scattering off of atoms in its path, this generates energetic charged recoil nuclei, (2) inelastic scattering in which the neutron is absorbed by the target nucleus forming an excited nucleus which then follows various modes of de-excitation resulting in a neutron of degraded energy, (3) capture, in which the neutron is finally absorbed, giving off a gamma or charged particle in the process. These neutron reactions create a secondary radiation spectrum formed of neutrons of degraded energy, gamma-rays, energetic recoil nuclei, alpha particles and protons.

The charged particle species formed is dependent on the interaction cross-section of the target nuclei.

2.2 Theory and Operation of a Proportional Counter as a Dosimeter

In theory, one can measure the total heating produced by the products of the DT reaction if a counter with known sensitivity to both the gamma induced electrons and the neutron induced charged particles is available. In practice, one can have a counter with a known sensitivity to either the neutron component or the gamma component, but not both. As there are more gamma induced electrons than neutron induced charged particles, it was determined that a measurement of the gamma heating would provide the basis for estimating the total heating.

The neutrons and gammas produced by the DT reactions in a fusion device will both interact with a detector placed in the radiation field. For a gamma heating measurement to be successful the detector must either be totally insensitive to neutron induced effects or be able to differentiate between the effects of both neutrons and gamma rays. Clearly a totally neutron insensitive detector is not possible, so a detector that can be made as neutron insensitive as possible and have the capability to differentiate between the gamma- and neutron-induced signals is sought. The need for signal differentiation eliminates two classes of detectors (film and TLDs) from consideration. The choice among the remaining four types (ion chambers, activation foils, proportional counters, and

liquid scintillators) is determined by considering each detector's neutron sensitivity and count rate efficiency.

A brief discussion of these detectors is in order. Liquid scintillation counters are very efficient (up to 5000 counts per second) and can differentiate between neutrons and gamma rays. However liquid scintillation counters^{7,15} operating in the energy region 50 keV to 1 MeV have difficulty resolving gamma induced signals from neutron induced signals. Gamma rays in the energy range from 0 to 1 MeV are the principal contributors to the gamma heating measurements, so liquid scintillation counters are inappropriate tools for measuring gamma heating. Activation foils are virtually gamma ray insensitive, but are limited in energy response to the gamma activation resonance energies of the foil material and require either a large foil sample or long exposures for acceptable statistics.^{15,16} It is conceivable that a judicious selection of foil materials will enable the experimenter to derive an estimate of neutron induced heating at discrete energy values in the spectrum of interest. However, activation foils can provide only a measure of the spectral shape and magnitude of the incident neutron field. It remains for the user to interpret the absorbed dose to the foil itself and then relate this dose to the dose experienced by the other materials in the experiment. Both activation foil techniques and liquid scintillation detectors are judged unsuitable for this measurement.

Ion chambers and proportional counters are very similar as both can be filled with heavy gases to make them less neutron

sensitive.^{17,18} The difference between the two detectors lie in how their respective output signals are generated. The output signal for an ion chamber is just the radiation induced electrical charge in the fill gas collected on its electrodes. An ion chamber is a very sensitive integrating dosimeter. As such it cannot distinguish between events of different energy-loss per unit path length, and cannot separate the gamma component from the neutron component in a mixed gamma and neutron field. Proportional counters are very efficient for all energies (up to 500 keV, depending on the fill gas), can differentiate signals, and their neutron sensitivity can be altered by changing the filling gas. The counter chosen to measure gamma heating in a mixed gamma and neutron field is the proportional counter.

A charged particle interacting with the gas in a cylindrical proportional counter will generate free electrons. These electrons migrate to the wire anode along electric field lines induced by the voltage difference between the anode and the cathode shell. As these free electrons approach to within an anode diameter of the anode, the electric field induces an electron avalanche. The collapse of this avalanche onto the wire anode changes the voltage on the anode, and this voltage change is the counter output. The amplitude and spatial dispersion of the electron avalanche is dependent on the energy and energy-loss per unit path length of the initiating charged particle. The amplitude of the avalanche determines the magnitude of the voltage change on the anode, and the spatial dispersion of the avalanche determines the rate of the signal rise.

Cavity ionization theory is the mathematical formalism describing how radiation interacts with an idealized detector. The theory can be broken up into two major approximations: (1) small cavity theory, in which the detector is considered as a cavity in the surrounding material so small that the presence of the cavity does not perturb the charged particle spectrum in the surroundings, and (2) large cavity theory, in which the cavity is so large that the charged particle spectrum in the cavity is unique to the contents of the cavity and is not influenced by its surroundings. The terms large and small refer not to the physical size of the detector, but rather to the size of the detector compared to the mean path length of the charged particle travelling in the detector material. Small cavity theory states that the charged-particle spectrum present in a sufficiently small cavity is representative of its surrounding materials,^{14,19-20} where the phrase 'sufficiently small cavity' is used to indicate a condition such that the presence of a cavity in the material of interest and its contents do not cause the charged-particle spectrum in the cavity to differ from that of the surrounding material. When this unperturbing cavity is realized in a physical detector, one has then achieved the famous Bragg-Gray condition.

When using a gas filled proportional counter as a dosimeter, its recorded output signal is just the energy loss spectrum of the charged particles passing through the counter. The relationship for the absorbed dose is:

$$D = \frac{1}{m} \int_0^{E_{\text{top}}} E \cdot R(E) dE, \quad (2.9)$$

where:

D is the absorbed dose,

m is the mass of the counter fill gas,

$R(E)$ is the tabulated charged particle energy loss distribution between energy E and $E+dE$.

More practically, the expression for the absorbed dose is expressed as the sum over the observed energy range of the product of discrete values in the spectrum and the energy at those points:

$$D = \frac{1}{m} \sum_{E_i=0}^{E_i=E_{\text{top}}} E_i \cdot R(E_i), \quad (2.10)$$

D is the approximate expression for the absorbed dose,

$R(E_i)$ is the measured value of the charged-particle energy-loss distribution at energy E_i .

The measurement gives no direct indication of the absorbed dose in the counter wall material or the absorbed dose in the surrounding material. Making the assumption that small cavity theory applies, the absorbed dose in the counter wall material as well as the absorbed dose of the other materials irradiated by the neutral radiation can be solved for, if the mechanisms for charged particle production and an expression for the energy loss of these charged particles in these materials are known.

Consider a region in space irradiated by a source of electrostatically neutral particles. The charged particle

distribution in this region results from the interaction of the neutral radiation spectrum with the material in the region. Picture a small pocket in this region containing a material different from that of the region having a density much less than that of the region such that its presence does not perturb the ambient charged particle distribution in the region. Small cavity theory states that: if the energy deposited by the charged particle distribution in the small pocket is measured, then the energy deposition in the surrounding material can be found if the energy loss mechanisms for both the pocket material and the surrounding material are known. Expanding on this idealized case, consider the wall material of the proportional counter as the material in the surrounding region and the counter fill gas as the material in the small pocket. The counter will conform to the limitations of small cavity theory if the fill gas is sufficiently dilute as to be transparent to the charged particles generated in the counter wall material and if no (or almost no) charged particles are formed in the fill gas. The absorbed dose to the counter wall material can be calculated if the absorbed dose in the fill gas is measured and the energy loss mechanisms for these charged particles in both the fill gas and the wall material are known. This can be expressed mathematically as;

$${}_c D_w = \left\langle \frac{1}{f} \right\rangle * {}_m D_g, \quad (2.11)$$

${}_c D_w$ is the absorbed dose in the wall,

${}_m D_g$ is the measured absorbed dose in the fill gas,

$\langle \frac{1}{f} \rangle$ is the spectrum averaged mass stopping power ratio for the counter wall material and the counter fill gas.

This spectrum averaged $1/f$ factor $\langle \frac{1}{f} \rangle$ is derived from an examination of how a charged-particle spectrum slowing down continuously in a solid medium with a small gas filled cavity loses energy to the medium and the gas.

Consider a solid medium with a small gas filled cavity, uniformly irradiated by a photon flux. Assume that all the electrons generated by photon interactions in this medium have an initial energy of T_0 , and that one electron is generated per unit mass of the medium. Assume also that the presence of the cavity does not perturb the electron distribution. Under these circumstances, electron equilibrium exist and the energy absorbed per unit mass in the medium is T_0 . The energy deposited per unit mass (dose) in the fill gas as these electrons passes through the cavity is:

$$D_{\text{gas}} = \int_0^{T_0} N_Z(T_\gamma, T) \left(\frac{1}{\rho} \cdot \frac{dT}{dx} \right)_{\text{gas}} dT, \quad (2.12)$$

where

$\left(\frac{1}{\rho} \cdot \frac{dT}{dx} \right)_{\text{gas}}$ is the mass stopping power of the gas,

$N_Z(T_\gamma, T)$ is the number of electrons in the medium with energies between T and $T+dT$.

In the continuous energy dissipation model, when electron equilibrium exist, the expression $N_Z(T_\gamma, T)$ is given by:^{7,9,14}

$$N_z(T_\gamma, T) = \frac{1}{\left(\frac{1}{\rho} \cdot \frac{dT}{dx}\right)_z}, \quad (2.13)$$

substituting (2.13) into (2.12) gives

$$D_{\text{gas}} = \int_0^{T_0} \frac{\left(\frac{1}{\rho} \cdot \frac{dT}{dx}\right)_{\text{gas}}}{\left(\frac{1}{\rho} \cdot \frac{dT}{dx}\right)_z} dT. \quad (2.14)$$

The energy loss per unit mass of gas divided by the energy loss per unit mass of solid is

$$\frac{1}{f} = \frac{1}{T_0} \int_0^{T_0} \frac{\left(\frac{1}{\rho} \cdot \frac{dT}{dx}\right)_{\text{gas}}}{\left(\frac{1}{\rho} \cdot \frac{dT}{dx}\right)_z} dT. \quad (2.15)$$

The quantity $(1/f)$ is a comparison of the energy deposition in the cavity fill gas to the energy deposition in the solid medium, when electron equilibrium exist for a source electron of energy T_0 . In the general case, the electrons have initial energies spread over a spectrum rather than having one unique initial energy. For the general case, the expression given in Equation 2.15 must be averaged over the spectrum of initial electron energies.

Let $A(T_\gamma, T_0)$ represent the photon induced electron spectrum, the spectrum averaged mass stopping power ratio $\langle \frac{1}{f} \rangle$ is given by:

$$\left\langle \frac{1}{f} \right\rangle = \frac{\int_0^{T_0} T_0 * A(T_\gamma, T_0) * \left[\frac{1}{T_0} \int_0^{T_0} \frac{\left(\frac{1}{\rho} \cdot \frac{dT}{dx} \right)_{\text{gas}}}{\left(\frac{1}{\rho} \cdot \frac{dT}{dx} \right)_Z} dT \right] dT_0}{\int_0^{T_0} T_0 * A(T_\gamma, T_0) dT_0}. \quad (2.16)$$

The above relations states that if one can measure the absorbed dose in one material, one can then estimate the absorbed dose in another material in the same radiation field (assuming electron equilibrium) if one can calculate the $\left\langle \frac{1}{f} \right\rangle$ factor for the two materials in the given radiation field. It was further observed by Fano²² that if the effective Z of the contents in the cavity and the Z of the cavity's surroundings are equivalent, then the charged-particle spectrum and the absorbed dose of both the surrounding material and the fill gas are equivalent. This relationship between effective Z and the absorbed dose is known as Fano's theorem. Now if one applies Fano's theorem in the construction and operation of a proportional counter the absorbed dose in the wall material will be nearly equivalent to the absorbed dose in the detector fill gas. A calculation of the $\left\langle \frac{1}{f} \right\rangle$ factor should yield a value of nearly 1.0, and Equation 2.11 and 2.16 can be used to estimate the absorbed dose in the counter wall material once the absorbed dose is measured for the fill gas.

The proportional counter used in this experiment was sufficiently small; a 750 keV electron has a range in the fill gas longer (~ 16 cm to 12.5 cm) than the long dimension of the counter, so that results of small cavity theory are applicable. That is, the gamma induced heating in materials exposed to a given radiation

spectrum can be calculated from the calculated $\langle \frac{1}{f} \rangle$ factor and the measured heating in the counter. Furthermore, if the counter is made to satisfy the physical conditions of Fano's theorem, then the calculated $\langle \frac{1}{f} \rangle$ factor for the counter wall material and the fill gas should be near unity if the calculation is correctly done. This application of Fano's theorem will serve as a validity check for the $\langle \frac{1}{f} \rangle$ factor calculation.

The counter used in the gamma heating measurements is presented here as an example. The steel walled counter is filled with a gas whose effective Z is matched as best as possible to that of the counter wall material, to satisfy Fano's theorem. The fill gas chosen was a mixture of 90% argon and 10% carbon dioxide. This mixture of argon and carbon dioxide was one of three gas mixtures considered. The others were a mixture of 90% argon and 10% methane, and a mixture of 93% argon and 7% krypton. The argon and krypton mixture was the best match for effective Z, but it tended to suffer electronic breakdown when confronted with a rapid bias-voltage change or sudden increase in fluence rates. The argon and methane filled counter had the best operational electronic characteristics, as it did not break down in any of the evaluation tests, but it was not chosen because the hydrogen atoms in methane yield a substantial recoil proton signal when the counter was exposed to a mixed gamma and neutron field. The operational characteristics of the argon and carbon dioxide filled counter lies in between those of the other two counters. The argon and carbon dioxide filled counter was nearly matched in effective Z to the counter's steel walls and while its

operational characteristics were not as stable as those of the argon and methane filled counter, it was far more stable than that of the argon and krypton filled counter. The measured energy deposition in the chosen fill gas should then be nearly equivalent to the energy deposition in the counter wall material.

The chosen fill gas is sufficiently heavy so that neutron induced recoil nuclei are not a great concern. Since the fill gas has no appreciable cross section for neutron activation, the measured energy-loss before signal separation is nearly all from gamma interactions. After signal separation, the measured result is just the gamma induced energy deposition in the counter fill gas. Now, if the gamma induced charged-particle spectra are known for both the counter fill gas and for the surrounding material exposed to the same radiation field, the $\langle \frac{1}{f} \rangle$ factor for estimating the gamma induced energy deposition in the surrounding material can be calculated from Equation 2.16.

2.3 Signal Separation

As noted in the Section 2.2, the output signal of the proportional counter is just the voltage change on the counter anode as the electrons produced by charged particle interactions with the fill gas impact the anode. The rate of the signal rise and the magnitude of this voltage change is dependent on the kinetic energy and the linear energy transfer (LET) coefficient of the initiating particle. It is these differences in the observed rate of the signal

risers that permits signal separation between signals initiated by electron and by other charged particles.

The process begins when a charged particle interacts in the counter fill gas forming a number of free electrons along its interaction track. The number of electrons formed per unit path length depends directly on the value of the LET. These electrons migrate along the radial electric field lines to the anode. As they travel closer to the anode, the field lines are geometrically constricted leading to high electric field values and gas multiplication: the energetic electrons strip more electrons from the fill gas forming an electron avalanche.^{19,23} The rate at which the signal rises depends on the radial dispersion of the avalanche across the field lines and is related to how many free electrons were created in the initial part of the charged particle's interaction track. That is, the rate of a signal's rise depends directly on the energy-loss per unit path length (LET) of the initiating charged particle. The greater the LET, the faster the rate of the signal rise.²⁴

These differences in the rate of signal rise for signals of differing origins are used to separate the high LET events from low LET events. Charged particles of different mass have different rates of energy loss per unit path length. This is evident from an examination of the Bethe-Bloch formula for differential spatial energy loss:⁸

$$\left(\frac{dE}{dx} \right) = \frac{4\pi N_A z^2 Z e^4 \rho}{(m_e c^2) A \beta^2} \left\{ \frac{\ln(2(m_e c^2) \beta^2 \gamma^2)}{I} - \beta^2 \right\} \quad (\text{eV/cm}) \quad (2.17)$$

where:

- z is the atomic number of the projectile,
- Z is the atomic number of the target atom,
- A is the atomic mass of the target,
- ρ is the atom density of the target,
- I is the ionization potential of the target atom,
- $m_e c^2$ is the electron rest energy.

One can, on the basis of signal pulse rise differences, partition the recorded signals into those arising from electron initiated events and those arising from atomic recoil initiated events or other charged particle initiated events. As gamma ray interactions produce only electrons, the low LET (slow rise time) events are associated with gamma activity. The high LET (fast rise time) signals that are associated with neutron-induced events are recognizable in the acquisition system's output and are removed from further consideration.

2.4 A Brief Note on the Numerical Methods Used in the $\langle 1/f \rangle$ Factor Calculation

The $\langle \frac{1}{f} \rangle$ factor used to relate the measured energy deposition in the counter fill gas to the surrounding material are derived from calculations of the charged particle spectrum averaged mass stopping powers for the fill gas and the counter wall material exposed to the same radiation field. The calculation of the charged particle

spectrum involve first a calculation of the propagation of the neutral radiations for the experiment. Representative neutron and gamma spectra of a given radiation field can be obtained by solving an approximation to the time independent form of the Boltzmann transport equation:^{14,25,26}

$$\begin{aligned} \Omega \nabla \psi(r, \Omega, E) + \sigma_t(r, E) \psi(r, \Omega, E) \\ = \int_0^{\infty} dE' \int_{-1}^1 d\Omega' [\chi(E) \nu \sigma_f(r, E') + \sigma_s(r, \Omega'; \Omega, E'; E)] \psi(r, \Omega', E') \\ + Q(r, \Omega, E) \end{aligned} \quad (2.18)$$

The Boltzmann equation is basically a conservation equation in 7-dimensional phase space (of neutrons in this case). The left hand side of the equal sign represent the loss terms (leakage and removal) from energy E and direction Ω , while the right hand side represent the possible sources of neutrons of energy E and direction Ω' (fission, inscattering and an external source term). Approximations to the angular and energy dependent terms in Equation. 2.18 were made to obtain a form of the transport equation suitable for processing on a computer. The energy dependent terms were discretized by applying the multi-energy-group approximation^{25,26} to the steady state transport equation. The multi-group equation has the form:

$$\begin{aligned} \Omega \nabla \psi_g(r, \Omega) + \sigma_{tg}(r) \psi_g(r, \Omega) \\ = \sum_{g'=1}^{IGM} \int_{-1}^1 d\Omega' [\chi_g \nu \sigma_{fg'}(r) + \sigma_{sg';g}(r, \Omega'; \Omega)] \psi_{g'}(r, \Omega') + Q_g(r, \Omega) \end{aligned} \quad (2.19)$$

The energy dependent terms (group fluxes, interaction cross sections, and the source terms) were treated as values averaged over the discrete energy intervals. A discretization of the angular variable into a few explicit directions in Equation 2.19 leads to the discrete ordinates approximation of the steady state transport equation. The discrete ordinates approximation can be written as:

$$\Omega_m \nabla \psi_{gm}(r) + \sigma_{tg}(r) \psi_{gm}(r) = \sum_{g'=1}^{IGM} [\chi_{g'} \nu \sigma_{fg'}(r) \psi_{g'}^{l=0}(r)] + \quad (2.20)$$

$$\sum_{g'=1}^{IGM} \sum_{l=0}^L \{(2l+1) P_l(\mu_m) \sigma_{sl,g';g}(r) \psi_{g'}^l(r)\} + Q_g^m(r)$$

$g = 1, 2, \dots, IGM,$

$m = 1, 2, \dots, MM,$

where:

$\psi_g^l(r) = \sum_{m=1}^{MM} w_m P_l(\mu_m) \psi_{gm}(r)$ is the zeroth, ..., Lth moments of

the group directional flux,

Ω is the directional vector,

$P_l(\mu_m)$ is the Lth Legendre polynomial evaluated at μ_m ,

L is the highest scattering order represented in the scattering cross sections,

w_m are a set of non-negative angular weights associated with each specific directional cosine μ_m .

This set of coupled equations can be solved numerically, if a set of interaction cross sections averaged over the energy groups of interest is provided.

As noted in Section 2.1, the major component of the gamma-induced secondary electron distribution is produced by Compton scattering. Making the assumption that the mechanism for all the gamma interactions in this problem are Compton scatter, the $\langle \frac{1}{f} \rangle$ factor calculation for the fill gas and for the counter wall material in the irradiation field were derived from using the Klein-Nishina model for Compton scatter and the calculated gamma spectrum.^{6,8,12} As the evaluation of the Klein-Nishina model involves several integrals, a brief review of the method used is given. The numerical integration scheme known as Simpson's rule was employed. Simpson's rule takes three adjacent points of a data distribution and fits them to a quadratic function, the area under the quadratic function is found for each three point interval and the sum of these areas divided by 3 are found for all data points considered. This sum is the numerical representation of the integral of the function defined by the data distribution. A more detailed treatment and rigorous derivation can be found in numerical methods text books.^{28,29}

Once the $\langle \frac{1}{f} \rangle$ factor for the counter wall material and the counter fill gas is found, the gamma heating of the counter wall material can be calculated from Equation 2.11. Calculation of the mass weighted KERMA distributions were made for Fe, Mg and C. The ratios Mg KERMA/Fe KERMA and C KERMA/Fe KERMA were formed. These KERMA ratios will provide an estimate of the gamma heating in the Mg

and C components of the experiment once the gamma heating in the counter wall material (Fe) is found.

3. Experimental Analysis

The ideas for measuring gamma heating presented in Chapter 2 were developed into a method for measuring gamma heating in a mixed gamma and neutron field, and are presented in the early portions (Sections 3.1 to 3.5) of this chapter. An experiment designed to demonstrate the utility of this measurement method is described, the results and error analysis of which are presented in the latter portions (Sections 3.6 and 3.7) of this chapter.

3.1 The Data Acquisition Apparatus

The data acquisition system consists of two main components: a proportional counter and the electronic circuits that process the counter output. The underlying physical principles of proportional counter operation are presented first, followed by a component by component discussion of the collection electronics, presented in a schematic fashion.

A circuit diagram representative of the cylindrical proportional counter and its pre-amplifier used in this experiment is presented in Figure 3.1. The proportional counter is depicted in cross section as a thin-walled cylindrical shell with a thin wire running along its z-axis in Figure 3.2. The cylindrical shell is sealed at the ends with insulating end plugs and is filled with a mixture of 90% argon and 10% CO₂ to a total pressure of 962 torr at a temperature of 292 K. A set of field definition tubes encases the

Figure 3.1 A block diagram of the counter-preamplifier arrangement.

Figure 3.2 An axial cross-sectional view of the proportional counter.
used in this experiment

ends of the anode wire and meets flush with the active volume of the counter. The cylindrical shell of the counter is electrically grounded to serve as the cathode. A positive DC high voltage, isolated by a large resistance, is applied to the thin central wire making it the anode. The anode is coupled to the pre-amplifier through a blocking capacitor, with the counter and high voltage lead on one side and the pre-amplifier on the other. The output of the pre-amplifier is sent over coaxial cables to the signal processing electronics.

As a charged particle interacts with the fill gas between the electrodes it loses its energy by stripping electrons from the fill gas. The stripped electrons migrate inward along field lines to the anode. These electrons gain energy from the electric field as they move closer to the anode, and they strip electrons from more and more gas atoms as they approach the anode. An electron avalanche forms within an anode diameter of the anode. The magnitude and duration of this avalanche depends on the energy-loss per unit path length of the initiating charged particle, the density of the counter fill gas and the electric field strength at the anode. A voltage change occurs on the anode when the electron avalanche impacts on it. This voltage change is the counter output for the initiating event.

In order to evaluate the voltage change that occurs at the anode as a result of radiation interaction in the counter, the signal must be processed and recorded. This is accomplished by electronically amplifying these voltage changes at the anode to useful levels (e. g. increase them to a level readable by a 0-10V

ADC) and then storing them in digital form for later manipulation. This task is accomplished through the acquisition electronics. The data acquisition hardware consists of a 16-bit Compaq XT personal computer which serves to initialize the logic conditions of the analog to digital converter (ADC) box as well as the data repository; a test pulse generator which provides a pseudo-random amplitude distribution to the pre-amplifier for live time calibration; a programmable high voltage supply to supply high voltage to the counter anode wire; and two amplifiers with different pass band characteristics to boost different aspects of the pre-amplified signal for the ADC to process. The output of the high voltage supply can be set manually for discrete voltage operation, or be driven by a cyclic ramping voltage for varying voltage operation. The present collection electronics system is shown in Figure 3.3.

The "X" amplifier has a 50 nano-second signal collection time constant, and the "Y" amplifier has a 2000 nano-second signal collection time constant. The long collection time constant of the "Y" amplifier allows it to observe the full induction effect of each event and its output is taken to be the magnitude of the signal. The short collection time constant of the "X" amplifier limits it to observing the initial signal rise of each event. The ratio of the "X" amplifier and the "Y" amplifier outputs for a given event serves as an indication of the rate of the signal rise for that event. These amplified quantities are routed to the ADC, which converts the analog voltage values of the signals with respect to the gas

Figure 3.3 A block diagram of the acquisition electronics.

amplification at the recorded bias voltage into digital values and passes them onto the XT for storage.

3.2 Determination of the Relative Gas Amplification in a Proportional Counter

The basic premise of proportional counter operation is that the energy-loss of a measured event E_i in data channel i , is related to the observed ionization I_i caused by that event in the counter by:^{14,27}

$$I_i = A(V) * E_i \quad (3.1)$$

where $A(V)$, known as the gas amplification is the proportionality constant for bias voltage (V) and it is a function of the counter properties and the applied bias voltage (V). The relationship between the bias voltage and the gas amplification is:

$$\text{Log}[A(V)] = C * V + k. \quad (3.2)$$

This expression states that the logarithmic value of the gas amplification is the sum of the voltage dependent properties $C * V$ and a constant (k) that defines the threshold value of $\text{log}(A)$ for this counter. The voltage dependent properties $C * V$ are commonly referred to collectively as the relative gas amplification, while the constant k is known as the absolute calibration constant.

The relationship between the relative gas amplification and the applied bias voltage can be determined by observing and recording the change of the counter output signal as the bias voltage is changed. For a given fill gas at a set pressure, a change in the counter bias

voltage leads to a change in the electric field. It is the electric field in the counter that accelerates the secondary electrons which strips neutral gas atoms of their electrons to form the electron avalanche, hence the gas amplification of the initiating event. In principle, this relationship between the bias voltage and relative gas amplification can be determined by exposing the counter to an external mono-ionizing radiation source and observing the channel into which the pulse height distribution's peak falls on successive exposures with the counter at different voltages. Holding all other parameters constant, the shifting of the peak is directly related to change in the bias voltage. An upward shift in the peak pulse height channel indicates a larger value for the relative gas amplification.

In practice, the counting system's gain due to its amplification electronics must first be determined. This is accomplished by introducing a test pulse signal into the system, while no bias voltage is applied. This test pulse serves as a relative reference gain setting for the system. Once the system gain is found, the relative gas amplification response of the counter can be determined by making the following observations.

The formalism for determining the response is given by a 5 step process: (1) the bias voltage is first reduced to zero, (2) a test pulse signal of known strength is fed into the system, (3) the amplifier settings are adjusted until the peak of the pulser signal falls into a channel defined as the reference pulse height channel, (4) the counter is then exposed to the gamma source, and voltage is applied to the anode until a well defined peak is observed, (5) the

channel in which this peak falls and the bias voltage that is applied are recorded.

The relative gas amplification produced by applying a bias voltage to this type of counter and electronics arrangement is given by substituting the appropriate values into the following mathematical expression for the system's amplification:³⁰

$$C*V = [(\frac{P_{ch}}{512}) * C_p * (\frac{E_d}{E_m}) * (20V)] / G \quad (3.3)$$

in which

- $C*V$ is the relative gas amplification of Equation. 3.2
- G is the electronic gain
- P_{ch} is the peak pulse channel number
- 512 is the maximum channel number
- C_p is the pre-amp feedback capacitance
- E_m is the energy corresponding to the longest chord
- E_d is the ionization potential of the fill gas.

The electronic gain and the peak pulse channel number are directly measured. The maximum channel number and the pre-amp feedback capacitance are known. The energy corresponding to that of an electron traversing the longest chord in the counter can be determined approximately by inserting the value of the longest chord into the following range relationship for electrons:¹³

$$\ln(R) = 6.63 - 3.2376 * \sqrt{10.2146 - \ln(E)} \quad (3.4)$$

for

$$0.01 < E < 2.5 \text{ MeV}$$

where

R = the range of the electron in units of mg/cm^2

= [range (cm)] * [mass density of the gas]

E = the kinetic energy of the electron

The ionization potentials for gases are found in published tables.³¹ The gas amplification is dependent upon the gas specie and fill-pressure as these two parameters determine the ionizing potential and the energy loss per unit path length of an electron in the counter. The relationship between applied voltage and the relative gas amplification can be found by observing the change in the peak pulse height channel number with changing voltage.

This was done by exposing the counter to a ^{60}Co gamma source and recording the spectrum peak channel as a function of the bias voltage. The result of a series of observations is shown in Figure 3.4, as a plot of $\text{Log}(A)$ values vs. the bias voltage (V). The relative gas amplification constant (C) of this counter is just the slope of the fitted line shown in Figure 3.4, and the equation of this line is

$$y = 9.375\text{E-}03 * V + k, \quad (3.5)$$

so that $C = 9.375\text{E-}03$.

The experimental error for these observations is equal to the drift of the bias voltage from the set value: for the high voltage supply used in these measurements, the voltage deviation in all cases was less than 15 volts resulting in error values of less than 1%. The relative gas amplification $C*V$ for any voltage value within the boundaries of the observation is taken from this plot. The

Figure 3.4 A data plot for determining the gas amplification constant of the proportional counter.

determination of the absolute energy calibration constant k (the true y-axis intercept) for this counter will be presented in Section 3.4.

3.3 The Continuously-Varied Bias voltage Acquisition (CBA) Mode

In taking data over a broad range of energy with a proportional counter, one encounters a physical limitation in the collection method: a proportional counter operating at a fixed (discrete) bias voltage will only sample a small region in energy. This limitation results from the need to provide gas amplification such that the counter provides a signal sufficiently strong as to be distinguishable from amplifier and cable noise at low amplifier gain, and yet not so strong as to incur space charge saturation in the counter. In fixed voltage operation, the complete picture of an observed spectrum must be derived by the normalization and piece-wise fitting of overlapping sets of data taken in separate exposures, each taken at a different bias voltage setting.

The disadvantages of using the discrete mode of data collection in observing a difficult to repeat exposure are patently obvious: one must either make many measurements with the same counter, each at a different bias voltage, or set up many proportional counters each with the same fill gas mixture and each operating at different bias voltages in parallel to make the measurement.

To overcome this difficulty a continuous voltage biasing mode for proportional counter data acquisition has been developed for this

application: the Continuously-varied Bias-voltage Acquisition (CBA) mode. This mode of operation is intended to enable the experimenter to measure the energy loss distribution over the entire energy range of interest in a single exposure. This method offers a marked improvement over the discrete voltage-biasing mode, such that an energy loss spectrum covering several orders of magnitude in energy can now be observed with a single counter in a single exposure. This is significant because with the counter operating in the CBA, the energy loss distribution for a given radiation spectrum can be obtained in one exposure instead of requiring multiple exposures with the attendant fitting and normalizations. As a consequence, equipment needs for data acquisition and the time spent in data analysis have been reduced substantially.

The CBA mode consists of a cyclic linear-ramp high voltage input to the counter and a table of calibration data to keep track of the gas-amplification associated with each recorded signal. A programmable high voltage supply driven by a cyclic linear-ramp signal provides the cyclic high voltage input. The cyclic linear-ramp signal is produced by a function generator chip and the range between endpoints can be manually adjusted by adjusting the input voltage to the chip. The voltage range is determined by noting where the region of interest lies in energy and then consulting the correspondence table that associates the gas amplification to the applied voltage. Care must be taken to select an upper voltage limit that is sufficiently high so that the weakest signals exceed the amplifiers' lower acceptance gate yet keep the applied voltage

sufficiently low so that electronic breakdown does not occurs in the gas. The choice of a cyclic linear-ramp rather than a sinusoidal input is predicated by the desire to increase acquisition time in the region between the voltage limits rather than around those limits.

Data collection begins by engaging the compiled FORTRAN executable file at the computer and entering the constants ($C \cdot V$ and k) of Equation 3.5. The program then generates a $\log(\text{gas-amplification})$ vs. voltage table for signal processing. The ADC is controlled as a logical device by the program and it is instructed to digitize the output of the "X" amplifier, the output of the "Y" amplifier and the voltage output of the high voltage supply at the moment of signal acceptance. These quantities are then passed on to the computer. The value of the $\log(\text{gas-amplification})$ at the sampled voltage is subtracted from the logarithmic values of the encoded amplifier output. A ratio is formed by dividing the "X" amplifier output by the "Y" amplifier output for each event. The resultant data are placed into arrays indexed by the sampled voltage value in the computer. The time (t), voltage (V), pulse height distribution $Y(t,V)$ and a distribution of the rate of the pulse rise times $X(Y)$ are saved for later processing. After the data are stored, the computer sends an enable signal to the ADC, which passes a clear input bit to the amplifiers and the next pulse is sampled.

The system live-time of each exposure is determined by feeding a pseudo white noise spectrum that runs from below the amplifier's lower level threshold to above its upper acceptance gate into the pre-amplifier. These 'white' signals fall into every active pulse-

height channel $Y(t,V)$ and are recorded along with the real events. The rate of the pulse rise-time for this pseudo random spectrum was set by hardware manipulation to fall into the five highest observable rise-time rate channels $X(Y)$, to allow discrimination from real signals. As the frequency and pulse width of these 'white' signals are known, the live-time of the system in a given energy region (pulse-height channel) can be determined by counting the number of 'white' signals in the corresponding pulse-height array.

The advantages of the CBA mode over the discrete voltage mode of counter operation are the reduction in analysis time and the elimination of separate exposures that characterized discrete voltage operation. In analyzing an exposure taken with the CBA mode, one can derive information over the entire span of interest without the need for multiple normalizations and matchings. The uniformity of equipment and environmental parameters during exposure is an added bonus.

3.4 Energy Calibration

As stated in Section 3.2, the relationship between the energy-loss of an observed event and its ionization in the counter is:

$$I_i = A(V) * E_i,$$

and that

$$\text{Log}[A(V)] = C * V + k$$

Having derived a value for the relative gas amplification constant C , the absolute gas amplification $A(V)$ can be solved for when the

absolute calibration constant k is known. The ionization energy observed by the counter of a charged particle interaction can be deduced from the pulse height of its signal. The pulse height of an event is dependent on the number of electrons produced by the energy-loss of the charged particle in the counter. The relationship between pulse height and ionization is given by^{27,30}

$$P(V,t) = A(V) * \left[\frac{EI-K}{I} \right] * \frac{C1}{t} \quad (3.6)$$

where

$P(V,t)$ = the observed pulse height,

$A(V)$ = the gas amplification,

EI = the ionization produced by a charged particle
in the proportional counter,

K = the threshold energy for ionization to take place,

I = the ionization potential of the gas,

$C1$ = $1.602 \cdot 10^{-19}$ coulomb/eV,

t = the collection time.

To derive the absolute calibration constant for a proportional counter, one needs to expose it to a charged particle source of known strength and well-behaved energy distribution in the energy range of the desired measurement.

Using the relationship between the range of an energetic electron and its kinetic energy given by Equation 3.4, and substituting the calculated value of the maximum active path-length of the counter for the range into this relationship, a value of 230.5 keV is found as the maximum kinetic energy of an electron observable

by this particular counter. That is, if a reaction in the counter produced an electron with a kinetic energy of 230.5 keV, it would be reported in the last channel (channel 512) of the ADC's output. However, observations made with this counter on a ^{60}Co gamma source reported ionizations that peaked at channel 130 out of a possible 512. As these data channels are separated logarithmically in ionization, it was concluded that these gamma signals were in the 50 keV range. It was determined that a beta decay isotope with an emission spectrum in this energy range would be best suited to provide energy calibration for this counter. Tritium, a beta decay isotope with a peak beta energy of 18.6 keV, was chosen to provide data for the absolute energy calibration constant, and trace amounts of it were injected into the counter fill gas.

The tritium doped counter was then placed into a shielded cell, and the beta decay emission spectrum was recorded by the collection electronics operating in the CBA mode. The recorded data were then plotted in the spirit of a Kurie plot³²⁻³⁵ to determine the absolute calibration constant k . To demonstrate this procedure, a short discussion of Kurie plotting is presented.

The emission probability in momentum space of a beta decay is given by³⁵

$$P(u)du = F(Z,E)*\text{Const}*(E_0-E)^2*u^2du. \quad (3.7)$$

Noting that $udu = m dE$, a change in variables in Equation 3.7 results in

$$P(E) = \text{Const}*F(Z,E)\sqrt{2mE}(E_0-E)^2, \quad (3.8)$$

the emission probability in energy for a given beta decay. Rearranging terms to get an expression that is linear in energy on the right hand side results in

$$\sqrt{\frac{P(E)}{\text{Const} \cdot F(Z, E) \sqrt{2mE}}} = (E_0 - E). \quad (3.9)$$

Kurie found that the energy endpoint of a given beta decay can be found by plotting the left hand side of Equation 3.9, which consists of known constants (c and m), a calculable result [$F(Z, E)$, the coulomb function of the daughter nucleus] and a measured quantity [$P(E)$] and equating the x-intercept as the point where $E = E_0$. With a slight modification to Equation 3.9, one can plot the probability of emission vs. ionization channel. The channel in which the endpoint falls then corresponds to an energy of 18.6 keV, and by substituting values into Equation 3.1, the absolute calibration constant for this particular counter is found to be $k = -7.78275$. The Kurie plot of the tritium decay used in this calibration is presented in Figure 3.5.

3.5 Signal Separation and Heating

As noted in the Section 2.3, the differential spatial energy loss of a charged particle depends upon its mass and initial kinetic energy. For two events that register the same pulse height (cause the same ionization) in the counter, the rate of the pulse rise time of the respective signals can be recorded. The rate of the rise time of a signal is proportional to the density of secondary electrons which impact the anode. A particle with a greater Linear Energy

Figure 3.5 A data plot for determining the absolute energy calibration constant for the proportional counter.

Transfer coefficient (LET) would generate a more spatially dense secondary electron distribution and would register a larger rate of signal rise for its signal pulse. The rate of the signal rise is an indication of the ionization rate for the observed signal. In the CBA mode this quantity is recorded in the $X(Y)$ array. The pulses can be sorted in LET in the $Y(t,V)$ array by the contents of the $X(Y)$ array.

A sorting subprogram linked to the main data analysis program was written in FORTRAN to perform the gamma and neutron signal separation. In this module, the signals arising from exposure of the counter in a mixed gamma and neutron field $Y_m(t,V)$ are sorted by the associated $X_m(Y)$ array. Those signals with $X(Y)$ values greater than a predetermined cutoff value were labelled neutron-induced events. This cutoff value was determined by observing the $X(Y)$ distribution arising from a pure gamma ray exposure. The $Y'_m(t,V)$ array is formed from the $Y_m(t,V)$ by subtracting out those events whose $X_m(Y)$ value is greater than the cutoff. The $Y'_m(t,V)$ array is then the energy-loss spectrum of the gamma induced secondary charged particles in the counter. This array is held for further processing to determine gamma heating. The FORTRAN programs used for data processing and reduction are presented in appendices A and B. To illustrate the separation process; the counter output from a ^{60}Co gamma source alone is presented in Figure 3.6, and a representation of the counter output from a typical mixed gamma and neutron exposure is presented in Figure 3.7. The x-axis of this figure represents the signal rise time. The y-axis represents selected energy groups. The z-axis

Figure 3.6 A representative ^{60}Co energy-loss spectrum taken with the PC operating in the CBA mode.

Figure 3.7 A representative mixed DT neutron and gamma energy-loss spectrum taken with the PC operating in the CBA mode.

gives the integrated counts per channel of the measurement. From Figure 3.6, one can conclude that gamma ray induced events have rise times that fall in or below channel fifteen (15) on the x-axis. This observed cutoff serves as the limiting criterion for separating the data shown in Figure 3.7. That is, for data collected in a mixed gamma and neutron environment, those data registered in rise time channels greater than channel 15 were disregarded in the heating calculation.

Heating in the counter fill gas is equivalent to the energy deposition in the counter divided by the mass of fill gas in the counter. It can be found from:

$$\text{Heating rate} = Q_k * \sum_{i=1}^K [(N_k * k)] / (t * m) \quad (3.10)$$

where

- N_k = number of counts at channel k,
- k = the channel number,
- Q_k = the energy width of each channel,
- t = the data collection time,
- m = mass of the counter fill gas,
- K = the total number of channels.

3.6 The Irradiation Experiment

The main purpose of the experiment is to demonstrate the ability of the data acquisition system to provide gamma heating data in a low-Z medium irradiated by DT fusion neutrons and gamma rays.

The experimental setup consists of a low-Z cubic lattice irradiated by a DT neutron generator with provisions to take heating data along the mid-line of the cubic lattice. The neutron generator used was a Texas Nuclear Model 9400. The generator consists of an accelerator flight tube connected to a deuterium ion source on one end and a tritium impregnated target on the other. The ion source consists of a plexi-glass tube fed by a deuterium gas line and attached to a high-voltage biased extractor fissure. The deuterium in the tube is bathed in RF radiation to induce gas ionization. The ionized deuterons are extracted from the tube through the fissure and fed into the lead end of the flight tube. Two pairs of deflection plates at the inlet of the flight tube provide focusing for the beam. The deuterium ions then pass through a region containing ten elements of 15 kV gradient each and are thus accelerated in the flight tube to an energy of 150 KeV before they impact onto the target. The target consists of a stainless-steel cup which holds a tritium impregnated titanium foil in the cross-section of the flight tube. These 150 keV deuterium (atomic and molecular) ions are focused onto the tritium impregnated target foil with the result that some of the deuterium and tritium fuse to form alpha particles and 14.8 MeV neutrons. Scattering reactions between these 14.8 MeV neutrons with material in the target housing and the accelerator walls produce copious amounts of gamma radiation. Figure 3.8 diagrams the workings of the model 9400.

The low-Z cubic lattice is formed of 144 rectangular (5 cm x 5 cm x 61 cm x 0.2 cm) magnesium sleeves, fitted with (4.5 cm x 4.5 cm

Figure 3.8 A block diagram of the Texas Nuclear model 9400 DT neutron generator.

Figure 3.9 A representative diagram of the experimental setup.

x 61 cm) rectangular graphite blocks stacked in a cubic array. A 40 cm long graphite block was especially machined with a channel 2.5 cm x 2.5 cm in cross-section to hold the proportional counter and its pre-amplifier. The cubic lattice is set on a reinforced, cart-mounted platform, which can be raised or lowered horizontally by means of a winch. This cubic lattice was placed 50cm from the target cup of the neutron generator, with the long dimension of the Mg sleeves perpendicular to the beam line. The experimental setup is shown schematically in Figure 3.9.

The neutron generator and the graphite cubic lattice are located in a large concrete vault in Building 315 at the Argonne National Laboratory. The control station and power supply for both the neutron generator and the proportional counter are situated outside a concrete labyrinth as diagrammed in Figure 3.10. Control logic and power are provided by cable connections between the control area and the vault.

The goals of this experiment were to determine (1) the applicability of the signal separation methodology and the CBA mode of proportional counter operation for gamma heating measurements in a mixed gamma and neutron field, and (2) the operating limits of this method. The experiment consists of recording the energy-loss spectra observed with the proportional counter in six positions along the central-line of the cubic lattice spaced progressively further away from the target. These six positions are shown in Figure 3.9. Great care was taken to align the mid-line of the lattice and the active volume of the counter with the beam line of the generator. The

Figure 3.10 The relative placement of the experiment and the control area.

gamma-induced heating at each position was found from the procedure detailed in the preceding section. The neutron output of each exposure was monitored and recorded by a BF_3 counter surrounded by a cylinder of polyethylene 10 cm in radius situated in a corner of the vault. The heating data from the six exposures were normalized by the number of source neutrons for the given exposure. The result is a radial gamma heating profile of the graphite cubic lattice.

3.7 Experimental Results and Error Analysis

Gamma heating measurements were made in the low-Z cubic lattice at the six positions indicated in Figure 3.9. The measurement made at position 4 was made in October of 1990, those measurements in positions 1,3,5, and 6 were made in November of 1990 and the measurement at position 2 was completed in January of 1991. This erratic measurement schedule was influenced by both the duty factor of the TN9400 and its availability. The positioning of the cubic lattice was slightly different (so that the exact midline of the lattice may have been moved 1 cm to either side of the beam line, with no change in the radial direction) for each series, as it was necessary to move the lattice away from the TN9400 to accommodate maintenance and other experiments. However as the sensitive volume of the counter was re-aligned with the generator beam line for each series of measurements, these interruptions should not adversely affect the measurements.

Figure 3.11 A logarithmic plot of the normalized measured heating in the counter fill gas.

Figure 3.11 is a logarithmic plot of the time and source strength normalized measured heating in the counter fill gas. From Figure 3.11, the measured heating seems to decrease exponentially as the counter is moved further into the lattice. The best fitted line through these data points gives a mass attenuation coefficient of $0.0119 \text{ cm}^2/\text{gm}$ for the magnesium and graphite lattice. This mass attenuation coefficient corresponds to the passage of 10+ MeV gamma rays through the lattice, a rather unphysical result. Clearly, the decrease in the heating rate as a function of position in the lattice is a more complicated process than the simple linear attenuation of a mono-energetic gamma ray source term.

The experimental error of each heating measurement depends on the following factors: (1) $\sum_{i=1}^K N_i$ the number of events sampled per measurement, (2) the systematic errors incurred in energy calibration (δs_c), (3) the systematic errors incurred in the determination of the fill gas mass (δs_m), and (4) the systematic errors incurred in the determination of signal separation (δs_e). Assuming that these contributions to the heating rate error are un-correlated, the mean square heating rate error (ΔH) can be found by applying³⁶

$$\langle \Delta s^2 \rangle = \langle \delta s_a^2 \rangle \left(\frac{ds}{da} \right) + \langle \delta s_b^2 \rangle \left(\frac{ds}{db} \right) + \langle \delta s_c^2 \rangle \left(\frac{ds}{dc} \right) + \dots$$

The error in the heating rate is given by the quadrature sum of four terms: (1) $\frac{\langle \Delta H_n^2 \rangle}{H^2}$, the fractional mean square error in the counting statistics, (2) $\frac{\langle \Delta H_c^2 \rangle}{H^2}$, the fractional mean square systematic error

incurred during the energy calibration procedures for this particular counter, (3) $\frac{\langle \Delta H_m^2 \rangle}{H^2}$, the fractional mean square systematic error from uncertainties incurred in the mass measurement of the counter fill gas, (4) $\frac{\langle \Delta H_s^2 \rangle}{H^2}$, the fractional mean square systematic error introduced into the data reduction procedures by the uncertainties in signal separation.

The fractional root mean square experimental error for this counter can be expressed as:

$$\frac{\sqrt{\langle \Delta H^2 \rangle}}{H} = \sqrt{\frac{\langle \Delta H_n^2 \rangle}{H^2} + \frac{\langle \Delta H_c^2 \rangle}{H^2} + \frac{\langle \Delta H_m^2 \rangle}{H^2} + \frac{\langle \Delta H_s^2 \rangle}{H^2}} \quad (3.11)$$

The first expression is just a statement on the dependence of the measured result to the length of exposure to the radiation source. The error of the experiment is inversely proportional to the square root of the number of events observed. A larger value for the time integrated flux leads to a smaller error term. This dependence scales to the ratio $\frac{1}{\sqrt{\sum_{i=1}^K N_i}}$ an order of magnitude reduction in the

error will requires a two order of magnitude increase in the total count. This route for error reduction is not feasible for irradiations with a weak source, a limited exposure time, or for counters with a low electronic breakdown threshold.

The mean square fractional systematic error introduced into the measurement by the energy calibration process $\left(\frac{\langle \Delta H_c^2 \rangle}{H^2}\right)$ is just the

square of the uncertainty (%) in determining the channel into which the 18.6 keV beta particle from tritium decay falls. The uncertainty in determining the channel into which the 18.6 keV beta particle falls by the using a Kurie type plot of the energy-loss spectrum is no more than one and one half percent.

The mass of the fill gas depends on four factors: (1) the atomic weight of the gas mixture, (2) the active volume of the counter, (3) the temperature at which the mixture is fed into the counter, and (4) the pressure to which the counter is filled. The active volume of a counter is known to within 0.1% of its true value, as the counter is a precision machined product. The temperature at the time of the filling was measured to within 0.5 degree accuracy. Likewise, the pressure of the fill gas was measured to within 1 torr (mg Hg) of its true value. The sum of these mean square fractional errors amounted to less than $(0.4\%)^2$. However, as the gas mixture was rated at 1% error (i.e. 90% +/- 1% Ar (mass 40) and 10% +/- 1% CO₂ (mass 44)), a mean square fractional $\left(\frac{\langle \Delta H_m^2 \rangle}{H^2}\right)$ of $(1.0\%)^2$ was assigned to the calculated mass of the fill gas.

The estimated mean square fractional error $\left(\frac{\langle \Delta H_s^2 \rangle}{H^2}\right)$ incurred by the signal separation process was determined by examining the portion of the counter output that did not exhibit a clear separation between the gamma and neutron induced signals. For the counter used in this measurement the overlap of signals exist in the energy region $5 \text{ keV} < E < 33 \text{ keV}$ (see Figure 3.7), whereas the total energy range sampled by the counter ranged from 1 keV to 110 keV. For all other energies

there exist a clear separation of the gamma-induced signals from the neutron-induced signals, though for energies greater than 33 keV the neutron-induced signals are miniscule when compared to the gamma-induced signals. The number of events falling into the energy bins corresponding to this overlap region account for 40% of the count total. However, this overlap region represents only 17% of the total energy deposition. Using the separation point determined by observing the region where signal separation is clearly defined (all energies above 33 keV), the high signal rise rate events are subtracted out of the data array. This procedure subtracts out events that account for 5% of the total energy deposited. Being conservative, an estimated mean square fractional error of $(5.0\%)^2$ was assigned to the separation technique used. The mean square fractional error incurred for the signal separation technique is clearly the principle source of error in the measurement.

The experimental errors and the contributing components for these measurements are presented in Table 3.1. Looking at column 3 of Table 3.1, one sees that the measurements with the greater exposure exhibited the lower errors. The product of the counts per channel times the energy corresponding to that channel are plotted against energy for each of these measurements in Figures 3.12 through 3.17. The area under the curve in figures 3.12 through 3.17 is the measured energy deposition in the counter for the six exposures. These Figures indicate the region in energy that contributes most to the heating lies between 4 keV and 20 keV.

Position (cm)	Measure Heating rate [H] (J/kg-DT-S)	Count Total (#)	$\langle \delta H_a \rangle^2 / H^2$ (%) ²	$\langle \delta H_m \rangle^2 / H^2$ (%) ²	$\langle \delta H_c \rangle^2 / H^2$ (%) ²	$\sqrt{\frac{\langle \delta H^2 \rangle}{H^2}}$ (%)	ΔH (J/kg-DT-S)
8	2.35E - 21	2,885,867	5.99	1.0	2.25	5.84	1.37E - 22
18	1.61E - 21	2,602,089	6.11	1.0	2.25	5.88	9.43E - 23
28	8.97E - 22	2,320,941	6.56	1.0	2.25	5.90	5.29E - 23
38	6.14E - 22	1,477,908	8.20	1.0	2.25	6.04	3.71E - 23
48	2.76E - 22	633,784	12.60	1.0	2.25	6.39	1.76E - 23
58	1.96E - 22	184,495	23.30	1.0	2.25	7.18	1.41E - 23

^aSystematic error incurred during energy calibration.

^bSystematic error incurred during fill gas mass determination.

^cSystematic error incurred during signal separation.

Table 3.1 Heating rate and error analysis data for the six counter positions.

Figure 3.12 The measured gamma energy-loss spectrum at position 1.

Figure 3.13 The measured gamma energy-loss spectrum at position 2.

Figure 3.14 The measured gamma energy-loss spectrum at position 3.

Figure 3.15 The measured gamma energy-loss spectrum at position 4.

Figure 3.16 The measured gamma energy-loss spectrum at position 5.

Figure 3.17 The measured gamma energy-loss spectrum at position 6.

3.8 Summary

Gamma heating was measured in the fill gas of a proportional counter which was placed in a low-Z lattice and irradiated by a mixed gamma and fast neutron source. The methodology developed in Sections 3.4 and 3.5 enabled energy calibration of the detector and signal separation of the counter output. The utility of the CBA mode of proportional counter operation was demonstrated.

The gamma heating in the counter wall material and the surrounding materials in the lattice can now be found if the appropriate $\langle 1/f \rangle$ factors are known. The $\langle 1/f \rangle$ factor can be calculated by applying the methodology for determining mass stopping powers discussed in Chapter 2 to this experiment. These calculations are presented in Chapter 4.

4. Calculation of the $\langle 1/f \rangle$ Factors

The experiment was modelled numerically to derive the $\langle 1/f \rangle$ factor for the proportional counter used in the low-Z lattice. The $\langle 1/f \rangle$ factor, within the framework of cavity theory provide the means to estimate the gamma heating for the counter wall material from the measured heating in the counter fill gas. The results of these calculations are presented, and the limitations of these calculation are discussed.

4.1 Problem Description

The measured gamma heating values presented in Chapter 3 were for heating in the counter fill gas. However, it is the gamma heating in the surrounding wall material that is desired. For this particular application where the wall of the proportional counter was sufficiently thick to isolate the fill gas from electrons produced in the MgC lattice, and where the fill gas density was kept sufficiently low so that the majority of the electrons that lost energy to the fill gas were produced by gamma interactions in the wall of the counter, under such circumstances small cavity theory applies. The relationship between the measured heating in the fill gas and the heating in the wall material can be found from a calculation of the $\langle 1/f \rangle$ factor for the fill gas and the wall material.

The direct and most physically correct method for calculating the $\langle 1/f \rangle$ factor requires the solution of a three-fold coupled

transport calculation: the propagation of neutrons through the bulk material and the associated propagation of the charged particle distribution generated by these neutrons as they interact in the counter wall material, the creation of gamma rays through neutron interactions and the propagation of these gamma rays in the bulk material, and finally the propagation of the secondary electron distribution generated in the counter wall material by the gamma rays. The calculated charged particle distributions are then folded in with tabulated (or calculated) mass stopping power data for materials of interest, referenced by charged particle energy to form the $\langle 1/f \rangle$ factor for the counter wall material and the fill gas. The $\langle 1/f \rangle$ factor is found by taking the ratio of the mass stopping power of Fe to the composite mass stopping power of the Ar and CO₂ mixture and then averaging this recoil electron energy dependent term over the source recoil electron spectrum. The requirements for carrying out the direct method of calculation for the $\langle 1/f \rangle$ factor are: (1) an algorithm for solving the coupled neutron-gamma-secondary charged particle transport problem, (2) tabulated mass stopping power data for the materials of interest referenced by charged particle energy or, (3) a computational model that calculates mass stopping powers for any given material.

The implementation of the direct method involves rather sophisticated computational tools. However, with a few simplifying assumptions, a calculation of the $\langle 1/f \rangle$ factors was attempted.

The first simplifying assumption was to ignore the neutron induced charged particles. In the actual experiment the neutron

induced signals (charged particle energy loss tracks) were removed as it was the gamma induced heating that was measured. This assumption has the net effect of eliminating the calculation for charged particle production due to direct neutron interactions and their propagation (transport). The calculation is then reduced to the solution of the coupled gamma and electron transport problem in the bulk and counter wall material.

The second assumption made was that the secondary electron distribution observed by the fill gas is due only to gamma interactions with the counter wall material. This implicitly assumes that the electrons generated outside the counter wall in the bulk material do not penetrate the counter wall and that there are no contributions to the electron distribution for gamma interactions with the fill gas. Basically, Bragg-Gray conditions for the counter are assumed. This assumption effectively de-couples the electron transport problem from the gamma transport problem. All that is necessary to calculate the electron distribution for the counter are a value for the gamma flux at the counter position and an electron emission model for gamma ray interaction in the counter wall material.

At this point a second method of solution for finding the $\langle 1/f \rangle$ factor is possible. The spectrum-averaged mass stopping power as a function of initial gamma ray energy have been tabulated for various materials, most notably tissue and bone equivalent materials. If such data exist for iron, argon and carbon dioxide, the respective spectrum-averaged mass stopping powers and the $\langle 1/f \rangle$ factor can be

found by summing the product of the gamma flux and the tabulated data. The answer is only approximate, as all the mass stopping powers should be averaged over the electron spectrum arising from gamma interactions in the counter wall material (iron), whereas the tabulated averaged mass stopping power data indexed by gamma energy for each material are averaged over the electron spectrum arising from gamma interactions with each material.

A third method of solution is possible if one is willing to make one more assumption about the interaction process. This third assumption is that the electron distribution produced through gamma interactions with the wall material are due to Compton scattering only, ignoring the contributions from pair production and the photo electric effect. This assumption can be justified as most of the gamma rays in the experiment are of energy less than 2 MeV and the wall material (iron) is of medium-Z. In this energy region for this material the dominant gamma interaction mechanism is Compton scattering. Having made this assumption, the distribution of electrons with respect to electron energy T arising from Compton scatter with a gamma ray of energy $h\nu$ can be solved for by taking the sum of the products of the Klein-Nishina expression for the recoil electron distribution with respect to electron energy for an initiating photon of energy $h\nu$, and the gamma flux at energy $h\nu$. The recoil electron distribution for a gamma ray of energy $h\nu$ interacting with material Z in a Compton scatter as expressed in the Klein-Nishina formulation was given in Equation 2.5:

$$\frac{d_e \sigma(h\nu_0; T)}{dT} z$$

$$= Z \left\{ \frac{\pi r_o^2}{\alpha^2 m_e c^2} \left[2 + \left(\frac{T}{h\nu_0 - T} \right)^2 \left[\frac{1}{\alpha^2} + \frac{h\nu_0 - T}{h\nu_0} - \frac{2}{\alpha} \frac{h\nu_0 - T}{T} \right] \right] \right\}$$

$$\left(\frac{\text{cm}^2}{\text{keV-atom}_Z} \right)$$

where:

$$\alpha \text{ is } \frac{E}{m_e c^2} = \frac{h\nu}{511.0 \text{ keV}},$$

r is the classical electron orbit radius ($2.818 \times 10^{-13} \text{ cm}$),

Z is the atomic number of the target atom,

T is the energy of the recoil electron.

Recall that Equation 2.8

$$N(E_i, T, X) = \Gamma(E_i, X) \frac{d_e \sigma(E_i; T)}{dT},$$

gives the Compton recoil electron distribution at position (X) for gamma rays of energy E_i . Extending Equation 2.8 for the general case of a gamma spectrum, the resultant Compton source recoil electron distribution at position (X) [$A(E_i, T, X)$] is the sum of the product of the recoil electron distribution [$\frac{d_e \sigma(h\nu_0; T)}{dT} z$] and the normalized gamma flux [$\Gamma(E_i, X)$]:

$$A(E_i, T, X) = \sum_{E_i=0}^{E_i=E_{\text{top}}} \Gamma(E_i, X) \frac{d_e \sigma(h\nu_0; T)}{dT} z. \quad (4.1)$$

The FORTRAN program TDIST.FOR was used to calculate $A(E_i, T, X)$, and it is presented in appendix C.

Recall from the discussion in section 2.2 that the $\langle 1/f \rangle$ factor is given by Equation 2.16:

$$\langle \frac{1}{f} \rangle = \frac{\int_0^{T_0} T_0 * A(T_\gamma, T_0) * [\frac{1}{T_0} \int_0^{T_0} \frac{(\frac{1}{\rho} \cdot \frac{dT}{dx})_{\text{gas}}}{(\frac{1}{\rho} \cdot \frac{dT}{dx})_z} dT] dT_0}{\int_0^{T_0} T_0 * A(T_\gamma, T_0) dT_0}.$$

The $\langle \frac{1}{f} \rangle$ factor for each counter position in the MgC lattice was found by substituting $A(E_i, T, X)$ for $A(T_\gamma, T_0)$ in Equation 2.16. The integrals in the above expression were found numerically using Simpson's rule. Simpson's rule is:

$$I = (\frac{\Delta T}{3}) [F(T_0) + F(T_n) + 4F(T_{\text{odd}}) + 2F(T_{\text{even}})], \quad (4.2)$$

I is the approximate value of the integral,

ΔT is the width of the energy interval between points,

$F(T)$ is the value of the integrand at point T .

The three functions $F_n(T)$ in the Simpson's rule formulation for this application are:

$$F_1(T) = \frac{(\frac{1}{\rho} \cdot \frac{dT}{dx})_{\text{gas}}}{(\frac{1}{\rho} \cdot \frac{dT}{dx})_z}, \quad (4.3)$$

$$F_2(T) = T_0 * A(E_i, T, X), \quad (4.4)$$

$$F_3(T) = F_2(T) * I_1, \quad (4.5)$$

where

$$I_1 = (\frac{1}{T_0}) (\frac{\Delta T}{3}) [F_1(T_0) + F_1(T_n) + 4F_1(T_{\text{odd}}) + 2F_1(T_{\text{even}})], \quad (4.6)$$

with $T_0 = 0$, T_0 , the upper limit of the integral in Equation 2.16 replaced by $T_n = E(\frac{2\alpha}{1+2\alpha})$. The FORTRAN program SPA3M.FOR used for these calculations is presented in Appendix D.

It is possible to infer the heating in the surrounding bulk material if the mass weighted KERMA distributions are known for both the counter wall and the surrounding bulk materials in the same irradiation spectrum. The ratios formed by the mass-weighted KERMA distributions of the surrounding bulk materials (Mg and C) and the mass-weighted KERMA distribution for the counter wall material serve as an indication of the dose to the bulk materials (assuming that the energy-loss mechanisms do not significantly differ) relative to the dose in the counter wall material.

To calculate the gamma-induced KERMA of a given material, one must know the gamma spectrum to which it is exposed, the charged particle production cross sections for that material, and the associated charged particle energy distribution for each type of interaction. The KERMA at any location in the radiation field is just the sum over all energies of the product of the energy averaged gamma spectrum, the charged particle generation cross sections and the sum over energy of the resultant charged particle energy distribution.^{35,37,38} This is expressed mathematically as:

$$\text{KERMA}(X) = \sum_{E=0}^{E_{\text{top}}} \Gamma(E'; E, X) * T_{\text{av}}(\alpha) \quad (4.7)$$

this is just a generalization of Equation 2.7, in which $\Gamma(E,X)$ the number of gamma ray of energy E is replaced by the sum $\Gamma(E';E,X)$ and summed over all gamma ray energies. The sum $\Gamma(E';E,X)$ is given by:

$$\Gamma(E';E,X) = \sum_{E_i=0}^{E_{top}} \Phi(E_i,X) \sigma_{n,g}(E_i) P_g(E_i;E') E_i, \quad (4.8)$$

where $P_g(E_i;E')$ is the gamma emission distribution for an initial neutron of kinetic energy E_i .

Recall from Chapter 2 that the dominant gamma interaction mechanism for material of Z less than 30 and gamma rays of energies between 300 keV and 6 MeV is Compton scattering and that the Klein-Nishina theory is sufficient for determining the Compton cross sections.⁶ The average energy of the associated recoil electron distribution can also be calculated on a per target electron basis from the Klein-Nishina expressions for Compton scattering. A FORTRAN program KNISH was written to perform these calculations. A listing of KNISH appears as Appendix E.

The gamma spectrum in the MgC lattice must be known for the KERMA distributions and the $\langle 1/f \rangle$ factor to be calculated. A direct measurement of the gamma spectrum in the MgC lattice was not possible; the proportional counter was set up for energy-loss measurements, and other detectors (Ge-Li and NaI)³⁹ have high sensitivity to the neutron component of the total spectrum. A calculation of the gamma spectrum in the MgC lattice was then necessary. As the sensitive volume of the counter was aligned with

the beam line of the neutron generator, the problem can be viewed roughly as a source propagation problem through a slab of material in one dimension. A discrete ordinates treatment of the transport problem in one dimension was used to model the experiment.

The experiment was modelled in the following manner. (1) A 14 MeV neutron propagation problem in a thin iron slab was implemented to simulate the neutron attenuation and gamma production that occurs in the stainless steel cup that holds the tritiated target foil in the deuterium beam line of the neutron generator. (2) The resulting neutron and gamma spectra are then each multiplied the factor $(\frac{0.5 \text{ cm}}{50.0 \text{ cm}})^2$ to account for the geometric dispersion between the target and the front face of the lattice, and are then used as input source terms for a neutron and gamma propagation problem through a 60 cm thick slab of magnesium and graphite in homogeneous mixture. The attenuation in air was neglected. (3) Once the gamma spectrum in the low-Z slab was calculated, the Compton recoil electron distributions for iron and the fill gas, as well as the KERMA distributions for iron, magnesium, and graphite at the six counter positions were solved for. Consequently the $\langle 1/f \rangle$ factor and the ratios of relative dose commitment were found for the materials in the MgC lattice.

4.2 The Numerical Model and the Nuclear Data Used

The numerical modelling tool used for this project was ANISN/PC.²⁶ ANISN/PC solves a discretized approximation to the

Boltzmann transport equation in one dimension. ANISN/PC can solve fluence rate propagation and eigenvalue search problems in one-dimensional slab, cylindrical or spherical geometry. Specifically ANISN/PC treats the energy dependent variables as group averaged quantities and it accounts for the angular dependence by using a finite set of angular quadratures. This code package is written in FORTRAN and was adapted for a micro-computer from the code ANISN/W.^{26,40}

The cross section set used in these calculations were formed by weighting the cross section data extracted from the ENDF/B-V nuclear data library with a flux distribution formed by the propagation of 14 MeV neutrons through a slab of the nuclides of interest. This was done by using the neutron cross section data processing utility MC²-2.⁴² MC²-2 is a FORTRAN program that permits the user to extract material-indexed neutron interaction data from the ENDF/B-V data library, weights the data with the fluence rate distribution of the user's choice and writes the binned data to an output file in ISOTXS format.^{26,41} The process involves setting up a 14 MeV neutron source propagation problem in MC²-2 and then instructing MC²-2 to use the resulting fluence rate distribution to weight the neutron cross section data for each isotope of interest. The energy group structure of the output is defined by the user in the MC²-2 input deck.

Using MC²-2, neutron interaction cross sections were generated for iron (Fe) in a 5 mm thick Fe slab, and magnesium (Mg) and graphite (¹²C) in a 60 cm thick C and Mg slab at the atomic densities

corresponding to that of the material in the target and lattice. The energy group structure defined for these sets were 21 equal lethargy groups each 0.5 lethargy units wide starting at the top energy of the cross section library (available to MC²-2), $E = 14.19$ MeV to a low energy limit of 0.0 eV. Table 4.1 gives the correspondence between the upper energy limit of each lethargy group and the group number. The weighting spectrum calculated by MC²-2 consisted of a sharp peak in the top group, and near zero elsewhere. The weighting spectrum for Mg and C is given in Figure 4.1.

The drawback with MC²-2 is that it does not have the capability to generate coupled neutron and gamma cross sections. The gamma cross sections used in the heating calculations were taken from the FLUNGP photon cross section library.^{26,43} The gamma production cross sections were tabulated for each material at each energy group using MC²-2. The gamma spectrum for each material was constructed by taking the sum over all neutron energies of the product of the neutron fluence rate, the gamma production cross section and the gamma emission distribution for each interaction. This expression was given by Equation 4.8:

$$\Gamma(E';E,X) = \sum_{E_i=0}^{E_{top}} \Phi(E_i,X) \sigma_{n,g}(E_i) P_g(E_i;E') E_i,$$

where $P_g(E_i;E')$ is the gamma emission distribution for an initial neutron of kinetic energy E_i . The gamma emission distributions were extracted from file 15 of the ENDF/B-V data library.⁴³

Table 4.1 Lethargy group to energy correspondence.

<u>Group</u> <u>Number</u>	<u>Upper Energy Limit</u> <u>of Group (eV)</u>
1	1.419E+07
2	8.607E+06
3	5.221E+06
4	3.166E+06
5	1.921E+06
6	1.165E+06
7	7.065E+05
8	4.285E+05
9	2.599E+05
10	1.576E+05
11	9.562E+04
12	5.799E+04
13	3.518E+04
14	2.134E+04
15	1.294E+04
16	7.848E+03
17	4.760E+03
18	2.887E+03
19	1.751E+03
20	1.062E+03
21	6.443E+02

Figure 4.1 The cross section weighting spectrum used in Mc²-2 for processing Mg and C neutron cross sections.

4.3 Setup and Execution of the Numerical Simulation

Having used MC²-2 to obtain neutron interaction cross sections for iron, magnesium, and graphite (¹²C), ANISN/PC was used to calculate the gamma spectrum in the low-Z lattice. As outline in Section 4.1, the problem is treated in four parts: a neutron propagation problem through an iron slab whose solution is taken as the source term for the second part, a gamma and neutron propagation problem through a homogeneous magnesium and graphite mixture, which in turn is used in a $\langle 1/f \rangle$ factor calculation for the fill gas and wall material and a calculation of the average KERMA for the materials in the MgC lattice.

The propagation of 14 MeV neutrons through a 5 mm thick iron slab was calculated with ANISN/PC. The problem was structured as the propagation of 14 MeV neutrons from a mono-energetic neutron source through a 5 mm thick slab of Fe. Iron cross sections for a P_3 Legendre expansion treatment of the scattering was used. A S_{16} quadrature set emphasizing forward scattering was used. The gamma production cross sections were treated as activity cross sections on a group by group basis. The resulting ANISN/PC output provided the reaction rates per energy group for gamma production in the iron slab and the source neutron spectrum for the neutron propagation problem in the magnesium and graphite lattice. The gamma emission spectrum

for iron is constructed according to Equation 4.8 and is presented in Figure 4.2.

The magnesium and graphite lattice was modelled as a 60 cm thick homogeneous magnesium and graphite slab in ANISN/PC. The slab was divided into a 3 zone problem with identical material properties in each zone and independent zone widths. This peculiar zone structure was adopted to provide fine mesh intervals at the boundaries of the slab to insure calculational convergence. A depiction of this zone structure within the slab is given in Figure 4.3. A S_{12} quadrature set was used in this calculation. The P_3 scattering cross section sets of magnesium and graphite were used. The neutron spectrum resulting from the neutron propagation problem through iron was multiplied by $(\frac{0.5 \text{ cm}}{50.0 \text{ cm}})^2$ to account for the geometric dispersion and used as the neutron source term in the magnesium and graphite slab. This neutron spectrum was fed into ANISN/PC as a shell source in the first mesh interval of the calculation. The results of this calculation provided the gamma production reaction rates and the neutron spectrum in the magnesium and graphite slab. Taking these reaction rates, the neutron spectrum at each mesh interval and the gamma emission spectra extracted from file 15 of the ENDF/B-V library, and using the procedure described by Equation 4.8, a set of distributed gamma sources were compiled for the gamma propagation problem.

Finally, a gamma propagation problem in the homogeneous magnesium and graphite slab was solved by ANISN/PC. Again, a S_{12} quadrature set was used. The P_3 scattering cross sections for gamma

Figure 4.2 Gamma emission spectrum from (n, γ) reactions in the Fe slab.

Figure 4.3 The zone structure used in modelling the MgC lattice for the homogeneous cases.

ray interaction in magnesium and graphite were extracted from the FLUNGP photon cross section library. The zone and mesh structure depicted in Figure 4.3 was used.

4.4 Results of the Numerical Analysis

The results of the calculations are presented as data plots in this section. All data are normalized on a source DT reaction and unit time basis except where noted.

The propagation and interaction of the DT source neutrons in the SS304 cup that holds the tritiated target in place was modelled by considering the propagation of DT neutrons through a 5 mm thick iron slab. The neutron source was characterized as a mono-energetic neutron source in the top energy interval of the cross-section library. The calculated neutron spectrum in the fifth interval divided by the geometric dispersion factor $(\frac{0.5 \text{ cm}}{50.0 \text{ cm}})^2$ is taken as the input neutron source for subsequent neutron calculations in the magnesium and graphite lattice. This modified neutron spectrum is plotted in Figure 4.4. The gamma spectrum was constructed by multiplying the neutron spectrum in the last mesh interval by the gamma production cross-sections in each energy group and then summing the product of this and the gamma emission probabilities for each group, this procedure was presented mathematically in Equation 4.8. This gamma spectrum, divided by the geometric dispersion factor $(\frac{0.5 \text{ cm}}{50.0 \text{ cm}})^2$ was used as the gamma source spectrum for the MgC lattice analysis, and it is presented in Figure 4.5.

Figure 4.4 The source neutron spectrum for the neutron propagation problem in the MgC slab.

Figure 4.5 The source gamma spectrum for the gamma propagation problem in the MgC slab.

Using the neutron spectrum derived in the target cup calculations, the propagation of neutrons through the MgC lattice was examined with ANISN/PC. The resulting neutron distribution is presented in Figure 4.6. Figures 4.7 and 4.8 represent the neutron spectrum measured at the front (Fig. 4.7) and back (Fig. 4.8) of the MgC lattice with a BC 501 counter. It is clearly seen from a comparison of these three figures, that the calculated result overestimates the neutron distribution in the lattice. The gamma production in the MgC lattice was derived by the same methodology that was used to derive the gamma spectrum of the target cup. The tabulated gamma production in the MgC lattice was used as a distributed source term for the gamma calculation. No plot of the tabulated gamma production in the MgC lattice is attempted as it would be necessary to plot the gamma energy emission spectra at each position.

The gamma spectrum was binned into ten equal energy groups, from 1 MeV to 10 MeV. The gamma spectrum obtained in the target cup calculation was used as an input shell source to the gamma propagation problem. The gamma emission spectra obtained in the neutron propagation problem were used as distributed sources in the gamma propagation problem. The calculated gamma spectra for the six mesh positions corresponding to the six detector placement positions are presented in Figure 4.9. The outstanding features of these spectra are the intensity of the gamma-rays under 1 MeV (iron has a

Figure 4.6 A logarithmic plot of the calculated neutron spectrum in the MgC slab.

Figure 4.7 The DT neutron spectrum measured at the front (relative to the target) of the MgC lattice.

Figure 4.8 The DT neutron spectrum measured at the rear (relative to the target) of the MgC lattice.

Figure 4.9 The calculated gamma spectrum at the six counter positions.

strong gamma line at 850 keV and annihilation radiation at 511 KeV) and small but significant contributions up to 9 MeV.

Having solved for the gamma propagation in the slab, the spectrum averaged mass stopping powers for the fill gas and the counter wall material were solved for according to the procedure outlined in Section 4.1. The mass stopping powers for electrons in Fe and the fill gas were interpolated from table 12.4 of the ICRU Report 37.⁴⁵ The calculated source Compton recoil electron spectra for the six counter positions are presented in Figures 4.10 through Figure 4.15. The discontinuities in these figures result from the coarse energy group structure used in the gamma calculations. A plot of the value of $\frac{1}{f}$ (Equation 2.15) as a function of source electron energy is given in Figure 4.16.

The mass-weighted KERMA distributions for the counter wall material (Fe) and the surrounding materials (Mg and C) were found by taking the sum over all energy groups of the product of the gamma flux, the material mass density (kg/atom), the Compton cross section for that material and the recoil electrons' energy as outlined in Equation 2.6 and Equation 4.7. From these KERMA distributions, the relative dose commitment ratios of Mg to Fe and C to Fe were formed throughout the assembly for relating heating in the counter wall to that of the surrounding materials. These ratios were formed by dividing the Mg and C KERMA distributions by the Fe KERMA distribution at each mesh.

Recall from Section 2.2, that a check of the $\langle 1/f \rangle$ factor calculations was proposed by having the proportional counter

Figure 4.10 The calculated source Compton electron spectrum at position 1.

Figure 4.11 The calculated source Compton electron spectrum at position 2.

Figure 4.12 The calculated source Compton electron spectrum at position 3

Figure 4.13 The calculated source Compton electron spectrum at position 4.

Figure 4.14 The calculated source Compton electron spectrum at position 5.

Figure 4.15 The calculated source Compton electron spectrum at position 6.

physically satisfy the requirements of Fano's theorem (i.e. match the effective Z of the counter fill gas to the Z of the counter wall material). The $\langle 1/f \rangle$ factor for materials satisfying Fano's theorem is 1.0. From Figure 4.17, the $\langle 1/f \rangle$ factor for Fe (the counter wall material) and the fill gas is nearly 1.0 everywhere in the lattice. This indicates that the calculations were correct (or at least consistent). The estimated gamma heating values for Fe, Mg and C are presented in Table 4.2.

4.5 Sensitivity Analysis for Different Material Geometry

In the calculation for the neutron propagation through the MgC lattice, the material composition was assumed homogeneous. This assumption was made as the magnesium constituted approximately 10% of the mass of the lattice. This assumption may have significantly influenced the neutron spectrum in the lattice, and hence changed the strength of the distributed gamma sources used in the gamma propagation problem. To test this, a neutron propagation calculation was made with ANISN/PC, with the MgC lattice represented as a 25 zone heterogeneous slab. The material composition and zone structure of the heterogeneous slab are shown in Figure 4.18. The results of this calculation and the results from the homogeneous calculation are presented in figures 4.19 through 4.24.

The two features of these plots that stand out are: (1) they all have the same general shape, and (2) the neutron flux for both cases basically passed through the MgC slabs in these calculations.

Figure 4.16 The 1/f factor as a function of electron energy.

Figure 4.17 The $\langle 1/f \rangle$ factor as a function of counter position.

Table 4.2 The estimated heating rates for Fe, Mg, and C.

Position (cm)	$\frac{1}{\langle f \rangle}$	$\frac{\text{KERMAN}}{\text{KERMA}_{\text{Fe}}}$			Estimated Heating Rate (J/Kg-DT-sec)		
		C	Mg		Fe	C	Mg
8	0.9511	0.244	0.910		2.23E-21	5.44E-22	2.03E-21
18	0.9515	0.244	0.910		1.53E-21	3.73E-22	1.39E-21
28	0.9518	0.244	0.910		8.54E-22	2.08E-22	7.77E-22
38	0.9521	0.244	0.910		5.85E-22	1.43E-22	5.32E-22
48	0.9523	0.244	0.910		2.63E-22	6.42E-23	2.39E-22
58	0.9525	0.244	0.910		1.86E-22	4.55E-23	1.70E-22

Figure 4.18 The zone structure used for the heterogeneous neutron propagation calculation.

Figure 4.19 The calculated heterogeneous and heterogeneous neutron spectra at counter position #1.

Figure 4.20 The calculated homogeneous and heterogeneous neutron spectra at counter position #2.

Figure 4.21 The calculated homogeneous and heterogeneous neutron spectra at counter position #3.

Figure 4.22 The calculated homogeneous and heterogeneous neutron spectra at counter position #4.

Figure 4.23 The calculated homogeneous and heterogeneous neutron spectra at counter position #5.

Figure 4.24 The calculated homogeneous and heterogeneous neutron spectra¹ at counter position #6.

Table 4.3 The Mc^2-2 derived interaction cross sections for graphite (C).

Group	(transport) (b)	(total) (b)	(n,gamma) (b)	(scatter) (b)
1	8.1360E-01	1.3068E+00	1.0898E-04	7.8705E-01
2	9.2630E-01	1.3880E+00	7.8977E-05	8.5727E-01
3	1.3378E+00	2.0010E+00	2.1397E-05	1.2294E+00
4	1.6280E+00	1.7568E+00	9.0685E-05	1.0913E+00
5	1.7996E+00	2.0605E+00	3.2427E-06	1.3193E+00
6	2.3030E+00	2.7066E+00	1.2746E-06	1.8231E+00
7	2.8843E+00	3.2890E+00	1.0370E-06	2.3148E+00
8	3.4141E+00	3.7666E+00	9.5935E-07	2.6072E+00
9	3.7776E+00	4.1102E+00	9.2577E-07	2.7385E+00
10	3.9927E+00	4.3354E+00	9.0631E-07	3.0307E+00
11	4.2215E+00	4.4918E+00	9.2959E-07	2.8227E+00
12	4.4434E+00	4.5801E+00	9.6024E-07	3.1778E+00
13	4.0914E+00	4.6426E+00	9.8131E-07	2.8124E+00
14	4.4946E+00	4.6764E+00	9.9255E-07	3.1682E+00
15	4.7692E+00	4.6978E+00	1.7673E-06	3.4429E+00
16	4.3540E+00	4.7124E+00	7.9676E-06	3.1273E+00
17	4.4655E+00	4.7220E+00	1.2195E-05	3.2044E+00
18	4.5210E+00	4.7287E+00	1.4820E-05	3.2380E+00
19	4.5226E+00	4.7329E+00	1.6417E-05	3.2666E+00
20	4.5223E+00	4.7354E+00	1.8860E-05	3.2447E+00
21	4.5014E+00	4.7369E+00	2.4155E-05	3.2380E+00

A closer examination of these calculations, specifically the interaction cross sections, revealed why this happened. The interaction cross sections for graphite (C) are presented in Table 4.3. A quick comparison of the within-group scattering cross sections (column 5) and the transport cross sections (column 2), indicates that within-group scatter dominates. The calculations are correct for the cross section set used.

4.6 Summary

A numerical analysis for the $\langle 1/f \rangle$ factor and the KERMA ratios used to estimate heating in other materials from gamma heating values measured in the counter were made with ANISN/PC and the Klein-Nishina treatment of Compton scattering. The calculated $\langle 1/f \rangle$ factor for the counter satisfied the check designed into the experiment to verify the validity of the calculation methodology. The sensitivity analysis done on the material representation seems to indicate no qualitative difference on the choice of material representation for these cross section sets.

5. Conclusions and Future Directions

The body of ideas and work presented in Chapters one through four are brought into focus. Conclusions are made on the viability of the techniques developed in this thesis for measuring gamma heating in low fluence, mixed radiation environments. Suggestions for further investigation into this and other related topics are presented.

5.1 Conclusions

The goals of this thesis project were to: (1) create a detector that is able to measure gamma heating in a low fluence, mixed gamma and neutron field with good confidence, (2) be able to perform this measurement over a broad energy range, and (3) develop a method to relate the heating measured by the detector to the heating experienced by other materials in the same radiation environment. The experimental and calculational methods are treated separately.

The results of the detector technology development efforts presented in Chapter 3 show that a proportional counter based detection system can provide gamma heating measurements with good confidence. The key attributes of this detection methodology are its ability to perform signal separation and its ability to take data over a broad range of energy deposition. These attributes of this detector and electronics arrangement allow the experimenter to

perform what were previously very difficult and arduous measurements with relative ease.

A method to estimate the heating to other materials in a given radiation field from the measured heating in the detector, based on a calculation of the dose commitment ratios for these materials and the detector wall material was shown. The results of the small cavity limit of cavity ionization theory was used to relate the measured heating in the counter fill gas to the counter wall material. The method of relating measured heating in one material to another by the use of $\langle 1/f \rangle$ factors was demonstrated. The calculations indicate that there exist a 5% difference between the absorbed dose in the counter wall material and the absorbed dose in the counter fill gas. As these calculations were made possible with the aid of many simplifying assumptions; a more detailed and complete series of calculations will give better results. Use was made of Fano's theorem to validate the $\langle 1/f \rangle$ factor calculations and its positive result indicate the numerical methods used in this thesis embodied the correct physics.

However, the results of the neutron propagation problems presented in Chapter four indicate that ANISN/PC is only adequate for a rough characterization of the radiation profile in a fast fluence rate system. The significance of the large within-group scattering cross section of graphite (Table 4.3), Mg and Fe is that 21 equal-width lethargy groups do not characterize the interactions of DT neutrons well. The implications for the $\langle 1/f \rangle$ factor calculations are: (1) the derived gamma emission spectrum may have been greater

than the true conditions, (2) the energy distribution of the calculated gamma spectrum was not well characterized. The applicability of ANISN/PC for future work in this field must be re-evaluated on the basis of whether or not a more detail energy group structure (more groups at the upper energy limit) is available. A coupled neutron and gamma cross section set would also be of great benefit.

5.2 Future Directions

The signal separation technique could benefit from using a heavier fill gas in the counter, as a high-Z gas would have a more pronounced response difference for events of different LET. However higher-Z gases would be increasingly sensitive to photoelectric absorption in soft gamma spectra, and this could complicate the calculation for the $\langle 1/f \rangle$ factor as one can not assume Compton scatter as the only gamma interaction in that instance. The merits of using a heavier counter fill gas to aid in signal separation should be investigated

The counter used in these measurements is limited by the characteristics of the analog amplifiers and the processing speed (4.77 MHz) of the data acquisition system to a maximum observable count rate of 2400 counts per second (cps). At higher count rates, the counting system will experience signal pile-up. This limitation can be removed if a faster data acquisition system is obtained. Of

course all the operating software must also be changed to interface with the faster processor.

The gamma heating measurement technique developed in this thesis should prove valuable to the fusion materials researcher with an interest in measuring the deposition of the energy released by the DT reaction in the candidate materials for next generation of fusion experiments. Gamma heating measurements can be made in the present generation of fusion devices with the techniques developed in this thesis, if provisions are made to transport and set up the proportional counter and the data acquisition system to such a site.

The data acquisition technique (the CBA) can be adapted to other applications less esoteric, such as serving as the driving electronics for a remotely operated radiation spectrometer capable of observing a broad energy range. Remotely operated radiation spectrometers have been deployed on space exploration probes, and their use have been considered for on site, non-intrusive monitoring of nuclear arms limitation treaty compliance. Previous remotely operated spectrometers either maximized their energy range at the expense of decreased energy resolution, or they optimized energy resolution by decreasing the observable energy range. The CBA mode of operation can drive a detector over a broad energy range while maintaining good energy resolution, as the CBA mode changes the input bias-voltage to the detector to observe different portions of the energy range, hence the possible count rate (resolution) for a given channel can be maximized.

The calculational methods used to model the experiment would benefit greatly from the use of a fine group coupled gamma and neutron cross section set. As ANISN/PC can only treat 21 energy groups and is limited to one spatial dimension, a more sophisticated treatment of the transport equation will produce more realistic results. A version of ANISN that can treat more than 21 energy groups would be acceptable, but a three-dimensional transport program such as MCNP would be best. Lastly a fine energy group structure coupled gamma electron transport routine that will allow for the effects of pair production and photo-electric effect as well as Compton scattering (e.g. MCNP4A) would be of immense value for future $\langle 1/f \rangle$ factor calculations.

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Appendix A: RANGE.FOR

```

$NODEBUG
$NOFLOATCALLS
$LARGE
$STORAGE:2
C*****
C  RANGE.FOR
C  DATA PEAK INTEGRATION FOR PROPORTIONAL COUNTER SPECTRA.
C  APPLICABLE FOR RAMP-VOLTAGE MODE DATA ONLY.
C
C  OBJECTIVES OF THIS CODE ARE:
C
C  1.  READ IN DATA GENERATED BY RAMPDA.EXE
C
C  2.  DISPLAY RAW DATA FOR SPOT ANALYSIS
C
C  3.  DO BACKGROUND, PULSER, AND RECOIL REJECTION
C
C  4.  GENERATE OUTPUT FOR HEATING CALCULATIONS
C*****
      DIMENSION IDAT(32,511),NDAT(32,511),TVAL(511),ETVAL(511),
      XTPLSE(511),WIDE(511),PRTS(511),DVAL(511),EDVAL(511),GAMS(511),
      XDATI(32,511),DATN(32,511),D(32),RATEO(511),GMS(32),HEN(32,511),
      1DMAX(511),KTPK(511),KTVL(511),KDPK(511),RKMAX(511),
      2KDVL(511),RKRA(511),HACK(511)

      COMMON Y(511),X(511),B(9),W(511)
      DOUBLE PRECISION B,EVLV,DPI
C
      INTEGER*4 NSEC,NNSEC,JTOT
      CHARACTER FNAME*16,PNAME*16,IDENT*72,JDENT*72,RESP*5,
      1DEFI*6
C
C  ESTABLISH THE LOG OF ENERGY ELOG AT ANY CHANNEL
C
      ELOG(I)=FLOAT(I+NYMIN-1)/64. + CAL
C
C  WHERE CAL = ALOG((LVL/GMAX)*FSEXA/4096.).
C
      1 FORMAT(47H INPUT A 10 CHAR. FILE NAME FOR 2-P DATA ARRAY. )
      2 FORMAT(A)
      3 FORMAT(I3)
      4 FORMAT(50H INPUT POS TO SAVE ON DISC, OR NEG TO DELETE SAVE.)
      5 FORMAT(6E12.5)
      6 FORMAT(33H INPUT(I3) THE Y CHANNEL(1-NCHY). )
      7 FORMAT(19H SPECTRUM VALLEY = I3, 15H TEST VALLEY = I3/
      X17H SPECTRUM PEAK = I3,13H TEST PEAK = I3/

```



```

X34H CHECK SPECTRUM BEFORE PROCEEDING. )
8 FORMAT(/45H-----MAIN MENU-----/
X49H ALL OPTIONS REACHED BY INPUTTING (I3) 1 TO 4). /
X49H 1...PRINT RAW DATA BETWEEN ANY CHANNEL LIMITS. /
X50H 2...DISPLAY AND PRINT 32-CHANNEL X/Y FOR ANY Y. /
X44H 3...CARRY OUT RECOIL BACKGROUND ANALYSIS. /
X49H 4...COMPLETE ANALYSIS AND OUTPUT FINAL RESULTS./)
9 FORMAT(///18X,27HLISTING OF ANALYSIS RESULTS //)
10 FORMAT(I5,3E18.8)
11 FORMAT(/4H J ,18H      BCKGRD
X18H      PRTS      ,18H      TIME      /)
12 FORMAT(49H CAN'T FIND CONSISTENT SET OF DATA PEAKS/VALLEYS. /\)
13 FORMAT(8F8.0)
14 FORMAT(32H INITIAL AVG DATA LINE WIDTH = F7.2/
X51H CHANNEL WHERE LINE BROADENS TO 1.5 TIMES INITIAL = I5/)
15 FORMAT(16I5)
16 FORMAT(43H INPUT A FILE NAME FOR THE DATA SPECTRUM. )
17 FORMAT(31H TOTAL POINTS AND START POINT = 2I5 )
18 FORMAT(10F8.0)
19 FORMAT(52H INPUT A FILE NAME FOR THE GAMMA BACKGROUND SPECTRUM
)
20 FORMAT(2I8)
21 FORMAT(/41H      TOTAL POINTS AND START POINT = 2I5 /
X32H      RUN TIME IN SECONDS = I8 /)
22 FORMAT(46H Y CHANNEL WHERE BACKGRD RATIO = .90 OF MAX = I5)
23 FORMAT(50H Y CHANNEL WHERE X/Y PROTON CUT-OFF CHANNEL IS 1 = I5
)
24 FORMAT(43H INPUT A .DAT FILE NAME FOR 32 X/Y SPECTRUM )
26 FORMAT(35H THE ENERGY FOR THE X/Y SPECTRUM IS E12.5 )
25 FORMAT(53H INPUT(I3/I3) LOW AND HIGH Y LIMITS FOR DATA
LISTING./)
27 FORMAT(53H INPUT NEGATIVE CHAN. NULL ABOVE AND SAVE FOR GRAPHER
)
28 FORMAT(45H INPUT THE ENERGY SCALE FACTOR FSEX (E12.5). )
29 FORMAT(36H THE Y (OR LOG(E)) CHANNEL NUMBER IS I5 )
30 FORMAT(44H INPUT NEGATIVE TO DELETE LOW X/Y CORRECTION )
32 FORMAT(/33H X/Y DISTRIBUTION FOR Y CHANNEL = I3)
C
C
C NCHY, THE NUMBER OF Y (ENERGY) CHANNELS, IS LESS THAN 512.
C THIS RESTRICTS A FLOATING POINT ARRAY TO LESS THAN 1 PAGE.
C THE NUMBER OF X/Y CHNNELS IS FIXED AT 32.
NCHY = 511
NYMIN=1
LTOT=NCHY
C NABS AND NORD ARE X AND Y POINT COUNT FOR PLOTTING ROUTINES.
C NABS=640
C NORD=200
NABS=720
NORD=348
C
3013 CONTINUE
C INPUT A 32XNCHY CHANNEL DATA ARRAY FROM DISC.

```

```

C   CONVERT TO FLOATING POINT. THEN ENTER MAIN MENU
C
203  DO 7519 J=1,NCHY
      HACK(J)=0.0
      DO 7519 I=1,32
        HEN(I,J)=0.0
        DATN(I,J)=0.0
7519 DATI(I,J)=0.0
C
      WRITE(*,1)
      READ(*,2) FNAME
      OPEN(10,FILE=FNAME,FORM='UNFORMATTED',STATUS='OLD')
      READ(10) FNAME
      WRITE(*,2) FNAME
      READ(10) IDENT
      WRITE(*,2) IDENT
      READ(10) NSEC
ccc      number of sec in integers
      READ(10) LVL
ccc      lower level cut-off set @896/4096
      READ(10) GMAX
ccc      max defined gas gain
      READ(10) IDAT
      CLOSE(10)
C
      DO208 I=1,NCHY
        HECK=0.0
        DO2081 J=1,32
          DATI(J,I)=FLOAT(IDAT(J,I)) + 32767.
2081  HECK=HECK+DATI(J,I)
        HACK(I)=HECK
208  CONTINUE
C.....DIAGNOSTICS.....
C      WRITE(*,7755)
C 7755 FORMAT('  THE DATA COLLAPSED OVER 32 CHANNELS',/)
C      DO 7733 J=1,NCHY
C 7733 WRITE(*,7744)J,HACK(J)
C 7744 FORMAT(5X,I4,E12.6)
      WCTOFF=.3
ccc      the low energy cut-off
      WRITE(*,28)
      READ(*,5) FSEXA
ccc      Full Scale Energy X Amplification
C  REMEMBER 10 VOLTS = (ENERGY X AMPLIFICATION) X CONSTANTS
C  I. E. (ENERGY X AMPLIFICATION) = CONSTANT
C
      CAL=ALOG((FLOAT(LVL)/GMAX)*FSEXA/4096.)
CC
      DO610 I=1,LTOT
610  W(I)=EXP(ELOG(I))+WCTOFF
C
C  MAIN MENU. OPTIONS SELECTED HERE.
200 WRITE(*,8)

```

```

        READ(*,3) IGO
        IF(IGO)200,200,201
201 IF(IGO-4)202,202,200
202 GO TO(204,205,206,199),IGO
C
        GO TO 200
C
C ONLY PRINT THE RAW DATA BETWEEN Y CHANNEL LIMITS AS INPUT.
C
204 CONTINUE
    OPEN(7,FILE='CBA.PRN',STATUS='NEW')
    WRITE(*,25)
    READ(*,3) ILO
    READ(*,3) IHI
    PAUSE 'PRINTER ON/OFF'
    WRITE(*,2) FNAME
    WRITE(7,2) FNAME
    WRITE(*,2) IDENT
    WRITE(7,2) IDENT
    DO152 J=ILO,IHI
    WRITE(*,15) J
    WRITE(7,15) J
    WRITE(7,18) (DATI(I,J),I=1,32)
152 WRITE(*,18) (DATI(I,J),I=1,32)
    CLOSE(7)
    GO TO 200
C
C*****
C    copy this section for future reference
C    NABS AND NORD ARE X AND Y POINT COUNT FOR PLOTTING ROUTINES.
C
C    DISPLAY THE 32 CHANNEL X/Y SPECTRUM FOR ANY Y AND ALSO
C    PRINT THE 32 CHANNEL X/Y SPECTRUM. NULL VALUE FOR Y TERMINATES.
C
205 WRITE(*,6)
    READ(*,3) IYZ
    IY=IYZ-NYMIN+1
    IF(IY-LTOT)117,117,200
117 IF(IY)200,200,116
116 WRITE(*,32) IY
    WRITE(*,18) (DATI(I,IY),I=1,32)
    UMAX=1
    DO113 I=1,32
    IF(DATI(I,IY)-UMAX)113,113,114
114 UMAX=DATI(I,IY)
113 CONTINUE
    CALL PLTINIT
    CALL LINAX(NABS,NORD)
    DO115 I=1,32
    IX=IFIX((FLOAT(I))*FLOAT(NABS)/32.)-1
    JY=IFIX(.95*FLOAT(NORD)*DATI(I,IY)/UMAX)
    IXX=IX-3
    IF(JY)120,120,121

```

```

120 JY=0
121 CALL SPLT(IXX,JY,-1,6)
    LENGTH=2
    JYY=JY-1
    IF(JYY)112,112,115
112 JYY=0
    LENGTH=1
115 CALL SPLT(IX,JYY,1,LENGTH)
    CALL PLTOUT
    WRITE(*,29) IY
    WRITE(*,26) W(IY)
    WRITE(*,27)
5178 READ(*,15) IKO
    IF(IKO)5178,602,205
602 DO603 I=1,32
    IF(I-IKO) 601,600,600
601 D(I)=0.0
    GO TO 603
600 D(I)=DATI(I,IY)
603 CONTINUE
    WRITE(*,24)
    READ(*,2) FNAME
    OPEN(10,FILE=FNAME,FORM='FORMATTED',STATUS='NEW')
    DO605 I=1,32
    XI=FLOAT(I)
605 WRITE(10,5) XI,D(I)
    CLOSE(10)
    GO TO 205
C*****
C*****
C
C ANALYSE FOR DATA AND LIVE TIME USING BACKGROUND SUBTRACTION.
C COLLAPSE TO A SINGLE 32-CHANNEL SPECTRUM D(I), LOCATE THE
C VALLEY CHANNELS BEFORE DATA PEAKS (N*VDAT) AND BEFORE
C LIVE TIME PEAK (N*VTEST).
C
C
C*** WE ONLY HAVE RECOILS AT HIGH ENERGY CHANNELS.
C
C
C
206 CONTINUE
    IBXY=0
C
    DO 7000 J=1,NCHY
        DMAX(J)=0.0
        RKRAT(J)=0.0
        DO 7000 I=1,32
            HEN(I,J)=DATI(I,J)
            IF(MOD(J,100))7000,8717,7000
8717     WRITE(*,110)HEN(I,J)
7000 CONTINUE
110 FORMAT(E12.6)

```

```

C
    DO 7100 J=1,NCHY
        DDUM=0.0
        DO 7101 I=1,32
            DDUM=DDUM+HEN(I,J)
7101    CONTINUE
        DMAX(J)=DDUM
7100 CONTINUE
C
    LMI=0
    JP=1
3713 IF(DMAX(JP)-1.0)3711,3711,3712
3711    JP=JP+1
        IF(JP-NCHY)3714,3714,3713
3714    PAUSE'    THERE IS NO DATA ..... ERROR'
3712 CONTINUE
    LMI=JP
C
    LUMP=0
    J1=NCHY
913    IF(DMAX(J1)-1.0)912,912,911
912    J1=J1-1
        IF(J1-1)914,914,913
914    PAUSE'    THERE IS NO DATA.... ERROR'
911 CONTINUE
    LUMP=J1
C
    NYMIN=LMI
    NYMAX=LUMP
    LTOT=IABS(LUMP-LMI)
    WRITE(*,8733)NYMIN,NYMAX,LTOT
8733 FORMAT(' NYMIN IS ',I3,/' NYMAX IS ',I3,/' LTOT IS '
    1,I3 )
C
    DO 7200 J=1,NCHY
        HDLTA=0.025*DMAX(J)
        I=32
783    IF(HEN(I-1,J)-HEN(I,J)+HDLTA)780,781,781
781    I=I-1
        IF(I-1)782,782,783
782    KTPK(J)=0
        KTVL(J)=0
        KDPK(J)=0
        KDVL(J)=0
        GOTO 7200
780    KTPK(J)=I
786    IF(HEN(I-1,J)-HEN(I,J))784,784,785
784    I=I-1
        IF(I-1)7821,7821,786
7821    KTVL(J)=0
        KDPK(J)=0
        RKMAX(J)=0.0
        KDVL(J)=0

```

```

      GOTO 7200
785   KTVL(J)=I
      I=I-1
789   IF(HEN(I-1,J)-HEN(I,J))788,788,787
787   I=I-1
      IF(I-1)7822,7822,789
7822  KDPK(J)=0
      RKMAX(J)=0.0
      KDV L(J)=0
      GOTO 7200
788   KDPK(J)=I
      RKMAX(J)=HEN(I,J)
      I=I-1
790   IF(HEN(I-1,J)-HEN(I,J))791,792,792
791   I=I-1
      IF(I-1)7823,7823,790
7823  KDV L(J)=0
      GOTO 7200
792   KDV L(J)=I
7200  CONTINUE
C
      J=NCHY
800   IF(KDPK(J-1)-KDPK(J)+4)802,802,801
801   J=J-1
      IF(J-1)2060,2060,800
802   JBREAK=J
      JBREAK=IABS(JBREAK)
      IBXY=IABS(KDV L(JBRAK))
      IF(IBXY.GT.18.OR.IBXY.LT.12)IBXY=14
      WRITE(*,2793)JBREAK,IBXY
2793  FORMAT(4X,'THE BREAK CHANNEL IN Y IS',I3,/,
1'THE X/Y SEPERATION IBXY IS',I3)
C
      IBB1=IABS(IBXY+4)
      DO 8000 JB1=1,LTOT
        DO 8000 IB1=IBB1,26
8000  HEN(IB1,JB1)=0.0
C
      IBB2=IABS(IBXY-2)
      DO 8100 JB1=1,LTOT
        DO 8200 IB2=IBB2,26
          FRAC=1.0
          HENT=0.0
          FRAC=FRAC-ABS(FLOAT(IB2-12)*0.08)
          IF(FRAC.LE.0.0)THEN
            FRAC=0.05
          ENDIF
          HENT=HEN(IB2,JB1)*FRAC
          IF(ABS(HENT).LT.0.02)HENT=0.02
8200  HEN(IB2,JB1)=HENT
8100  CONTINUE
C
C

```

```

      DO 7500 J=1,NCHY
        DO 7500 I=1,32
          DATI(I,J)=HEN(I,J)
7500 CONTINUE
2060 CONTINUE
C.....ACTIVATE ONLY IF SCREEN GRAPHICS ARE NECESSARY..
C 3200 WRITE(*,6)
C      READ(*,3) IYZ
C      IY=IYZ-NYMIN+1
C      IF(IY-LTOT)3117,3117,3200
C 3117 IF(IY)3200,3200,3116
C 3116 WRITE(*,32) IY
C      WRITE(*,18) (HEN(I,IY),I=1,32)
C      UMAX=1
C      DO3113 I=1,32
C      IF(DATI(I,IY)-UMAX)3113,3113,3114
C 3114 UMAX=DATI(I,IY)
C 3113 CONTINUE
C      CALL PLTINIT
C      CALL LINAX(NABS,NORD)
C      DO3115 I=1,32
C      IX=IFIX((FLOAT(I))*FLOAT(NABS)/32.)-1
C      JY=IFIX(.95*FLOAT(NORD)*HEN(I,IY)/UMAX)
C      IXX=IX-3
C      IF(JY)3120,3120,3121
C 3120 JY=0
C 3121 CALL SPLT(IXX,JY,-1,6)
C      LENGTH=2
C      JYY=JY-1
C      IF(JYY)3112,3112,3115
C 3112 JYY=0
C      LENGTH=1
C 3115 CALL SPLT(IX,JYY,1,LENGTH)
C      CALL PLTOUT
C
C*****
C
C
C      NOW READ IN A BACKGROUND FILE, DELETE ITS PULSER DATA
C      AND SUBTRACT IT FROM THE MODIFIED DATA FILE.
C
      UMAX=0.0
      DO128 I=1,32
      UDUM=0.0
      DO129 J=1,NCHY
129 UDUM=UDUM+DATI(I,J)
      IF(UDUM-UMAX)128,128,127
127 UMAX=UDUM
128 D(I)=UDUM
C.....OUTPUT..
9178 READ(*,15) IKO
      IF(IKO)9178,9602,9205
9602 DO9603 I=1,32

```

```

      IF(I-IKO) 9601,9603,9603
9601 D(I)=0.0
      GO TO 9603
9603 CONTINUE
      WRITE(*,24)
      READ(*,2) FNAME
      OPEN(10,FILE=FNAME,FORM='FORMATTED',STATUS='NEW')
      DO9605 I=1,32
      XI=FLOAT(I)
9605 WRITE(10,5) XI,D(I)
      CLOSE(10)
9205 CONTINUE
C   PLOT THE COLLAPSED X/Y SPECTRUM AND SHOW VALLEY CHANNELS.
      CALL PLTINIT
      CALL LINAX(NABS,NORD)
      DO165 I=1,32
      IX=IFIX((FLOAT(I))*FLOAT(NABS)/32.)-1
      JY=IFIX(.95*FLOAT(NORD)*D(I)/UMAX)
      IXX=IX-3
      CALL SPLT(IXX,JY,-1,6)
      LENGTH=2
      JYY=JY-1
      IF(JYY)162,162,165
162 JYY=0
      LENGTH=1
165 CALL SPLT(IX,JYY,1,LENGTH)
      CALL PLTOUT
C
      DO 7517 J=NCHY
        DO 7517 I=1,32
7517 DATN(I,J)=0.0
C
      WRITE(*,19)
      READ(*,2) FNAME
      OPEN(10,FILE=FNAME,FORM='UNFORMATTED',STATUS='OLD')
      READ(10) FNAME
      WRITE(*,2) FNAME
      READ(10) JDENT
      WRITE(*,2) JDENT
      READ(10) NNSEC
      READ(10) NNII
      READ(10) GGGG
      READ(10) NDAT
      CLOSE(10)
      DO207 I=1,NCHY
      DO207 J=1,32
207 DATN(J,I)=FLOAT(NDAT(J,I)) + 32767.
C
C   DELETE TEST PULSES FROM BACKGROUND SPECTRUM.
      N1=26
      DO446 J=1,NCHY
      DO446 I1=N1,32
446 DATN(I1,J)=0.0

```



```

C
C   NOW SUBTRACT THE BACKGROUND FROM THE LIVE DATA
C
      DO 7513 J=1,NCHY
        GDAM=0.0
        DO 7513 I=1,32
          GDAM=DATI(I,J)-DATN(I,J)
          DATI(I,J)=GDAM
          IF(DATI(I,J).LE.0.0)DATI(I,J)=0.0
7513 CONTINUE
C
C      N2=IBXY+1
C      DO 7514 J=1,LTOT
C        PDRT=0.0
C        DO 7514 I3=N2,N1
C          PDRT=DATI(I3,J)-DATN(I3,J)
C          DATI(I3,J)=PDRT
C 7514 CONTINUE
      GO TO 200
C
C*****
C
C      PUT THE DATA INTO ARRAYS GAMS & TPLSE
C
199 CONTINUE
C
      DO 7523 J=1,NCHY
        GAMS(J)=0.0
        PRTS(J)=0.0
        TPLSE(J)=0.0
7523 CONTINUE
C
      DO 7524 JB1=1,LTOT
        GMSA=0.0
        DO 7525 I2=1,26
7525      GMSA=GMSA+DATI(I2,JB1)
        GAMS(JB1)=GMSA
7524 CONTINUE
C
C      DO 7528 JB1=1,LTOT
C        PSLET=0.0
C        DO 7529 I4=27,32
7529      PSLET=PSLET+DATI(I4,JB1)
        TPLSE(JB1)=PSLET
7528 CONTINUE
C
      DO 6715 J=1,NCHY
        IF(GAMS(J).LE.0.0)GAMS(J)=1.0
        IF(TPLSE(J).LE.0.0)TPLSE(J)=1.0
6715 CONTINUE
C   FINAL EDIT OF RESULTS.
      PAUSE 'PRINTER ON/OFF FOR FINAL EDIT'

```

```

        WRITE(*,9)
        WRITE(*,2) IDENT
        WRITE(*,21) LTOT,NYMIN,NSEC
        WRITE(*,11)
        LCNTR=18
        I=1
280  WRITE(*,10) I,GAMS(I)PRTS(I),TPLSE(I)
        I=I+1
        IF(I-LTOT)283,283,284
283  LCNTR=LCNTR+1
        IF(LCNTR-58)280,281,281
281  WRITE(*,282)
        LCNTR=1
282  FORMAT(/////////)
        GO TO 280
C  OPTION TO SAVE DATA ON DISC.
284  WRITE(*,4)
        READ(*,3) IGO
        IF(IGO)298,299,299
299  CONTINUE
        JTOT=0
C
        WRITE(*,16)
        READ(*,2) PNAME
        OPEN(10,FILE=PNAME,FORM='FORMATTED',STATUS='NEW')
        WRITE(10,2) PNAME
        WRITE(10,2) IDENT
        WRITE(10,20) NSEC
        WRITE(10,15) LTOT
        WRITE(*,1615)LTOT
1615  FORMAT(5X,' NPT IS:',I5)
        WRITE(10,15) NYMIN
        WRITE(*,1616)NYMIN
1616  FORMAT(5X,' IBS = ',I5)
        WRITE(10,20) LVL
        WRITE(*,1617)LVL
1617  FORMAT(5X,' LVL IS ',I5)
        WRITE(10,5) GMAX
        WRITE(*,1618) GMAX
1618  FORMAT(5X,' GMAX IS ',E12.5)
        PAUSE
        WRITE(10,5) (GAMS(I),I=1,LTOT)
        WRITE(10,5) (PRTS(I),I=1,LTOT)
        WRITE(10,18) (TPLSE(I),I=1,LTOT)
298  CLOSE(10)
        WRITE(*,1622)
1622  FORMAT(' ENTER BEGIN TO CONTINUE WITH NEW FILE')
        READ(*,1621)RESP
1621  FORMAT(A5)
        IF(RESP.EQ.'BEGIN')THEN
            GOTO 3013
        ENDIF
        STOP

```

```

      END
C*****
C
C   DERIVE THE FULL WIDTH AT HALF MAXIMUM OF THE DATA PEAK OVER
C   THE RANGE OF DATA FROM ICH1 TO ICH2 FOR THE D(I) ARRAY.
C
      FUNCTION FWHM(ICH1,ICH2,D)
      DIMENSION D(32)
C
      CMAX=0.0
      DO1 K=ICH1,ICH2
      IF(D(K)-CMAX)1,1,2
2    CMAX=D(K)
      IMAX=K
1    CONTINUE
      HALF=0.5*CMAX
      K=IMAX
5    IF(D(K)-HALF)3,3,4
4    K=K-1
      IF(K-ICH1)8,8,5
8    VLO=ICH1
      GO TO 9
3    U=D(K+1)-D(K)
      IF(U)11,11,10
11   VLO=FLOAT(K)+.5
      GO TO 9
10   VLO=FLOAT(K)+(HALF-D(K))/U
9    DO6 K=IMAX,ICH2
      IF(D(K)-HALF)7,6,6
6    CONTINUE
7    U=D(K-1)-D(K)
      IF(U)12,12,13
12   VHI=FLOAT(K)-.5
      GO TO 14
13   VHI=FLOAT(K)-(HALF-D(K))/U
14   FWHM=VHI-VLO
      RETURN
      END
C*****
C
C   FUNCTION HILO (LH,ILO,IHI,D) RETURNS MAXIMUM (LH=1) OR
C   MINIMUM(LH=0)
C   COUNT CHANNEL NUMBER OF THE ARRAY D(I) IN THE INTERVAL ILO TO IHI.
C
      FUNCTION HILO(LH,ILO,IHI,D)
      DIMENSION D(32)
C
      IF(LH)1,1,2
1    U=1.E06
      GO TO 3
2    U=0.0
3    DO4 I=ILO,IHI
      IF(LH)5,5,6

```

```

5 IF(D(I)-U)7,4,4
7 U=D(I)
  LOHI=I
  GO TO 4
6 IF(D(I)-U)4,4,8
8 U=D(I)
  LOHI=I
4 HILO=FLOAT(LOHI)
  RETURN
  END
C*****
C SUBROUTINE PLTINIT INITIALIZES PLOTTING ROUTINES.
C
  SUBROUTINE PLTINIT
C
  call qcolor(1,3)
  CALL QSMODE(6)
  RETURN
  END
C
C*****
C
C SUBROUTINE SPLT(IX,IY,IHV,LENGTH) PLOTS ON THE STORAGE SCOPE A
C VERTICAL(IHV POSITIVE) LINE OR A HORIZONTAL(IHV NEGATIVE) LINE
C OF LENGTH LENGTH STARTING AT IX AND IY.
C
  SUBROUTINE SPLT(IX,IY,IHV,LENGTH)
C
  IF(IHV)1,2,2
1 NX=IX+LENGTH
  CALL QLINE(IX,IY,NX,IY,1)
  RETURN
2 NY=IY+LENGTH
  CALL QLINE(IX,IY,IX,NY,1)
  RETURN
  END
C*****
C
C SUBROUTINE LINAX DRAWS LINEAR AXES, 32 CHANNEL TICS FOR ABSCISSA.
C
  SUBROUTINE LINAX(NABS,NORD)
C
  CALL SPLT(0,0,1,NORD)
  CALL SPLT(0,0,-1,NABS)
  DEL=FLOAT(NABS)/32.
  LENGTH=NORD/40
  IX=IFIX(DEL)
  I=1
1 CALL SPLT(IX,0,1,LENGTH)
  IX=IFIX(DEL*FLOAT(I+1))
  I=I+1
  IF(I-32)1,1,2
2 RETURN

```

```

      END
C
Cc*****
C
C  SUBROUTINE PLTOUT RETURNS FROM PLOTTING ROUTINES.
C
      SUBROUTINE PLTOUT
C
      CHARACTER*1 CHAR
C  1 format(a)
C    read(*,1) char
      CALL QINPUT(CHAR,0)
      CALL QSMODE(2)
      RETURN
      END
C
Cc*****
C  LEAST SQUARES POLYNOMIAL FIT. M(<=9) IS THE ORDER, N THE ARRAY
SIZE.
      SUBROUTINE LSQPOL(M,N)
C
      DIMENSION A(9,9),PIVOT(9),IPIVOT(9),INDEX(9,2),C(511,9)
      COMMON Y(511),X(511),B(9),W(511)
      EQUIVALENCE(AMAX,T,SWAP),(IROW,JROW),(ICOLUM,JCOLUM)
      DOUBLE PRECISION A,B,AMAX,XI,XN,PIVOT,DETERM,C,T,SWAP
C
      DO 520 I=1,N
520  C(I,1)=1.D 00
      DO530 J=2,M
      DO 530 I= 1,N
530  C(I,J)=C(I,J-1)*X(I)
      DO 560 I = 1,M
      B(I) = 0.0
      DO 550 J = 1,M
      A(I,J) = 0.0
      DO 550 K = 1,N
550  A(I,J) = A(I,J) + C(K,I)*C(K,J)*W(K)
      DO 560 K = 1,N
560  B(I) = B(I) + C(K,I)*Y(K)*W(K)
C
C  INITIALIZATION      (MATINV CALCULATIONS)
C
      DETERM=1.0
      DO 570 J = 1,M
570  IPIVOT(J)=0
C
      DO 690 I=1,M
C
C  SEARCH FOR PIVOT ELEMENT
      AMAX=0.0
      DO620 J=1,M
      IF (IPIVOT(J)-1)580,620,580
580  DO 610 K=1,M

```

```

      IF (IPIVOT(K)-1) 590,610,740
590 IF(DABS(AMAX)-DABS(A(J,K)))600,610,610
600 IROW=J
      ICOLUM=K
      AMAX=A(J,K)
610 CONTINUE
620 CONTINUE
      IPIVOT(ICOLUM)=IPIVOT(ICOLUM)+1
C
C INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
C
      IF (IROW-ICOLUM) 630,650,630
630 DETERM=-DETERM
      DO 640 L=1,M
      SWAP=A(IROW,L)
      A(IROW,L)=A(ICOLUM,L)
640 A(ICOLUM,L)=SWAP
      SWAP = B(IROW)
      B(IROW) = B(ICOLUM)
      B(ICOLUM) = SWAP
650 INDEX(I,1)=IROW
      INDEX(I,2)=ICOLUM
      PIVOT(I)=A(ICOLUM,ICOLUM)
      DETERM=DETERM*PIVOT(I)
C
C DIVIDE PIVOT ROW BY PIVOT ELEMENT
C
      A(ICOLUM,ICOLUM)=1.0
      DO 660 L=1,M
660 A(ICOLUM,L)=A(ICOLUM,L)/PIVOT(I)
      B(ICOLUM) = B(ICOLUM)/PIVOT(I)
C
C REDUCE NON-PIVOT ROWS
C
      DO 690 L1=1,M
      IF(L1-ICOLUM) 670,690,670
670 T=A(L1,ICOLUM)
      A(L1,ICOLUM)=0.0
      DO 680 L=1,M
680 A(L1,L)=A(L1,L)-A(ICOLUM,L)*T
      B(L1) = B(L1) - B(ICOLUM)*T
690 CONTINUE
740 RETURN
C
      END

```

Appendix B: RANY.FOR

```

C*****
C
C      A CODE SEGMENT TO DECODE AND PLOT THE OUTPUT OF
C      RANGE.FOR. ENERGY CALIBRATION IS PROVIDED BY THE
C      KURIE PLOT OF A TRITIUM SPECTRUM PROVIDED BY THE USER
C
C*****
$NODEBUG
$NOFLOATCALLS
C  RANY.FOR
C  TO BE USED WITH AN IBM COMPATIBLE AND RAMP VOLTAGE BIASING.
C  CONVERT C-P(e-) PULSE-HEIGHT SPECTRA TO ENERGY WEIGHTED
C  GAMMA SPECTRUM.
C
C      DIMENSION FLXL(511),ERFL(511),RES(511),RAPS(511),
C      XTIME(511),PAPS(511),ENRGY(511),WHION(511),
C      YWHAMP(511),ETR(511),FRLV(511),taps(511),GAMS(511),
C      Zcode(511),TEPS(511),CHION(511)
C
C      real*8 BETA,DET,TMEP,ET1,CEMAX,delt,ET2,HEAT
C      INTEGER*4 IDUMM
C      CHARACTER FNAME*16,FLNAME*72,IDENT*72,JDENT*72,
C      1PARAM*3,ACC*3,DEFI*6,FFNAM*16
C
C  THE LOG OF ENERGY AT ANY CHANNEL I, ELOG(I), IS RELATED
C  TO I, THE CHANNEL NUMBER, IBS, THE CHANNEL SHIFT FROM
C  RANGE4A, AND THE CALIBRATION FACTOR, CAL, BY
C
C      ELOG(I) = (FLOAT(I+IBS) -1.0 )/64. + CAL
C
C  WHERE CAL = ALOG( (LVL/GMAX)*FSEXA/4096) .
C  ELOG IS THE "IONIZATION" ENERGY, NOT THE "TRUE" ENERGY.
C
C  WE WILL RECONCILE ELOG WITH TRUE ENERGY BE PLOTTING A H3
C  DECAY SPECTRUM ON THE SAME SCALE AND INTERCOMPARING THE
C  KNOWN ENERGY OF THE DECAY END-POINT AND THE SCALE
C
C  FSEXA IS THE PRODUCT OF THE FULL-SCALE ENERGY AND
C  MULTIPLICATION A. FSEXA IS FIXED AND MUST BE IDENTICAL
C  FOR ALL A VALUES. LVL IS THE ADC Y CHAN BIAS AND MAXG IS
C  THE MAXIMUM GAS GAIN.
C
C  FROM THE ENERGY E AND THE SLOPE TAKING FULL FRACTIONAL WIDTH FW AS
C
C      FWHM(E)=SQRT(FW*FW+0.17/E)
C
C  1 FORMAT(37H INPUT FILE NAME FOR THE HEADER DATA. )
C  2 FORMAT(6E12.5)
C  3 FORMAT(8F8.0)
C  4 FORMAT(10F8.1)
C  5 FORMAT(///16H  RMPSNS OUTPUT. //)
C  7 FORMAT(10F8.2)

```

```

8 FORMAT(44H INPUT(I5) IGO NEGATIVE TO DELETE DISC SAVE. )
9 FORMAT(/9H ENERGY,10H FLUX,11H ERROR,10H RESLN.
)
10 FORMAT(I5)
11 FORMAT(/32H TOTAL POINTS AND STARTING POINT 2I8/
X17H ADC Y-BIAS LEVEL I8 /
X19H MAXIMUM GAS GAIN = E12.5/
X26H THE RUN TIME IN SECONDS = I8 /
X34H THE CALIBRATION TIME IN SECONDS = I8 //)
12 FORMAT(40H INPUT A 10 CHAR. HEADER DATA FILE NAME. )
13 FORMAT(A)
14 FORMAT(7H MAX= E11.4)
15 FORMAT(47H INPUT A 10 CHAR. RECOIL-PROTON DATA FILE NAME. )
16 FORMAT(18H FRST DEC = 1 KEV )
17 FORMAT(51H INPUT(E12.5) THE REFERENCE CALIBRATION ENERGY ERF. /
X53H THEN INPUT(D15.8/) THE TOP 5 POLYNOMIAL COEFFICIENTS /
X60H IN AN M=6 LSQPOL FIT TO THE RATIO OF THE OBSERVED VARIATION
/
X52H OF NEUTRON SPECTRUM (PER LETHARGY) TO THE ERF VALUE /
X36H AS A FUNCTION OF X=LOG(ENERGY/ERF). /)
18 FORMAT(2I8)
19 FORMAT(F10.3,E11.4,E10.3,F6.3)
20 FORMAT(45H INPUT A 10 CHARACTER FILE NAME FOR THE SAVED /
X24H FINAL NEUTRON SPECTRUM. )
21 FORMAT( ' INPUT THE FILE NAME FOR THE CALIBRATION SPECTRUM ' )
22 FORMAT(/51H LIST ENERGIES AND THEN LIST PROTON
SPECTRA(/LETHY)//)
23 FORMAT(4D15.8)
24 FORMAT(10F8.3)
25 FORMAT(8E10.4)
950 FORMAT(37H INPUT(E12.5) THE ENERGY SCALE FSEX.A.)
951 FORMAT(45H INPUT(E12.5) THE HYDROGEN ATOM CONTENT HATM.)
952 FORMAT(35H THE LOGGED TEST PULSE COUNTS/SEC = E12.5 /
X28H INPUT(E12.5) CORRECT VALUE. )
953 FORMAT(43H INPUT(E12.5) UPPER ENERGY LIMIT IN OUTPUT. )
1001 FORMAT(16I5)
9091 FORMAT(A6)
C
NABS=720
NORD=348
C INPUT THE SPECTRUM OF C-P RECOILS GAMS AND THE TEST
C PULSER SPECTRUM TIME TOGETHER WITH OTHER DATA AS PRODUCED
C BY THE ANALYSIS OF THE RAW DATA IN RANGE.FOR
C
DO 7311 J=1,511
RAPS(J)=0.0
FLXL(J)=0.0
RES(J)=0.0
ERFL(J)=0.0
TIME(J)=0.0
PAPS(J)=0.0
ENRGY(J)=0.0
WHION(J)=0.0

```



```

        CHION(J)=0.0
        GAMS(J)=0.0
        TAPS(J)=0.0
        FRLV(J)=0.0
        ETR(J)=0.0
        WHAMP(J)=0.0
        CODE(J)=0.0
        TEPS(J)=0.0
7311 CONTINUE
165 WRITE(*,15)
    READ(*,13) FNAME
    OPEN(10,FILE=FNAME,FORM='FORMATTED',STATUS='OLD')
    READ(10,13) FNAME
    READ(10,13) IDENT
    WRITE(*,13) FNAME
    WRITE(*,13) IDENT
C   NPT AND IBS ARE THE TOTAL POINTS AND THE STARTING POINT.
    READ(10,18) NSEC
    READ(10,1001) NPT
    READ(10,1001) IBS
    READ(10,18) LVL
    READ(10,2) GMAX
    READ(10,9091) DEFI
    READ(10,2) (GAMS(I),I=1,NPT)
    READ(10,2) (RAPS(I),I=1,NPT)
    READ(10,7) (TIME(I),I=1,NPT)
    CLOSE(10)
C
C.....GET RID OF THE NONSENSE NUMBERS...
C
C      DO 6715 I=1,NPT
C          IF(TIME(I).LE.0.0)TIME(I)=1.0
C          IF(GAMS(I).LE.0.0)GAMS(I)=0.0
C6715 CONTINUE
C
C
C      WRITE(*,1831)GMAX,ibs
1831 FORMAT(6X,' GMAX is',E12.5,'ibs is',i4)
C
C*****
C READ THE CALIBRATION SPECTRA. THESE INCLUDE BOTH 'WHITE
C IONIZATION' WHION, AND 'WHITE AMPLITUDE' WHAMP AS
C DERIVED FROM THE SPECIAL TEST PULSE CALIBRATION RUN
C OPTION IN RAMPDA.
C
    WRITE(*,21)
    READ(*,13) FLNAME
    OPEN(10,FILE=FLNAME,FORM='FORMATTED',STATUS='OLD')
    READ(10,13) FLNAME
    READ(10,13) JDENT
    WRITE(*,13) FLNAME
    WRITE(*,13) JDENT
    READ(10,18) KSEC

```

```

      READ(10,2) CPS
      READ(10,18) NNII
      READ(10,2) GGGG
      READ(10,2) (WHION(I),I=1,511)
      READ(10,3) (WHAMP(I),I=1,511)
      CLOSE(10)
      WRITE(*,11) NPT,IBS,LVL,GMAX,NSEC,KSEC
C
C RE-ENTER CPS. VALUE FROM CALIBRATION MAY BE INCORRECT IF RAMP
C RANGE LIMITS EXCEED TABLE LIMITS.
      WRITE(*,952) CPS
      READ(*,2) CPS
C
C INPUT DATA WHICH INCLUDES THE FOLLOWING:
C 1) A VALUE FOR THE PRODUCT OF FULL-SCALE ENERGY AND
C GAS MULTIPLICATION, FSEX. FSEX IS A CONSTANT FOR ALL A.
C FROM IT, THE QUANTITY CAL IS DERIVED TO ALLOW CONVERSION
C OF THE LOG CHANNEL SCALE APPROPRIATE TO THE RAW DATA TO
C LOG ENERGY. USING FSEX, CAN FORM THE "IONIZATION"
C ENERGY MESH, ENRGY(I).
C
      WRITE(*,950)
      READ(*,2) FSEX
      CAL = ALOG((FLOAT(LVL)/GMAX)*FSEX/4096.)
C
C ASSUME A W CUTOFF, WCUTOFF, OF .3 KEV FOR GAS.
C
      WCUTOFF=.3
      DO705 I=1,NPT
705 ENRGY(I)=(exp(elog(i)-1.001534)+WCUTOFF)
      ETOP=ENRGY(NPT)
      EBOT=ENRGY(1)
C
      WRITE(*,2831)EBOT
      WRITE(*,2831)ETOP
      2831 format(6X,'EBOT/ETOP IS',E12.5)
C***** plots the raw data generated by RANGE *****
C
      PAUSE ' PLOT GAMS '
      CALL PLARRAY(GAMS,NPT,EBOT,ETOP)
C
C***** plots the time array generated by rmpdna ****
C
      PAUSE ' PLOT TIME '
      CALL PLARRAY(TIME,NPT,EBOT,ETOP)
C
C SHIFT THE CALIBRATION SPECTRUM TO CONFORM WITH IBS AS THE
C INITIAL POINT AND NPT AS THE POINT COUNT; SAME AS FOR THE
C DATA SPECTRUM. EDIT THE DATA USING PLOT ROUTINE.
C
      DO3000 I=1,NPT
      II=I+IBS-1
      WHION(I)=WHION(II)

```

```

3000 WHAMP(I)=WHAMP(II)
      PAUSE ' PLOT WHAMP '
      CALL PLARRAY(WHAMP,NPT,EBOT,ETOP)
C
C WEIGHT WHION USING AN ARBITRARY ENERGY-DEPENDENT TERM TO
C REDUCE DEPENDENCE UPON CHANNEL NUMBER I. THEN PLOT.
C
      DO2888 I=1,NPT
      II=I+IBS-1
      AMUL=EXP(FLOAT(II)/64.)
2888 WHION(I)=WHION(I)/AMUL
      PAUSE ' PLOT CHANNEL-WEIGHTED WHION '
      CALL PLARRAY(WHION,NPT,EBOT,ETOP)
C
C SMOOTH THE TIME SPECTRUM AND PLOT.
      CALL SMOOTH(TIME,NPT)
      PAUSE ' PLOT THE SMOOTHED TIME SPECTRUM '
      CALL PLARRAY(TIME,NPT,EBOT,ETOP)
C
C NORMALIZE THE DATA SPECTRUM TO SMOOTHED TIME SPECTRUM.
C THEN PLOT THE TIME NORMALIZED DATA SPECTRUM.
C
      DO2806 I=1,NPT
2806 PAPS(I)=GAMS(I)/TIME(I)
      PAUSE ' PLOT THE TIME NORMALIZED SPECTRUM '
      CALL PLARRAY(PAPS,NPT,EBOT,ETOP)
C
C FORM THE CALIBRATION RATIO WHION/WHAMP AND DENOTE BY
C FRLV. SMOOTH AND PLOT.
C
      DO1709 I=1,NPT
1709 FRLV(I)=WHION(I)/WHAMP(I)
      CALL SMOOTH(FRLV,NPT)
      PAUSE ' PLOT SMOOTHED CALIBRATION RATIO '
      CALL PLARRAY(FRLV,NPT,EBOT,ETOP)
C
C FORM THE CALIBRATION-CORRECTED ABSOLUTE DATA SPECTRUM
C PER UNIT ENERGY. USE THE TEST PULSER COUNTS/SEC CPS TO
C SCALE FLUX TO AN ABSOLUTE VALUE. ALSO REQUIRE ENERGY,FSE,
C CORRESPONDING TO ACTIVE COUNTING REGION, WHICH IS 4096-
C LVL RATHER THAN FULL 4096.
C
      FSE=FSEXA*FLOAT(4096-LVL)/4096.
      DO1890 I=1,NPT
1890 GAMS(I)=CPS*GAMS(I)/(FSE*FRLV(I))
      PAUSE ' PLOT NORMALIZED(NOT TIME)GAMS SPECTRUM WITH
X CHANNEL WEIGHTING '
      CALL PLARRAY(GAMS,NPT,EBOT,ETOP)
C
      DO1823 I=1,NPT
1823 PAPS(I)=CPS*PAPS(I)/(FSE*FRLV(I))
      PAUSE ' PLOT NORMALIZED SPECTRUM WITH CHANNEL WEIGHTING '
      CALL PLARRAY(PAPS,NPT,EBOT,ETOP)

```

```

CALL PLTOUT
C
  PAUSE ' PRINTER IF WANT TO SAVE OUTPUT. '
  WRITE(*,5)
  WRITE(*,13) FNAME
  WRITE(*,13) IDENT
  WRITE(*,9)
  DO723 I=1,NPT
723  WRITE(*,19) ENRGY(I),GAMS(I),ERFL(I),RES(I)
      WRITE(*,22)
      WRITE(*,25) (ETR(I),I=1,NPT)
      WRITE(*,25) (GAMS(I),I=1,NPT)
C
C  SAVE DATA ON DISC OR DELETE SAVE IF IGO NEG.
  WRITE(*,8)
  READ(*,10) IGO
  IF(IGO)165,718,718
718  WRITE(*,20)
      READ(*,13) FNAME
      OPEN(10,FILE=FNAME,STATUS='NEW')
      WRITE(10,13) FNAME
      WRITE(10,13) IDENT
      WRITE(10,10) NPT
      DO724 I=1,NPT
          WRITE(10,725) I,ENRGY(I),PAPS(I),GAMS(I)
724  CONTINUE
725  FORMAT(4X,I3,2X,3(E12.6,2X))
      CLOSE(10)
C
  GO TO 165
  END
C
C  THE ROUTINE SMOOTH(ASMTH,NPT) PRODUCES THE SMOOTHED ARRAY ASMTH
C  FROM THE INPUT ARRAY. ARRAY CONTAINS NPT POINTS.
C
  SUBROUTINE SMOOTH(ASMTH,NPT)
  DIMENSION ASMTH(511),RES(511)
C
C  SMOOTH THE ARRAY ASMTH TWICE OVER 5 ADJACENT POINTS.
  KKK=-2
184  DO179 I=1,NPT
179  RES(I)=ASMTH(I)
      ASMTH(1)=RES(1)
      ASMTH(2)=(RES(1)+RES(2)+RES(3))/3.
      ASMTH(NPT)=RES(NPT)
      ASMTH(NPT-1)=(RES(NPT)+RES(NPT-1)+RES(NPT-2))/3.
      I=3
173  IMIN=I-2
      IMAX=I+2
      IF(IMAX-NPT)170,170,180
170  DMM=0.0
      DO172 J=IMIN,IMAX
172  DMM=DMM+RES(J)

```

```

        ASMTI(I)=DMM/5.
        I=I+1
        GO TO 173
180 KKK=KKK+1
        IF(KKK)184,183,183
183 RETURN
        END
C
C SUBROUTINE PLARRAY SCALES AND PLOTS THE ARRAY TEMP.
C
        FUNCTION PLARRAY(TEMP,NPT,EBOT,ETOP)
C
        DIMENSION TEMP(511)
        1 FORMAT(27H INPUT (F8.1) ENERGY MARKER )
        2 FORMAT(F8.1)
        3 FORMAT(16H ENERGY LIMITS = 2F8.1)
        4 FORMAT(16H ENERGY MARKER = F8.1)
C NABS AND NORD ARE X AND Y POINTS AVAILABLE FOR PLOTTING.
C NABS=640
C NORD=200
C GET MAXIMUM VALUE OF SPECTRUM FOR PLOT NORMALIZATION.
        PMAX=0.0
        DO30 I=1,NPT
            IF(TEMP(I)-PMAX)30,30,31
31 PMAX=TEMP(I)
30 CONTINUE
C INITIALIZE TO PLOT THE CONTENTS OF THE TEMP ARRAY.
33 WRITE(*,1)
        READ(*,2) ENGY
        IF(ENGY)34,34,35
35 IF(ENGY-EBOT)33,36,36
36 IF(ENGY-ETOP)37,37,33
37 CALL PLTINIT
        WRITE(*,3) EBOT,ETOP
        WRITE(*,4) ENGY
        NDEK=2
        CALL LINLOGAX(NABS,NORD,NDEK)
C PLOT THE TIME NORMALIZED SPECTRA.
        DO32 I=1,NPT
            LYY=IFIX(.95*TEMP(I)*FLOAT(NORD)/PMAX)
            LXX=IFIX(FLOAT(I)*FLOAT(NABS)/FLOAT(NPT))
32 CALL SPLT(LXX,LYY,1,1)
            LXX=IFIX(FLOAT(NABS)*ALOG(ENGY/EBOT)/ALOG(ETOP/EBOT))
            CALL SPLT(LXX,0,1,NORD)
            CALL PLTOUT
            GO TO 33
34 RETURN
        END
C
C ROUTINE LINLOGAX(NABS,NORD) DRAWS A VERTICAL MARKER AND A
C HORIZONTAL LOGARITHMIC MARKER OVER NDEK DECADES.
C
        FUNCTION LINLOGAX(NABS,NORD,NDEK)

```

```

C
C FIRST DRAW VERTICAL TICKS.
  CALL SPLT(0,0,1,NORD)
  IDEL=NORD/10
  LENGTH=NABS/40
  IY=IDEL-1
  DO1 I=1,10
    CALL SPLT(0,IY,-1,LENGTH)
  1 IY=IY+IDEL
C THEN DRAW HORIZONTAL LOGARITHMIC TICKS.
  CALL SPLT(0,0,-1,NABS)
  IDEL=NABS/NDEK
  SCL=FLOAT(IDEL)
  LENGTH=NORD/25
  IX=IDEL-1
  DO2 I=1,NDEK
    CALL SPLT(IX,0,1,LENGTH)
  2 IX=IX+IDEL
    IX=IFIX(SCL*ALOG(2.)/ALOG(10.))-1.)
    LENGTH=LENGTH/2
    DO3 I=1,NDEK
      CALL SPLT(IX,0,1,LENGTH)
  3 IX=IX+IDEL
    IX=IFIX(SCL*ALOG(4.)/ALOG(10.))-1.)
    DO4 I=1,NDEK
      CALL SPLT(IX,0,1,LENGTH)
  4 IX=IX+IDEL
    IX=IFIX(SCL*ALOG(8.)/ALOG(10.))-1.)
    DO5 I=1,NDEK
      CALL SPLT(IX,0,1,LENGTH)
  5 IX=IX+IDEL
  RETURN
  END

C
C FUNCTION PLTINIT INITIALIZES PLOTTING ROUTINES.
C
  FUNCTION PLTINIT
C
  CALL QSMODE(6)
  RETURN
  END

C
C SUBROUTINE SPLT(IX,IY,IHV,LENGTH) PLOTS ON THE SCREEN A
C VERTICAL(IHV POSITIVE) LINE OR A HORIZONTAL(IHV NEGATIVE) LINE
C OF LENGTH LENGTH STARTING AT IX AND IY.
C
  FUNCTION SPLT(IX,IY,IHV,LENGTH)
C
  IF(IHV)1,2,2
  1 NX=IX+LENGTH
    CALL QLINE(IX,IY,NX,IY,1)
    RETURN
  2 NY=IY+LENGTH

```

```

        CALL QLINE(IX,IY,IX,NY,1)
        RETURN
    END
C
C
C FUNCTION PLTOUT RETURNS FROM PLOTTING ROUTINES.
C
    FUNCTION PLTOUT
C
    CHARACTER CHAR
C 1 FORMAT(A)
C    READ(*,1) CHAR
    CALL QINPUT(CHAR,0)
    CALL QSMODE(2)
    RETURN
    END

```



```

C          DISTRIBUTION ARISING FROM A GAMMA SPECTRUM;
C          TRED(T) IS JUST THE SUM OVER T OF RED(T;E):
C
C          TRED(T) = SUM { RED(T;E) } FROM 0 TO T=E'
C          E' = E(2A/(1+2A))
C.....
C
C          PROGRAM TDIST
C          IMPLICIT REAL*8(A-H,O-Z)
C          DIMENSION E(10),PE(10,951),GAMMA(10),RED(10,951),
C          1TRED(951),ALPHA(10),ALP2(10),CONST(10),T(951),
C          2DPE(10,951),SM(951)
C          CHARACTER FILENM*20,HEADER*64,MORE*1
C
C          200  FORMAT(6X,'WHAT IS THE ENERGY OF GAMMA GROUP',2X,
C          +I3,'IN keV')
C          201  FORMAT(F10.4)
C          202  FORMAT(8X,'INPUT OUT FILE NAME(CR) INPUT HEADER(CR)')
C          203  FORMAT(A16)
C          204  FORMAT(A64)
C          205  FORMAT(I3,E12.4,E12.4)
C          206  FORMAT(3x,'num is',I4)
C          208  FORMAT(6X,'WHAT IS THE FLUX OF GAMMA GROUP',2X,
C          +I3,'IN #/cm2-DT-sec')
C          209  FORMAT(E12.4)
C          210  FORMAT(4X,'ARE MORE GAMMA SPECTRA FORTHCOMING (Y/N)')
C          211  FORMAT(A1)
C
C          C..... INITIALIZE THE ARRAYS
C
C          DO 100 I = 1,10
C             E(I) = 0.0
C             GAMMA(I) = 1.0
C             ALPHA(I) = 0.0
C             CONST(I) = 0.0
C             ALP2(I) = 0.0
C             TRED(I) = 0.0
C             DO 100 J = 1,951
C                T(J) = 0.0
C                SM(J) = 0.0
C                PE(I,J) = 0.0
C                RED(I,J) = 0.0
C                DPE(I,J) = 0.0
C          100  CONTINUE
C
C          C..... READ IN THE GAMMA ENERGY GROUP STRUCTURE IN keV
C
C          DO 101 I = 1,10
C             WRITE(*,200)I
C             READ(*,201)E(I)
C          101  CONTINUE

```

```

C
C..... SET UP THE PE(E;T) CALCULATION
C
DO 300 I = 1,10
  ALPHA(I) = E(I)/511.0
  ALP2(I) = (ALPHA(I))**2
  CONST(I) = (4.577311/(ALP2(I)*511.0))
  AP = 2.0*ALPHA(I)
  CORE = AP/(1.0+AP)
  NUM = 1 + INT(E(I)*CORE/10.0)
  WRITE(*,206)NUM
C
DO 301 J = 1,NUM
  T(J) = (J-1)*10.0
  S1 = ( (T(J)+0.01)/(E(I)-T(J)+0.01) )
  S12 = (S1)**2
  S2 = (E(I)-T(J))/E(I)
  S3 = 2.0/(ALPHA(I)*S1)
  S4 = 1.0/ALP2(I)
  DPE(I,J)=CONST(I)*(2.0+S12*(S4+S2-S3))*E(I)
  PE(I,J)=DPE(I,J)
301 CONTINUE
C
DO 302 J = 1,NUM
  NER = INT(T(J)/10.0) + 1
  EM = 0.0
  DO 303 J1 = 1,NER
    COEFF = 4.0
    IF(MOD(J1,2).NE.0)COEFF = 2.0
    IF(J1.EQ.1.OR.J1.EQ.NER)THEN
      SM(J1)=DPE(I,J1)
    ELSE
      SM(J1)=COEFF*DPE(I,J1)
    ENDIF
    EM=EM+(SM(J1)*10.0/3.0)
303 CONTINUE
  PE(I,J) = EM
C 302 CONTINUE
300 CONTINUE
C
700 CONTINUE
C ***** READ IN THE GAMMA FLUX PER DT REACTION **
DO 102 I = 1,10
  WRITE(*,208)I
  READ(*,209)GAMMA(I)
102 CONTINUE
C
C MAKE UP THE BASIS ARRAY FOR THE GAMMA SPECTRUM
C
DO 306 I = 1,10
  DO 306 J= 1,NUM
    RED(I,J) = GAMMA(I)*PE(I,J)
306 CONTINUE

```

```

C      DO 304 J2 = 1,951
        TRED(J2)=RED(1,J2)+RED(2,J2)+RED(3,J2)+RED(4,J2)+
        1RED(5,J2)+RED(6,J2)+RED(7,J2)+RED(8,J2)+RED(9,J2)+
        2RED(10,J2)
304    CONTINUE
C
C..... OK THE ELECTRON DISTRIBUTION IN ENERGY IN 10 keV
C      INTERVALS ARE FOUND
C
        WRITE(*,202)
        READ(*,203)FILENM
        READ(*,204)HEADER
        OPEN(7,FILE=FILENM,STATUS='NEW')
        WRITE(7,203)FILENM
        WRITE(7,204)HEADER
        DO 305 J2 = 1,951
            WRITE(7,205)J2,T(J2),TRED(J2)
305    CONTINUE
        CLOSE(7)
        WRITE(*,210)
        READ(*,211)MORE
        IF(MORE.EQ.'Y'.OR.MORE.EQ.'y')GOTO 700
        STOP
        END

```

Appendix D: SPASM.FOR

```

C*****
C
C
C      PROGRAM SPASM.FOR
C
C      THIS CODE SEGMENT WILL CALCULATE FROM THE SOURCE
C      ELECTRON DISTRIBUTION FROM THE COMPTON INDUCED RECOIL
C      ELECTRON DISTRIBUTION FOUND IN TDIST.FOR AND THE
C      APPROPRIATE ELECTRON MASS STOPPING POWER RATIO, THE
C      SPECTRUM AVERAGED MASS STOPING POWER.
C
C      THE ELECTRON MASS STOPPING POWER RATIO IS FOR Fe
C      AND Ar
C
C      THIS SPECTRUM AVERAGED MASS STOPPING POWER IS GIVEN BY:
C
C      SX/RHO =  INTEGRAL[ T*PHI(T)*{S(T)/RHO}dT]
C                FROM 0 TO Ttop/ INTEGRAT[ T*PHI(T)dT]
C
C      {S(T)/RHO} IS THE ELECTRON MASS STOPPING POWER, AND IT
C      IS GIVEN BY INTERPOLATION OF THE VALUES IN ICRU#37
C      THESE HAVE TO BE READ IN FROM DISK.
C
C      THE OUTPUT ARRAY IS TO BE WRITTEN TO FILE, WITH A
C      RECURSIVE LOOP.
C*****
C
C      PROGRAM SPASM
C      IMPLICIT REAL*8(A-H,O-Z)
C      DIMENSION SOURCE(951),STOP(951),F1(951),F2(951),
C      IDUM1(951),DUM2(951)
C      CHARACTER FILENM*16,FILNAM*16,FILOUT*16,HEADER*64,
C      ICOMMENT*64,HEADR2*64,MASS*1,GAMMA*1
C
C200  FORMAT(4X,'WHAT IS THE NAME OF THE FLUX SOURCE FILE?')
C201  FORMAT(A16)
C202  FORMAT(A64)
C203  FORMAT(I3,E12.4,E12.4)
C2030 FORMAT(E11.3)
C204  FORMAT(4X,'WHAT IS THE STOPPING POWER FILE CALLED?')
C205  FORMAT(4X,'GIVE A NAME FOR THE AVERAGED POWER')
C206  FORMAT(4X,'WRITE IN SOME IDENTIFYING COMMENTS')
C207  FORMAT(3X,'THE AVERAGED STOPPING POWER IS: ',E12.4)
C701  FORMAT(A1)
C702  FORMAT(2X,'TRY ANOTHER SOURCE ELECTRON SPECTRUM?
(Y/N)')
C703  FORMAT(2X,'THE VALUE OF SAFF IS: ',E12.4)
C
C      DO 100 J = 1,951
C          SOURCE(J) = 0.0

```

```

        STOP(J) = 0.0
        F1(J) = 0.0
        F2(J) = 0.0
        IDUM1(J) = 0
        DUM2(J) = 0.0
100  CONTINUE
C
C..... READ IN THE STOPPING POWER FOR X .....
C
800  CONTINUE
      WRITE(*,204)
      READ(*,201)FILNAM
      OPEN(7,FILE=FILNAM)
      READ(7,201)FILNAM
      READ(7,202)HEADR2
      DO 401 J = 1,951
      READ(7,2030)STOP(J)
401  CONTINUE
      CLOSE(7)
C
C..... READ IN THE SOURCE TERM (TDIST.FOR OUTPUT) ....
C
900  CONTINUE
      WRITE(*,200)
      READ(*,201)FILENM
      OPEN(7,FILE=FILENM)
      READ(7,201)FILENM
      READ(7,202)HEADER
      DO 400 J = 1,951
      READ(7,203)IDUM1(J),DUM2(J),SOURCE(J)
400  CONTINUE
      CLOSE(7)
C
C..... SET UP THE INTEGRATION .....
C
        SR = 0.0
        SAR = 0.0
        SM = 0.0
        SAM = 0.0
        SAFF = 0.0
        DO 301 J = 1,951
          F1(J) = SOURCE(J)*STOP(J)*DUM2(J)
          F2(J) = SOURCE(J)*DUM2(J)
          COEFF = 4.0
          IF(MOD(J,2).NE.0)COEFF = 2.0
          IF(J.EQ.1.OR.J.EQ.951)THEN
            SM = SM + F1(J)
            SAM = SAM + F2(J)
          ELSE
            SM = SM + (COEFF*F1(J))
            SAM = SAM + (COEFF*F2(J))
          ENDIF
301  CONTINUE

```

```
SR = SR + ((SM*10.0)/3.0)
SAR = SAR + ((SAM*10.0)/3.0)
SAFF = SR/SAR
```

C

C... OUTPUT THE SPECTRUM AVERAGED MASS STOPPING POWER

C

```
WRITE(*,205)
READ(*,201)FILOUT
WRITE(*,206)
READ(*,202)COMMENT
OPEN(8,FILE=FILOUT,STATUS='NEW')
WRITE(8,201)FILOUT
WRITE(8,202)COMMENT
WRITE(8,207)SAFF
CLOSE(8)
WRITE(*,703)SAFF
WRITE(*,702)
READ(*,701)GAMMA
IF(GAMMA.EQ.'Y'.OR.GAMMA.EQ.'y')GOTO 900
STOP
END
```

Appendix E: KNISH.FOR

```

C*****
C
C
C      A SHORT PROGRAM TO GENERATE KLEIN-NISHINA CROSS SECTIONS
C
C      ALL DATA TAKEN FROM ROBLEY D. EVANS IN RADIATION DOSIMETRY
C
C      SIGMAE = (8*Pi*r**2)/3 * {1-2*ALPHA+(26*ALPHA**2)/5-
C              (133*ALPHA**3)/10+(1144*ALPHA**4)/35-
C              (544*ALPHA**5)/7 + (3784*ALPHA**6)/21}
C      FOR ALPHA < 5
C
C      SIGMAE = Pi*r**2 * { 1 + 2LN(2*ALPHA)}/(2*ALPHA)
C
C      FOR ALPHA > 5.....WHERE ALPHA = E/5.11E+5 eV C
C
C      SIGMAA = (8*r**2)/3 * { ALPHA - 4.2*ALPHA**2 + 14.7*ALPHA**3
C              - 46.1714*ALPHA**4 + 134.286*ALPHA**5
C              - 369.143*ALPHA**6}.....ALPHA < 5
C
C      SIGMAA + (2Pi*R**2) ( (2*(1+ALPHA)**2/( (1+2ALPHA)ALPHA**2)) -
C              ( (1+3ALPHA)/(1+2ALPHA)**2) -
C              ( (1+ALPHA)*(2ALPHA**2-2ALPHA-1)/
C              (ALPHA**3(1+2ALPHA)**2) ) -
C              ( 4ALPHA**2/(3(1+2ALPHA)**3) ) -
C              ( ((1+ALPHA)/ALPHA**3) - (1/2ALPHA)
C              + (1/2ALPHA**3) ) * LN(1+2ALPHA) )
C
C      FOR ALPHA > 5
C
C      ALL IN UNITS OF CM/ELECTRON
C
C      THE AVERAGE RECOIL ELECTRON ENERGY IS THEN:
C
C      T(E)= E*(SIGMAA(E)/SIGMAE(E))
C
C      THIS PROGRAM WILL GENERATE THE SIGMAS FROM USER SUPPLIED
C      E 's, IT WILL ALSO GENERATE T(E) FOR A GIVEN MATERIAL
C      FROM USER SUPPLIED ELEMENT #.
C
C      THIS PROGRAM IS GOOD FOR 5 ISOTOPES AT 100 ENERGY
C      POSITIONS EACH.....
C*****
C
C
C      PROGRAM KNISHIN
C      IMPLICIT REAL*8(A-H,O-Z)
C      DIMENSION A(100),SIGMAA(100),SIGMAE(100),
C      +T(100),ENRGY(100),A2(100),A3(100),A4(100),
C      +A5(100),A6(100),AL1(100),AL2(100),AL3(100),LABEL(5)
C      CHARACTER FNAME*16,LABEL*16
C      INTEGER NUM,I,J,I1,J1,NEGP,IZ(5)

```

```

C
C      INITIALIZE ARRAYS
C
      Pi = 3.1416
      R = 7.941124E-26
      S1B = 8.0*Pi*R/3.0
      S2A = 2.0*Pi*R
      S2B = Pi*R
C
      DO 1200 J=1,100
          A(J) =0.0
          A2(J)=0.0
          A3(J)=0.0
          A4(J)=0.0
          A5(J)=0.0
          A6(J)=0.0
          SIGMAA(J)=0.0
          SIGMAE(J)=0.0
          T(J)=0.0
          AL1(J)=0.0
          AL2(J)=0.0
          AL3(J)=0.0
1200      CONTINUE
C
C      LETS INPUT SOME DATA
C
      WRITE(*,100)
      READ(*,101)NEGP
      WRITE(*,102)
      READ(*,103)NUM
100      FORMAT(6X,'PLEASE SUPPLY THE NUM OF ENERGY GROUPS')
101      FORMAT(I3)
102      FORMAT(6X,'PLEASE SUPPLY THE NUMBER OF ELEMENTS')
103      FORMAT(I2)
C
      DO 1219 I1=1,NUM
          WRITE(*,131)I1
          READ(*,132)IZ(I1),LABEL(I1)
1219      CONTINUE
          DO 1209 J1=1,NEGP
              WRITE(*,104)J1
              READ(*,105)ENRGY(J1)
1209      CONTINUE
104      FORMAT(6X,'PLEASE GIVE ENERGY IN eV AT GROUP ',I3)
105      FORMAT(E10.4)
131      FORMAT(6X,'PLEASE GIVE THE ATOMIC # AND LABEL OF ELEMENT
#',I2)
132      FORMAT(I3,/,A16)
C
      DO 1202 J1=1,NEGP
          A(J1) = (ENRGY(J1)/5.11E+05)
          A2(J1)=A(J1)**2.0
          A3(J1)=A(J1)**3.0

```



```

A4(J1)=A(J1)**4.0
A5(J1)=A(J1)**5.0
A6(J1)=A(J1)**6.0
AL1(J1)=(1.0+A(J1))
AL2(J1)=(1.0+(2.0*A(J1)))
AL3(J1)=(1.0+(3.0*A(J1)))
1202 CONTINUE
C
DO 1203 J1=1,NEGP
  IF(A(J1).LE.0.25)THEN
C
    TERM1=(4.20*A2(J1))
    TERM2=(14.7*A3(J1))
    TERM3=(46.1714*A4(J1))
    TERM4=(134.286*A5(J1))
    TERM5=(369.143*A6(J1))
    TERM6=(A(J1)-TERM1+TERM2-TERM3+TERM4-TERM5)
    SIGMAA(J1)=(S1B*TERM6)
C
    SERM1=(2.0*A(J1))
    SERM2=(5.2*A2(J1))
    SERM3=(13.3*A3(J1))
    SERM4=(32.6857*A4(J1))
    SERM5=(77.7143*A5(J1))
    SERM6=(180.19*A6(J1))
    SERM7=(SERM2-SERM1-SERM3+SERM4-SERM5+SERM6+1.0)
    SIGMAE(J1)=(S1B*SERM7)
C
    T(J1)=(ENRGY(J1)*(SIGMAA(J1)/SIGMAE(J1)))
C
C
    ELSEIF(A(J1).GT.0.25)THEN
C
C
C
C
    UERM1=AL1(J1)**2
    UERM2=AL2(J1)**2
    U1=((2.0*UERM1)/(A2(J1)*AL2(J1)))
    U2=(AL3(J1)/UERM2)
    U3=(2.0*A2(J1)-2.0*A(J1)-1.0)
    U4=((AL1(J1)*U3)/(A2(J1)*UERM2))
    U5=(4.0*A2(J1))/(3.0*AL2(J1)*UERM2)
    U6=DLOG(AL2(J1))
    U7=(1.0+A(J1))/A3(J1)
    U8=1.0/(2.0*A(J1))
    U9=1.0/(2.0*A3(J1))
    U10=U9-U8+U7
    U11=U10*U6
    SIG=U1-U2-U4-U5-U11
    SIGMAA(J1)=S2A*SIG
C
    B2=2.0*A(J1)
    B3=DLOG(B2)

```

```

        SIGMAE(J1)=(S2B*(1.0+2.0*B3)/B2)
C
        T(J1) = ENRGY(J1)*(SIGMAA(J1)/SIGMAE(J1))
C
        ENDIF
1203  CONTINUE
C
C        PUT OUTPUT INTO AN ASCII FILE
C
        WRITE(*,120)
        READ(*,121)FNAME
        OPEN(7,FILE=FNAME,STATUS='NEW')
        WRITE(7,121)FNAME
        DO 1300 I1=1,NUM
            WRITE(7,122)IZ(I1),LABEL(I1)
            WRITE(7,110)
            Z=DBLE(IZ(I1))
            DO 1204 J1=1,NEGP
                SGMAA=Z*SIGMAA(J1)
                SGMAE=Z*SIGMAE(J1)
                SGXT=SGMAE*T(J1)
                WRITE(7,111)J1,ENRGY(J1),SGMAA,SGMAE,T(J1),SGXT
1204  CONTINUE
1300  CONTINUE
120  FORMAT(6X,'PLEASE GIVE A NAME FOR THE OUTPUT FILE')
121  FORMAT(/,A16)
122  FORMAT(6X,'DATA FOR ELEMENT NUMBER:',I3,2X,A16)
110  FORMAT(1X,'GROUP    ENERGY eV          SIGMAA          SIGMAE
+      T          SGXT')
111  FORMAT(4X,I2,5(1X,E10.4))
        CLOSE(7)
        STOP
        END

```

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