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# REACTOR GAMMA SPECTROMETRY: STATUS

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## I. INTRODUCTION

In reactor environments, the radiation field is comprised of two principal components, neutrons and gamma-rays. The history of reactor development reveals an initial concern for the neutron component of the radiation field that was virtually overriding. Such an initial emphasis is, of course, completely understandable. After all, fission reactors are neutron chain multiplying assemblies and only after a considerable amount of time were significant effects due to the gamma-ray component in reactor design, shielding, and safety actually recognized. Recognition of these effects has provided the impetus for improved characterization of reactor gamma-ray energy deposition and spectra. These general motivations have been summarized in a review paper presented at the second of this on-going series of ASTM-EURATOM international symposia.[1]

In contrast with these general motivations, more specialized needs often arise for reactor gamma-ray spectral data. For example, there exists the specific needs of radiation damage specialists using high power radiation test facilities to test, develop, and improve reactor fuels and materials. For these specialists, the temperature of a given radiation damage experiment is a crucial variable. Such radiation damage experiments can neither be properly designed nor analyzed without an adequate knowledge of the temperature history of the irradiation. The temperature history can ultimately depend, in turn, upon the reactor gamma-ray component, since the source of reactor heat generation can principally arise through gamma-ray interactions.

The most fundamental quantity underlying the description of the reactor gamma-ray component is the absolute gamma-ray energy spectrum.

Radiation effects arising from the gamma-component are induced by the interaction of the absolute gamma-ray energy spectrum in the reactor environment. Consequently, accurate definition of this absolute spectrum is the goal of both theory and experiment. In light of these motivations there now exist urgent and pragmatic needs for reactor benchmark gamma-ray spectrometry data. To this end, requirements have been defined for in-core gamma-ray spectrometry in U. S. Light Water Reactor (LWR) and Breeder Reactor (BR) programs.

In reactor environments, gamma-ray spectra are continuous and the absolute magnitude as well as the general shape of the gamma continuum are of paramount importance. Consequently, conventional methods of gamma-ray detection are not suitable for in-core gamma-ray spectrometry. To meet these specific needs, a method of continuous gamma-ray spectrometry, namely Compton Recoil Gamma-Ray Spectrometry, was developed for in-situ observations in reactor environments.[2-4] In addition to applications in reactor science,[5-8] it has been used to measure gamma continuua which arise in such applied disciplines as shielding, dosimetry,[9] health physics,[10] radiobioligy and environmental science.[11,12] A brief summary of these earlier efforts can be found in the aforementioned review.[1]

Our purpose here is to present current work with Compton Recoil Gamma-Ray Spectrometry including developments in experimental technique as well as recent reactor spectrometry measurements. The current status of the method is described in the next two sections, which deal with gamma spectrometry probe design and response characteristics, respectively. In the remaining two sections, emphasis is given to gamma spectrometry work in U. S. LWR and BR programs. Gamma spectrometry in BR environments are outlined by focussing on start-up plans for the Fast Test Reactor (FTR).[13] In the last section, gamma spectrometry results are presented for a LWR pressure vessel mockup in the Poolside Critical Assembly (PCA) at Oak Ridge National Laboratory (ORNL).[14]

## II. SPECTROMETER DESIGN

The basic elements that comprise the gamma probe are displayed in Figure 1. Different lithium drifted silicon solid state detectors (Si(Li)) can be housed in the same vacuum chamber with little or no change in mounting hardware. Three configurations have been used to date: a 1 $cm^3$ planar detector, a 2 $cm^3$ planar detector, and a 12 $cm^3$ coaxial detector.

A summary status of the current spectrometer design is given below.

(1) The inclusion of a miniaturized vac-ion pump (0.1 l/s), which is capable of maintaining a probe pressure of $10^{-6}$ torr at ∿ 43°C

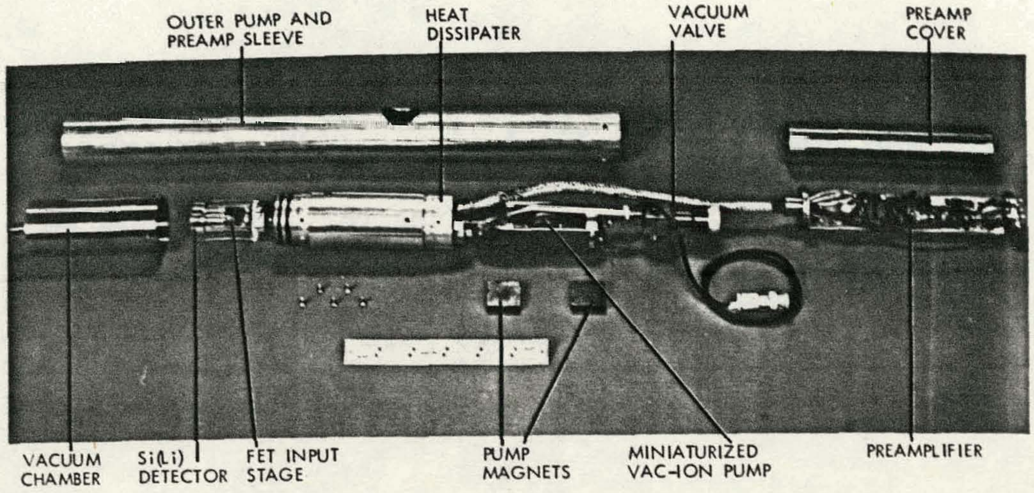

FIGURE 1. Detector Probe for Continuous Compton Recoil Gamma-Ray Spectrometry.

ambient, offers three improvements:

(a) increased thermal insulation due to a reduction in vacuum chamber pressure by a factor of $10^3$ or more;
(b) reduced overall probe size;
(c) extended probe flexibility.

(2) A smaller more efficient Peltier junction thermoelectric cooler (TEC) is used, which increases cooling capacity, reduces the heat load, and is capable of cooling the sensor and FET first input stage to 50°C below the aluminum heat dissapator temperature.

(3) A slotted aluminum radiator, which acts as a heat dissapator, can maintain the hot side of the TEC at 20°C in small reactor access ports of up to 40°C ambient. If necessary this slotted aluminum radiator can be cooled by forced gas flow.

(4) The net result of (1), (2), and (3) acting in consort is improved probe temperature stability; thus eliminating temperature dependent effects for most in-core gamma-ray spectrometry.

(5) The preamplifier, which is a slightly modified and extensively reconfigured version of the ORTEC 142A design possesses near ideal characteristics for Compton Recoil Gamma-Ray Spectrometry with a rise time adjusted to 50 nsec and a combined preamp plus cooled sensor noise level of 50 $\mu$V (RMS). As a consequence, electron energy resolution of approximately 5 keV (FWHM) at 0.661 meV($^{137}$Cs photo-peak energy) has been achieved.

(6) Overall pulse processing instrumentation has significantly evolved over earlier electronic circuitry, see Figure 2.

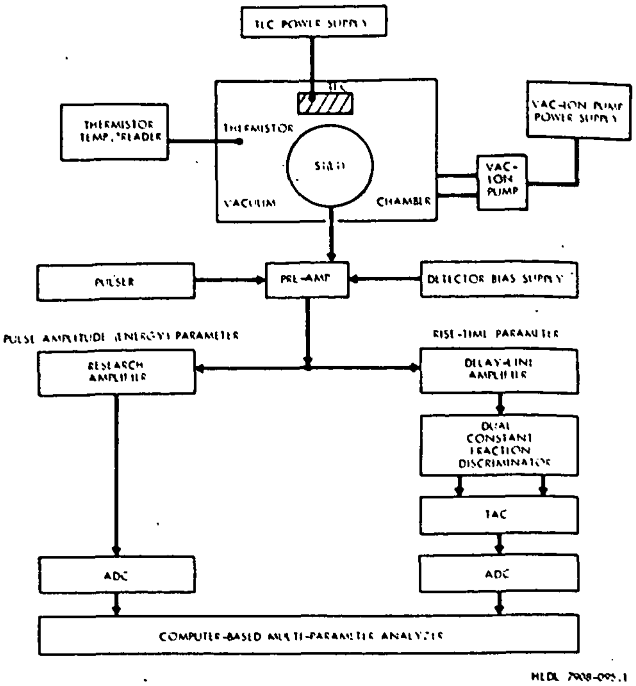

FIGURE 2. Instrumentation Block Diagram for Compton Recoil Gamma-Ray Spectrometry.[1]

(7) The net result of (5) and (6) acting in consort produces:

(a) excellent rise time resolution, see Figure 3;
(b) aside from noise broadening, rise time observations which are essentially independent of pulse-height (energy);
(c) the capability of accurately measuring Si(Li) detector sensitive volume (see section III below);
(d) accurate characterization of overall energy - angular response.

## III. RESPONSE CHARACTERISTICS

For absolute measurements, the extent of the sensitive region of the Si(Li) detectors used in Compton Recoil Gamma-Ray Spectrometry is of critical importance.[9] The capabilities of the current spectrometry system now permit quantitative measurement of this sensitive volume by resolving differences in pulse rise time between the sensitive and semi-sensitive regions. To date the planar 1 and 2 cc Si(Li) detectors have been investigated by stepping a 0.060" diameter beam of $^{54}$Mn gamma-rays across their surfaces.

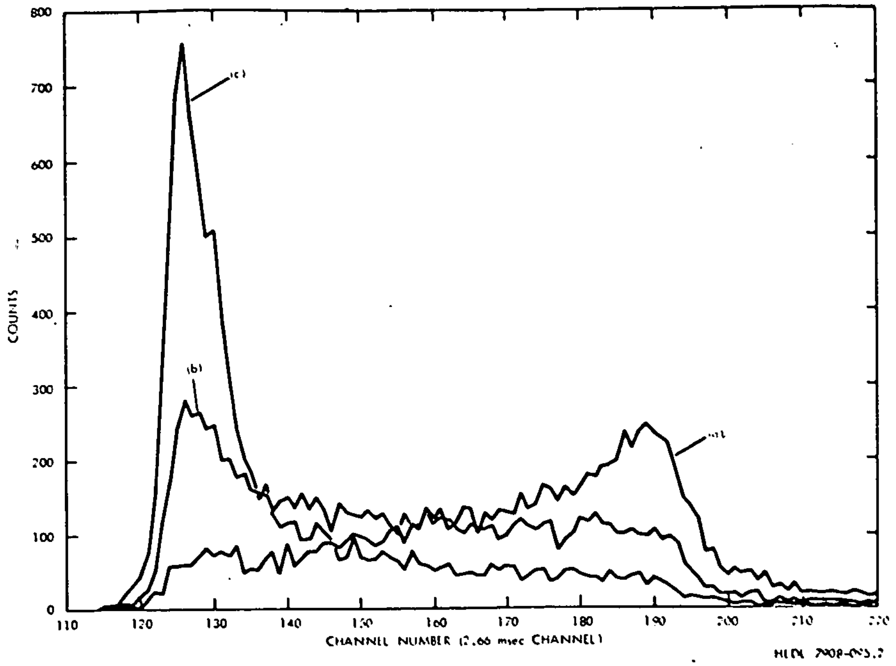

FIGURE 3. Typical Rise Time Spectra Used for Defining the Sensitive Volume of a 2 cc Planar Si(Li) Detector. The Electron Energy Window Chosen For the Collimated Beam of $^{54}$Mn Gamma Rays Was 0.64 to 0.32 MeV. (a), (b), and (c) are the 0.00, 0.05", and 0.10" Side Traverse Spectra, Respectively. The 0.00" Position Corresponds to the Edge of the Detector. The Total Integrated Counts for Each Step Was 20000.

Typical response rise time spectra (RTS) for a 2 cc detector are displayed in Figure 3. Note the shift from predominantly slow to fast rise time events as one steps away from the detector face down its side. The (c) type spectrum is observed as the traverse continues until the last two .050" steps, where the (b) and (a) type spectra are repeated, respectively. Traverses across the face and back of the detector follow the same general pattern. Thus, the two important regions of the detector are dimensionally defined: the semi-sensitive outer shell with its slower rise time pulses (due to trapping and E-field reduction which are a result of under or over compensation of lattice impurities) and the sensitive volume with its faster rising pulses.

Of perhaps greater significance is the fact that the sensitivity of these RTS observations enables one to measure the finite-size retention probability of recoil electrons in these Si(Li) detectors. The retention probability, P, of electrons in the finite sensitive volume of a detector depends on a number of variables. In general, P depends upon the gamma-ray energy $\mathcal{E}_0$, the recoil electron energy, E, and the angle of incidence of the gamma-ray $\theta$. Hence the retention probability is generally denoted by $P(\epsilon_o, E, \theta)$.

Heretofore RTS measurements of such sensitivity could not be carried out, thus necessitating certain simplifying assumptions in the unfolding analysis of observed electron spectra.[2-4] In particular, it was assumed that P was independent of both $\epsilon_o$ and $\theta$. With the present capabilities of observing RTS, one no longer need rely on such assumptions and more accurate data analysis can thereby be performed. On the other hand, these very capabilities permit investigation of the validity of these earlier assumptions.

Response measurements are carried out with a point source of gamma-rays, which is rotated about the detector from the face (0° incidence) to the back (180° incidence) in 45° steps. Rise time and energy data are accumulated at each position in a two-parameter, 64 x 64 channel, mode. Figure 3 displays a typical response RTS. The retention probability $P(\epsilon_o, E, \theta)$ is obtained by, first, fitting the faster rise time peak with a Gaussian distribution. Then the area under this Gaussian distribution is divided by the total number of counts in the RTS to obtain $P(\epsilon_o, E, \theta)$. Calculations are performed for all electron energy bins, $E_i$, at each angle of incidence.

Table 1 presents the results of such response determinations of $P(\epsilon_o, E, \theta)$ for the 1 cc planar Si(Li) detector using a point source of $^{54}$Mn ($\epsilon_o = 0.835$ MeV). This table reveals that the retention probability is a very slowly varying function of $\theta$. Similar response measurements with point sources of different gamma-ray energy also reveal that P is a slowly varying function of $\epsilon_o$. Such measurements show, in fact, that P is independent of $\epsilon_o$ within the present limits of experimental uncertainty.

Consequently, these preliminary data demonstrate that to a good approximation $P(\epsilon_o, E, \theta)$ reduces to P(E), i.e., the retention probability depends only upon recoil electron energy. This result supports the assumptions invoked in earlier work, which were based upon a Markovian formulation of the retention probability. In such a Markovian approximation, the probability of electron escape from the finite sensitive volume of the detector depends solely upon the recoil electron energy E and is independent of the mode ($\epsilon_o$, $\theta$) which produced the recoil electron.

## IV. GAMMA SPECTROMETRY PLANS FOR THE FTR

A reactor characterization program (RCP) has been planned and scheduled for the Fast Test Reactor (FTR) at startup, which consists of Very Low Power (VLP), Low Power (LP), and High Power (HP) irradiations. In-core gamma-ray spectrometry will be carried out at VLP

Table 1

FINITE SIZE RETENTION PROBABILITY
$P(\epsilon_0, E, \theta)$ for $\epsilon_0 = 0.835$ MeV ($^{54}$Mn)

| ENERGY MeV | ANGLE OF INCIDENCE | | | | | AVERAGE OVER ALL ANGLES |
|---|---|---|---|---|---|---|
| | 0° | 45° | 90° | 135° | 165° | |
| 0.10 | 0.15 | 0.14 | 0.13 | 0.14 | 0.15 | 0.14 |
| 0.14 | 0.17 | 0.18 | 0.17 | 0.18 | 0.19 | 0.18 |
| 0.18 | 0.20 | 0.20 | 0.20 | 0.21 | 0.20 | 0.20 |
| 0.22 | 0.21 | 0.22 | 0.21 | 0.21 | 0.22 | 0.22 |
| 0.26 | 0.22 | 0.24 | 0.23 | 0.22 | 0.23 | 0.23 |
| 0.30 | 0.24 | 0.24 | 0.23 | 0.22 | 0.22 | 0.23 |
| 0.34 | 0.24 | 0.25 | 0.23 | 0.22 | 0.22 | 0.23 |
| 0.38 | 0.23 | 0.24 | 0.23 | 0.22 | 0.22 | 0.23 |
| 0.42 | 0.28 | 0.25 | 0.23 | 0.22 | 0.22 | 0.24 |
| 0.46 | 0.24 | 0.28 | 0.24 | 0.23 | 0.22 | 0.24 |
| 0.50 | 0.25 | 0.26 | 0.26 | 0.22 | 0.22 | 0.24 |
| 0.54 | 0.25 | 0.24 | 0.23 | 0.22 | 0.20 | 0.23 |
| 0.58 | 0.23 | 0.23 | 0.22 | 0.21 | 0.21 | 0.22 |

in a specially designed FTR insert called the In-Reactor Thimble (IRT). The IRT insert replaces a centrally located fuel assembly (No. 2201) in the FTR core for VLP measurements and provides an adequate environment for the operation of the in-core fission chamber, ionization chambers, and spectrometry probes.

Actually in-core continuous gamma-ray spectrometry is planned as the very first experiment to be conducted in the IRT. As such, it will be carried out concurrently with fuel loading in the third trisector of FTR. Axial locations at mid-plane and in the lower axial reflector, about 80 cm below mid-plane, have been assigned for these measurements.

Two Si(Li) detectors, the planar 2 $cm^3$ and the coaxial 12 $cm^3$, will be used in the IRT. Background rates for these experiments are expected to be very high. Estimated background rates at mid-plane with all rods in (keff = 0.90) are roughly 5 x $10^3$ and $10^5$ count/s for the smaller and larger detector, respectively. These high background count rates stem from the spontaneous fission rate of FTR core 1 fuel, which is 22 weight percent plutonium.

Total VLP gamma count rates, with rods adjusted for keff = 0.95 to 0.98, will be roughly 2 to 5 times higher. Even for these very high rates, it may still be possible to collect data in a two-parameter mode for the smaller 2 $cm^3$ planar detector. However, data collection for the larger 12 $cm^3$ coaxial detector will probably be restricted to the one-parameter mode. In this manner, spectral sensitivity will be extended up to roughly 4 MeV and perhaps higher.

## V. GAMMA SPECTROMETRY IN LWR ENVIRONMENTS

Gamma continuua were observed in the low power pressure vessel (PV) mockup at the PCA. This mockup represents a controlled irradiation field set up at the ORNL to study and quantify the complex radiation field which arises in LWR-PV environments. Measurement of continuous gamma spectra is of particular interest in the LWR-PV Irradiation Surveillance Dosimetry Program. There is need for improved gamma heating data to aid in the design of high power LWR-PV irradiation experiments. In addition, fission threshold dosimeters used in LWR-PV environs can possess non-negligible contributions induced by photo-fission. Consequently, these photo-fission contributions must be more accurately assessed.[15,16]

Gamma measurements were restricted to the interior of the PV block in this work. Observations were carried out at midplane in the T/4, T/2, and 3T/4 locations* using a 12/13 configuration (i.e., water gaps of 12 and 13 cm for the distances between the core face and thermal shield and between the thermal shield and PV face, respectively). At each location foreground data was collected with the reactor at a power level of a few watts and background data was collected with the reactor shutdown. As a representative case, the foreground and background electron spectra observed at the T/4 location with a 2 $cm^3$ planar Si(Li) detector are presented in Figure 4. The corresponding unfolded gamma spectra are displayed in Figure 5. These results can only be regarded as preliminary because analyses for both finite-size effects and experimental error have not as yet been performed.

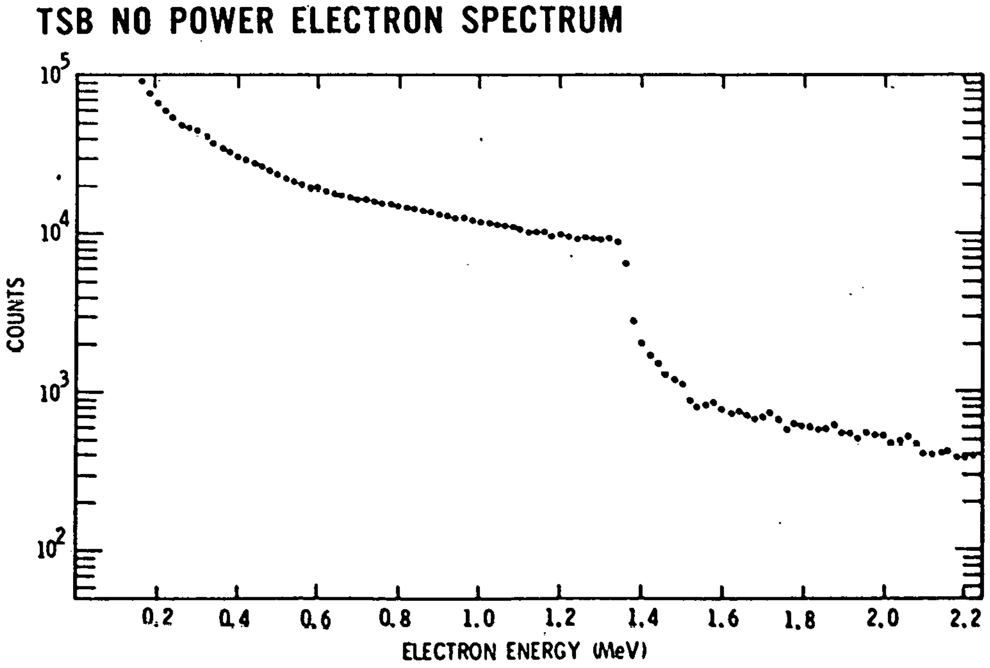

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FIGURE 4a. Background Electron Spectrum

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*The T/4, T/2 and 3T/4 designations represent distances from the front face of a PV block whose total thickness is T.

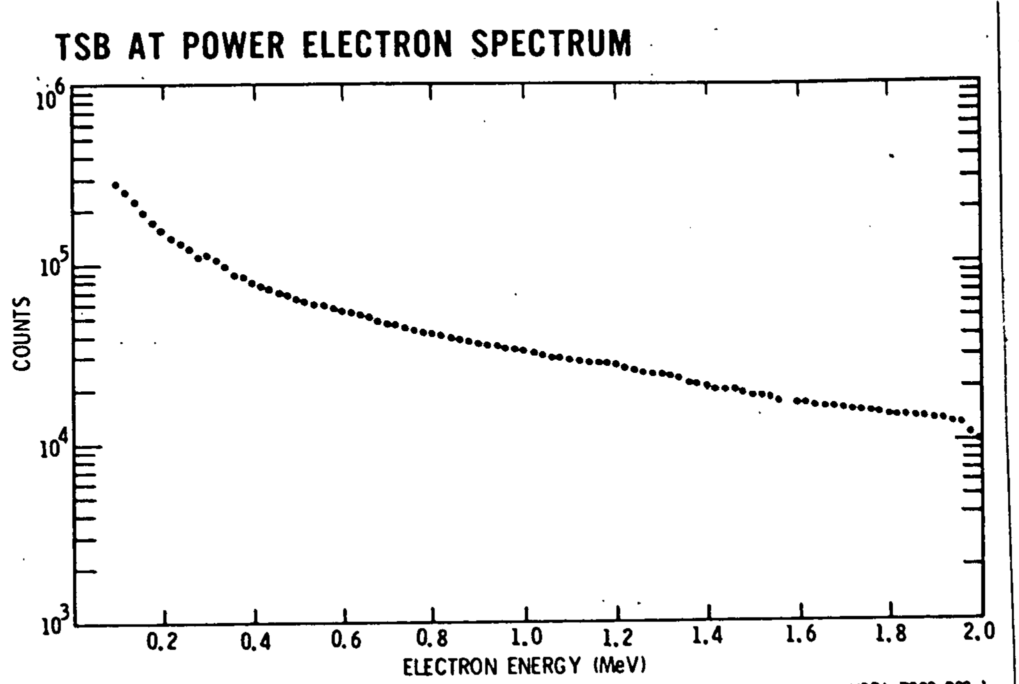

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FIGURE 4b. Foreground Electron Spectrum

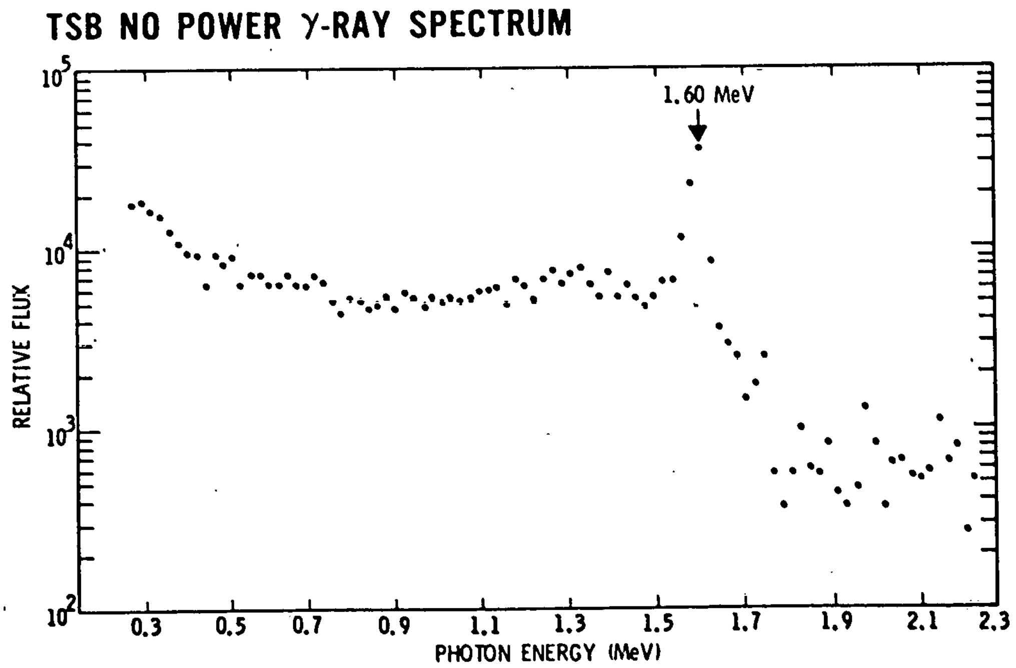

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FIGURE 5a. Background Gamma Ray Spectrum

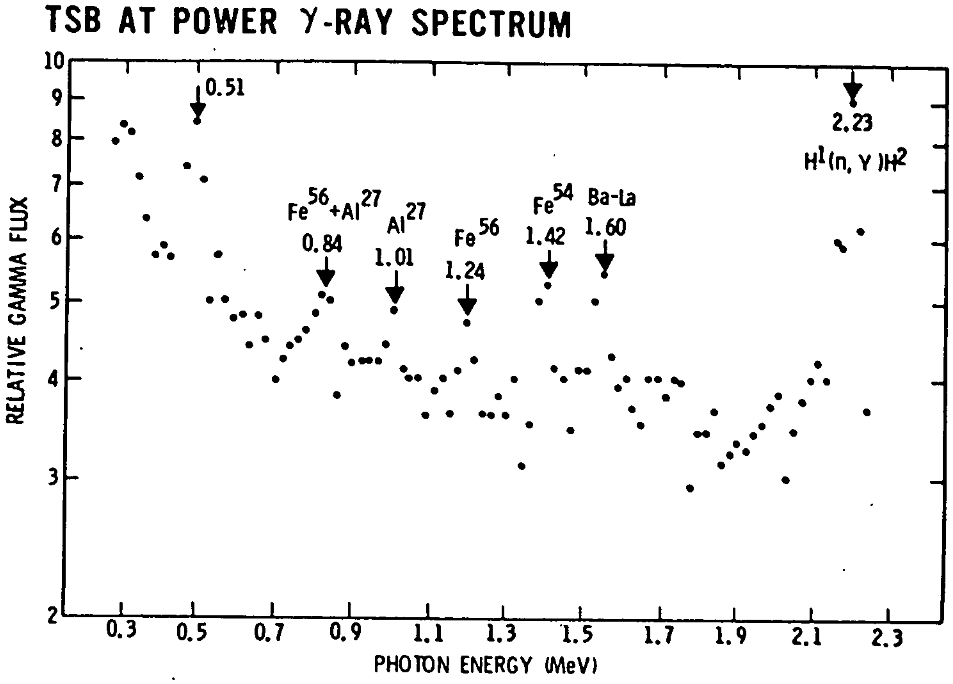

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FIGURE 5b. Foreground Gamma Ray Spectrum

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