SOME GAMMA-RAY SHIELDING MEASUREMENTS MADE AT ALTITUDES GREATER THAN 115,000 FEET USING LARGE Ge(Li) DETECTORS*

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A series of balloon-flight experiments at altitudes greater than 115,000 feet has been conducted to gain information relative to the use of composite shields (passive and/or active) for shielding large-volume, lithium-drifted, germanium (Ge(Li)) detectors used in gamma-ray spectrometers at these altitudes. The measurements were made in the gamma-ray energy region 60 keV $\leq E_\gamma \leq$ 2 MeV and clearly illustrate the necessity of using a dense gamma-ray shield protected by an active charged-particle shield for effective shielding of these detectors in the primary cosmic-ray environment. Data showing the pulse-height spectra of the environmental gamma radiation as measured at 5.3 and 3.8 gms/cm^2 residual atmosphere with an unshielded diode detector is also presented.

INTRODUCTION

The purpose of the work reported in this paper was to study the effectiveness in the primary cosmic-ray environment of a composite gamma-ray detector shield incorporating both active and passive shielding material to reduce the background in a proposed gamma-ray spectrometer[1] for astrophysical measurements. In addition, it was desired to ascertain the reliability of using lithium-drifted, germanium (Ge(Li)) diodes as gamma-ray detectors in both balloon-flight and orbital experimentation.

DESCRIPTION OF THE INSTRUMENTS AND SHIELDS

The required shielding for the proposed spectrometer was determined initially by Monte Carlo and other computational methods at ORNL with the assistance of members of the Mathematics and Neutron Physics Divisions. A mock-up of the calculated shield was built for balloon-flight tests as shown on the right in fig. 1. Basically the shield was a composite of active and passive elements designed to either detect a background-producing event or to physically prevent undesired radiation from reaching the spectrometer. The outer shield consists of a scintillating plastic (NE-103) region on the outside both to detect charged particles and, by using a thickness of four inches of this hydrogeneous material, to moderate the high energy neutrons which born as a result of the charged-particle interactions or which enter the shield from the outside. The scintillations which occur in the plastic at the time of the interaction are detected by the photomultiplier tubes and are used to provide signals to "gate off" the analysis of all pulses from the gamma-ray detector for 8 μsec after the interaction.

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Thus, the gamma rays reaching the detector during this period are not recorded on the supposition that they are probably the results of the interaction.

Most of the neutrons which enter the shield from the outside or are born in the shield as a result of charged-particle interactions are moderated to a sufficiently low energy to be stopped in a 1/2-in.-thick layer of LiF immediately inside the plastic. Low-energy neutrons are captured in the ^{6}Li with the subsequent emission of an alpha particle ($^6\text{Li}(n,\alpha)t$) rather than a gamma ray as with other common thermal-neutron shielding material; i.e., $^{10}\text{B}(n,\alpha)^7\text{Li}^* \rightarrow {}^7\text{Li} + \gamma(478\text{ keV})$. Fast neutrons, which penetrate both the lithium and lead with little difficulty, are often elastically scattered in the plastic and produce anticoincidence signals by virtue of the ionizations produced by the recoil proton. Thus gamma-ray pulses resulting from neutron interactions in the detector or inner shield are further reduced.

Since gamma rays easily penetrate the plastic and lithium due to their low density, it is necessary to include a high-Z material in the shield to attenuate this radiation. Lead was used for the mock-up, but it is proposed that bismuth be used in the final shield because of its relatively high threshold for neutron inelastic scattering compared to lead[2]. This gamma-ray shield as well as all other passive components of the configuration are placed inside the thermal-neutron and active plastic shields to reduce the neutron interactions and subsequent gamma-ray production in these materials. A total thickness of two inches of lead was used in the balloon measurements. Finally, the mock-up includes a 1/4-in.-thick layer of stainless steel to suppress the fluorescent radiation which originates in the lead (K x-ray at ≃ 88 keV).

This mock-up of the shield was tested at ORNL by Rodda, Macklin, and Gibbons[3] with a pulsed-neutron source generated by the 3 MV Van de Graaff accelerator. The shielded detector as shown in fig. 1 was exposed to 1.7-MeV neutrons (a typical energy for evaporation neutrons) with the plastic anticoincidence shield operated in the passive mode and then with shield operated in the active mode. Time-of-flight techniques were used to separate the prompt gamma-ray spectra from the delayed spectra. The results showed a reduced neutron sensitivity for this detector compared to NaI(Tℓ), a reduction of about one order of magnitude in the observed number of inelastic scattering events in the Ge(Li) detector due only to the passive plastic shield, and an additional reduction of another order of magnitude in these events with the plastic shield operating in the active mode.

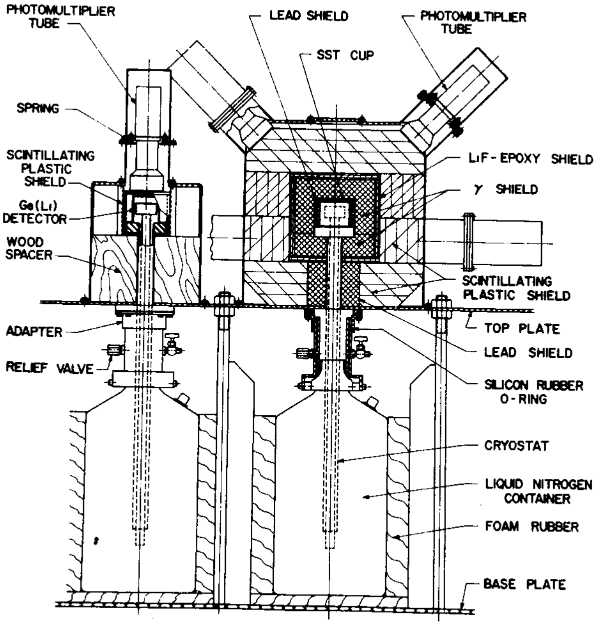

Fig. 1

During the first two balloon flight of the series, the pulse-height spectra of the environmental gamma radiation were obtained with the use of the detector shown on the left in fig. 1. The Ge(Li) detector in this configuration was unshielded except for the 1/8-in.-thick aluminum of the container and a 1/4-in.- thick plastic anticoincidence shield. In both configurations, the 25-cc Ge(Li) detectors were thermally coupled to a reservoir of liquid nitrogen (LN_2) by means of a long vacuum-sealed cryostat. A vacuum-tight adapter collar was used to prevent excessive boil-off of the LN_2 at high altitudes and both instruments were rigidly mounted in a stable frame for support and protection during the flights.

MEASURED PULSE-HEIGHT SPECTRA OF THE ENVIRONMENTAL GAMMA RAYS

The pulse-height spectra of natural gamma radiation as measured with the unshielded diode at 116.5- and 125.8 kilofeet are shown in fig. 2. The spectrum measured at 125.8 kilofeet was obtained with the anticoincidence shield (A/C) inoperative and probably includes some pulses produced by electrons - especially in the low energy region. Both spectra show distributions corresponding to E_γ^{-2} (E_γ = gamma-ray energy) below about 600 keV. Above this energy there is a strong indication that the distribution changes to E_γ^{-1}. This is not inconsistent with the findings of Perlow and Kissinger[4] who argue that the spectrum of natural gamma radiation in the atmosphere is primarily the result of two sources: (1) bremstrahlung radiation resulting from electrons produced by the decay of μ-mesons (see also ref. 5) which gives rise to the E_γ^{-1} component, and (2) photons degraded in energy by multiple Compton scattering to

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Comparison of the Experimental Values of the 511 keV Photon Flux in the Atmosphere

Reference	Date of Flight	Pressure (g/cm^2)	Detector	Intensity (gammas cm^{-2} sec^{-1})
1	May–June 1964	[a]	$1\frac{3}{4}$-in.-diam by 2-in.-high NaI (no anticoincidence shield)	0.34
1	June–July 1964	[a]	Same	0.40
2	May 2, 1961	6	2-in.-diam by $2\frac{1}{4}$-in.-high NaI, $\frac{1}{8}$-in.-thick NE-102 plastic anticoincidence shield	0.31 ± 0.03
3	December 1966 to April 1968[b]	3.7	3-in.-diam by 3-in.-high CsI, $\frac{1}{2}$-in.-thick NE-102 plastic anticoincidence shield	Varied from 0.16 ± 0.02 to 0.21 ± 0.02
4	May 5, 1968	4.7	22-cc Ge(Li) with a 2.25-in. NaI anti-coincidence shield with opening to collimate incoming vertical radiation	0.47
This work	November 4, 1967	5.3	20-cc Ge(Li) with $\frac{1}{4}$-in.-thick NE-103 plastic anticoincidence shield	0.48 ± 0.03
This work	May 29, 1967	3.8	Same	0.38 ± 0.09

[a] Taken from curves published by the experimenter based on data taken to about 10 g/cm^2. Values quoted here were read from the curve at 5 g/cm^2.

[b] Reported variation of the intensity during this period.

[1] Robert Rocchia, *Gamma Radiation in Space and in the Atmosphere*, CEA report R-2939 (1966).

[2] L. E. Peterson, *J. Geophys. Res.* 68, 979 (1963).

[3] E. L. Chupp, D. J. Forrest, P. J. Lavakare, and A. A. Sarkady, *Bull. Am. Phys. Soc.* 13, 1399 (1968).

[4] E. A. Womack and J. W. Overbeck, *Bull. Am. Phys. Soc.* 13, 1398 (1968).

TABLE I

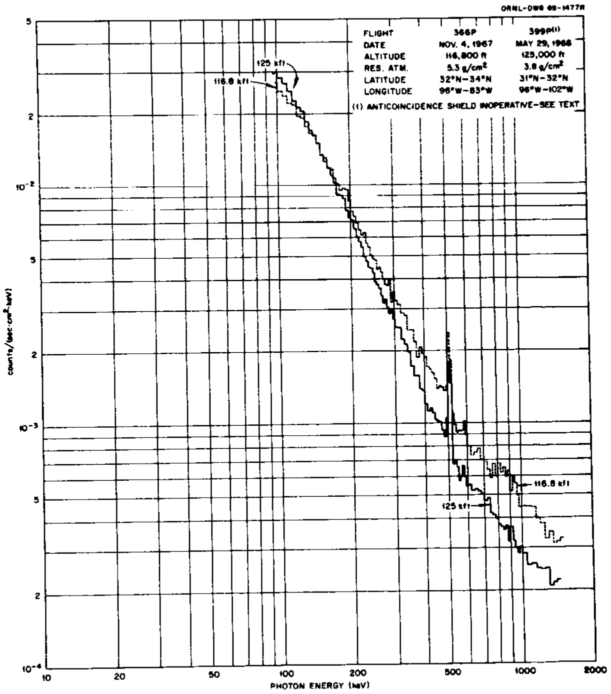
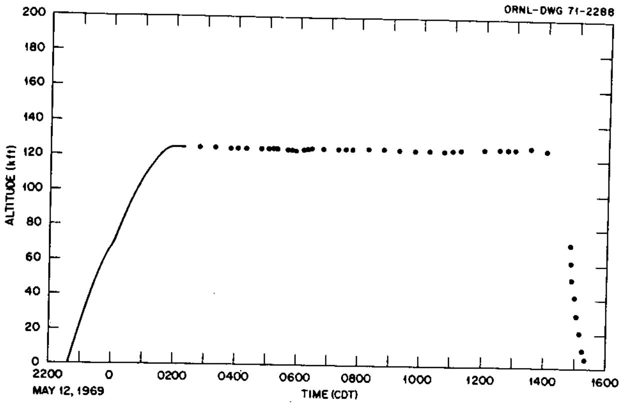


Fig. 2

produce the E_{γ}^{-2} component. The only distinct monoenergetic gamma ray present in the data is the 511-keV annihilation photon. The values of the intensities of this photon as reported by other experimenters[5-8] are compared to the values derived from these data in Table 1. There is a spread of a factor of three in these reported measurements. This variation, which is larger than would be expected from the altitude differences, may reflect in part temporal variations in the cosmic-ray intensity at the time of the measurements.



Time-Altitude Profile for Balloon Flight 69A.

Fig. 3

ALTITUDE DEPENDENCE OF THE DATA

Representative of the balloon flights in this series is the one launched on May 12, 1969 at the NCAR Balloon Facility in Palestine, Texas. Fig. 3 shows the time-altitude profile for the flight. The balloon ascended at an average rate of 650 fpm to a float altitude of 124 kilofeet. It remained at this altitude for about 13 hours. From about 5000 feet until termination of the flight, the following data were recorded.

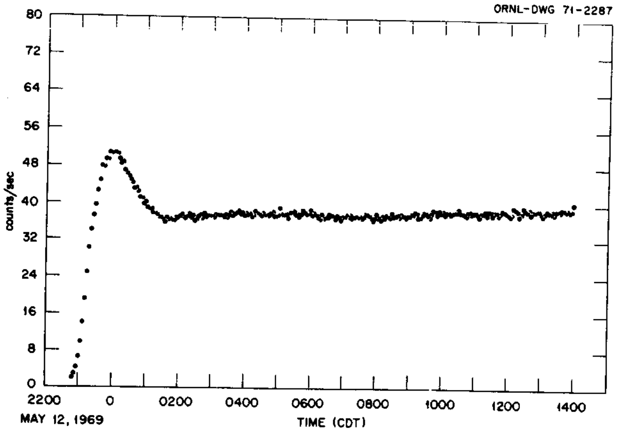
1. Pulse-height spectrum of pulses in the Ge(Li) diode detector not associated with pulses in the plastic shield.

2. Integral count-rate of all pulses in the Ge(Li) diode detector not associated with pulses in the plastic shield.

3. Integral count-rate of all pulses in the Ge(Li) diode detector.

4. Integral count-rate of all pulses in the plastic shield above a bias levels at ~ 500 keV.

The count rate for all data channels remained essentially constant after reaching float altitude as illustrated in fig. 4 which shows the count rate as a function of time for all pulses occurring in the Ge(Li) detector. Each of the data channels showed similar constancy.



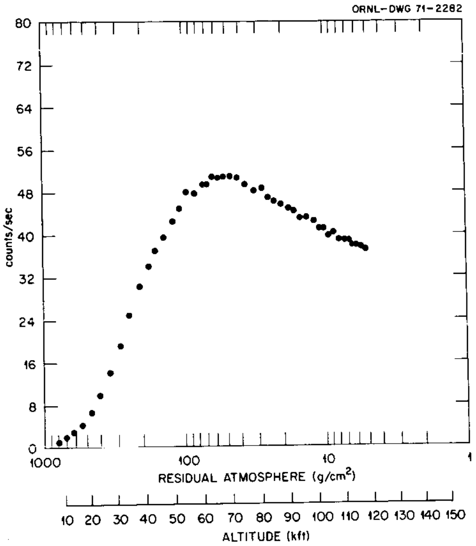
Diode Count Rate as a Function of Altitude; Flight 69A.

Fig. 4

Fig. 5 shows the same data as fig. 4 except that the count rate is now shown as a function of atmospheric pressure. The data between about 500 gms/cm^2 and 150 gms/cm^2 is well represented by exponential law

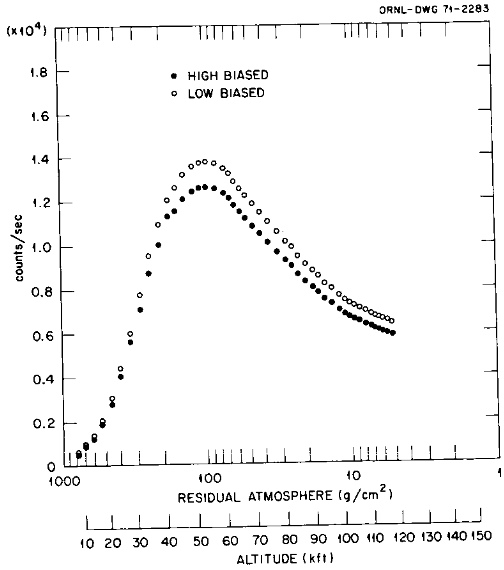
$$I(P) \sim e^{-P/Po}$$

with P_o = 158 gms/cm^2. The peak counting rate occurs at about 50 gms/cm^2 in the atmosphere. Rocchia[5] has shown that the production of photons at 511 keV in lead peaks at about 83gms/cm^2 (atmosphere) whereas the production of photons in air reaches a maximum at about 100 gms/cm^2. We speculate, then that the data shown in fig. 5 may reflect, in part, a production of photons in the shield. Fig. 6 shows the count rate in the plastic shield at two bias levels - 150 keV (low bias) and 500 keV (high bias). The analysis of pulses in the Ge(Li) detector was gated off by all pulses greater than the 500-keV level. These data show maxima at 100 gms/cm^2 and follow an exponential law, as before, with a P_o of 187 gms/cm^2 and 194 gms/cm^2 for the high-biased and low-biased data respectively. There is a difference in count rate of only about 10% at the maxima of the curves. The anticoincidence rates between the Ge(Li) detector and the plastic shield at the two bias levels are shown in fig. 7. There is no significant difference in these count rates, indicating that the diode rate was indeed being biased by good pulses in the plastic rather than noise pulses. Since these data represent pulses that are not associated with events in the shield, they must represent the natural gamma radiation and possibly neutral particles which leak through the shield and interact in the detector. Again, these data are described by an exponential law with P_o = 175 gms/cm^2 and with the maximum count rate occurring at 100 gms/cm^2. Rocchia's[5] measurements of the atmospheric photon count rate as a function of atmospheric pressure shows P_o = 170 gms/cm^2 with the maximum count rate at 95 gms/cm^2. Consequently, it is felt that the pulses accepted from the Ge(Li) detector as a result of these gating pulses are indeed correlated with true atmospheric photons and do not originate in the shield.



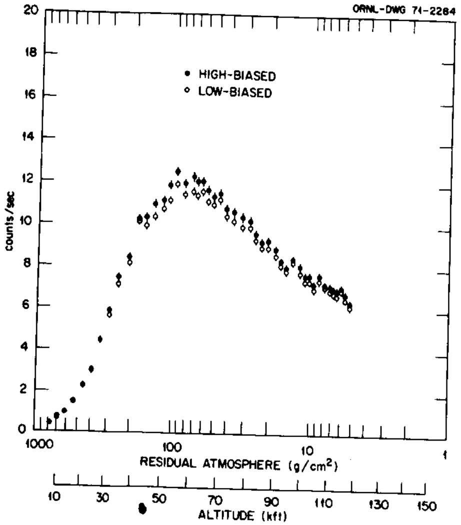
Diode Count Rate as a Function of Altitude; Flight 69A.

Fig. 5



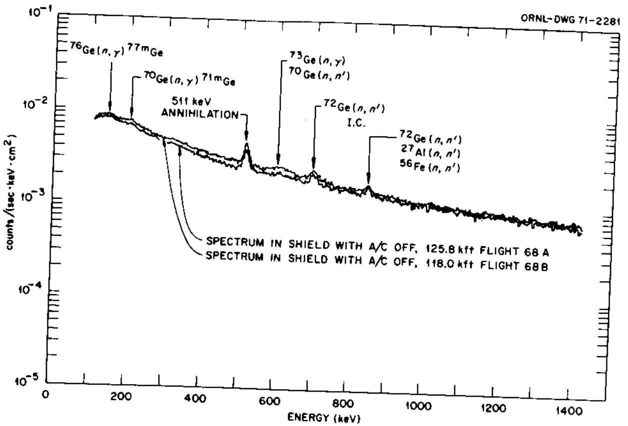
High-Biased and Low-Biased Plastic Count Rates; Flight 69A.

Fig. 6



High-Biased and Low-Biased A/C Rates vs Altitude; Flight 69A.

Fig. 7



The Pulse-Height Spectrum in a Passive Shield at Two Altitudes.

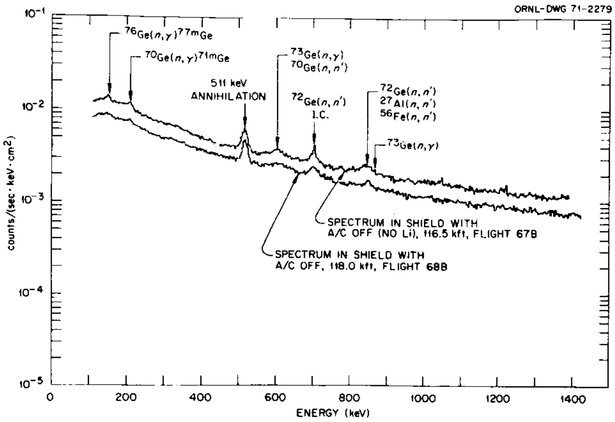
Fig. 8

MEASURED ENERGY SPECTRA

During the series of balloon flight, measurements were made of effects on the energy spectrum when various shield parameters were changed. In flights 68A and 68B, the spectra inside the shield were obtained at 125.8 KFT and at 118.0 KFT respectively with the anticoincidence shield inoperative. These data are shown in fig. 8. There are prominent gamma-ray peaks through out the pulse-height spectrum. The reaction which produce the lines are:

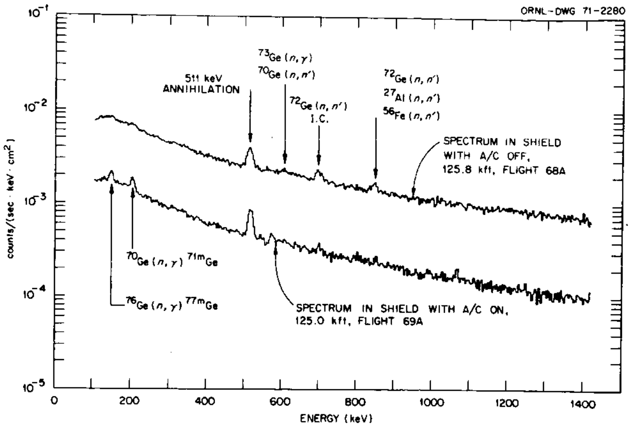
138 keV	$^{74}Ge(n,\gamma)^{75m}Ge$ (48 sec)
198 keV	$^{70}Ge(n,\gamma)^{71m}Ge$ (20 msec)
511 keV	Annihilation
600 keV	$^{74}Ge(n,n'\gamma)^{74}Ge$
696 keV	$^{72}Ge(n,n'\gamma)^{72}Ge$ (422 nsec IC transition)
845 keV	$^{72}Ge(n,n'\gamma)^{72}Ge$

The lines at 138 keV and 198 keV have been observed by Womack[6] in a measurement similar to these and the lines resulting from neutron-inelastic-scattering events in the detector were reported by Rodda, et al.[3]. To see the effectiveness of LiF thermal-neutron shield, flights 67B and 68B were made at approximately the same altitude with the LiF removed from the shield during flight 67B. The results are shown in fig. 9. There is a constant reduction in the intensity over the whole energy range with the LiF in the shield. This is attributable to the reduction by the Li of thermal neutrons in the shield and the subsequent reduction of high-energy capture gamma rays. On the other hand, the relative intensities of the gamma-ray peaks are not significantly reduced. This would be expected if these peaks are the result of fast-neutron interactions in the detector as discussed above. Although Rodda[3] did detect thermal-neutron-capture gamma rays in the germanium at 600, 695 and 870 keV and possibly at 967 keV, the continued prominence of these lines with the LiF shield in and the elimination of the peaks in these data with the anticoincidence shield active as discussed later led us to conclude that lines in these data are indeed the results of the interactions of fast neutrons born during cosmic-ray events in the plastic shield.



The Pulse-Height Spectrum in a Passive Shield with and Without Lithium.

Fig. 9



The Pulse-Height Spectrum in an Active and Passive Shield at 125 kft.

Fig. 10

The effectiveness of the total shield with the anticoincidence shield active is presented in the final set of data shown in fig. 10. These data were obtained at essentially the same altitude for comparison. The most distinctive difference in the two spectra is the virtual elimination of the gamma ray peaks by the use of the active plastic shield. The lines at 139 keV and 198 keV, which are due to neutron capture in germanium isotopes and the subsequent transition from long-lived isomeric states, do appear to be enhanced in the total-shield data. This may be explained, at least in part, by the fact that the life-time of both the isomers involved is sufficiently long to persist beyond the 8-μsec anticoincidence gate time. The overall reduction in the intensity of the spectrum is due to the elimination from the gated pulse-height spectrum those photons which are born during or within 8 μsec after a shower occurs.

CONCLUSIONS

The shielding of sensitive gamma-ray detectors for use in gamma-ray spectrometers in the primary cosmic-ray environment is a complex undertaking. Calculations suffer from the lack of adequate input data and the necessity of using complex geometries in realistic shields. Balloon-flight measurements, such as the one described here, to test specific shield designs may be the most reliable approach. The studies reported here have indicated that the use of a sufficiently thick external active shield such as scintillating plastic is almost essential to effectively stop charged particles and aid in the thermalization of neutrons. Plastic serves well in this capacity since it is hydrogeneous and not subject to induced long-lived activity by the neutron and charged particle interactions. A high-density material of sufficient thickness to overcome the effects of the gamma-ray "build-up factor" in the material must be used to attenuate the gamma radiation which results from cosmic-ray interactions on which enter the shield from the outside. The use of a thermal-neutron shield between the plastic and the inner shield was shown to be desirable in preventing capture gamma rays in the shield. With the exception of gamma rays from long-lived isomers in germanium and annihilation radiation, the shield described here utilizing a sufficiently long anticoincidence gate time has reduced the unwanted peaks in the background spectrum to an almost insignificant level. As proposed for the final shield design but not discussed here, an inner anticoincidence shield immediately adjacent to the detector is desirable especially for the suppression of Compton-scattered photons from events in the detector. For example, it is estimated that a 1-in.-thick layer of NaI(Tℓ) inside the shield discussed here would reduce the background continuum to less than 10^{-5} counts per (sec. keV cm^2) for energies greater than 500 keV. This is almost a factor of ten lower than the best published, totally active shield[6] for this energy region with which we are familiar.

ACKNOWLEDGMENTS

The work reported here required the cooperation of too many people to recognize individually. We would especially like to thank the NCAR people at Palestine, Texas who handled all the launches, tracking and recovery operations for this series of flight. They all worked long hours, lost much sleep, and traveled many miles to ascertain that everything possible was done to assure the success of each flight and the safe recovery of the "package".

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