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ORNL-TM-3877

Contract No. W-7405-eng-26

Neutron Physics Division

MEASUREMENT OF THE NEUTRON ENERGY SPECTRUM AT 9 g/cm^2 RESIDUAL ATMOSPHERE*†

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*This work was funded by USAEC Activity 05 03 02; flight costs and participation by NASA personnel provided by NASA-MSFC (Space Science Laboratory), Huntsville, Alabama.

†Submitted for journal publication.

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JUNE 1973

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ABSTRACT

An experiment to measure the neutron energy spectrum at an altitude corresponding to 9 g/cm^2 residual atmosphere was performed near solar maximum. The non-directional spectrometer employed was flown at geomagnetic latitude 40° N from Palestine, Texas, on June 17, 1969. The experimental arrangement is described, the data reduction scheme is discussed, and the results are presented for the neutron spectrum in the energy range from 3 to 60 MeV. The spectrum is compared with those from other experiments and from calculations. The intensity is greater than the calculations of Lingenfelter after application of an altitude correction, but is lower than the measurement of Preszler, Simnett, and White and the calculations of Armstrong, Chandler, and Barish.

The decay of neutrons, produced by the interaction of cosmic rays in the atmosphere and subsequently leaving it (so-called "cosmic-ray albedo neutrons"), was suggested initially by *Singer* [1958] as a mechanism to explain the observed protons in the Van Allen belt. *Hess et al.* [1959] had measured the spectrum of neutrons in the atmosphere and these measurements were used as the basis for subsequent calculations designed to test this "Cosmic Ray Albedo Neutron Decay" (CRAND) theory [*Hess*, 1959; *Newkirk*, 1963; *Lingenfelter*, 1963]. Additional measurements of neutrons at high altitudes [*Mendell* and *Korff*, 1963; *Haymes*, 1964; *Boella et al.*, 1965; *Merker et al.*, 1969] appeared to confirm the spectrum of *Hess et al.* [1959] to about 20 MeV since calculated extrapolations from these measurements agreed with the calculated neutron flux of *Newkirk* [1963] and *Lingenfelter* [1963] which use the measurements of *Hess et al.* [1959]. Note that the experiments referenced above report but limited spectral information. *Mendell* and *Korff* [1963] used equipment having only two energy channels, and assumed an exponential spectral shape to arrive at a neutron flux for comparison with the calculations. *Haymes* [1964] reports a power law spectrum obtained from a proton recoil spectrum from about 2 MeV to about 8 MeV. *Boella et al.* [1965] assumed one of the calculated spectra and converted it to expected counting rates for comparison with their measured ones. *Merker et al.* [1969] used a seven-channel analyzer to cover the energy range from 1 to 10 MeV.

Calculation of the proton injection into the radiation belt by *Dragt et al.* [1966] using the CRAND neutrons as the source indicated, however, that this source is too small by a factor of 50 to account for the observed flux of protons with energies in excess of about 20 MeV.

Measurements by *Imhof* and *Reagan* [1969] in the 10- to 50-MeV region confirmed the presence of a large discrepancy.

The measurements of *Hess et al.* [1959] which formed the underpinning for all the CRAND calculations were performed with counters which had minimal sensitivity in the energy region from roughly 10 to 100 MeV. The greatest discrepancies between calculated and measured intensities are noted for protons in this very energy region. A program was therefore started in 1966 at Oak Ridge National Laboratory to reduce the uncertainty in the neutron spectrum at high altitude in the energy region from 3 to 60 MeV. The upper limit was chosen because of the availability of detector calibration facilities to this energy, and the lower limit followed from the experimental scheme employed. The data gathering program culminated in a balloon flight from Palestine, Texas, on June 17, 1969.

In this paper we will first describe the instrument used, then discuss the data-gathering balloon flight, display some of the data obtained during the flight, and finally present the data analysis and the results thereof.

INSTRUMENTATION

To fulfill the goals of the experimental effort a spectrometer was required which would measure neutrons, over a wide energy range, in the presence of charged particles and gamma rays. To reduce the local production of neutrons the device should have fairly low mass. The output of the spectrometer had to be convertible into a neutron spectrum with few,

if any, prior assumptions about the incident spectrum. Finally, budgetary constraints limited development of special purpose equipment. The spectrometer described below meets these criteria.

The neutron detector was a 1.8-in.-diam by 1.7-in.-high right circular cylinder of NE-213 (Nuclear Enterprises, Inc., San Carlos, California). It is a property of this liquid organic scintillator that a light pulse produced by the passage of a slow heavy particle (e.g., proton, alpha particle) through the material has different time-decay properties from that produced by an electron. NE-213 contains only hydrogen and carbon (in the ratio of 1.213:1), thus limiting the possible interactions. It was therefore chosen as the detector material since it enabled us to distinguish between neutron-induced events and gamma-ray induced events by pulse-shape discrimination techniques. The resultant pulse-height spectrum can then be converted to a neutron spectrum using spectrum unfolding methods [*Burrus* and *Verbinski*, 1969].

The NE-213 was encased in a 1/16-in.-thick aluminum can, coated on the inside with NE-561 (Nuclear Enterprises, Inc., San Carlos, California) which is a compatible reflector material. The detector can was mounted on an RCA type 8575 photomultiplier tube and was electrically connected to the photocathode. The assembly was wrapped in black electrical tape, covered with a magnetic shield which was also operated at cathode potential, and covered with more electrical tape. This mode of electrical operation is recommended by the tube manufacturer.

Since the basis of operation of this detector is its response to charged particles, care must be taken to distinguish the recoil particles

from those which may be incident upon the detector. We therefore surrounded the neutron detector assembly with a 1/4-in.-thick "mantle" of NE-110 (Nuclear Enterprises, Inc., San Carlos, California), a solid organic scintillator. The thickness was chosen because a normally incident minimum ionizing particle will deposit slightly more than 1 MeV in the scintillator, yielding a signal which was easily detectable. The mantle was viewed by a second RCA type 8575 photomultiplier, and the output of this tube was placed in anticoincidence with the output of the neutron detector, thus inhibiting analysis if both the mantle and the neutron detector recorded an event within 200 ns.

A number of constraints influenced the design of the package which housed the detector assembly. Firstly, the operating temperature of the detector assembly had to be held within the range 15° to 65°C. The lower limit was set by the lowest temperature at which the NE-213 would operate, and the upper limit by the structural limitation of the NE-110 (J. B. Heath, Nuclear Enterprises, Ltd., Winnipeg, Canada, private communication, 1967). This requirement was met by encasing the detector assembly in an insulated container maintained at surface atmospheric pressure so that convection could aid in temperature redistribution.

Secondly, we had to eliminate high voltage arcing at float altitude. This problem was solved by including the high voltage power supplies in the pressure can surrounding the detector assembly.

Finally, we wished to reduce the background due to neutrons produced in the gondola itself which, including ballast, weighed over 1000 lbs.

We therefore decided to lower the detector assembly after launch to about 90 ft below the gondola.

The final detector package then consisted of a 1/16-in.-thick aluminum pressure can housing the detector assembly, high voltage supplies for the photomultiplier tubes, a preamplifier for the neutron detector signals, a small heater, and two temperature sensors. This can was surrounded by 1.5 in. of Nopcofoam B-610 (NOPCO Chemical Company, No. Arlington, N. J.) insulation, and the whole encased in a 16-ga. sheet steel can to protect it on impact, since it was easier to ensure the impace survival of the package than to attempt to retract it into the gondola at the conclusion of the flight. Figure 1 shows the detector assembly and inner can.

In addition to the decision whether a pulse should be rejected due to a coincidence with the mantle as mentioned above, the electronics used for the experiment had to perform two functions: pulse-height analysis (PHA) and pulse-shape discrimination (PSD). A block diagram is shown in Fig. 2.

Let us first discuss the PHA function, which is the simpler and more conventional of the two. The output pulse from dynode 8 of the photomultiplier was amplified and shaped in the preamplifier and double-delay-line amplifier. The latter had two outputs, of which one was delayed by 1.0 μs with respect to the other. The delayed pulse was analyzed in a conventional analog-to-digital converter (ADC) whence it went directly to the telemetry.

Pulse-shape discrimination (PSD) is generally performed either by partial cancellation of the output pulse [*Forté et al.*, 1969; *St. Onge*

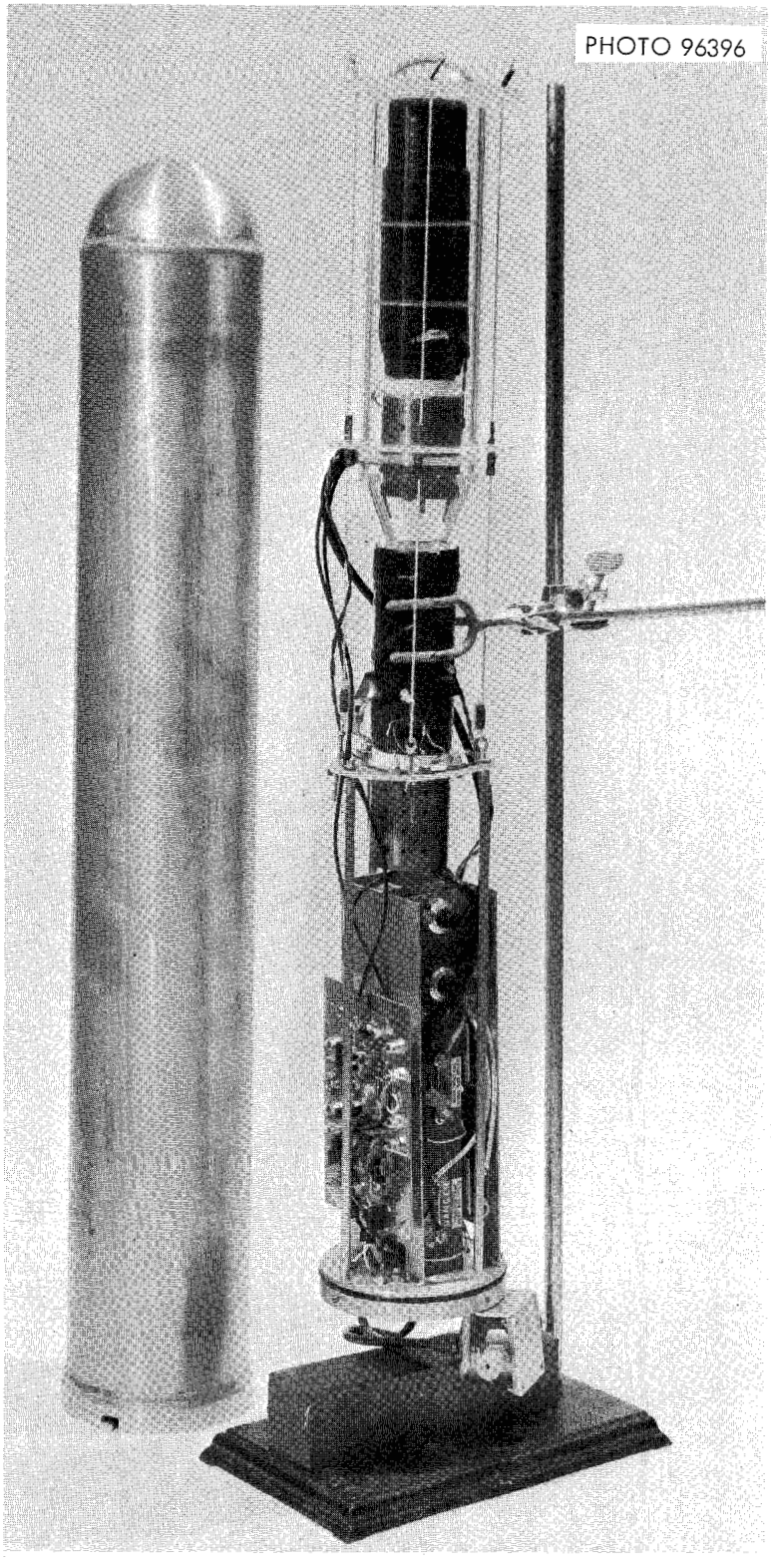

Fig. 1. Detector Assembly and Aluminum Pressure Can. The preamplifier (left) and high voltage supplies are shown mounted under the detectors.

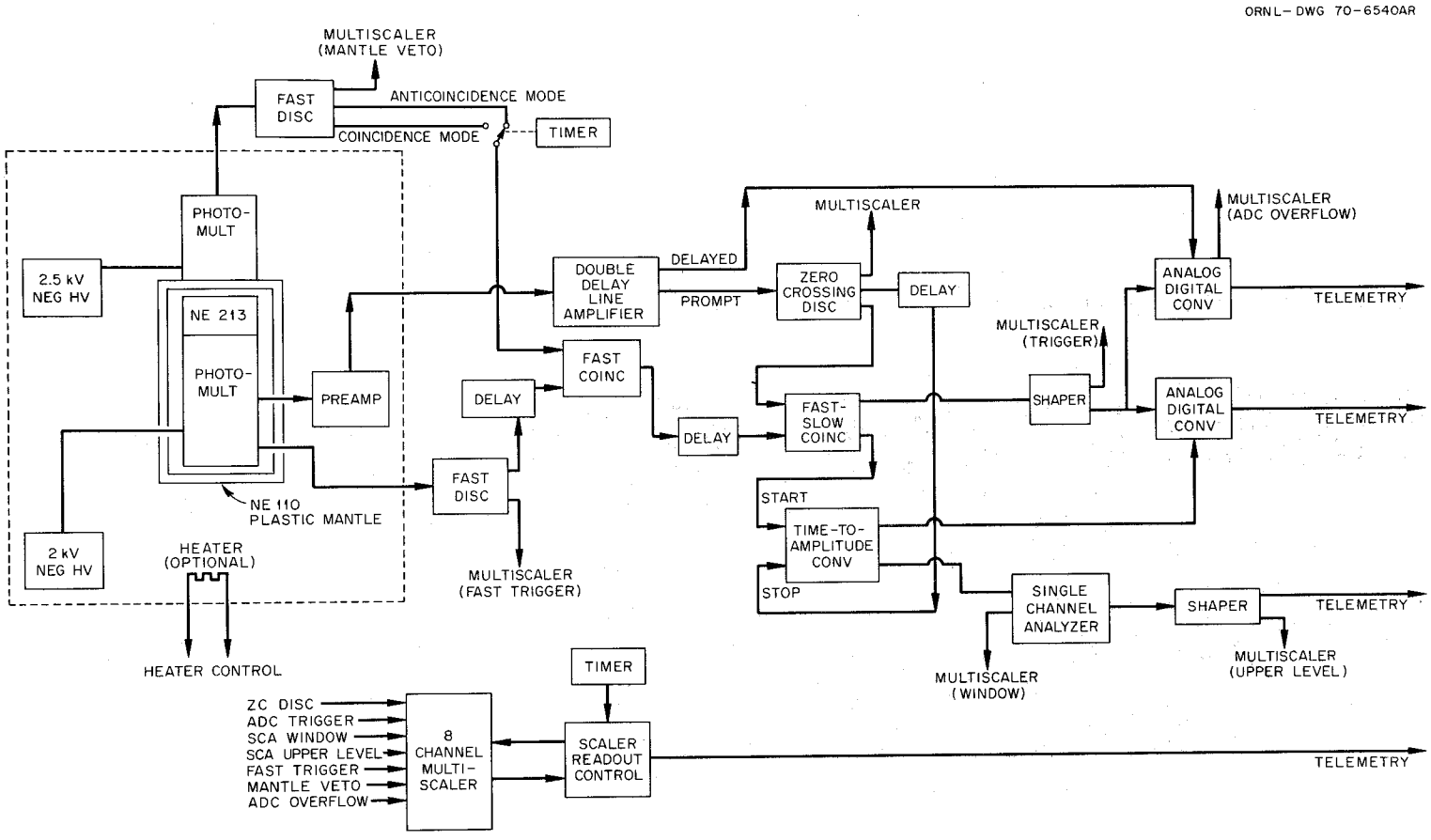

Fig. 2. Block Diagram of the Electronics.

and *Lockwood*, 1969] or by measuring the difference in the rise time of the charge pulse. We chose the latter method as sensed by the time difference in the crossing of the baseline of a doubly differentiated pulse. The anode pulse from the photomultiplier coupled to the NE-213, after shaping in a fast discriminator and being delayed for proper timing, set the timing for the start of the time-to-amplitude converter (TAC). The TAC was stopped by the prompt output of the zero-crossing discriminator. The fast coincidence circuit shown in the figure was used for the anti-coincidence veto, and the fast-slow coincidence ensured that the bias setting of the zero-crossing discriminator governed the acceptance of pulses for analysis. This type of operation reduced the amplitude-dependent timing spread in the system.

The PSD TAC output was analyzed in a separate ADC which had a common trigger with the PHA ADC. Thus, for each pulse analyzed in the PHA channel there appeared a corresponding analysis in the PSD channel. The telemetry readout was arranged to move the output from both ADC's sequentially with an identification bit set to indicate the PSD data channel.

The TAC output was also analyzed on board in a single-channel analyzer which set a bit in the telemetry buffer if the PSD pulse fell into a time range corresponding to a neutron event. This feature provided a certain redundancy since the decision as to the type of event can also be made at the time of data analysis from the pulse-shape parameter determined in the PSD ADC. The hardware decision made by the single-channel analyzer was used as an on-line feature to route the pulses in a ground-based multi-

channel analyzer which was used to monitor the output of the spectrometer.

Figure 2 also shows seven scalers in which the total number of events at certain points in the system were collected, and which were multiplexed onto a separate telemetry channel. These scalers were read out every five minutes under the control of an on-board timer, and the scalers were reset after readout.

Once each hour the system was calibrated using a ^{22}Na source which was mounted at the top of the mantle. For this measurement the gain of the amplifier was increased by a factor of 25. Two sets of calibration data were taken, one with the mantle in anticoincidence with the neutron detector, the other with the mantle in coincidence. A comparison of the counts in the two modes with values determined prior to take-off could be used to monitor the proper operation of the mantle.

The instruments used throughout the experiment were laboratory-type NIM modules. Many of them were obtained from commercial vendors, with the remainder designed and built at ORNL. It was also necessary to modify some of the commercial modules for our application. Because laboratory-type equipment was used we had to satisfy ourselves that it would function properly in the environment found at float altitude. Tests of equipment functioning in an environmental chamber showed that electronic drift occurred over a period of time. We believe this was due to the formation of "hot spots" within the modules due to insufficient convection cooling in the rarified atmosphere. We therefore decided to enclose the instrumentation in a pressure-tight box and maintain it at surface pressure ($\sim$ 1000 mb). All equipment was tested to operate properly over a 10° to 50°C

temperature range. Figure 3 shows the equipment installed in the box. Note that only the instruments required for the spectrometer were mounted in the box. The telemetry, which was furnished by Marshall Space Flight Center, Huntsville, Alabama, did not require this temperature protection and was therefore mounted separately.

In addition to the two telemetry channels shown in Fig. 2 which carried the ADC information and the scaler readout, respectively, we transmitted the output from pressure and temperature sensors and from voltage monitors via an additional channel. These quantities were sampled ten times per second and transmitted as analog information.

BALLOON FLIGHT AND DATA ACQUISITION

The detector and associated equipment were launched at 0627 hours CDT on June 17, 1969, from Palestine, Texas, by personnel of the NCAR Balloon Flight Station. The balloon chosen for the flight was a Winzen (Winzen Research, Inc., Minneapolis, Minn.) 2.90×10^6 ft^3 balloon constructed of 1.5-mil polyethylene. As the balloon reached 1000 ft altitude the detector assembly was lowered by ground command. The average rate of ascent was 258.8 m/min, and float altitude of about 32 km was reached about 0830 hours CDT. The balloon floated slowly westward until the flight was terminated from the chase plane at 1800 hours CDT, chosen to permit a daylight recovery of the equipment. A trajectory of the flight is shown in Fig. 4. The equipment was recovered in good condition near Bronte, Texas, and returned to Palestine. When the system was checked out after return to ORNL it still functioned correctly.

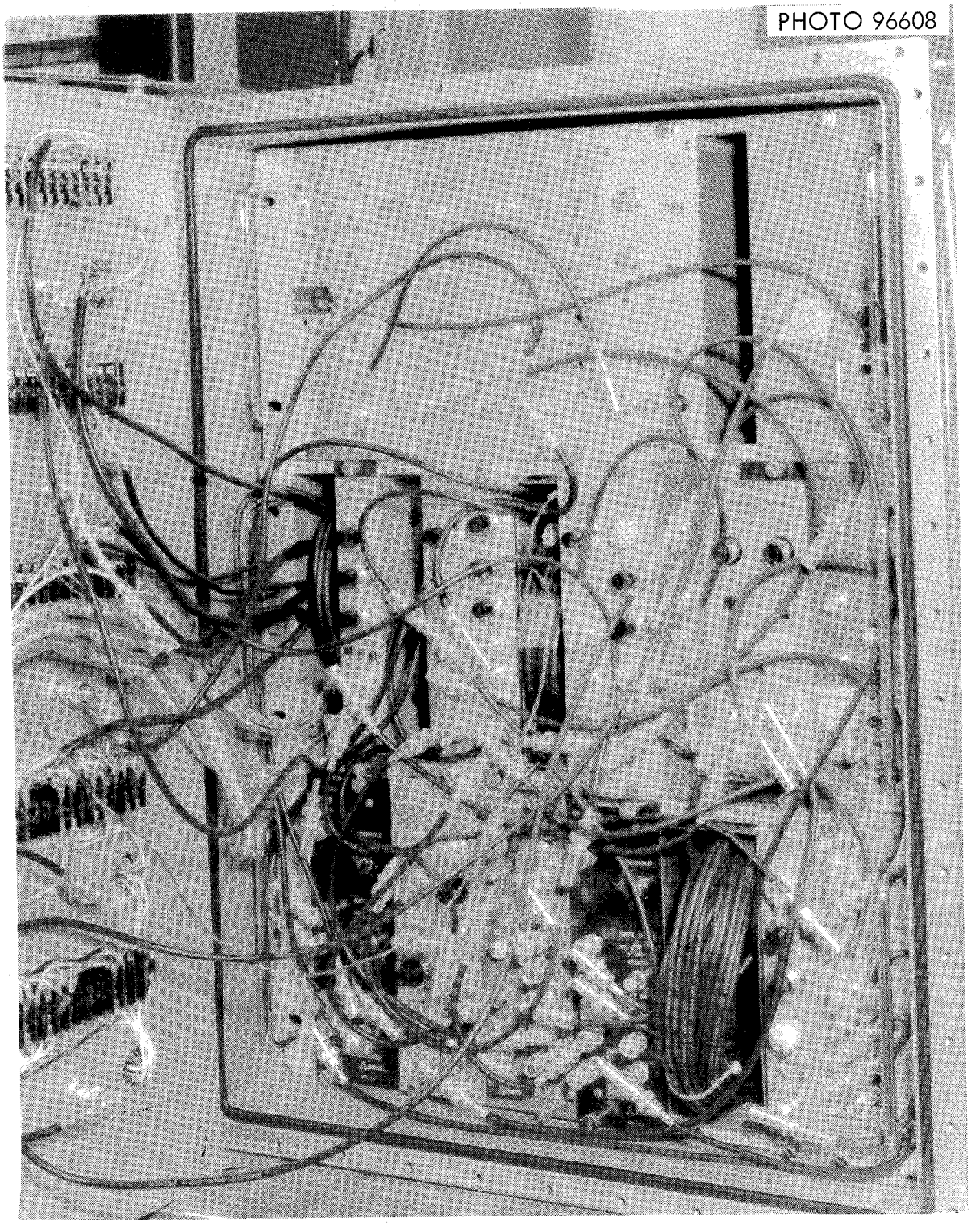

Fig. 3. The Electronic Equipment Mounted in Its Pressure Box. Note the use of standard NIM modules.

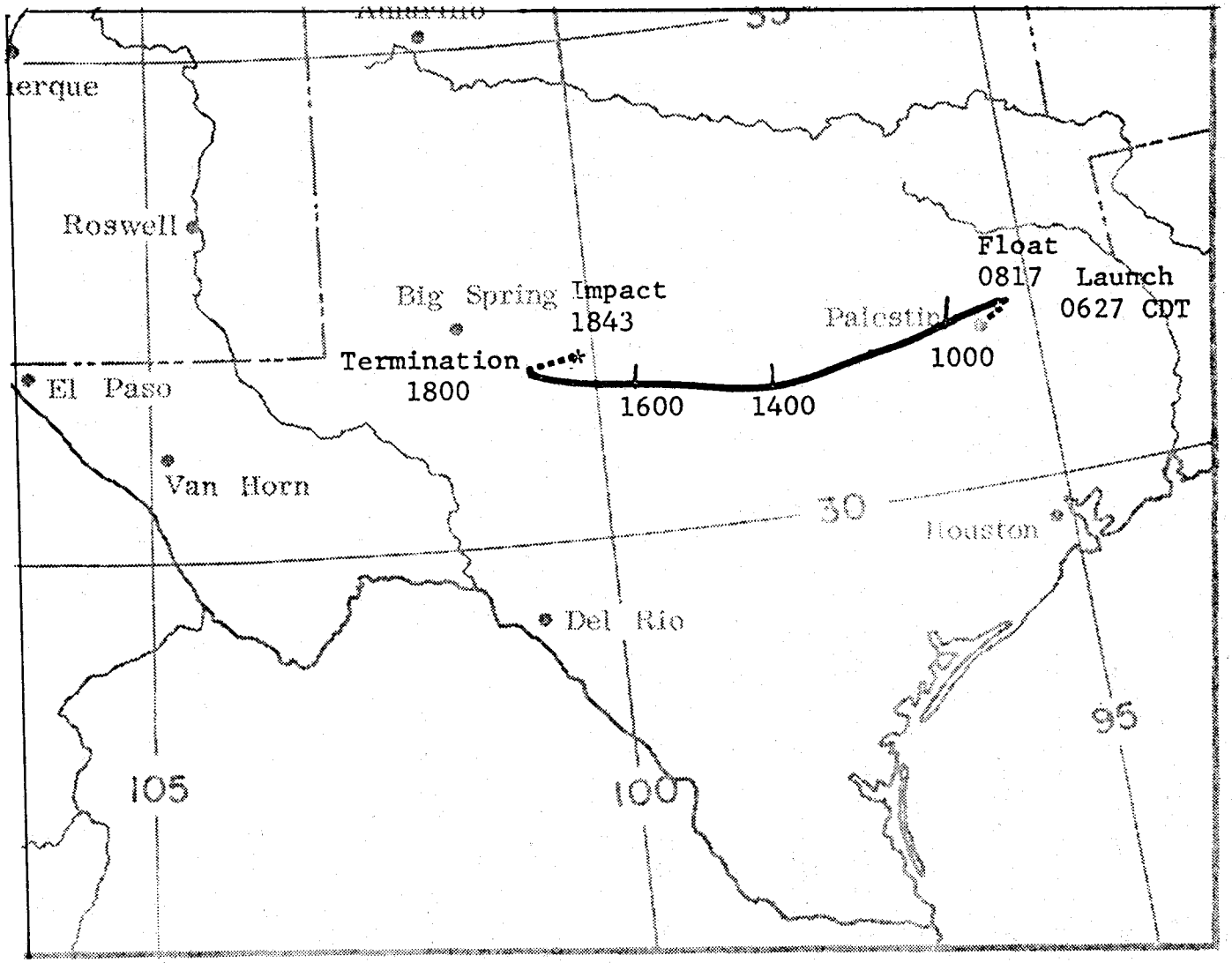

Fig. 4. Flight Trajectory.

As was mentioned in the preceding section, the data taken during the flight were telemetered to the ground in real time. A base station was maintained at Palestine for the reception of the data, and a mobile station had deployed in the anticipated direction of float to the San Angelo airport. As it happened, the balloon was in excellent telemetry contact with the base station throughout the flight, so the back-up capability represented by this station was not required.

The data on the three telemetry channels were recorded in real time on a broad-band analog magnetic tape. The recorder ran continuously; about 18 minutes of data could be recorded on one tape, and tapes could be changed in but a few seconds. A total of 39 tapes were used.

The data from the ADC's, representing pulse-height analysis and pulse-shape discrimination data, were demodulated on-line and stored in a multichannel analyzer for diagnostic purposes. The memory of the latter was divided into four 256-channel section: gamma-ray and neutron pulse-height data were routed into the first and second quadrant, respectively, and the PSD information into the third quadrant. Figure 5 shows typical displays from the CRT of the analyzer. The information stored in the analyzer was extracted on punched paper tape every hour, and the analyzer cleared, prior to the detector calibration. Data for each calibration mode were accumulated separately, and also punched out separately. Figure 6 shows a representative set of displays from the calibrations. Punching out the information assured the availability as back-up of most of the information which was stored on magnetic tape.

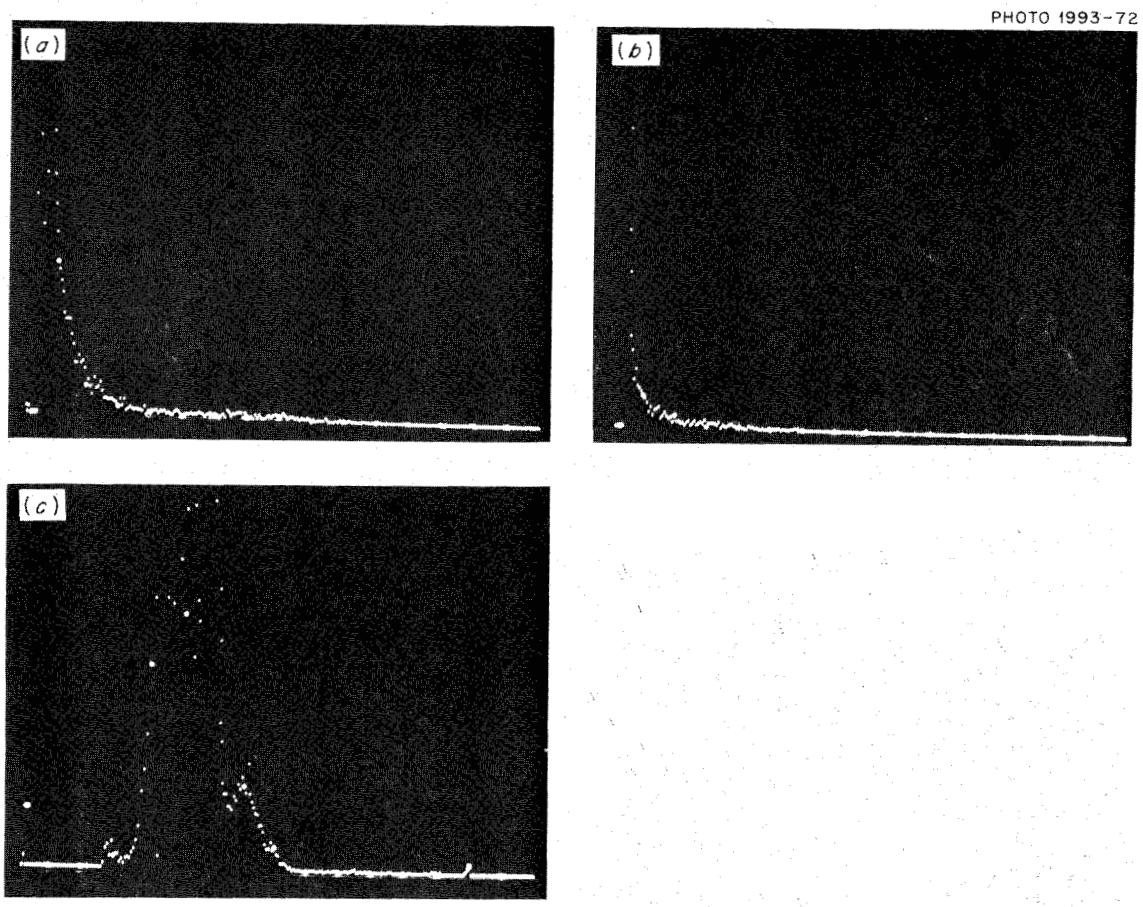

Fig. 5. Displays of the Spectra Accumulated in the Multichannel Analyzer. (a) Gamma-ray pulse-height spectrum, (b) neutron pulse-height spectrum, (c) total PSD spectrum. The scale for the last was chosen to emphasize the neutron peak (right), thus causing the gamma-ray peak to overflow full scale.

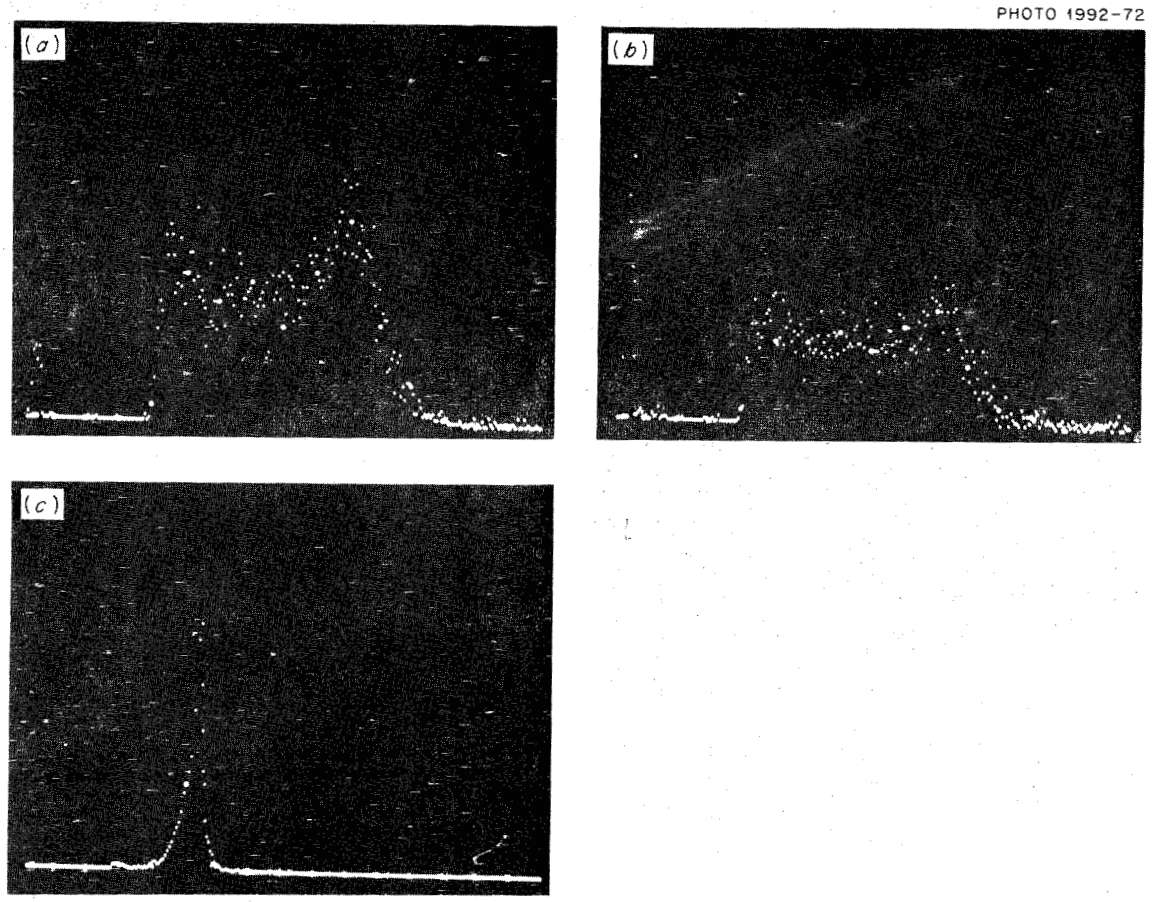

Fig. 6. Displays of the Spectra Accumulated in the Multichannel Analyzer During the Calibration Phases. (a) ^{22}Na pulse-height spectrum, mantle in anticoincidence, (b) ^{22}Na pulse height spectrum, mantle in coincidence, (c) PSD spectrum.

The scaler information was printed out on a Hewlett-Packard printer. Since the scalers were automatically cleared after read-out, large deviations between consecutive sets would immediately indicate serious trouble.

The analog information was read out periodically by manually selecting the commutator position corresponding to the desired analog signal, and printing the reading from a digital voltmeter. We felt that rapid changes in the analog quantities sampled would only occur in the event of a catastrophic failure which we could observe both from the analyzer display and the scaler output, so that a rather infrequent read-out rate of once ever thirty minutes seemed adequate.

Inspection of the data, shown in Fig. 7, revealed that the temperature inside the mantle, which had to be kept above 15°C, varied between 43.6°C prior to take-off and 23.4°C shortly before termination of the flight; the temperature outside of the mantle varied from 44.5°C to 20.6°C; the temperature at the top of the instrument box varied from 35.5°C to 52.1°C. The temperature requirements for the detector assembly were thus easily met. Though the temperature in the instrument box was a bit higher than we preferred, no degradation of instrument performance was observed.

Figures 8 and 9 show the data for the various battery voltages, and for the pressure in the detector assembly housing and the instrument box, respectively. The pressure in the instrument box appears somewhat more stable, but the possible slight leak in the detector assembly housing was of no consequence to the experiment.

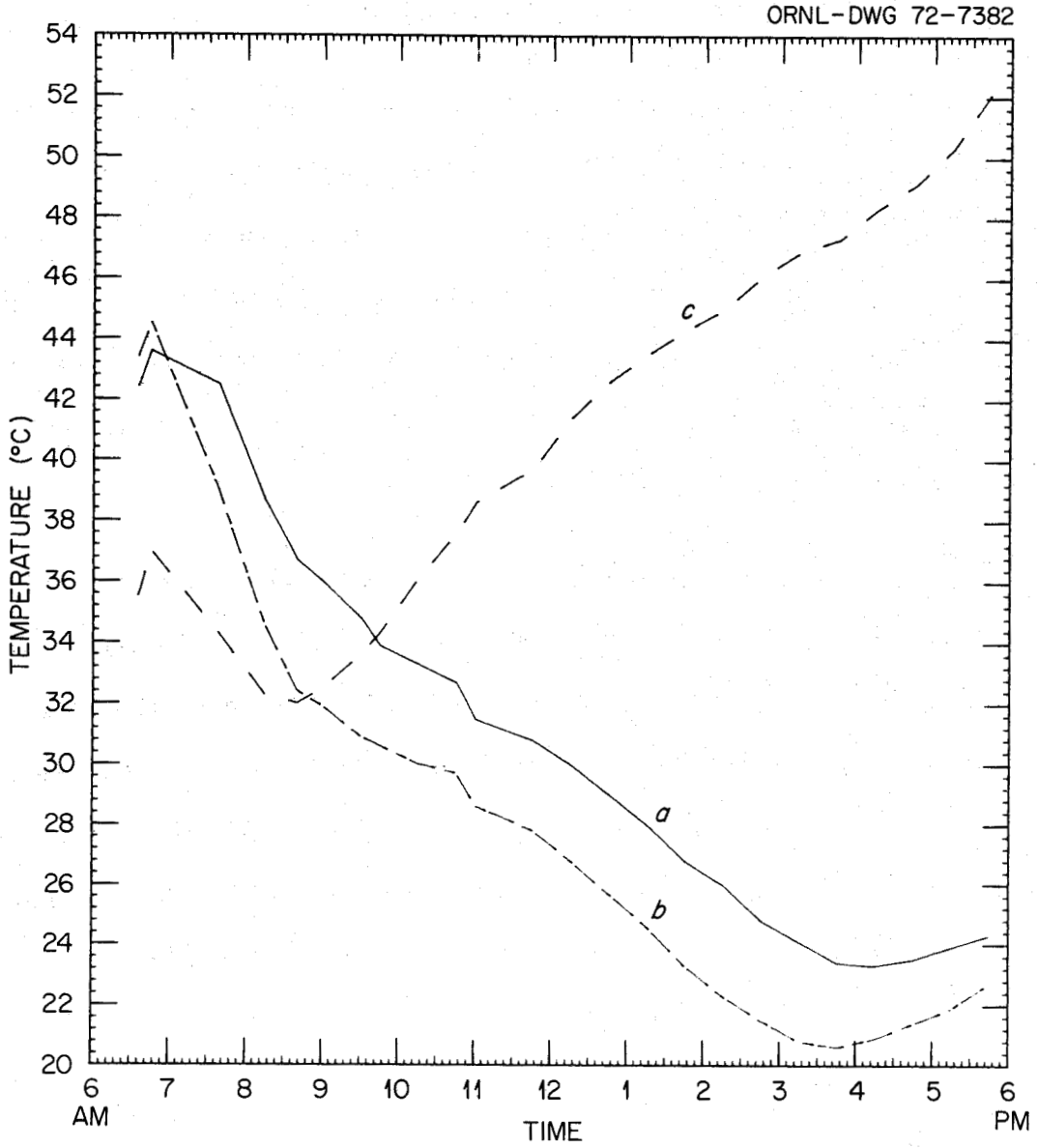

Fig. 7. Temperatures at Three Points in the Equipment. (a) temperature inside the mantle, (b) temperature outside the mantle, (c) temperature at top of instrument box.

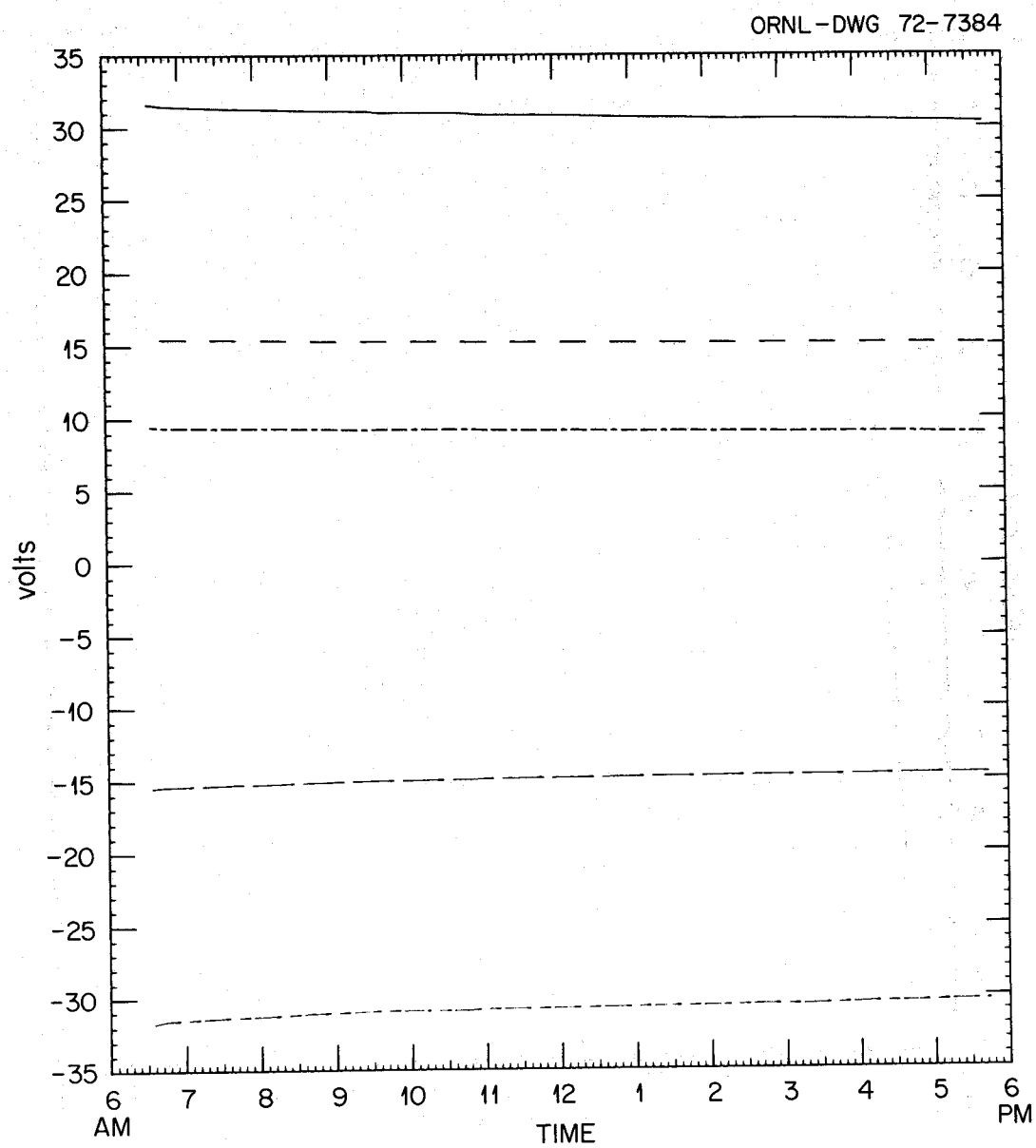

Fig. 8. Battery Voltages.

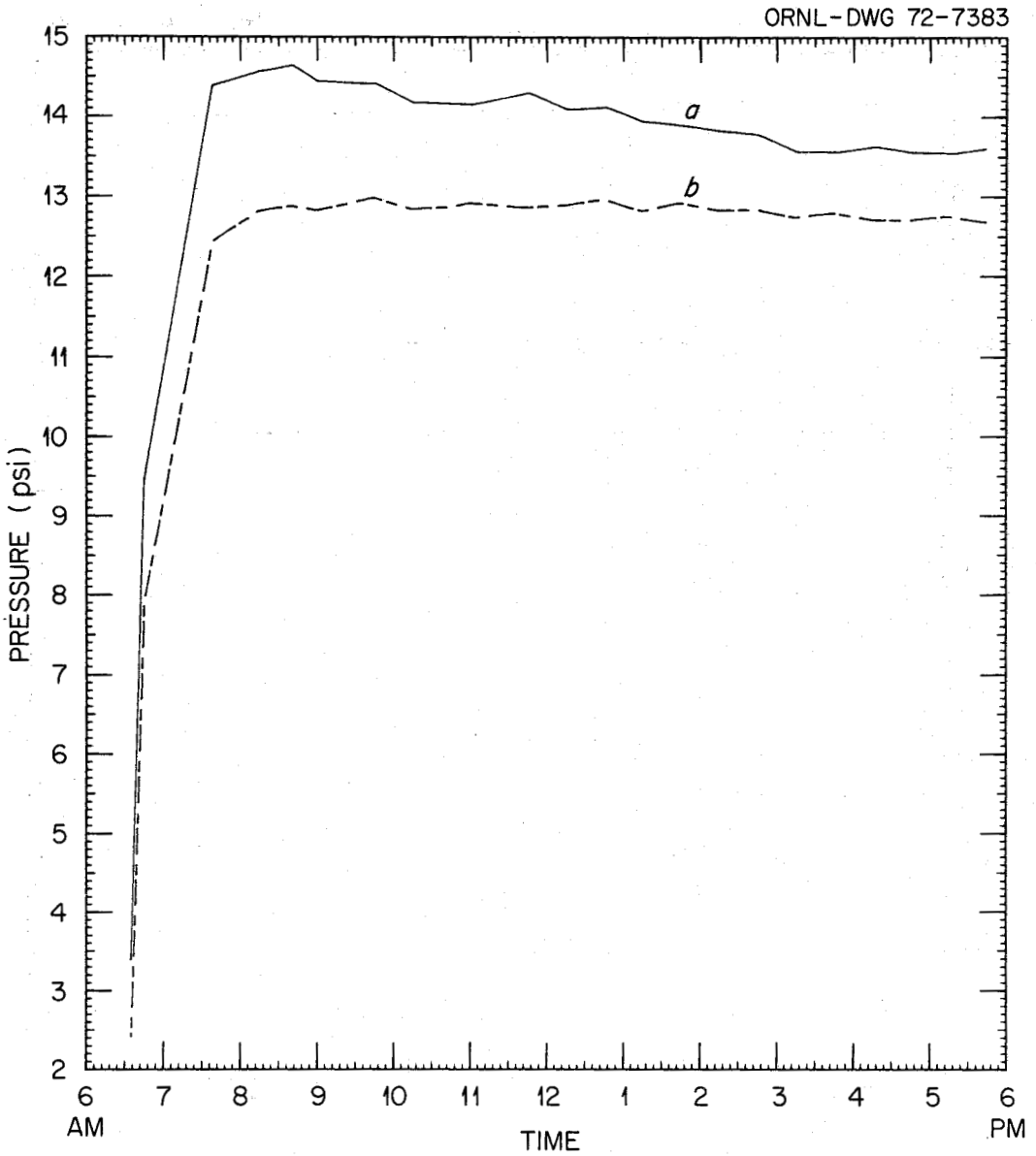

Fig. 9. Relative Pressure Inside (a) Detector Can and (b) Instrument Box with Respect to Outside Pressure.

DATA ANALYSIS

Since the PSD and PHA information recorded on the magnetic tapes was not in a form suitable for input to a computer the data format was converted using a PDP-8 with a specially constructed interface to accept the data from a playback recorder and store them on computer-compatible magnetic tape [*Marston*, 1969]. A scaler in which the pulses from the telemetry channel were recorded served as a relative clock and was recorded with each event. Each on-line tape was converted into a separate file on the new tape, thus permitting later selection of events covering a particular time interval.

The data obtained at float altitude, i.e., those collected between 0836 and 1757 hours, were selected for further analysis. Examination of the data from the multichannel analyzer had already established that there was no observable drift in the electronics so that all data in that time interval could be combined directly. We found that during certain periods, a high percentage of erroneous data as defined by impossible bit patterns had been recorded, probably as the result of electrical interference. We therefore adopted the criterion that any record containing more than 31 erroneous events (out of 256 events per record) was omitted from the analysis. The total data taking time was, of course, also reduced accordingly. Less than 5% of the total apparent events were so eliminated.

The first task was the establishment of a bias level for the PSD data since this determined which events would be related to neutrons and which to gamma rays. The data were displayed as a two-dimensional matrix of pulse-height channel versus pulse-shape channel. It was found that the

PSD bias should vary with pulse height, and this variation was taken into account in the sorting program. The data were then sorted into six spectra representing, respectively, neutron pulse height, neutron PSD, gamma pulse height, gamma PSD, calibration in anticoincidence mode, and calibration in coincidence mode. The sorting into the first three spectra was straightforward, the distinction between PHA and PSD information being made on the basis of the PSD flag set by the balloon spectrometer hardware, and between neutrons and gamma rays on the basis of the corresponding PSD pulse lying above (neutron) or below (gamma) the PSD bias established for that amplitude channel. The gamma PSD spectrum was determined in the same manner; however, due to the large number of gamma counts, only every 64th count was recorded in the spectrum. The neutron and gamma pulse-height spectra are shown in Fig. 10.

The determination of the advent of the calibration mode deserves some comment. The clock time at which the calibration in each mode occurred was known because it was determined by the precision timers employed. However, clock time was not registered on the data tapes so that this information could not be correlated to the data. As was pointed out in the section on instrumentation above, the gain of the amplifier was increased during the calibration by a factor of 25. This resulted in an apparent minimum pulse-height bias setting for gamma rays of channel 60. The criterion for determining the onset of calibration was therefore chosen to be three consecutive gamma-ray events with pulse height greater than or equal to that corresponding to channel 60. The end of the calibration was signalled by three consecutive gamma-ray events with pulse height less than channel 60. During the calibration no events were registered in the

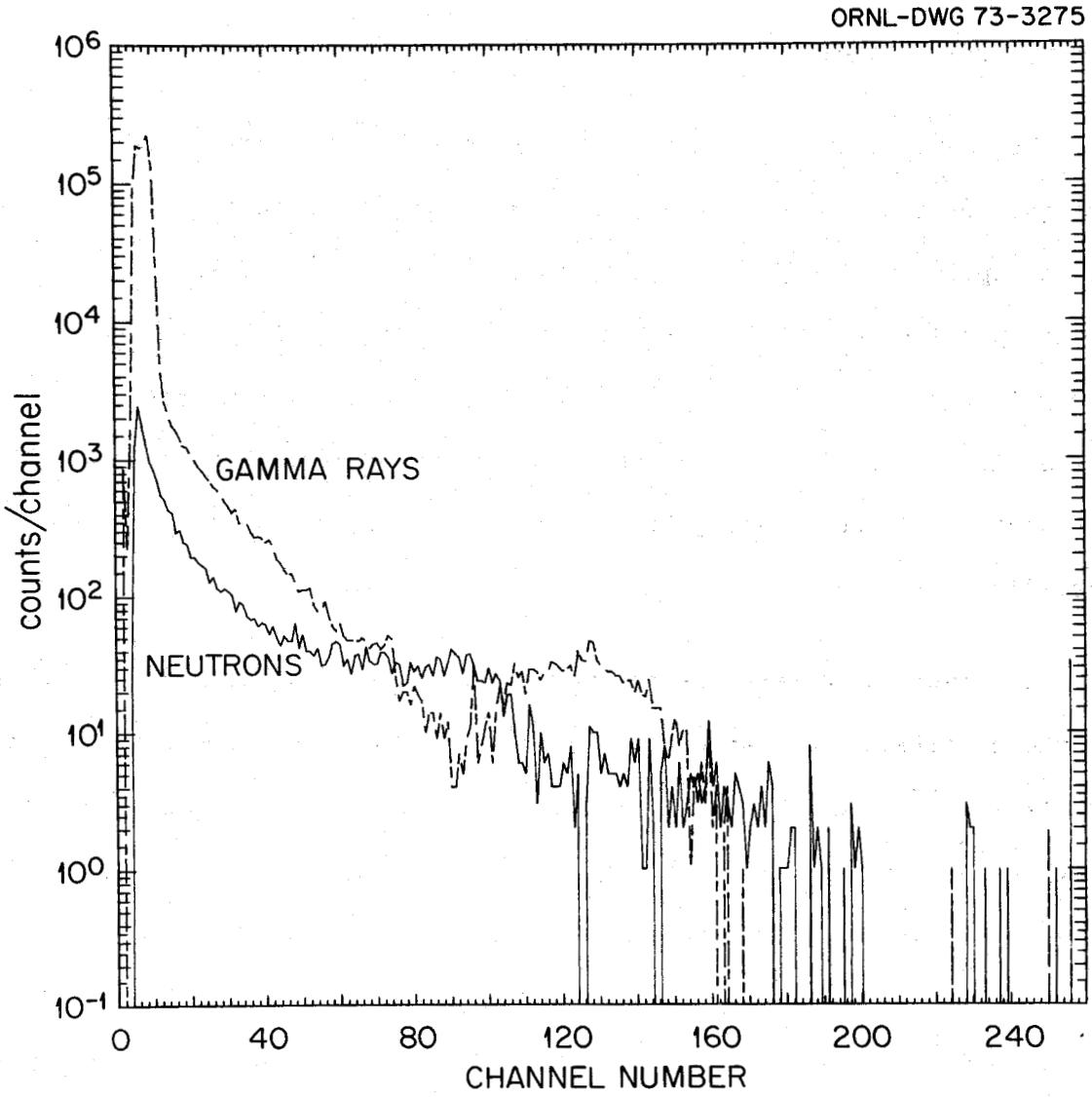

Fig. 10. Neutron and Gamma-Ray Pulse-Height Spectra.

neutron spectrum because of the change in gain. The duration of the calibration mode was determined by printing out the value of the clock scaler corresponding to the first pulse in the calibration mode, and again for the last pulse.

The data taken during the calibration mode were used to establish the gain of the system as well as the zero pulse-height offset which had to be applied to the data because the zero of the ADC as determined from a straight line through two known points did not lie in channel zero. The gain was determined from a least-squares fit to an analytical estimate [*Zobel* and *Hall*, 1971]. The offset was determined from the pulse-height bias cutoff channel, taking into account the known gain change in the amplifier.

In order to convert the pulse-height spectrum due to neutron events in the scintillator to an energy spectrum, one must employ some form of spectrum unfolding. The program package chosen for this purpose was the FERD package, a variant of FERDoR [*Burrus* and *Verbinski*, 1969; *R. W. Peelle*, 1971]. The use of this program requires the construction of a detector response matrix of pulse-height spectrum versus energy of a unit source of monoenergetic neutrons and also a so-called window matrix which establishes the energy resolution of the results.

It was clearly impractical to attempt to calibrate the detector assembly at a sufficient number of energies with the accuracy required to permit the use of such experimental response functions for the response matrix. However, *Verbinski et al.* [1968], had very carefully calibrated a quite similar detector at energies between 0.2 and 22 MeV, and a Monte

Carlo program (05S) [*Textor* and *Verbinski*, 1968] had been written specifically to enable estimation of pulse-height spectra for incident neutrons, taking into account multiple neutron interactions in the scintillator. We therefore decided to use 05S to calculate a set of response functions.

05S, in order to achieve running speed, contains several simplifying assumptions. First, it assumes that the only material present in the system is NE-213; in our case this assumption is not bad since the can enclosing the scintillator is quite thin, and the mantle is also a hydrocarbon of similar composition. Second, 05S assumes a parallel beam of monoenergetic neutrons incident upon the detector; this assumption is poor for this work, and program changes were developed to assess the effect of an isotropic flux and the anticoincidence mantle upon the calculated results. Finally, 05S had no provisions for the geometry of the detector corresponding to the assembly which we employed, but assumed that the detector was a right circular cylinder. The changeover to the actual geometry also involved additional coding. As might be expected, the effect of the changes is most pronounced for the low-energy neutrons where absorption in the mantle would be only partially compensated by in-scattering into the detector. At high energies, in-scattering is more important. Over the energy region from 2.21 MeV to 70 MeV the change, referred to the geometry of *Verbinski et al.* [1968], amounted to no more than 25% with the sign changing at about 10 MeV.

A Monte Carlo program such as 05S depends critically upon the cross sections supplied to it. Since the program assumes the whole system to consist of one material the problem is simplified in that only the cross

sections for neutron interactions with hydrogen and carbon must be known. The difficulties in our problem arise because the interaction cross sections in carbon which give rise to secondary particles, i.e., (n,α), (n,n'3α), (n,p), (n,pn), (n,2n) reactions, are poorly known, if at all, over most of the energy range of interest. The measurements of *Verbinski et al.* [1968] provided checkpoints to 22 MeV against which the cross sections used could be tested as well as the code. To extend the range further, a calibration of the same detector as used by Verbinski as well as of the balloon detector assembly was performed with monoenergetic neutrons of 37.4 MeV [*Cohen et al.*, 1969]. A set of cross sections was developed which, in conjunction with 05S, could be used to represent the measurement. The set was extended past our calibration to 70 MeV. Comparison by *Wachter et al.* [1972] with their measurements confirmed the adequacy of this set to 60 MeV.

To construct a response matrix out of the monoenergetic response functions produced by 05S required binning the response functions in the same bins as were used to bin the experimental pulse-height data, and interpolating among them to arrive at functions corresponding to the proper energies. The generation of the response matrix was performed by the program package RESPMG [*Burrus* and *Freestone*, 1970]. For the window functions, we chose Gaussians of 30% resolution full width at half maximum amplitude to obtain the energy spectrum.

Using these matrices FERD calculated an upper and a lower bound to the energy spectrum, chosen in our case to represent approximately a 68% confidence interval. This interval took into account not only the errors

in the input data but also a contribution to the uncertainty due to the unfolding process.

We have estimated the contribution to the neutron spectrum due to neutrons generated in the iron and aluminum cans in (p,n) reactions. Briefly, we approximated the proton spectrum calculated for 10 g/cm^2 residual atmosphere [*T. W. Armstrong*, Oak Ridge National Laboratory, private communication, 1972] by

$$P(E) = 3.1236 \times 10^{-24}\ E^{1.8056} \qquad (0 \leq E \leq 5 \times 10^7)$$

$$P(E) = 3.1120 \times 10^{-2}\ E^{-1.0515} \qquad (5 \times 10^7 \leq E \leq 5 \times 10^9)$$

where P is the number of protons/(eV-cm^{2}sec) and E is the proton energy in eV. The neutron production cross section was obtained from calculations of ***Bertini*** [1963, 1966] for aluminum and chromium, with the latter used to represent iron. The cross-section data were represented by

$$\sigma(E) = 0.49782\ E^{0.053226} \text{ barns for aluminum}$$

$$\sigma(E) = 0.54339\ E^{0.21777} \text{ barns for chromium}$$

where the energy E is expressed in MeV. It should be noted that these expressions overestimate the cross section in the proton energy region from threshold to about 50 MeV. As a first approximation to the neutron production it was assumed that the neutrons moved from their birth place with the same energy and direction as the creating proton, and that the latter constituted an isotropic field. Ascribing the full proton energy to each neutron overestimates the production of high-energy neutrons; this appeared desirable as a conservative assumption.

The neutron production rate was then calculated from the product of the number of protons derived above, the macroscopic cross section for neutron production, and the average can thickness. The maximum relative contribution to the spectrum from this calculation occurred at 50 MeV where it amounted to ∿3.5%. We therefore concluded that no correction need be applied to the results of the FERD calculation to account for contributions from the immediate environment of the detector.

Another source of uncertainty is the PSD bias setting. Again due to the scarcity of counts in the higher pulse-height channels it was difficult to make a unique bias assignment. The error assigned to each pulse-height bin to be used in the analysis includes only the statistical uncertainty in the observed counts, with no allowance for possible error in the bias.

RESULTS AND DISCUSSION

The results of the data analysis described above are shown in Fig. 11, together with results of other experiments [*Heidbreder et al.*, 1970; *Jenkins et al.*, 1971; *Preszler et al.*, 1972; *Leavitt*, 1972]. In Fig. 12 our results are compared with calculations [*Lingenfelter*, 1963; *Freden* and *White*, 1962; *Armstrong et al.*, 1972].

The first noteworthy feature of our data is the apparent structure. Examination of the pulse-height spectrum shows a bump or shoulder in the region from channel 76 to channel 103, corresponding to the maximum pulse height obtainable from neutron energies of 16.8 MeV to 21.6 MeV, respectively. There is also a noticeable dip in the gamma-ray pulse-height spectrum in this region. Since there is the possibility of improper PSD

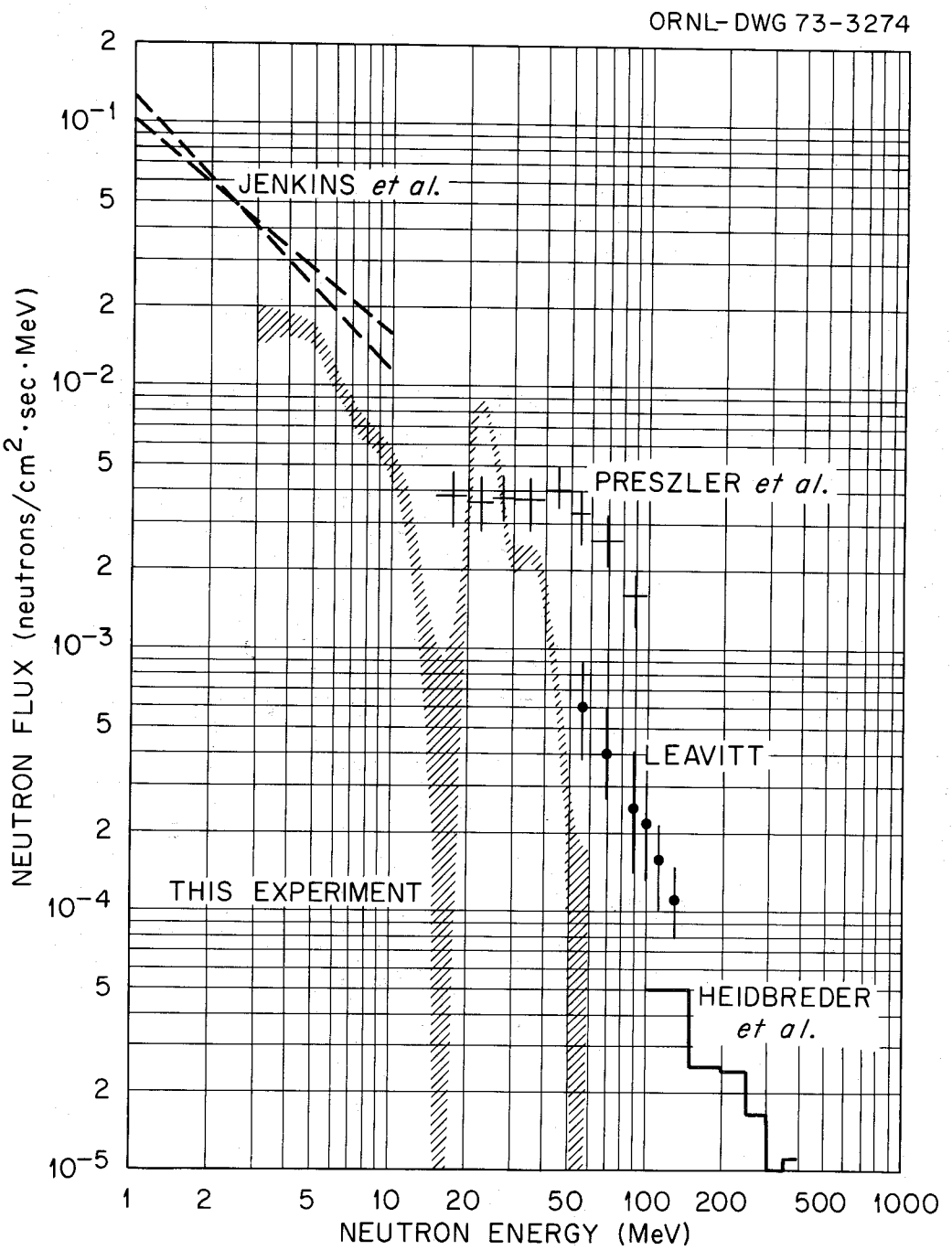

Fig. 11. Neutron Spectra Measured in the Energy Range from 1 to 400 MeV.

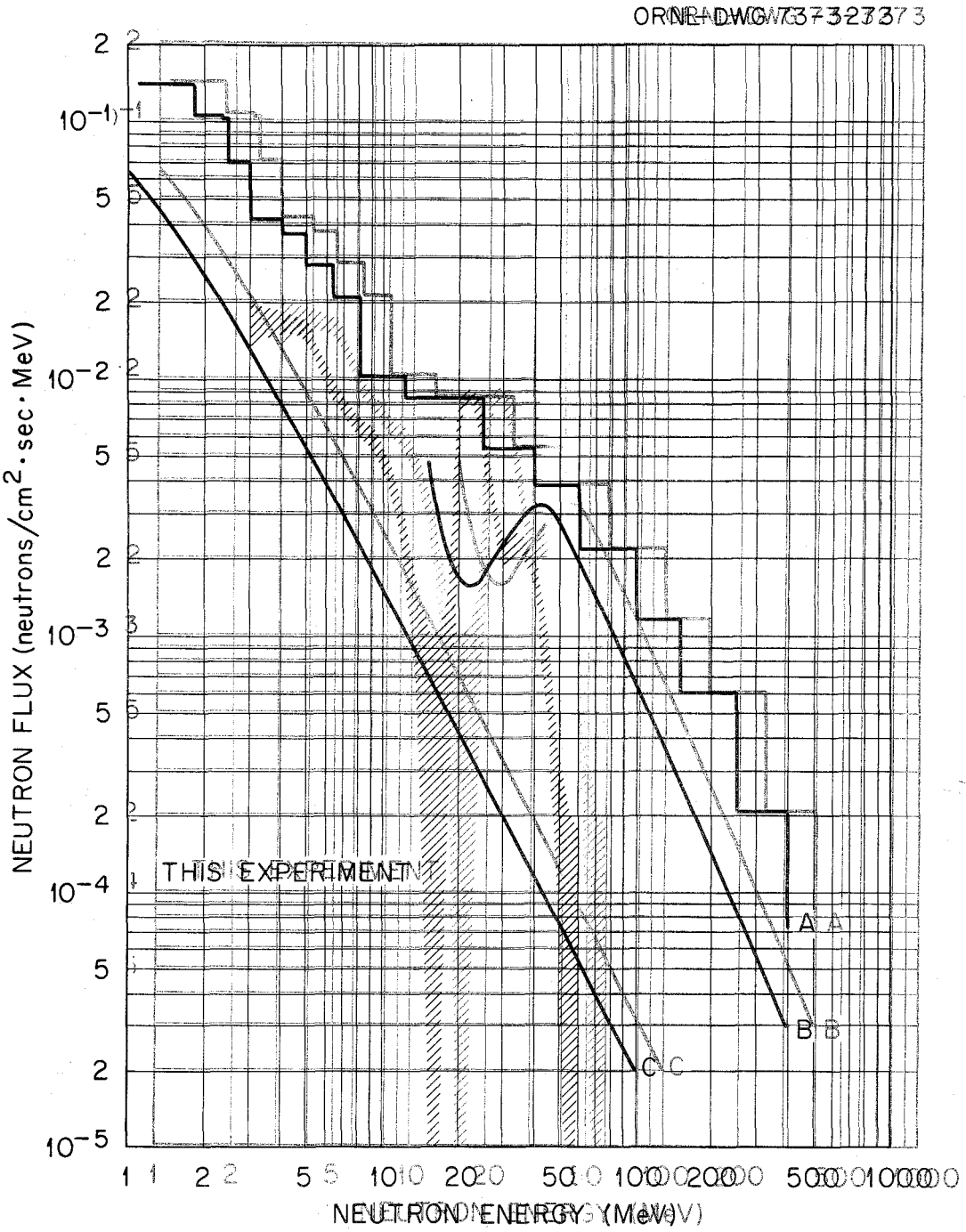

Fig. 12.2. Results of This Experiment as Compared with Various Calculations: (A) Armstrong et al., (B) Freden and White as Modified by Preszler et al., (C) Lingenfelter. The shaded band represents our experimental results.

bias selection as discussed above, particularly toward the upper end of this range, the spectrum was re-calculated under the assumption that half the difference between the neutron and gamma-ray counts in this interval should be ascribed to gamma rays, thus reducing the shoulder. This rather drastic change did indeed reduce the peak height and raised the dip, but did not eliminate either. The average integrated neutron flux between 11 and 30 MeV changed by less than 10%, well within the uncertainty limits.

Concerning a comparison of our results with those of others, it must be noted that the data shown are those reported by the investigators, and thus represent a variety of experimental conditions.

The experiment performed under conditions most similar to ours is that of *Heidbreder et al.* (flight data September 15, 1969; altitude 7 g/cm^2 residual atmosphere). While there is a gap in the energy range covered, it is clear that our data are consistent with theirs. Unfortunately, their results are based on only ten events in which the neutron was moving in an upward direction, out of a total of 17 events. Multiplication of their result by 1.7 to account for all the neutrons for comparison with our data would not significantly alter the agreement.

The spectrum of *Jenkins et al.* was taken between June 7 and September 30, 1969 by a neutron detector aboard OGO 6. Our experiments thus occurred at essentially the same part of the solar cycle. The slope of our data below 10 MeV is not inconsistent with their results, being -1.28 ± 0.21 compared to their -0.90 ± 0.10. It also agrees with the results of *Merker et al.* [1965] who find -1.08 ± 0.1. However, our results differ

in magnitude from Jenkins' by roughly a factor of 2, our results being lower. From the results of *Haymes* [1964] for the variation of the neutron flux with altitude one would expect a decrease of about a factor of 2 from 10 g/cm^2 to 0 g/cm^2. Armstrong's calculations predict a factor of about 1.8, in substantial agreement. On the other hand, Lingenfelter's calculations indicate an increase in the neutron flux as one goes from 40° to 90° geomagnetic lattitude by about a factor of 2; since Jenkins' data refer to the polar region, their results should be decreased by this factor to compare with ours. The two effects (altitude and latitude) thus are expected approximately to cancel, thus leaving a discrepancy of about a factor of 2. Part of the discrepancy could be caused by neutrons produced by charged particles in the presumably more massive environs of their detector.

Preszler et al. obtained their data on September 26, 1971 at an altitude of 4.65 g/cm^2 but in the same geomagnetic latitude as our flight. Direct comparison of the results indicates reasonable agreement between 20 and 35 MeV; however, above this energy our spectrum falls off more sharply than theirs. Again we have offsetting relative corrections here, for altitude and point in solar cycle. The altitude correction (determined as above) indicates that the results from *Preszler et al.* should be increased by about 20% to compare with ours. The solar cycle correction [from *Lingenfelter*, 1963] amounts also to about 20% and requires a decrease in their results.

Finally, we have the preliminary results of Leavitt taken with a neutron spectrometer aboard OSO-6. Since these data are still preliminary

we will not make detailed comparisons. Suffice it to state that they are surely not inconsistent with our results.

If we compare our data to the calculations we note immediately the similarity in shape between our data and the curve of *Freden* and *White* (which is shown as modified by *Pressler et al.*). It is very tempting to assume that there was an error in the gain of the spectrometer, which could account for such a shift. However, we very carefully examined our gain determination not only as integrated over the flight (from which the gain was taken) but also as determined hourly so as to establish a drift, if any. As a result of these considerations we are convinced that there was no gain drift during the flight, and the gain as determined from these data is correct.

In comparing our data to the calculations of *Armstrong et al.* we note not only the difference in shape but also in magnitude. The geophysical conditions are the same, and the strong difference in predicted and observed pulse-height spectra extends far down into the energy region where instrument testing was secure and pulse-shape discrimination was unambiguous.

To ensure that the intensity difference was not created in the data analysis we constructed a response matrix corresponding to the center energies of the bins in Armstrong's calculations. Multiplication of the calculated spectrum with this response matrix then yielded a pseudo pulse-height spectrum which would be expected assuming Armstrong's neutron flux. Comparison of this spectrum with our experimentally observed pulse-height spectrum is shown in Fig. 13. The three rather obvious shoulders in the pseudo spectrum are due to the limited number of response functions used in this calculation, and should therefore be smoothed by eye. It is apparent that except for pulse heights corresponding to about 20 MeV the pseudo spectrum has about 2 to 4 times the intensity of the observed one, a discrepancy consistent with that observed in the unfolded results.

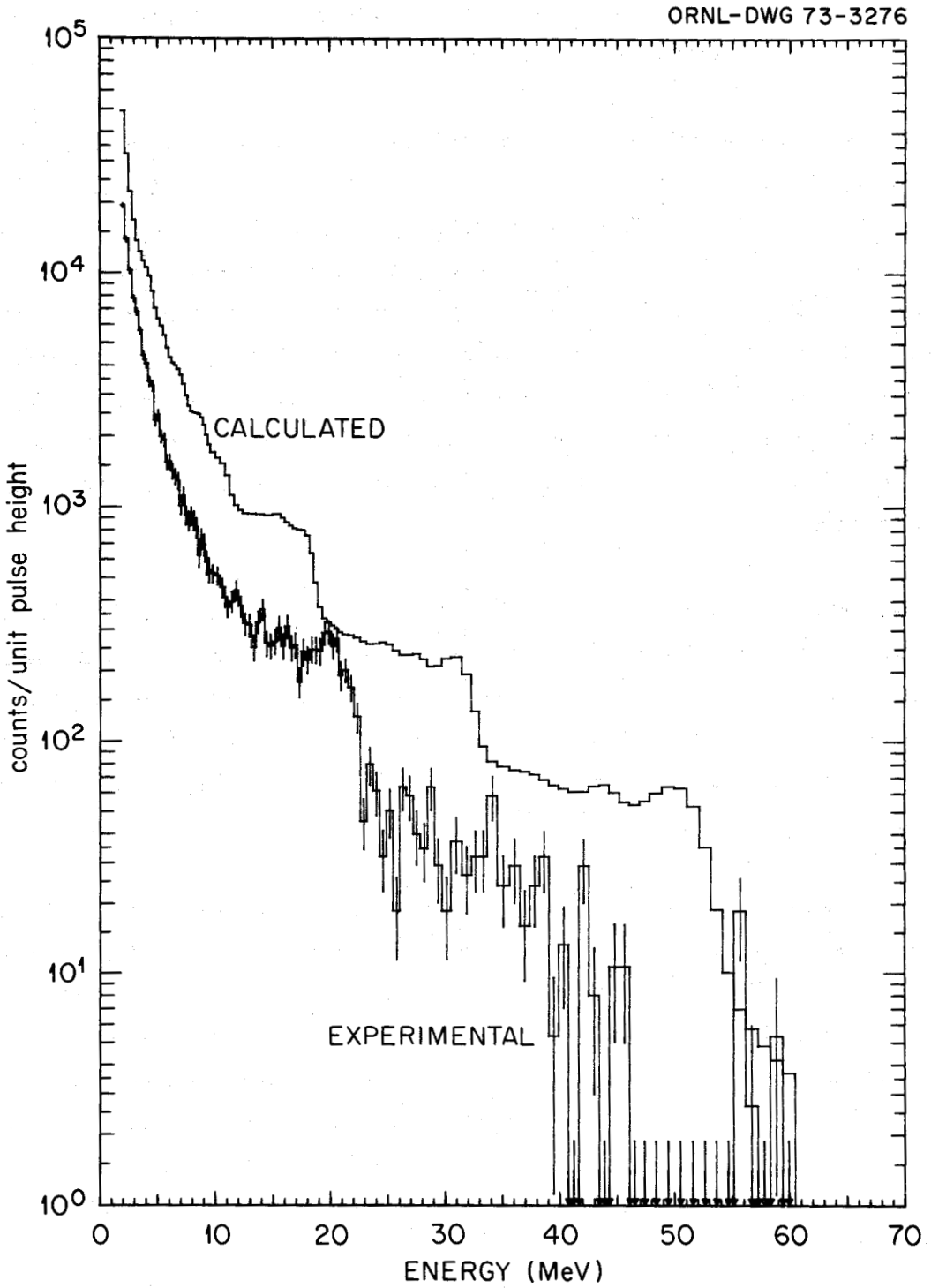

Fig. 13. Comparison of the Experimentally Determined Binned Pulse-Height Spectrum with a Pseudo-Spectrum Calculated on the Basis of Armstrong et al. The Abscissa Represents the Energy of a Neutron Which Can Produce that Maximum Proton Recoil Pulse Height.

The Lingenfelter spectrum is shown principally for historical reasons because it has been widely used. Since this spectrum relates to the top of the atmosphere, i.e., 0 g/cm^2, it should be increased by about a factor of 2 for comparison with our data. The trend of our data, ignoring the structure, is not incompatible with the shape calculated by Lingenfelter. However, our spectrum exceeds his by about a factor of 3, or is 50% greater than his corrected for altitude.

It is difficult for us to account for the difference between our results and those of *Preszler et al.* obtained with a much more complex and less fully demonstrated spectrometer system, or the calculations of *Armstrong et al.* While our results suffer due to a paucity of data at the higher energies, as discussed in previous sections, we feel that these considerations should not apply to the region below, say, 10 MeV, where we experience no trouble in separating counts due to neutrons and gammas unambiguously, and have enough counts for good statistics. Yet even in this region do our results differ markedly from Armstrong's calculations or Jenkins' results.

CONCLUSIONS

We have measured the neutron energy spectrum at 9 g/cm^2 in the energy range from 3 to 60 MeV. The results appear consistent with those of *Leavitt* [1972] and *Heidbreder et al.* [1970] but differ from those of *Jenkins et al.* [1971] and *Pressler et al.* [1972]. Our results also differ from the calculations of *Lingenfelter* [1962] and *Armstrong et al.* [1973]. To the extent that our data exceed Lingenfelter's calculations they increase the importance of the CRAND mechanism as a source of Van Allen belt protons. However, the increase is far from sufficient to remove the discrepancy. We suggest that additional work will be required to determine the reason for the differences.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the staff of the NCAR Scientific Balloon Facility for the smooth launch and recovery of the experiment, to Messrs. K. M. Hinkle and J. Spivey, NASA-MSFC, and C. Morring, Brown Engineering, Huntsville, Alabama, for their assistance in the recording of the data; to the staff of the ORNL Computing Center for assistance in the data reduction process; to Mr. R. T. Santoro, Dr. J. W. Wachter, and especially Dr. R. W. Peelle for many helpful discussions; and to Dr. F. C. Maienschein for his continued support and encouragement.

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