

The NSBRI/APL Neutron Energy Spectrometer

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Long-term interplanetary space travel and habitation produce enhanced risks to astronauts as a result of the high-energy cosmic rays and protons unmitigated by any thick planetary atmospheres and protective magnetic fields such as those of Earth. The high-energy collisions of these cosmic rays and protons with thick structures and thin atmospheres produce a secondary “beam” of charged particle fragments and neutrons that are more numerous than the incident primary particles. Since 1997, APL has been developing a compact, real-time neutron energy spectrometer to help monitor the radiation environment inside interplanetary transport vehicles and on planetary surfaces.

BACKGROUND

In 1997, NASA founded the National Space Biomedical Research Institute (NSBRI),¹ a consortium of 12 institutions, to study human health problems associated with prolonged space travel and countermeasures to those risks. APL and the Hopkins School of Medicine are charter members of NSBRI. The institute worked with NASA on the Bioastronautics Roadmap² that identifies about 55 critical risks of spaceflight and categorizes the risks into 12 risk areas. APL has been involved in research in a number of these risk areas associated with long spaceflights including bone loss³ and other physiological changes.⁴ This article discusses another problem for human space travel—radiation effects—and APL’s role in the evolution of a neutron energy spectrometer to monitor the radiation environment likely to be experienced by humans within transport vehicles and on other planetary surfaces.

SCOPE OF INVESTIGATION

High-energy charged particles of extra-galactic, galactic, and solar origin collide with spacecraft structures in Earth orbit outside the atmosphere and in interplanetary travel beyond the Earth’s magnetosphere. These primary particles create a number of secondary particles inside the structures that can produce a significant ionizing radiation environment. This radiation is a threat to astronauts and others on long-term space missions and produces an increased risk of carcinogenesis, acute and late central nervous system risks, DNA damage, and chronic and degenerative tissue risks.^{2,5} Specifically, the primary high-energy cosmic rays and trapped protons collide with spacecraft materials such as aluminum and silicon to create secondary particles that are charged particle fragments and neutrons inside structures. The effect of tens of grams per square centimeter of structure or atmosphere is to convert and multiply the primary

proton “beam” into a secondary environment dominated by neutrons. Charged protons are readily detected, and instruments are already in existence for this task. Neutrons are electrically neutral and much more difficult to detect. These neutrons are estimated to contribute 10–30% of the radiation dose inside space structures such as the International Space Station (ISS)⁶ and cannot be ignored. Currently no compact, portable, real-time neutron detector instrumentation is available for use inside spacecraft or on planetary surfaces.

Similar to the very low-energy thermal neutrons (0.025 eV) at sea level on Earth, the much higher-energy neutrons in space can readily penetrate into the human body where they are moderated or slowed by body tissue, which is primarily water. Whereas thermal neutrons, which must be captured by elements such as lithium or boron (rare in the human body) to deposit significant energy, the high-energy neutrons are readily scattered and slowed. They then have a much greater probability of interacting by elastic or inelastic reactions and depositing significant energy in the soft organ tissue near the center of the body (e.g., liver and spleen). Therefore, the carcinogenesis risk is significantly greater for such critical body organs than on Earth’s surface where the environment is dominated by thermal neutrons.

Other biological radiation effects of concern for astronauts are the possible breakage of DNA double strands caused by single hits of neutrons, protons, and massive heavy ions, which could produce latent genetic defects, and damage to localized areas of the brain, which may cause latent perceptual problems or immediate seizures.² This latter biological effect is akin to the damage experienced in integrated circuit memories by the single-event effects resulting from single neutron, proton, or heavy ion strikes in space.

In a February 2004 interview, Dr. Frank Cucinotta, the Chief Radiation Officer at NASA Johnson Space Center, stated that NASA weighs radiation danger in units of cancer risk. A healthy 40-year-old nonsmoking male has a 20% chance of eventually dying from cancer. The added risk of a 1000-day Mars mission is somewhere between 1% and 19%, with the large uncertainty a result of the lack of knowledge about how the human body will react to increased levels of ionizing radiation. The odds are worse, nearly double, for female astronauts because of the sensitivity of the breasts and ovaries to radiation. Obviously, a 40% chance of a life-ending cancer after return to Earth is unacceptable to Dr. Cucinotta and NASA.

In the NASA Bioastronautics Roadmap,² radiation effects on humans are of the greatest concern for a Mars mission. Risks addressed by monitoring the astronauts’ environments are as follows:

- Risk 28: Carcinogenesis, i.e., increased cancer mortality caused by radiation—Priority 1

- Risk 29: Acute and late radiation damage to the central nervous system, including changes in motor function and neurological disorders—Priority 1
- Risk 30: Degenerative tissue disease, including cardiac and digestive diseases and cataracts—Priority 1
- Risk 31: Acute radiation syndromes from intense solar particle events or synergistic effects from exposure to radiation, microgravity, and other spacecraft environmental factors—Priority 1

There are two critical physical questions related to these biological risks:

1. How do the thickness, design, and material composition of space vehicles affect the internal radiation environment and biological assessment?
2. What are the risks from energetic solar particle events, and what impact do they have on operations, extra-vehicular activity, and surface exploration?

Monitoring of the neutron environment helps supply data to answer these questions and to enable radiobiologists to assess the increased risk of cancer for astronauts.

An allied topic of investigation, in addition to monitoring the existing neutron environment inside space vehicles or on planetary surfaces, is how to design vehicles and habitats so as to minimize the transformation and multiplication of the primary cosmic ray beam.^{7,8} After collision with thick structures, the total secondary radiation environment of charged particle fragments and neutrons has a higher flux than the primary cosmic ray beam. In addition, the lower energies of these secondaries increase their probability of interaction in astronauts’ bodies. Structural and shielding materials should be chosen to minimize the production of neutrons and heavy ion fragments in the energy ranges that pose the greatest threat for deposition of radiation dose or dose equivalent in the human body. Recent accelerator experiments have shown that aluminum, the most commonly used spacecraft material, is the worst with respect to the production of secondary high-energy neutrons.⁹ Since it is impractical to create a habitat thickness that is equivalent to the range of the incident high-energy cosmic rays (hundreds of centimeters in water or aluminum), current efforts for space habitat design concentrate on materials with high hydrogen content for efficient protection from neutrons and protons and high atomic number/atomic mass ratio for electronic scattering of charged particles.

Dr. Tracy Yang of Johnson Space Center stated that NASA’s greatest need for knowledge of the astronaut’s long-term radiation environment was a compact neutron energy spectrometer. Instrument development began in May 1997.

NEUTRON SPECTROMETER HARDWARE DESIGN

APL originally proposed to design and build a portable, low-power, robust neutron spectrometer that would measure the neutron spectrum from 20 keV to 500 MeV with at least 10% energy resolution. Covering such a large spectrum, however, requires more than one detector system. Our initial concept was for two detector systems: a helium-3 (^3He) proportional counter for low-energy neutrons (10 keV–5 MeV) and a silicon solid-state detector for neutrons in the range of several MeV to 500 MeV. It became apparent that the low neutron capture cross section of the ^3He tube above 1 MeV and the inherent noise floor in the silicon detector below 10 MeV made it desirable to use a third detector system in the “fast” neutron region between 1 and 10 MeV. We selected a plastic organic Bicorn 454 scintillator detector for the fast neutron region. Since the Bicorn 454 is a scintillator, a photomultiplier tube must be mated to it to detect and collect the light produced by the neutron interactions.

In February 2003 our concept for a Mars Lander neutron spectrometer was published.¹⁰ Figure 1 shows our

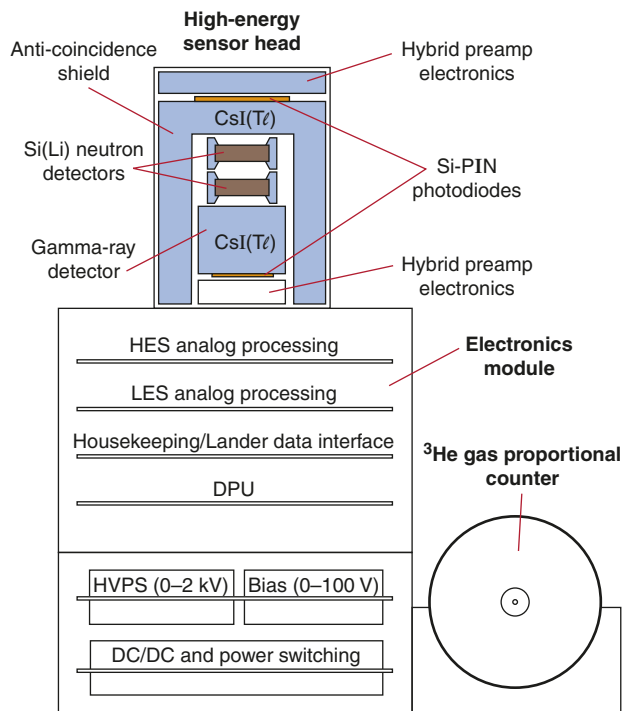


Figure 1. Proposed neutron spectrometer instrument design for the subsequently cancelled Mars 2003 Lander mission. The two detectors shown are a ^3He gas proportional counter tube for the low-energy neutrons and a pair of thick lithium-drifted (Si(Li)) silicon detectors inside the cesium-iodide tellurium-doped (CsI(Tl)) scintillator veto enclosure for the high-energy neutrons. The scintillator light is collected by a pair of silicon (Si-PIN) photodiodes. The electronics module contains high-energy spectrometer (HES) and low-energy spectrometer (LES) analog processing, a data processing unit (DPU), a spacecraft interface, power switching and conversion, and low- and high-voltage power supplies (HVPS).

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The high-energy spectrometer (HES) detects neutrons in the energy range from several MeV to 500 MeV. Its primary detector is a 5-mm-thick lithium-drifted silicon detector that produces a pulse height proportional to the charge or energy deposited by neutron–silicon atom elastic and inelastic collisions. From the start it was recognized that an anti-coincidence shield/circuit would be necessary to discriminate against charged particles depositing energy in the thick silicon detector and that it would have to be quite efficient to keep the signal-to-noise ratio reasonable. Consequently, we designed and fabricated a cesium iodide (CsI) cylindrical detector scintillating tube that snugly contained the 5-mm-thick detector. We were able to successfully operate and evaluate the combined detector system at the Indiana University Cyclotron Facility (IUCF) in September 2001 using 200-MeV protons and at the Columbia University Radiological Research Accelerator Facility (RARAF) in November 2001 with 10- to 20-MeV neutrons. We found that the detector system and the associated front-end electronics could operate up to a maximum data rate of 3 kHz.

The medium-energy spectrometer (MES, not shown in Fig. 1) detects neutrons in the energy range of 1–10 MeV. The detector consists of the Bicorn 454 plastic organic scintillator as mentioned earlier. The MES uses a simple technique to ensure that an event in the detector is caused by a neutron. To first order, a neutron enters the detector and scatters off multiple hydrogen atoms. This scattering thermalizes the neutrons. After a short time these very low-energy neutrons may be captured by the boron-loaded scintillator. The neutron capture has a standard pulse height associated with it. The time between the thermalizing and capturing of the neutron is related to the amount of boron in the detector and can be characterized at RARAF using neutrons of known energies. Therefore, the technique to ensure that a neutron caused an event is a time-correlated double pulse from the detector, with the second pulse having the characteristics of a capture. This technique has a few parasitic problems. One, not all thermalized neutrons are captured; we call these “escapes.” Two, it is possible for two events within the detector to simulate a neutron event. Modeling and calibration are used to characterize the escapes and aliasing.

The low-energy spectrometer (LES) detects neutrons from 10 keV up to 1 MeV and consists of a ^3He proportional counter tube. Rise-time techniques are used on the output pulse of the ^3He tube to determine if a neutron created the event within the detector. There are two dominant reaction modes of a neutron with ^3He (Ref. 11). One is an absorption mode that breaks the ^3He into a proton and triton, releasing 764 keV of kinetic energy to the products of the reaction. Therefore,

thermal or epi-thermal neutrons will produce a pulse height proportional to 764 keV, which serves as a useful calibration tool. Higher-energy neutrons can also be absorbed within the gas, releasing 764 keV plus the incoming neutron energy in the reaction products. The second main reaction mode is ^3He target recoils. Neutrons or charged particles can elastically scatter from a ^3He atom and deposit energy in the detector's sensitive volume. Helium-3 absorption reactions normally produce longer rise times, so knowing the rise time for each event is important. Known incident neutron energies are used at RARAF to calibrate rise times and pulse heights. Modeling is also used to correct the raw data.

THICK SILICON DETECTOR RESPONSE FUNCTION

We performed experiments with high-energy neutrons (20–800 MeV) at Los Alamos Neutron Science Center (LANSCE) in August 2000 and determined the response function of the 5-mm-thick silicon detector for these neutrons. We observed an efficiency enhancement in the thick silicon detector as a result of pion creation above neutron energies of 300 MeV as expected. After successfully deconvolving the energy deposition spectra in the silicon detector to deduce the most probable incident neutron energy spectra and comparing them to the LANSCE beam monitor results, we ran a blind experiment in which we had no knowledge of the beam characteristics. Our deconvolution procedure successfully deduced the blind experiment neutron energy spectrum established by LANSCE calculations (Fig. 2).

We published our basic spectrum inversion methodology in a February 2003 article.¹² The methodology is

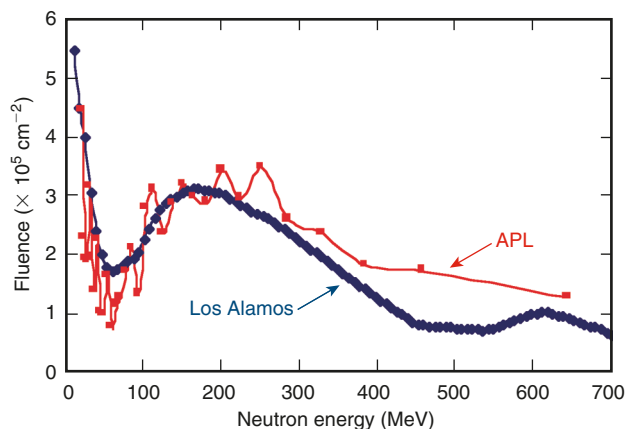


Figure 2. Results from the Los Alamos blind experiment. The neutron fluence spectrum was modified by changing the switchyard moderators without the experimenters' knowledge. The silicon detector spectrum was determined by our response function methodology, while the Los Alamos calculation is based on Monte Carlo N -particle code calculations for the particular switchyard moderator.

based on measurement of the detector response function for high-energy neutrons and inversion of this response function with measured deposition data to deduce neutron energy spectra.

Neutrons, being electrically uncharged, do not directly deposit energy in detectors. Instead, some reaction with the neutron must occur that creates charged secondary particles or energetic photons for the neutron to be detected. For high-energy neutrons, these secondary particles deposit a distribution of energies in a detector for a given incident neutron energy. The response of the detector captures the deposited energy distributions for mono-energetic neutron exposures and can be used to predict energy deposition in the detector from a general exposure using

$$C_i = \sum_j c_{ij} = \sum_j A_{ij} \varphi_j \Delta E_j, \quad (1)$$

where C_i is the number of events depositing energy in the detector for the i th deposited energy bin, A_{ij} is the matrix form of the detector response, and $\varphi_j \Delta E_j$ is the total number of neutrons in the j th incident energy bin.

To measure a neutron spectrum, the count spectrum C_i for a source environment is measured, and Eq. 1 is inverted with the known response matrix to give $\varphi_j \Delta E_j$, the unknown neutron energy spectrum. The silicon detector spectrum in Fig. 2 was determined using this process. We have found that standard Matlab inversion routines using iterative techniques give good estimates of neutron spectra from Eq. 1.

While the LANSCE experiments provided a good measure of the response matrix for the 5-mm Si detector, the results are unique to that detector. Therefore, we used the Clemson University Proton Interactions in Devices (CUPID) computer model to predict the response of a generic 5-mm-thick detector.¹³ CUPID uses a cascade-evaporation model of the underlying nuclear reactions to predict secondary particle generation, track the secondaries through the volume, and calculate total energy deposition from all particles associated with individual reactions. The highest energy deposition from each neutron energy bin predicted by CUPID is shown in Fig. 3, along with the actual highest deposition measured in the LANSCE experiments for the same neutron energies. Clearly, this model fails to accurately predict the response.

Pions are generated in nuclear reactions when the incident neutron energy is above about 250 MeV, and any generated pions in our detector will not deposit significant energy in the reaction. Therefore, pion generation represents a loss of deposited energy not accounted for in the CUPID model. As part of this research effort, a new version, called Pion (later PiCUPID), was developed that did include pion generation. As seen in Fig. 3, Pion

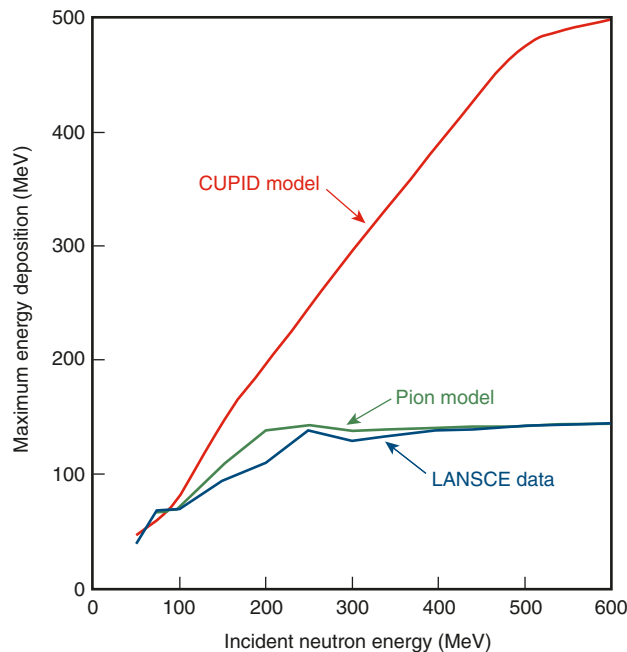


Figure 3. Comparison of two models (CUPID and Pion) of the detector response matrix with results from the LANSCE experiments.

does faithfully predict the detector response. PiCUPID has also been used successfully to generate the response matrix for a much smaller silicon detector used in the CRRES (Combined Release and Radiation Effects Satellite) Micro-Electronics Package Pulse Height Analyzer¹⁴ to explore the relative contribution of low-energy protons, high-energy protons, and galactic cosmic ray environments in near-Earth orbit and to evaluate the accuracy of standard NASA trapped proton models.

The effect of pions demonstrated by the comparison with experimental data has a larger implication. The high-energy particle transport codes being developed by NASA for simulation of the environments inside large manned space vehicles and planetary habitats must accurately use the correct partition of energy in each generation of interaction during transport through material combinations. Our results emphasize the need to treat the pion component correctly.

FLIGHT TESTING

Aircraft Flights

As a product of our initial NSBRI funding during fiscal years 1998–2001 we designed and fabricated an engineering prototype neutron spectrometer that was flown on F-15 and F-18 aircraft from NASA Dryden Flight Center. The spectrometer consisted of both low- and high-energy subsystems. Low-energy neutrons (0.025 eV–1 MeV) were detected using the ³He gas tube and included thermal and epithermal neutrons.

High-energy neutrons (5–800 MeV) were detected using a 5-mm-thick lithium drifted silicon solid-state device. Both low- and high-energy spectrometers underwent ground-based evaluation and calibration using radioactive sources and accelerator facilities.

The aircraft neutron spectrometer was flown on two flights on 13 and 14 August 2001 in a pod under the wing of the F-18. A third successful flight in the same pod under the fuselage of the F-15 was executed in October 2001. As expected, the neutron flux increased dramatically as the aircraft achieved a 40,000-ft altitude (Fig. 4). The main result from the three flights was the verification of our engineering design, not the limited data obtained because of the short duration (≈ 2 h) of the flights. The value for our hardware was the proven approach in handling high voltage at the high-altitude corona region to be used for balloon flights.

Balloon Flights

Efforts in 2002 and 2003 were directed at designing and fabricating a neutron spectrometer for high-altitude balloon flights. The electronics were made more robust and compact for the balloon flight instrument. The detector suite was changed to include an MES for the fast neutrons in the 1- to 20-MeV energy range in addition to the thick silicon detector for the >20-MeV neutron energies. The ³He tube was not included for the low-energy neutrons (10 keV–1 MeV) since this conventional system had been validated on the aircraft flights and will be readily available for future flight efforts. The MES, as noted earlier, was a Bicron 454 plastic scintillator detector system that borrows from the development of a similar system for the APL unmanned MESSENGER mission to Mercury. Sophisticated energy deposition signal time discrimination allowed both scattering and capture peaks of the neutrons in the Bicron detector to be observed for individual counts and energies.

Balloon flights were executed from Fort Sumner, New Mexico, at an altitude of 85,000 ft on two

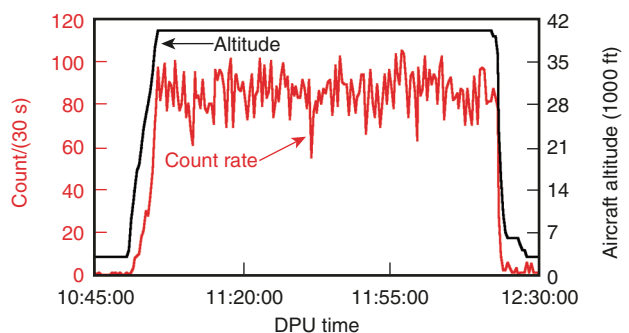


Figure 4. Aircraft flight ³He tube counts versus DPU time. Note that the counts are the count rate integrated for 30 s.

occasions: 9 October 2002 and 9 October 2003. The 85,000-ft altitude was chosen since the amount of atmosphere remaining ($\approx 20 \text{ g/cm}^2$) is the same as the amount of carbon dioxide at the surface of Mars and was expected to yield a reasonable simulation of the downward neutron spectrum on Mars. The October 2002 flight did not yield any useful scientific data as a result of engineering problems with the high-voltage connection to the silicon detector and ground loop issues between the electronics and the aluminum container of the instrument.

During January to April 2003 we improved our balloon flight instrument design and made it more robust and reliable. We qualified it for flight at the National Scientific Balloon Facility at Fort Sumner in May 2003. The October 2003 balloon flight at 85,000 ft for approximately 20 h of float time yielded useful scientific data from the thick silicon detector for high-energy neutrons. The balloon flight instrument is shown in Fig. 5. Figure 6 is a photograph of the launch with our payload at the bottom on a gondola. Both balloon and payload were recovered.

Initial analysis showed that we obtained a highly moderated neutron energy spectrum, with the majority of neutrons in the energy range between 20 and 35 MeV. Modeling of the detector shielding geometry is necessary to deduce the spectrum incident on the instrument container relative to that measured at the detector location. This modeling includes the inherent shielding of our aluminum instrument package, the 1 atmosphere of air pressure inside the container, and the CsI charged particle discrimination scintillator that surrounds the silicon detector. Figure 7 is a diagram of the components of the radiation environment that must be considered when deducing the neutron spectrum incident upon the

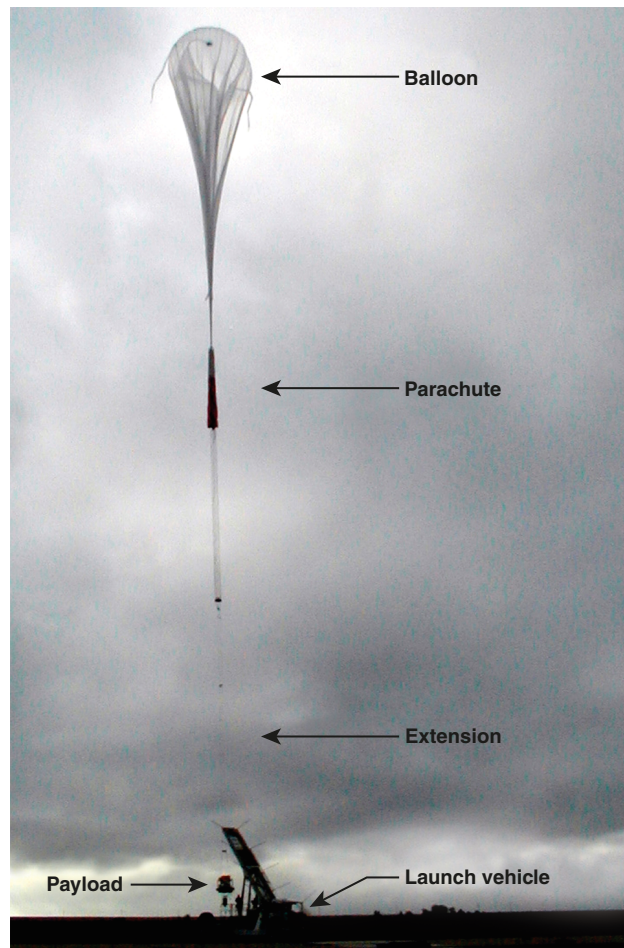


Figure 6. October 2003 launch of the helium-filled balloon. The parachute enables a safe payload (on the gondola at the bottom) return. The balloon started east from Fort Sumner, New Mexico, then turned around, headed west, and was brought down near Socorro, New Mexico, approximately 120 mi from the launch site, after 24 h.

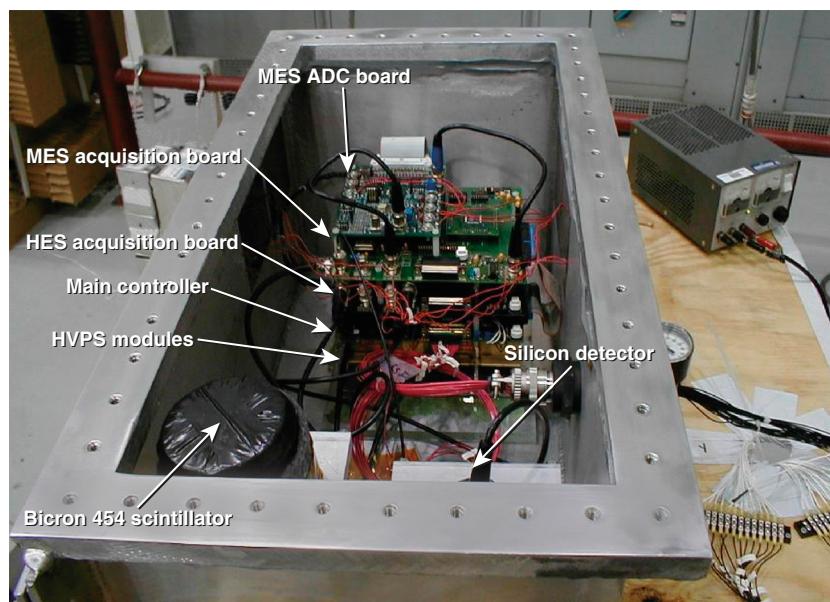


Figure 5. October 2003 balloon flight instrument.

spectrometer from the one observed at the thick silicon detector.

Preliminary simulations with the GEANT (GEometry ANd Tracking) code¹⁵ are aimed at producing an energy deposition spectrum for the thick silicon detector with transport through all the surrounding materials taken into consideration. The incident spectrum that produces the observed deposition spectra is the most probable neutron spectrum at 85,000 ft or under 20 g/cm^2 of atmosphere.

The deconvolved neutron energy spectrum for the 5-mm-thick silicon detector inferred using the measured detector response function is the most probable spectrum observed at the detector location. Modeling

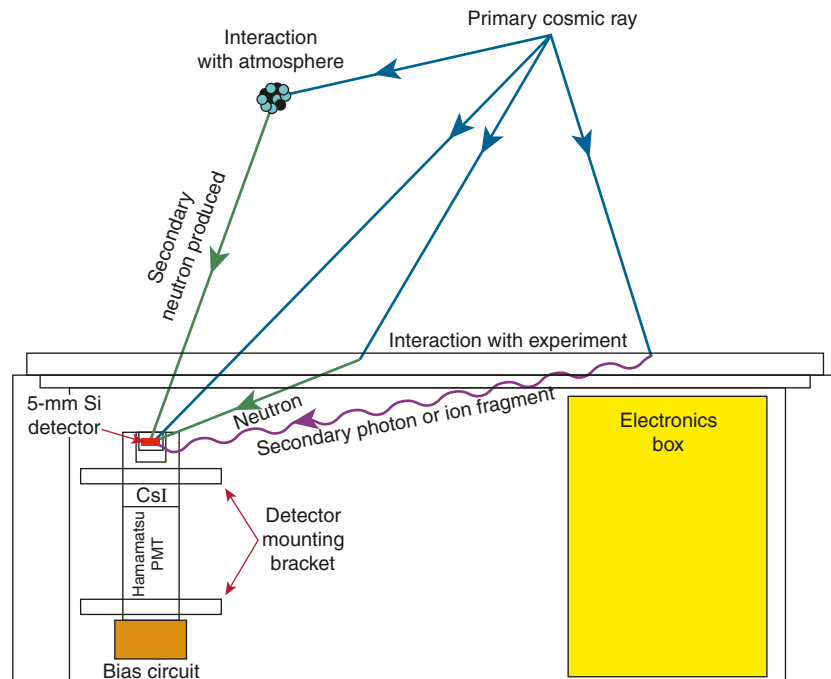


Figure 7. Diagram of the neutron energy spectrometer showing the components of the natural environment at an altitude of 85,000 ft that can contribute to events in the thick silicon detector (PMT = photo-multiplier tube).

will enable us to estimate the contributions of secondary neutrons produced by the instrument package so we can distinguish these neutrons from those produced by the atmosphere. Modeling will also allow us to correct for the number of primary and secondary cosmic ray ions, ion fragments, and photons that may have escaped the CsI anti-coincidence detector in the balloon flight configuration.

SPACECRAFT SHIELDING MATERIAL STUDIES

In January 2000 we were notified that the proposal we had submitted to NASA, "Development of a Neutron Spectrometer to Assess Biological Radiation Damage Behind Spacecraft Materials," would be funded for 3.5 years, from May 2000 to November 2003. For the evaluation of spacecraft structural and shielding materials we built a two-detector stack version of the neutron spectrometer compatible with ground-based accelerator research.¹⁶ Since an accelerator beam is unidirectional compared to the omnidirectional space environment, the charged particle veto detector can just be a thin silicon transmission detector in front of the 5-mm-thick silicon detector. We verified its successful operation at the RARAF in November 2001, then proceeded with spacecraft shielding experiments using 200-MeV proton beams at the IUCF in November 2002 and November 2003 and 500-MeV proton beams at TRIUMF in Vancouver, Canada, in September 2003. (TRIUMF, which

originally stood for TRI-University Meson Facility, has since expanded to include many more members.) Aluminum, carbon, and polyethylene block targets were used to simulate spacecraft materials.

Beam currents at both TRIUMF and IUCF were generally on the order of 0.1–0.2 nA, yielding proton fluxes in the range of 5×10^6 to 2×10^7 protons per $\text{cm}^2 \cdot \text{s}$. Sufficient shield material was used so that the 200-MeV primary proton beam at IUCF was completely absorbed at normal incidence or 0° and could not interfere with the neutron detection by excessively triggering the front silicon transmission detector, thereby causing a high charged particle veto rate.

The experiments were carried out by putting detectors at evenly spaced angles in the forward hemisphere a distance of 31.8 cm from the exit face of the shield material block, with the detector stack aligned

on the center line for the appropriate angle. The resulting thicknesses of aluminum, polyethylene, and graphite were in the 12.7- to 33.0-cm range, resulting in areal densities of 34.4 g/cm^2 for aluminum, 30.9 g/cm^2 for graphite, 30.7 g/cm^2 for polyethylene, and 36.9 g/cm^2 for the aluminum/polyethylene combination. Fortunately, this range of areal densities encompasses the amount of shielding present inside the ISS, so the neutron spectra produced by the protons should be representative and relevant to the ISS radiation environment.

The results⁹ yielded neutron production energy spectra showing the reduced yield from carbon-based materials and the moderating (scattering) effects of polyethylene when compared to aluminum. Our data validate the recent conclusion about aluminum being the least suitable spacecraft material with respect to increased neutron production and human radiation effects.

As an example, Fig. 8 shows the normalized (neutrons produced over a small solid angle centered at 0° or 30° per incident proton on the front face of the material block) integral neutron production energy spectra at or near the forward direction for aluminum, carbon, and polyethylene at 200 and 500 MeV. There are no significant differences between materials at 500 MeV, where a major portion of the proton beam can pass through the thick target without interacting. However, at 200 MeV, where the proton beam is stopped even at 0° , aluminum produces a factor of 5–20 more neutrons above 100 MeV. At the higher neutron energies, carbon by itself is the equivalent of polyethylene; below 50 MeV, polyethylene

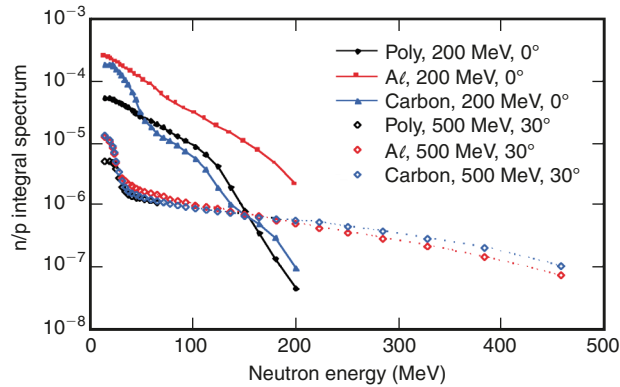


Figure 8. Neutrons produced over a small solid angle per incident 200- or 500-MeV proton for three different spacecraft material blocks near the forward or beam direction.

moderates and reduces the neutron production compared to both aluminum and carbon.

Similar data on polyethylene at large angles (60° from the beam-target axis) show the significant moderating effect of polyethylene, which results in neutrons being scattered from the forward direction to lateral directions. At 60° there is a reduction in neutrons in the 45- to 135-MeV energy range, with a consequent increase in the number of neutrons in the 14- to 45-MeV energy range.

Thus, the effect of angle is complex and exhibits a strong interaction with the type of material. While polyethylene reduces the neutron flux in the forward direction, it increases the flux at large angles from the beam direction below about 50 MeV. Note that neutrons with energy less than 20 MeV are considered more damaging for biological effects. The ultimate solution to the space habitat shielding problem will be an optimization of the material(s) and thickness that minimizes the flux, or fluence, of charged particles, charged particle fragments, and neutrons in the appropriate energy range(s) and consequently minimizes the dose equivalent to the astronauts. Modeling with sophisticated particle transport codes will be a major part of this effort.

CURRENT R&D

Combined Ion and Neutron Spectrometer

In March 2004 we were notified by NSBRI that our proposal to develop a combined ion and neutron spectrometer (CINS) for a potential compact global radiation monitor would be funded for 4 years. The specific objectives are to

- Design and fabricate a prototype CINS for space applications
- Calibrate and evaluate the response functions of the CINS detector systems using ground-based accelerator beams of appropriate type and energy

- Use CINS in a ground-based accelerator comparison with traditionally used space instrumentation such as the tissue equivalent proportional counter
- Examine the effects of baseline and new radiation shielding materials as countermeasures by measuring charged and neutral secondary particle generation from a simulated space environment

The prototype instrument will be developed using heritage from the neutron energy spectrometer developed under previous NSBRI grants described above, instrument electronics from unmanned spacecraft missions such as MESSENGER, and the design and operation of the Mars Odyssey Orbiter MARIE (Mars Radiation Environment Experiment) instrument.

MARIE has three significant problems. (1) Preamplifier gains are too high, so that hits from any heavy ion with linear energy transfer >35 keV per micrometer of path length result in saturation of the electronics. (2) The trigger detectors are noisy, so the thresholds must be kept high to avoid an excessive event rate due to spurious triggers; the high thresholds then cause the detector to be blind to protons with energies above about 100 MeV, and the exact energy cutoff is not well known or easily determined. (3) The event rate is limited to about three per second, adequate during times when the Sun is not active or even moderately active, but inadequate during intense solar particle events.

The CINS will use silicon stacks to detect charged particles similar to those used for purposes of dosimetry flying on the ISS and on the 2001 Mars Odyssey Orbiter. It will also incorporate several improvements, the most important of which will be in the electronics. MARIE currently can provide a dynamic range of only about 100:1; we intend to expand this range by a factor of 10 to 20 through better design of the electronics and more careful attention to amplifier gains. The next most important improvement will be in the capability of the system to handle the high rates that occur during solar particle events. The MARIE design is limited by CPU hardware and software to a data rate of about three triggers per second; we expect to increase this by at least a factor of 10 by implementing a more modern CPU and data bus.

Antarctic Balloon Flight Instrument

In June 2004 we were notified that we would be funded under a subcontract from NASA Marshall Space Flight Center to develop and supply a balloon-borne neutron spectrometer (BBNS) for the Deep Space Test Bed missions to be flown on high-altitude ($\approx 125,000$ ft) balloons from Antarctica over the next several years, beginning in December 2005. In addition to verifying the performance of engineering systems, these missions of several weeks each will simulate the interplanetary

radiation environment by simultaneously monitoring (1) the incident cosmic ray spectrum at the top of the atmosphere with the minimal magnetic field shielding of the South Pole and (2) the “interior” spectra produced behind different common and innovative spacecraft shielding materials. We are designing and fabricating a third-generation balloon flight instrument for these missions. The BBNS will include all three detector systems for the first time (the ^3He tube, the Bicron 454 scintillator, and the 5-mm-thick silicon inside a CsI charged particle discriminator). It will monitor the complete neutron energy spectrum, under the several different types of shielding, rotating on a 4-ft-dia. carousel above the BBNS detector housing on the multideck balloon gondola.

Several engineering changes from past versions of the neutron spectrometer were required in order to enable this mission. Space on the deck below the carousel is limited; therefore, the neutron spectrometer was broken up into two boxes, a detector box and an electronics box (to be placed on a lower deck). The BBNS instrument will need to function with more autonomy than past versions. Payload recovery is not guaranteed, so the data logging procedures will change, and the operating temperature range for the BBNS will be higher than past versions. Significant attention is being paid to mechanical and system issues to meet the different requirements of this mission.

SUMMARY

The NSBRI/APL Neutron Energy Spectrometer is built with three detector systems: a thick lithium-drifted solid-state detector, solid-state scintillators, and a gas tube to cover the desired energy range of neutrons of interest to radiobiologists as well as to discriminate against charged particles. The instrument is designed with robustness for aircraft and balloon flights. It has evolved since 1997 from evaluations of several types of individual detectors with radioactive sources and accelerator beams. The next step is to produce a spaceflight instrument suitable for interplanetary missions. Allied ground-based investigations using high-energy accelerator beams on thick targets have contributed to the search for better spacecraft structural and radiation shielding materials.

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