STATUS OF LDEF IONIZING RADIATION MEASUREMENTS AND ANALYSIS

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INTRODUCTION

At this symposium significant new data and analyses have been reported in cosmic ray research, radiation dosimetry, induced radioactivity and radiation environment modeling. Measurements of induced radioactivity and absorbed dose are nearly complete, but much analysis and modeling remains. Measurements and analyses of passive nuclear track detectors (PNTD), used to derive the cosmic ray composition and spectra, and linear energy transfer (LET) spectra, are only a few percent complete, but important results have already emerged.

As one might expect at this stage of the research, some of the new information has produced questions rather than answers. Low-energy heavy nuclei detected by two experiments are not compatible with known solar or cosmic components. Various data sets on absorbed dose are not consistent, and a new trapped proton environment model does not match the absorbed dose data. A search for cosmogenic nuclei other than ^{7}Be on LDEF surfaces has produced an unexpected result, and some activation data relating to neutrons is not yet understood. Most of these issues will be resolved by the analysis of further experiment data, calibrations, or the application of the large LDEF data set that offers alternate data or analysis techniques bearing on the same problem.

The scope of the papers at this symposium defy a compact technical summary. In this paper I have attempted to group the new information that I noted under the topics listed below. The papers generally are expository and have excellent illustrations, and I refer to their figures rather than reproduce them here. The general program and objectives of ionizing radiation measurements and analyses on LDEF has been described previously (ref. 1).

A. INDUCED RADIOACTIVITY

The induced radioactivity program for LDEF has a number of objectives. The induced activity when carefully measured, converted to specific activity, and compared to calculations from environment models serves as a "dosimeter" separate from techniques such as thermoluminescence dosimetry (TLD). While each technique has potential sources of systematic errors, they are mostly independent. The study of induced radioactivity in spacecraft materials, and methods to model it, are of strong interest in gamma ray astronomy where the local background is often a limiting factor in detector sensitivity. A few nuclear transmutations occur principally by neutron absorbtion, and these may be used to study the secondary neutron flux in the presence of the large primary proton flux.

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Papers were presented at this symposium (ref. 2,3,4,5) which describe the instrumentation used for low background high resolution spectroscopy, the data reduction techniques, and some of the results measured at each facility. References (2) and (6) describe some of the considerations required to correct gamma ray line counting rates to specific activity (picoCuries/kg). Calculations which use the trapped proton and cosmic ray environments to predict results for specific nuclide production, and some results, were described in reference (3). Progress in collecting all activation data and placing it in a corrected data set for an eventual archive is described (ref. 6).

A comprehensive status report on the activation measurements and analyses was reported at this symposium (ref. 7). A summary of the sample materials, current results, and preliminary analyses is included. That paper contains new data from aluminum and steel structural samples, and on neutron activation in the cobalt, indium, and tantalum "intentional samples." Preliminary analysis of the induced activity in LDEF was presented at the First LDEF Symposium (ref. 8). Three dimensional calculations using a detailed LDEF mass model and directional proton models are in progress, but results were not presented at the 2nd Symposium. The induced radioactivity team has obviously made considerable progress as summarized in references (6) and (7), and will produce an archived data set which will be invaluable to space radiation environments research and gamma ray astronomy. The induced activity data, along with the three-dimensional calculations, may be required to help resolve the differences in LDEF absorbed dose data sets (ref. 9,10,11).

B. ABSORBED DOSE MEASUREMENTS

At the First Symposium absorbed dose measurements were presented from experiments M0004, P0004, P0006, and A0015 (ref. 12,13), which gave a tidy picture of the dose from 0.5 to 15 g/cm^2 shielding depth on the west side and from 1.37 to 2.90 g/cm^2 on the east side of LDEF, with a west/east ratio close to pre-recovery dose-shielding-depth profiles (ref. 14). Those early results, although they did not match pre-recovery calculations (ref. 14,15), were consistent with first-order calculations using a new directional proton model folded with a simple plane-slab shielding (ref. 16). The P0004, P0006, M0004, and A0015 data was summarized at this symposium (ref. 11), with additional details for the P0006 results.

New data from two experiments, in several more trays, have been presented at the second symposium. This data extends to shielding depths of 8x10^{-2} g/cm^2 for AO 138-7 (ref. 10) and to thinner shielding (<10^{-2} g/cm^2) for experiment M0003 (ref. 9), where the trapped electrons contribute the majority of the absorbed dose. Some data from these experiments overlap the shielding range of experiments M0004, P0004, P0006, and A0015, where protons dominate the dose.

In the range of shielding thickness dominated by trapped protons and where most data overlap (≥ 0.2 g/cm^2), the absorbed dose picture is no longer so tidy (see Figure 3, ref. 17). The differences between data are greatest at the thinner shielding depths (a factor of 2 -3 at ~1 gm/cm^2). The agreement is much better (~30%) at 5 g/cm^2 (where fewer experiments contribute data). Figure 3, ref. 17, summarizes the available data above 0.2 g/cm^2 and contains data from the west, east, and Earth sides of LDEF. Accounting for different locations and local shielding variations will not reconcile all differences.

At thin shielding depths where the electron dose dominates (less than ~3×10^{-1} g/cm^2), the measurements (refs. 9,10) agree with pre-recovery calculations within a factor of ~2 down to shielding depths ~.01 g/cm^2, where the dose measurement (2×10^4 rads) becomes asymptotic for thinner shielding. We note that in pre-recovery estimates (ref. 14) the dose increased to ~3×10^5 rads at "zero" effective shielding. Possible detector saturation effects are being investigated (ref. 9).

Effort is underway to resolve the differences between measurements and between modeling predictions and measurements. Further calibrations and studies of detector effects are in progress (ref. 9). In the environmental modeling effort, data on induced radioactivity will be used to derive an independent estimate of the absorbed dose in the 0.2 - 5.0 g/cm^2 shielding range (ref. 18).

C. LET SPECTRA AND HEAVY ION DOSIMETRY

Plastic Nuclear Track Detectors (PNTD's) were used on LDEF to measure both external (charge and energy spectra) and internal (charge and energy spectra of slowed primaries, secondary particles, and the Linear Energy Transfer spectra) radiation environments. Thin sheets of CR39, Lexan, Cellulose nitrate (CN), polycarbonates, mica, and others, are etched after the flight with strong base solutions. The geometry of the resulting microscopic conical pits at the entrance to radiation damage tracks are measured in multiple layers of detector, and further analysis provides the charge, energy, etc. of the charged ionizing particles. The technique is powerful, but time consuming. No more than 10% of the PNTD's on LDEF have been analyzed (including the cosmic ray experiments discussed below). Nevertheless, important new results have been reported at this conference, and these results confirm the significance of LDEF data in the fields of cosmic rays and radiation dosimetry.

With the attitude stability of LDEF, it is possible for the first time to comprehensively study the directional properties of LET spectra in spacecraft. These properties are a consequence of the directionality of the primary radiation and secondary particles produced by them, and the geometry of the shielding around the detection point. Such directional effects in the composite LET spectra from all particles (ref. 19, Figure 3) and in the directional characteristics of short range secondary recoils from trapped protons (ref. 20) were reported at this symposium.

The long exposure of LDEF has permitted a unique study of short range recoil particles. These particles have very high LET values, exceeding that of relativistic iron nuclei. New detector etching and analysis procedures have been developed, which coupled with the high density of the short range (~3 μm to ~20 μm) "recoil" particles in the LDEF exposure, has given a new measure of their LET contribution, which extends above 10^3 keV/μm - H_2O (ref. 19, Figure 4). These data will allow new modeling techniques to be applied that promise a more physically complete and more accurate prediction of LET spectra for future missions (ref. 18). The data already available will permit an assessment of the shortcomings in the present methods of predictions.

Improvement in the accuracy of LET predictions is significant for all future space programs. The decreased device size and increased number of devices per chip in contemporary microcircuits, along with a growing awareness of the SEU problem, have recently motivated design requirements for SEU susceptibility analysis on future spacecraft electronic systems. The

recoil particles dominate the high end of the LET spectra and have a large quality factor (QF), or effectiveness, in producing biological damage. An accurate prediction of the LET spectra is therefore important for assessing crew health risk.

D. ENVIRONMENT MODELING AND THREE-DIMENSIONAL SHIELDING EFFECTS

At the First Post-Retrieval Symposium, preliminary model calculations (ref. 16) of absorbed dose and some activation products were reported. Those calculations used a new trapped proton directional model coupled with a simple planar shield located perpendicular to each proton flux vector. This "3D/1D" calculation assumed a typical LDEF altitude of 450 km. The directional (3D) proton model incorporates the flux and spectra from the omnidirectional AP8 "Vette" models. This preliminary modeling effort produced results for absorbed dose on the east and west sides of LDEF, for Na^{22} in aluminum experiment tray clamps, and for Mn^{54} in samples from the steel trunnions. The model predictions were all within 50% of the measured values.

The next logical steps were to provide a more accurate proton fluence, reflecting in detail the altitude profile of LDEF and the effects of the solar activity during the mission, and to incorporate an accurate three-dimensional mass model of LDEF.

Reference (21) describes the factors that were used to derive a "corrected" proton flux and fluence. These include a continuous correction for solar activity rather than the MAX/MIN step used before, a 10-step altitude and atmospheric scale height profile and a modified magnetic moment. These changes reduced the calculated mission proton fluence by 20% from pre-recovery estimates.

The three-dimensional mass model of the LDEF structure and experiments is described in reference 22. This model includes the LDEF ring and longeron structure and all LDEF experiment trays, with four of the trays which contain dosimeters modeled in detail. The mass model is also being used in the analysis of the cosmic ray experiments.

The full three-dimensional environment modeling has been applied to predict the absorbed dose at measurement locations on LDEF (ref. 17). This produced some surprises! On the west and Earth sides of LDEF at shielding depths between 0.5 - 15 g/cm^2, the model predicts about half the dose measured in three experiments (Figures 4, 5, 7 (ref. 17)). On the east side the model predicts about 80% of the measured dose (Fig. 6, ref. 17). One may conclude from this that the flux in the AP8 proton model, which is the basis for the flux values in the directional proton model, is too low.

The full three-dimensional LDEF model predicts a smaller east/west anisotropy than measured. In the three-dimensional trapped proton model, this is affected by atmospheric scale height, which is a model parameter. In Figures 10 and 11 (ref. 17) the anisotropy is shown to be strongly dependent on the shielding depth and geometry with the larger west side flux influencing the results at east side measurement points.

The 3D model is presently being applied to the induced activity data from aluminum tray clamps around the circumference of LDEF (ref. 18) to provide a test of the model independent of

the absorbed dose data. An examination of the effect of varying parameters that depend on the environment (flux, atmospheric scale height, etc.) is also planned.

Absorbed dose measurements on LDEF at shielding depths of less than 0.2 g/cm^2 (ref. 9, 10) are almost entirely due to trapped electrons. These measurements have been compared with calculations using the AE8 electron environment model and the results are shown in Fig. 12 (ref. 18) and Fig. 2 (ref. 10). The measurements and predictions agree within a factor of 2 between 0.2 g/cm^2 and 0.01 g/cm^2. Measurements at smaller shielding depths were well below predictions, but the differences are likely due to detector saturation effects that are being investigated with calibrations (ref. 9).

The directional properties of the primary particles combined with the attitude stability of LDEF, and its shielding geometry, caused directional effects that were observed in data from passive nuclear track detectors (PNTD). Anisotropy of detected heavy cosmic ray nuclei, protons, and secondary particles in P0006 were reported (ref. 23) and the LET spectra from experiments P0006 and A0015 exhibited directional characteristics (ref. 19, 20). These observed directional characteristics depend strongly on the local shielding, and modeling of them will require the three-dimensional mass model.

E. COSMOGENIC NUCLEI (^{7}Be, ^{10}Be, ETC.)

The radioisotope ^{7}Be was discovered on the leading side (east) of LDEF, but was absent on the trailing side (ref. 24). It was quickly determined that its most likely source was the transmutation of atmospheric oxygen and nitrogen by cosmic ray protons and secondary neutrons. This occurs predominantly in the stratosphere (~25 km altitude) and its production rate is easily calculated and has been well documented by air sample measurements. Its concentration at the LDEF altitude (~350 km), per unit mass of air, must be several orders of magnitude higher than in the stratosphere to explain the amount (~10^6 radioactive nuclei/cm^2) accommodated on the front surface of LDEF.

Since the half life of ^{7}Be is 53 days, no new measurement from LDEF since the first symposium (reference 24) have been possible. However, the LDEF discovery has motivated new studies to understand the atmospheric transport mechanisms (25) and the spacecraft surface accommodation of ^{7}Be and similar metallic ions. Further experiments on the Concorde aircraft (See 1*) the shuttle (See 2*), and on the Russian RESURS-F1 spacecraft (See 3*) are planned.

At this symposium a project to detect other cosmogenic nuclei (^{10}B, ^{14}C, etc.) by the technique of accelerator mass spectrometry (AMS) is described (ref. 26). A measurement of ^{10}Be is of particular interest as a test of the diffusion transport hypothesis. The ratio ^{7}Be/^{10}Be at orbital altitudes should depend only on half-life and isotopic mass, with atmospheric chemical effects being the same for both isotopes. ^{10}Be was found on both leading and trailing edge Al tray clamps by AMS at levels >10^6 atoms cm^{-2}. In a post-conference addendum (ref. 26) the authors report the contamination by ^{10}Be ($t_{1/2}$ ~ Myrs) of a variety of industrial aluminums. It is known that ^{10}Be is detectable in thunderstorm precipitation (See 4*) and that the principal ore of Al, bauxite, is usally found in surface deposits. AMS experiments are continuing to measure ^{10}Be on other LDEF substrates. and to search for other cosmogenic nuclei.

*Private communications: P.R. Truscott [1], J.C. Gregory [2], G.W. Phillips [3], C. Frederick [4]

Additional information on Phillips [3] found on last page, below references.

F. COSMIC RAYS AND OTHER HEAVY IONS

From scanning of etched Lexan detector material, the "Ultra Heavy Cosmic Ray Experiment" (A0178) investigators, have determined that ≥ 2800 ultra-heavy cosmic rays (UHCR) with atomic number Z > 65 will eventually be analyzed. This is more than 10 times the UHCR data produced by previous orbiting experiments (Skylab, Ariel 6, and HEAO-3), and should yield ~30 actinides (Z ≥ 90). Following extensive post-flight calibrations and detector tests to achieve optimum elemental resolution, 65 events have been fully analyzed. Figure 5 in reference (27) displays the analyzed events and shows two actinide nuclei clearly separated from the heaviest stable elements (Z ≤ 83). This appears to support the excellent charge resolution (± 0.8 e) estimated from detector temperature history, track fading studies, and calibrations. This experiment will significantly advance the knowledge of nucleosynthesis in supernovae (the only site of actinide production), the relative contributions of various nucleosynthetic processes to the cosmic ray flux, and the propagation history of the UHCR in the galaxy.

The "Heavy Ions in Space" Experiment (M0001), although it suffered some loss in CR39 detector sensitivity, shows excellent charge resolution (reference 28). Significant effort has been placed in understanding the detector sensitivity, resolution, and optimum etching conditions of the CR39 detector, which is detailed in reference 28. UHCR events above Z = 45 are being measured and about 1100 events will eventually be analyzed (more than twice the previous data available for 45 ≤ Z ≤ 92). The complementary data of A0178 and M0001 will place stringent tests on models of cosmic ray nucleosynthesis and propagation in the galaxy.

In the analysis of M0001 data reported at this Symposium the emphasis was on the heavy nuclei with energies below the "geomagnetic cut off" of fully ionized galactic cosmic rays, which have a minimum energy of 800 MeV/nucleon in the LDEF orbit. About 250 events below 800 MeV/n which stopped in the thick detector stack have been analyzed to yield the composition and spectra. An unexpected fluence of "iron group" particles, with manganese (Z = 25) the most abundant, over the energy range ~100 to 500 MeV/n were found. As detailed in reference 28, these results are inconsistent with "anomalous cosmic rays" (because of their composition) and solar energetic particles (because of composition and energy). Only a few percent of the available data on these particles has been analyzed, and further work may confirm a new low-energy component of the cosmic ray flux. The present data also indicate that partially ionized iron nuclei from the strong solar flares in 1989 might have reached the LDEF orbit. Analysis at this point also shows that the spectra of argon and neon "anomalous cosmic rays" will be measured up to ~300 MeV, or at least a stringent upper limits on their fluence will be set at that energy.

The "Heavy Ion Measurement" (M0002), and corrollary detectors carried in "Biostack" (A0015) have produced data on low energy (10 - 240 MeV/n) heavy ions (Z = 6 → 26) (ref. 29). The analysis of these data extends the "new cosmic ray component" measurement (ref. 28, Figure 7), to lower energy and has provided important new information about low energy heavy ions in the trapped radiation belts (Figure 2, ref. 29). The M0002 data contain new information on their composition, and temporal changes in their intensity. Such data are required to understand their injection and loss in the trapped belts.

G. STATUS SUMMARY, AND THE FUTURE

The papers at this symposium show not only the progress in data analysis and the significant results already achieved, but indicate what is yet to be done.

The absorbed dose measurements with thermoluminescent dosimeters (TLD's) have been completed, but some proton acceleration calibrations are in progress to resolve differences with predictions, and to confirm pre-flight calibrations. The final absorbed dose results, calibrations and other ground tests, information concerning detector shielding, and comparisons with model predictions, will be collected for the LDEF archive.

Most of the induced activity measurements have been performed, although a few measurements are continuing on samples with long half-life nuclides. There is a significant effort remaining to resolve small systematic differences between counting laboratories, to reduce all sample data to specific activity, and to convert the data from different laboratories to a standard format for archive. The final archive will contain the standard format data, correction methods, specific activity for samples, shielding information, and relevant comparisons with environment models.

The passive nuclear track detectors (PNTD) used for dosimetry (LET spectra and heavy ion fluences and spectra) and for cosmic ray composition and spectra required considerable test sample processing and analysis, and post-flight calibration. About 10% of the PNTDs have been processed, measured, and analyzed, and the analysis rate is increasing. However, it will be three or more years (depending upon the experiment and specific objective) before all this analysis is completed. Significant dosimetry data with shielding information and environment comparisons will be placed in the LDEF final report. Final results and interpretations for galactic and anomalous cosmic rays, trapped heavy ions, and the possible new component of heavy ions will be published in refereed journals.

In the radiation environment modeling the preliminary analysis of absorbed dose and induced radioactivity have been completed with the approximate "3D/1D" approach. The full three-dimensional approach (which includes the directional trapped proton flux and the full LDEF mass model) has been applied to the absorbed dose data. The model predicts less dose (~50%) and anisotrophy than observed, demonstrating the need for model adjustment. Reference (18) summarizes the LDEF data available now, and in the future, for environment model comparisons. That paper also describes the status and the future program of model comparisons. The first priority is to compare the induced activity data with a full three-dimensional model to determine if the absorbed dose model/data differences are confirmed. Deficiencies in the directional trapped proton model can then be addressed and model parameters (flux, atmospheric scale height, etc.) adjusted accordingly. The next major effort in modeling is to develop techniques to predict the feature in the LET spectra (beyond 10^3 keV/μm) that is due to target recoils and other secondaries. This feature, which is not included in present methods, will be modeled with a combination of the primary particle spectra and secondaries from the High Energy Transport Code. Neutrons are a yet uncertain component to radiation dose in spacecraft, and LDEF has data from fission foil detectors and induced radioactivity to help resolve this question. Modeling calculations are planned to examine in detail the proton vs neutron effects in the fission foil detectors, and to examine specific activation lines that are principally due to neutrons. The

revised and new environment models developed with the LDEF data will be documented and placed in an accessible data base for use in future programs.

The discovery of ^{7}Be on LDEF has motivated a number of efforts to explain its surprisingly large concentration at LDEF altitudes. These include future measurements in the stratosphere on high altitude aircraft, and on several spacecraft. Atmospheric circulation modeling of ^{7}Be transport is also in progress. Accelerator mass spectrometery is being employed on a number of LDEF substrates to detect other cosmogenic species such as ^{10}Be. These efforts will hopefully resolve the LDEF ^{7}Be origin as due to exceptionally efficient vertical transport in the atmosphere, or some other process such as solar flare particle interactions in the atmosphere.

This symposium demonstrated the power of experiments with passive radiation detectors and induced activity measurements, exposed for a long period in space, to make significant advances in radiation dosimetry, environment modeling, and cosmic ray astrophysics. The radiation experiments were not designed as an ensemble, nor was the long exposure anticipated; but every experiment that has been analyzed has made a significant contribution, some with unexpected, and remarkable, results. However, these experiments leave significant measurement to be made. Reference (30) describes a number of "radiation" experiments (but not all) that would be important to perform on a future LDEF spacecraft. They would utilize recently developed detectors of higher resolution and detectors with better sensitivity to further explore the ultra heavy and anomalous cosmic rays. Low power motor-driven arrays of PNTDs would allow time resolution for anomalous cosmic ray studies. Cosmogenic nuclei would be studied with small motor-driven, time-resolved sample plates. Many aspects of dosimetry, such as the "recoil" feature in the LET spectra, and neutrons, need to be further studied with detectors specifically designed for the purpose. Rapid post-flight analysis of activation to measure short lifetime nuclides would be important in several contexts. Such experiments on an LDEF-2 would be as productive, and cost-effective, as those on LDEF-1.

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