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LDEF Satellite Radiation Study

Science Applications International Corporation
An Employee-Owned Company

by

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1. Introduction

This report covers work performed by Science Applications International Corporation for the NASA Marshall Space Flight Center under contract NAS8-38566 entitled "LDEF Satellite Radiation Study" during the period 17 June 1990 to 30 September 1993. The basic objective of the study was to evaluate the accuracy of presently used models and computational methods for defining the ionizing radiation environment for spacecraft in low Earth orbit by making comparisons with measurements made on the Long Duration Exposure Facility (LDEF) satellite, which was recovered in 1990 after almost six years in space.

The scope of this work included model predictions for various components of the space radiation environment (trapped electrons, trapped protons, and galactic cosmic rays) and comparisons with a variety of different types of measurements made on LDEF (particle fluence, absorbed dose, LET spectra, and induced radioactivity). A detailed geometry/mass model of the LDEF spacecraft and experiment packages was developed to take into account shielding effects in computing the radiation transport of the ambient environment to the detector locations. The results give a quantitative evaluation of present environment model uncertainties, indicate areas needed for model improvements, and provide radiation design guidance for future missions in low Earth orbit.

Results from the work on this contract have been described in several publications and presentations, which are listed in the Bibliograph (Section 2) and can be categorized as follows:

<u>Journal Papers</u>

- Contributions to the pre-recovery estimates of LDEF radiation exposure have been published in the Journal of Nuclear Tracks and Radiation Measurements [Bibliography listing 1].
- A summary paper [2] comparing predictions and LDEF measurements has been accepted for publication in the Advances in Space Research journal.

<u>LDEF Post-Retrieval Symposia</u>

- Papers were presented at the First LDEF Post-Retrieval Symposium and published in the symposium proceedings [3, 4, 5].
- Papers were presented at the Second LDEF Post-Retrieval Symposium and published in the symposium proceedings [6-9].

Space Radiation Workshops

- Study results have been reported at international workshops on space radiation environments sponsored by NASA-MSFC [10] and by the European Space Agency [11].

IRSIG Meetings

- Results from this study have been reported at several meetings of the LDEF Ionizing Radiation Special Investigation Group chaired at MSFC [12-15].

Space Station IREER Board

- To make available LDEF results to aid in the radiation environment definition for Space Station design, findings from the work here were briefed to the Space Station Ionizing Radiation Environment and Effects Review Board [16].

The remainder of this report is organized as follows:

- Section 3 contains a summary of the main conclusions from model comparisons with LDEF data on trapped proton dose and trapped proton anisotropy.

- Section 4 gives an overview of the importance of LDEF data for evaluating space radiation model uncertainties for application to spacecraft in low Earth orbit, a summary of the calculational methods, models, and computer codes used in the study, and predicted vs. observed comparisons for the trapped proton radiation dose and a subset of the induced radioactivity measurements.

- Section 5 describes work on development of a 3-D mass model of the LDEF spacecraft for use in radiation transport calculations.

- Section 6 contains predicted vs. measured results for trapped proton and trapped electron doses and trapped proton directionality.

- Section 7 describes the 3-D mass modeling of certain experiment trays and dosimetry, and their incorporation into the spacecraft model discussed earlier in Sec. 5.

- The final section gives the status of model comparisons and data availability for the various sets of LDEF measurements at the conclusion of the study.

2. Bibliograph of Publications Under This Contract

1. E. V. Benton, H. Heinrich, T. A. Parnell, T. W. Armstrong, J. H. Derrickson, G. J. Fishman, A. L. Frank, J. W. Watts, and B. Wiegel, "Ionizing Radiation Exposure of LDEF (Pre-Recovery Estimates)", Nucl. Tracks Radiat. Meas. 20, 75 (1992).

2. T. W. Armstrong, B. L. Colborn, B. A. Harmon, T. A. Parnell, J. W. Watts, Jr., and E. V. Benton, "Comparison of Model Predictions with LDEF Satellite Radiation Measurements", Presentation at COSPAR92 World Space Congress, Washington, D.C., 28 August - 5 September 1992 (accepted for publication in Advances in Space Research).

3. T. W. Armstrong, B. L. Colborn, and J. W. Watts, Jr., "Ionizing Radiation Calculations and Comparisons with LDEF DATA", Proceedings of First LDEF Post-Retrieval Symposium, 2-8 June 1991, Kissimmee FL, NASA CP-3134 (1992).

4. B. L. Colborn and T. W. Armstrong, "LDEF Geometry/Mass Model for Radiation Analyses", Proceedings of First LDEF Post-Retrieval Symposium, 2-8 June 1991, Kissimmee FL, NASA CP-3134 (1992).

5. J. W. Watts, T. A. Parnell, James H. Derrickson, T. W. Armstrong, and E. V. Benton, "Prediction of LDEF Ionizing Radiation Environment", Proceedings of First LDEF Post-Retrieval Symposium, 2-8 June 1991, Kissimmee FL, NASA CP-3134 (1992).

6. T. W. Armstrong and B. L. Colborn, "Radiation Model Predictions and Validation Using LDEF Satellite Data", Proceedings of Second LDEF Post-Retrieval Symposium, 1-5 June 1992, San Diego CA, NASA CP 3194 (1993).

7. B. L. Colborn and T. W. Armstrong, "Development and Application of a 3-D Geometry/Mass Model for LDEF Satellite Ionizing Radiation Assessments", Proceedings of Second LDEF Post-Retrieval Symposium, 1-5 June 1992, San Diego CA, NASA CP 3194 (1993).

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9. John W. Watts, T. W. Armstrong, and B. L. Colborn, "Revised Predictions of LDEF Exposure to Trapped Protons", Second LDEF Post-Retrieval Symposium, 1-5 June 1992, San Diego, CA, NASA CP 3194 (1993).

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2. Bibliograph of Publications Under This Contract (cont'd)

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13. T. W. Armstrong and B. L. Colborn, "LDEF Ionizing Radiation Calculations: Preliminary Results, Comparisons with Data, and Plans", Presentation at LDEF Ionizing Radiation Special Investigation Group Meeting, NASA Marshall Space Flight Center, Huntsville AL, 24-25 January 1991.

14. T. W. Armstrong and B. L. Colborn, "LDEF Induced Radioactivity Calculations", Presentation at LDEF Ionizing Radiation Special Investigation Group Meeting, NASA Marshall Space Flight Center, Huntsville AL, 24-25 January 1991.

15. B. L. Colborn and T. W. Armstrong, "LDEF Mass/Geometry Model for Ionizing Radiation Assessments", Presentation at LDEF Ionizing Radiation Special Investigation Group Meeting, NASA Marshall Space Flight Center, Huntsville AL, 24-25 January 1991.

16. T. W. Armstrong, "Validation of SSF Ionizing Radiation Environment Models Using Recent Satellite Data", Proceedings of Space Station Freedom Program Ionizing Radiation Environments and Effects Review Board Meeting, NASA Marshall Space Flight Center, Huntsville AL, 11 August 1992.

Section 3

COMPARISON OF MODEL PREDICTIONS WITH LDEF SATELLITE RADIATION MEASUREMENTS

COMPARISON OF MODEL PREDICTIONS WITH LDEF SATELLITE RADIATION MEASUREMENTS+

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ABSTRACT

Some early results are summarized from a program under way to utilize LDEF satellite data for evaluating and improving current models of the space radiation environment in low Earth orbit. Reported here are predictions and comparisons with some of the LDEF dose and induced radioactivity data, which are used to check the accuracy of current models describing the magnitude and directionality of the trapped proton environment. Preliminary findings are that the environment models underestimate both dose and activation from trapped protons by a factor of about two, and the observed anisotropy is higher than predicted.

INTRODUCTION

Data from the Long Duration Exposure Facility (LDEF) satellite, recovered in 1990 after almost six years in space, provide an important opportunity for testing and updating ionizing radiation models for application to future missions in low Earth orbit. In particular, the LDEF orbit parameters (28.5° circular, 479-319 km altitude) are essentially the same as planned for Space Station Freedom.

The LDEF mission had several features important to radiation model validation: (a) a variety of different types of passive radiation dosimetry (thermoluminescent dosimeters, plastic nuclear track detectors, activation samples, etc.) were on board at multiple locations and shielding depths /1/, providing a high-confidence data set for benchmarking the models; (b) the data have high statistical accuracy due to the long mission duration, which is particularly important for checking model predictions of the high-LET component of cosmic rays and nuclear interaction products; and (c) the LDEF spacecraft had a very stable orientation which, together with dosimetry placements at various positions around the spacecraft, provides data to test models describing the directionality of the radiation environment.

Data analysis in progress /2/ for radiation dosimeters aboard LDEF, and from the radioactivity induced in numerous spacecraft components, is expected to provide an extensive data base that will allow the accuracy of several different types of models to be evaluated, including those for predicting trapped proton, trapped electron, and galactic cosmic ray environments; anisotropy of trapped proton exposure; absorbed dose and linear energy transfer (LET) spectra at various shielding thicknesses; and spacecraft-generated secondary particle fluxes.

A calculational program utilizing LDEF data for radiation model validation is under way /3/. A summary of some early results on assessments of the trapped proton environment is reported here.

PREDICTION METHODS

Environment Models -- The standard AP8 trapped proton model /4/ was used to predict orbit-average omnidirectional flux spectra, with the procedures detailed in /5/ applied to account for altitude and solar cycle variations. The LDEF trapped proton exposure is anisotropic, with protons confined mainly in planes perpendicular to the local geomagnetic field direction and with in-plane asymmetry due to the east-west effect. The model developed by Watts et al. /6/ was used to predict this directionality of the trapped proton environment.

Spacecraft Model -- The LDEF radiation dosimetry data is influenced to varying degrees by material shielding effects due to the dosimeter itself, nearby components and experiments, and the spacecraft structure. To help ensure that differences between predictions and measurements are due to the radiation environment and not masked by shielding effects, a detailed three-dimensional geometry model of the LDEF spacecraft and experiment trays has been developed /7/ for use in radiation transport calculations.

+Presentation at COSPAR 92, World Space Congress, Washington, D. C., 28 Aug. - 5 Sept. 1992; accepted for publication in *Advances in Space Research.*

Radiation Transport -- Three-dimensional radiation transport calculations were performed using the 3-D LDEF spacecraft model and the solid angle sectoring approximation, with the solid angle around each dose point divided into 720 equal solid angle increments. Transport calculations for each direction were carried out using the Burrell code /8/, which employs the straightahead approximation together with fits to stopping power and range relations to obtain an analytical solution to the transport equation.

RESULTS AND DISCUSSION

Trapped Proton Dose

Predictions have been made /9/ to compare with the dose measurements reported by Frank et al. /10/ and by Reitz /11 from thermoluminescent dosimeters (TLDs), and a summary is shown in Fig. 1 for TLDs at various positions on the spacecraft and for shielding depths (aluminum equivalent) in the range of ≈ 0.5 to 16 g/cm^2. For this shielding range, the trapped electron dose is small /12/, and doses from solar particle events and galactic cosmic rays are essentially negligible due to the high geomagnetic cutoff for the low-inclination LDEF orbit /13/, so the dose for these TLDs is dominated by trapped protons.

Fig. 1 shows that the AP8 model gives a lower dose than observed for all spacecraft locations and shielding depths, with the predictions usually about a factor of two lower than measured. The dose ratios are practically constant with shielding depth, indicating that the model environment is too low over a wide range of proton energies.

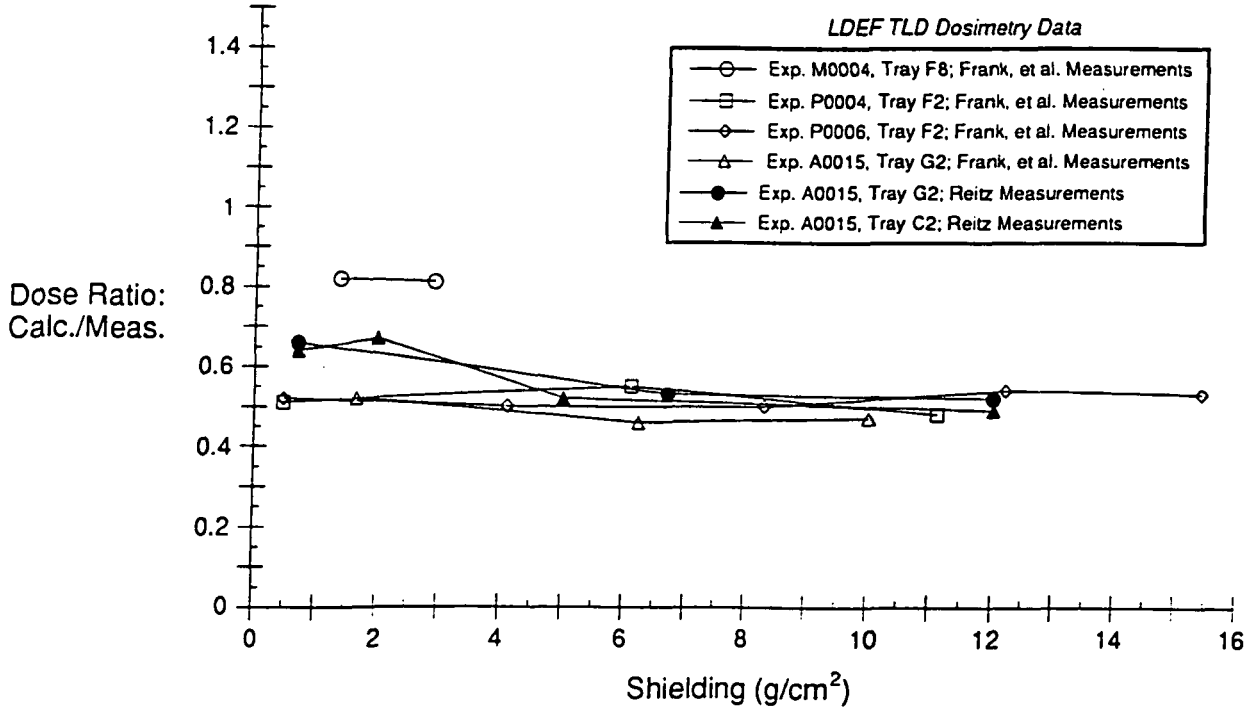

Fig. 1. Ratio of calculated absorbed dose (tissue) to dose measurements by Frank, et al. /10/ and Reitz /11/ for TLDs at shielding depths (aluminum equivalent) on LDEF where the trapped proton contribution dominates. Included are results for TLD placements on the high-dose trailing (west) edge of the spacecraft (Experiments P0004 and P0006), low-dose leading (east) edge (Exp. M0004), and on the earth end (Exp. A0015).

Trapped Proton Anisotropy

For a few cases TLD dosimeters with similar shielding were located near the trailing (west) and leading (east) side of the spacecraft, so some data on the dose anisotropy due to trapped protons are available for comparison. For these cases (shielding depths 1.4 to 2.9 g/cm^2), the measured /10/ dose anisotropy (trailing-to-leading dose ratio) is ≈ 2.5, compared to a predicted ratio of ≈ 1.4.

A more detailed mapping of the environment anisotropy is available from measurements /14/ of induced radioactivity in the aluminum clamps (1.3 g/cm^2 thick) used to secure experiment trays on the spacecraft (Fig. 2). These measurements give the ^{22}Na activity (half-life = 2.6 y, production threshold ≈ 25 MeV) in tray clamps at various locations, providing the angular dependence of activation relative to the spacecraft velocity vector. Predictions to compare with these data were made using the transport methods described above to obtain the directional trapped proton flux spectra in the clamps, which were then folded

with available data on energy-dependent ^{22}Na production cross sections to obtain the activation. (Scoping calculations /13/ using detailed Monte Carlo transport techniques, but for a simple 1-D spacecraft model, show that the contributions from secondary particles, and from galactic proton and albedo neutron sources, are expected to be small for the case of tray clamp activation.)

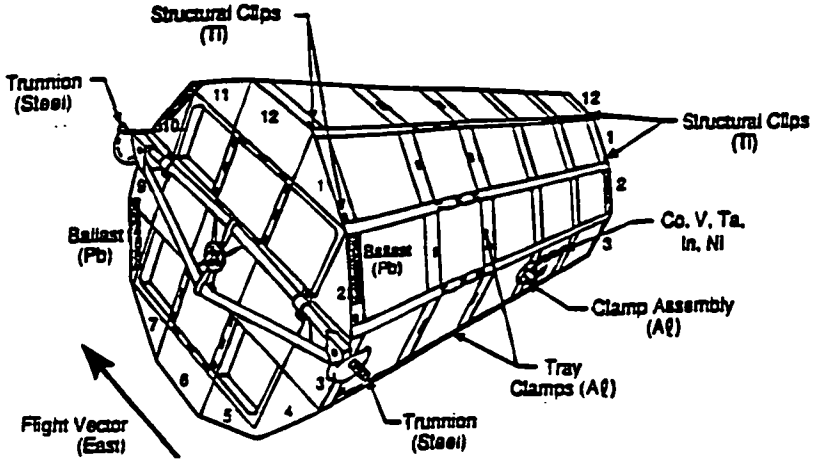

Fig. 2. Location of LDEF spacecraft components and activation samples where measurements of induced radioactivity are being made /14/, including typical locations of tray clamps whose measured activation is used here for testing predictions of trapped proton anisotropy.

The predicted activation is lower in magnitude, and not as directional, as the measured activation (Fig. 3). The measured anisotropy in terms of the west/east ratio is 1.7 compared to a predicted ratio of 1.3, which is less than the difference found for the dose anisotropy. The predicted magnitude of the activation is about a factor of two lower than measured, which is consistent with the dose comparisons.

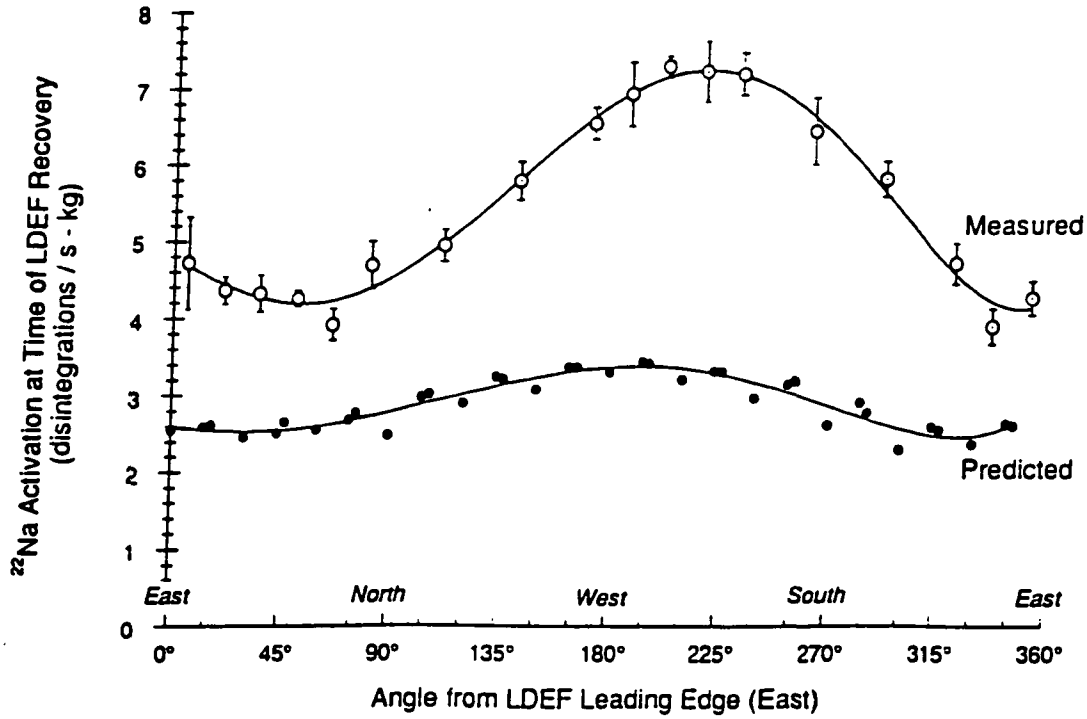

Fig. 3. Predicted vs. measured /14/ ^{22}Na activation of aluminum experiment tray clamps on LDEF showing angular variation due to anisotropy of trapped protons.

The difference between measured and predicted directionality may be due to approximations in the effective atmospheric scale heights /6/ needed as model input. The appropriate scale heights, representing average atmospheric density variations over trapped proton trajectories, are not well known from first principles, but can strongly influence the predicted angular distributions. LDEF data may provide a basis for determining more accurate effective scale heights for model input. The calculations also indicate that the predicted anisotropy is quite sensitive to the spacecraft geometry model used; earlier scoping estimates for a simplified 1-D spacecraft model gave a much higher anisotropy /14/.

CONCLUSIONS

Based on early results in comparing model predictions with LDEF satellite ionizing radiation data, the standard AP8 model underpredicts the trapped proton flux in low Earth orbit by about a factor of two. This conclusion is based on comparisons with LDEF data for both dose (mainly due to exposure during solar minimum) and ^{22}Na activation (produced during both solar minimum and solar maximum). This difference between measurement and prediction is not totally unexpected since a factor of two uncertainty is often quoted for the AP8 model, but the difference is larger than indicated by some Shuttle measurements (e.g., /15/). Predictions of the directional effects of trapped protons, based on the anisotropy model of Watts et al./6/ with a detailed spacecraft model and 3-D transport calculations to take into account shielding effects, give a weaker anisotropy than observed on LDEF, both in terms of dose and activation. This underprediction of the anisotropy is probably due to the approximate nature of the effective atmospheric scale heights currently used as input to the anisotropy model. These conclusions should be regarded as tentative since additional predictions and comparisons with other LDEF radiation data are still in progress.

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Section 4

IONIZING RADIATION CALCULATIONS AND COMPARISONS WITH LDEF DATA

IONIZING RADIATION CALCULATIONS AND COMPARISONS WITH LDEF DATA*+

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SUMMARY

In conjunction with the analysis of LDEF ionizing radiation dosimetry data, a calculational program is in progress to aid in data interpretation and to assess the accuracy of current radiation models for future mission applications. To estimate the ionizing radiation environment at the LDEF dosimeter locations, scoping calculations for a simplified (one-dimensional) LDEF mass model have been made of the primary and secondary radiations produced as a function of shielding thickness due to trapped proton, galactic proton, and atmospheric (neutron and proton cosmic-ray albedo) exposures. Preliminary comparisons of predictions with LDEF induced radioactivity and dose measurements have been made to test a recently developed model of trapped proton anisotropy.

INTRODUCTION

Purpose

A calculational program is in progress as part of the LDEF ionizing radiation investigations, with the following objectives:

Data Analysis Support - Calculations are being used to help interpret the LDEF ionizing radiation measurements. In most cases the LDEF dosimetry data represent an integration of several effects, such as contributions from different environment sources (galactic and trapped radiation), influence of shielding variations (from both experimental apparatus and spacecraft structure), and secondary particle contributions from nuclear interactions. The calculations can be used to "unfold" the dosimetry data to estimate the influence of these individual effects, which is needed if the LDEF data are to be fully applicable for future missions having different orbit parameters and spacecraft configurations.

Model Validation - LDEF data are being utilized to evaluate the accuracy of present ionizing radiation models. This includes models for predicting both the "external" environments (ionizing radiation fields external to the spacecraft) and the "internal" environments (ionizing radiation environments at locations internal to the spacecraft, which include the effects of radiation interactions and transport).

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* Work partially supported by NASA Marshall Space Flight Center, Huntsville, AL, Contract NAS8-38566.
+ Presentation at First LDEF Post-Retrieval Symposium, 2-8 June 1991, Kissimmee FL; published in Proceedings Report NASA CP-3134 (1992).

Future Mission Applications - The overall objective of the calculational program is to fully utilize the LDEF data to test and revise current ionizing radiation models for future mission applications. This should result in more accurate models for predicting crew dose for planned long duration missions (Space Station Freedom, Space Exploration Initiative) and for assessing radiation backgrounds to sensors and determining achievable measurement sensitivities for planned space-based observatories (e.g., Earth Observing Observatory). Furthermore, benchmarking models with LDEF data will reduce present model uncertainties involved in assigning hardware design margins for meeting mission radiation requirements. This will help prevent both "under-design" (which can lead to reduced mission performance) and "over-design" (resulting in excessive costs).

LDEF Data for Radiation Model Validation

The LDEF mission had several unique features that are important to the validation of ionizing radiation models:

Well Instrumented - A variety of different types of radiation dosimetry, with multiple dosimeters of each type,were onboard, providing a high-confidence data set for benchmarking the models. Also, dosimeters were placed at various locations on the spacecraft and behind various thicknesses of shielding, allowing tests of both external environment models and the transport models for predicting the radiation environment internal to the spacecraft.

Long Exposure - Dosimetry results have high statistical accuracy due to the long mission duration. This is particularly important for checking model predictions of the high-LET component of cosmic rays and nuclear interaction products, which is of key importance in assessing radiation-induced biological and electronics damage.

Fixed Orientation - The very stable orientation of LDEF during the entire mission (< 0.2°, ref. 1), together with dosimetry placements at various positions around the spacecraft, allow the directionality of the incident radiation to be measured. This provides a unique opportunity for testing a recently-developed model (ref. 2) for predicting the directionality of the trapped proton flux. Since the radiation dose (at most shielding depths) for spacecraft in low-earth orbit is dominated by the trapped proton exposure, this anisotropy may have practical importance for planned fixed-orientation spacecraft in low-earth orbit, such as for Space Station Freedom.

Thus, the LDEF data provide a significant opportunity for model improvement in addressing ionizing radiation issues for future missions, as summarized in figure 1.

APPROACH

Figure 2 gives an overview of the calculational approach and indicates some of the specific models being used. External environment models include the AP8 and AE8 models for trapped protons and electrons (refs. 3,4), the MSFC model for predicting trapped proton anisotropy (ref. 2), and the galactic proton and heavy ion environments given by the NRL CREME model (ref. 5). Transport models include both simplified, one-dimensional models commonly used in quick assessments of space radiation effects -- the MSFC analytical models for proton and electron-bremsstrahlung transport (refs. 6,7), SHIELDOSE (ref. 8), and CREME (ref. 5) -- as well as three-dimensional Monte Carlo codes, HETC (ref. 9) and MORSE (ref. 10). The Monte Carlo codes take into account in detail the secondary particle production and transport and can treat three-dimensional, multimedia spacecraft models, capabilities which are needed in some cases for definitive comparisons with the LDEF measurements.

This calculational approach can provide predictions for all of the different types of LDEF radiation measurements - namely: (a) induced radioactivity, including both the activation of metal samples (Ni, Co, V, Ta, and In) placed in LDEF experiment packages and the activation of various spacecraft structural components (e.g., trunnions, experiment tray clamps); (b) measurements of tissue-equivalent absorbed dose using thermoluminescence detectors (TLDs); (c) measurements of linear-energy-transfer (LET) spectra by plastic nuclear track detectors (PNTDs); and (d) particle fluence and energy spectra, including secondary neutrons, as measured by fission foils, specific activation reactions, low-energy neutron detectors (^{6}LiF foils), and PNTDs.

The shaded areas in figure 2 indicate the emphasis of the modeling to date. An important approximation for the initial calculations is that a very simplified (in most cases one-dimensional) spacecraft model has been used. To obtain definitive comparisons with most of the measurements, detailed shielding variations about the detector need to be taken into account, so development of a 3-D LDEF mass model for radiation calculations is underway (ref. 11).

RESULTS

Emphasis of the initial calculations has been in two areas: (a) scoping calculations of the importance of different exposure sources and secondary particles to the induced radiation environment, and (b) calculations and comparisons with measurements to check the accuracy of a recent model for predicting the anisotropy of trapped protons.

Scoping Calculations

The penetrating radiation environment for the LDEF orbit consisted of protons (with a relatively small contribution of heavier ions) trapped in the earth's magnetic field, protons and heavier ions of galactic origin, and albedo neutrons and protons due to galactic cosmic-ray bombardment of the earth's atmosphere (ref. 12). Since the angular variation of these sources is quite different (figure 3), and since material attenuation within LDEF is different for each source, an important question for data interpretation concerns the magnitude of the contribution from each component at the LDEF measurement locations. Thus, a set of scoping calculations was made to obtain a general indication of: (a) the importance of different space radiation sources, (b) the importance of secondary particles generated within LDEF, and (c) the spatial variation of the induced radiation environment.

The calculations were carried out using Monte Carlo transport methods, with the SAIC version of the HETC code (ref. 13) for high-energy transport and the MORSE code for low-energy (< 20 MeV) neutron transport. These were only scoping estimates because several important approximations have been made in this initial work -- e.g., a one-dimensional (aluminum slab) model of LDEF was used, and the angular variation of the incident radiation (particularly the trapped proton anisotropy) was not accurately simulated. Subsequent calculations using a 3-D LDEF mass model are planned to remove these approximations.

Example results are shown in figure 4 for the depth-dependent particle fluence, and figure 5 shows fluence spectra at a particular depth (10 g/cm^2). (To roughly relate these depths in terms of areal density to LDEF, if the LDEF spacecraft is represented as a cylinder the average areal density is 32 g/cm^2 across the diameter and and 68 g/cm^2 end to end.) These results indicate that the contribution from albedo neutrons and protons is negligible, and that the relative importance of

trapped vs. galactic sources depends on the shielding depth and radiation effect of interest. In terms of fluence over all energies, figure 5 shows that secondary neutrons dominate for depths $\gtrsim 10$ g/cm^2.

A report on additional results from these calculations, including the induced radioactivity in aluminum and stainless steel produced by different sources and particle types, is available (ref. 14), and a summary has been accepted for journal publication (ref. 15).

Trapped Proton Anisotropy

The ionizing radiation dose at most shielding depths for spacecraft in low-earth orbit (LEO) is produced mainly by trapped protons in the South Atlantic Anomaly (SAA) region. The standard NASA models (AP8MIN and AP8MAX) for describing the trapped proton environment do not provide an angular dependence, although the proton flux is actually highly anisotropic in the SAA. This anisotropy has not been an important practical consideration for most previous LEO missions because the varying spacecraft attitude during passage through the radiation belt "averages out" anisotropic effects over many orbits. However, for the fixed orientation of LDEF, and for several planned missions (e.g., Space Station Freedom, Earth Observing Satellite) where the spacecraft will be gravity-gradient stabilized, the cumulative proton exposure will remain anisotropic, and will result in a highly nonuniform dose distribution around the spacecraft.

Watts, et al. (ref. 2) have recently developed a model to predict orbit-average, angular dependent trapped proton flux spectra from the standard omnidirectional AP8MIN and AP8MAX data bases. Since trapped proton anisotropy effects may be an important consideration for Space Station design and operation, a priority for the calculational work has been to utilize LDEF data to evaluate the accuracy of this anisotropy model, as summarized below. These initial results must be considered as preliminary because of several simplifications in the calculations to date, and because the LDEF data are not yet fully analyzed.

Anisotropy of Tray Clamp Activation

The measured induced radioactivity of the aluminum clamps (ref. 16) used to secure the LDEF experiment trays provides very appropriate data for checking the anisotropy model since these clamps are located on all sides of the spacecraft and at various directions relative to the flight vector. Also, since the clamps are located on the outer surface and are thin (1.3 g/cm^2), we expect (based on the scoping Monte Carlo calculations; e.g., figure 4) the activation from galactic protons and secondary particles to be small, so the measured activation is predominantly from the primary trapped protons.

The ^{22}Na production in aluminum has been predicted as a function of direction (in the horizontal plane perpendicular to the LDEF longitudinal axis) and for various shielding depths (figure 6). These calculations were made for a point behind an aluminum slab shield (assuming that the direction normal to the plane is pointed in the plotted direction, and assuming that no particles enter from the "back side" of the plane). The proton transport code of Burrell (ref. 6) was used. The angular distribution of the trapped protons were taken from a pre-computed data base for discrete altitudes (ref. 17), with results for 450 km and solar minimum used here; thus, the properly averaged angular spectra for solar cycle variation and the varying altitudes during the LDEF mission have not yet been applied.

The results (figure 6) show minimum activation near the East (leading edge) of the spacecraft and maximum activation near the West (trailing) direction. The predicted anisotropy in terms of the ratio of West-side activation to East-side activation varies from a factor of about 1.8 near the surface to a factor of 3.5 at 10 g/cm^2 depth. This increase in anisotropy with depth is due to the increasing anisotropy of the incident protons at higher energies (refs. 2, 18).

A comparison of the predicted ^{22}Na activation at a depth corresponding to the mid-depth of the tray clamp (0.64 g/cm^2) with the measured activation (ref. 16) is shown in fig. 7, indicating very good agreement for these preliminary comparisons. The angular variations are similar in shape, with the maximum/minimum ratio with respect to direction being 1.8 for the measurements vs. 2.0 for the calculations.

The calculated results in figure 7 are lower than the measurements by about 15% for directions in the vicinity of West, and lower by about 50% for directions near East. These preliminary absolute magnitude comparisons suggest a better accuracy for the AP8 trapped proton model than the factor of two uncertainty commonly quoted.

Dose Anisotropy

Predictions of the absorbed dose anisotropy have also been made and compared with the initial TLD measurements reported by Benton, et al. (ref. 19) for Experiments P0006 (bay-row location F-2, near the trailing edge) and M0004 (tray position F-8, near leading edge). These initial calculations were also made assuming one-dimensional, plane-geometry shielding, so the results are preliminary.

The predicted ratios are compared with the measured P0006-to-M0004 TLD dose ratios (using data from ref. 18 with interpolation applied to obtain common shielding depths) in figure 8. These preliminary comparisons also indicate that the anisotropy model predictions are consistent with LDEF data.

Directionality of Trunnion Activation

The measured spatial dependence of radioisotopes produced in the stainless steel LDEF trunnions (refs. 20, 21) also provide an opportunity for checking the anisotropy model. To date, calculations have been made to compare with only a small subset of the measured data, with some initial comparisons for the ^{54}Mn activity given here.

The calculations were made for a "simplified" 3-D geometry with the body of the LDEF spacecraft and experiment trays modeled as a homogeneous aluminum cylinder (with an average density to preserve the total mass), and with the earth-end trunnion represented as a stainless steel rod. The activation at a point in the trunnion was computed by: (a) determining the areal density along a 3-D grid of rays emanating from the point (720 rays were used, corresponding to the polar-azimuthal angular grid used in generating the directional proton environment), (b) computing the attenuation for each ray using the Burrell 1-D proton transport code, with solid-angle weighting for each ray to get the cumulative proton spectrum at the point, and (c) folding this spectrum with cross sections for ^{54}Mn production from the constituents of stainless steel.

Shown in figure 9 is a comparison of the calculational results with the measurements of Moss and Reedy (ref. 20) for the radial distribution of ^{54}Mn produced in a section of the trunnion centered 3.5 in. from the end ("Section D" in fig. 8a of ref. 20) of the East (leading edge)

trunnion. These results are for two angular segments of the trunnion having surface normals pointed in the zenith direction (labeled "space") and toward the center of the earth (labeled "earth"). The trapped proton anisotropy model predicts that the external fluxes directed toward the "space" and "earth" directions should be essentially the same, whereas the measurements and transport calculation results indicate a lower activation in the space direction. A separate calculation made with only the trunnion present shows that the lower activation observed in the space direction is due to the shielding effect of the LDEF spacecraft.

The agreement between the predicted and measured activations in figure 9 is quite good near the surface of the trunnion, but the agreement becomes somewhatworse near the center. Results from the 1-D Monte Carlo calculations (ref. 14) show that galactic protons contribute substantially at penetration depths comparable to the center of the trunnion. Thus, the underprediction of the activation deep into the trunnion indicated in figure 9 may be due to the neglect of incident galactic protons in these initial calculations.

CONCLUSIONS

LDEF has provided unique data which, based on preliminary comparisons of initial measurements and predictions, confirms a recently developed model for the anisotropy of trapped protons. This anisotropy is important in predicting the radiation exposure of other fixed-orientation spacecraft in LEO, such as the planned Space Station and Earth Observing Satellite missions.

Preliminary comparisons also indicate that the LDEF radiation dosimetry data are in good agreement with predictions using AP8 trapped proton flux model. Such results can help quantify the limits on safety margins commonly applied to account for radiation environment modeling uncertainties in spacecraft design and parts selection and in crew dose assessments.

The emphasis of near-term future calculations is expected to be on model comparisons with LDEF LET measurements (e.g., ref. 22). LET spectra generally provide a more stringent test of the environment and transport models than considered to date for induced radioactivity and dose comparisons, and LET is fundamental in assessing electronics upsets and biological damage. For future calculations a three-dimensional LDEF geometry/mass model will be implemented to properly account for dosimetry shielding effects and provide more definitive assessments of the radiation models.

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Unique Features of LDEF Mission	*Importance to Ionizing Radiation Data Collection*	*Importance to Model/Code Validation*	*Importance to Future LEO Missions*
• Well-instrumented for ionizing radiation measurements	• Extensive radiation dosimetry: *- 6 different types of dosimetry* *- multiple dosimeters of each type (≈ 200 TLD's, > 500 PNDT's, > 400 activation samples)* *- multiple dosimetry locations (in 16 different experimental trays)*	• Data sufficiently extensive and detailed to allow variety of modeling checks - e.g.: *- absorbed dose* *- proton and heavy ion fluence* *- energy spectra* *- LET spectra* *- secondary neutron fluence and spectra*	• Allows benchmarking and improvements of predictive methods for addressing ionizing radiation issues: *- dose to astronauts* *- electronics upset/burnout* *- materials damage* *- radiations backgrounds to sensitive instrumentation*
• Long mission duration	• High statistical accuracy of dosimetry results	• Unprecedented data accuracy for checking model predictions of high-LET radiation from high-Z cosmic rays and nuclear recoils	• High-LET radiation component is of key importance in assessing "single-hit" phenomena: *- biological effects* *- Single-Event-Upsets of electronics*
• Fixed orientation (< 0.2° wobble during mission)	• Allows measurement of trapped proton anisotropy	• Unprecedented data for testing models of trapped proton anisotropy	• Trapped proton anisotropy important for LEO, fixed-orientation spacecraft (such as Space Station Freedom, EOS)

Fig. 1. Significance of LDEF data for validation of ionizing radiation models.

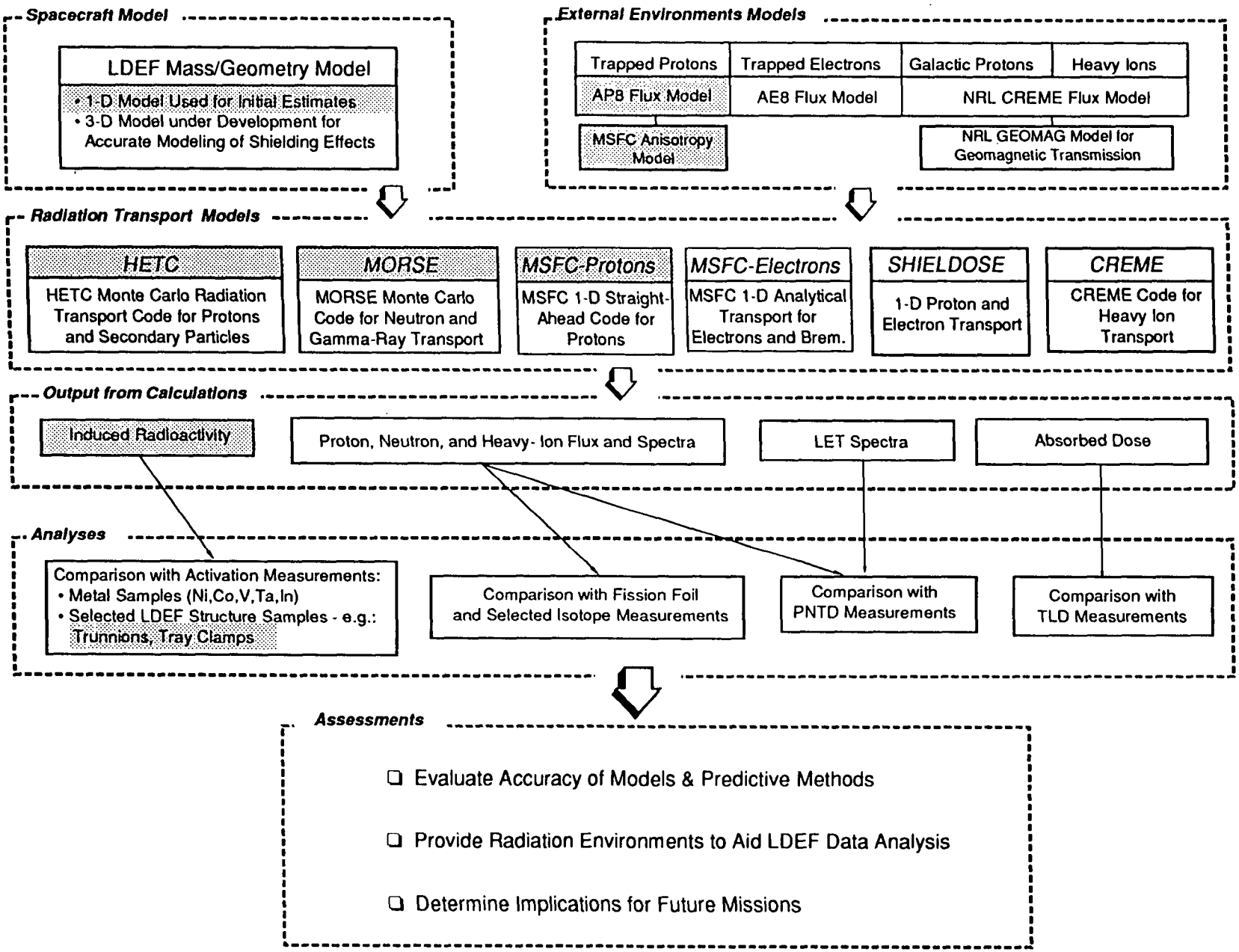

Fig. 2. Overview of approach and models for LDEF ionizing radiation calculations.

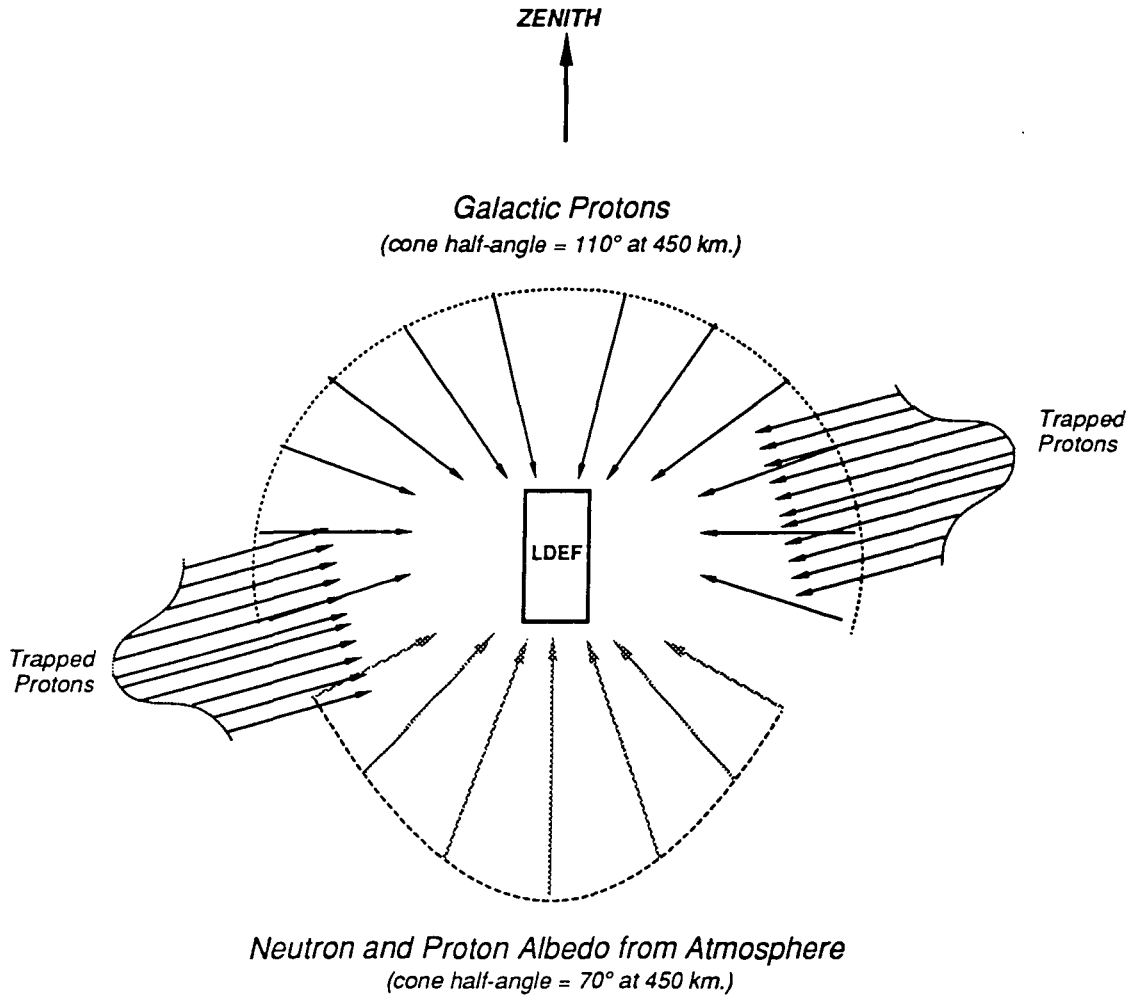

Fig. 3. Illustration of the nonuniform angular variation of LDEF exposure to ionizing radiation.

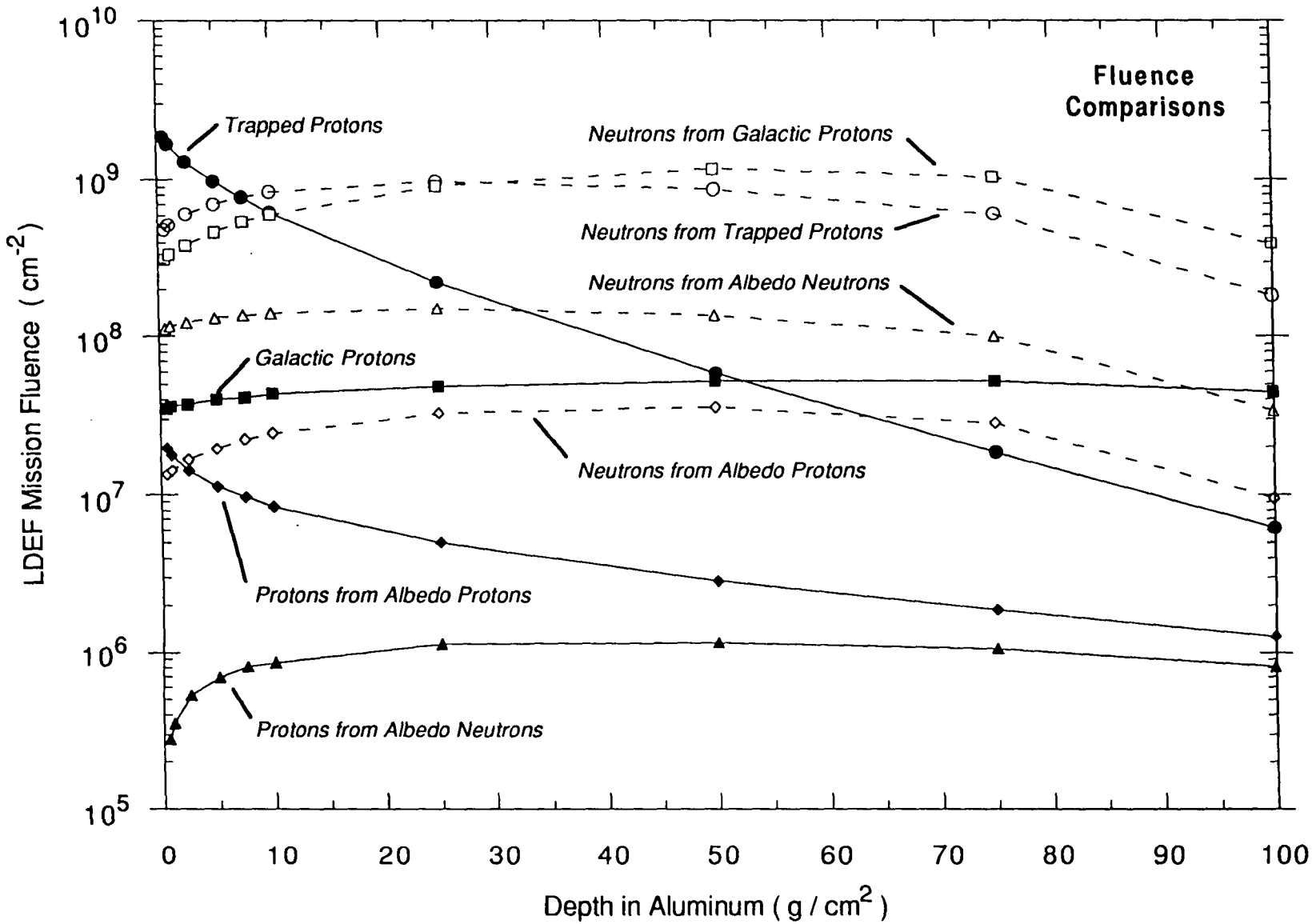

Fig. 4. Predicted depth dependence of proton (primary and secondary) and neutron fluences over all energies produced by trapped proton, galactic proton, albedo proton, and albedo neutron environments over the duration of the LDEF mission. The different environments are all assumed incident isotropically on one side (0 depth) of an aluminum slab 100 g/cm^2 in thickness.

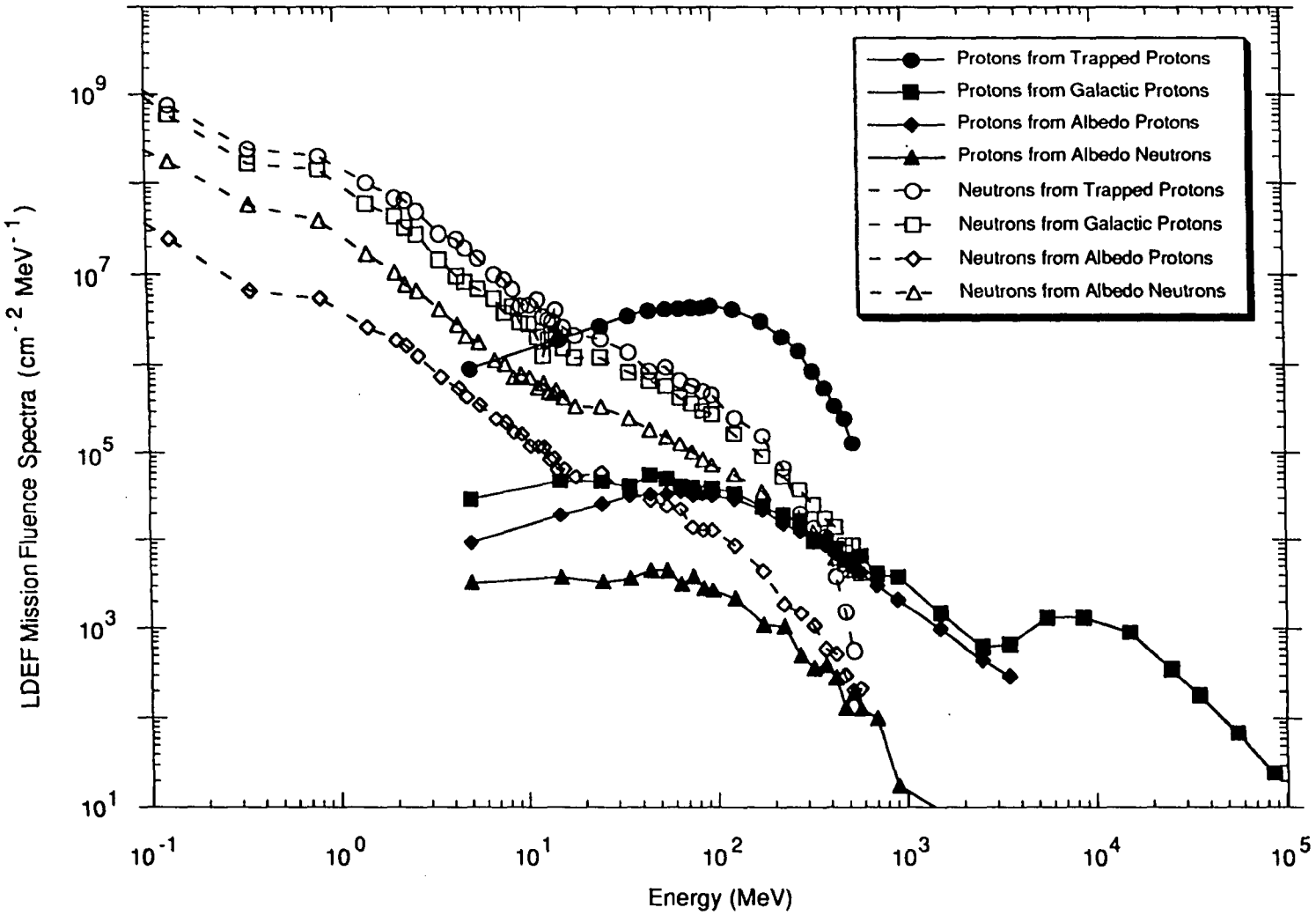

Fig. 5. Comparison of predicted proton (primary and secondary) and neutron fluence spectra at a depth of 10 g/cm^2 in aluminum from LDEF exposure to ionizing radiation sources.

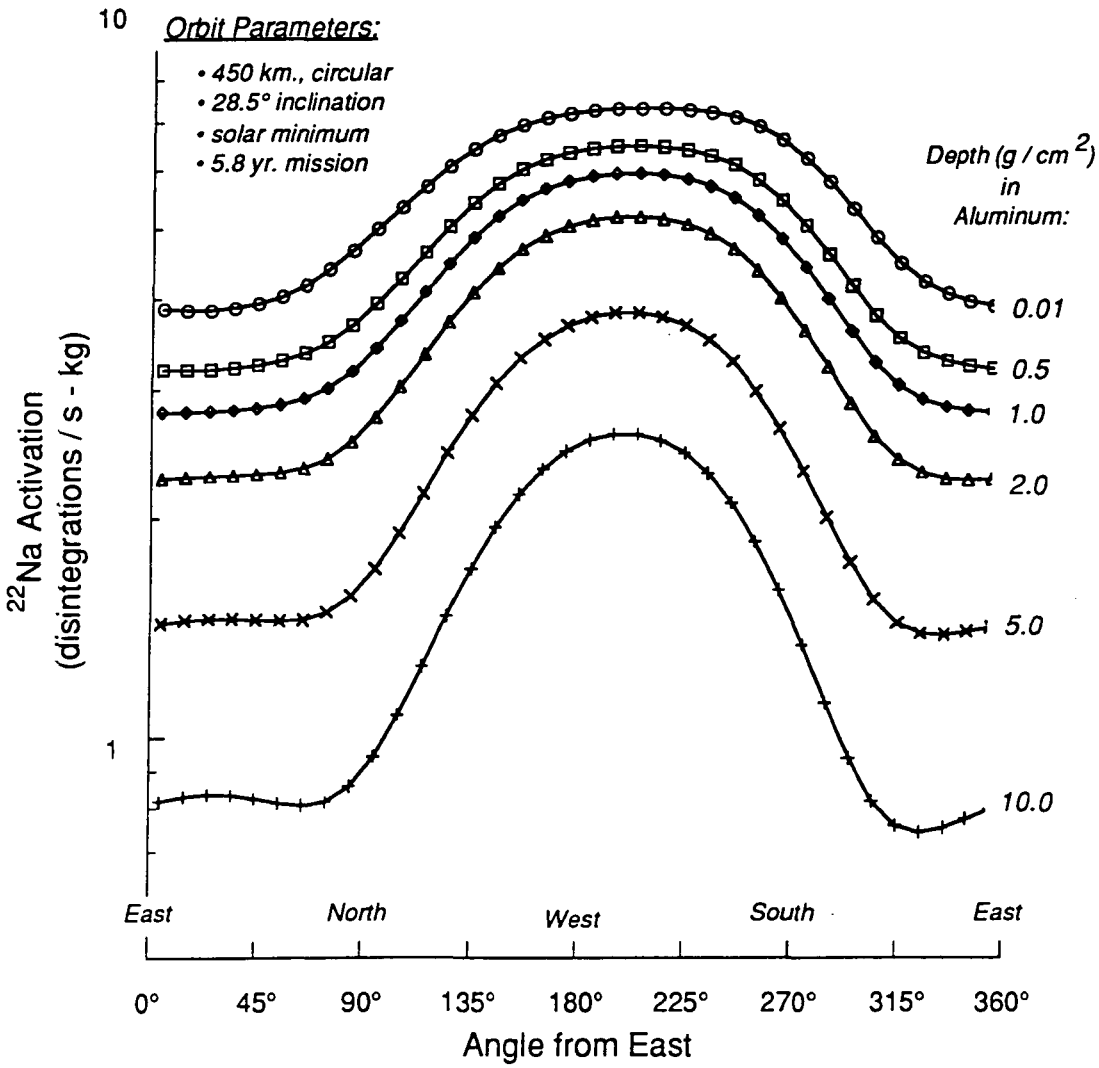

Fig. 6. Predicted directionality of ^{22}Na production in aluminum due to trapped proton anisotropy.

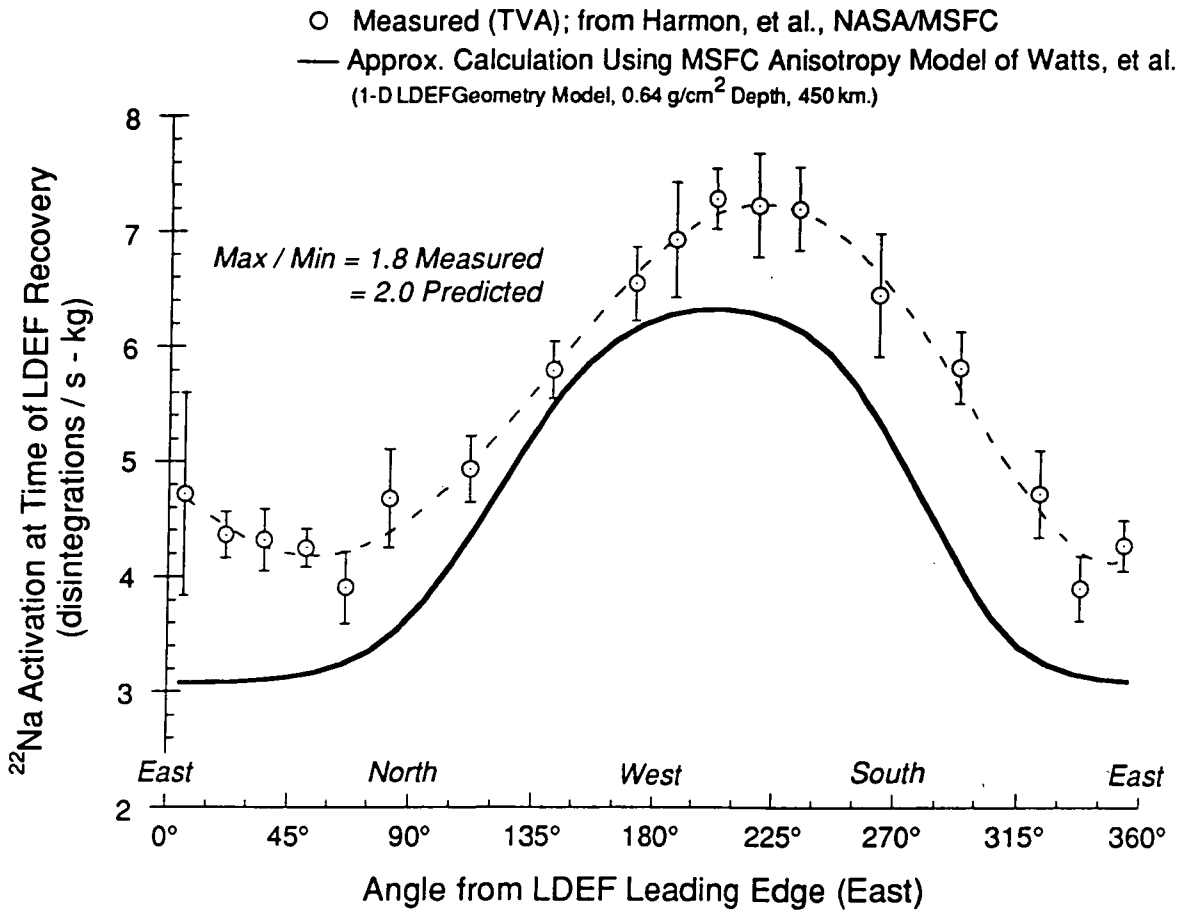

Fig. 7. Preliminary comparison of predicted vs. measured (ref. 16) effects of trapped proton anisotropy in terms of ^{22}Na radioactivity induced in aluminum clamps of LDEF experiment trays.

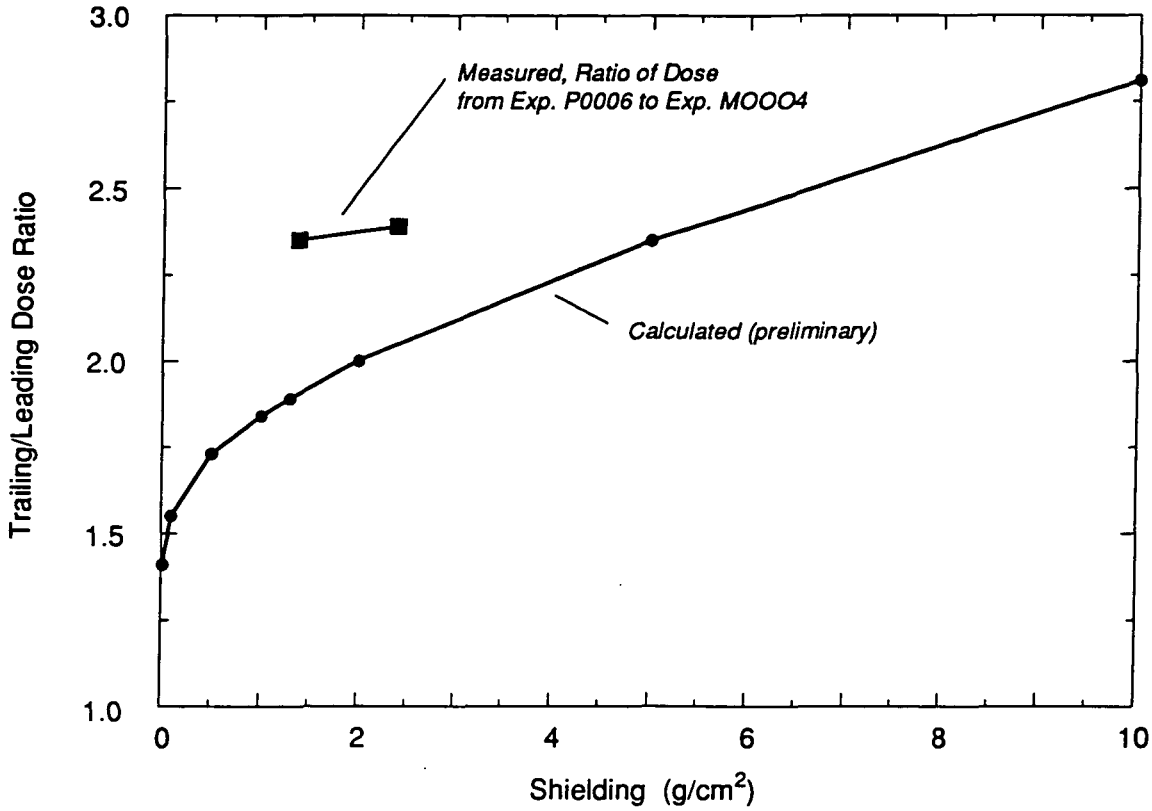

Fig. 8. Calculated ratio of absorbed dose in tissue as function of shielding depth (aluminum equivalent) on trailing (West) vs. leading (East) side of LDEF compared with ratio from the TLD (thermoluminescent dosimetry) measurements of Experiments P0006 and M0004 (ref. 19).

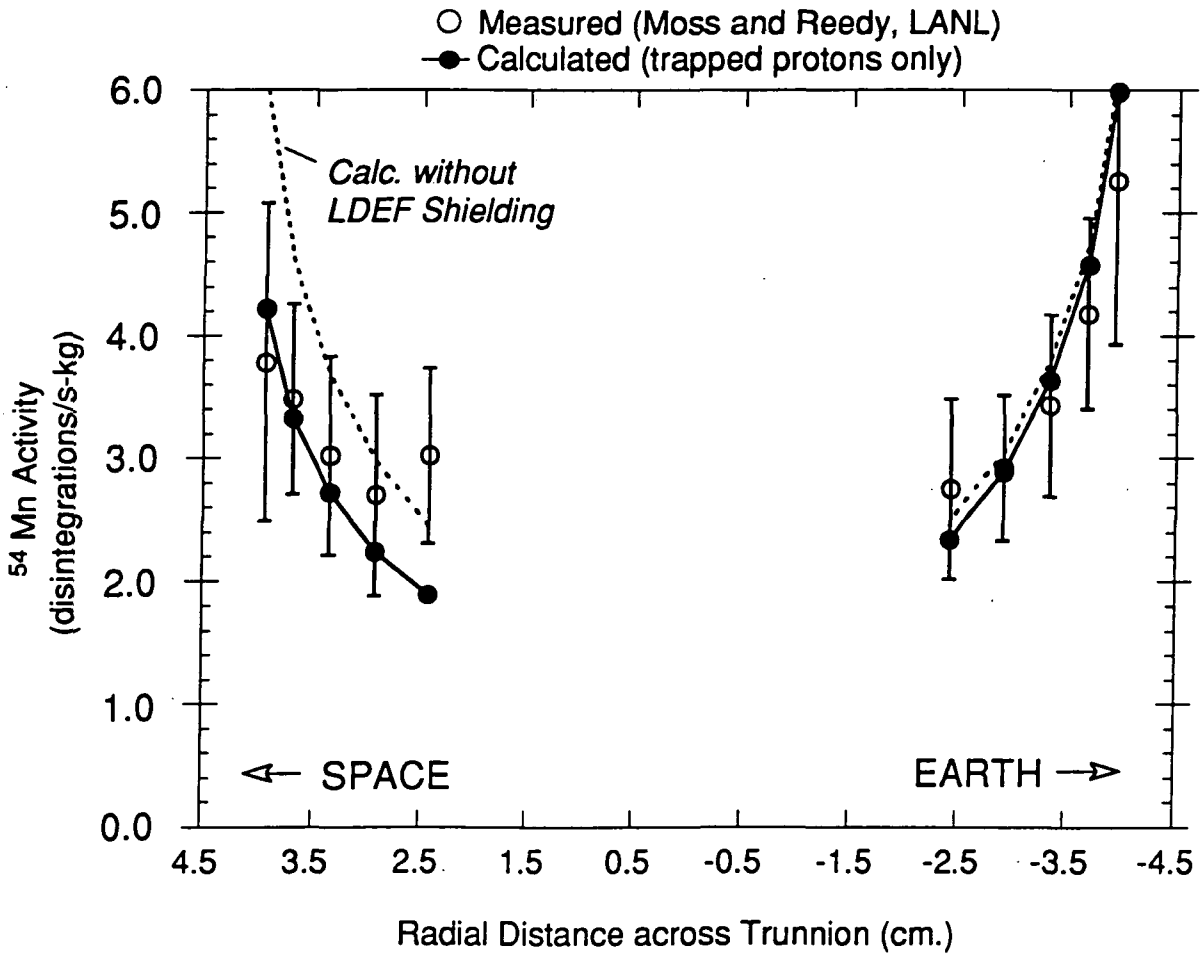

Fig. 9. Comparison of calculated and measured (ref. 20) induced radioactivity in leading (East) LDEF trunnion. The solid curves were calculated with a geometry that included a mass representation of the LDEF spacecraft and the trunnion. For the dotted curves the spacecraft was removed.

Section 5

LDEF GEOMETRY/MASS MODEL FOR RADIATION ANALYSES

LDEF GEOMETRY/MASS MODEL FOR RADIATION ANALYSES*+

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SUMMARY

A three-dimensional geometry/mass model of LDEF is under development for ionizing radiation analyses. This model, together with ray-tracing algorithms, is being programmed for use both as a stand-alone code in determining 3-D shielding distributions at dosimetry locations and as a geometry module that can be interfaced with radiation transport codes.

INTRODUCTION

To aid in the interpretation of ionizing radiation dosimetry data, and to obtain more accurate comparisons of dosimetry measurements with model predictions, a three-dimensional geometry/mass model of the Long Duration Exposure Facility (LDEF) satellite is under development. The modeling approach and level of detail being incorporated is described below.

APPROACH

Three general categories of LDEF components are defined for modeling purposes (fig. 1). The major structural components of the spacecraft are being modeled individually, as illustrated in fig. 2. The mass of other components of the spacecraft ("miscellaneous" category of fig. 1, which amounts to about 5% of the total mass) is combined with the mass of the larger components, except that the thermal covers are modeled individually. The third category is the experiment trays, containing the tray itself and the contents of the experiment. Since the weight of individual experiments varies substantially (fig. 3), each of the 84 experiment trays is modeled separately.

For experiment trays containing radiation dosimetry, "detailed" modeling of major components within the tray is being performed so that local shielding variations in the vicinity of the dosimeters can be accounted for (fig. 4). For trays not containing ionizing radiation dosimeters, only the volume and mass of the trays are preserved. The contents of these "generic" trays are modeled as homogeneous aluminum of reduced density.

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+ Presentation at First LDEF Post-Retrieval Symposium, 2-8 June 1991, Kissimmee FL; published in Proceedings Report NASA CP-3134 (1992).

Input data for the model is based on information provided by the LDEF Project Office (J. Jones) and others at LaRC (R. Shearer), including engineering drawings of the spacecraft and pre-flight weight estimates and layouts of individual experiments, and information on component layouts and materials descriptions obtained from individual experimenters.

The combinatorial geometry methodology is being used. In this method Boolean logic is applied to combine descriptions of simple body shapes to simulate complex geometries.

The model is being programmed to allow operation in either of two modes: as a geometry module which can be interfaced with radiation transport codes, and as a stand-alone program with ray tracing (fig. 5). In this latter mode, the areal density and material composition along rays emanating from specified points can be computed to form a 3-D grid of shielding variations about the point. For dosimeters where individual particle tracks are measured, this ray-tracing mode will allow rays to be started that have directions corresponding to the track direction, so the material traversed in reaching the dosimeter can be estimated for individual tracks.

STATUS

At present the LDEF spacecraft structure with generic experiment trays has been modeled. Detailed modeling for several of the trays containing ionizing radiation dosimeters (Experiments P0004, P0006, and M0004) is in progress.

Category	Component	No. Places	Weight (lbs.)	Weight %	Modeling Approach
STRUCTURE	Center Ring	1	2,073	9.7%	Modeled as individual component.
	Longerons	24	2,280	10.7%	Modeled as individual components.
	End Frames	2	1,374	6.4%	Modeled as individual components.
	Diagonal Tubes	8	926	4.3%	Modeled as individual components.
	Intercostal Rings	72	758	3.5%	Modeled as individual components.
	Trunions,Pins, & Scuff Plates	10	501	2.3%	Modeled as individual components.
	End Support Beams	5	285	1.3%	Modeled as individual components.
	TOTAL STRUCTURE:		8,197	38.3%	
MISCELLANEOUS	Batteries	2	100	0.5%	Included as part of earth-end support beam weight.
	Initiate Electronics	1	105	0.5%	Included as part of center ring weight.
	Wiring	-	100	0.5%	Included as part of center ring weight.
	Nuts and Bolts	-	200	0.9%	Included as part of center ring weight.
	Damper Assembly	1	62	0.3%	Included as part of space-end support beam weight.
	Thermal Covers (Ends)	12	154	0.7%	Modeled as individual components.
	Ballast Plates	11	365	1.7%	Included as part of end frames.
	TOTAL MISCELLANEOUS:		1,086	5.1%	
EXPERIMENTS	Experiment Components + Trays	84	12,110	56.6%	Modeled each experiment tray separately, with individual experiment weights preserved. Modeling detail for components varies with experiment type.
	TOTAL LDEF WEIGHT:		21,393	100.0%	

Fig. 1. Level of detail incorporated in LDEF geometry/mass model.

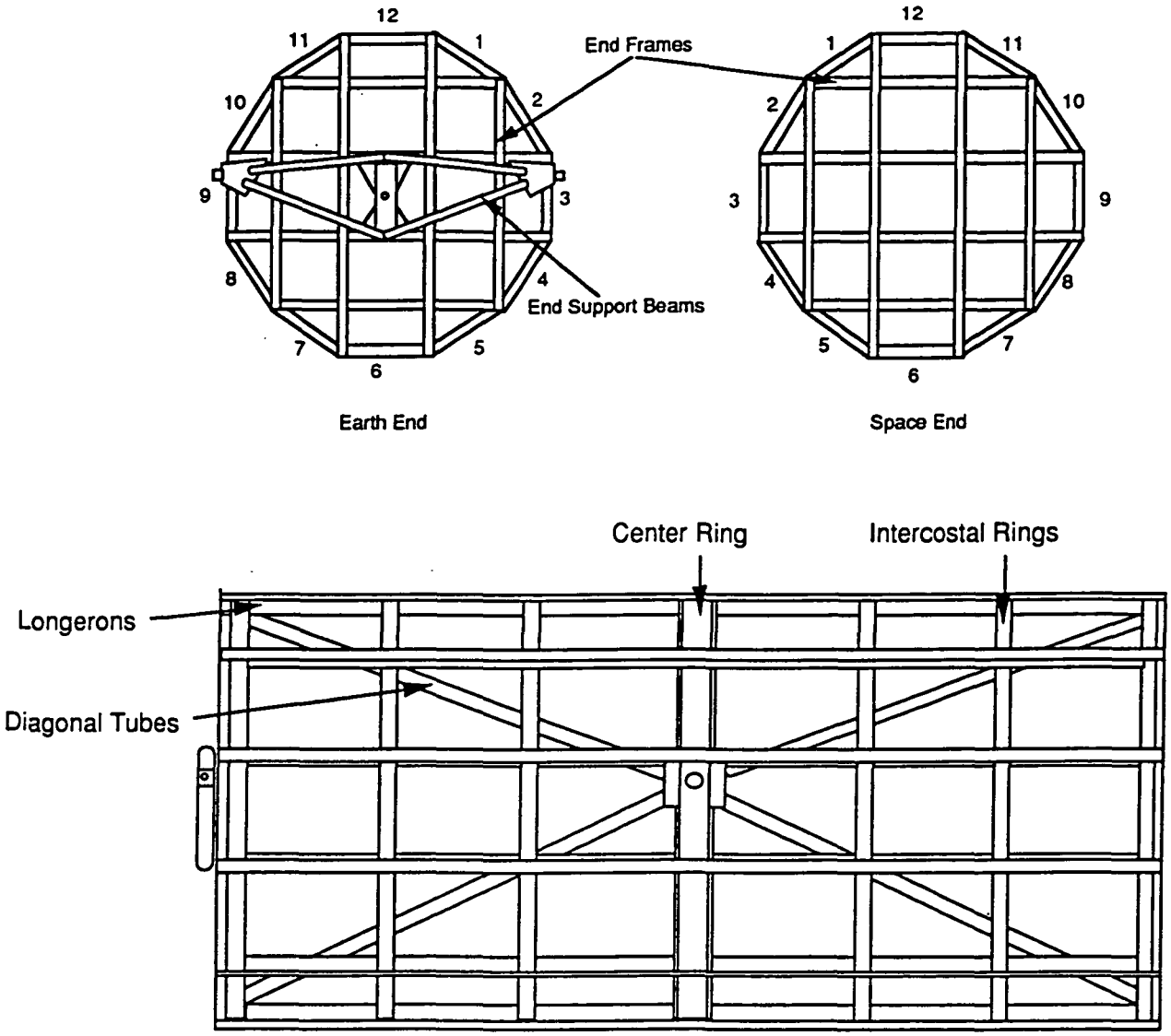


Fig. 2. Model of LDEF spacecraft structure.

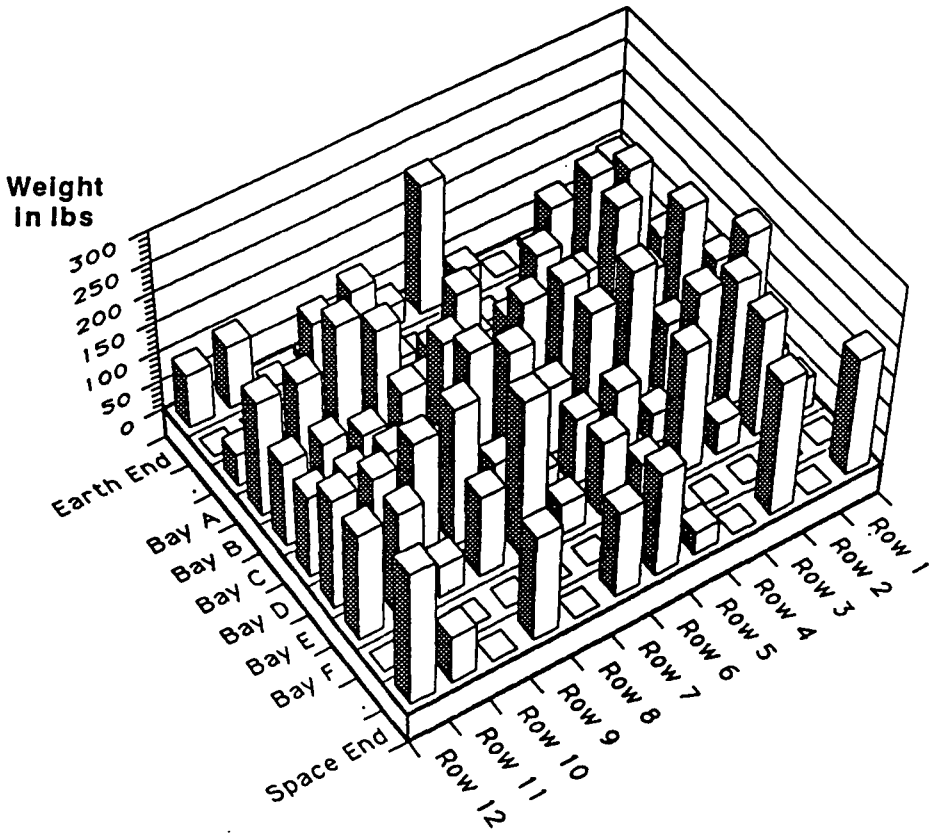
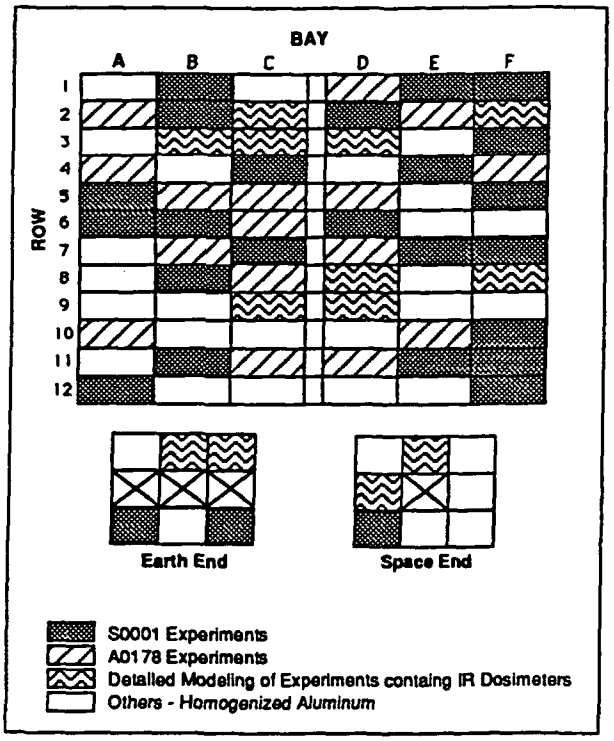


Fig. 3. Weights of individual experiments on LDEF.



Level of Detail for Modeling Experiments:

No. Trays	Model	Experiments
26	Al plate	S0001: Space Debris (LaRC)
16	Al+plastic plates	A0178: Ultra-heavy Cosmic-Ray Expt. (Dublin Inst., ESTEC)
13	"detailed"	Experiments containing IR dosimetry - see NOTE
29	homogenized Al	(all others)

NOTE: Trays Containing IR Dosimetery for Detailed Modeling are:

Tray Bay-Row	Experiment No.	Experiment	Dosimetry
C-2, G-2	A-0015	Biostack (DFVLR)	TLD's, PNTD's
C-3, C-9	A-0114	Atomic Oxygen (UAH, MSFC)	Activation Samples
B-3	A-0138	Optical Fibers (CERT/ONERA - DERTS)	TLD'S
H-3, H-12	M0001	Heavy Ions (NRL)	PNTD's
D-3,D-9,G-12	M0002-1	Trapped Proton Spect. (AFGPL,MSFC, et al.)	PNTD's,TLD's,Act.
E-6	M0002-2	Heavy Cosmic-Ray Nuclei (U. Keil)	PNTD's
D-3,D-8,D-9	M0003	Space Envr. Effects on Matls. (Aerospace)	TLD's
F-8	M0004	Space Envr. Effects on Optics (AFWL)	TLD's, PNTD's
C-2	M0006	Space Envr. Effects (AFTAC, Grumman)	TLD's
F-2	P0004	SEEDS	TLD's, PNTD's
F-2	P0008	LET Spectrum Meas. (Univ. SF, MSFC)	TLD's, PNTD's, Fiss. & Act. Samples

Fig. 4. Modeling approach for LDEF experiments.

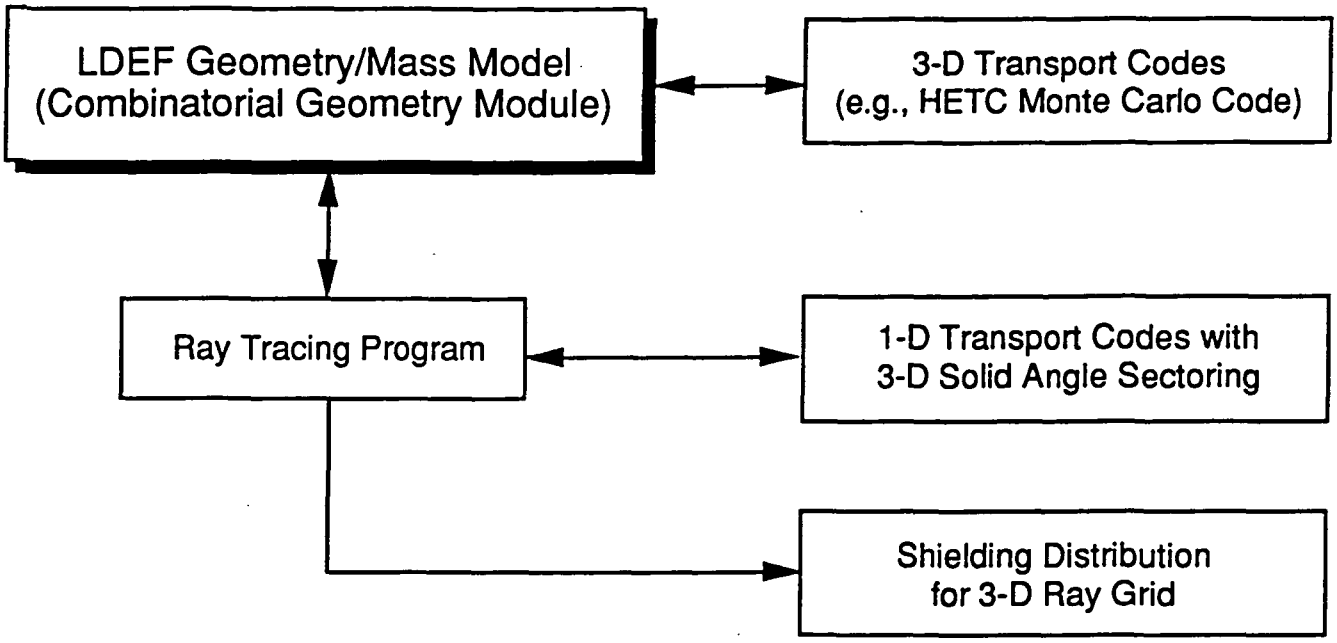


Fig. 5. Utility of LDEF geometry/mass model.

Section 6

RADIATION MODEL PREDICTIONS AND VALIDATIONS USING LDEF SATELLITE DATA

RADIATION MODEL PREDICTIONS AND VALIDATION USING LDEF SATELLITE DATA*+

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SUMMARY

Predictions and comparisons with the radiation dose measurements on LDEF by thermoluminescent dosimeters have been made to evaluate the accuracy of models currently used in defining the ionizing radiation environment for low Earth orbit missions. The calculations include a detailed simulation of the radiation exposure (altitude and solar cycle variations, directional dependence) and shielding effects (three-dimensional LDEF geometry model) so that differences in the predicted and observed doses can be attributed to environment model uncertainties. The LDEF dose data are utilized to assess the accuracy of models describing the trapped proton flux, the trapped proton directionality, and the trapped electron flux.

INTRODUCTION

Radiation dosimetry data from the Long Duration Exposure Facility (LDEF) mission are being utilized to evaluate the accuracy of current ionizing radiation environment models and to identify model improvements needed for future mission applications in low Earth orbit. A calculational program is in progress to compare model predictions with the different types of LDEF ionizing radiation measurements (dose, activation, LET spectra, secondary particles, etc.), and the status of this work is summarized in a companion paper (ref. 1).

The scope of the present paper is restricted to model predictions and comparisons with LDEF thermoluminescent dosimetry (TLD) measurements of the radiation dose. These TLD measurements provide one set of data for evaluating the accuracy of environment models describing the trapped proton flux, the trapped proton directionality, and the trapped electron flux. Assessments of trapped radiation models utilizing other LDEF data sets from plastic nuclear track detectors and activation sample measurements of induced radioactivity are in progress.

*Work supported by NASA Marshall Space Flight Center, Huntsville, AL, Contracts NAS8-38770 and NAS8-39386.
+Presentation at Second LDEF Post-Retrieval Symposium, San Diego CA, 1-5 June 1992; published in Proceedings Report NASA CP-3194 (1993).

CALCULATIONAL METHOD

Environment Model -- Results from the calculations of Watts, et al. (ref. 2) are used to model the LDEF exposure to trapped protons. These calculations are based on the standard AP8 omnidirectional proton flux model (ref. 3), with altitude and solar cycle variations during the LDEF mission included, and with the MSFC anisotropy model (ref. 4) applied to determine the trapped proton directionality. In the calculations here, the directionality was taken into account by using different incident energy spectra along directions defined by a 3-D angular grid of 720 equal solid angle intervals about the dose point. Example spectra are shown in Fig. 1.

Spacecraft Model -- The LDEF radiation dosimetry data is influenced by material shielding effects due to the dosimeter itself, nearby components and experiments, and the spacecraft structure. It is necessary to isolate shielding effects particular to the LDEF spacecraft so that the evaluated model uncertainties can be attributed to the ambient radiation environment and so that the results have applicability to other missions with different spacecraft configurations. To help ensure that differences between predictions and measurements are due to the external radiation environment and not shielding effects, a detailed three-dimensional geometry/mass model of the LDEF spacecraft and selected experiment trays has been developed (ref. 5), and this 3-D model has been used to take into account shielding effects for the dose predictions here.

Radiation Transport -- Three-dimensional radiation transport calculations were performed using the 3-D LDEF geometry/mass model and the solid angle sectoring approximation, in which the solid angle around each dose point is divided into small sectors and the shielding attenuation along "ray" directions through each sector is computed. Transport calculations using different trapped proton energy spectra for each direction were carried out using the MSFC code written by Burrell (ref. 6), which employs the straightahead approximation together with fits to stopping power and range relations to obtain an analytical solution of the transport equation. The attenuation is computed for material along each ray direction representing a solid angle sector, the attenuated fluence spectrum is folded with the stopping power for tissue, and the results summed for all rays to obtain the tissue dose.

An example TLD shielding distribution used in computing the radiation attenuation is shown in Fig. 2. Shown are areal densities (aluminum equivalent) along rays emanating at the midpoints of 720 equal solid angle bins surrounding the TLD. The TLD in this case is located in one of the canisters containing tomato seeds in tray F2 (SEEDS experiment, Exp. No. P0004). The outward directed TLD normal is at $\varphi = 240°$ and $\theta = 90°$, where $+\varphi$ is measured from south (row 6) and $+\theta$ from the zenith direction. Also indicated in Fig. 2 is the constant shielding corresponding to a spherical geometry model having a radius equal to the vertical (minimum) TLD shielding, which is the simple geometry model assumed for some of the scoping

estimates in the LDEF pre-recovery dose predictions (ref. 7). As evident, the spherical geometry model substantially underestimates the dosimetry shielding.

RESULTS

TLD measurements were made at various locations on the LDEF spacecraft and at various shielding depths in the experiment trays. Fig. 3 summarizes the TLD data presently available at the larger shielding depths ($\gtrsim$ 0.5 g/cm^2) where trapped protons dominate the dose contribution. The data shown are from dosimeters located: (a) on the trailing (west) side of the spacecraft, consisting of the measurements by Frank, et al. (ref. 8) for TLDs located in experiment tray F2 (Exps. P0004 and P0006), measurements by Frank, et al. (ref. 8) and Reitz (ref. 9) in tray C2 (Exp. A0015), and measurements by Bourrieau (ref. 10) in tray B3 (Exp. A0138-7); (b) on the earth-end of the spacecraft, consisting of measurements by Frank, et al. (ref. 8) and Reitz (ref. 9) in tray G2 (Exp. A0015); and (c) on the leading (east) side, consisting of measurements by Frank, et al. (ref. 8) in tray F8 (Exp. M0004) and by Blake and Imamoto (ref. 11) in tray D9 (Exp. M0003). In two cases, the Exp. M0006 measurements of Chang, et al. (ref. 12) and some of the Exp. M0003 measurements of Blake and Imamoto (ref. 11), TLD assemblies were located in drawers of the experiment trays which were closed 40 weeks into the mission. Thus, the shielding changed during flight in these cases, and results from these measurements are not included in Fig. 3.

The doses in Fig. 3, and in subsequent graphs of this type, are plotted as a function of the "vertical" shielding thickness in g/cm^2 of aluminum equivalent material (based on equivalent ranges for 100-MeV protons), where the vertical direction is along the normal from the TLD face outward from the LDEF interior. This vertical direction generally corresponds to the direction of minimum shielding, although there are exceptions, such as for the TLDs located near the edge of the thick detector stack in Exp. P0006.

Predicted doses and comparisons with the data of Fig. 3 are given below with the objective being to evaluate the accuracy of models describing the magnitude of the trapped proton flux and its angular dependence. Subsequent comparisons using previous predictions (ref. 7) are then made with the TLD data at thin shielding depths where the dose contribution is dominated by incident electrons to assess the accuracy of trapped electron flux models.

Trapped Proton Dose

Figs. 4-6 compare predicted and measured doses for TLDs in LDEF experiment trays located on the trailing edge, earth end, and leading edge of the spacecraft, respectively. Predictions for Exps. P0004 and P0006 located in tray F2 and Exp. M0004 in tray F8 are based on a detailed geometry modeling of the tray

contents (ref. 4); for other cases (trays B3, C2, and G2) the tray contents were modeled as a single homogenized material (aluminum) with reduced density, so the dosimetry shielding is approximate for these cases. For the TLDs located in the Exp. P0006 detector stack, both measurements and calculations show appreciable variation of the dose for different locations within the TLD array for the same vertical shielding depth; the computed doses shown for P0006 are for a point in the middle of the array, and the measured values are the minimum values observed (ref. 9) across the array. The values shown for the Reitz measurements in Exp. A0015 are averages of the reported data (ref. 8) for TLD types 100 and 700.

A summary of the predicted and measured doses is given in Fig. 7. These results show that the AP8 trapped proton flux model gives a lower dose than observed from TLD measurements aboard LDEF for all spacecraft locations and shielding depths, with the predictions usually about a factor of two lower than measured. The predicted-to-measured dose ratios are practically constant with shielding depth, indicating that the trapped proton model environment is too low by about the same factor over a wide range of proton energies. Since the total mission dose is accumulated during the early high-altitude portion of the flight, which occurred predominately during the solar minimum phase of the solar cycle (ref. 2), these conclusions refer to the solar minimum version (AP8MIN) of the AP8 trapped proton model. (Model comparisons with available LDEF induced radioactivity measurements, ref. 13, for relatively short half-life radioisotopes should enable a check of the AP8MAX model since the latter part of the flight took place during solar maximum.)

The present dose predictions based on a detailed LDEF geometry model and an anisotropic trapped proton environment differ from early scoping estimates (ref. 7) made as part of the LDEF pre-recovery predictions in which simple geometry models (sphere and planar) and an omnidirectional trapped proton environment model were used. The difference is illustrated in Fig. 8 for comparisons with the TLD data of Exps. P0004 and P0006. While the omnidirectional, spherical geometry calculations (fortuitously) agree with the data, the more accurate models give doses about a factor two lower than the measurements. This illustrates that directional effects and a reasonably detailed spacecraft geometry model are needed in utilizing LDEF data for definitive assessments of uncertainties in the radiation environment.

Trapped Proton Anisotropy

For the low inclination (28.5°) of LDEF orbits, the dose from galactic cosmic rays is very small due to geomagnetic shielding, and, except for near-surface shielding depths where the trapped electron environment is important, the absorbed dose measurements on LDEF are due almost entirely to the trapped proton exposure during passes through the South Atlantic Anomaly (SAA). In the SAA region at LDEF altitudes, protons are "mirroring" in the geomagnetic field, with trajectories confined mainly in planes perpendicular to the local magnetic field direction and with in-plane asymmetry due to the east-west effect.

Since LDEF had a very stable orientation during the entire mission, measurements at various positions around the spacecraft provide data for evaluating the proton anisotropy model used.

In several cases TLD dosimeters at similar shielding depths were located near the trailing (row 3) and leading (row 9) edges of the spacecraft. These data and predictions in terms of the ratio of trailing-to-leading edge doses are shown in Fig. 9. The measured anisotropy is generally higher than predicted by the MSFC anisotropy model; e.g., the measured anisotropy for Exps. P0004/M0004 and Exps. P0006/M0004 is a factor of ≈ 2.4, whereas the calculated anisotropy factor for these cases is ≈ 1.4.

To further investigate the difference found between measured and predicted trapped proton directionality, several calculations were performed to determine the influence of spacecraft geometry on the predicted anisotropy. Fig. 10 shows the angular variation of dose at a particular depth (4 g/cm^2) for three assumed geometries: (a) the curve labeled "LDEF" was computed using the three-dimensional LDEF spacecraft model, (b) the curve labeled "Cylinder" was computed for a cylindrical spacecraft geometry having the same diameter, length, and total mass as LDEF but with the mass uniformly distributed within the cylinder, and (c) the "Plane" curve is for a planar shielding geometry with infinite backing and lateral dimensions and with the plane normal vector pointed in the plotted direction. These results for different model geometries show significantly different characteristic shapes for the angular variation of the dose. The detailed 3-D spacecraft model exhibits a local enhancement of the dose on the east side of the spacecraft, which is not present for the homogeneous cylinder or planar models. This dose "bump" on the east side is due to the fact that the interior of LDEF underneath the experiment trays contains relatively little mass, so the high flux incident on the west side "streams" through the hollow interior and contributes to the dose on the east side. This radiation streaming through the interior of LDEF can also influence the anisotropy observed at different shielding depths because at deeper depths on the east side the west-side flux contribution becomes larger. This is illustrated in Fig. 11 where the dose at various depths is calculated around the center ring of the spacecraft structure using the 3-D LDEF model. At small depths (e.g., 0.5 g/cm^2) the west side dose is higher, at about 10 g/cm^2 depth the west and east side doses are about the same, and at larger depths (e.g., 14 g/cm^2), corresponding roughly to the bottom of most of the experiment trays, the east side dose is higher.

While these calculations on geometry effects do not fully explain the difference found between the measured and predicted dose anisotropy, they do indicate that the observed anisotropy can be substantially influenced by the spacecraft configuration and that a realistic spacecraft geometry model is necessary in interpreting the measurements and in applying the data to other spacecraft configurations for future missions.

Trapped Electron Dose

Two experiments on LDEF contained TLDs with sufficiently thin shielding that the response is dominated by incident electrons. Measured TLD doses for these cases have been reported by Blake and Imamoto (ref. 11) for Exp. M0003 and by Bourrieau (ref. 10) for Exp. A0138-7. Results from these measurements are plotted in Fig 12 together with the pre-recovery predictions made by Watts (ref. 7) using the AE8MIN and AE8MAX trapped electron environment models (ref. 14). The predictions are for a planar shield with infinite backing, which is expected to be an adequate geometry approximation in this case because of the shallow shielding penetration of the electrons and secondary bremsstrahlung. The M0003 results reported by Blake and Imamoto for dose in the TLD lithium fluoride have been multiplied by 1.25, the stopping power ratio of water to lithium fluoride for electrons in the applicable energy range, to compare with the calculated results in terms of tissue dose. M0003 measurements were also made for thinner shielding than shown in Fig. 12, but these data points are not included here because, as discussed by Blake and Imamoto, the results are suspect at present due to possible TLD saturation effects.

Fig. 12 shows that for small shielding depths where the incident electron flux is predicted to clearly dominate the dose ($\lesssim 0.1$ g/cm^2, corresponding to $\lesssim 15$ mils of aluminum shielding), there is general agreement between the predictions and measurements. The largest difference is at a shielding depth of about 0.04 g/cm^2, where the predicted dose is lower than measured by a factor of two; near 0.01 g/cm^2, the predicted dose is higher by a factor of 1.5. Blake and Imamoto (ref. 11) point out that the flattening of the measured dose profile near 2×10^4 rads for very thin shielding may be due to TLD saturation effects caused by very high doses in a thin layer of the TLD near the outboard surface and by the steep dose gradient within the TLD thickness. Thus, this may account for at least part of the difference between measurements and predictions in the thin shielding region $\lesssim 3 \times 10^{-2}$ g/cm^2 of Fig. 12 rather than environment modeling uncertainties.

CONCLUSIONS

Based on the radiation dose measurements by thermoluminescent dosimeters on LDEF, the AP8 proton model at solar minimum (AP8MIN) underpredicts the trapped proton flux in low Earth orbit by about a factor of two. This difference between measurement and prediction is not totally unexpected since a factor of two uncertainty is often associated with the AP8 model, but the difference here is larger than indicated by some Shuttle measurements (e.g., ref. 15). The higher radiation dose observed for TLDs on the trailing edge of the spacecraft is in agreement with calculations using the MSFC model for describing the angular dependence of the trapped proton environment, although the measured dose anisotropy, based on the relatively few trailing-to-leading edge TLD positions onboard at common shielding depths, is somewhat

higher than predicted. For thin shielding where incident electrons dominate the dose, predictions based on the AE8MIN trapped electron flux model are in general agreement with the TLD measurements (within a factor of two). Some of this difference may be due to saturation effects in the TLDs, which is still under investigation (ref. 11).

These conclusions should be regarded as tentative since additional calculations and comparisons with other LDEF radiation data are still in progress. For example, measurements of the induced radioactivity in various metal samples, some located in close proximity to the TLDs, provide additional data for evaluating the trapped proton flux model and will allow a cross-check of the conclusions here based on model comparisons with TLD data. Also, a more detailed mapping of the proton anisotropy is available from activation measurements, and these data are expected to provide a more definitive test of the trapped proton anisotropy model. These, and other, model comparisons with the LDEF ionizing radiation data are underway.

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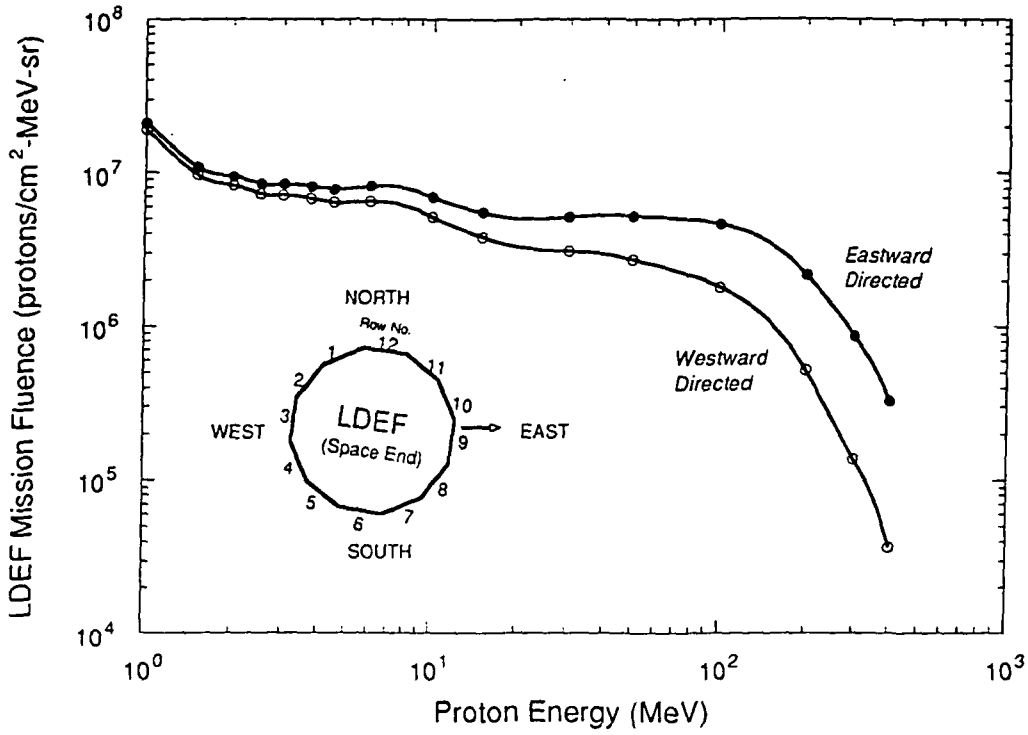

Figure 1. Directionality of LDEF radiation exposure to trapped proton environment. Example fluence spectra are shown for only two directions, the eastward-directed fluence (incident on west side of LDEF) and the westward-directed fluence.

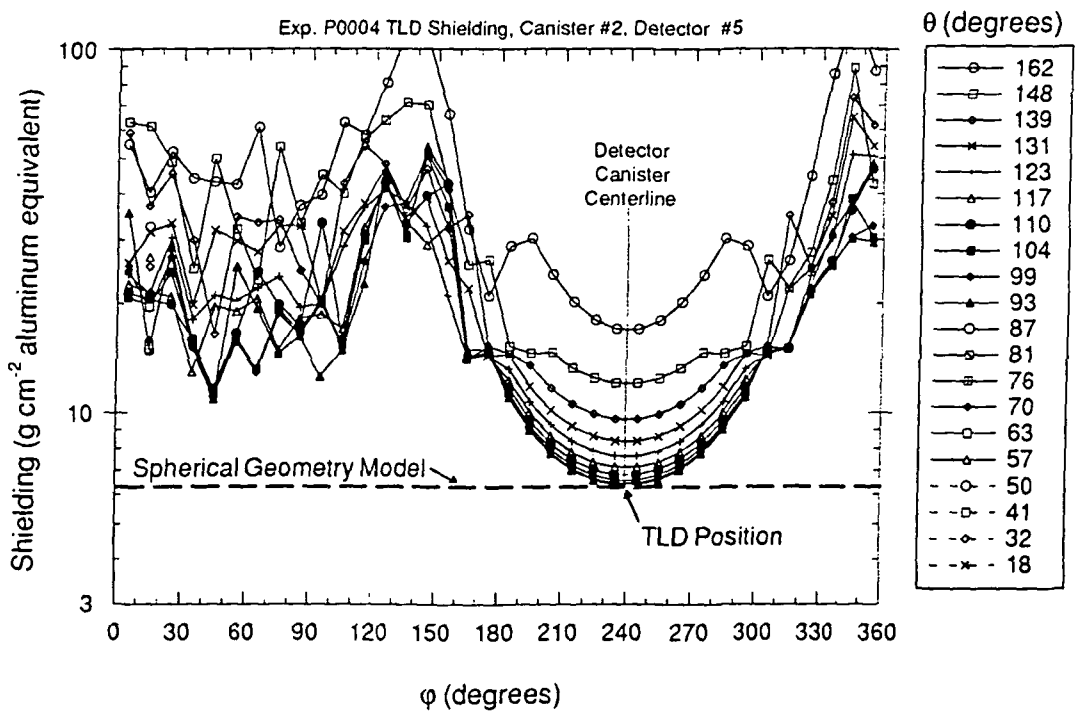

Figure 2. Example of shielding distributions generated using the 3-D spacecraft geometry model in predicting LDEF thermoluminescent dosimetry (TLD) response. Shown are areal densities along rays specified by the angles φ and θ (defined in text) emanating from a particular TLD location in the SEEDS experiment canister (Exp. P0004). The constant shielding for a simple 1-D spherical geometry model (used in some LDEF pre-recovery dose estimates) is shown for comparison.

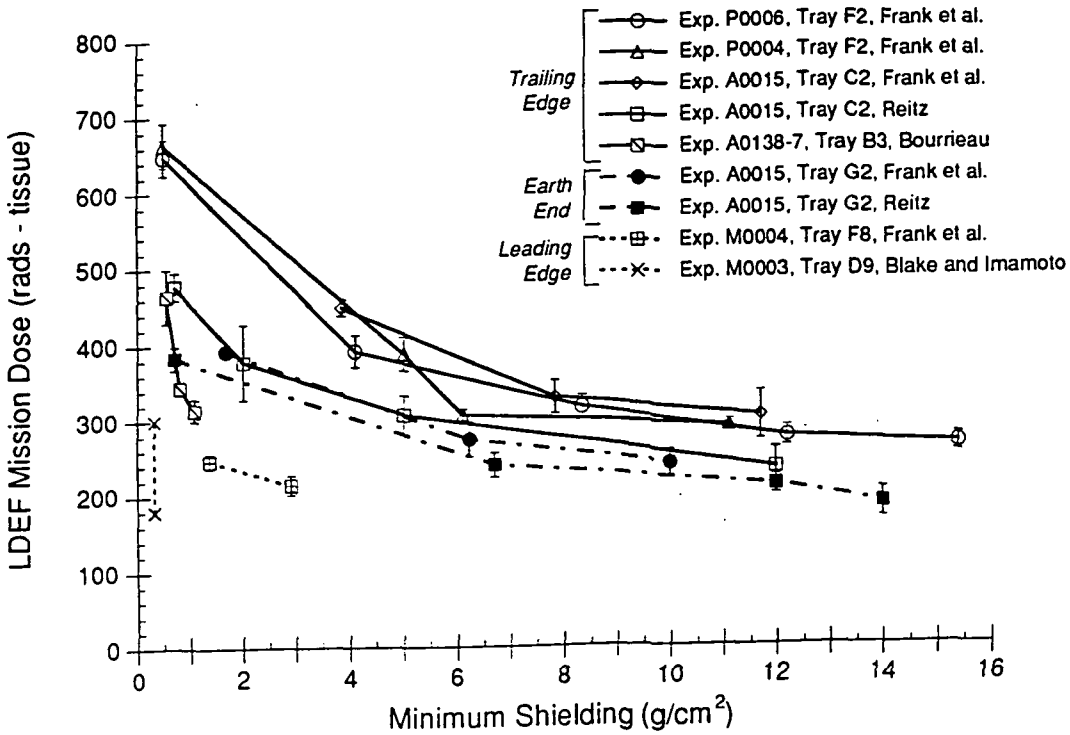

Figure 3. Summary of ionizing radiation dose measurements made on LDEF by thermoluminescent dosimeters (TLDs) at shielding depths where the dose is dominated by trapped protons.

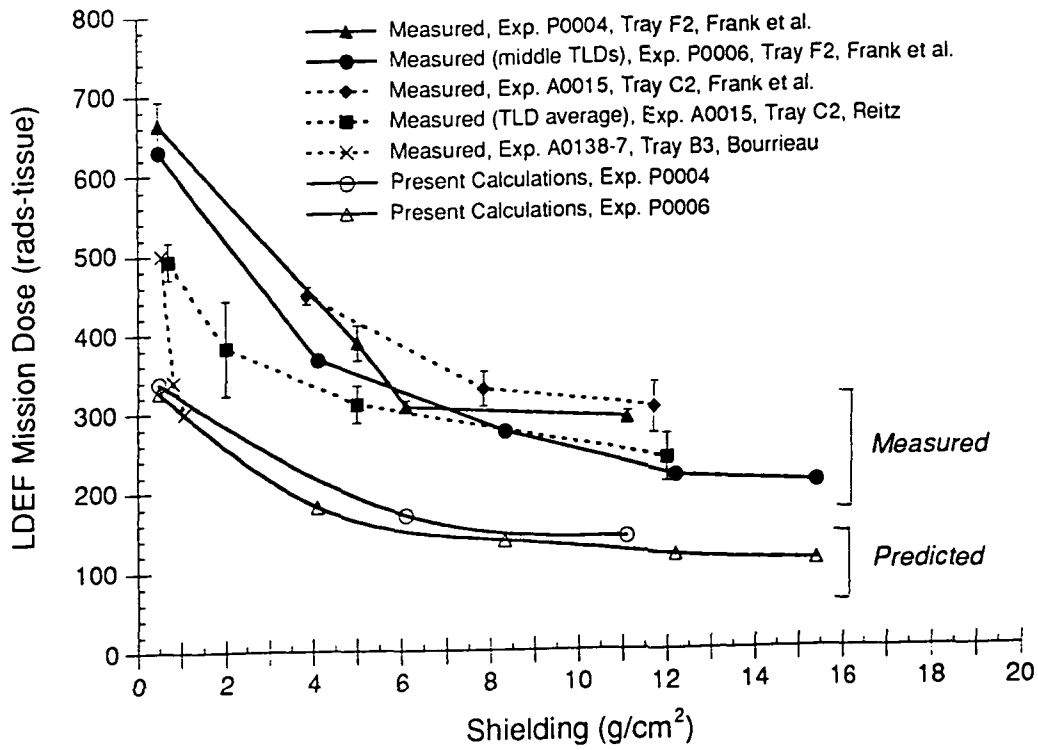

Figure 4. Predicted vs. measured radiation dose due to trapped proton environment for LDEF experiments on trailing (west) side of spacecraft.

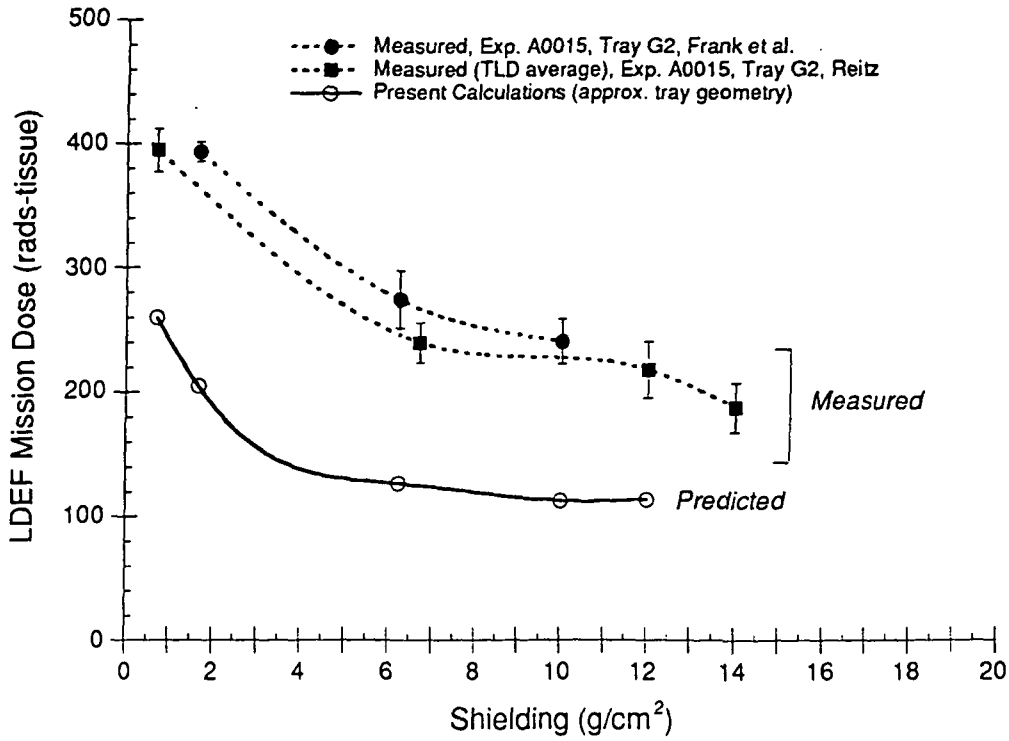

Figure 5. Predicted vs. measured radiation dose due to trapped proton environment for LDEF experiments on earth end of spacecraft.

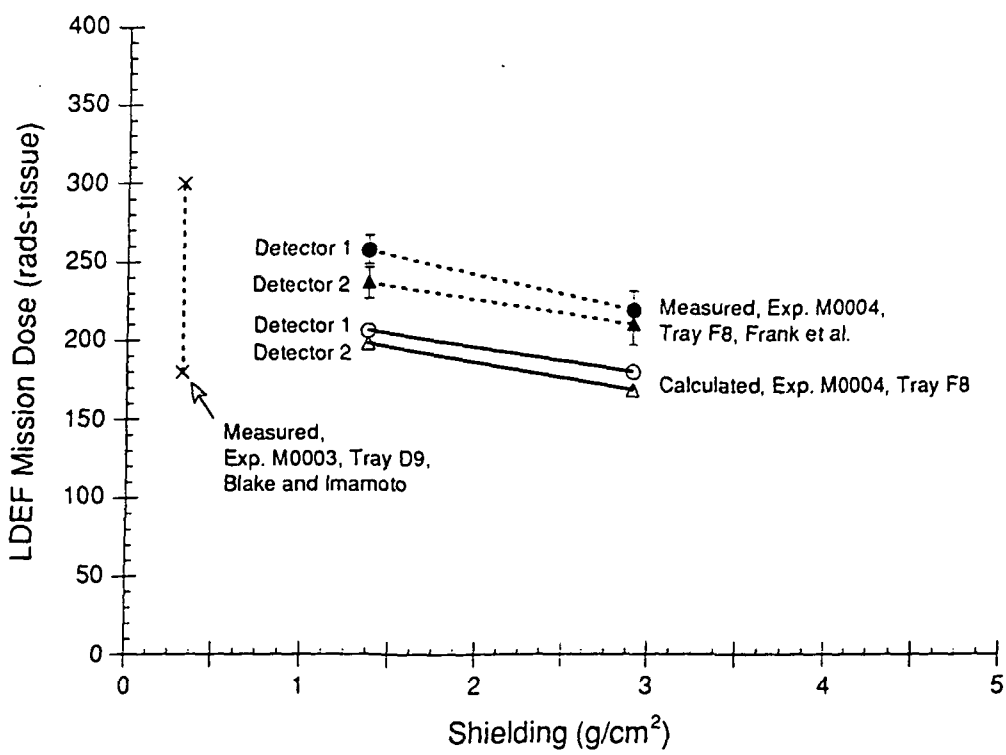

Figure 6. Predicted vs. measured radiation dose due to trapped proton environment for LDEF experiments on leading (east) side of spacecraft.

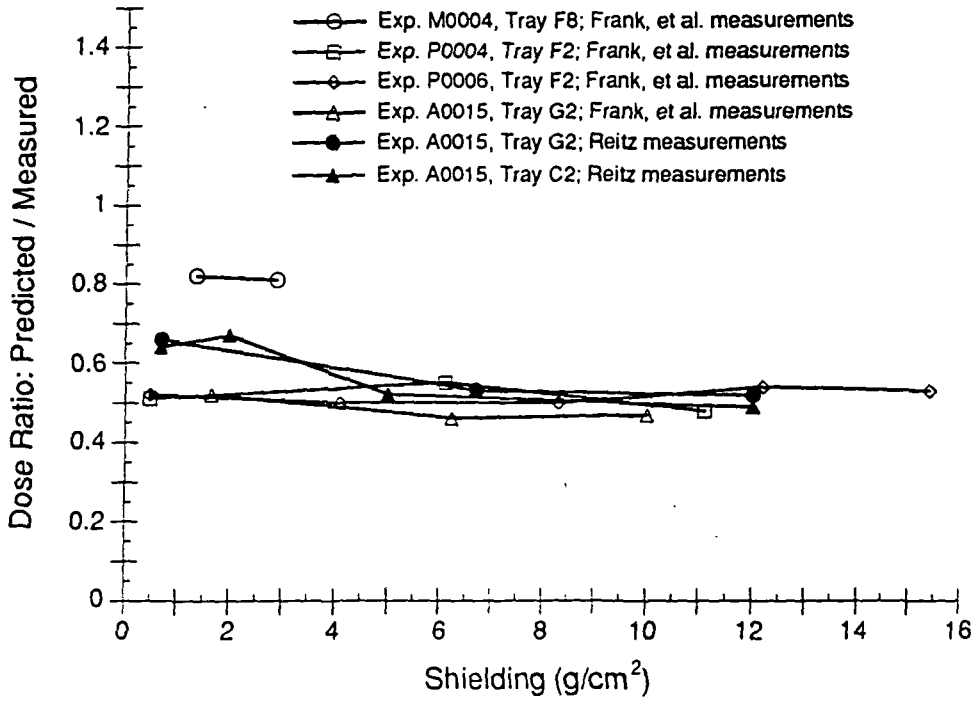

Figure 7. Ratio of predicted-to-measured radiation dose (in tissue) due to trapped proton environment based on LDEF data from thermoluminescent dosimeters.

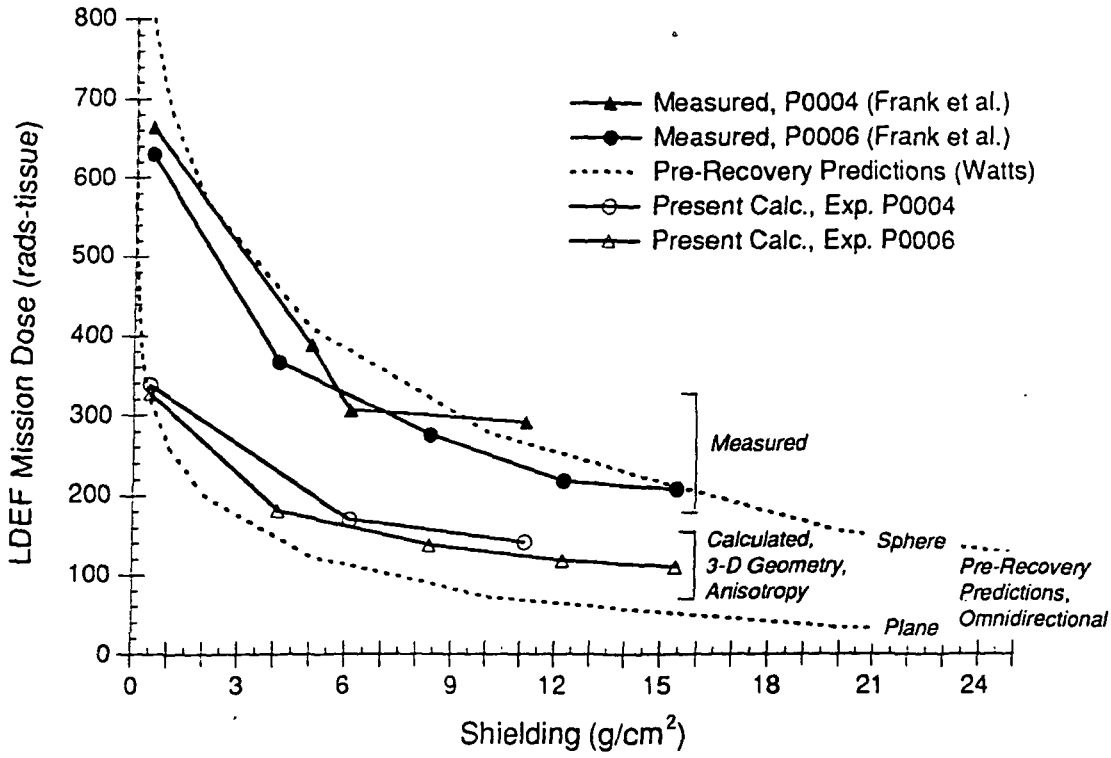

Figure 8. Influence of geomery model and environment anisotropy on predicting LDEF dose from trapped protons.

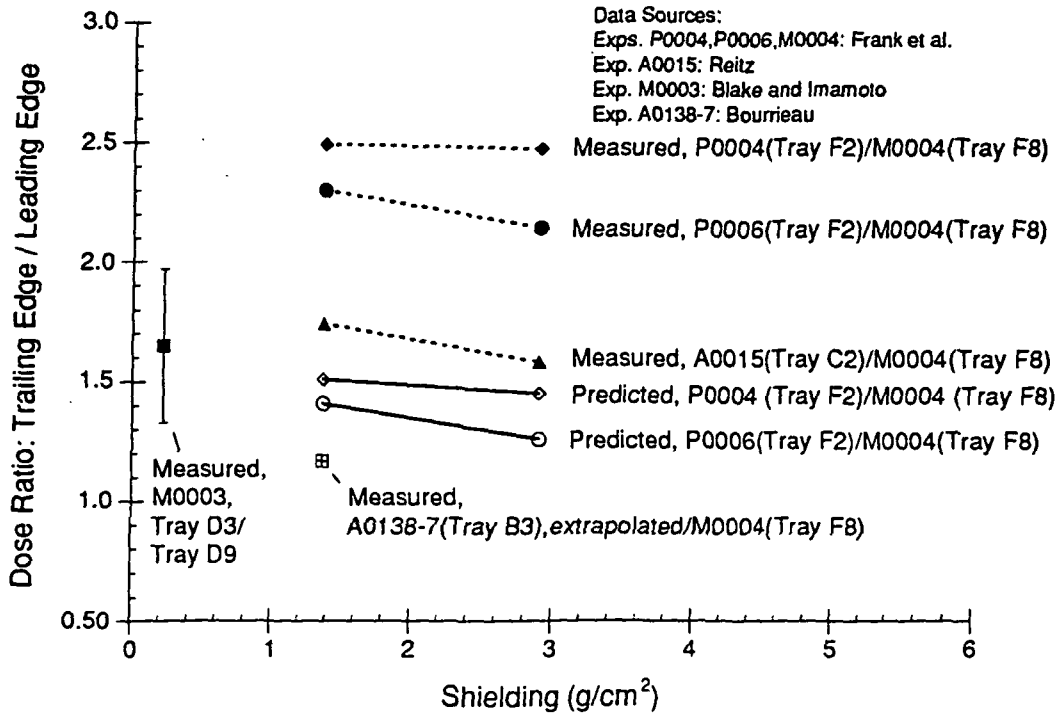

Figure 9. Radiation dose anisotropy on LDEF due to the directionality of the trapped proton environment. Shown are predicted and measured values of the ratio for the dose on the trailing (west) side LDEF to the dose on leading (east) side.

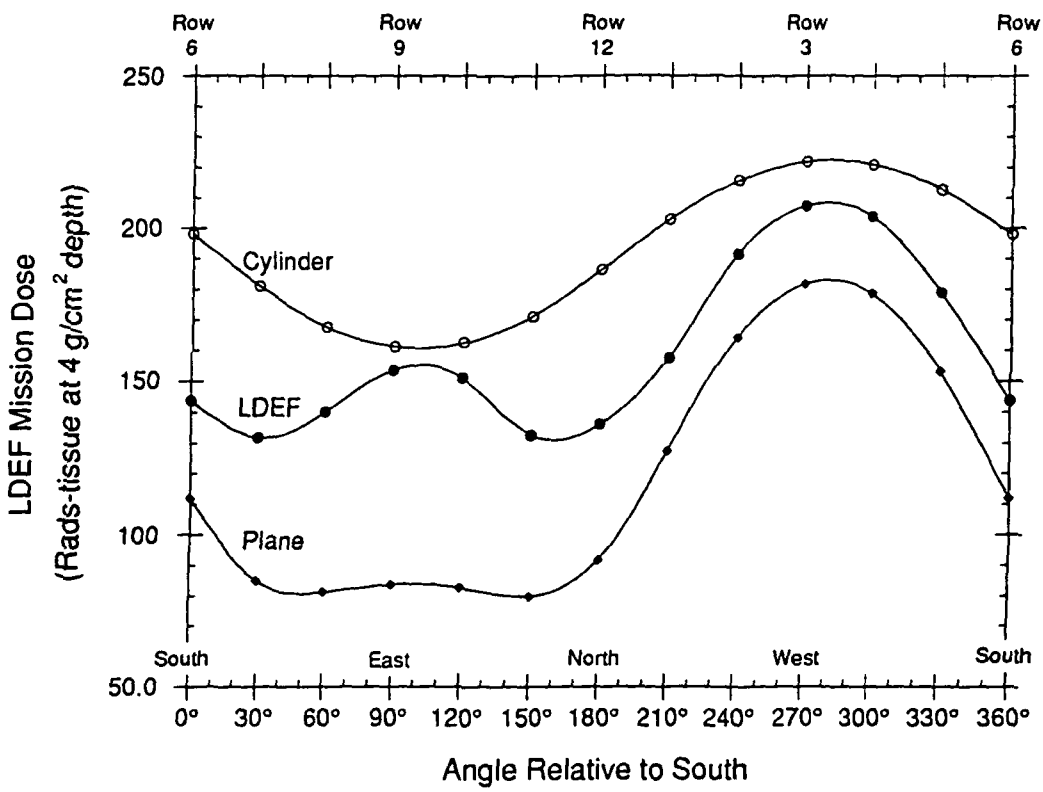

Figure 10. Influence of geomery model on predicted directionality of absorbed dose for LDEF mission due to trapped proton exposure.

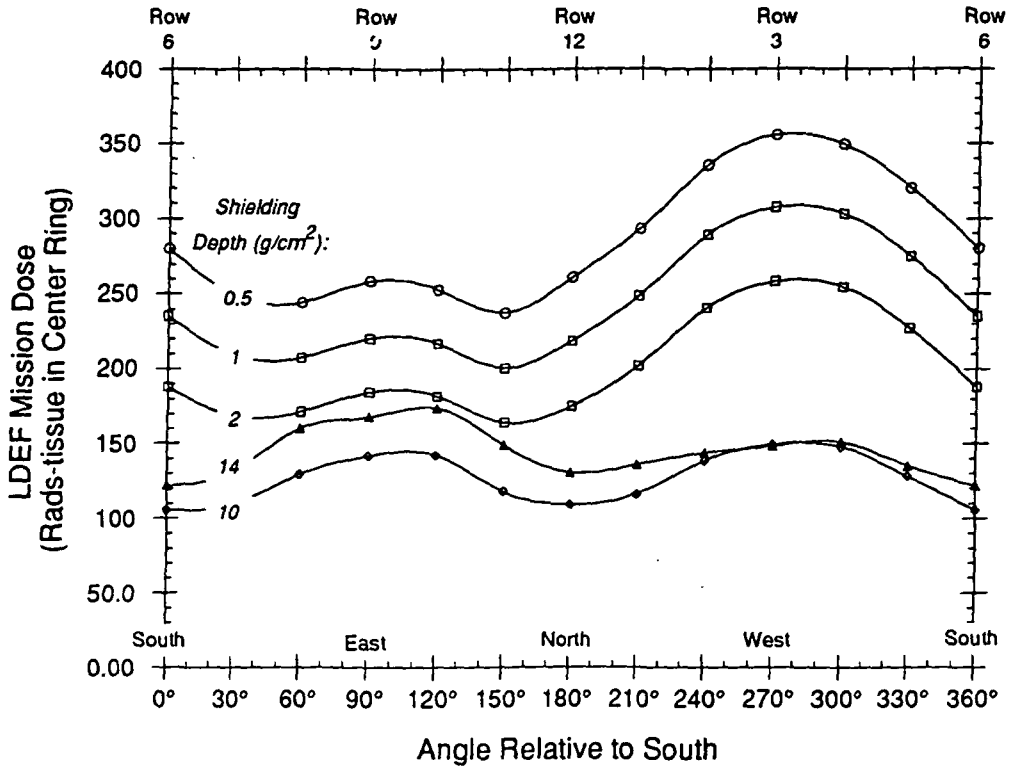

Figure 11. Influence of shielding depth on predicted directionality of absorbed dose from trapped protons. The dose is calculated in the center ring of the LDEF spacecraft using a 3-D geometry/mass model.

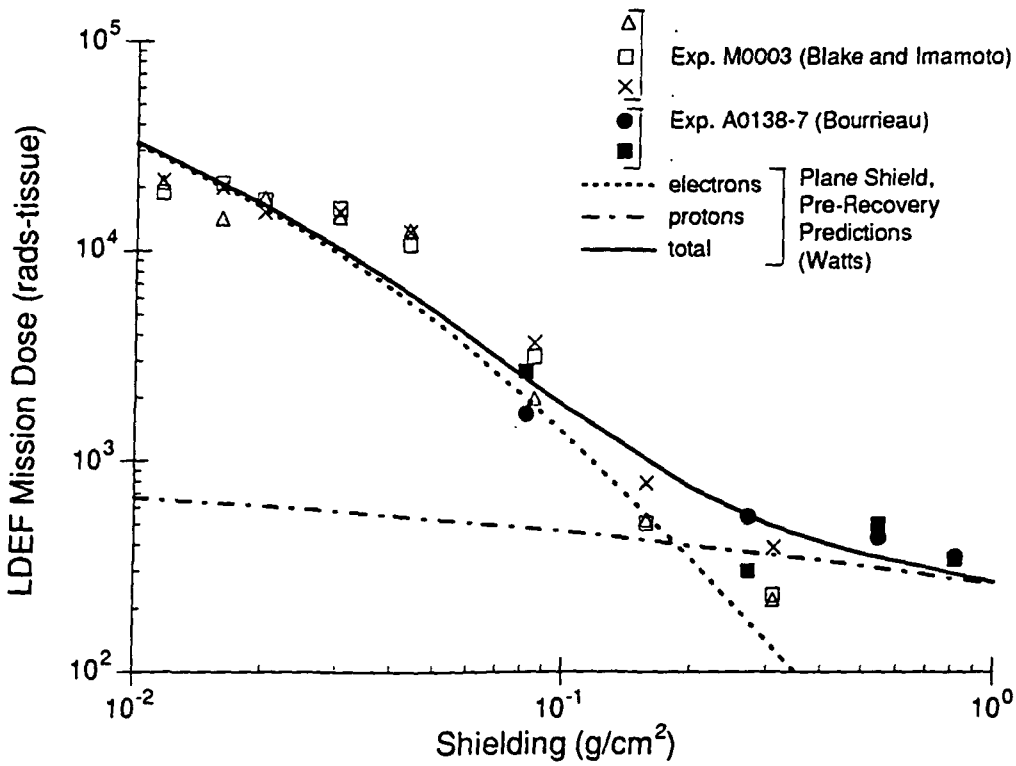

Figure 12. Comparison of measured and predicted absorbed dose for thermoluminescent dosimeters on LDEF having thin shielding where the dose is due to the trapped electron environment.

Section 7

DEVELOPMENT AND APPLICATION OF A 3-D GEOMETRY/MASS MODEL FOR LDEF SATELLITE IONIZING RADIATION ASSESSMENTS

DEVELOPMENT AND APPLICATION OF A 3-D GEOMETRY/MASS MODEL FOR LDEF SATELLITE IONIZING RADIATION ASSESSMENTS*+

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SUMMARY

A three-dimensional geometry and mass model of the LDEF spacecraft and experiment trays has been developed for use in predictions and data interpretation related to ionizing radiation measurements. The modeling approach, level of detailed incorporated, example models for specific experiments and radiation dosimeters, and example applications of the model are described.

INTRODUCTION

Measurements of the ionizing radiation and effects on the Long Duration Exposure Facility (LDEF) satellite provide new data important to attaining a more accurate definition of the space radiation environment. An important issue in interpreting the LDEF radiation dosimetry data, and in performing definitive predictions to compare with the data, is the influence of material shielding effects. For example, data for the absorbed dose from geomagnetically trapped protons indicate a strong anisotropy for measurements made at different locations on LDEF (ref. 1), and measured LET (linear energy transfer) spectra from galactic cosmic rays also exhibit a directional response (ref. 2). A question in interpreting these results is to what extent this angular response is due to the directionality of the space radiation environment, which would be common to other spacecraft having orbit parameters similar to LDEF, as opposed to the influence of shielding variations particular to the LDEF experiment/spacecraft configuration.

The purpose of the present work is to provide a geometry and mass model of LDEF incorporating sufficient detail that it can be applied in determining the influence of material shielding on ionizing radiation measurements and predictions. The model can be utilized as an aid in data interpretation by "unfolding" shielding effects from the LDEF radiation dosimeter responses.

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+Presentation at Second LDEF Post-Retrieval Symposium, San Diego CA, 1-5 June 1992; published in Proceedings Report NASA CP-3194 (1993).

MODELING APPROACH

Initial work on the development of a LDEF geometry/mass model, which included the spacecraft structure and individual experiment trays but provide no detailed modeling of the tray contents, has been reported earlier (ref. 3) The model has now been extended to include a detailed description of the contents of several trays (F2, F8, H3, and H12).

The rationale of this tray selection for detailed modeling is as follows: Tray F2 (containing Exps. P0004 and P0006) and Tray F8 (containing Exp. M0004) are located near the trailing and leading edges of LDEF, respectively, and contain radiation dosimeters important to assessing the directionality of the trapped proton exposure (ref. 1). Furthermore, other measurements from the P0006 experiment in Tray F2 show a directional dependence of the spectra from heavy ions in galactic cosmic rays (ref. 2), and shielding variations around this experiment are needed in interpreting the data. Preliminary data from Exp. M0001 in Trays H3 and H12 indicate a higher heavy ion flux than expected entering the detector from the direction of the interior of the LDEF spacecraft (ref. 4), and the influence of shielding on relating the observed ion spectra to the incident space spectra is of interest in interpreting these data.

Methodology

The LDEF geometry/mass model has been programmed in FORTRAN using the combinatorial geometry methodology of describing complex three-dimensional configurations. The computer version of the geometry module used here has been operated for many years in radiation transport applications, and is the geometry module commonly used with the HETC radiation transport code (ref. 5).

The combinatorial geometry method describes three-dimensional material configurations by applying logical operators to form unions, differences, and intersections in combining simple solid bodies (spheres, boxes, cylinders, etc.) to form a complex geometry. Material properties are assigned to each zone defined by these operators, and ray-tracing algorithms are included to provide the pathlength and material identifier for each zone traversed. This material identifier is used as an index to retrieve information (density, atomic compositions, etc.) from a materials properties table. As an aid in debugging, we have used the SABRINA code (ref. 6) to obtain a graphical output of the geometry input data.

Input Data Sources

Input data for constructing the LDEF model has been obtained from engineering drawings, preflight reports from experimenters describing component layouts, dimensions, and materials for individual

experiments, and pre- and post-flight photographs, all kindly provided by the LDEF Project Science Office (ref. 7). Key modeling input was the weight of individual experiment trays and all spacecraft structural components provided by NASA LaRC from pre-flight center-of-mass and flight dynamics analyses (ref. 8). Dimensions for the experiment trays and descriptions of certain electronics and data storage components common to various experiments were obtained from the LDEF Experimenter Users Handbook (ref. 9). General descriptions and photographs of individual experiments from Clark, et al. (ref. 10) were also helpful.

Information needed for the detailed modeling of Exps. P0004, P0006, and M0004 was provided by Benton and Frank (ref. 11), and a detailed description of Exp. M0001 was provided by Tylka and Adams (ref. 12).

Level of Detail Incorporated

The LDEF spacecraft is considered to be comprised of the following general categories for modeling purposes: spacecraft structure, miscellaneous spacecraft components, and experiments, which includes the experiment trays and components (Tables I-III). The 84 experiment trays on LDEF can be further divided into four subcategories: (a) space debris experiments (26 trays), for which the tray contents can be adequately modeled as an aluminum plate; (b) ultra-heavy cosmic ray experiments (16 trays), for which the contents can be simply modeled as aluminum plus plastic; (c) trays containing ionizing radiation dosimeters (13 trays), for which some detailed modeling of the tray components is desirable, and (d) all other experiments (29 trays), for which the tray is considered to be filled with aluminum having a reduced density such that the individual tray weight is preserved. Thus, each individual experiment tray is modeled, with the actual weights of the trays and contents included, but only the contents of selected trays are modeled in detail for assessing shielding effects on the radiation dosimeter responses. Of the 13 trays indicated in Table III as containing ionizing radiation dosimetry, four trays (F2, F8, H3 and H12) are modeled in detail.

Experiment Models

Some of the geometry models of the LDEF ionizing radiation experiments are shown here as examples; other models and details of the modeling procedure are given in ref. 13. Fig. 1 shows a view of the LDEF spacecraft model with experiment trays, including the four experiment trays in which the contents are modeled in detail.

Fig. 2 shows the component layout in tray F2 and the corresponding combinatorial geometry model. This tray contains the six canisters of tomato seeds (SEEDS experiment) with the thermoluminescent

dosimeters (TLDs) of Exp. P0004 for measuring radiation dose at various positions in the seed canisters. This tray also contains the Exp. P0006 detector stack, which includes several types of radiation detectors: TLDs, plastic nuclear track detectors (PNTDs), activation materials, and neutron detection foils. The Exp. P0006 detector model is shown in more detail in Fig. 3.

The layout and geometry model of tray F8 containing Exp. M0004 on space environment effects on fiber optics is shown in Fig. 4. This tray contains two radiation dosimetry packets in each of two canisters, with each packet containing both TLDs and PNTDs.

The modeling assumptions for these and other trays in terms of geometry and material simplifications are detailed in ref. 13.

APPLICATIONS

The LDEF geometry module program can be applied in several operational modes: (a) as a stand-alone program, material thicknesses along rays emanating from specified spatial points and a specified angular grid can be generated to provide three-dimensional shielding variations around various dosimetry components; (b) such shielding distributions can also be used as input to one-dimensional transport codes which use solid angle sectoring to approximate three-dimensional radiation transport; and (c) the geometry module can be interface with detailed three-dimensional Monte Carlo radiation transport codes (e.g., HETC).

The geometry/mass model is currently being utilized in several studies related to predictions and comparisons with LDEF radiation dosimetry data and in the interpretation of LDEF radiation measurements. The model has been used with radiation transport calculations to predict the directionality of the radiation dose measured on LDEF (ref. 14), which showed that 3-D shielding effects were very important in comparing with the dosimetry data, and the model has been used by NRL (ref. 12) in analyzing results from the Exp. M0001 heavy ion experiment.

Shielding calculations using the LDEF geometry/mass model are also being made to investigate the directionality of protons and heavy ions observed (ref. 2) in Exp. P0006 plastic nuclear track detectors. An example model application (stand-alone mode) is given in Fig. 5, which shows the shielding distribution in a horizontal plane around one of the PNTD side modules of Exp. P0006. Here a local coordinate system is used with the angle α measured in a plane parallel to the tray top. The "dips" in the shielding distribution designated as (a), (b), and (c) occur for directions between the seed canisters, with the large peak in the distribution (d) corresponding to directions going through lower trays (toward earth-end) and through the center ring of the spacecraft structure. The other P0006 side modules see a similar horizontal shielding

distribution but displaced by 90°. Such shielding variations can have an important influence on the observed radiation environment.

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Table I. Level of Detail for Modeling LDEF Spacecraft

Category	Component	No. Places	Weight (lbs.)	Weight %	Modeling Approach
STRUCTURE	Center Ring	1	2,073	9.7%	Modeled as individual component.
	Longerons	24	2,280	10.7%	Modeled as individual components.
	End Frames	2	1,374	6.4%	Modeled as individual components.
	Diagonal Tubes	8	926	4.3%	Modeled as individual components.
	Intercostal Rings	72	758	3.5%	Modeled as individual components.
	Trunions,Pins,Scuff Plts	10	501	2.3%	Modeled as individual components.
	End Support Beams	5	285	1.3%	Modeled as individual components.
	TOTAL STRUCTURE:		8,197	38.3%	
MISCELLANEOUS	Batteries	2	100	0.5%	Included as part of earth-end support beam.
	Initiate Electronics	1	105	0.5%	Included as part of center ring weight.
	Wiring	-	100	0.5%	Included as part of center ring weight.
	Nuts and Bolts	-	200	0.9%	Included as part of center ring weight.
	Damper Assembly	1	62	0.3%	Modeled as individual component.
	Thermal Covers (Ends)	12	154	0.7%	Modeled as individual components.
	Ballast Plates	11	365	1.7%	Included as part of end frames.
	TOTAL MISCELLANEOUS:		1,086	5.1%	
EXPERI-MENTS	Experiment Components and Trays	84	12,110	56.6%	Modeled each experiment tray separately, with individual experiment weights preserved. Modeling for components varies with experiment type.
	TOTAL LDEF WEIGHT:		21,393	100.0%	

Table II. Level of Detail for Modeling Experiments

No. Trays	Model	Experiments
26	Al plate	S0001: Space Debris (LaRC)
16	Al+plastic plates	A0178: Ultra-heavy Cosmic-Ray Expt. (Dublin Inst., ESTEC)
13	"detailed"	Selected experiments containing ionizing rdiation dosimetry.
29	homogenized Al	(all others)

Table III. Trays Containing Ionizing Radiation Dosimetry

Tray Bay-Row	Experiment No.	Experiment	Dosimetry
C-2, G-2	A-0015	Biostack (DFVLR)	TLD's, PNTD's
C-3, C-9	A-0114	Atomic Oxygen (UAH, MSFC)	Activation Samples
B-3	A-0138	Optical Fibers (CERT/ONERA - DERTS)	TLD'S
H-3, H-12	M0001	Heavy Ions (NRL)	PNTD's
D-3,D-9,G-12	M0002-1	Trapped Proton Spect. (AFGPL,MSFC, et al.)	PNTD's,TLD's,Act.
E-6	M0002-2	Heavy Cosmic-Ray Nuclei (U. Kell)	PNTD's
D-3,D-8,D-9	M0003	Space Envr. Effects on Matls. (Aerospace)	TLD's
F-8	M0004	Space Envr. Effects on Optics (AFWL)	TLD's, PNTD's
C-2	M0006	Space Envr. Effects (AFTAC, Grumman)	TLD's
F-2	P0004	SEEDS (Univ. SF)	TLD's, PNTD's
F-2	P0006	LET Spectrum Meas. (Univ. SF, MSFC)	TLD's, PNTD's, Fiss. & Act. Samples

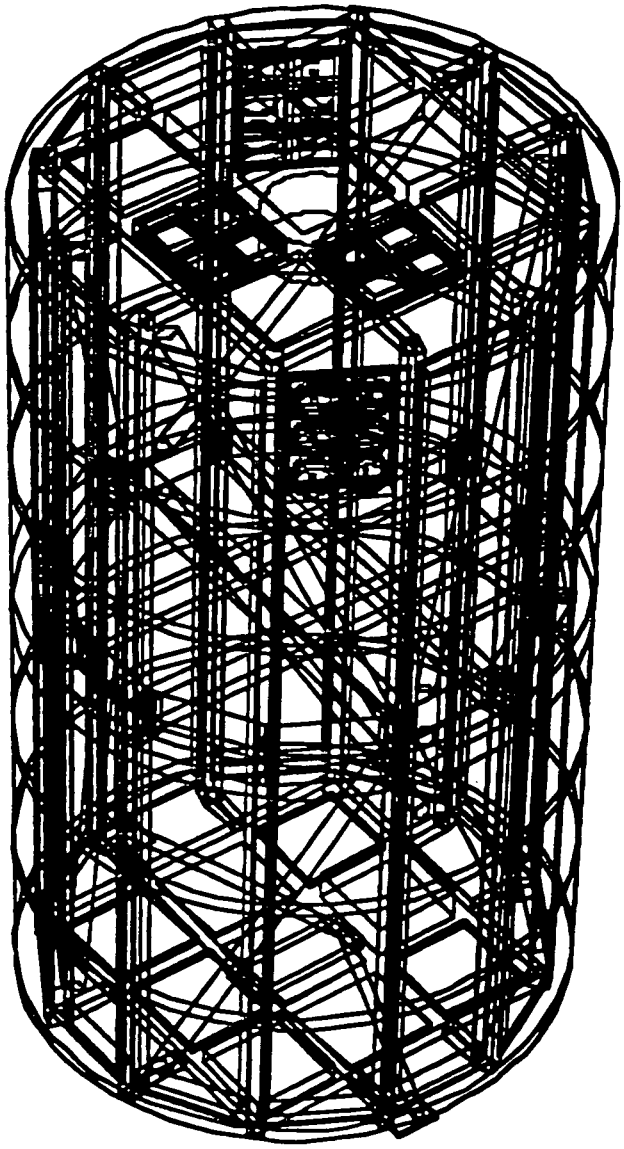


Figure 1. Combinatorial geometry model of LDEF spacecraft with the four experiment trays (F2, F8, H3, and H12) containing radiation dosimeters which have been modeled in detail.

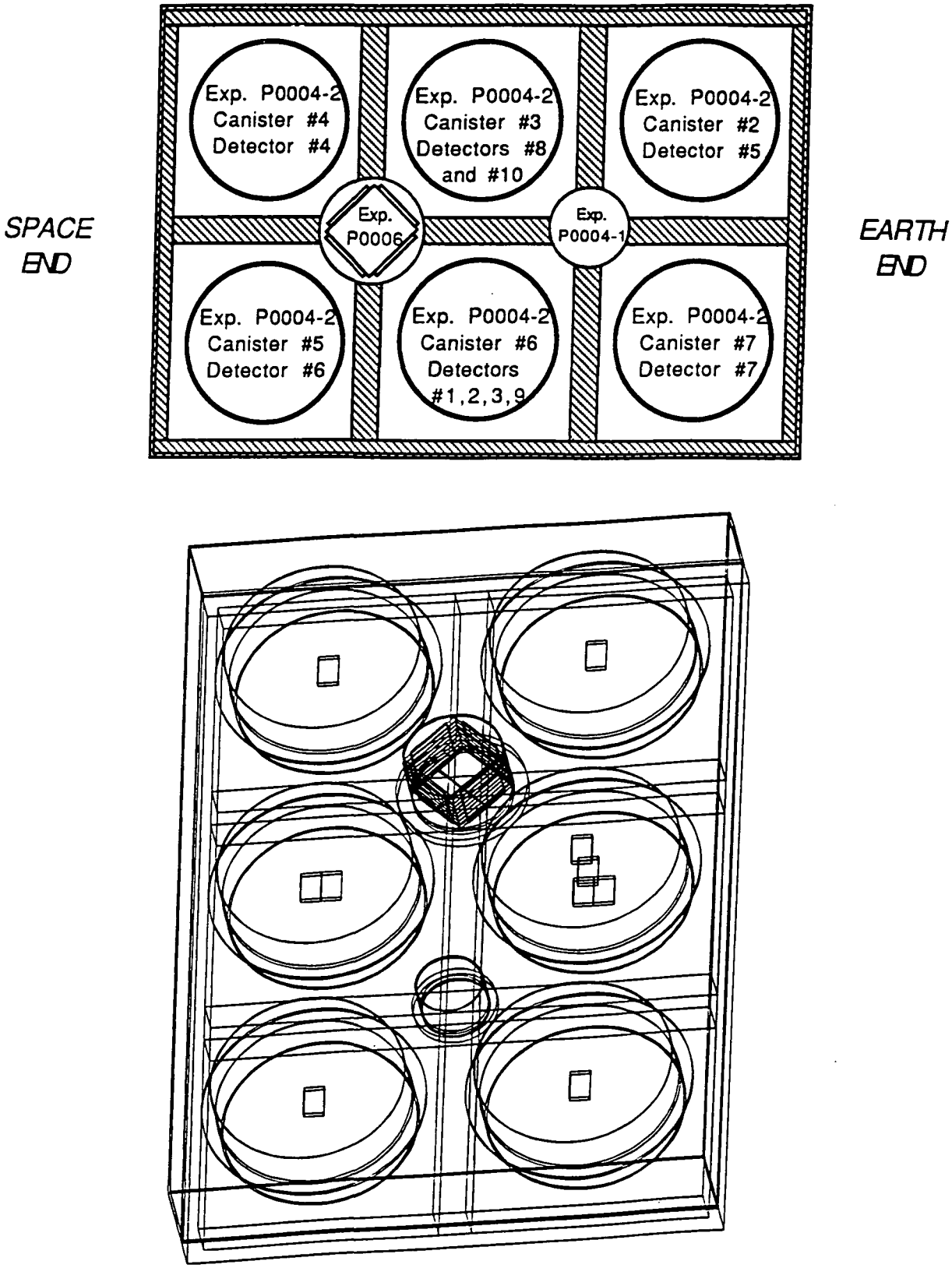


Figure 2. Layout of components in LDEF experiment tray F2 containing radiation dosimetry (top) and combinatorial geometry model (bottom), showing TLD packets (Exp. P0004) in the seed canisters and the Exp. P0006 detector stack.

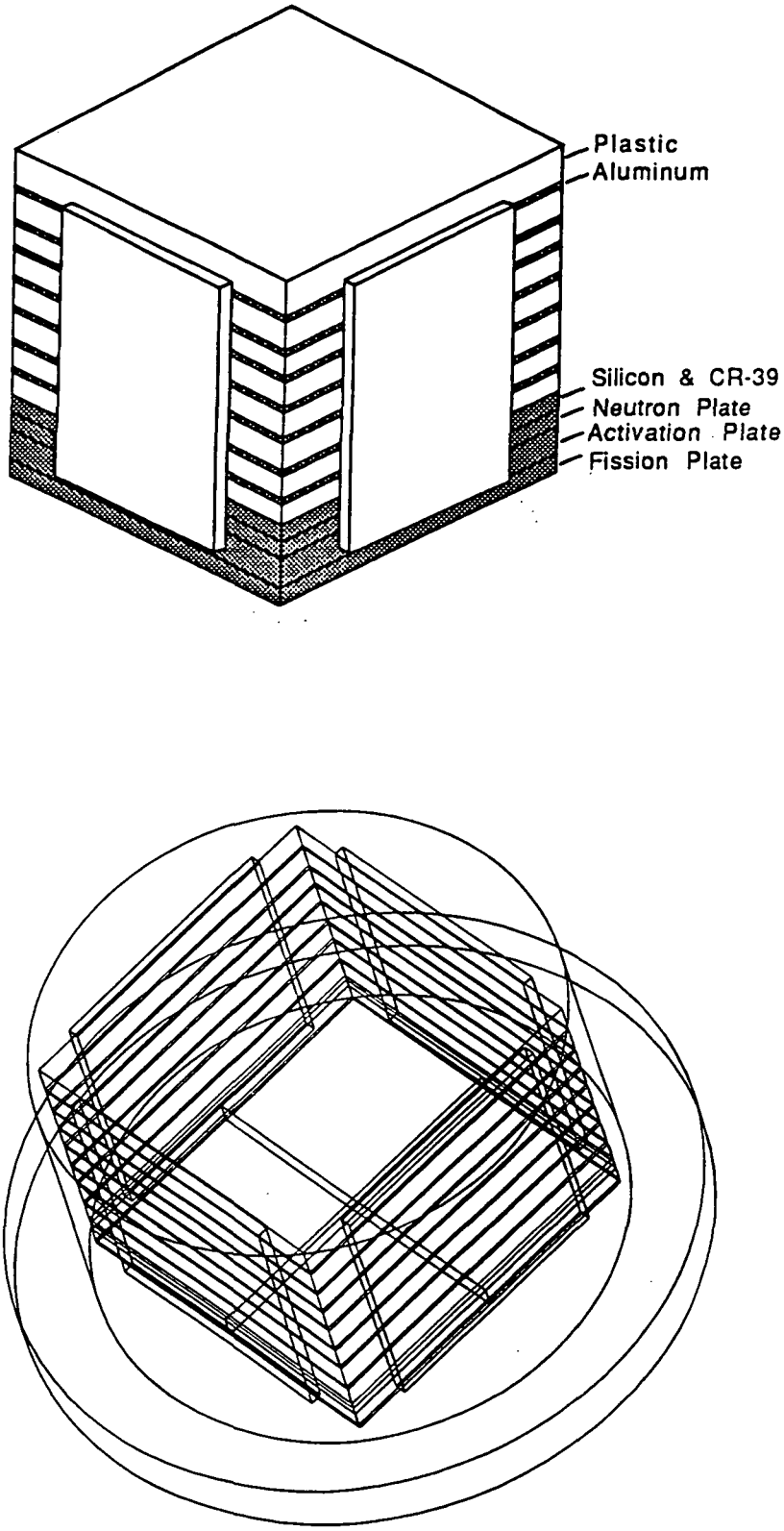
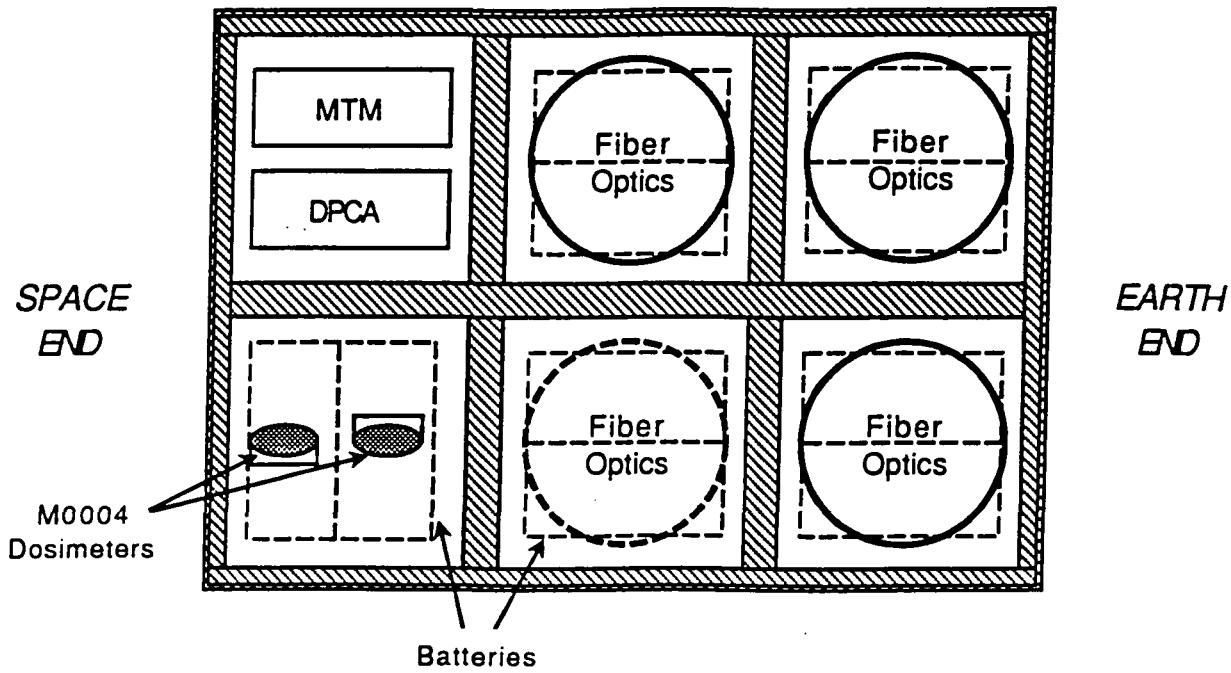


Figure 3. Material layers modeled in the Exp. P0006 detector stack (top) and corrresponding combinatorial geometry model of detector and canisters (bottom).



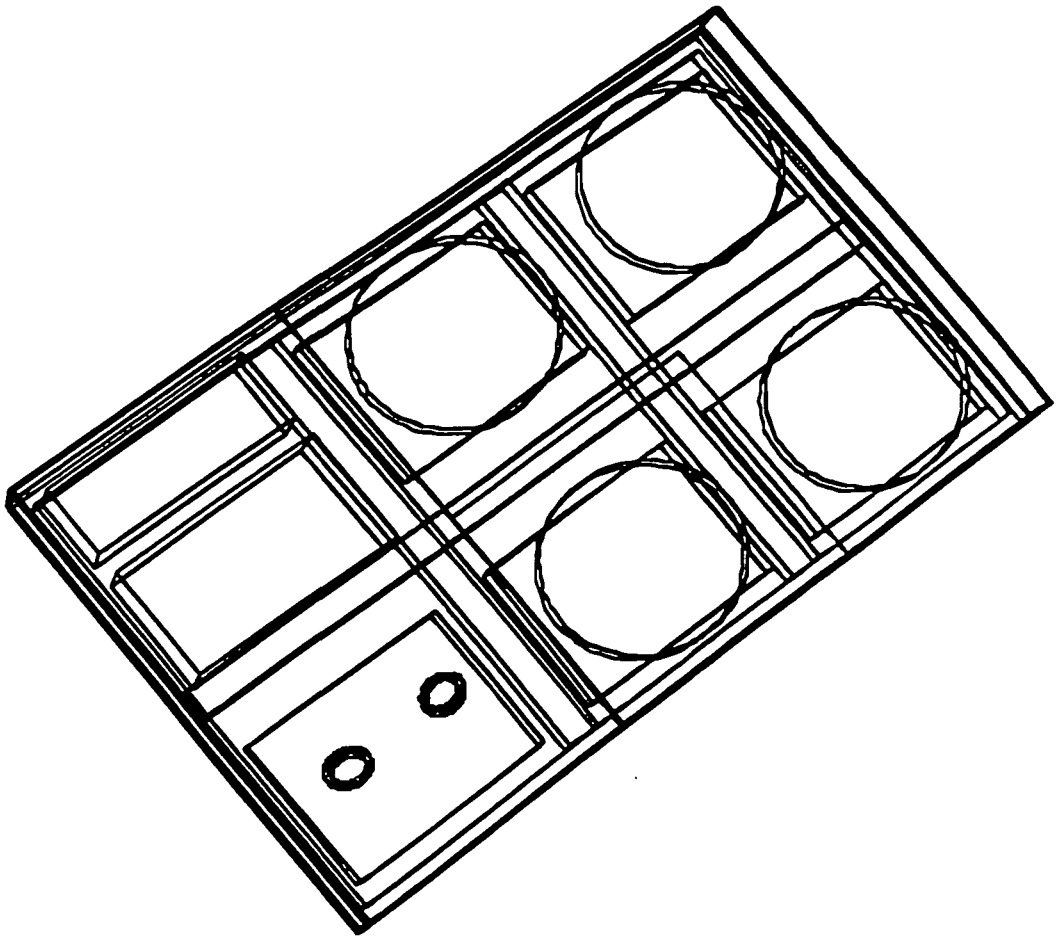


Figure 4. Layout of LDEF tray F8 containing Exp. M0004 radiation dosimeters (top) and corresponding geometry model (bottom).

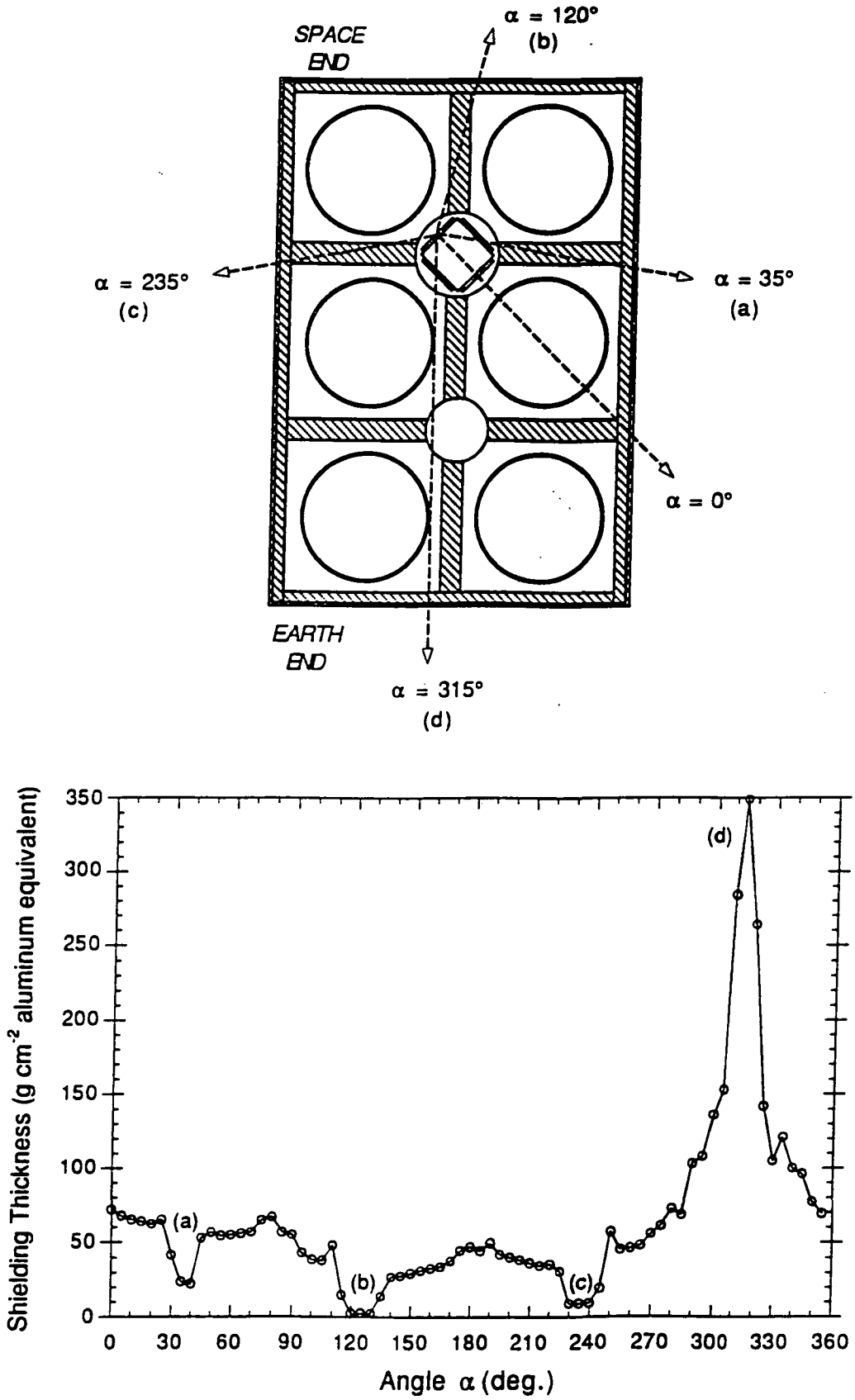


Figure 5. Shielding distribution in horizontal plane for a point on the surface of the detector module of Exp. P0006.

Section 8

FUTURE DIRECTIONS FOR LDEF IONIZING RADIATION MODELING AND ASSESSMENTS

FUTURE DIRECTIONS FOR LDEF IONIZING RADIATION MODELING AND ASSESSMENTS* +

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SUMMARY

A calculational program utilizing data from radiation dosimetry measurements aboard the LDEF satellite to reduce the uncertainties in current models defining the ionizing radiation environment is in progress. Most of the effort to date has been on using LDEF radiation dose measurements to evaluate models defining the geomagnetically trapped radiation, which has provided results applicable to radiation design assessments being performed for Space Station Freedom. Plans for future data comparisons, model evaluations, and assessments using additional LDEF data sets (LET spectra, induced radioactivity, and particle spectra) are discussed.

INTRODUCTION

Ionizing radiation measurements on the Long Duration Exposure Facility (LDEF) satellite provide a unique opportunity for reducing present uncertainties in models used in defining the space radiation environment. The LDEF mission had several features particularly important to radiation model validation -- e.g., various types of radiation detectors were aboard, providing an extensive data set; because of the long mission duration, the data have unparalleled statistical accuracy; and, the LDEF spacecraft had a very stable orientation during the flight, allowing unprecedented data to be obtained on the directionality of the space environment. The radiation measurements performed and key results from analyses to date are summarized in refs. 1 and 2.

A calculational program is in progress as part of the LDEF ionizing radiation investigations. The scope of the program includes model predictions in support of data analysis and interpretation, calculations for data comparisons and model accuracy assessments, and model updates. The overall objective is to utilize the LDEF data to provide models that give a more accurate definition of the ionizing radiation environment. This will enable more accurate radiation designs and design margin assessments for future missions in low Earth orbit, which in turn will help reduce risk and cost. Specific models which can be improved utilizing LDEF data, and their importance in addressing particular radiation issues for planned missions, are discussed in ref. 3.

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The purpose of the present paper is to summarize the current status and future emphasis of the LDEF ionizing radiation modeling work. The next section gives an overview of the calculations made to date, followed by summaries of the status in terms of specific tasks and in terms of comparisons which have been made with different measurement data sets. The emphasis of planned radiation modeling work and related assessments is discussed in the last section.

OVERVIEW

Calculations made to date for LDEF ionizing radiation assessments and for model comparisons with dosimetry data can be categorized as follows:

Phase 0: Pre-Recovery Predictions -- To aid in the planning and interpretation of radiation dosimetry data analyses, pre-recovery estimates were made to characterize the expected radiation environment experienced by LDEF and the general features and magnitude of the induced environment and radiation effects expected to be observed (ref. 4). This work included estimates of the expected radiation environment (refs. 5,6) absorbed dose (ref. 5), LET spectra (ref. 7), and induced radioactivity (ref. 6). These calculations were of a scoping nature and included numerous approximations -- e.g., the directionality of the environment was ignored and shielding calculations were based on simple one-dimensional geometries.

Phase 1: Preliminary Calculations and Data Comparisons -- Several approximate calculations were carried out to obtain some quick comparisons with the initial data analysis results (e.g., ref. 8). This included preliminary comparisons of model predictions with absorbed dose and activation data, which were reported at the First LDEF Symposium (refs. 9, 10). Various approximations were made in the calculations to obtain these quick-look comparisons -- e.g., one-dimensional geometries were assumed, and the environment definition was incomplete, with anisotropy and orbit altitude variations neglected in most cases.

Phase 2: Definitive Modeling and Data Comparisons -- To obtain more accurate modeling and definitive comparisons with the more complete data becoming available, basic calculational work was needed in two areas: (a) a complete definition of the LDEF trapped proton exposure, taking into account directionality, altitude variation and solar cycle dependence, and (b) a realistic (three-dimensional) geometry/mass model of the LDEF spacecraft and dosimetry experiments in order to adequately account for shielding effects. This work has been completed and reported at this symposium (refs. 11, 12). These improved models have been initially applied for 3-D dose predictions and data comparisons, with results reported at this symposium (refs. 13, 14).

Future Work -- The emphasis of future calculations is on using the revised environment definitions and 3-D geometry/mass model to make definitive predictions and comparisons with other LDEF radiation data (LET spectra, induced radioactivity, secondary particles, etc.) as it becomes available. Specific predictions and planned data comparisons are outlined in the next two sections.

STATUS

In this section a breakdown of the completed and planned calculational tasks is given with the status of each task indicated.

Most of the work on assessing LDEF exposure to the radiation environment has been completed (Table I). Initial estimates (refs. 5,6) of the exposure were made to determine the importance of all sources (trapped protons, trapped electrons, galactic cosmic rays, earth albedo neutrons, and albedo protons) to different radiation effects. Initial work on the definition of the trapped proton environment was incomplete in that the altitude and solar cycle dependence of directional trapped proton spectra were not determined, but revised estimates using the MSFC anisotropy model (ref. 15) to obtain vector fluxes have now been completed (ref. 11). An input parameter to the MSFC trapped proton anisotropy model is the effective scale height of the atmosphere, which represents an average over proton trajectories and is difficult to estimate from first principles. LDEF data provide a basis for investigating appropriate scale height values for model input, and such studies are planned. Measurements of the LET spectra from heavy ions in the galactic cosmic ray (GCR) spectra indicate strong directionality (ref. 16). While this observed directionality is expected to be influenced by shielding variations, there are indications that the directionality of the external environment is a factor also (ref. 16). Thus, some additional environment definition work to estimate the angular dependence of the GCR heavy ion exposure may be needed for definitive comparisons with the observed LET directionality.

Key to obtaining definitive model predictions for data comparisons is a realistic treatment of shielding effects. As indicated in Table II, work on development of a detailed, 3-D geometry/mass model of LDEF is now completed (refs. 12, 17), and this model is currently being used in radiation transport calculations and other shielding assessments.

With the work on revised trapped proton environment calculations and 3-D geometry modeling completed, definitive predictions with state-of-the-art modeling accuracy can be performed to compare with the LDEF radiation dosimetry data. Initial calculations using these models have been made for the absorbed dose and comparisons made with the LDEF measurements (refs. 13. 18-20) using thermoluminescent dosimeters (TLDs), as indicated in Table III. These comparisons, which are complete except for some revisions that may be needed when results from final data analyses become available, provide a test of the accuracy of current trapped proton flux models (ref. 21) for low Earth orbit missions and provide partial data needed to check models describing the directionality of the environment.

Several experiments on LDEF contained plastic nuclear track detectors (PNDTs) that measured the linear energy transfer (LET) spectra (Table IV, ref. 1). Model predictions and comparisons with these data are important because LET has a key role in estimating various radiation effects, and because preliminary LET measurement results (ref. 22) indicate a high-LET component which is not predicted by pre-recovery estimates (Fig. 1), but which may have important practical significance. LET calculational tasks involve

several steps (Table IV), including 3-D transport calculations to account for shielding variations and the directionality of the environment, influence of secondaries from heavy ion fragmentation, and an extension of present calculational methods to account for target recoils and fragments, which is needed to compare with the unique data from LDEF on the high-LET tail of the spectrum. For definitive comparisons with the LET measurements, the calculations should, as suggested by the USF group (footnote 1), include the response function of the track detectors, which involves including energy and angular-dependent relations for track detection from observations for different track etch rates and from calibration experiments using accelerator beams.

Several measurements of the secondary neutron fluence were made on LDEF using ^{6}LiF foils (ref. 23) and activation samples (ref. 24). These data provide an opportunity to evaluate the accuracy of nuclear models and radiation transport techniques for predicting secondary neutron spectra in spacecraft, which is of interest in mission radiation assessments because such secondary particles contribute to biological damage, radiation backgrounds to sensitive instrumentation, and radiation damage to electronics. Planned calculations related to this are listed in Table V. Since the ^{6}LiF measurements may be influenced by the high proton fluence present, some initial calculations delineating the neutron vs. proton response are needed for the particular radiation environment experience by LDEF. To obtain a definitive estimate of the neutron fluence for data comparisons, a detailed transport calculation using Monte Carlo methods (HETC code) and the 3-D geometry/mass model of LDEF is planned with trapped , galactic, and albedo environment sources included. Intercomparisons using the two data sets from ^{6}LiF and activation will provide a check on the consistency of the neutron measurement methods.

Preliminary data on high-energy neutron and proton spectra are available (refs. 23, 25) from various fission foil measurements (Table V). Since fission is induced by both neutrons and protons, the relative contribution to the fission data will first need to be investigated. Of particular interest is the data from tantalum foils, where the fission threshold is above the energy of trapped protons, so the activation in this case is a measure of the galactic fluence only.

Induced radioactivity measurements are available from both metal samples placed aboard LDEF and from the analysis of various spacecraft components (refs. 24, 26-29), as summarized in Table VI. The activation of samples placed in the P0006 experiment, which also contained TLDs for dose measurements, is of particular interest for model comparisons because this will provide a cross-check on the differences found between measured and predicted doses. The activation samples also included some elements (Co, Ta) where the activation for particular isotopes is only from neutron-induced reactions, providing a cross-check on the ^{6}LiF neutron measurements and related calculations.

Several approximate calculations (ref. 10) were made to get some early preliminary comparisons with the activation measurements on spacecraft components (Table VI). Planned are more definitive calculations that remove the early approximations indicated in Table VI. Calculations to compare with the tray clamp activation data are of special interest because these measurements provide a detailed mapping of the directional effects of trapped protons, providing a test of the accuracy of the MSFC anisotropy model. Data

on the production of various radioisotopes in the LDEF spacecraft trunnions is of interest for model validation because it provides a measure of directional and secondary particle effects and contains contributions from both trapped and galactic sources. Measurements for other spacecraft components, such as the keel and end plates, provide additional directional data for model validation and confirmation.

DATA AVAILABLE FOR MODEL VALIDATION

In this section the status of work on radiation model validation is given in terms of the data available and comparisons which have been made.

Essentially all of the data on absorbed dose measurements using TLDs is available (Table VII), and the results of model comparisons are given in ref. 14. Initial results for measured LET spectra from PNTDs are available (Table VIII) but much data analysis remains, and LET model predictions to compare with the PNTD data are TBD (To Be Done).

Preliminary data on neutron and proton fluence and spectra from fission and ^{6}LiF foil measurements are available (Table IX), but results from some recent accelerator calibration tests need to be incorporated to complete the data analysis (footnote 1). Thus, only very preliminary model comparisons have been made to compare with this data.

The counting of intentionally placed activation samples on LDEF for the case of neutron measurements (Co and Ta samples) has been completed (Table X), but analyses to determine absolute neutron fluences are still in progress (footnote 2). Measurements for the other activation sample materials (Table X) are essentially complete, with intercomparisons and final data analyses nearing completion. Data available from induced radioactivity measurements in spacecraft components, and the status of calculations and comparisons, are summarized in Table XI.

FUTURE WORK

As indicated above, to date calculations have been made to compare with only a portion of the LDEF radiation dosimetry data. Preliminary evaluations have been made of environment models defining the trapped proton flux, the directionality of trapped protons, and the trapped electron flux. Interim results based on these early comparisons indicate that the proton flux model (ref. 21) underpredicts the observed dose by about a factor of two (ref. 14). The basic validity of the MSFC trapped proton anisotropy model (ref. 15) has been verified (ref. 14). However, preliminary results indicate that the observed directionality is somewhat stronger than predicted, and additional data comparisons are needed to resolve this issue. The few results to date on electron dose measurements indicate that the accuracy of electron flux environment models (ref. 30) for LDEF-type orbits is about a factor of two (ref. 14), but the validity of some of the data is still

being checked (ref. 20). These findings, while only tentative at present, have already been important in establishing realistic radiation design margins for Space Station Freedom, and additional model environment accuracy assessments utilizing the full set of LDEF radiation dosimetry data (outlined below) are expected to provide important input for upcoming Space Station Freedom radiation design verification evaluations.

The emphasis of future radiation modeling work and related assessments is summarized below.

Calculations and Data Comparisons

Work to date has concentrated on model comparisons with the LDEF absorbed dose data. Subsequent work will emphasize data comparisons and model evaluations for the other measured data sets, with general priorities as discussed below. These planned comparisons will provide a test of modeling accuracies for predicting not only the ambient environment but the induced environment inside spacecraft and instrument packages as well. Furthermore, these additional data comparisons provide more stringent tests of predictive capabilities in that the model evaluations will include more detailed comparisons with differential data (LET and particle spectra), in contrast to the integral-type data (dose) comparisons made to date.

LET Spectra -- Modeling and data comparisons for LET spectra are of high priority for future work for several reasons: Accurate predictive capabilities for LET spectra are of practical significance for mission applications due to the fundamental role of LET in assessing various radiation effects, such as biological damage, electronics upset, and sensor noise. Also, the LET data from LDEF are unique due to their high-statistical accuracy and the data show features at high LET that are not accounted for in present models (Fig. 1). Updated models that take into account the LDEF observations are of practical importance in radiation assessments for spacecraft in orbits similar to LDEF, such as planned for Space Station Freedom.

Activation -- Planned model comparisons with the activation data from induced radioactivity measurements are important in evaluating models for predicting both ambient and induced environments. Of high priority here are comparisons with the experiment tray clamp activation data, which will allow detailed anisotropy model evaluations, and comparisons with the Exp. P0006 activation samples, which will provide a check of the present tentative conclusions on the accuracy of trapped proton flux models based on absorbed dose comparisons.

Secondaries and Particle Spectra -- Model comparisons with fission foil data, measurements of certain radioisotopes in activation samples, and ^{6}LiF data will allow evaluation of models and transport methods for predicting secondary particle fluences inside spacecraft. Coarse spectral information for protons and neutrons are also available from these data. Also of interest here is model comparisons with the tantalum foil measurements, which will provide a check of model predictions for the GCR proton fluence at the geomagnetic cutoff of low inclination (28.5°) orbits.

Assessments

From the calculations and data comparisons outlined above, intercomparisons taking into account all of the LDEF radiation dosimetry data sets are planned, including consistency checks comparing LDEF results where possible with previous flights. Quantitative assessments of model uncertainties will be performed and model improvements made, with documentation and dissemination of the updated models, data bases, and related computer codes provided for future mission applications.

Thus, the product goal of this planned work is improved models for predicting the ambient and induced ionizing radiation environments. While measurements of radiation effects for some of the newer component technologies (e.g., radiation sensitive microelectronics and sensors) were not included on LDEF, the improved radiation environment definitions from LDEF, together with ground-based measurements of component radiation susceptibilities, will enable improved radiation effects predictions for future missions and evolving component technologies despite the lack of LDEF radiation effects data for specific components. In this way, the LDEF radiation modeling results can have a significant impact on radiation assessments for future missions by reducing risk and cost associated with radiation designs and tests.

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Table I. *Status of LDEF Radiation Environment Calculations*

	Task	Status	Comment
I. Environments Predictions	1. Initial calculations of trapped proton exposure	Completed	• Published, ref. 5
	2. Estimates of expoure from galactic and earth albedo radiation	Completed	• Published, ref. 6
	3. Revise directional trapped proton exposure, taking into account: • altitude variation • solar cycle variation	Completed	• Reported at San Diego meeting, ref. 3
	4. Sensitivity of scale height and pitch angle assumptions used as input to anisotropy model	Later	• Use LDEF data to verify anisotropy model input parameters
	5. Directional GCR spectra	Later	• Expected to be needed to agree with observed LET directionality

Table II. Status of LDEF Spacecraft/Experiment Geometry Modeling for Shielding Calculations

	Task	Status	Comment
II. 3-D LDEF Mass Model	1. 3-D Model of spacecraft structure and generic experiment trays	Completed	• Reported at Orlando meeting, ref. 17
	2. Extend model to include detailed experiment tray modeling	Completed	• Reported at San Diego meeting, ref. 12
	3. Generate 3-D shielding distributions for Exps. P0004 and P0006	Completed	"Directional shielding " provided to aid in qualitative interpretation of directional fluences and LET

Table III. Status of LDEF Absorbed Dose Calculations

	Task	Status	Comment
III. Absorbed Dose	1. Pre-recovery predictions for simple 1-D shielding geometries	Completed	• Published, ref. 5
	2. Absorbed dose calculations and comparisons using 3-D mass model and updated trapped proton spectra	Completed	• Reported at San Diego meeting, ref. 14

Table IV. Status of LDEF Linear Energy Transfer (LET) Spectra Calculations

	Task	Status	Comment
IV. LET Spectra	1. Initial calculations based on 3-D geometry for primary trapped protons and GCR	Later	• First priority: comparisons with P0006 and P0004 • Second priority: comparisons with other experiments - A0015, etc.
	2. Sensitivity calculations - infuence of secondaries, directionality of GCR (and trapped) environment, etc.	Later	• Compare with above
	3. Modeling of LET spectra components, including high-energy tail (unique data)	Later	• Calculate components of LET spectra due to charge,energy, particle type composition, directionality, and secondaries • comparisons for P0004, P0006, and A0015
	4. Silicon calculations and data comparisons	Later	• Compare with measured products from Si wafers (SEU applicability)
	5. Couple transport with etching parameters to predict track features	Later	• USF suggestion to aid track measurement interpretation, and more definitive comparisons

Table V. Status of LDEF Neutron and Proton Spectra Calculations

	Task	Status	Comment
V. Neutron and Proton Spectra	1. Calculation of Low-Energy Neutron Flux	Later	• Compare with 6LiF measurements of thermal and epithermal neutrons (Exps. P0004, P0006. A0015) •Intercomparisons with activation data •*Investgate 6LiF respnse to* protons vs neutrons • Include all sources (trapped, GCR, albedo); HETC calc.
	2. Calculation of High-Energy Neutron and Proton Spectra	Later	• Compare with U, Th, Bi, Ta fission foil measurements (Exps. P0006 and A0015) • Assess fission contributions from neutrons vs. protons • Infer GCR fluence from Ta fission;assess calibration

Table VI. Status of LDEF Activation Calculations

	Task	Status	Comment
VI. Activation Samples	1. Calculations for metal sample set in Exp. P0006	Later	• Compare radionuclide measurements for V, In, Ni, Ta • Provides check on dose predictions and measurements
	2. Calculations for metal sample sets in other exps. (A0114, M0001, M0002)	Later	• Includes Co samples, with neutron induced activation
VII. Spacecraft Components	1. Initial tray clamp calculations to compare with early data	Completed	• 1-D geometry calc., approx. anisotropy environ., simplified transport • Reported at Orlando meeting, ref. 3
	2. Definitive tray clamp, end plate, and keel plate calculations	Later	• HETC calc. with secondaries, all sources, 3-D geometry model, revised anisotropy environment
	3. Initial trunnion calculations to compare with early data	Completed	• 3-D geometry, but trapped protons only, no secondaries • Reported at Orlando meeting, ref. 3
	4. Definitive trunnion calculations	Later	• HETC calculations with secondaries, trapped and GCR sources

Table VII. Absorbed Dose Data Available and Status of Calculations

Exp. No.	Exp. Name	Exp. Tray	No. Detector Locations	Total No. TLDs	Data Presently Available ?	Status of Calc. and Comparisons
P0006	LETSME	F2	5	180	yes	completed
M0004	Fiber Optics	F8	4	28	yes	completed
A0015	Biostack	C2,G2	7	56	yes	completed
M0003	Effects on Mat'ls	D4, D8	8	104	yes	completed
A0138-7	FRECOPA	B3	5	10	yes	completed
M0006	Environ. Effects	C2			prelim.	

Table VIII. LET Data Available and Status of Calculations

Exp. No.	Exp. Name	Exp. Tray	No. PNTD Stacks	Data Presently Available ?	Status of Calc. and Comparisons
P0006	LETSME	F2	10	initial results	TBD
P0004	SEEDS	F2	10	initial results	TBD
A0015	Biostack	C2, G2	9	initial results	TBD

Table IX. Neutron and Proton Spectra Data Available and Status of Calculations

Exp. No.	Exp. Name	Exp. Tray	Dosimetry	Data Presently Available ?	Status of Calc. and Comparisons
P0006	LETSME	F2	Plate #1: 6LiF, Bi, Ta Plate #2: U, Th	prelim	TBD
P0004	SEEDS	F2	6LiF - 2 locations	prelim	TBD
A0015	Biostack	C2 G2	6LiF,U,Th,Bi,Ta 6LiF, U,Th,Bi,Ta	prelim	TBD
P0006, A0114, M0001, M0002	intentionally placed activation samples	F2, C3, C9, H12, G12	In,Ta In, Ta Co, In, Ta Co, In, Ta Co, In, Ta	yes (a) yes (a) yes (a) yes (a) yes (a)	TBD TBD TBD TBD TBD

(a) Counting complete; analyses to determine absolute fluences in progress.

Table X. Activation Data Available for Metal Samples and Status of Calculations

Contained in Exp. No.	Exp. Tray	Data Presently Available? (a) Activation Sample: Co	Ni	Ta	In	V	Status of Calc. and Comparisons
P0006	F2	—	yes	yes	yes	yes	TBD
A0114	C9	yes	yes	yes	yes	yes	TBD
A0114	C3	—	yes	yes	yes	yes	TBD
M0001	H12	yes	yes	yes	yes	yes	TBD
M0002	G12	yes	yes	yes	yes	yes	TBD

(a) Measurements essentially complete; intercomparisons and final data analyses nearing completion.

Table XI. Activation Data Available for Spacecraft Components and Status of Calculations

Component	Data Available ?	Status of Calc. and Comparisons
Al tray clamps	yes (a)	• prelim comparisons completed • definitive calc. & comparisons TBD
Al end plates	most (ESR-1,ESR-5)	TBD
Al keel plates	most (KP-3,4,9,10)	TBD
Trunnions	yes	• prelim comparisons completed • definitive calc. & comparisons TBD
Titanium clips, Al-alloy Scuff Plates, Pb ballast, etc.	most	TBD

(a) Measurements essentially complete; additional measurements on clamps from space and earth ends, and additional counting to reduce statistics for selected cases, are planned.

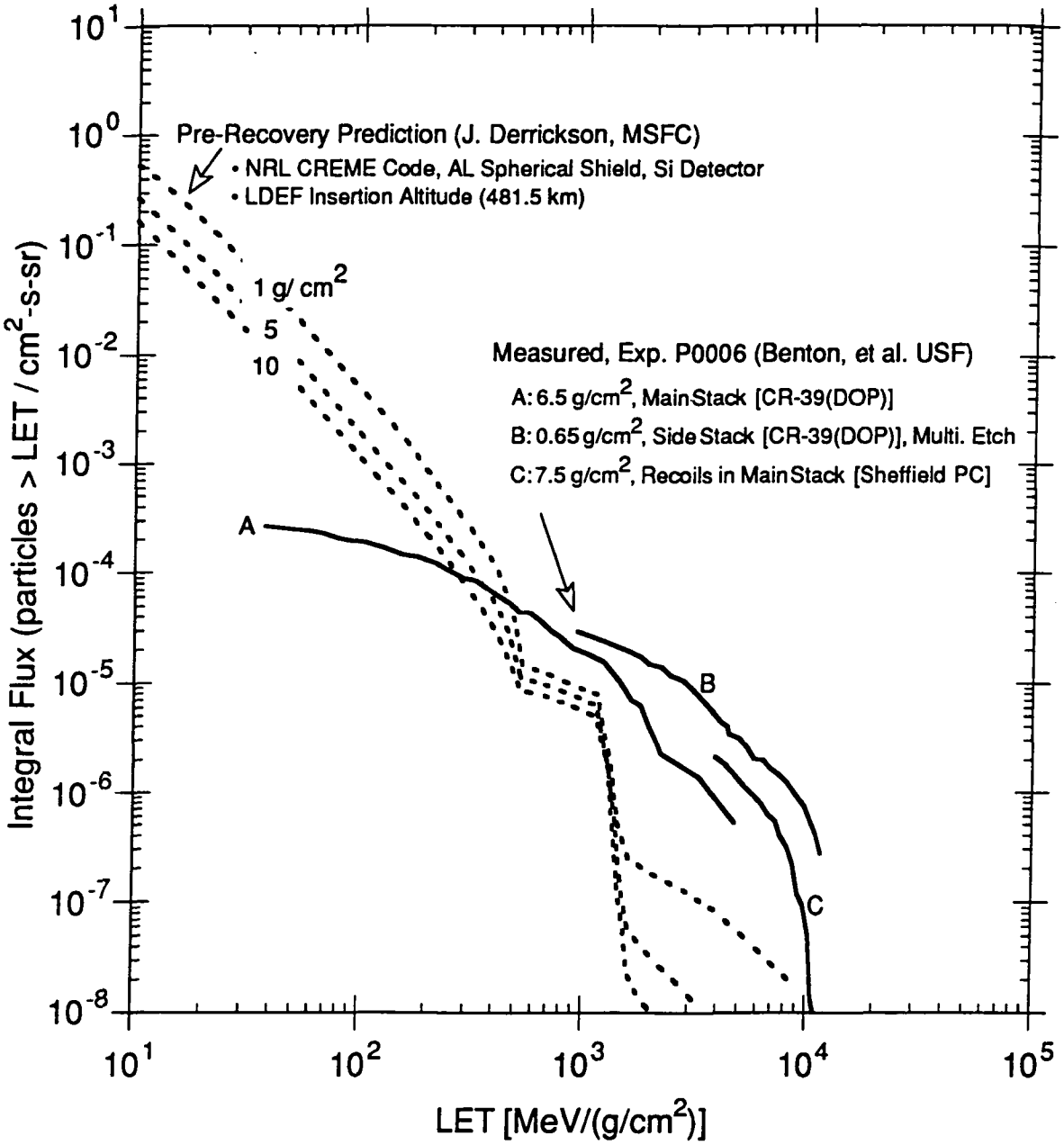

Figure 1. Comparison of LDEF pre-recovery predictions of linear energy transfer (LET) spectra (ref. 7) with interim results from measured spectra in Exp. P0006 (ref. 22). The predictions were made using the CREME code (ref. 31) and 1-D spherical shielding.

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The accuracy of models and computational methods for defining the ionizing radiation environment for spacecraft in low Earth orbit is evaluated using data from the Long Duration Exposure Facility (LDEF) satellite. Included are model predictions for various components of the space radiation environment (trapped electrons, trapped protons, and galactic cosmic rays) and comparisons with a variety of different types of measurements made on LDEF (particle fluence, absorbed dose, LET spectra, and induced radioactivity).

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