FUTURE DIRECTIONS FOR LDEF IONIZING RADIATION MODELING AND ASSESSMENTS*

T. W. Armstrong and B. L. Colborn
Science Applications International Corporation
Route 2, Prospect, TN 38477
Phone: 615/468-2603, Fax: 615/468-2676

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.

*Work supported by NASA Marshall Space Flight Center, Huntsville, AL, Contract NAS8-39386.

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 results to date indicate that accuracy of electron flux environment models (ref. 30) for LDEF-type orbits is

about a factor of two (ref. 14). 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 those 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 is also available from these data. Also of interest here are 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.

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.

REFERENCES

1. Parnell, T. A.: Summary of Ionizing Radiation Analysis on the Long Duration Exposure Facility. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

2. Parnell, T. A.: Status of LDEF Ionizing Radiation Measurements and Analyses. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

3. Armstrong, T. W. and Colborn, B. L.: Ionizing Radiation Calculations and Comparisons with LDEF Data. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

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

5. Watts, J. W., Jr.: Predictions of LDEF Fluxes and Dose Due to Geomagnetically Trapped Protons and Electrons. In: Ionizing Radiation Exposure of LDEF: Pre-recovery Predictions (E.V. Benton, et al.), *Nucl. Tracks. Radiat. Meas.* 20, 75 (1992).

6. Armstrong, T. W. and Colborn, B. L.: Predictions of Induced Radoactivity for Spacecraft in Low Earth Orbit. *Nucl. Tracks Radiat. Meas.* 20, 101 (1992).

7. Derrickson, J. H.: Linear Energy Transfer Spectra for the LDEF Mission. In: Ionizing Radiation Exposure of LDEF: Pre-recovery Predictions (E.V. Benton, et al.), *Nucl. Tracks. Radiat. Meas.* 20, 75 (1992).

8. Harmon, B. A.; Fishman, G. J.; Parnell, T. A.; Benton, E. V. and Frank, A. L.: LDEF Radiation Measurements: Preliminary Results. *Nucl. Tracks Radiat. Meas.* 20, 131 (1992).

9. Watts, John W.; Parnell, T. A.; Derrickson, James H.; Armstrong, T. W. and Benton, E. V.: Predictions of LDEF Ionizing Radiation Environment. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

10. Armstrong, T. W.; Colborn, B. L. and Watts, J. W., Jr.: Ionizing Radiation Calculations and Comparisons with LDEF Data. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

11. Watts, J. W. Jr.; Armstrong, T. W. and Colborn, B. L.: Revised Predictions of LDEF Exposure to Trapped Protons. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

12. Colborn, B. L. and Armstrong, T. W.: Development and Application of a 3-D Geometry/Mass Model for LDEF Satellite Ionizing Radiation Assessments. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

13. Frank, A. L.; Benton, E. V.; Armstrong, T. W. and Colborn, B. L.: Absorbed Dose Measurements and Predictions on LDEF. Second LDEF Post Retrieval Symposium, NASA CP-3194, 1993.

14. Armstrong, T. W. and Colborn, B. L.: Radiation Model Predictions and Validation Using LDEF Satellite Data. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

15. Watts, J. W., Jr.; Parnell, T. A. and Heckman, H. H.: Approximate Angular Distribution and Spectra for Geomagnetically Trapped Protons in Low-Earth Orbit. In: *High Energy Radiation Background in Space*, Proc. AIP Conf., Vol. 186, pp. 75-85, American Institute of Physics, New York, 1989.

16. Csige, I.; Benton, E. V.; Frigo, L.; Parnell, T. A.; Watts, J. W. Jr.; Armstrong, T. W. and Colborn, B. L.: Three-Dimensional Shielding Effects on Charged Particle Fluences Measured in the P0006 Experiment on LDEF. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

17. Colborn, B. L. and Armstrong, T. W.: LDEF Geometry/Mass Model for Radiation Analyses. First LDEF Post-Retrieval, NASA CP-3134, 1992.

18. Reitz, G.: Preliminary Total Dose Measurements on LDEF. *Adv. Space Res.*, 12, No. 2, 369, (1992).

19. Bourrieau, J.: LDEF Dosimetric Measurement Results (AO 138-7 Experiment). Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

20. Blake, J. B. and Imamoto, S. S.: A Measurement of the Radiation Dose to LDEF by Passive Dosimetry. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

21. Sawyer, Donald M. and Vette, James I.: AP-8 Traped Proton Environment for Solar Maximum and Solar Minimum. Goddard Space Flight Center, National Science Data Center, NSSDC/WDC-A-R&S 76-06 (1976).

22. Benton, E. V.; Csige, I.; Oda, K.; Henke, R. P.; Frank, A. L.; Benton, E. R.; Frigo, L. A.; Parnell, T. A.; Watts, J. W. Jr. and Derrickson, J. H.: LET Spectra Measurements of Charged Particles in the P0006 Experiment on LDEF. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

23. Benton, E. V.; Frank, A. L.; Benton, E. R.; Csige, I.; Parnell, T. A.; and Watts, J. W., Jr.: Radiation Exposure of LDEF: Initial Results. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

24. Harmon, B. A.; Fishman, G. J.; Parnell, T. A. and Laird, C. E.: Induced Activation Study of LDEF. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

25. LDEF Experiment P0006 Linear Energy Transfer Spectrum Measurement (LETSME), Quick Look Report. Eril Research, Inc. NASA MSFC Contractor Final Report NAS8-38188, Dec. 1990.

26. Reedy, Robert C.; Moss, Calvin E.; Bobias, George S. and Masarik, Jozef: Radioactivities Induced in Some LDEF Samples. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

27. Winn, W. G.: Gamma-Ray Spectrometry of LDEF Samples. Westinghouse Savannah River Company, WSRC-RD-91-16, February 1992.

28. Smith, Alan R. and Hurley, Donna L.: A Photon-Phreak Digs the LDEF Happening. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

29. Reeves, James H.; Arthur, Richard J. and Brodzinski, Ronald L.: Sensitivity of LDEF Foil Analyses Using Ultra-Low Background Germanium and Large NaI (Tl) Multidimensional Spectrometers. Second LDEF Post-Retrieval Symposium, NASA CP-3194, 1993.

30. Vette, James I.: The AE-8 Trapped Electron Model Environment. National Space Science Data Center, Goddard Space Flight Center, NSSDC/WDC-A-R&S 91-24, Nov. 1991.

31. Adams, James H. Jr.: Cosmic Ray Effects on Microelectronics, Part IV. Naval Research Laboratory, NRL Memorandum Report 5901, December 1986.

FOOTNOTES

1. Benton, E. V. and Csige, I., Univ. San Francisco, priv. comm., 1992.

2. B. A. Harmon, NASA Marshall Space Flight Center, priv. comm., 1992.

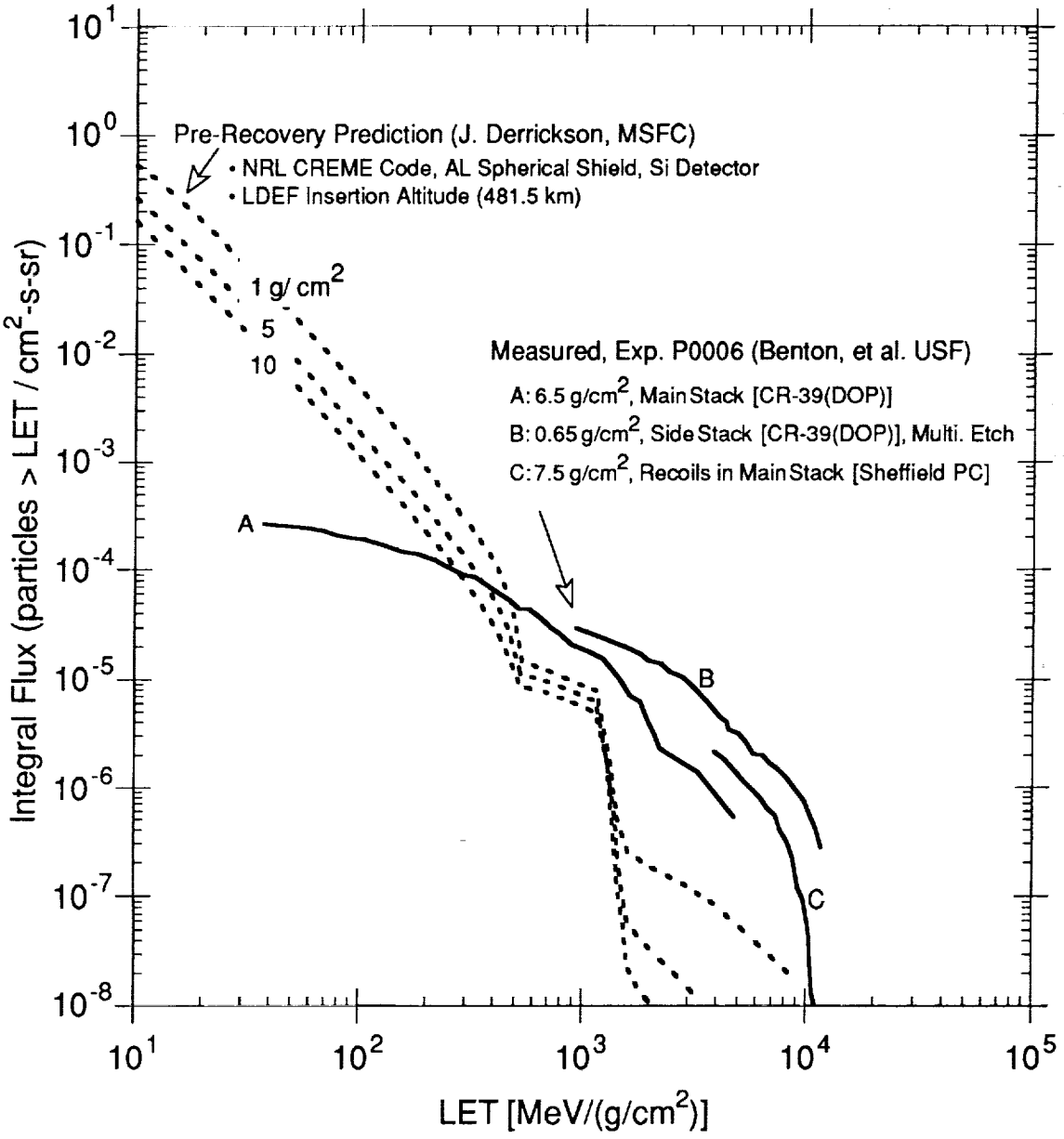

Figure 1. Comparison of LDEF pre-recovery predictions of linear energy transfer (LET) spectra (ref. 7) with interim results from measured spectra in Exp. P0006 (ref. 22). The predictions were made using the CREME code (ref. 31) and 1-D spherical shielding.