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DISCOVERY OF BE-7 ACCRETION IN LOW EARTH ORBIT

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We observed strong ^7Be activity on the surface of the Long Duration Exposure Facility (LDEF) during the first complete gamma-ray survey of a large spacecraft after its return to earth. This is the first known evidence for accretion of a radioactive isotope onto an orbiting spacecraft. ^7Be is produced by spallation reactions of cosmic rays on nitrogen and oxygen in the upper atmosphere. However, the observed density is much greater than expected due to cosmic ray production in situ; this is significant for models of atmospheric mixing. ^7Be may be a valuable tracer in future studies of the upper atmosphere. Other isotopes seen during the survey, the strongest being ^{22}Na , are due to activation of spacecraft components while in orbit. We discuss the likely accretion of other cosmic-ray produced isotopes and their possible effects on spacecraft in low-earth orbit.

THE LDEF SPACECRAFT

The Long Duration Exposure Facility (LDEF) was launched by the Space Shuttle Challenger on 7 April 1984. It was retrieved in orbit by the Shuttle Columbia on 12 January 1990 and brought back to Earth on 20 January 1990. The LDEF carried a broad range of passive or low-powered experiments designed to study the space environment in low-earth orbit and to determine the effects of the environment on various materials, coatings, spacecraft components, and lastly, 12 million tomato seeds. The spacecraft is a 12-sided cylindrical aluminum structure, 9.1 m long by 4.2 m diameter, with a total weight of about 9700 kg. Along the sides and on both ends were 86

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experimental trays, designed to be brought back to earth and analyzed in the laboratory by investigators from across the US, Canada, and Europe. The tomato seeds were distributed to school children to be grown and studied as science projects.

The LDEF was to have remained in orbit for a year, but recovery was delayed due to the Challenger accident, and exposure lasted over five and one half years. It was launched into a nearly circular orbit at an altitude of 480 km and an inclination of 28.5 degrees, where it was exposed continuously to cosmic rays, interplanetary dust and the residual atmosphere. In addition, the orbit took it through the South Atlantic Anomaly (SAA) exposing the spacecraft to energetic trapped protons and electrons. In the months prior to retrieval, the orbit was decaying rapidly and LDEF was down to an altitude of 310 km when recovered by the shuttle.

The LDEF spacecraft was gravity-gradient stabilized while in orbit so that its axis was aligned to the Earth's radius vector, with one end always pointed toward space and the other end toward Earth. Also, rotation about this axis was stabilized with respect to the orbital velocity so that the leading edge was always side number 9 (plus about 8 degrees). There were a number of duplicate experimental trays positioned around LDEF in order to get information about the differential flux of particles and micrometeoroids. The LDEF orbital velocity (7.8 km/s at retrieval) exceeded the average thermal velocity of the rarified atmosphere so that exposure to the atmosphere was primarily on the leading edge of the spacecraft.

GAMMA-RAY SURVEY

After landing, LDEF was returned to Kennedy Space Center (KSC) for post-recovery examination. There, the spacecraft was mounted on a stand so that it could be rotated about its axis for inspection. During this period, an array of high-purity germanium detectors from the Naval Research Laboratory (NRL) and single detectors from the Institute for Space Science and Technology (ISST), were used to conduct the first detailed gamma-ray survey of a large spacecraft after exposure in low-earth orbit. The residual gamma-ray emission depends both on the flux of high-energy particles to which LDEF was exposed and on the particular materials in each experimental tray. To observe the distribution of gamma-ray activity about the spacecraft, we set up the array with detectors facing each tray position along one side of LDEF. The single detectors were positioned at each end facing one of the experimental trays. The distance from the detectors to each tray was about 0.6 m. Background spectra were taken prior to the arrival of LDEF, and the detectors were calibrated in place using known gamma-ray sources.

After the arrival and setup of LDEF, spectra were taken along each side for a minimum of 12 hours. The LDEF was then rotated so that a new side faced the array and new trays faced the detectors at each end. In this manner the entire spacecraft was surveyed over a period of about two weeks. During the disassembly period which followed, spectra were taken of selected experimental trays after they were removed from LDEF.

^{22}Na AND ^7Be ACTIVITIES

We expected to see gamma rays from the decay of isotopes produced by the long bombardment of energetic protons, neutrons, and heavier cosmic rays. The highest activity was expected from ^{22}Na , which has a half-life of 2.6 years and is produced by spallation from high-energy protons on the aluminum of the spacecraft body and experimental trays. At equilibrium, the activity from ^7Be , another spallation product with a 53 day half-life, was expected to be lower than ^{22}Na in intensity by two orders of magnitude. Data analysis capabilities during the survey were limited and consisted mainly of plotting spectra and identifying peaks. As expected, the strongest gamma-ray line at 1274 keV was from ^{22}Na . The 478 keV line from ^7Be was unexpectedly strong at some positions around the LDEF and much weaker at other positions. After the survey was complete, a preliminary plot of count rate versus position around the spacecraft showed a strong enhancement of ^7Be at the leading edge compared to the trailing edge. During post-collection data analysis, spectra were analyzed for each detector and peak intensities were extracted using the computer program HYPERMET¹. Fig. 1 shows the ^{22}Na and ^7Be activities for each side of LDEF, corrected for decay from the date of retrieval of the spacecraft.

LDEF ACTIVITY

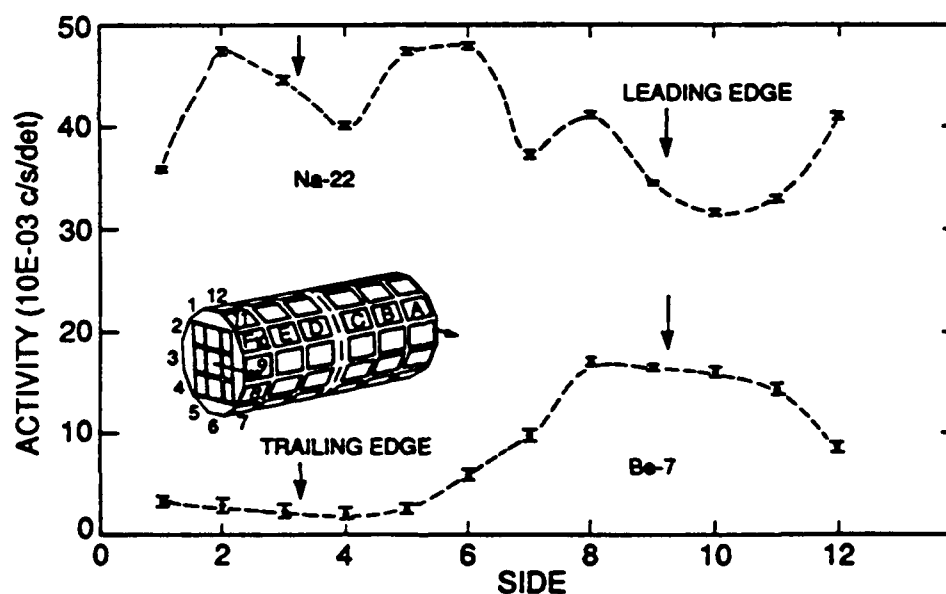


Fig. 1. Comparison of Activities of ^7Be (Lower) and ^{22}Na (Upper) Seen During the Gamma-Ray Survey of the LDEF Spacecraft. The average counts per second per detector are shown for each side of LDEF for an average detector efficiency of 38.8% at 1332 MeV relative to a 7.6 x 7.6 cm diameter NaI(Tl) detector. The error bars include statistical and peak-fitting uncertainties. As a visual aid, dashed curves are drawn connecting the data points. The overlay is a diagram of LDEF.

The distribution of ^{22}Na activity in Fig. 1 shows a small trailing edge enhancement, although there is some variance due to the distribution of aluminum and other activation material around the spacecraft. The trailing edge enhancement might be explained by the asymmetry in the trapped proton flux in the SAA. This flux is strongly peaked from the westward direction, the trailing direction in orbit². Although many of the trapped protons are energetic enough to penetrate LDEF, they could produce the asymmetry seen in the activation data. Several other less intense activation lines were also observed and will be reported elsewhere³.

In contrast to the ^{22}Na distribution, a strong leading edge enhancement for the ^7Be activity is evident in Fig. 1. The weak activity seen from the trailing edge can be wholly accounted for by penetration of gamma rays from the opposite side of the hollow spacecraft. This distribution of the ^7Be activity is not consistent with any known mechanism for activation of the spacecraft materials. It can only be explained by accretion of the isotope onto the leading surfaces of LDEF as it moved through the thin upper atmosphere in orbit.

The overlay in Fig. 1 gives a diagram of LDEF. Each experimental tray position around the cylinder is identified by the side, numbered 1 through 12, and the row lettered A through F. The view is toward the space end and the leading edge; the arrow vectors indicate the direction of the orbital velocity. Fig. 2 shows a two dimensional mapping of the ^7Be and ^{22}Na activity. The mapping shows the data as it would appear after cutting the cylinder between rows 1 and 12 and unrolling it flat. The data for each tray position is plotted by side (running from 1 to 12) along the right axis and by row (running from A to F) along the left axis. The leading and trailing edges in orbit are identified by the dashed lines in the figure. The ^7Be activity is shown to be distributed along the entire leading edge and not confined to a single tray. The data tend to be somewhat higher in the middle compared to the edges of the spacecraft. This can be explained by gamma rays from adjacent trays penetrating the 3 mm lead collimators which surrounded the detectors. Similarly, the weak trailing edge activity can be explained by penetration of gamma rays from the opposite leading edge.

The absence of ^7Be activity on the trailing edge was confirmed by measurements of gamma-ray spectra from individual experimental trays after they were removed from LDEF. Fig. 3 shows a comparison of spectra from nearly identical trays from the leading and trailing edges, containing germanium plates covered with a thin foil designed to capture interplanetary dust particles. The ^7Be peak is indicated in the figure and appears only on the tray from the leading edge.

Further confirmation of the lack of ^7Be on the trailing edge of LDEF came from low-level activity measurements of aluminum plates and tray clamps by NASA/Marshall Space Flight Center⁴ (MSFC), which showed ^7Be activity only on the parts from the leading edge. In addition, they showed that an acid etch of an aluminum plate from the leading edge removed most of the activity, demonstrating that most of the ^7Be is found on the surface.

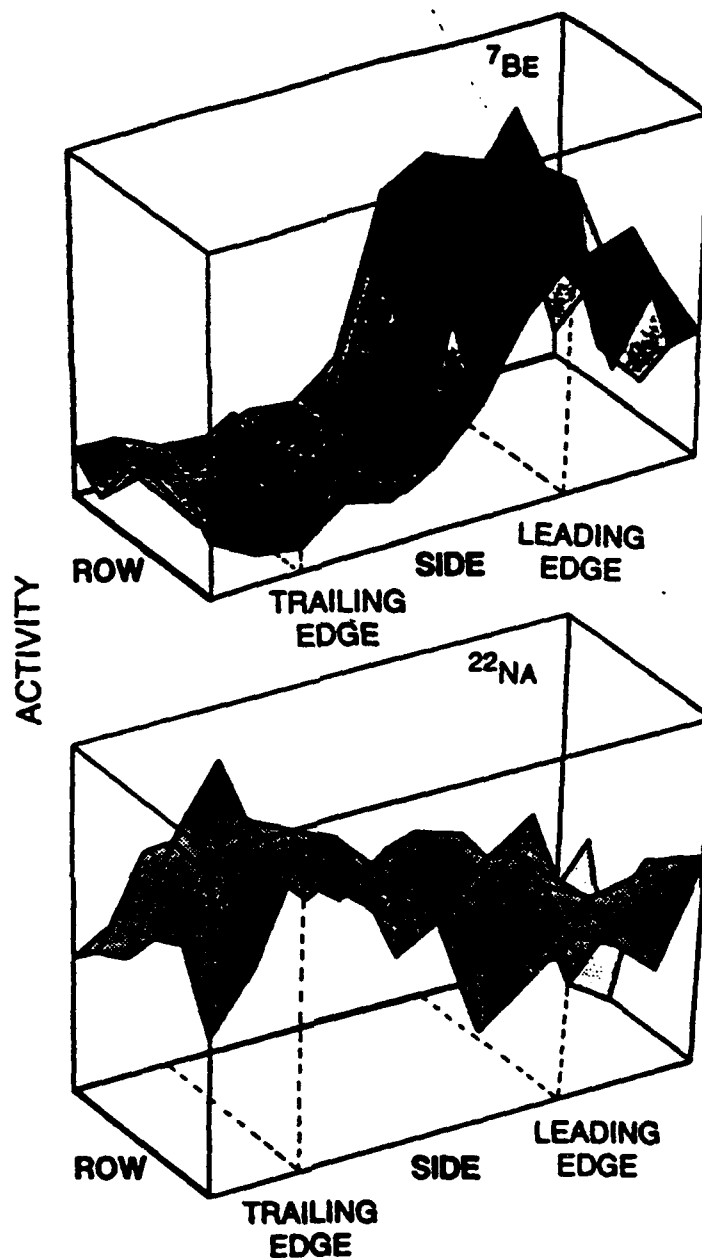


Fig. 2. Map of the Distribution of ^7Be and ^{22}Na activities around the LDEF spacecraft. There are 12 sides along the right axis and six rows along the left axis, with data from one experimental tray plotted for each row and side. The dashed lines indicate the positions of the leading and trailing edges. The ^7Be activity is strongly peaked along the leading edge, while the ^{22}Na activity is higher along the trailing edge.

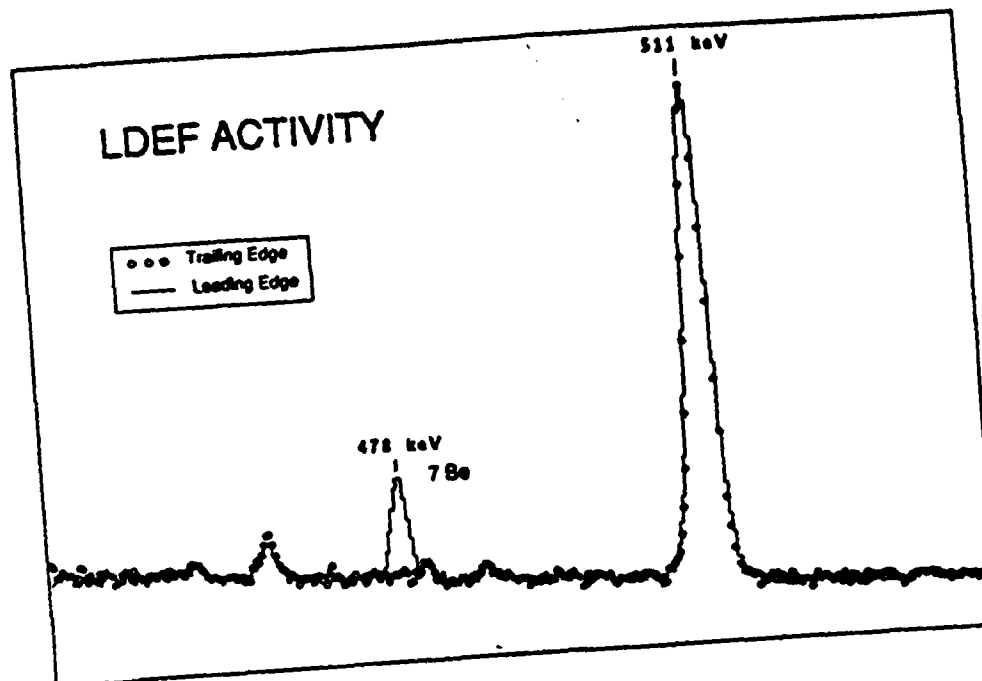


Fig. 3. Comparison of Gamma-Ray Spectra of Germanium Plates from Trays E3 and E3 After Their Removal from LDEF. Shown is the region including the 478 keV gamma ray from ^7Be which is seen on tray E3 near the leading edge and not on tray E3 at the trailing edge. The 511 keV peak due to positron annihilation is seen both in the background and from ^{22}Na . The weaker unlabeled peaks are all in the background.

DENSITY OF ^7Be IN THE UPPER ATMOSPHERE

Assuming that the ^7Be was accreted onto the surface of LDEF in low-earth orbit, the question arises: how did it get there with such intensity? ^7Be is produced by spallation interactions of high-energy cosmic rays primarily on nitrogen and oxygen in the upper atmosphere. (These complex nuclear disintegrations are called "stars" from their appearance in photographic emulsions.) From the literature, we can estimate the ^7Be density at 310 km due to cosmic ray production for comparison to our measurements. Using curves of cosmic ray interaction rates derived from measurements during a period of high solar activity⁵ and trapped proton fluences, we obtain an estimated ^7Be density of 5.4×10^{-5} atoms/ m^3 , due to production in situ (see the Appendix for details.) From our measurements we can derive a minimum ^7Be density in orbit of 0.10 ± 0.03 atoms/ m^3 . This exceeds the estimated in-situ production by a factor of 1800.

It is difficult to explain such a large enhancement in the ^7Be density. One possibility is the mixing of air from the poles where the star production rate is higher than at lower latitudes, which are partially shielded from cosmic rays by the Earth's magnetic field. Measurements in the stratosphere⁶ imply

significant mixing between polar and low-latitude air, showing increases by a factor of 2 to 5 over the equilibrium value at 31° N. In the upper atmosphere, above 120 km, the polar production rate is about a factor of 10 higher than the average rate from 0° to 30° latitude⁵. Thus, complete displacement by polar air would still leave a factor of 180 unexplained.

A second possible source of increased activity is diffusion or convection of ⁷Be from air at lower altitudes where production rates are higher due to increased atmospheric density. During periods of high solar activity⁷, the estimated in-situ production rate increases by a factor of 300 from an altitude of 310 km down to 120 km, which is approximately the altitude where diffusive equilibrium begins⁸. Because ⁷Be is considerably lighter than the mean atmospheric molecular weight, it will tend to diffuse upward; because the atmosphere is so thin, diffusion will be rapid. The equilibrium distribution of atmospheric molecules due to diffusion is a decreasing exponential function of the altitude with a scale height⁹ which is proportional directly to the temperature and inversely to the atomic weight. The mean global temperature¹⁰ rises rapidly from about 380K at 120 km to 1040K above 200 km. During periods of high solar activity, temperatures as high as 1700K have been measured^{11,12}. For ⁷Be, this corresponds to a scale height of 206 km and an average thermal velocity of 2.5 km/s. Several large solar flares occurred in 1989, including the late September-early October flare which was the largest in 33 years and had a very hard spectrum¹³. Such events cause heating and expansion of the upper atmosphere, where winds have been measured at several hundred meters per second^{11,12}, driven by solar activity, diurnal solar heating and geomagnetic storms. These act both to mix polar and lower latitude air and to transport air upward from lower altitudes^{9,11}.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE SPACECRAFT

Our observations of ⁷Be activity on the leading surfaces of the LDEF spacecraft imply a minimum density for ⁷Be in low-earth orbit which greatly exceeds the local equilibrium due to cosmic-ray production in situ. One possible explanation would require the transport by diffusion or atmospheric mixing of ⁷Be from much lower altitudes and higher latitudes into the LDEF orbit. Thus, the current results should be important for validating and refining models of the upper atmosphere. With more extensive measurements, ⁷Be should prove valuable as a natural tracer for studies of upper atmospheric mixing. Our next step is to use existing atmospheric circulation models and a calculation of ⁷Be production rates at lower altitudes to predict the upward transport of ⁷Be. Future observations should focus on sampling at both lower and higher altitudes and should extend to polar latitudes. These should be closely correlated with data on wind, temperature, pressure and solar activity.

In addition, the observation of the accretion of significant quantities of ⁷Be is an indication of possibly similar behavior for other light cosmic-ray produced isotopes. Table 1 gives the spallation yields⁵ for all light isotopes with yields greater than or of the order of ⁷Be. Also given are their half-lives and decay modes. ³He is stable and non-reactive. The remaining isotopes,

other than ^7Be , are all pure beta emitters and thus would not be seen in the present survey. They could, however, be significant sources of noise for low-level sensors on spacecraft in low-earth orbit and could slowly degrade other components by coating or by surface reactions. Lithium, the decay product of ^7Be , could affect exposed semiconductor sensors even in very low concentrations. As a result of our observations, other groups are currently looking for trace amounts of Li and ^{14}C on LDEF components^{14,15}.

Table 1
COSMIC RAY PRODUCED LIGHT ISOTOPES

<u>Isotope</u>	<u>Yield/Star</u>	<u>Half-life</u>	<u>Decay Modes</u>
^{14}C	1.5*	$5.7 \times 10^4 \text{ y}$	beta
^3H	0.14	12.3 y	beta
^3He	0.12	stable	none
^7Be	0.045	53 d	ec ⁺ , gamma
^{10}Be	0.025	$1.6 \times 10^6 \text{ y}$	beta

* Relative yield, produced mainly by thermal neutrons

+ Electron capture

APPENDIX

Equilibrium ^7Be Density from Cosmic-Ray Production. Lal and Peters⁵ provide curves of cosmic-ray produced interaction rates (stars per gram of air per second) versus latitude and altitude, using a model derived from measurements during a period of high solar activity. From these curves and the known spallation yields⁵, we obtain a ^7Be production rate per gram of air between 0° and 30° latitude of 9.0×10^{-5} atoms/g-s at the "top" of the atmosphere (above 120 km). The mean atmospheric density during periods of high solar activity⁷ at an altitude of 310 km is about $6.1 \times 10^{-8} \text{ g/m}^3$. This gives an in-situ production rate for ^7Be at 310 km of 5.5×10^{-12} atoms/ m^3 -s. Multiplying by the equivalent in seconds of the 77 day mean ^7Be lifetime gives an equilibrium density for ^7Be of 3.6×10^{-5} atoms/ m^3 , due to production in situ.

The trapped proton flux provides an added production source of ^7Be at 310 km. Using the trapped proton fluence for solar maximum given by Stassinopolis¹⁶, production cross sections⁵, and an atmospheric density for November/December 1989 calculated by Hickey¹⁷, the average equilibrium density of ^7Be is 1.8×10^{-5} atoms/ m^3 . The total density is then 5.4×10^{-5} atoms/ m^3 . However, the density calculated for the trapped protons is somewhat misleading since virtually all the production occurs in the South Atlantic Anomaly where the density would be considerably higher.

Radiation Survey of the LDEF Spacecraft

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Abstract

We report the first complete γ -ray survey of a large spacecraft, the Long Duration Exposure Facility (LDEF). The survey was conducted using an array of germanium detectors from the U.S. Naval Research Laboratory (NRL) and individual detectors from the Institute for Space Science and Technology (ISST) to study the accumulation and distribution of radioisotopes induced in the wide variety of materials present on LDEF. ^{22}Na , ^7Be , ^{54}Mn , and the positron annihilation line were all strongly observed. Also observed were traces of ^{58}Co , ^{57}Co , and ^{60}Co . The most striking feature of the data was the unexpected distribution of ^7Be , which was predominately observed on the leading surfaces of the spacecraft. The evidence clearly indicates an accretion of the ^7Be onto the surface of the LDEF. This is the first known observation of the deposition of a radioisotope onto the surface of a spacecraft. ^7Be is a spallation product of cosmic rays on nitrogen and oxygen in the upper atmosphere[1]. To explain the surface density of 5.4×10^5 atoms/cm², the light ^7Be atom must be transported up from lower altitudes.

1. Introduction

Cosmic ray and trapped particle bombardment produces small quantities of radioisotopes in most materials located in earth orbit. The question of production rate and resulting dose from these radioisotopes is a complex one depending on such factors as altitude, orbital inclination, solar activity, materials present, and the spacecraft geometry. The impact of

induced radioactivity, although secondary to direct cosmic ray radiation, may be of importance in long duration missions such as the space station, interplanetary missions, x-ray and γ -ray observatories. Information on the quantity and distribution of radioisotopes in the LDEF should enable predictions of activation on future missions. The induced activity may also provide a measure of the secondary fast neutron flux which contributes a major fraction of the biological dose in low earth orbit.

The retrieval of the LDEF spacecraft provided a unique opportunity to study the long term buildup of induced radioactivity as a result of its longevity in space, nearly six years, and the variety of materials on board. LDEF was launched by the space shuttle Challenger on April 7, 1984 into an orbit with 480 km altitude and 28.5° inclination. LDEF was originally scheduled for a one year exposure time but due to the Challenger accident it was not retrieved until January 12, 1990 by the shuttle Columbia at an altitude of 310 km, shortly before its impending reentry from orbit.

LDEF consisted of a twelve sided cylindrical aluminum frame, 9.1 m long by 4.2 m diameter, weighing 9700 kg. On all twelve sides and both ends of the frame a total of 86 experimental trays were mounted. LDEF carried a diverse range of passive and low powered experiments to study the space/radiation environment in low earth orbit. Of particular emphasis were experiments to study the results of micrometeorites, atomic oxygen, thermal cycling and radiation damage on materials, coatings and/or devices considered for potential use on future spacecraft and the space

station Freedom. The spacecraft was gravity-gradient stabilized while in orbit so that its main axis was always radially oriented relative to the earth and rotationally stabilized so the side facing the direction of motion or leading edge was always side 9 (plus eight degrees). Upon return, Colombia and LDEF were flown from Edwards Air Force base to the Kennedy Space Center as quickly as possible in a low altitude flight (10,000 ft.) to avoid additional activation. At Kennedy LDEF was mounted on a trailer which allowed for rotation and was transferred to the Spacecraft Assembly and Evaluation Facility (SAEF II) clean room where these measurements and the spacecraft disassembly took place.

II. Radiation Survey

On February 4, 1990 a γ -ray survey of the LDEF spacecraft was begun using six germanium detector arrays from NRL positioned facing the six experimental trays along one side of the LDEF and two germanium detectors from ISST positioned one on each end to determine the spatial distribution of the induced activity. The detectors were placed 60 cm from the LDEF to insure spacecraft safety and to allow a field-of-view of the collimated detector pods sufficient to view one experimental tray. Each side was measured for at least 12 hours during the night over a period of 15 days allowing two sides to be repeated. The average NRL detector efficiency is 38.8% compared to a 7.6 by 7.6 cm NaI(Tl) detector at 1.3 MeV. The ISST detectors have efficiencies of 18% and 30% for the earth and space ends respectively. The detectors were calibrated for efficiency using ^{60}Co , ^{152}Eu , and

^{88}Y sources in a geometry similar to the experimental conditions. Energy calibrations for the detectors were performed during each measurement using ten prominent background γ -ray peaks.

Prior to the arrival of the LDEF, a background spectrum was acquired for a total time of 112 hours in the SAEF II clean room. However, the background was measured without the LDEF trailer support structure due to logistical constraints. We observed peaks in the background from ^{40}K , ^{226}Ra and its daughters, the ^{232}Th chain, ^{137}Cs , ^{58}Co , ^{60}Co , ^{235}U , and possibly ^{235}U . During the LDEF observation the background count rates declined by approximately 20% due to the shielding effects of the LDEF and support trailer. Radon related peaks were observed to decline by 50%.

III. Gamma-ray Observations

The original intent of a gamma ray survey of the LDEF was to identify and map the distribution of activation isotopes as soon after retrieval as possible. It was also hoped that a global survey would observe and identify any unexpected activity from the many different materials present on the LDEF in order to direct further investigation at low γ -ray background research facilities. The expected activity results from cosmic ray and trapped proton spallation and secondary neutron induced reactions in aluminum and steel.

The gamma-ray data were acquired and stored in event mode format for subsequent analysis. The final peak intensities were extracted using HYPERMET

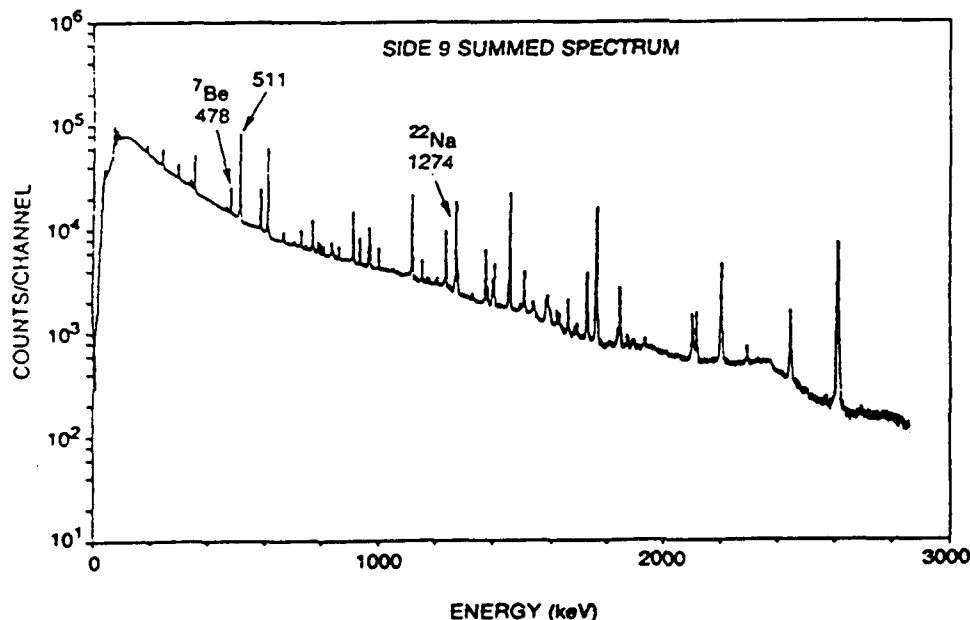


Figure 1. Summed spectrum from side 9 of LDEF accumulated for 29 hours. The ^{7}Be , ^{22}Na , and positron annihilation peaks are indicated along with their energies in keV. The energy calibration is 0.706 keV/channel.

Fig. 1 is the spectrum from side 9 on the leading edge of LDEF.

A. Activity from ^{22}Na and ^7Be

Strong activity was observed from the 1274 keV gamma ray of ^{22}Na and the 478 keV gamma ray of ^7Be . ^{22}Na (2.6 year half-life) is a spallation product of high energy protons on aluminum, which comprises at least 6100 kg of the total LDEF mass of 9700 kg. Fig. 2 shows the distribution of ^{22}Na activity on each of the twelve sides of the LDEF. The variation in activity is primarily attributed to the distribution of aluminum mass. The data does show a trend of a small increase in activity toward the trailing side of the spacecraft. This asymmetry was predicted as a result of the large asymmetry in the trapped proton flux which is strongly peaked in the westward direction. When both the directionality and the penetrability of the trapped proton flux are considered a small increase along the trailing side is expected[3].

^7Be was also observed in significant quantity as shown in Fig. 2. ^7Be is also produced by spallation of protons on aluminum but with a cross section two orders of magnitude lower than the ^{22}Na production cross section. Since neither the distribution nor the absolute quantity of ^7Be track the ^{22}Na distribution, the major source of ^7Be can not be spallation in aluminum. The peak activity is at the leading edge which is eight times larger than the trailing edge activity. Further, the weak trailing edge signal can be accounted for by the penetration of gamma rays from the opposite side of the virtually hollow spacecraft. The absence of ^7Be on the trailing edge was confirmed by measurements of gamma ray spectra from individual trays after their removal. Fig. 3 shows a comparison of spectra taken from nearly identical trays removed from the leading and trailing sides. No ^7Be was observed on the trays from the trailing side. Across the leading side the distribution of activity from pod to pod indicates a distributed rather than point source. The distribution and regularity of the ^7Be observed can be readily explained by the accretion of the isotope onto the spacecraft from the rarified atmosphere in low earth orbit. The peak surface density resulting from our measurements is $5.4 \pm 1.5 \times 10^9$ atoms/m².

The surface accretion hypothesis is further supported in subsequent low-background laboratory analysis of tray clamps, aluminum plates, steel bolts and pins removed from the LDEF[4]. The lack of ^7Be on the trailing edge was confirmed. Further, chemical etching of the surface of the aluminum plates removed most of the ^7Be activity. Clearly, the observed ^7Be activity results from surface deposition.

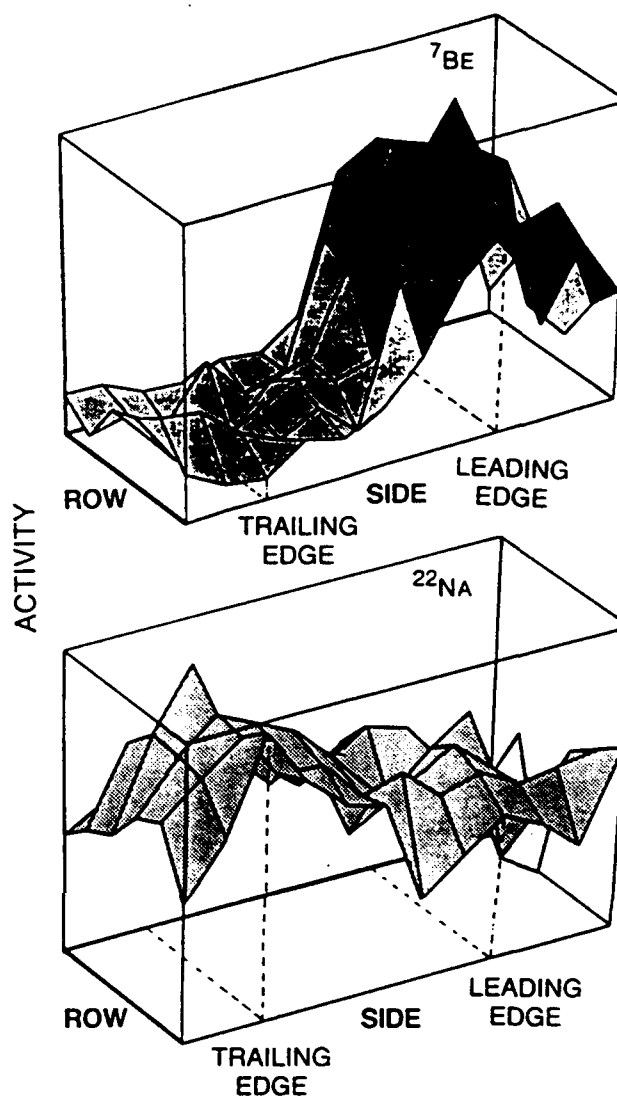


Figure 2. Distributional map of ^7Be and ^{22}Na activities around the LDEF. There are twelve sides around LDEF and six experiment trays (rows) per side. Each intersection point is the activity measured in one detector pod. The dashed lines indicated both the leading and trailing sides.

B. Other Activity

The activity observed for all isotopes is given in Table I. Except as noted, the activity given is the average over the survey of all sides in excess of any activity observed in the background. All activities except the annihilation line are corrected back to the landing time. The distribution of activity is given in Fig. 4 for each isotope. The most prominent gamma ray line is the positron annihilation line. The net annihilation activity given in Table I is larger than the .070 counts per second per detector background.

^{22}Na decay contributes to the positron emission; however, the expected contribution should be about .036 counts per second per detector based on the magnitude of 1274 keV line. Only one third of the annihilation activity can be attributed to ^{22}Na . Another source of positrons and thus the 511 keV γ -ray line is direct, ground level cosmic-ray production and pair production from high energy background gamma rays within the LDEF while the spacecraft was in the SAEF II. If the ground level production was the source of the remaining activity, the distribution of activity should vary only with mass density from side to side. However, the distribution of the annihilation peak in Fig. 4 shows the same trailing edge increase as the ^{22}Na distribution in Fig. 2 which is attributed

to the anisotropic trapped proton flux. This suggests that a significant fraction of the annihilation line is from other activation isotopes.

^{54}Mn is a product of proton and neutron induced reactions in nickel, cobalt and iron. The ^{54}Mn is shown in Fig. 4 along with the much weaker peaks observed for ^{56}Co , ^{57}Co and ^{60}Co . These are also activation products of nickel, cobalt and iron. There is little indication of any spatial variation of the distribution of these isotopes. Both ^{56}Co and ^{60}Co were observed in the background spectra at a level of 3.4×10^{-4} c/s/d and 7.5×10^{-4} c/s/d respectively. No other isotopes have yet been definitively identified although very small peaks are seen at several energies.

Table I. Observed LDEF Gamma-Ray Activities.

Isotope	E_γ (keV)	Halflife	Activity ($\times 10^{-3}$ c/s/det.)	(% error)
^{22}Na *	1274	2.6 yr	39.7	0.3
^7Be	478	53 d	23.0	3.
^{54}Mn	835	312 d	3.1	4.
^{56}Co	847	78 d	.75	25.
^{57}Co **	122	272 d	2.8	22.7
^{60}Co	1173, 1332	5.3 yr	.34	27.
Annihilation	511	-	112.	.8

* Peak activity given for ^7Be
 ** Only 4 sides included in ^{57}Co activity

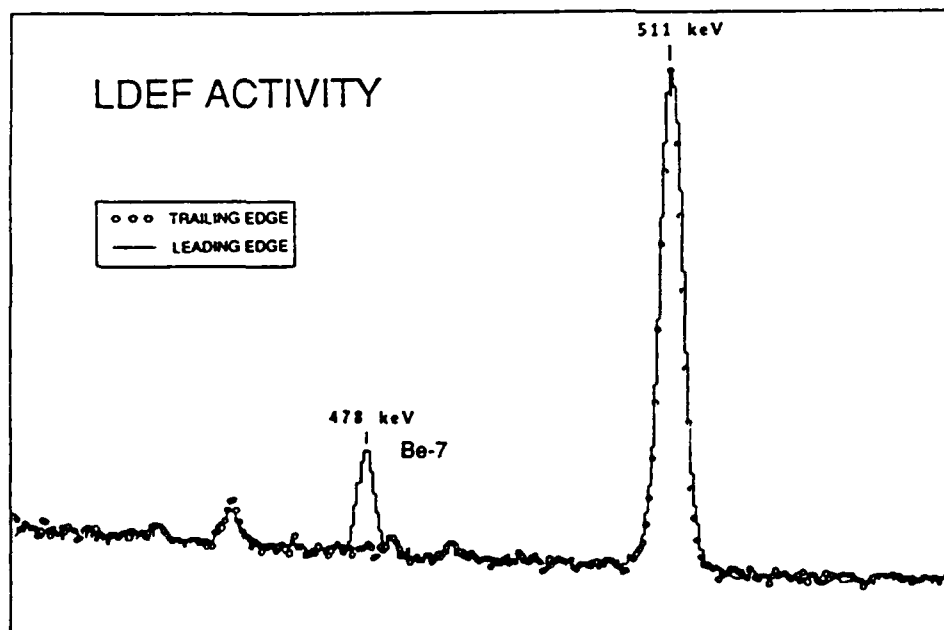


Figure 3. Comparison of the ^7Be peak in the gamma ray spectra from the nearly identical trays E3 and E8 acquired after their removal from the LDEF. Tray E8 which was near the leading edge shows a clear ^7Be peak while E3 on the trailing edge shows no evidence of ^7Be .

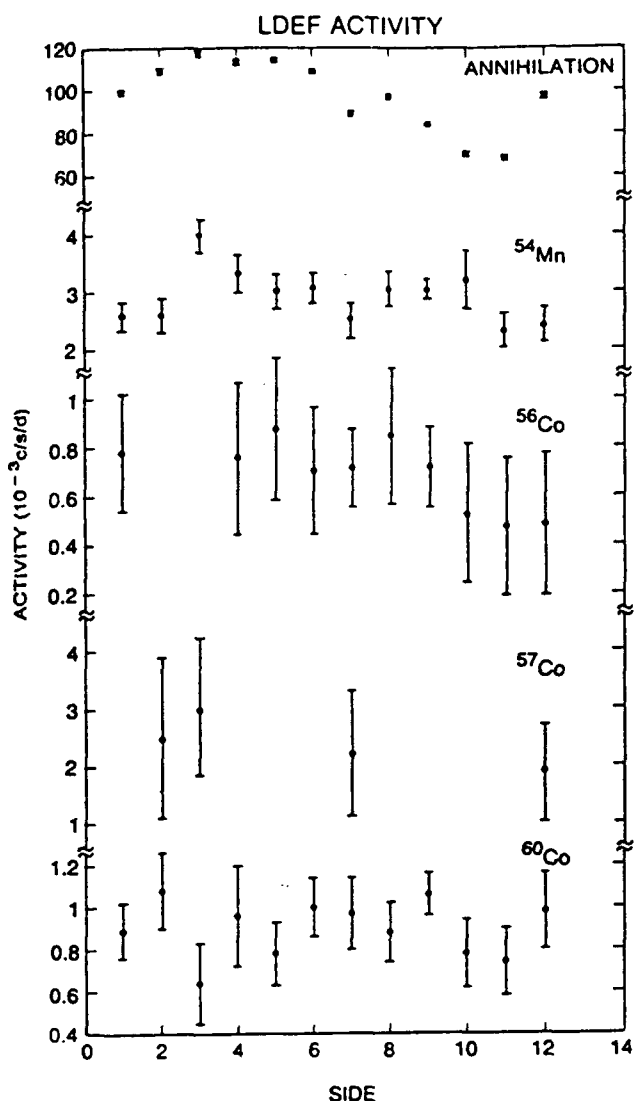


Figure 4. Distribution of net activity from the positron annihilation line, ^{54}Mn , ^{56}Co , ^{57}Co , and ^{60}Co after background subtraction. Error bars are the statistical and peak fitting errors only.

IV. Analysis of Activity

A. ^7Be Activity

The most surprising finding of our gamma ray survey is the deposition of ^7Be on the leading surface of the LDEF. This, the first observation of the accretion of a radioactive isotope on a spacecraft, leads to the question: what is the minimum density of ^7Be

at LDEF's orbital altitude? Assuming 100% adherence of ^7Be to the surface of the LDEF and the volume of space swept during one mean lifetime of ^7Be , our measurements imply a minimum density of 0.10 ± 0.03 atoms/ m^3 at an altitude of 310 km. Next, what is the origin of the ^7Be ? Spallation of cosmic rays on nitrogen and oxygen in the upper atmosphere is a known source of ^7Be [1]. Calculations of the production in situ based on the cosmic ray flux, the spallation yield of ^7Be , and the atmospheric density during the period before the LDEF's retrieval are a factor of 2800 too low to account for the minimum density derived from our measurements[5]. The most feasible explanation of the source of ^7Be is the diffusive transport from lower altitudes. Higher air densities increase the production rate by a factor of 300 at 120 km compared to 310 km. An additional contribution could be the mixing of polar air into lower latitudes. Increased cosmic-ray flux at high latitudes increases the production of ^7Be by one order of magnitude. An open question remains whether existing atmospheric transport models can quantitatively explain the observed density.

B. ^{22}Na and Other Activity

The survey geometry does not lend itself to determination of an absolute quantity of the isotopes produced in situ. The activation isotopes are produced in specific materials throughout the spacecraft. A precise quantitation of the activity using the survey data is impossible because of the spatial distribution of the activity and the attenuation of intervening materials. Investigation of specific materials removed from the LDEF is underway at several low background gamma-ray counting facilities[8] to determine precise activation rates. An order of magnitude estimate of the ^{22}Na activity assuming a uniform hollow shell for the structure gives an activity of approximately 4 ± 2 Bq/kg of aluminum. In the LDEF Induced Radioactivity Analysis plan, the production of ^{22}Na and other isotopes will be used to verify calculations based on realistic models of cosmic-rays, trapped particles, secondary radiation, nuclear reactions, and the spacecraft geometry. The average activity agrees remarkably well with preliminary activation calculations[7] of 3 to 6.5 Bq/kg depending on surface orientation.

The detection of the ^{54}Mn , cobalt isotopes and the positron annihilation line were anticipated. The global survey found no unusual distribution of these isotopes nor any other unexpected activity.

V. Conclusions and Remarks

The surprising discovery of the surface deposition of ^7Be on a spacecraft in low earth orbit has led to a number of new questions. Can atmospheric transport models account for the minimum density calculated from our observations? Alternatively, the ^7Be density may become a unique tracer for atmospheric modeling. There are also other isotopes produced in the upper atmosphere such as ^{14}C . These isotopes, most of which are not γ -ray emitters, may also be present on spacecraft surfaces of in quantities greater than ^7Be . This work has prompted a search for the surface deposition of ^{14}C on LDEF[8]. ^7Be decays into lithium which will gradually accumulate on the spacecraft. Can this lithium affect exposed semiconductor sensors such as electro-optical devices? ^7Be , ^{14}C and other isotopes will accumulate in the cabin atmosphere as well during long duration manned missions. Both the production and biological uptake must be considered in order to determine whether these isotopes must be filtered from the air.

The level of ^{22}Na and other long-lived radioisotope activity observed is small (a few Bq/kg or less). Observation of small levels of additional activity is anticipated from experiments at low-level counting laboratories. These results indicate that, in general, few problems should result from the long-lived induced activity. However radioisotopes with 20 day half-lives or less were not observed. In order to better determine the overall level of induced activity in space, short-lived isotopes must be measured by surveys immediately after the return of the space shuttle or by direct γ -ray measurements in space.

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DISCOVERY OF BE-7 ACCRETION ON THE LDEF SPACECRAFT

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DISCOVERY OF BE-7 ACCRETION ON THE LDEF SPACECRAFT

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ABSTRACT

We observed strong ^7Be activity on the surface of the Long Duration Exposure Facility (LDEF) during the first complete gamma-ray survey of a large spacecraft after its return to earth. This is the first known evidence for accretion of a radioactive isotope onto an orbiting spacecraft. ^7Be is produced by spallation reactions of cosmic rays on nitrogen and oxygen in the upper atmosphere. However, the observed density is much greater than expected due to cosmic ray production in situ; this is significant for models of atmospheric mixing. ^7Be may be a valuable tracer in future studies of the upper atmosphere. Other isotopes seen during the survey, the strongest being ^{22}Na , are due to activation of spacecraft components while in orbit. We discuss the likely accretion of other cosmic-ray produced isotopes and their possible effects on spacecraft in low-earth orbit.

THE LDEF SPACECRAFT

The Long Duration Exposure Facility (LDEF) was launched by the Space Shuttle Challenger on 7 April 1984. It was retrieved in orbit by the Shuttle Columbia on 12 January 1990 and brought back to Earth on 20 January 1990. The LDEF carried a broad range of passive or low-powered experiments designed to study the space environment in low-earth orbit and to determine the effects of the environment on various materials, coatings, spacecraft components, and lastly, 12 million tomato seeds. The spacecraft is a 12-sided cylindrical aluminum structure, 9.1 m long by 4.2 m diameter, with a total weight of about 9700 kg. Along the sides and on both ends were 86 experimental trays, designed to be brought back to earth and analyzed in the laboratory by investigators from across the US, Canada, and Europe. The tomato seeds were distributed to school children to be grown and studied as science projects.

The LDEF was to have remained in orbit for a year, but recovery was delayed due to the Challenger accident, and exposure lasted over five and one half years. It was launched into a nearly circular orbit at an altitude of 480 km and an inclination of 28.5 degrees, where it was exposed continuously to cosmic rays, interplanetary dust and the residual atmosphere. In addition, the orbit took it through the South Atlantic Anomaly (SAA) exposing the spacecraft to energetic trapped protons and electrons. In the months prior to retrieval, the orbit was decaying rapidly and LDEF was down to an altitude of 310 km when recovered by the shuttle.

The LDEF spacecraft was gravity-gradient stabilized while in orbit so that its axis was aligned to the Earth's radius vector, with one end always pointed toward space and the other end toward Earth. Also, rotation about this axis was stabilized with respect to the orbital velocity so that the leading edge was always side number 9 (plus about 8 degrees). There were a number of duplicate experimental trays positioned around LDEF in order to get information about the differential flux of particles and micrometeoroids. The LDEF orbital velocity (7.8 km/s at retrieval) exceeded the average thermal velocity of the rarified atmosphere so that exposure to the atmosphere was primarily on the leading edge of the spacecraft.

GAMMA-RAY SURVEY

After landing, LDEF was returned to Kennedy Space Center (KSC) for post-recovery examination. There, the spacecraft was mounted on a stand so that it could be rotated about its axis for inspection. During this period, an array of high-purity germanium detectors from the Naval Research Laboratory (NRL) and single detectors from the Institute for Space Science and Technology (ISST), were used to conduct the first detailed gamma-ray survey of a large spacecraft after exposure in low-earth orbit. The residual gamma-ray emission depends both on the flux of high-energy particles to which LDEF was exposed and on the particular materials in each experimental tray. To observe the distribution of gamma-ray activity about the spacecraft, we set up the array with detectors facing each tray position along one side of LDEF. The single detectors were positioned at each end facing one of the experimental trays. The distance from the detectors to each tray was about 0.6 m. Background spectra were taken prior to the arrival of LDEF, and the detectors were calibrated in place using known gamma-ray sources.

After the arrival and setup of LDEF, spectra were taken along each side for a minimum of 12 hours. The LDEF was then rotated so that a new side faced the array and new trays faced the detectors at each end. In this manner the entire spacecraft was surveyed over a period of about two weeks. During the disassembly period which followed, spectra were taken of selected experimental trays after they were removed from LDEF.

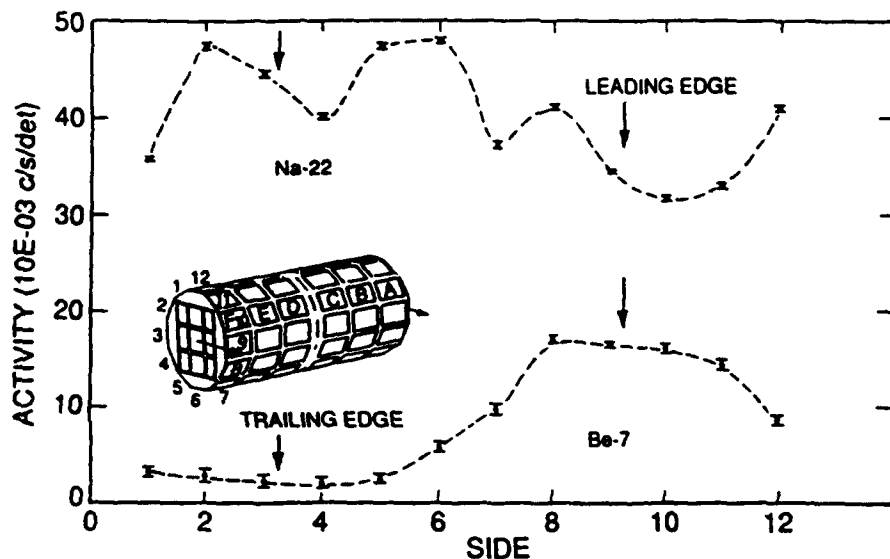
^{22}Na AND ^7Be ACTIVITIES

We expected to see gamma rays from the decay of isotopes produced by the long bombardment of energetic protons, neutrons, and heavier cosmic rays. The highest activity was expected from ^{22}Na , which has a half-life of 2.6 years and is produced by spallation from high-energy protons on the aluminum of the spacecraft body and experimental trays. At equilibrium, the activity from ^7Be , another spallation product with a 53 day half-life, was expected to be lower than ^{22}Na in intensity by two orders of magnitude. Data analysis capabilities during the survey were limited and consisted mainly of plotting spectra and identifying peaks. As expected, the strongest gamma-ray line at 1274 keV was from ^{22}Na . The 478 keV line from ^7Be was unexpectedly strong at some positions around the LDEF and much weaker at other positions. After the survey was complete, a preliminary plot of count rate versus position around the spacecraft showed a strong enhancement of ^7Be at the leading edge compared to the trailing edge.

During post-collection data analysis, spectra were analyzed for each detector and peak intensities were extracted using the computer program HYPERMET¹. Figure 1 shows the ^{22}Na and ^7Be activities for each side of LDEF, corrected for decay from the date of retrieval of the spacecraft. A strong leading edge enhancement is evident for the ^7Be activity. The weak activity seen from the trailing edge can be wholly accounted for by penetration of gamma rays from the opposite side of the hollow spacecraft. This distribution of the ^7Be activity can only be explained by accretion of the isotope onto the leading surfaces of LDEF as it moved through the thin upper atmosphere in orbit.

The absence of ^7Be activity on the trailing edge was confirmed by measurements of gamma-ray spectra from individual experimental trays after they were removed from LDEF. Figure 2 shows a comparison of spectra from nearly identical trays from the leading and trailing edges, containing germanium plates covered with a thin foil designed to capture interplanetary dust particles. The ^7Be peak is indicated in the figure and appears only on the tray from the leading edge.

LDEF ACTIVITY



a diagram of LDEF showing the sides numbered 1 through 12 and the tray positions lettered A through F. The view is toward the space end and the leading edge; the arrow vectors indicate the direction of the orbital velocity.

Figure 1. Comparison of activities of ^7Be (lower) and ^{22}Na (upper) seen during the gamma-ray survey of the LDEF spacecraft. The average counts per second per detector is shown for each side of LDEF for an average detector efficiency of 38.8% at 1332 MeV relative to a 7.6 x 7.6 cm diameter NaI(Tl) detector. The error bars include statistical and peak-fitting uncertainties. As a visual aid, dashed curves are drawn connecting the data points. The overlay is

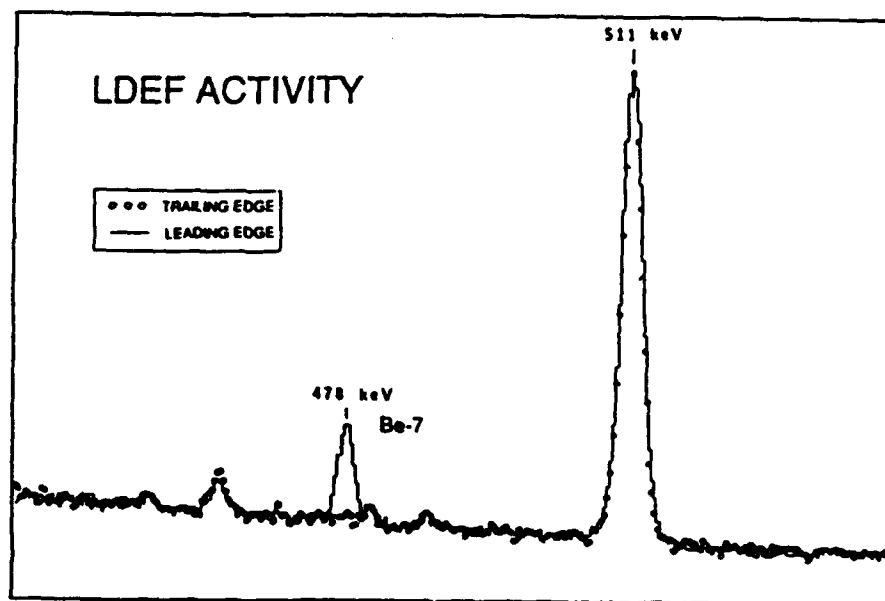


Figure 2. Comparison of gamma-ray spectra of germanium plates from trays E3 and E8 after their removal from LDEF. Shown is the region including the 478 keV gamma ray from ^7Be which is seen on tray E8 near the leading edge and not on tray E3 at the trailing edge. The 511 keV peak due to positron annihilation is seen both in the background and from ^{22}Na . The weaker unlabeled peaks are all in the background.

Further confirmation of the lack of ^7Be on the trailing edge of LDEF came from low-level activity measurements of aluminum plates and tray clamps by NASA/Marshall Space Flight Center² (MSFC), which showed ^7Be activity only on the parts from the leading edge. In addition, they showed that an acid etch of an aluminum plate from the leading edge removed most of the activity, demonstrating that most of the ^7Be is found on the surface.

In contrast to the ^7Be activity, the distribution of ^{22}Na activity in Figure 1 shows perhaps a small trailing edge enhancement, although there is considerable variance due to the distribution of aluminum and other activation material around the spacecraft. The trailing edge enhancement might be explained by the asymmetry in the trapped proton flux, which is strongly peaked from the westward direction³, the trailing direction in orbit. Although many of the trapped protons are energetic enough to penetrate LDEF, they could produce the weak asymmetry seen in the activation data. Several other less intense activation lines were also observed and will be reported elsewhere⁴.

DENSITY OF ^7Be IN THE UPPER ATMOSPHERE

Assuming that the ^7Be was accreted onto the surface of LDEF in low-earth orbit, the question arises: how did it get there with such intensity? ^7Be is produced by spallation interactions of high-energy cosmic rays primarily on nitrogen and oxygen in the upper atmosphere. (These complex nuclear disintegrations are called "stars" from their appearance in photographic emulsions.) From the literature, we can estimate the ^7Be density at 310 km due to cosmic ray production for comparison to our measurements. Using curves of cosmic ray interaction rates derived from measurements during a period of high solar activity⁵, we obtain an estimated ^7Be density of 3.6×10^{-5} atoms/ m^3 , due to production in situ (see the Appendix for details.) From our measurements we can derive a minimum ^7Be density in orbit of 0.10 ± 0.03 atoms/ m^3 . This exceeds the estimated in-situ production by a factor of 2800.

It is difficult to explain such a large enhancement in the ^7Be density. One possibility is the mixing of air from the poles where the star production rate is higher than at lower latitudes, which are partially shielded from cosmic rays by the Earth's magnetic field. Measurements in the stratosphere⁶ imply significant mixing between polar and low-latitude air, showing increases by a factor of 2 to 5 over the equilibrium value at 31° N. In the upper atmosphere, above 120 km, the polar production rate is about a factor of 10 higher than the average rate from 0° to 30° latitude⁵. Thus, complete displacement by polar air would still leave a factor of 280 unexplained.

A second possible source of increased activity is diffusion or convection of ^7Be from air at lower altitudes where production rates are higher due to increased atmospheric density. During periods of high solar activity⁷, the estimated in-situ production rate increases by a factor of 300 from an altitude of 310 km down to 120 km, which is approximately the altitude where diffusive equilibrium begins⁸. Because ^7Be is considerably lighter than the mean atmospheric molecular weight, it will tend to diffuse upward; because the atmosphere is so thin, diffusion will be rapid. The equilibrium distribution of atmospheric molecules due to diffusion is a decreasing exponential function of the altitude with a scale height⁹ which is proportional directly to the temperature and inversely to the atomic weight. The mean global temperature¹⁰ rises rapidly from about 380K at 120 km to 1040K above 200 km. During periods of high solar activity, temperatures as high as 1700K have been measured^{11,12}. For ^7Be , this corresponds to a scale height of 206 km and an

average thermal velocity of 2.5 km/s. Several large solar flares occurred in 1989, including the late September-early October flare which was the largest in 33 years and had a very hard spectrum¹³. Such events cause heating and expansion of the upper atmosphere, where winds have been measured at several hundred meters per second^{11,12}, driven by solar activity, diurnal solar heating and geomagnetic storms. These act both to mix polar and lower latitude air and to transport air upward from lower altitudes^{9,11}.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE SPACECRAFT

Our observations of ⁷Be activity on the leading surfaces of the LDEF spacecraft imply a minimum density for ⁷Be in low-earth orbit which greatly exceeds the local equilibrium due to cosmic-ray production in situ. One possible explanation would require the transport by diffusion or atmospheric mixing of ⁷Be from much lower altitudes and higher latitudes into the LDEF orbit. Thus, the current results should be important for validating and refining models of the upper atmosphere. With more extensive measurements, ⁷Be should prove valuable as a natural tracer for studies of upper atmospheric mixing. Future observations should focus on sampling at both lower and higher altitudes and should extend to polar latitudes. These should be closely correlated with data on wind, temperature, pressure and solar activity.

In addition, the observation of the accretion of significant quantities of ⁷Be is an indication of possibly similar behavior for other light cosmic-ray produced isotopes. Table 1 gives the spallation yields⁵ for all light isotopes with yields greater than or of the order of ⁷Be. Also given are their half-lives and decay modes. ³He is stable and non-reactive. The remaining isotopes, other than ⁷Be, are all pure beta emitters and thus would not be seen in the present survey. They could, however, be significant sources of noise for low-level sensors on spacecraft in low-earth orbit and could slowly degrade other components by coating or by surface reactions. Lithium, the decay product of ⁷Be, could affect exposed semiconductor sensors even in very low concentrations. As a result of our observations, other groups are currently looking for trace amounts of Li and ¹⁴C on LDEF components^{14,15}.

Table 1. COSMIC RAY PRODUCED LIGHT ISOTOPES

Isotope	Yield/Star	Half-life	Decay Modes
¹⁴ C	1.5 ^a	5.7 x 10 ⁴ y	beta
³ H	0.14	12.3 y	beta
³ He	0.12	stable	none
⁷ Be	0.045	53 d	ec ^b , gamma
¹⁰ Be	0.025	1.6 x 10 ⁶ y	beta

^a Relative yield, produced mainly by thermal neutrons

^b Electron capture

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APPENDIX

Equilibrium ^7Be Density from Cosmic-Ray Production. Lal and Peters⁵ provide curves of cosmic-ray produced interaction rates (stars per gram of air per second) versus latitude and altitude, using a model derived from measurements during a period of high solar activity. From these curves and the known spallation yields⁵, we obtain a ^7Be production rate per gram of air between 0° and 30° latitude of 9.0×10^{-5} atoms/g-s at the "top" of the atmosphere (above 120 km). The mean atmospheric density during periods of high solar activity⁷ at an altitude of 310 km is about 6.1×10^{-8} g/m³. This gives an in-situ production rate for ^7Be at 310 km of 5.5×10^{-12} atoms/m³-s. Multiplying by the equivalent in seconds of the 77 day mean ^7Be lifetime gives an equilibrium density for ^7Be of 3.6×10^{-5} atoms/m³, due to production in situ.

Minimum ^7Be Density from Our Measurements. Our measurements of the ^7Be activity on the LDEF leading edge give an average surface density for ^7Be of $(5.4 \pm 1.4) \times 10^9$ atoms/m², corrected to the date of retrieval of the spacecraft. With an orbital velocity of 7.8 km/s, LDEF traveled a distance of 5.2×10^{10} m during one mean lifetime of ^7Be . Assuming 100% adherence of ^7Be to the surface of LDEF, this implies a minimum density in orbit for ^7Be of 0.10 ± 0.03 atoms/m³. (Less than 100% adherence would imply an even greater ^7Be density in orbit.)

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OBSERVATION OF Be-7 ON THE SURFACE OF THE LDEF SPACECRAFT

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Heading

We report a first observation of the radioisotope Be-7 on the surface of an orbiting spacecraft, the Long Duration Exposure Facility (LDEF). Be-7, like C-14, is produced by cosmic ray reactions with nuclei of atmospheric gas atoms. The presence of the cosmogenic isotope on the LDEF is interpreted to be a two-step process of atmospheric transport from much lower altitudes, followed by accretion onto the surface of the spacecraft. Such a process has never been observed before.

The Long Duration Exposure Facility (LDEF) was launched by the space shuttle Challenger on 7 April 1984 into a nearly circular orbit with an inclination of 28.5 degrees and an altitude of 480 km. It was retrieved by the space shuttle Columbia on 12 January 1990 at an altitude of 310 km. Because of its large mass, long space exposure, and wide variety of materials onboard, the LDEF provided a unique opportunity for induced radioactivity studies. These measurements are still in progress and will be reported elsewhere.

The LDEF spacecraft is a twelve-sided cylindrical aluminum structure, 9.1 m long by 4.3 m in diameter (see Fig. 1). It consists of an open grid to which were attached various experiment trays designed to measure the effects of long space exposure on spacecraft materials and components. Throughout its orbital lifetime, the spacecraft was passively stabilized about all three axes of rotation, allowing one end of the spacecraft to always point toward the Earth, and fixed leading and trailing sides with respect to the orbital motion.

After its return to the Kennedy Space Center, gamma ray spectra were obtained along each side of the spacecraft using a germanium detector array provided by the Naval Research Laboratory. Measurements were also made of selected components from the spacecraft. The gamma ray line at 478 keV from Be-7 radioactive decay was unambiguously observed to emanate from the leading side of the spacecraft, as shown in Fig. 1. The weaker signal observed from the trailing side of the spacecraft can be traced to the attenuated gamma ray flux from the

leading surfaces.

Individual components were brought to the Marshall Space Flight Center in order to quantify the residual radioactivity on the LDEF. A high purity germanium detector inside a low level background facility was used to obtain spectra of small aluminum and steel samples taken from the leading and trailing sides. In Figs. 2 and 3, gamma spectra of two identical aluminum plates and two steel trunnion end pieces taken from the leading and trailing sides of the spacecraft are shown. A clear Be-7 signal was seen on the leading side, with little or no signal above background on the trailing side.

A polished aluminum plate, used as a thermal control surface in LDEF Experiment A0114 [1], was subjected to several tests to determine the depth of penetration and the form of deposition of the Be-7. The surface was coated with collodion, stripped to remove all loose particles, then wiped firmly with xylene. Less than 10% of the surface activity was removed by this process, indicating that the Be-7 was neither associated with dust particles nor other soluble surface contaminants. An acid etch, without a stable beryllium carrier, removed several tens of microns of the aluminum surface, and most of the Be-7 activity (the remainder was assumed to be re-deposited). This suggests that the Be-7 ions are trapped in the metal oxide surface layer, which would imply that a chemical interaction with the surface is taking place. Such a process was previously unknown, with the exception of the atomic oxygen effect [1].

In Table I, the measured number of Be-7 atoms per unit area on various spacecraft surfaces is shown. The results are corrected to the retrieval date of 12 Jan 1990 and for the offset angle from the leading direction.

The areal density for Be-7 on the aluminum and steel is the same within the experimental uncertainty, and is apparently not a strong function of the type or surface condition of the metal. The Teflon thermal coating, however, which was used on many LDEF experiment trays, has a density of Be-7 an order of magnitude lower. The reason for this apparent difference in uptake efficiency is unknown, but could be related to the material's covalently-bonded structure. The explanation may be complicated, also, by the observed erosion of the Teflon surface by atomic oxygen.

The appearance of Be-7 on the leading surfaces, as shown in Figs. 1-3, rules out direct production of the isotope within the spacecraft by the incident radiation flux. In striking contrast to the distribution of Be-7, the increased flux of geomagnetically-trapped protons from the west in this type of orbit [2] results in higher spallation-induced activities on the trailing side of the spacecraft (See Figs. 2 and 3.). Such induced activity is also not confined to the surface. While we do observe a small Be-7 signal from aluminum samples taken from the trailing side of the spacecraft, this contribution is at a level we expect from reactions with the incident flux, and is about two orders of magnitude smaller than the leading side surface activity. This leads us to conclude that the Be-7 must have accumulated on the spacecraft surfaces from the ambient atmosphere at orbital altitudes.

The short-lived isotope Be-7 was first detected in the atmosphere by Arnold and Al-Salih in 1955 [3], and later mapped by others as a function of altitude and latitude [4-8]. It is produced in the atmosphere by high-energy cosmic ray interactions with air as are other radioisotopes such as C-14 and H-3. Once formed, Be-7

ions are presumed to rapidly oxidize and attach to small aerosol particles, providing a downward transport mechanism from peak production regions of the atmosphere [9-16]. The primary removal process for Be-7, which occurs on a timescale comparable to its mean lifetime, is the washout of the aerosol-attached Be-7 in rainwater [3-6].

At a given latitude above about 20 km, the production rate of Be-7 varies vertically in proportion to the oxygen-nitrogen gas density. Peak production per unit volume occurs in the lower stratosphere, at about 20 km, below which the cosmic ray flux becomes substantially attenuated. At higher altitudes the number of Be-7 atoms produced per unit volume decreases rapidly, but the number of Be-7 atoms per unit mass of air, or concentration, should be essentially constant. Balloon and aircraft measurements [6,15] are in approximate agreement with this, though few measurements extend much above the peak production altitudes.

We can calculate the concentration of Be-7 at 310 km from the data in Table I, assuming the trapping efficiency on the metal surfaces is near unity. Using the LDEF orbital velocity of 7.8 km/s and the 76 day mean lifetime of Be-7, we find a density of 1.2×10^{-7} atoms per cc, or a relative concentration of 3.8×10^6 atoms per gram of air. In the peak production region, at altitude 20 km, previous measurements [4-8] yield a concentration of 10^3 Be-7 atoms per gram of air, or about 0.1 atoms per cc, in agreement with a simple calculation using the known cosmic ray flux. Thus the measured concentration of Be-7 per unit mass of air at 310 km is three to four orders of magnitude in excess of the concentration at 20-50 km.

Concentrations of Be-7 in the 300 km range far in excess of that which can be produced in air at that altitude is evidence

for a new removal process for stratospheric Be-7.

Although the mechanism for upward transport is complex, we must assume that some Be-7 must escape upwards before attachment by aerosols. This diffusion must take place on a timescale similar to the mean lifetime of Be-7.

Systematic low-level induced radioactivity measurements of LDEF materials have not revealed other nuclides with similar surface segregation behavior; in particular, we have not found the heavier ones which would suggest a meteoritic origin [17]. While Be-7 will decay in orbit, there are other non-radioactive light isotopes produced by cosmic rays with similar altitude distributions. Their concentrations should be much higher than that of Be-7, though more difficult to measure. We are currently attempting to detect other atmospheric cosmic ray-produced isotopes on LDEF surfaces using accelerator mass spectrometry [18].

The use of satellite surfaces to sweep up rare atmospheric species may prove to be a new method of investigating atmospheric mixing processes at orbital altitudes.

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Acknowledgements

We are grateful for the outstanding support of the LDEF Project Office,
NASA Langley Research Center and in particular the LDEF Project
Scientist, Dr. W. Kinard.

LDEF Be-7 Surface Concentrations*

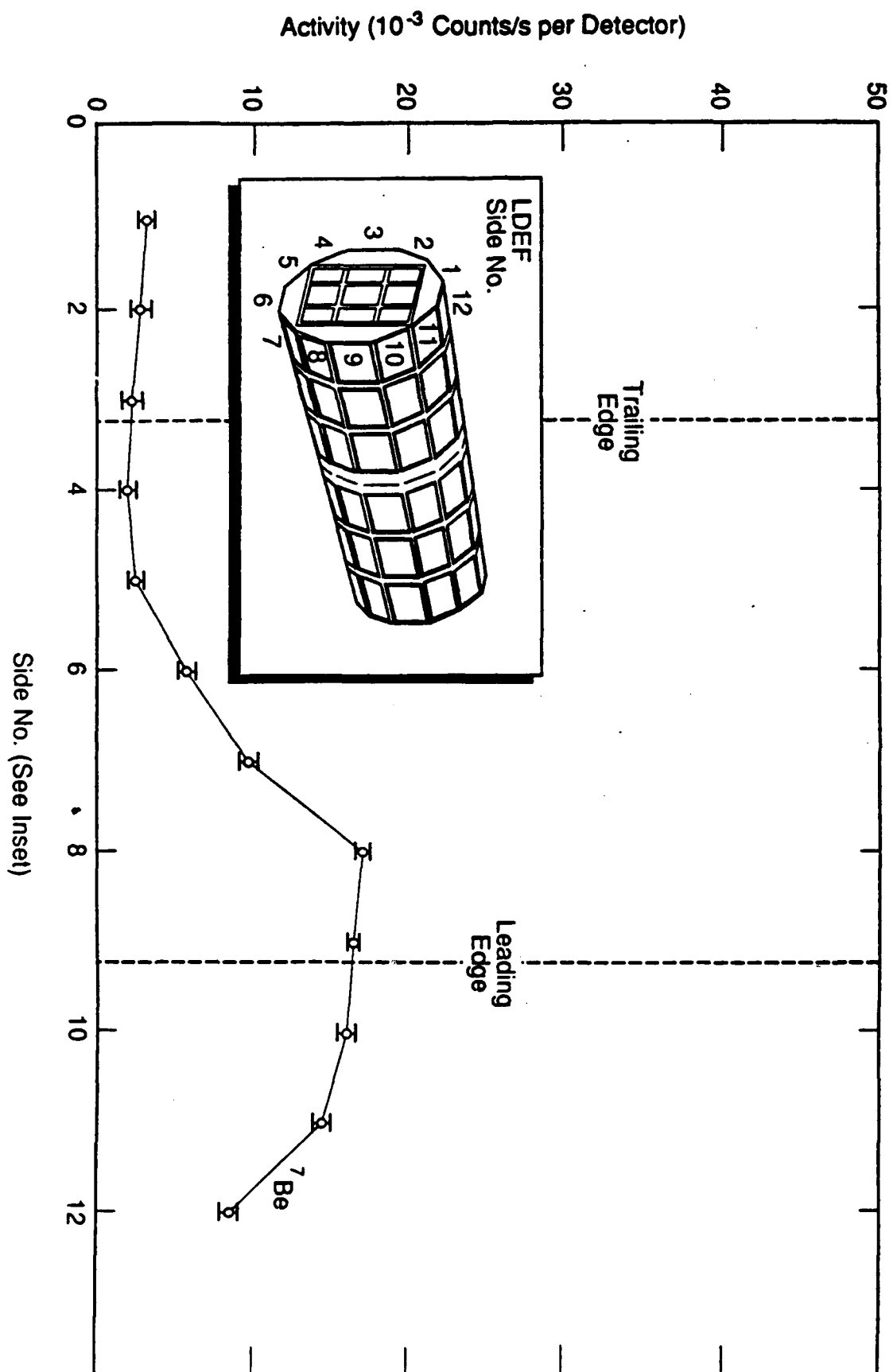
Material	Be-7 Area1 Density (x 10e5 atoms/cm2)
Stainless steel trunnion face	5.3 +- 0.7
Polished aluminum plate- Exp. A0114	6.7 +- 1.0
Anodized aluminum experiment tray. clamp	4.6 +- 0.5
Teflon thermal cover	0.9 +- 0.2

* Corrected for decay since recovery and for surface orientation relative to spacecraft ram direction.

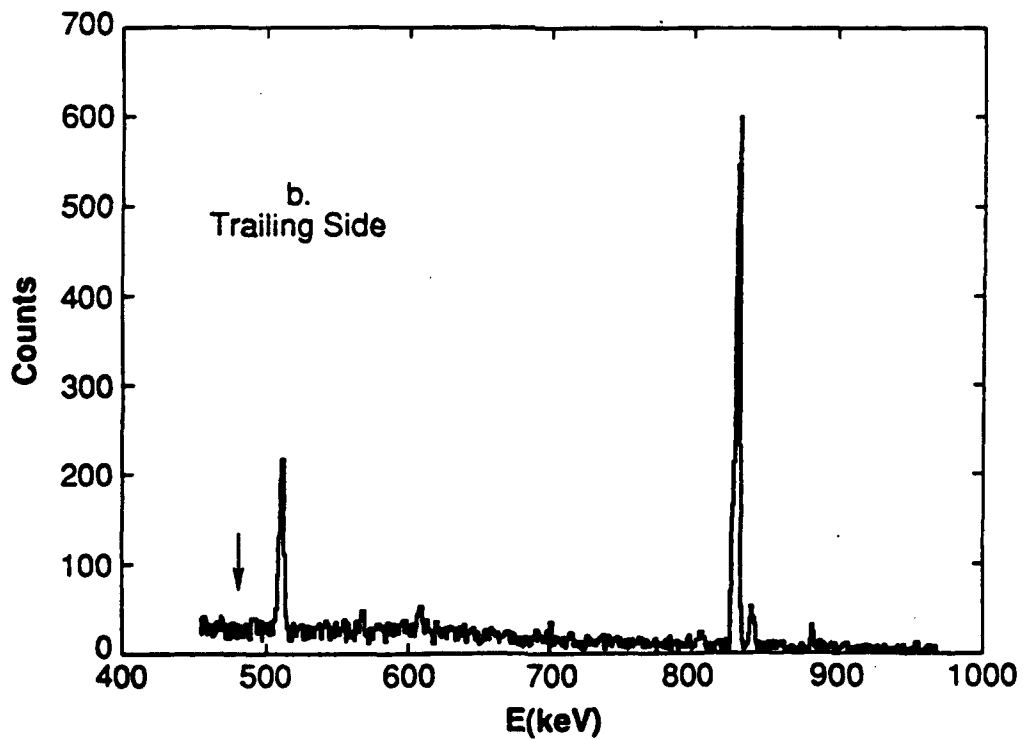
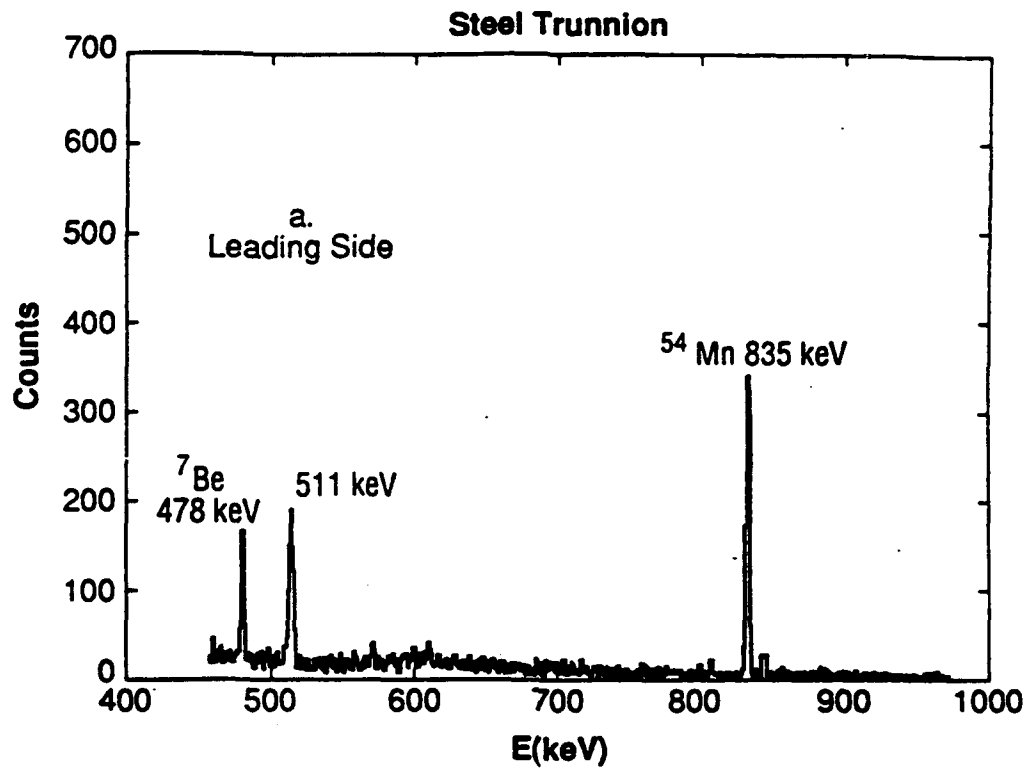
Figure Captions

1. The activity of Be-7 measured from the twelve sides of the LDEF spacecraft at the Kennedy Space Flight Center, corrected to the date of retrieval.
2. Gamma ray spectra of aluminum plates on the leading and trailing sides of LDEF. The isotope Be-7 is identified by the strong line at 478 keV seen on the leading side but not on the trailing side. The strong line at 511 keV is produced by e^+ annihilation gamma rays from the spallation product Na-22, as well as laboratory background.
3. Gamma ray spectra of two stainless steel trunnion pin-end pieces from the leading and trailing directions of the spacecraft. As in Figure 2, the Be-7 isotope is seen only on the leading side of LDEF. The 835 keV line from the spallation product Mn-54 is observed on both sides of the spacecraft, but is stronger on the trailing side due to increased proton flux from the west.

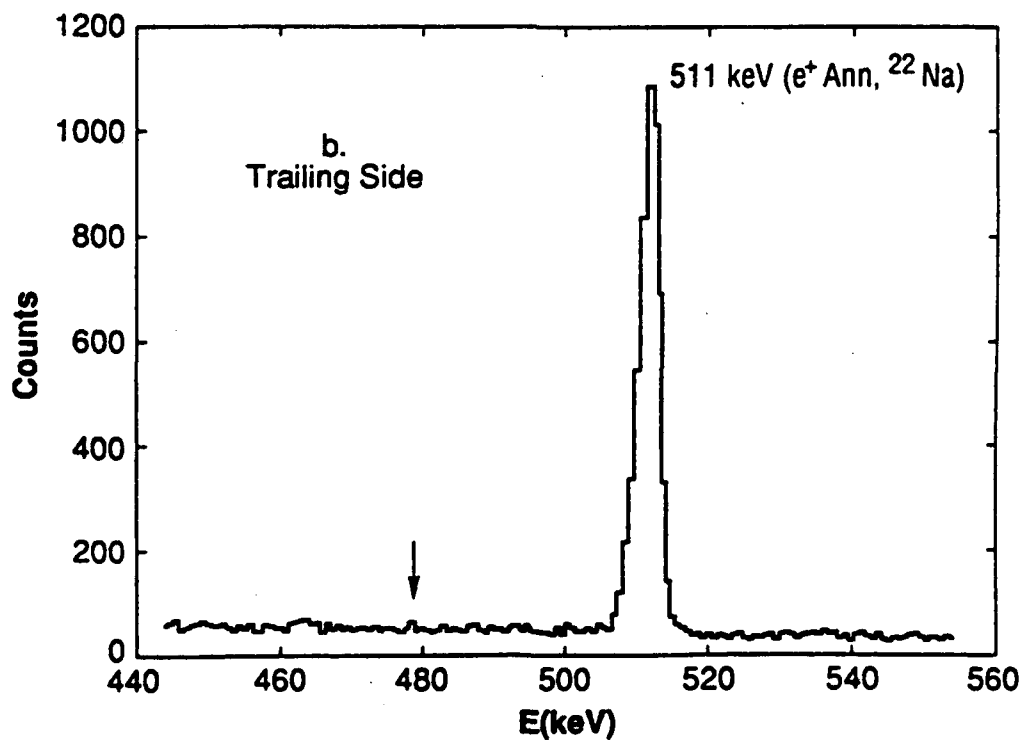
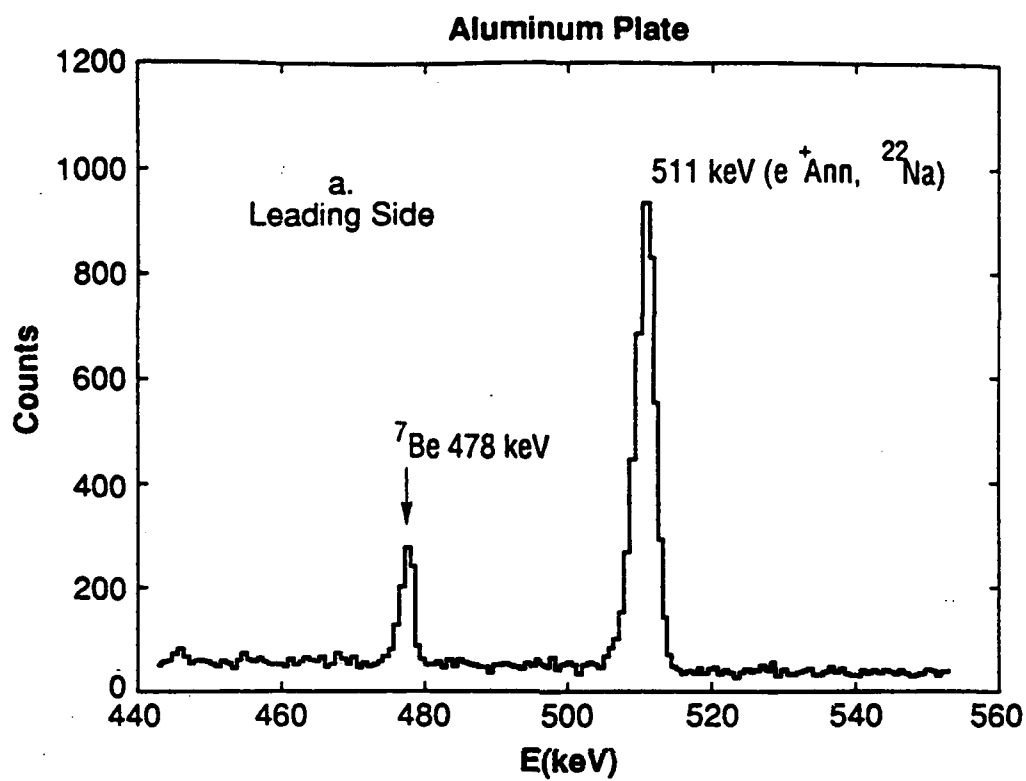
LDEF (Total Spacecraft) Acquired Radioactivity



LDEF Acquired Activity



LDEF Acquired Activity



Presented to the Workshop on Ionizing Radiation Environment Models and Methods
Huntsville, AL, 16-18 April, 1991

RADIATION SURVEY OF THE LDEF SPACECRAFT

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The retrieval of the Long Duration Exposure Facility (LDEF) spacecraft in January 1990 after nearly six years in orbit offered a unique opportunity to study the long term buildup of induced radioactivity in the large variety of materials on board. We conducted the first complete gamma-ray survey of a large spacecraft on LDEF shortly after its return to earth in January 1990.

The spacecraft is a 12-sided cylindrical aluminum structure, 9.1 m long by 4.2 m diameter. It was launched into a nearly circular orbit at an altitude of 480 km and an inclination of 28.5 degrees and retrieved at about 310 km. The spacecraft was gravity gradient stabilized so that the same side was always the leading edge in orbit. The photograph (third viewgraph) shows the survey with the NRL array aligned along one side of LDEF. Single detectors from ISST were used to look at the ends. Data were taken overnight for at least 12 hours on each side, and the spacecraft was rotated so that each night we obtained data from a different side. In this way we were able to map the gamma radiation around the spacecraft^{1,2}.

The following viewgraph shows the summed spectrum for side 9 which was at the leading edge. Most of the peaks are due to background, but the three strongest peaks from LDEF activity are indicated at 1274 keV from decay of ^{22}Na , 478 keV from ^7Be , and 511 keV from positron annihilation (the result of β^+ decaying nuclei both in the background and from LDEF.) Both ^7Be and ^{22}Na are known to be spallation products from high-energy protons on aluminum, the predominant material of the spacecraft frame and tray holders. However, the ^7Be peak was surprisingly strong since its spallation cross section is two orders of magnitude lower than ^{22}Na . Weaker gamma rays (not indicated in the viewgraph)

were observed from LDEF due to decay of ^{54}Mn and $^{56,57,60}\text{Co}$, the result of activation of nickel and iron from the stainless steel in the spacecraft.

The next viewgraph shows a two dimensional mapping of the ^7Be and ^{22}Na activities around LDEF as they would appear after cutting the spacecraft between rows 1 and 12 and unrolling it flat. The data for each tray position is plotted by side (running from 1 to 12) along the right axis and by row (running from A to F) along the left axis. The dashed lines indicate the leading and trailing edges. ^{22}Na shows nearly a factor of two enhancement of the trailing edge activity over the leading edge. This can be explained by the strong east-west anisotropy in the trapped proton flux at the South Atlantic Anomaly, which has been discussed frequently at this conference, since the trailing edge was always in the westward looking direction in orbit.

In contrast, the ^7Be activity is strongly peaked at the leading edge. The trailing edge is down by a factor of eight and is consistent with zero after accounting for penetration of gamma rays from the opposite side through the hollow spacecraft. This distribution of the ^7Be activity is not consistent with any known mechanism for activation of the spacecraft materials. It can only be explained by accretion of the isotope onto the leading surfaces of LDEF as it moved through the thin upper atmosphere in orbit.

The absence of ^7Be activity on the trailing edge was confirmed by measurements of gamma-ray spectra from individual experimental trays after they were removed from LDEF. The following viewgraph shows a comparison of spectra from nearly identical trays from the leading and trailing edges, containing germanium plates covered with a thin foil designed to capture interplanetary dust particles. The ^7Be peak is indicated in the figure and appears only on the tray from the leading edge.

Further confirmation of the lack of ^7Be on the trailing edge of LDEF came from low-level activity measurements of aluminum plates and tray clamps by NASA/Marshall Space Flight Center (MSFC), which showed ^7Be activity only on the parts from the leading edge. In addition, they showed that an acid etch of an aluminum plate from the leading edge removed most of the activity, demonstrating that most of the ^7Be is found on the surface³.

Given the evidence that ^7Be was accreted onto LDEF in orbit, how can we understand its presence and intensity at the LDEF orbital altitude? ^7Be is one of several cosmogenic or cosmic-ray produced nuclei which result from spallation interactions of high energy cosmic rays with nitrogen and oxygen nuclei in the upper atmosphere. However, it is the only product with both appreciable yield and gamma-ray activity. Others such as ^{14}C and ^{10}Be are pure beta emitters and thus would not have been observed in our survey of the LDEF.

From our observations we obtain a density for ^7Be on the LDEF leading edge of $(5.4 \pm 1.4) \times 10^9$ atoms/m², corrected to the date of retrieval⁴. Dividing by the distance traveled by LDEF in one mean lifetime in orbit, gives a minimum ^7Be density of 0.10 ± 0.03 atoms/m³ assuming 100% adherence to the surface. This number can be compared to the equilibrium density of 5.4×10^{-5} due to production in-situ by cosmic rays and energetic trapped protons at the LDEF altitude. This gives a ratio of observed to in-situ production densities of a factor of 1800.

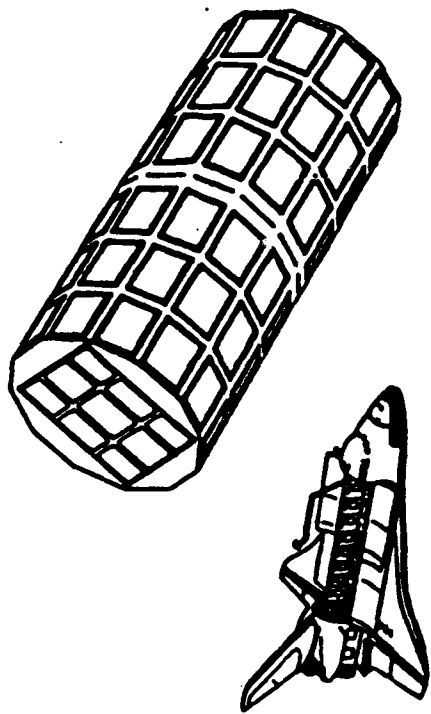
How can we explain such a large increase in ^7Be density? If it was not produced in-situ it must have been produced elsewhere and transported into the LDEF orbit. There are three possible sources of increased production:

1. Polar air. The cosmic-ray flux increases at the poles due to lack of shielding by the earth's magnetic field. Production at 90° latitude is about a factor of 10 higher than 0° to 30° .
2. Higher altitude. Production increases due to increased trapped proton flux at higher altitudes. A factor of 6 is gained at 400 km relative to 310 km.
3. Lower altitude air. Production increases rapidly below 120 km due to increasing atmospheric densities. During periods of high solar activity, such as occurred during the last few months in orbit, production is up by a factor of 300 at 120 km relative to 310 km and is up by a factor of 7000 at 100 km. (Maximum production occurs at about 20 km with measured densities of about 10^5 atoms/ m^3 , a factor of 10^6 over our minimum observed density at 310 km.)

Thus, the source of the increased density must be production at much lower altitudes. How then did this production get transported up to the altitude of the LDEF orbit? Because Be^7 is much lighter than the average atmospheric molecular weight it will tend to diffuse upward. In addition, there were several large solar flares during the fall of 1989 shortly before LDEF was retrieved (the next to last viewgraph shows the flare beginning on 29 September.) These cause heating and expansion of the upper atmosphere which will increase the diffusion rate. Geomagnetic storms accompanying the solar flares can produce large upwellings of polar air and mixing of polar and lower latitude air.

A combination of diffusion and convection by upper atmospheric winds is likely required to explain our observed densities. To show this conclusively would require coupling of a detailed model of upper atmospheric circulation with a model of ^7Be production. Additional data on densities of ^7Be at altitudes between 100 and 300 km and extending to polar latitudes would be useful for tracing upper atmospheric transport and mixing and for model validation. Since ^7Be has a 53 day half-life, we only observed the average density over the last few months of the LDEF time in orbit. Further measurements are needed to determine whether the high densities we observed are transient and whether they are significantly lower during periods of lesser solar activity. The following references contain further details on our measurements and additional references.

1. G.W. Phillips et al., Proceedings, ESA Space Environmental Analysis Workshop, ESTEC, Noordwijk, the Netherlands, 9-12 October 1990 (to be published.)
2. S.E. King et al., Conference Record of the 1990 IEEE Nuclear Science Symposium, Arlington, VA, 22-27 October 1990, 481-486 (also IEEE Transactions in Nuclear Science, to be published.)
3. G.J. Fishman et al., Nature 349 (1991) 678-680.
4. G.W. Phillips et al., Proceedings, 14th Annual AAS Guidance and Control Conference, 2-6 February 1991, Keystone, CO (to be published.)



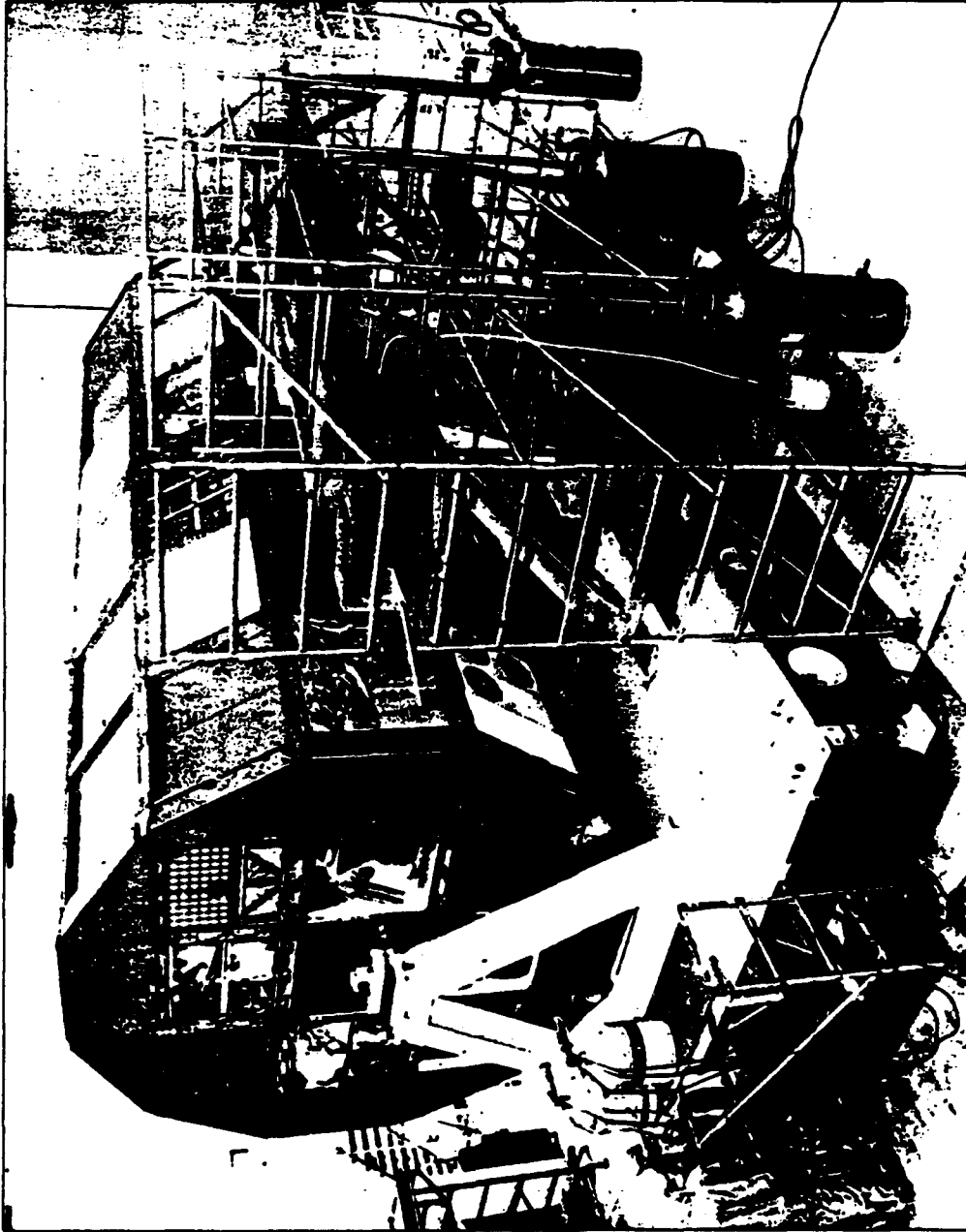
RADIATION SURVEY OF THE LDEF SPACECRAFT

PRESENTED BY GARY PHILLIPS

**NAVAL RESEARCH LABORATORY
WASHINGTON, DC**

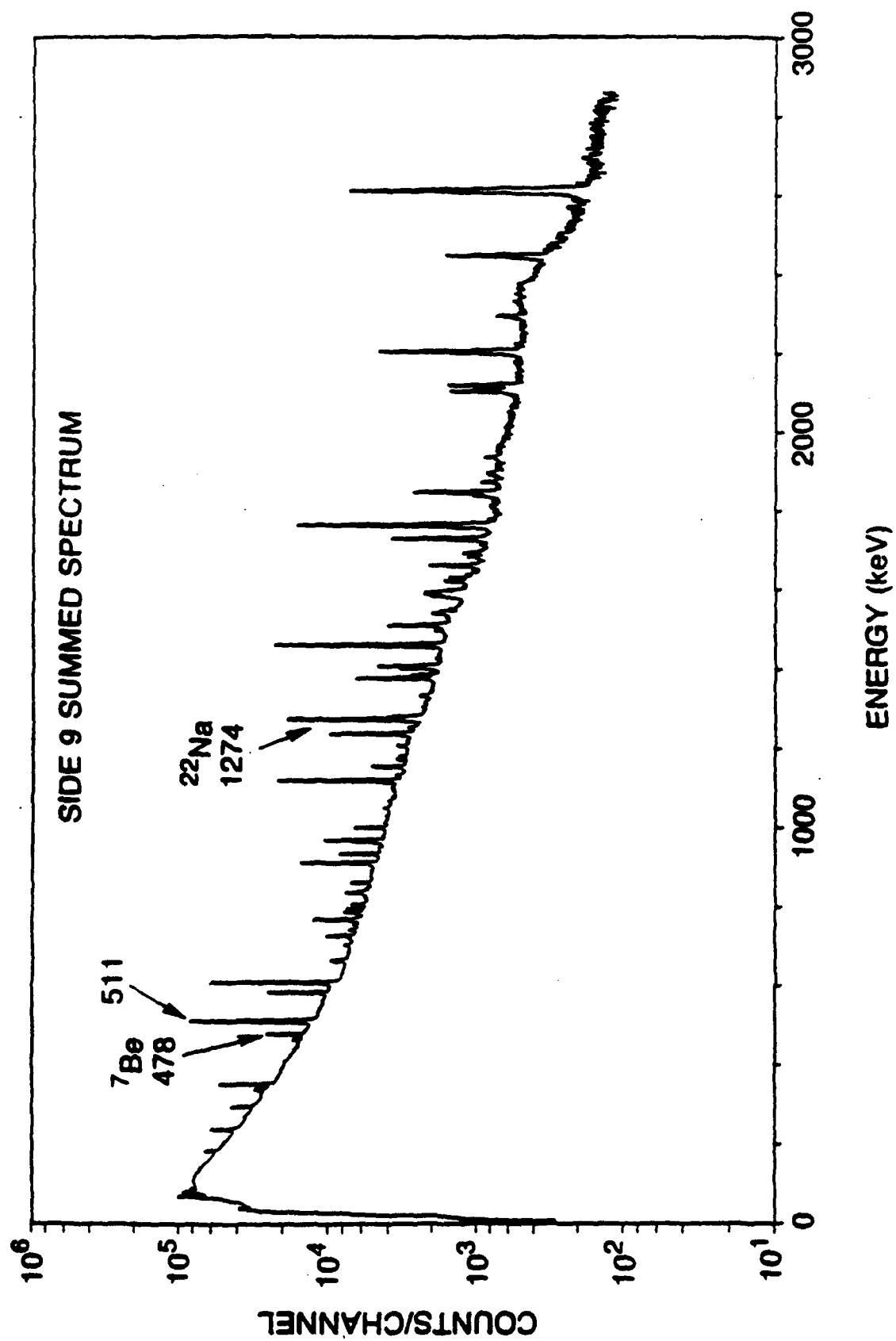
PARTICIPANTS - LDEF SPACECRAFT GAMMA-RAY SURVEY

- **NAVAL RESEARCH LABORATORY, WASHINGTON, DC
G.W. PHILLIPS, S.E. KING, R.A. AUGUST, J.C. RITTER, J.H. CUTCHIN (SFA)**
 - **UNIVERSITY OF FLORIDA, GAINESVILLE, FL
P.S. HASKINS**
 - **INSTITUTE OF SPACE SCIENCE AND TECHNOLOGY, GAINESVILLE, FL
J.E. MCKISSON, ED.W. ELY, A.G. WEINSENBERGER**
 - **MISSISSIPPI STATE UNIVERSITY, MISSISSIPPI STATE, MS
R.B. PIERCEY, T. DYBLER**
-

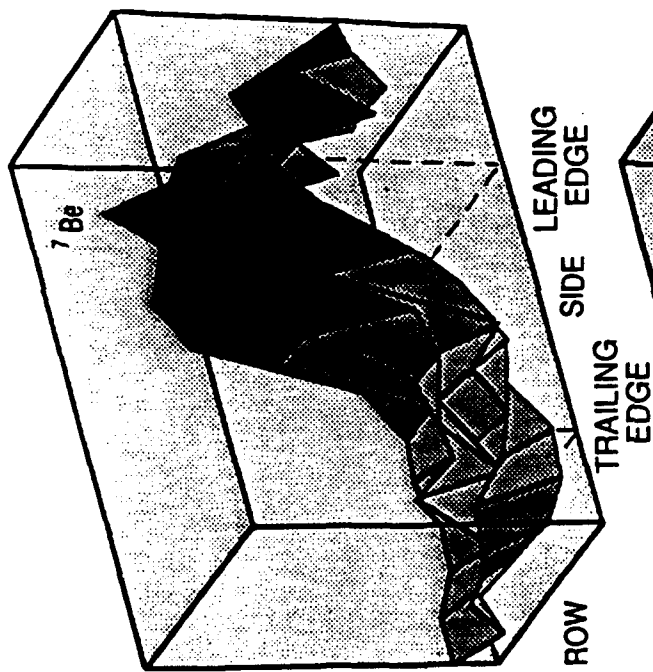


NRL array (arrow) set up for the radiation survey of LDEF. The gamma-ray detectors were inside the six rectangular boxes on the rolling scaffolds. These were rolled back out of the way during the day and rolled up for taking data during the overnight shifts. Single detectors from ISST are set up at the end of the spacecraft.

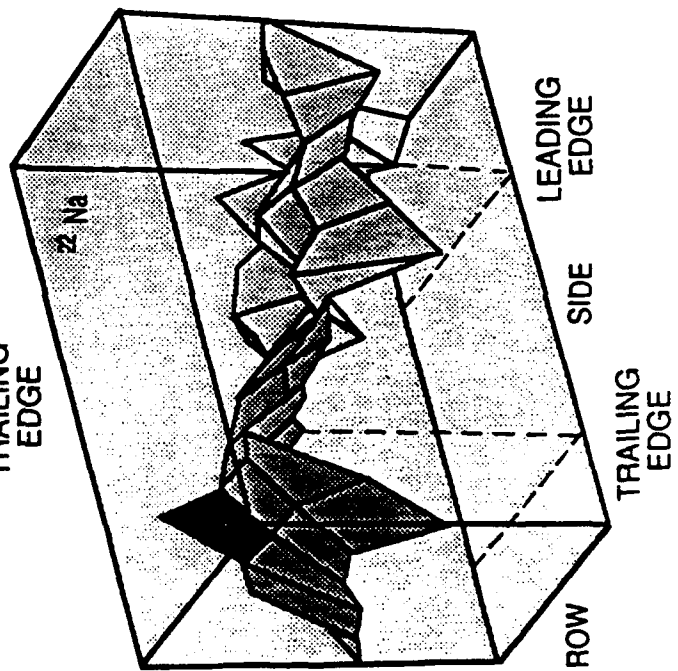
(photo by Michael Savell)



LDEF ACTIVITY



ACTIVITY



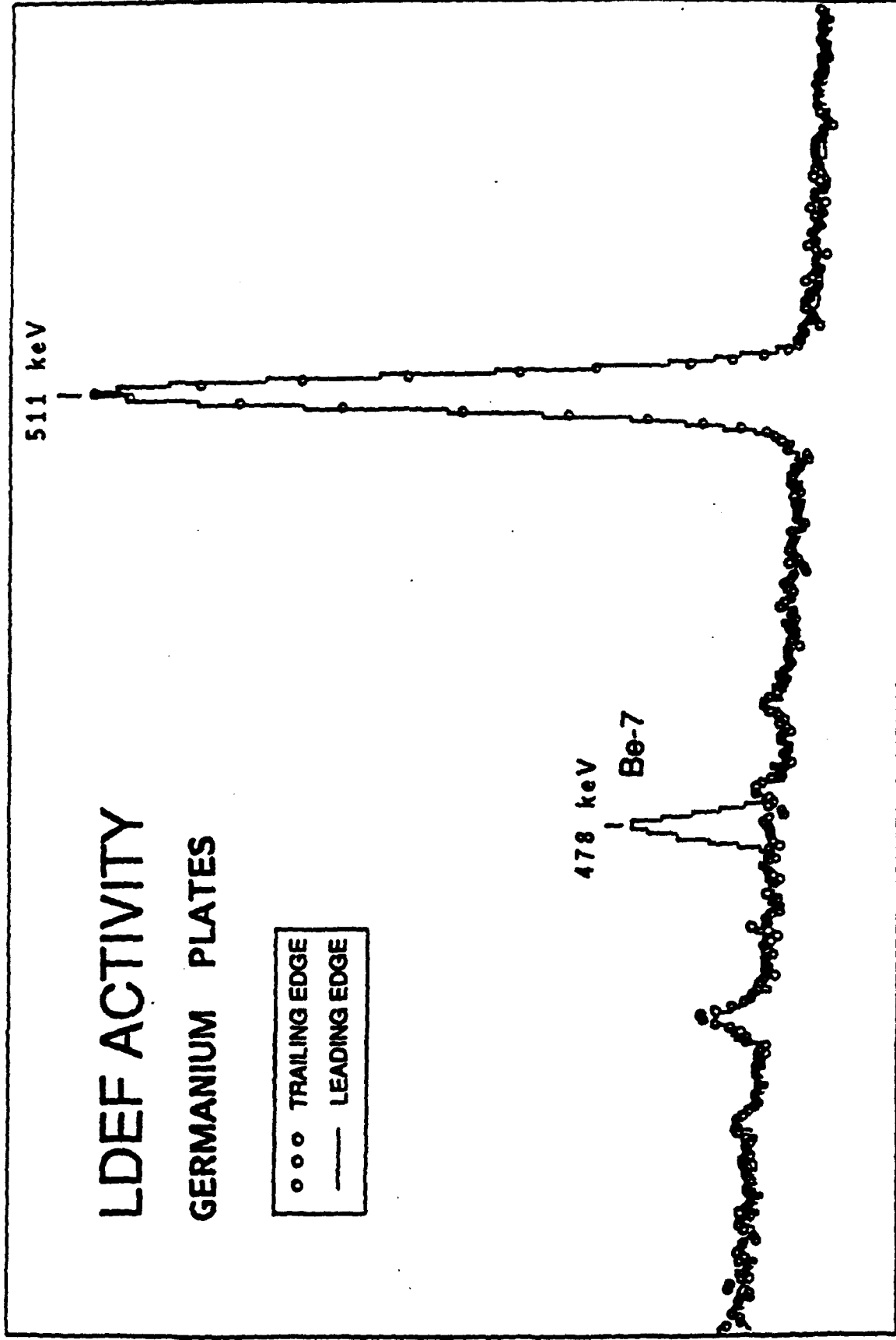
LDEF ACTIVITY GERMANIUM PLATES

ooo TRAILING EDGE
— LEADING EDGE

511 keV

478 keV

Be-7



ORIGIN OF BE-7 IN THE UPPER ATMOSPHERE

- PRODUCED BY SPALLATION INTERACTIONS (STARS) OF HIGH ENERGY COSMIC RAYS WITH NUCLEI OF NITROGEN AND OXYGEN IN THE ATMOSPHERE
 - ONE OF SEVERAL COSMOGENIC (COSMIC-RAY PRODUCED) NUCLEI
 - ONLY ONE WITH APPRECIABLE YIELD AND GAMMA-RAY ACTIVITY
-

IN-SITU BE-7 PRODUCTION VERSUS OBSERVED DENSITY

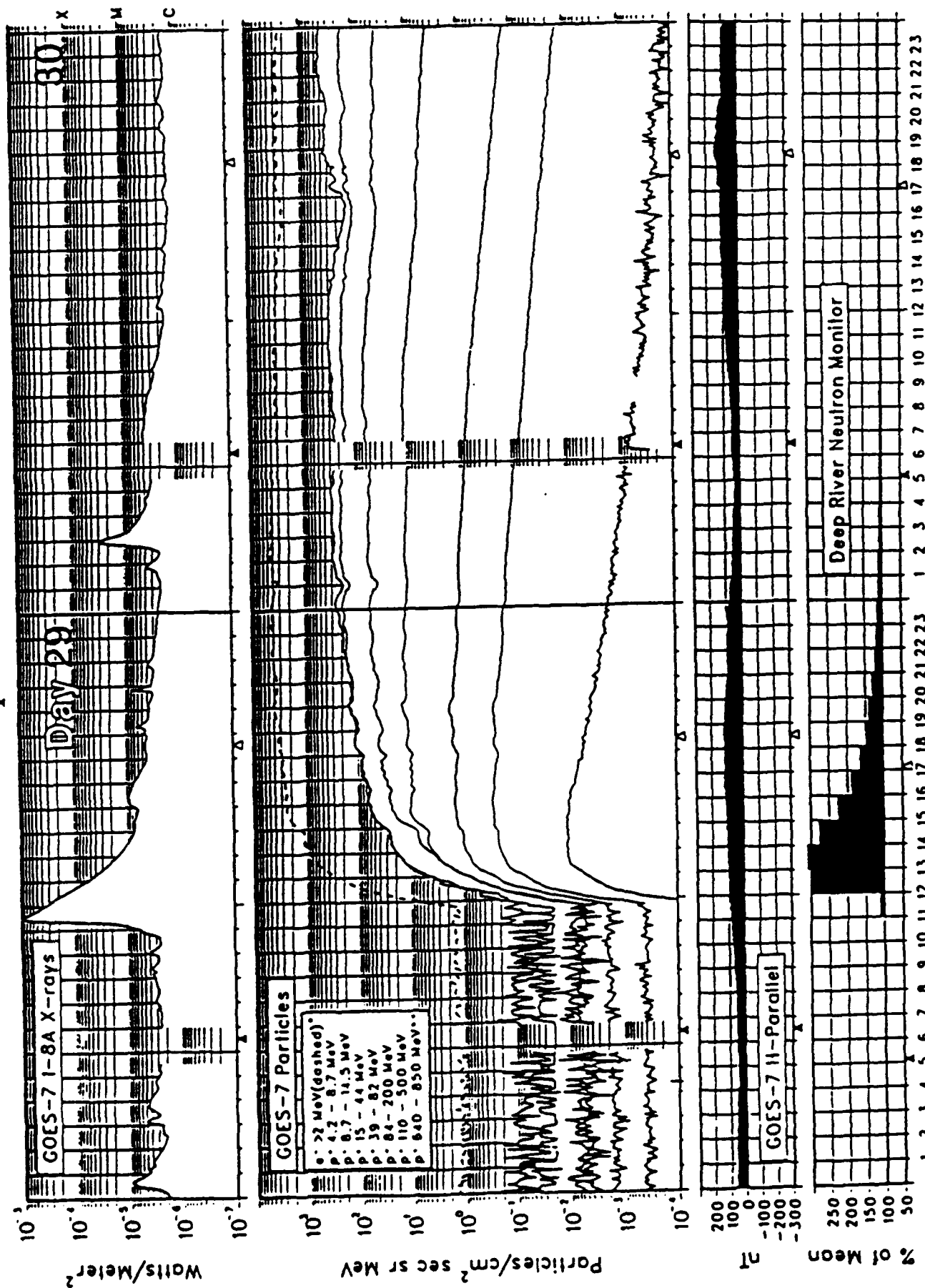
- MINIMUM BE⁷ DENSITY
FROM OUR OBSERVATIONS
(assuming 100% adherence) 0.10 ± 0.03 atoms/m³
 - MAXIMUM EQUILIBRIUM DENSITY
FROM IN-SITU PRODUCTION
(from cosmic rays and trapped protons) 5.4 x 10⁻⁵ atoms/m³
 - RATIO OF OBSERVED TO IN-SITU DENSITIES 1800
-

POSSIBLE SOURCES OF INCREASED BE-7 ACTIVITY

- POLAR AIR
(EQUATORIAL AIR SHIELDED BY EARTH'S MAGNETIC FIELD)
IN SITU PRODUCTION RATIO
90° LATITUDE / 0°-30° LATITUDE ≈ 10
 - HIGHER ALTITUDE AIR
(INCREASED TRAPPED FLUX)
IN SITU PRODUCTION RATIO DURING HIGH SOLAR ACTIVITY
400 KM ALTITUDE / 310 KM ALTITUDE ≈ 6
 - LOWER ALTITUDE AIR
(INCREASED ATMOSPHERIC DENSITY)
IN SITU PRODUCTION RATIO DURING HIGH SOLAR ACTIVITY
120 KM ALTITUDE / 310 KM ALTITUDE ≈ 300
100 KM ALTITUDE / 310 KM ALTITUDE ≈ 7000
-

SOLAR-TERRESTRIAL ENVIRONMENT

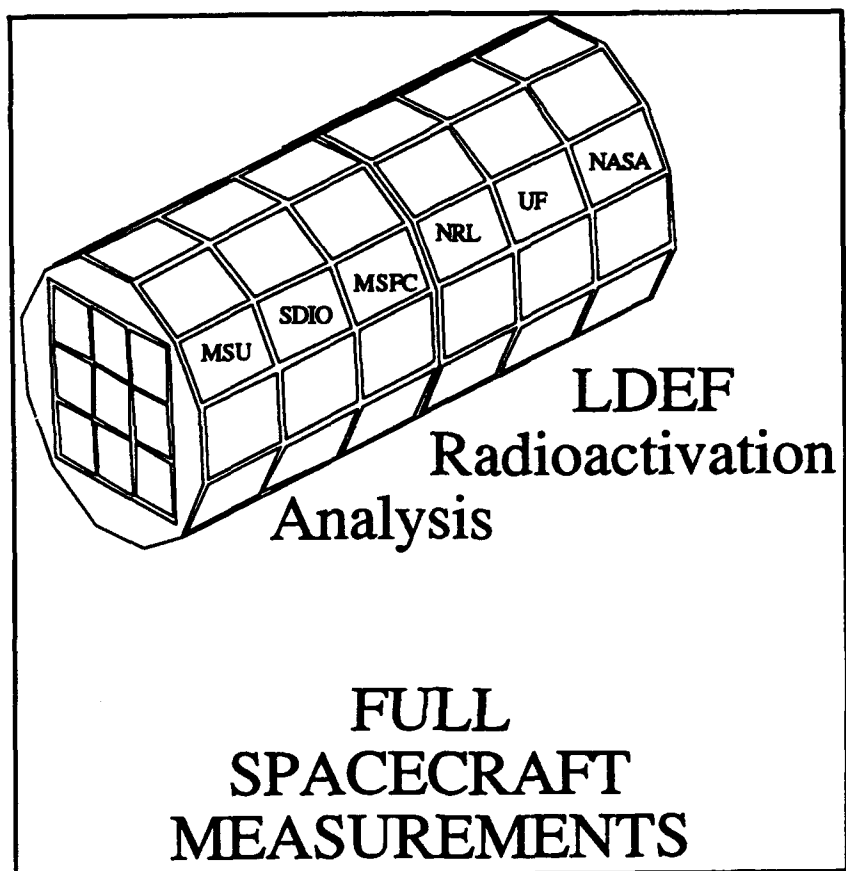
September 1989



NORR/NDCG BOULDER

CONCLUSIONS

- WE HAVE CONDUCTED A COMPLETE GAMMA-RAY SURVEY OF THE FIRST MAJOR SPACECRAFT RETURNED FROM SPACE
 - A SURPRISING RESULT WAS THE LARGE BE-7 ACTIVITY
 - THIS WAS THE FIRST OBSERVATION OF BE-7 ON A SPACECRAFT
 - DATA ARE ONLY CONSISTENT WITH ACCRETION IN LOW-EARTH ORBIT
 - DENSITY FAR EXCEEDS EQUILIBRIUM FROM COSMIC RAY PRODUCTION
 - MOST LIKELY SOURCE IS TRANSPORT BY DIFFUSION AND CONVECTION FROM 120 KM ALTITUDES OR BELOW
 - BE-7 SHOULD PROVE TO BE A VALUABLE TRACER FOR STUDIES OF UPPER ATMOSPHERE TRANSPORT AND MIXING
-



Final Report

**Residual Activation Studies of NASA's
Long Duration Exposure Facility**

Final Report

Rodney B. Piercey

**Mississippi State University
Mississippi State, Mississippi**

January 1990 to December 1990

**Prepared for the Department of the Navy, Naval Research Laboratory
Under Grant No. N00014-90-J-2006**

**This report was prepared as an account of work sponsored by the Naval Research
Laboratory.**

Table of Contents

I. Introduction.....	1
II. Experimental Measurements.....	1
III. Data Analysis.....	3
IV. Results.....	5
V. Publications	5

I. Introduction

The research activities of the experimental nuclear astrophysics group at Mississippi State University carried out under grant No. N00014-90-J-2006 are reported here. These activities included the planning and execution of the full spacecraft measurements of the Long Duration Exposure Facility (LDEF) after it was retrieved from low earth orbit on January 12, 1990 by the space shuttle. Also included are the data analysis and reporting activities associated with the project. Scientists from Mississippi State University, University of Florida and the Naval Research Laboratory participated as a part of a collaboration to make the measurements reported here. The LDEF provided the unique opportunity of measuring a large structure after exposure to low-earth orbit for nearly 6 years (launched April 7, 1984). This was the first complete gamma-ray survey of a large spacecraft and several activation products were indentified on the spacecraft. The overall program was a enormous success and provided new data on both the nature of spacecraft radioactivation and the composition of the high altitude atmosphere. Of major significance was the observation for the first time of a radioisotope, ^7Be , accreted on the surface of a spacecraft. Studies are continuing into the production and transport mechanism associated with the concentration of ^7Be observed.

II. Experimental Measurements

The LDEF full spacecraft measurements were carried out in February and March of 1990 at Kennedy Space Center. Background measurements were made in the SAEF-II area before the LDEF arrived. The LDEF spacecraft arrived mounted on the LATS vehicle and was positioned in the SAEF-II area for inspection. High resolution gamma-ray spectra were acquired for each row/bay position on the LDEF using intrinsic germanium detectors. The data from the detectors were written to 8 mm Exabyte tapes for later analysis. A preliminary on-line analysis uncovered the unexpected presence of the ^7Be transition at 477 keV.

The LDEF was brought into the SAEF-II area on the LATS vehicle for inspection and measurement. Six detector arrays supplied by the Naval Research Laboratory were positioned in front of a row of LDEF experiment trays for measurement as shown in figures 1 and 2. The LATS vehicle was capable of rotating the LDEF to any angular orientation so that all row/bay locations on the LDEF were accessible without moving the detectors. As the LDEF rotated about its long axis each row of trays was positioned in front of the detector arrays. In addition, separate germanium detectors were positioned on either end of the LDEF. The six NRL detector pods occasionally had to be moved out of the way during daytime operations but counting was performed throughout the night on whichever station was left adjacent to the detector pods.

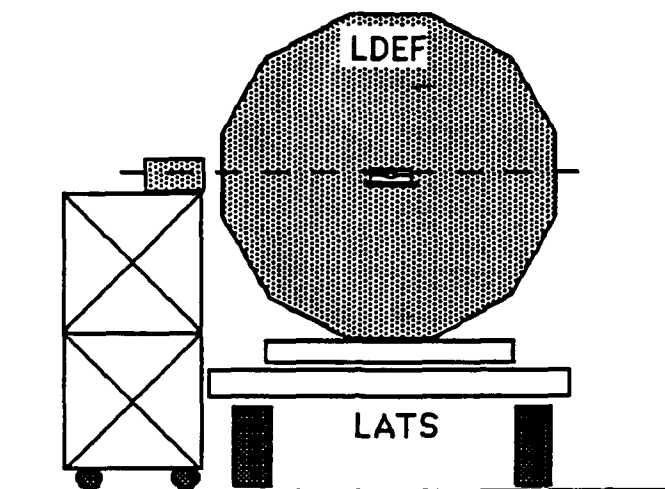


Figure 1. Positions of the NRL-PODs with respect to the LDEF and LATS vehicle (end view).

Figure 1 shows an end view of the LDEF and LATS vehicle illustrating how the detector pods were align along the radial direction. The measurement of the tray positions on the ends of LDEF were made with two portable cooled germanium detectors.

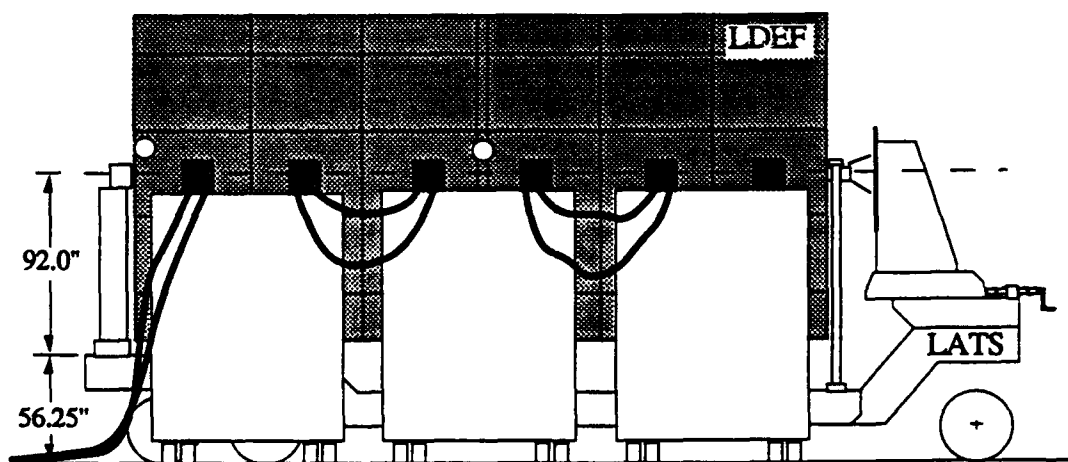


Figure 2. Positions of the NRL-PODs with respect to the LDEF and LATS vehicle (side view).

A side view of the detector array geometry is shown in Figure 2. By using one array for each bay of experiment stations, the detector array could be left stationary while the LDEF was rotated.

III. Data Analysis

The data is analyzed as an activity of a certain species versus to position on the surface of the LDEF. This variation over the surface is due to the presence of different construction materials and the nature of the LDEF orbit (see figure 3). During the data acquisition the data were scanned for unexpected peaks. Preliminary results are shown in figures 4 and 5. As is illustrated in the attached publications, the two lines at 1274 and 477 keV turned out to be the strongest activity measured on the LDEF. The full data tapes generated during the LDEF radiation measurements were re-analyzed at MSU using a Macintosh computer. All 8 mm tapes were re-scanned and several spectra were generated for each experiment tray. In all nearly 300 spectra were generated. The line intensities were determined in each of the spectra for the 477 (^7Be), 1274 (^{22}Na) and 1460 (^{40}K) keV gamma-ray lines. The lines intensities were corrected for detector efficiency and plotted as a surface to illustrate the variation of the surface over the LDEF spacecraft. The final surfaces may be seen in the attached publications.

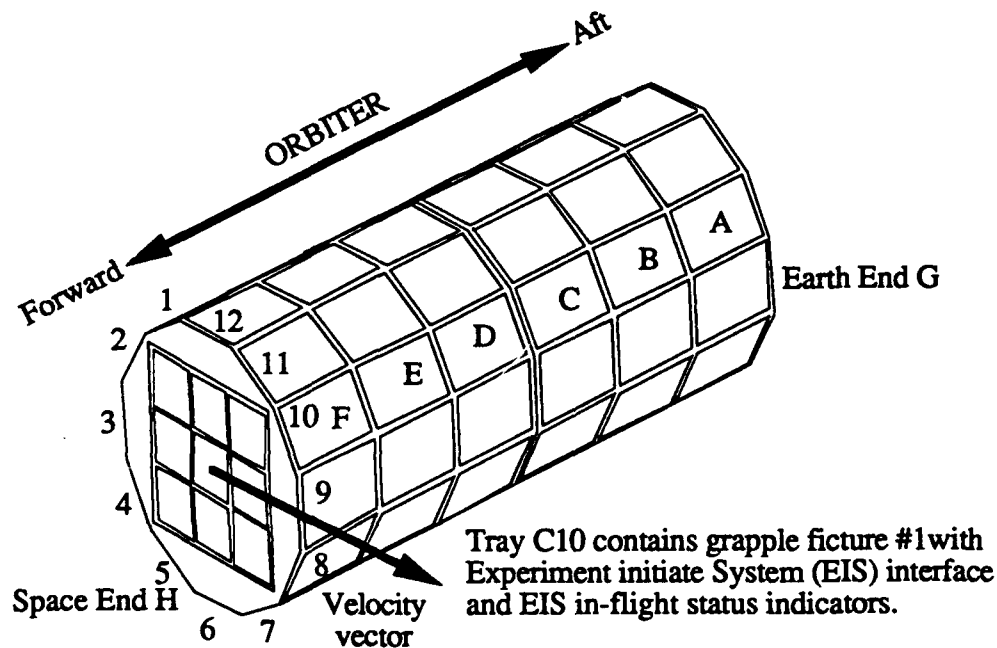


Figure 3 The Long Duration Exposure Facility (LDEF) remained in a gravity gradient, ram-stable orbit during its stay in space.

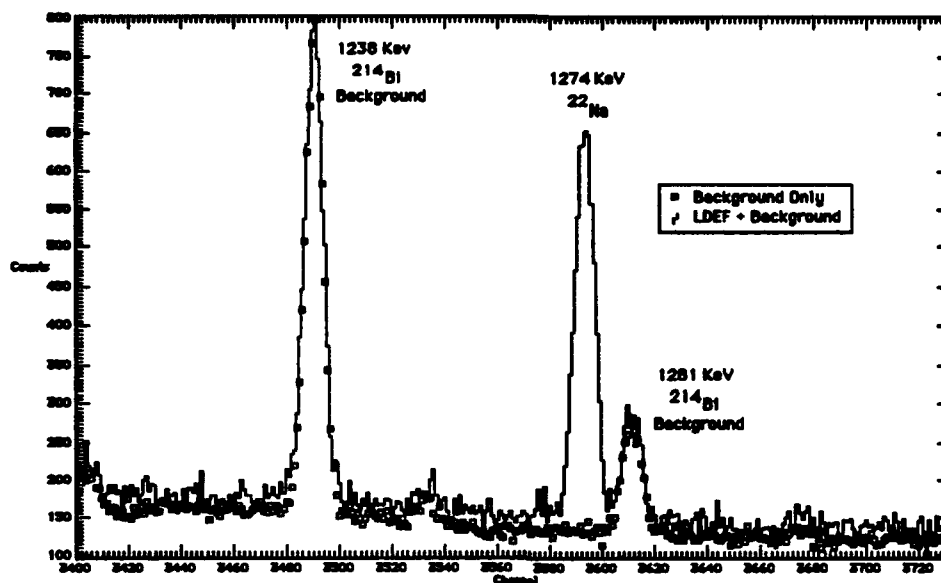


Figure 4. Background compared to LDEF measurement in the region around the 1274 keV ^{22}Na line.

Figure 3 shows a preliminary result from one detector on the space end of LDEF compared to background taken in the SAEF-II High Bay with no LDEF present. The line at 1274 keV comes from the decay of ^{22}Na which is a result of nuclear reactions between the aluminum on LDEF and the high energy proton flux encountered in orbit.

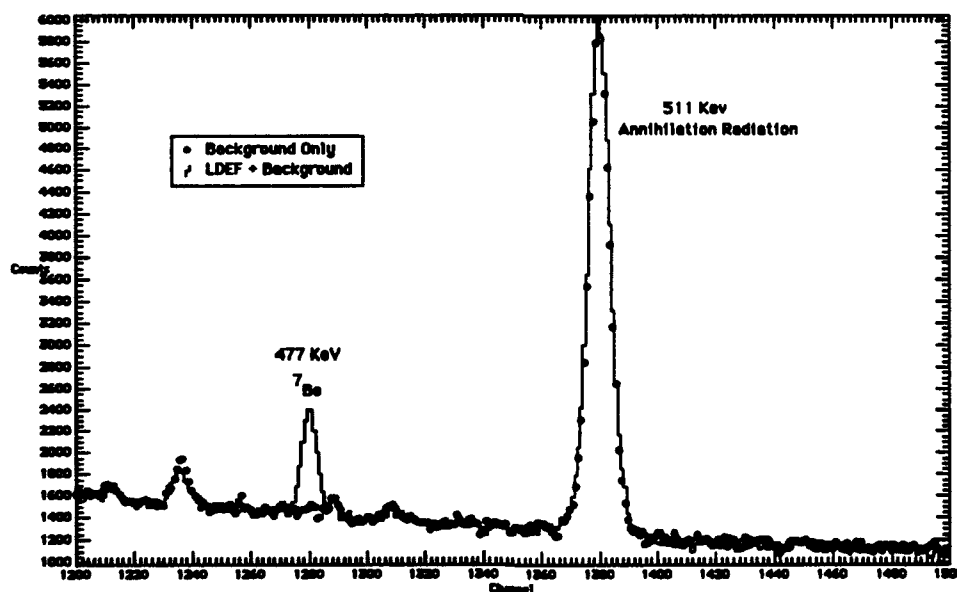


Figure 4. Background compared to LDEF measurement in the region around the 477 keV ^7Be line.

Figure 5 shows a similar comparison for the line at 477 keV which comes for the ^7Be contamination.

IV. Results

The results of our investigations are described in detail in the attached publications. In addition to being the first full gamma-ray measurements of a large spacecraft they include the first observation of the accretion of a radionuclide on the surface of a spacecraft and the observation of an anomalously high concentration of ^7Be in low-earth orbit.

V. Publications

"Discovery of ^7Be Accretion in Low Earth Orbit," G.W. Phillips, S.E. King, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, Proceeding of 14th Annual Guidance and Control Conference, AAS 91-076, (Feb. 2-6, 1991).

"Observation of ^7Be on the Surface of the LDEF Spacecraft," G.J. Fishman, B.A. Harmon, J.C. Gregory, T.A. Parnell, P. Peters, G.W. Phillips, S.E. King, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, Nature Vol. 349, pp 678-680 (Feb. 1991)

"Radiation Survey of the LDEF Spacecraft," S.E. King, G.W. Phillips, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, IEEE Transactions on Nuclear Science, Vol. 38 No. 2, pp. 525-530 (April 1991).

"Observations of Beryllium-7 on the LDEF Spacecraft," G.W. Phillips, S.E. King, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, Submitted to ESA Space Environmental Analysis Workshop, ESTEC, October, 1990.

"Observations of Beryllium-7 in LEO Atmosphere," S.E. King, G.W. Phillips, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, Bull. Am. Astr. Soc. 20, p. 1673, (1990).

"Radiation Survey of the LDEF Spacecraft," G.W. Phillips, S.E. King, R.A. August, J.C. Ritter, J.H. Cutchin, P.S. Haskins, J.E. Mckisson, D.W. Ely, A.G. Weisenberger, R.B. Piercey, T. Dybler, (Presented to the Workshop on Ionizing Radiation Environment Models and Methods, Huntsville, AL, 16-18 April, 1991).