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, ^{7}Be, ^{54}Mn, and the positron annihilation line were all strongly observed. Also observed were traces of ^{56}Co, ^{57}Co, and ^{60}Co. The most striking feature of the data was the unexpected distribution of ^{7}Be, which was predominately observed on the leading surfaces of the spacecraft. The evidence clearly indicates an accretion of the ^{7}Be onto the surface of the LDEF. This is the first known observation of the deposition of a radioisotope onto the surface of a spacecraft. ^{7}Be is a spallation product of cosmic rays on nitrogen and oxygen in the upper atmosphere[1]. To explain the surface density of 5.4 x 10^5 atoms/cm^2, the light ^{7}Be atom must be transported up from lower altitudes.

I. 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

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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 survey 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 in position due to logistical constraints. We observed peaks in the background from ^{40}K, ^{226}Ra and its daughters, the ^{232}Th chain, ^{137}Cs, ^{56}Co, ^{60}Co, ^{238}U, and possibly ^{235}U. During the LDEF observations, the background count rates declined by approximately 20% due to the shielding effects of the LDEF and its 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[2].

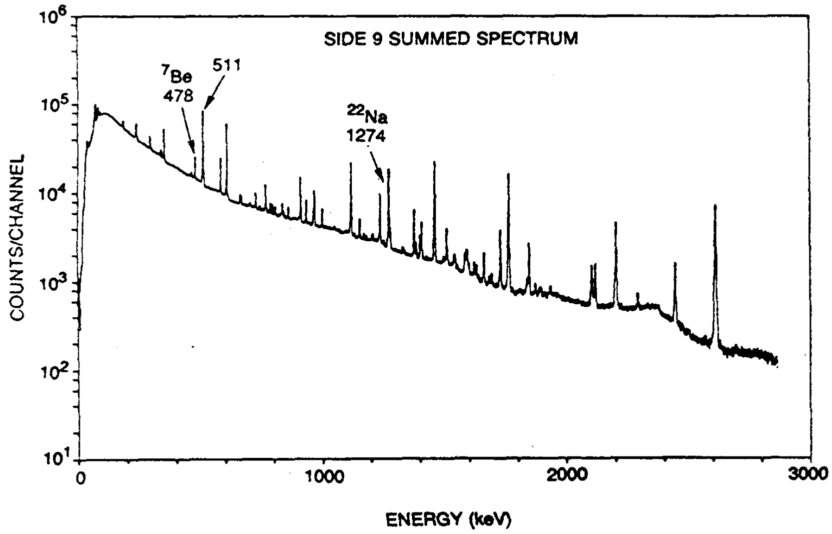

Figure 1. Summed spectrum from side 9 of LDEF accumulated for 29 hours. The ^{7}Be, ^{22}Na, and positron annihilation peaks are indicated along with their energies in keV. The energy calibration is 0.706 keV/channel.

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

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

Strong activity was observed from the 1274 keV gamma ray of ^{22}Na and the 478 keV gamma ray of ^{7}Be. ^{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].

^{7}Be was also observed in significant quantity as shown in Fig. 2. ^{7}Be 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 ^{7}Be track the ^{22}Na distribution, the major source of ^{7}Be 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 ^{7}Be 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 ^{7}Be 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 ^{7}Be 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/m^{2}.

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 ^{7}Be on the trailing edge was confirmed. Further, chemical etching of the surface of the aluminum plates removed most of the ^{7}Be activity. Clearly, the observed ^{7}Be activity results from surface deposition.

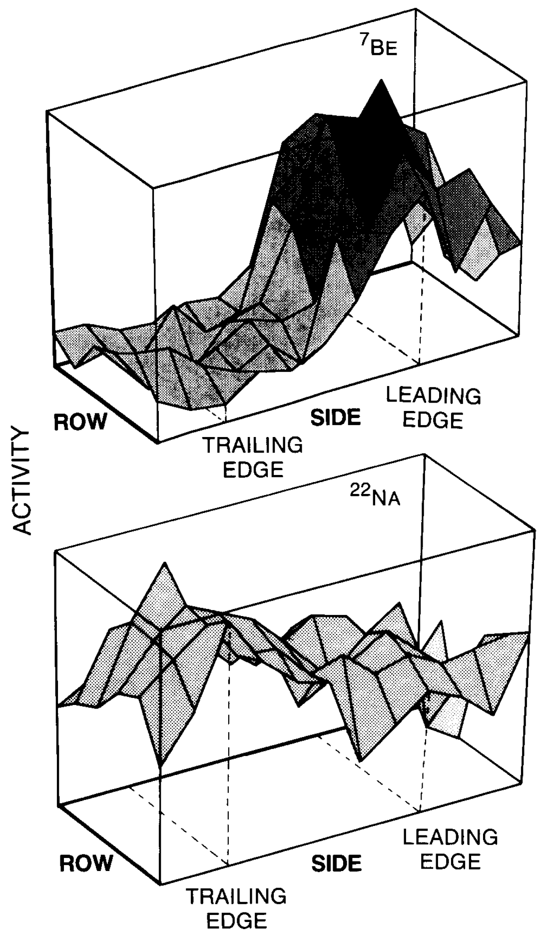

Figure 2. Distributional map of ^{7}Be and ^{22}Na activities around the LDEF. There are twelve sides around LDEF and six experiment trays (rows) per side. Each intersection point is the activity measured in one detector pod. The dashed lines indicated both the leading and trailing sides.

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 x 10^{-4} c/s/d and 7.5 x 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 ($x10^{-3}$ c/s/det.)	(% error)
^{22}Na	1274	2.6 yr	39.7	0.3
^{7}Be*	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 ^{7}Be
** Only 4 sides included in ^{57}Co activity

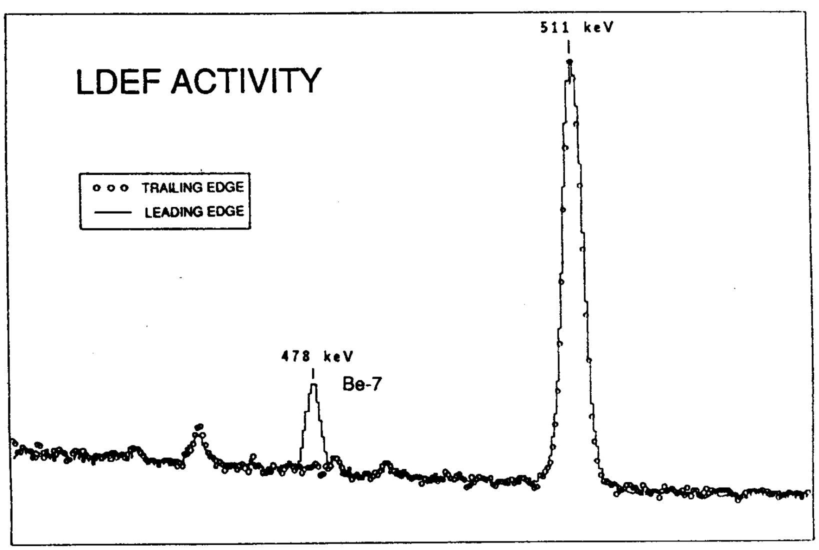

Figure 3. Comparison of the ^{7}Be peak in the gamma ray spectra from the nearly identical trays E3 and E8 acquired after their removal from the LDEF. Tray E8 which was near the leading edge shows a clear ^{7}Be peak while E3 on the trailing edge shows no evidence of ^{7}Be.

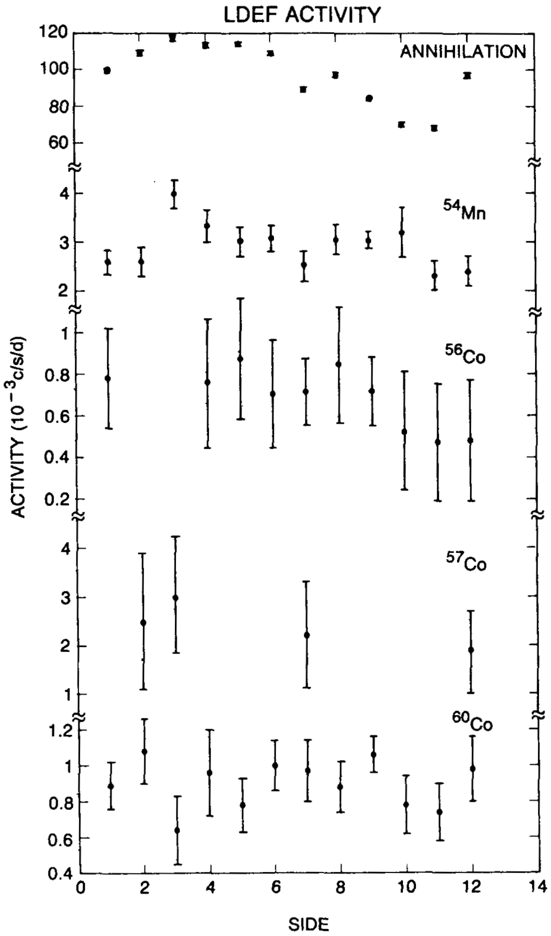

Figure 4. Distribution of net activity from the positron annihilation line, ^{54}Mn, ^{56}Co, ^{57}Co, and ^{60}Co after background subtraction. Error bars are the statistical and peak fitting errors only.

IV. Analysis of Activity

A. ^{7}Be Activity

The most surprising finding of our gamma ray survey is the deposition of ^{7}Be 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 ^{7}Be at LDEF's orbital altitude? Assuming 100% adherence of ^{7}Be to the surface of the LDEF and the volume of space swept during one mean lifetime of ^{7}Be, 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 ^{7}Be? Spallation of cosmic rays on nitrogen and oxygen in the upper atmosphere is a known source of ^{7}Be[1]. Calculations of the production in situ based on the cosmic ray flux, the spallation yield of ^{7}Be, 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 ^{7}Be 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 ^{7}Be 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[6] 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 ^{7}Be 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 ^{7}Be 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 ^{7}Be. This work has prompted a search for the surface deposition of ^{14}C on LDEF[8]. ^{7}Be decays into lithium which will gradually accumulate on the spacecraft. Can this lithium affect exposed semiconductor sensors such as electro-optical devices? ^{7}Be, ^{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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