Meteoroid and Orbital Debris Record of the Long Duration Exposure Facility's Frame

Michael Zolensky*
NASA Johnson Space Center, Houston, Texas 77058
Dale Atkinson†
POD Associates, Albuquerque, New Mexico 87106
Thomas See‡
Lockheed Engineering and Science Company, Houston, Texas 77058
Martha Allbrooks§
S-Cubed, Albuquerque, New Mexico 87106
Charles Simon¶
McDonnell Center for Space Sciences, Washington University, St. Louis, Missouri 63130
Miria Finckenor**
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
and
Jack Warren‡‡
Lockheed Engineering and Science Company, Houston, Texas 77058

The Long Duration Exposure Facility (LDEF) was recovered in January 1990, following 5.7 years of continuous exposure in low Earth orbit. The gravity-stabilized nature of LDEF permits the resolution of the flux and trajectories of impacting meteoroids and space-debris particulates. We have completed the collection of high-resolution stereoscopic video imaging of all large impact features on the entire LDEF, and present here the preliminary results for the aluminum frame of the spacecraft. The raw data indicate possible extreme directionalities in impacting particulates for sizes greater than approximately 0.1 mm in diameter, which are not explained by current modeling. Following a Gaussian curve fit to the data, the leading-edge/trailing-edge ratio of large impact feature frequency observed for the LDEF is approximately 20:1, in good agreement with existing models (Zook, H. A., "Flux vs Direction of Impacts on LDEF by Meteoroids and Orbital Debris," ***Lunar and Planetary Science XXI,*** **Lunar and Planetary Inst., Houston, TX, 1990, pp. 1385–1386). Finally, we present a list of recommendations for further LDEF analyses that will be necessary to ensure the safe design of spacecraft.**

Introduction

THE Long Duration Exposure Facility (LDEF) was recovered in January 1990, following 5.7 years of exposure of 130 m^2 of surface area in low Earth orbit (250–179 n.mi. altitude). The LDEF spacecraft is an open-grid cylindrical structure on which a series of rectangular trays used for mounting experiment hardware were attached. These trays faced in 14 directions, 12 along the sides (called "rows" in the trade) and two on the ends. In addition, portions of the LDEF frame, tray attachment clamps, and half of the tray lips (flanges) faced in directions between each of the 12 side tray-facing directions. An on-orbit photograph of the LDEF appears in Fig. 1. Since the LDEF was gravity-stabilized, elements of the LDEF faced in 26 different directions that were fixed relative to the spacecraft's velocity vector. Thus, studies of the impact record of the LDEF will permit the resolution of the flux and trajectories of meteoroid and space debris particulates.

The LDEF was host to several individual experiments designed to characterize aspects of the meteoroid and space-debris environment in low Earth orbit. It was realized from the beginning, however, that the most complete way to accom-

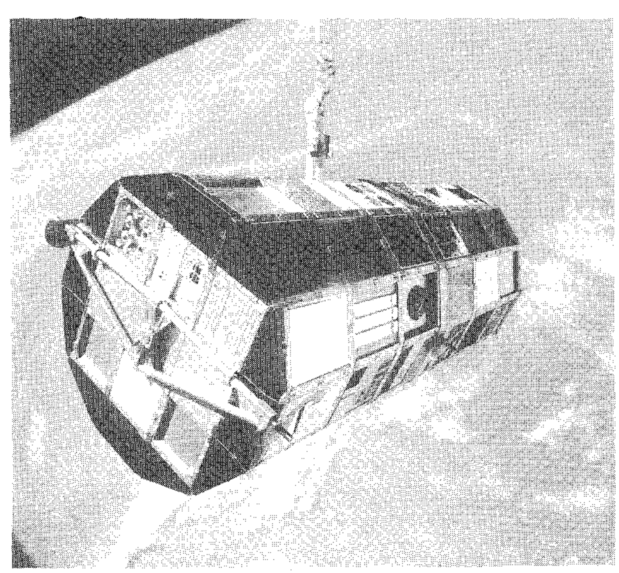

Fig. 1 Photograph of the LDEF taken by the crew of the Space Shuttle that deployed it in April 1984.

Received Sept. 19, 1990; first revision received Dec. 17, 1990; second revision received Jan. 24, 1991; accepted for publication Feb. 2, 1991.

*Space Scientist, Planetary Science Branch, SN2.
†Research Scientist, 2309 Renard Place SE.
‡Principal Scientist, 2400 NASA Road 1.
§Research Scientist, 2501 Yale SE.
¶Research Scientist.
**Space Scientist.
‡‡Scientist, 2400 NASA Road 1.

plish this goal was to exploit the impact record of the entire LDEF. The Meteoroid and Debris Special Investigation Group (hereafter Meteoroid and Debris SIG) was organized to achieve this end.

One of our first activities was to assist in the initial documentation of the LDEF in the Spacecraft Assembly and Encapsulation Facility II clean room at the Kennedy Space Center (KSC). Meteoroid and Debris SIG members at KSC harvested a specific set of data for all large impacts, which included 1) the size, type, location, and additional characteristics of all impact features deserving of documentation (for our purposes, impact craters and penetration holes measuring ≥0.5 mm in diameter for thick surfaces, ≥0.3 mm in diameter for thinner blanket-type materials; a total of approximately 5000 features satisfied these criteria), 2) digitized, stereo, color imaging of these same 5000 large impact features, and 3) an accounting of all impact features large enough to be observed visually, but too small to warrant detailed documentation (approximately 30,000 impact features below the size thresholds specified above). In addition, we collected any other information on impact features that could be gathered visually. The digitized images of impact features collected at KSC are now in the process of being reduced to yield accurate impact crater diameter and depth data (accurate to within 5%). A detailed preliminary description of the cratering record of the entire LDEF has already been prepared,[2] and is beyond the scope of this short publication. Here, we present a preliminary accounting of the impact record of the aluminum frame of the LDEF, which has the benefit of being a single homogeneous material continuously exposed in all 26 facing directions of the LDEF for its entire 5.7 year lifetime.

Finally, we present a series of recommendations that, if implemented, would provide necessary data for the design and safe operation of spacecraft in low Earth orbit, while simultaneously yielding an unparalleled view of the meteoroid and debris complex.

Data-Acquisition Procedures

This section describes the various procedures and equipment used by the Meteoroid and Debris SIG during deintegration operations of the LDEF at KSC, and provides the background necessary for understanding the data presented.

During a three-month period, from February through April 1990, members of the Meteoroid and Debris SIG were active during all stages of the deintegration of the LDEF, and documented the impact features present on its surface. At this time, we photodocumented all impact features measuring ≥0.5 mm in diameter present on structural surfaces, and all impact features ≥0.3 mm in diameter in thin materials, such as thermal-control blankets. The dual size threshold was employed due to the differing processes involved in hypervelocity impact into foils vs materials with far greater thicknesses; a 1 mm diam particulate might make a 1 mm diam penetration hole through a sufficiently thin foil, but a 5 mm diam impact crater into a section of aluminum frame. Thus, the dual size threshold will be helpful when our impact results are later recalculated in terms of impactors of constant mass. We made a visual survey, only, of all smaller, but visible, impact features. The photodocumentation was required due to the destructive nature of most of the analyses planned for the LDEF surfaces; we anticipate that many subsequent analyses of LDEF surfaces will destroy much of the impact record.

Our impact feature documentation was performed with three dedicated stereomicroscopic imaging systems. Each stereomicroscopic imaging system consisted, at its heart, of a Wild Leitz M8 stereomicroscope body. Between the top of the M8 body and the 45-deg-inclined binocular eyepiece tube was a beam splitter directing 50% of the incoming light to the binocular eyepiece tube and 50% to camera systems. Attached to both sides of the beam splitter were Cine/TV tubes, on each of which was attached a custom camera adapter compatible with either Nikon F3-HP 35-mm cameras or Sony XC-711 CCD video cameras. The microscope/camera system was attached to a microscope carrier on a fully articulated surgical floor stand. This integrated system provided complete mobility of the microscope/camera system, and permitted the microscope to be moved into virtually any position. This system is shown in use during the frame survey in Fig. 2.

Output from the Sony CCD video cameras was carried to a computer system for digitization and storage. The computer system consisted of an NEC Portable Powermate 386 SX portable computer, to which was added a Data Translations DT2871 frame grabber/digitizing board, a Data Translations DT2869 encoder/multiplexer board, two Javelin CVM-13A video monitors, and two Storage Dimensions MAXTOR LS800AT-E External Laser WORM disk drives.

To permit the measurement of impact feature locations on each LDEF experiment and frame member, three identical electronic Coordinate Registration Systems (CRS) were fabricated from components by Prototype Machine Corporation, St. Louis, Missouri. The systems consisted of electronic linear spars (Mitutoyo AT11N) mated to drafting system sliding tracks (Vemco V-track 630) and fitted with custom fabricated, adjustable height 3x spotter scopes. The upper and lower lenses of the spotter scopes were etched with a crosshair and 1.0 mm circle, respectively; the lenses were physically separated by several centimeters. This lens arrangement prevented positioning errors due to parallax by allowing the crosshairs to be reliably positioned in the center of the circle. The signals from the electronic spars were displayed on a digital readout unit (DRO; Mitutoyo ALC-EC). Each CRS was paired to an LDEF experiment tray stand (called a rotator) for use with the stereomicroscopic imaging systems. In some cases, (e.g., on most small subcomponents, such as clamps, bolts, shims, reflectors, and on the LDEF frame), a metric tape measure or scale was used to determine the coordinates of impact features.

All experiment trays and associated clamps, shims, reflectors, and steel bolts were surveyed as they were removed from the LDEF. The experiment tray location, impact feature number, experiment number, image file name, feature coordinates, image magnification, comments, and other critical information were appended to the bottom of each collected image. Any additional comments on the image(s) were separately recorded in logbooks. The only nondocumented surfaces were the insides of several small active canisters that opened and closed on orbit. The impact features from these experiments will, however, be documented later.

The Meteoroid and Debris SIG survey of the LDEF frame was conducted following the removal of all of the experiment trays and thermal panels from the LDEF. The purpose of this

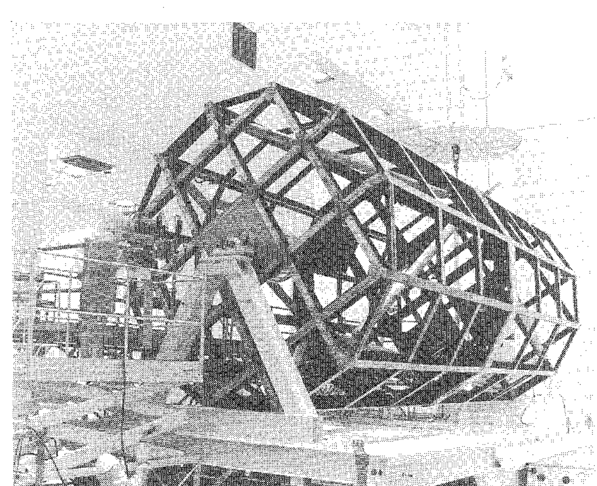

Fig. 2 Photograph of the stereomicroscopic imaging system used to document impact features at KSC (view of the frame survey; the imaging system is on the stand at left).

survey was to identify and photodocument features of interest residing on the longerons and intercostals that composed the skeletal framework of the LDEF spacecraft. This survey became necessary because portions of all LDEF frame members were exposed between tray flanges, i.e., the LDEF experiment trays did not completely cover the underlying frame. All LDEF frame members consisted of 6061-T6 chromic-anodized aluminum.

All experiment trays were affixed to the LDEF frame by means of 6061-T6 chromic-anodized aluminum clamps, measuring 4.8 × 12.7 × 0.45 cm thick. These clamps also faced in all LDEF directions, although the total surface area of the clamps (3.5 m^2) was considerably less than that presented by the LDEF frame (15.4 m^2). All clamps were surveyed for large impact features at KSC. Approximately one-half of these clamps have been retained by the Meteoroid and Debris SIG for further analysis; the remaining clamps are in the possession of the LDEF Materials SIG.

All experiment trays were also constructed of chromic-anodized 6061-T6 aluminum, and were either 1.6 or 3.2 mm thick. The flanges of each experiment tray, thus, constitute a third homogeneous material facing in all LDEF directions. These flanges were surveyed for impact features, along with the experimental surfaces of each tray. Again, the total surface area of the tray flanges (6.6 m^2) is significantly less than that of the frame.

All of the digitized images of LDEF impact features will be reduced to provide precise diameter and depth information. However, we optically measured impact feature diameters at KSC so that preliminary reports (such as this) would be possible. These diameter measurements should be accurate to within 10%. The results of the more accurate (within 5%) reduction of the digitized imaging will not be available for some months.

All crater measurements presented here are center-of-rim to center-of-rim diameters. This concept is explained graphically in Fig. 3. The majority of impact features examined at KSC possessed raised rims, some of which were irregular in shape, resembling a flower with folded back "petals." For more information regarding hypervelocity impacts and the morphologies presented by impact features, consult Anderson[3] and Kinslow.[4] In practice, the microscope was focused on the top of the feature's rim, and the center of the ridge in focus was used to make the estimated diameter measurements. When highly asymmetric rim shapes were present, the maximum and minimum diameters were measured, and the minimum measurement used to produce the results reported here. Penetration holes were not present on any of the LDEF frame members.

To foster continued studies, we have carefully selected a large variety of materials from LDEF displaying impact features, and returned them to the Curatorial Facility at the Johnson Space Center (JSC). It is our intention to resurvey curated LDEF surfaces in order to document smaller features than those documented at KSC during LDEF deintegration activities, and also to verify the accuracy of the large impact feature diameter measurements made at KSC. All of the LDEF surfaces obtained by the Meteoroid and Debris SIG for curation are also available for allocation to qualified investigators.

Results and Discussion

The Meteoroid and Debris SIG survey of the entire LDEF spacecraft identified a total of approximately 34,000 features on all space-exposed surfaces, including three features located on interior portions of structural-frame members. The latter three features were undoubtedly formed by projectiles passing through spaces present between tray flanges and the LDEF frame. Table 1 indicates the disposition of the documented impact features among the 1) experiment tray surfaces (including thermal panels), 2) tray flanges, 3) clamps, bolts, and shims, and 4) frame. As explained earlier, a dual minimum size criteria was employed for impact feature documentation, 0.5 mm for thick materials, 0.3 mm for thin films. Table 2 presents the impact frequencies observed for each row (side) of the LDEF

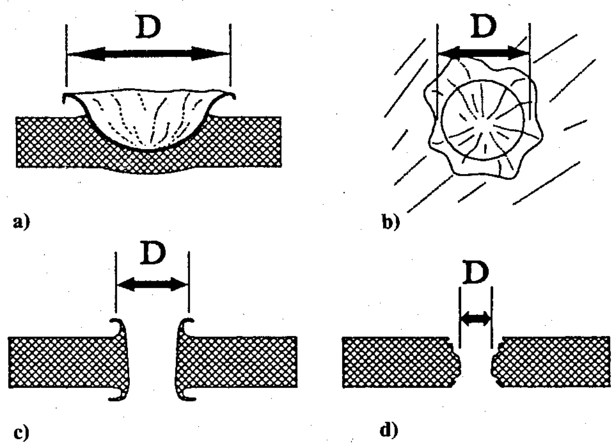

Fig. 3 Cartoon illustrates the physical meaning of the center-of-rim to center-of-rim diameter measurement employed for crater documentation: a) cross-sectional view of a feature with a symmetrical rim and overturned lips, b) top view of a, c) cross-sectional view of a penetration feature with symmetrical rim and overturned lips, d) cross-sectional view of a penetration feature without a rim.

Table 1 Feature summary for all LDEF surfaces[a]

	Clamps, bolts and shims	Tray flanges	Experimental surfaces	Frame	Totals
>0.3 mm[b]	——	——	763	——	763
>0.5 mm	161	419	2106	433	3119
Totals	161	419	2869	433	3882

[a]Does not describe the disposition of over 30,000 catalogued impact features with diameters below threshold size.
[b]Entry pertains only to foil materials present on experimental surfaces, where the size threshold was 0.3 mm; entries are not counted twice in the table.

Table 2 Areas and impact frequencies for the LDEF frame

Row	Area, m^2	Impacts/area
1	0.613	9.8
1-2[a]	0.535	13.2
2	0.610	4.9
2-3	0.535	1.9
3	0.613	4.9
3-4	0.535	1.9
4	0.610	4.9
4-5	0.535	1.9
5	0.613	11.5
5-6	0.535	7.5
6	0.610	13.1
6-7	0.535	20.8
7	0.613	21.3
7-8	0.535	47.2
8	0.610	55.7
8-9	0.535	50.9
9	0.613	41.0
9-10	0.535	67.9
10	0.610	67.2
10-11	0.535	67.9
11	0.613	37.7
11-12	0.535	26.4
12	0.610	21.3
12-1	0.535	30.2
Space end	0.787	30.5
Earth end	0.787	~0

[a]Notation for an LDEF side facing in a direction intermediate between two principal rows, in this case rows 1 and 2.

frame, as well as for both its Earth- and space-facing ends. All of these impacts were at least 0.5 mm in diameter.

The total surface area of the LDEF frame exposed to the low Earth environment, and potential impacts, amounted to 15.4 m^2, and varied from 0.53 to 0.79 m^2 in the 26 different LDEF-facing directions. The total number of large (>0.5 mm in diameter) impacts present on the frame was 433, and the areal density of impacts varied from essentially 0 to 78.5 impacts/m^2. It is, therefore, clear that the population of impact features and space-exposed area of the LDEF frame are statistically large enough to warrant serious consideration here.

Modeling of the meteoroid and debris environment in low Earth orbit assumes and suggests (respectively) that particulate orbital trajectories are random relative to the LDEF before orbital motion is taken into account. One would, therefore, expect a very definite result for the relative impact frequency for a gravity stabilized object in Earth orbit. There should be a forward-facing (in the direction of the velocity vector, or apex direction) enhancement of the impact frequency, relative to that of the rear-facing (trailing or antapex) direction.[1] Depending on the velocity distribution of meteoroids, Zook predicted that the apex/antapex crater frequency ratio could range between 12 and 30, for 0.5 mm diam craters. On the LDEF, the nominal apex direction was row 9, and row 3 was the nominal antapex direction. The ratio of impact frequency for row 9:row 3, for large (>0.5 mm diam) impact features, is approximately 10.

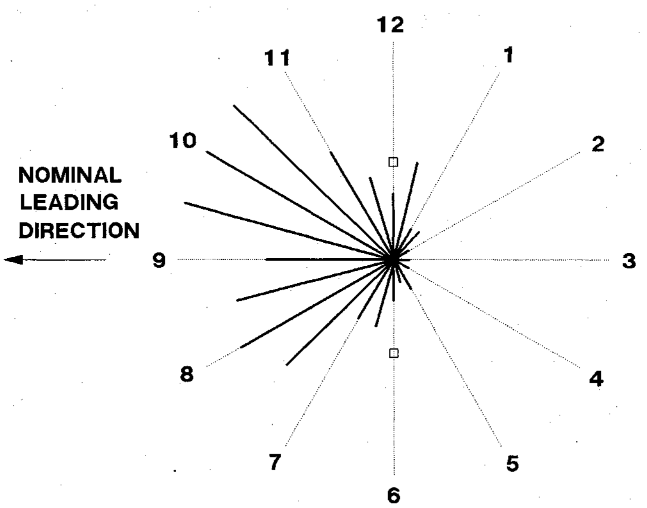

Fig. 4 Relative impact frequency (for large impactors) observed for the 12 LDEF rows, and their intermediate facing directions. Row 9 is the nominal leading direction, row 3 is the nominal trailing direction. The length of the heavy lines indicate the magnitudes of the relative impact frequency in each direction. The open squares along rows 12 and 6 indicate the magnitude of the relative impact frequency of the space-facing end of the LDEF. Impacts on the space-facing end should have resulted almost entirely from meteoroids.

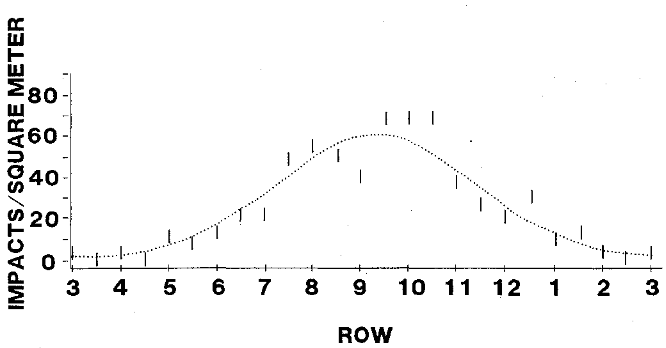

Fig. 5 Plot of impact frequency for each LDEF row, with the measured frequencies indicated by vertical bars. Superimposed on these data is a Gaussian curve (dotted).

One should also expect a regular increase in the impact frequency from row 3 (a minimum) towards row 9 (the maximum). This result is clearly not observed from the preliminary raw data for the LDEF frame presented in Fig. 4. Maxima in the impact frequency are observed on either side of row 9, but row 9 itself shows a dramatic impact frequency decrease. Although a minor impact frequency decrease might be expected in the exact apex direction, this value is far exceeded by the observed 50% decrease from either direction adjacent to row 9.[5]

In Fig. 5, we present the results of fitting of a Gaussian curve, through the method of least squares, to the impact frequency data for the LDEF frame. We note that there is no a priori physical basis for the selection of a Gaussian distribution for this data; however, its fit was superior to other attempted fits. It is clearly possible to better fit these data with a more complex function, but the gain in understanding from this exercise would not be clear. The Gaussian curve that best fits LDEF frame impact frequency data has a maximum near row 9, the nominal leading-edge direction. It is interesting that the ratio of leading:trailing edge impact frequency for the Gaussian curve is approximately 20:1, which is in better agreement with previous modeling of the particulate environment in low Earth orbit[1] than the raw data.

If the results for the impact frequency of the LDEF frame are accurate, as further studies by both the Meteoroid and Debris SIG and various LDEF Principal Investigators should determine, then it suggests that some principal components of the particulate complex in low Earth orbit have non-random trajectories. These would be particles larger than approximately 0.1 mm in diameter, judging by the crater diameters. Modeling suggests that micrometeoroids predominate in this size range.[1] These results could, therefore, have important implications for future modeling of the particulate population in low Earth orbit.

On the other hand, these results are preliminary. The impact feature diameters presented here have large associated measurement errors (±10%). As shown in Fig. 4, some LDEF directions show an apparent change in flux by nearly a factor of two, with only a 15 deg change in direction (the angular change from one LDEF facing direction to the next). Even a single mono-directional flux of particulates on LDEF frame surfaces should not show such rapid variations. Since the flux should change with the cosine of the angular direction change,[1] and cos 15 deg is 0.966, one would not expect even a 10% change in the apparent crater frequency with such a direction change.

There are various possible explanations for the apparent disagreement between the existing model of particulates in low Earth orbit and the observed LDEF frame impact record. It is possible that some measurement or selection bias crept into the frame surveying activities, although we consider this to be highly unlikely. Another possible explanation for the observed rapid crater frequency changes is a local source of particulates, such as the Space Shuttle. We also consider this situation to be unlikely, as we have now resurveyed these same surfaces in the laboratory under more controlled conditions, as mentioned above, in order to verify the accuracy of our KSC measurements. It is possible that particulates in low Earth orbit should not be modeled as a single mono-directional population. We also look forward with anticipation to hearing the results of LDEF investigators with experiments facing in the key directions. Until such time as these results are available, the safest course would be to make use of extrapolations from the Gaussian curve fit to the data.

Recommendations

Our experience with the documentation of LDEF places us in an excellent position to make recommendations regarding future meteoroid and space debris characterizations from the analysis of surfaces exposed in space. Our examination of LDEF has reinforced the view, largely based on our experience with the Solar Maximum Satellite,[6] that most any surface exposed in low Earth orbit may contain important information related to the general collisional environment and certainly related to its own dynamic response and behavior during hypervelocity impacts. In as much as the entire dynamic range of particulates in low Earth orbit may not be suitably simulated in the laboratory, each surface returned from space potentially represents a unique opportunity. We recommend that impact feature documentation work be repeated, at reasonable intervals, on future spacecraft exposed for long durations so that the changing debris environment in low Earth orbit can be monitored. We recommend that a period of five to ten years between such efforts would be reasonable.

It is paramount to subject such surfaces to survey-type analysis, such as that conducted on LDEF. The potential variety of impact features must be assessed, documented, and understood. Such surveys will provide the context for detailed examinations by specialized interests, which are generally performed on a limited number of carefully selected samples. The surveys render the detailed analyses purposeful and efficient, and also constitute the first step in the proper preservation and curation of valuable specimens.

We were very satisfied with the specific procedures we developed to permit documentation of the impact record of LDEF; we suggest that these procedures be reviewed by workers proposing to survey space hardware in the future. We note that, despite our best efforts at scheduling this work, the time available for the completion of the LDEF surveying was only barely adequate for the purpose, and we recommend that this factor be taken into careful account in any future survey operations.

We here make specific suggestions to permit the full realization of the opportunities offered by LDEF.

We have now produced a preliminary report on our investigations performed at KSC. We are proceeding with the reduction of the stereo images collected of each documented feature, so that impact crater depths and more accurate feature diameters may be obtained. These data are critical to a satisfactory understanding of the meteoroid and debris environment and the survivability of space hardware. However, the meteoroid and debris environment may only be understood in detail if compositional (including isotopic) analysis of a statistically representative population of LDEF impacts is performed. Our experience with hardware returned from the Solar Maximum Satellite points out the critical requirement for such analyses in the discrimination of natural meteoroids from space debris. In particular, LDEF surfaces that exposed identical materials in most or all LDEF-facing directions should be utilized for these compositional analyses. These materials include the experiment tray clamps, Teflon thermal blankets, and the frame of the LDEF itself. A comprehensive sampling of these critical materials has been obtained by the Meteoroid and Debris SIG, and is now available for analysis by qualified workers.

To increase the survivability of space hardware to impact-related degradation and damage, the understanding of the morphology of impact features must be improved. The Teflon thermal blankets must be analyzed to determine the causes of ring formation and excessive delamination of layers, which degrade the thermal control capabilities of the blankets. Their performance as meteorite bumper shields should also be evaluated. In assessing impact-caused degradation of thermal surfaces, the delamination of thermal-control paints must be examined also. Finally, the fracture, delamination, and optical degradation of solar cell cover glasses and sensor mirrors must be understood. This includes the effects caused by impacts into the interior walls and baffles of sensor telescopes, with resulting ejecta onto the sensor optics. This work would best be performed in conjunction with the LDEF Materials Principal Investigators and the Materials SIG.

Near-term design decisions for large-scale space structures, such as Space Station Freedom and the Strategic Defense System, will benefit from LDEF results only if the latter appear in a timely fashion. We recommend and encourage all meteoroid and debris Principal Investigators and SIG participants to respond and to assist by providing preliminary data and results for incorporation into an up-to-date database, largely formatted along engineering needs. Specifically, even preliminary data on the directionality of natural and man-made impactors, and of the damage caused to a wide variety of spacecraft materials, are needed.

We also recommend that the population of small impactors be characterized through surveying of the smallest size fraction of impact features on LDEF surfaces. Some of this work is already being performed by various LDEF Principal Investigators. However, the Meteoroid and Debris SIG possesses identical suitable surfaces that faced in more LDEF pointing directions than any one individual investigator. Our surveying operations could, thus, augment the data to be provided by the LDEF Principal Investigators.

To permit analytical results to be available for consideration by designers of Space Station Freedom and the Strategic Defense System, we recommend that this described work be given immediate support.

As advertised, LDEF should provide meteoroid workers with a unique view of the meteoroid complex. We recommend that compositional, isotopic, and mineralogic analyses be performed upon impactor residues contained within the LDEF impact features, particularly those that faced in directions not frequented by space debris particulates.

We recommend that the preliminary publication here described[2] be superseded, in approximately two years, by a document containing the collected results of continued Meteoroid and Debris SIG supported analyses of LDEF impact features, together with a summary of parallel investigations by LDEF Principal Investigators. The Curatorial Facility at JSC has developed an LDEF impact feature database that should be used by all meteoroid and debris workers. This database should provide a unifying framework for all LDEF meteoroid and debris data, and serve as the foundation for the subsequent Meteoroid and Debris SIG publication.

In conclusion, we emphasize once again: the opportunities afforded by LDEF are unique. The characterization and documentation of impact features described in our publication is but a first step in realizing this potential, and in providing guidelines for promising, detailed investigations. Without timely and adequate support of the latter studies, improved understanding of interplanetary dust, the nature of orbital debris, and of their combined collisional threat to spacecraft will not be possible.

Acknowledgments

This publication was made possible by the tireless efforts of many contributors. We gratefully acknowledge the support provided by NASA and the LDEF Project Office, and the Strategic Defense Initiative Organization. Although the authors were responsible for much of the planning and execution of data collection activities during the deintegration of the LDEF, numerous other individuals contributed their time to this effort. Some of the surveying work was performed by Eric Christiansen, Frank Cardenas, Samantha Lapin, Mike Black, Joe Secary, Reggie West, and Tim Stephenson. We thank the other members of the Meteoroid and Debris SIG for their help in the planning of these operations; in particular, we thank Fred Hörz and Don Humes for continued advice and support. The outstanding support of the LDEF Ground Operations Team and LDEF Project Office personnel greatly facilitated our ability to complete this effort. Equipment fabrication and development required the efforts of Frank Cardenas, Gerald Haynes, Bill Davidson, Herman Lyle, Richard Ybanez, Ron Bernhard, Anthony Biondo, and Bebe Serrato. Curatorial and computer algorithm support were supplied by Claire Dardano, Eric Nielsen, Clyde Sapp, Bill Brown, Jimmy Holder, Rita Sosa, Anita Dodson, and Ron Bastien. We appreciate thoughtful reviews of this paper by Herb Zook, Don Kessler, and anonymous reviewers. This report, and the LDEF itself, would not have been possible without the career-long support by Project Scientist William Kinard.

References

[1]Zook, H. A., "Flux vs Direction of Impacts on LDEF by Meteoroids and Orbital Debris," *Lunar and Planetary Science XXI*, Lunar and Planetary Inst., Houston, TX, 1990, pp. 1385–1386.

[2]See, T., Allbrooks, M., Atkinson, D., Simon, C., and Zolensky, M., *Meteoroid and Debris Impact Features Documented on the Long Duration Exposure Facility*, Planetary Science Branch Pub. 84, NASA Johnson Space Center, Houston, TX, 1990.

[3]Anderson, C. E. (ed.), *Hypervelocity Impact, Proceedings of the 1986 Symposium, International Journal of Impact Engineering*, Pergamon Press, 1987.

[4]Kinslow, R. (ed.), *High-Velocity Impact Phenomena*, Academic, New York, 1970.

[5]Zook, H., and Kessler, D., personal communications, SM3, NASA Johnson Space Center, Houston, TX, 1990.

[6]Warren, J. L., et al., "The Detection and Observation of Meteoroid and Space Debris Impact Features on the Solar Max Satellite," *Proceedings of the 19th Lunar and Planetary Science Conference*, edited by G. Ryder and V. Sharpton, Lunar and Planetary Inst., Houston, TX, 1989, pp. 641–657.

Antoni K. Jakubowski
Associate Editor