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INTERIM REPORT OF THE METEOROID AND DEBRIS SPECIAL INVESTIGATION GROUP

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SUMMARY

The LDEF Meteoroid and Debris Special Investigation Group (hereafter M&D SIG) was formed to maximize the data harvest from LDEF by permitting the characterization of the meteoroid and space debris impact record of the entire satellite. Thus, our work is complementary to that of the various M&D PIs, all of whom are members of the SIG. This presentation will summarize recent results and discussions concerning five critical SIG goals: 1) classification of impactors based upon composition of residues, 2) small impact (microimpact) features, 3) impact cratering and penetration data to derive projectile sizes and masses, 4) particulate flux estimates in low-Earth orbit, and 5) the LDEF Meteoroid and Debris database.

INTRODUCTION

A meeting of the Meteoroid and Debris Special Investigation Group (M&D SIG) was held in March of 1992. We reviewed progress towards the M&D SIG goal of using the entire LDEF satellite to define the meteoroid and space debris environment in low-Earth orbit. M&D SIG members are at work on numerous projects, including use of 3-D impact feature images to derive precise crater depth and diameter information, detailed examination of the impact record of the LDEF frame (which provided common material exposed in all pointing directions), examination of impact damage on aluminum panels, characterization of impactor residues, and modelling of the Near-Earth particulate environment using M&D SIG data. All of these activities are reported separately in this conference proceedings document.

One determination of the recent M&D SIG meeting was that consensus should be met by the membership on five key activities; these are (a) establishment of standard criteria for distinguishing natural from man-made impactors, (b) characterization of same for very small impact features (<10 um diameter), (c) use of laboratory simulations for calibration of impactor properties from observed impact features, (d) use of LDEF results to calculate particulate flux in low-Earth orbit, and (e) use of a standardized database for M&D results. This report is a first attempt to address these critical issues in a forum accessible to other LDEF investigators and the community at large, both for information purposes and also to invite critique from the larger community. Consensus on these issues has not always been achieved, as will become obvious. However, we are able to delineate the scope of disagreements and suggest ways of resolving them. For example, we recognize that much future work will necessarily concern calibration of craters in aluminum (the most common material on the LDEF), and cratering and penetration processes in the Teflon thermal blankets.

As the reader has now discovered, this paper is not a global overview of M&D SIG activities, but is narrowly focussed. We discuss each critical issue below, in the order in which presented above.

CRITERIA FOR DISTINGUISHING NATURAL FROM MAN-MADE IMPACTORS

Introduction

Since different capture experiments on LDEF employed different collection schemes and different analysis techniques, it has proved difficult to establish universal criteria for distinguishing between natural and man-made impactors. The situation becomes more complex for the entire LDEF with its myriad of experimental surfaces and analytical investigations. However, in the interest of promoting the comparisons of results from many laboratories, we propose the following classification scheme. This scheme has been employed for some LDEF studies already (ref. 1).

Contamination

Clearly, the level and composition of contamination must be carefully established before analysis of residues should be attempted. Also, supposedly well-understood LDEF materials often contain impurities which, though minute on a gross scale, are important at the scale necessary for analysis of impactor residues. LDEF surfaces are sprinkled with particles of alkali-halide salts (from oceanic spray and human waste), paint flakes containing high concentrations of Ti and/or Zn and/or Mg (from LDEF paints that were shed due to the action of atomic oxygen and ultraviolet radiation, flakes of Al from blankets and antenna arrays, and other less characterized materials.

Because of ubiquitous Si contamination on LDEF (from outgassing RTV?) particular care must be employed in use of this element for establishing criteria. This is particularly unfortunate since Si is an important element in meteoroids. Other elements found within this particular contaminating material include O, C, H, Na, K and Ca.

Criteria For Natural Impactors

Any of these constitute sufficient conditions:

A Chemical Criteria
- (1) Mainly Fe with minor S and/or Ni
- (2) Various proportions of Mg, Fe and Ca + minor S, Ni, and/or Al
- (3) Fe+Cr only if O is also present in same residue grains and outgassed RTV contamination is not locally evident
- (4) Non-terrestrial isotopic compositions
- (5) Presence of solar wind implanted He or Ne
- (6) Given that impact residues are frequently fractionated, comparisons between ratios of refractory to volatile elements can also be employed to establish criteria for origin. Useful ratios are Al/Mg, Ca/Mg and Ti/Mg (see ref. 2 for application of these ratios).

B Physical Criteria
- (1) Presence of solar flare tracks

C Mineralogical Criteria
- (1) Contains olivine, pyroxenes, ferromagnesian phyllosilicates (serpentines, smectites) and/or Fe-Ni sulfides

Criteria For Man-made Impactors

Not any of the above criteria; also:

D General Criteria
- (1) Mainly Al or Al_2O_3 + minor Fe, Ni, Cr, Cl, Na or C
- (2) Mainly Fe with accessory Cd, Ti, V, Cr, Ni, Mn, Co, Cu or Zn with the latter elements present in abundances greater than to be expected for common minerals. A common man-made material is stainless steel consisting of Fe, Cr and Ni.
- (3) Various proportions of Ca, Al, Si, Ti, K, Zn, Co, Sn, Pb, Cu, S, Cl, Au or Ag.

Surface Specific Criteria

Au- No change
Ge- No change
Al- Expect Al contamination to affect criteria A1, A2 and D2. Criteria D1 will not apply
Steel- Expect Fe and Cr contamination to affect criteria A1 and A2. Be careful when applying criteria A3 or D2.

MICROIMPACT FEATURES

A subcommittee of the M&D SIG has summarized all data gathered on micro-craters or perforations (features nominally <10 μm in diameter) found on LDEF surfaces. The goal is to issue a final summary report that will include all reported impact flux data in several formats in order to allow maximum utilization by the various communities. The M&D SIG practice of reporting all primary data along with any interpretive data will be followed. The final report will also include summaries of information reported in the literature or directly to the M&D SIG concerning micro-impactor chemical compositions and developments and new insights into the theoretical and semi-empirical prediction of micro particle fluxes and velocity distributions in low-Earth orbit (LEO).

This interim report lists the LDEF cumulative micro particle crater/penetration fluxes reported to date in the literature (refs. 3-9, ft notes 1-4)* or directly to this committee (ref. 10, ft notes 5-6). Table 1 lists the flux data (number/m^2/s) along with LDEF experiment numbers and bay locations, the time periods of exposure, the types and amounts of surface materials scanned, the scanning methods, the minimum detectable crater diameters (>90% confidence) as reported by the individual investigators, and the number of impact features counted. Data is grouped by LDEF locations and exposure times and listed in order of increasing minimum feature size. The sources for the tabulated data are listed at the end of the table. Data for micro-craters and penetration holes in Teflon thermal blankets are not included at this time, but will be added along with other data for the next interim report. These blankets are a valuable source of impact data, but the size of micro craters that can be observed will be limited by the surface texture of the Teflon blankets, which is highly variable and results from atomic oxygen and ultraviolet radiation damage.

The LDEF community is encouraged to contribute new information on small impact features. Several of the investigators who supplied information for this report have undertaken the difficult task of converting data from different LDEF surfaces (metals, foils, ceramics) into a common format. Most notably, Horz et al. (ref. 3), Mandeville et al. (ref. 4, ft note 1) and especially McDonnell, et al. (refs. 5-7) have discussed and applied conversion formulae extensively. Interested readers are referred to these sources for more information. Further refinement in these procedures can be expected as more data is collected and correlated. The committee's final report will contain the latest versions of these investigators' formulae.

There are numerous empirical and semi-empirical relationships developed to convert impact crater and penetration hole morphology in metals, crystalline materials and thin films (metal and polymeric) to particle mass or size, or equivalent crater size in aluminum, or equivalent penetration thickness for aluminum film. All such methods are dependent on general assumptions about impactor density and velocity and interaction with the target. Velocity and density assumptions can be applied unilaterally to all features on a given LDEF side and provide an acceptable level of comparison for a statistically large sample set. Average velocities for micro-particles striking the various sides of LDEF can be calculated from reported flux data with modest accuracy. In addition, as data on impactor chemical composition is reported, greater insight into the range and average densities of micro impactors can be gained.

The portions of conversion formulas that involve terms dependent on the physical properties of the target materials as they relate to interaction with hypervelocity micro-impactors can be accurately determined in many cases by empirical evaluation. Van de Graaff accelerators are useful for determining material response to hypervelocity micro-particle impacts. While there is some test data on Fe and Al metals and foils, much more data is needed for these as well as for micro-particle impacts into crystalline materials such as Si and Ge. However, a thorough review of the literature concerning micro-particle hypervelocity impacts into these materials may provide enough data to determine the cratering characteristics of these events under orbital conditions.

* See footnote section that follows the reference list.

Table 1. Cumulative particulate impact fluxes observed on LDEF surfaces for small craters (<10 μm).

LDEF Exp.	Tray	Time Period	Material Scanned	Total Area Scanned (cm^2)	Scanning Method	Min. Detectable Crater dia. (μm)	Number of Impacts	Cumulative Flux ($m^{-2}s^{-1}$)	Ref. or *Ft note*
ROW 1									
Clamp 8	A01	5.77 yrs	Al	2	SEM[9]	4	8	$2.2x10^{-4}$*	*8*
ROW 3									
A0201	C03	Day 1-8	MOS[1]	942	electron.[2]	0.4[3]	64	$9.8x10^{-4}$	*4*
A0201	C03	Day 1-8	MOS[4]	629	electron.[2]	1.0[5]	3	$6.9x10^{-5}$*	*4*
A0138	B03	Day 10-280	Au[13]	2.1	SEM[9]	1	[1]	$2.0x10^{-4}$	11
A0201	C03	Day 9-346	MOS[1]	942	electron.[2]	0.4[3]	391	$1.4x10^{-4}$	*4*
A0201	C03	Day 9-346	MOS[4]	619	electron.[2]	1.0[5]	183	$1.0x10^{-4}$	*4*
A0138	B03	Day 10-280	Al[14]	25	SEM[9]	2	5	$8.6x10^{-5}$*	11
A0138	B03	5.77 yrs	Al[15]	4	SEM[9]	1	15	$2.1x10^{-4}$	4,11
A0138	B03	5.77 yrs	Al[15]	2	SEM[9]	1	[8]	$2.2x10^{-4}$*	4,11
A0138	B03	5.77 yrs	Al[15]	8.6	SEM[9]	2	6	$3.8x10^{-5}$*	4,11
A0138	B03	5.77 yrs	Al[15]	9.9	SEM[9]	3	4	$2.2x10^{-5}$*	4,11
A0023	C03	5.77 yrs	Al[12]	53	optical	4	[22]	$2.3x10^{-5}$	6
A0201	C03	5.77 yrs	MOS[4]	570	optical	1.0[5]	275	$2.7x10^{-5}$	*6*
A0023	C03	5.77 yrs	Al[11]	53	optical	5	[6]	$6.2x10^{-6}$*	6
A0023	C03	5.77 yrs	Al[7]	203	optical	7	26	$7.0x10^{-6}$	6
A0201	C03	5.77 yrs	MOS[4]	294	optical	14	12	$2.2x10^{-6}$	6
ROW 6									
A0201	D06	Day 1-8	MOS[1]	942	electron.[2]	0.4[3]	17	$2.6x10^{-4}$	*4*
A0201	D06	Day 1-8	MOS[4]	629	electron.[2]	1.0[5]	2	$4.6x10^{-5}$*	*4*
A0201	D06	Day 9-346	MOS[1]	860	electron.[2]	0.4[3]	3012	$1.2x10^{-3}$	*4*
A0201	D06	Day 9-346	MOS[4]	622	electron.[2]	1.0[5]	1198	$6.6x10^{-4}$	*4*
A0201	D06	5.77 yrs	MOS[4]	59	optical	1.0[5]	411	$3.8x10^{-4}$	*6*
A0201	D06	5.77 yrs	MOS[4]	59	optical	1.0[5]	114	$1.1x10^{-4}$	*6*
A0023	E06	5.77 yrs	Al[10]	107	optical	3	[1158]	$6.0x10^{-4}$	6
A0023	E06	5.77 yrs	Al[12]	53	optical	4	[218]	$2.2x10^{-4}$	6
A0023	E06	5.77 yrs	Al[11]	53	optical	5	[187]	$1.9x10^{-4}$	6
A0023	E06	5.77 yrs	Al[7]	203	optical	7	570	$1.1x10^{-4}$	*6*

Table 1. Continued

LDEF Exp.	Tray	Time Period	Material Scanned	Total Area Scanned (cm^2)	Scanning Method	Min. Detectable Crater dia. (μm)	Number of Impacts	Cumulative Flux ($m^{-2}s^{-1}$)	Ref. or *ft note*
ROW 7									
Clamp 1	C07	5.77 yrs	Al	2	SEM[9]	2	10	2.7×10^{-4}	2
ROW 8									
A0187	E08	5.5 yrs	Ge[16]	2.2	SEM[9]	0.25	184	4.8×10^{-3}	5
A0187	E08	5.5 yrs	Ge[16]	7	SEM[9]	1	389	3.2×10^{-3}	5
A0187	E08	5.5 yrs	Ge[16]	7	SEM[9]	2	189	1.6×10^{-3}	5
A0187	E08	5.5 yrs	Ge[16]	7	SEM[9]	4	56	4.6×10^{-4}	5
ROW 9									
A0201	C09	Day 1-8	MOS[1]	923	electron.[2]	0.4[3]	232	3.6×10^{-3}	4
A0201	C09	Day 1-8	MOS[4]	629	electron.[2]	1.0[5]	72	1.7×10^{-3}*	4
A0201	C09	Day 9-346	MOS[1]	874	electron.[2]	0.4[3]	4308	1.6×10^{-3}	4
A0201	C09	Day 9-346	MOS[4]	599	electron.[2]	1.0[5]	1470	8.1×10^{-4}	4
A0201	C09	5.77 yrs	MOS[4]	59	optical	1.0[5]	934	8.7×10^{-4}	6
A0023	C09	5.77 yrs	Al[7]	102	optical	7	435	2.3×10^{-4}	6
A0023	C09	5.77 yrs	Al[8]	26	optical	8	110	2.3×10^{-4}	11
ROW 12									
A0201	B12	Day 1-8	MOS[1]	942	electron.[2]	0.4[3]	59	9.1×10^{-4}	4
A0201	B12	Day 1-8	MOS[4]	629	electron.[2]	1.0[5]	4	9.2×10^{-5}*	4
A0201	B12	Day 9-346	MOS[1]	874	electron.[2]	0.4[3]	2408	8.6×10^{-4}	4
A0201	B12	Day 9-346	MOS[4]	605	electron.[2]	1.0[5]	1077	6.1×10^{-4}	4
A0201	B12	5.77 yrs	MOS[4]	59	optical	1.0[5]	430	3.9×10^{-4}	6
A0201	B12	5.77 yrs	MOS[4]	39	optical	14[6]	66	9.3×10^{-5}	6
A0023	D12	5.77 yrs	Al[10]	53	optical	3	[361]	3.7×10^{-4}	6
A0023	D12	5.77 yrs	Al[11]	107	optical	5	[298]	1.5×10^{-4}	6
A0023	D12	5.77 yrs	Al[7]	203	optical	7	467	1.3×10^{-4}	6

Table 1. Continued

LDEF Exp.	Tray	Time Period	Material Scanned	Total Area Scanned (cm^2)	Scanning Method	Min. Detectable Crater dia. (μm)	Number of Impacts	Cumulative Flux ($m^{-2}s^{-1}$)	Ref. or *ft note*
EARTH-FACING									
A0201	G10	Day 1-8	MOS[1]	943	electron.[2]	0.4[3]	16	$2.5x10^{-4}$	*4*
A0201	G10	Day 1-8	MOS[4]	629	electron.[2]	1.0[5]	0	$<2.3x10^{-5}$*	*4*
A0201	G10	Day 9-346	MOS[1]	893	electron.[2]	0.4[3]	28	$1.1x10^{-5}$	*4*
A0201	G10	Day 9-346	MOS[4]	619	electron.[2]	1.0[5]	29	$1.6x10^{-5}$	*4*
A0201	G10	5.77 yrs	MOS[4]	354	optical	1.0[5]	185	$2.9x10^{-5}$	*6*
A0201	G10	5.77 yrs	MOS[4]	354	optical	14[6]	1	$1.6x10^{-7}$*	*6*
SPACE-FACING									
A0201	H11	Day 1-8	MOS[1]	688	electron.[2]	0.4[3]	33	$6.9x10^{-4}$	*4*
A0201	H11	Day 1-8	MOS[4]	472	electron.[2]	1.0[5]	5	$1.5x10^{-4}$*	*4*
A0201	H11	Day 9-346	MOS[1]	677	electron.[2]	0.4[3]	347	$1.8x10^{-4}$	*4*
A0201	H11	Day 9-346	MOS[4]	461	electron.[2]	1.0[5]	150	$1.1x10^{-4}$	*4*
A0201	H11	5.77 yrs	MOS[4]	157	optical	1.0[5]	171	$6.0x10^{-5}$	*6*
A0201	H11	5.77 yrs	MOS[4]	177	optical	14[6]	55	$1.7x10^{-5}$	*6*
A0023	H11	5.77 yrs	Al[7]	310	optical	7	193	$3.4x10^{-5}$	6
A0023	H11	5.77 yrs	Al[8]	0.5	SEM[9]	2	20	$2.2x10^{-3}$	2
A0023	H11	5.77 yrs	Al[8]	0.5	SEM[9]	4	15	$5.8x10^{-4}$	2

Notes

Values in brackets [ ] are subject to verification.
Fluxes marked with an asterisk * were calculated from undersized sample sets (<10 impacts).

[1] 0.4 μm SiO_2 on Si
[2] Electronic signals
[3] Equivalent to 1 μm in Al
[4] 1 μm SiO_2 on Si
[5] Equivalent to 3 μm in Al
[6] Spall diameter
[7] 4.8 μm foil
[8] 25 μm foil
[9] Scanning Electron Microscopy
[10] 2 μm foil
[11] 3.7 μm foil
[12] 3.1 μm foil
[13] 125 μm foil
[14] 5 μm foil
[15] Plate
[16] 200 μm wafer

Data from penetrations and cratering in aluminum foils on LDEF can provide the means for calibration of the crater size relationship between Al and other materials. This data can also be used to calibrate the sensitivity of the Interplanetary Dust Experiment (IDE) sensors (A0201). Crater-size distributions in these materials can also be compared. Additional information is highly desirable on micro-crater densities and size distributions on other materials on LDEF, especially optically-smooth surfaces.

Several important observations are immediately evident from the data in Table 1. Singer, Mulholland and co-workers (refs. 8-9, ft note 4), have reported a short-term increase in micro-particle debris impacts on LDEF following deployment and attributed the source to Shuttle activities. Electronic data from the A0201 high-sensitivity sensors located on the Earth, Space and West (anti-ram) sides of the satellite showed a greatly increased flux of micro-particle impacts during the first 8 days following deployment. The impact fluxes on the low sensitivity A0201 sensors on these same locations were the same or less than their respective first year fluxes, indicating that the vast majority of the particles must be submicron. The impact fluxes (for the initial 8 days) on both types of A0201 sensors mounted on the east (ram) side of LDEF were approximately double their first year fluxes. Further examination of this data combined with refined IDE sensor sensitivity relations derived from orbital data and from archived ground test data should define a narrower size range for these debris particles.

There is fairly good agreement of the density of small crater densities for all surfaces on a particular side of LDEF that were exposed for the entire 5.77 year mission. Comparison of Al foil and plate data from the West and North sides of LDEF (trays C03 and D-12, respectively) with the IDE (Exp. A0201) sensor data from the same locations (ref. 10) indicates that the 1.0 μm metal-oxide-semiconductor (MOS) sensors were triggered by particles that would leave an ~3 μm diameter crater in Al. This is based on the determination of McDonnell, et al. (ref. 6), that the marginal perforation limit, f, for the A0023 thin foils was given by:

$$f = (0.59)(1.15)D_C = 0.68D_C$$

where D_C is the crater diameter at the foil surface. While no 5.77 year flux data is available for the IDE 0.4 μm MOS sensors (due to power loss), a first order estimate of the sensitivity factor can be derived from the ratio of the insulator thickness:

$$(0.4/1.0) \times 3\ \mu m = 1.2\ \mu m \text{ equivalent Al crater size}$$

There is much to be said (and much that has been said) about the reported flux distributions listed in Table 1. These tasks are appropriately left to the community and a summary of their efforts will appear in the committee's final report. However, a question of long term micro-particle impact flux variation on the West side of LDEF by factor of 2 is raised by the temporal data reported to this committee by Mulholland, et al. (ref. 9, ft note 4), and Mandeville (ft note 6). According to these investigators, a higher particulate flux rate occurred during the first year of LDEF's orbit compared to the 5.77 year average flux. Mulholland also reported first year fluxes on LDEF's space-facing and North (row 12) sides that were about twice as great as the 5.77 year average fluxes for these locations (ref. 10). The East (ram) sensors showed no significant variation in the first year and 5.77 year impact fluxes. South (row 6) side sensors have not been evaluated yet. Earth-facing panel IDE sensors showed a 5.77 year flux rate that was twice as high as the rate during the first year, and no large particle impacts were noted on these sensors. These are interesting results that may eventually be correlated with orbital or natural events by the community.

Because of the reported long term temporal variations in micro-particle impact fluxes, it is imperative to correlate all other temporal impact data available from surfaces that were only exposed during the first year of LDEF's orbit. Data from optically smooth surfaces are preferred to other surfaces because of a reduced crater-size detection threshold.

Another question of interest to this committee is: what are the smallest size primary impacts observed on LDEF? Walker and Swan (ft note 5) have reported results from high magnification (1000X) SEM scans of their optically-smooth Ge capture cells located on row 8 (Table 1). In general, all craters on row 8 Ge wafers had associated spall zones. The exposure time for these surfaces is given as ~5.5 years because they were initially covered with 2 μm thick metallized Mylar films that apparently failed during the first few months of orbit. The smallest craters found by the researchers were ~0.1 μm in diameter. In most cases the surface texture of metal samples precludes identification of such small features.

In summary, this interim report of the M&D SIG Micro Crater Committee has

(1) listed the micro-particle cumulative flux data reported to date,
(2) noted general consistency among the 5.77 year flux rates reported from different surfaces,
(3) identified long term temporal variations in the reported "average" flux rates,
(4) listed the cumulative flux data for the smallest features identified on LDEF (0.1 μm craters in Ge) to date.

The following tasks are required to develop a comprehensive data base on micro-particle impacts on LDEF:

(1) More ground test data are needed on hypervelocity (10-20 km/s) micro-particle impacts into crystalline materials such as Si and Ge. A thorough review of the literature should define the needs for additional test data.
(2) Additional information is highly desirable on micro-crater densities and size distributions on other materials on LDEF, especially optically-smooth surfaces.
(3) It is imperative to correlate all other temporal impact data available from surfaces that were only exposed during the first year of LDEF's orbit.
(4) Chemical analysis information on particle sources should be collected.

Although the fourth point listed has not been discussed in detail in this interim report, a significant data base on micro-particle residue analyses is under development (see refs. 2 & 11, ft note 1). Several hundred impact sites have been analyzed by various investigators, and significant new data was presented at the Second LDEF Post-Retrieval Conference in June 1992.

CONVERSION OF IMPACT FEATURE DIMENSIONS INTO PROJECTILE PROPERTIES: CALIBRATION OF LDEF FEATURES

Introduction

An important goal of the M&D SIG is to reconstruct the initial impact conditions for individual impact craters and penetration holes, as well as the average conditions characterizing any given population of impact features. Of specific interest is the derivation of projectile properties, such as size, mass, and kinetic energy, and their relative and absolute frequencies typical for a given population of impact features, and ultimately for the entire LDEF. These frequencies constitute first order information for the reconstruction of possible sources and source mechanisms for both natural and man-made particles. They also form the basis for any predictive capabilities regarding collisional hazards to operations in LEO. As a consequence, the dimensional analysis of impact features and the conversion of these dimensions into projectile properties constitutes a high priority activity of the M&D SIG.

Such efforts are frequently also referred to as "calibrations" because they utilize craters and penetration holes produced under known laboratory conditions. The latter reveal significant dependency on impact velocity, angle of incidence and diverse physical properties of both the target and projectile materials, such as density, compressive strengths, porosity, and material-yield criteria under high dynamic compressive and tensile stresses. As a consequence, results obtained under a specific set of laboratory conditions are not readily applied to another set of conditions. Substantial efforts by many workers, both experimentalists and theoreticians, are underway to understand the effects of absolute projectile size (dimensional scaling), velocity (velocity scaling) and material properties (strength scaling) that control the size of an impact feature, including combined parameters such as kinetic energy (energy scaling). Proper interpretation of LDEF impact features depends on the correct scaling of all parameters, yet improved dimensional scaling and velocity scaling rank foremost in the goals of LDEF workers, because the current experimental data base suffers from a paucity of information at appropriate projectile sizes (1-1000 μm) and velocities (>10 km/s).

This report reviews some of the existing experimental data and their generalizations to permit interpretation of LDEF craters and penetration holes. It does not intend to provide a complete overview of the extensive impact literature. We will also demonstrate that computer based impact simulations have evolved into powerful tools to permit extrapolation of laboratory results to conditions beyond those actually simulated.

Experimental Calibration

All calibration activities begin with well-controlled experiments, combined with standardized measurement techniques. For example, when measuring the diameters of craters or perforation-holes several different diameter measurements can be made. The diameters can be measured at the original surface of the impacted material (this is the preferred measurement), or they can be measured at the center of the crater/perforation lip, or they can be measured at the outer lip edges. These diameters can differ by factors of two to four from each other for the smallest craters. If the type of measurement is well-documented, and if the impactor and target materials are well-characterized and the impact characteristics (i.e. velocity, angle of incidence) are known, it may be possible to convert these measurements to equivalent diameters at the original surface of the impacted materials. For calibration, the better characterized the laboratory conditions, the more useful the data. The impactor and target materials should have well-known physical properties, including knowledge of how these properties vary with the extreme temperatures and pressures characteristic of hypervelocity impacts. If the impact data will be used to calibrate or benchmark a hydrodynamics computer code, the materials' equations of state must also be well known. For these reasons, initial calibration experiments typically use such materials as aluminum, stainless steel, or lexan. In addition, initial calibration experiments often use the same material (e.g. aluminum) for both target and impactor.

Several experimental techniques are available for performing calibration tests. All of these techniques have positive and negative features, and there is not currently one which directly simulates all aspects of the meteoroid and debris impact environments. For determining material properties and equations of state, flat-plate impact experiments at the velocities of interest are the best technique. The capability to get the appropriate velocities with the correct types of materials is the primary issue in calibration testing. Various types of accelerators (e.g. Van de Graaff electrostatic accelerators, plasma-drag accelerators or light-gas guns) can achieve different velocity regimes, but with a limited range of particle sizes, shapes and materials. For example, two-stage, light-gas guns are available which can launch almost any material larger than ~50 μm, of many different shapes, to velocities typically <8 km/s. On the other hand, Van de Graaff accelerators can launch particles at velocities exceeding 20 km/s, yet only for submicron-sized, surface-conducting and highly-charged projectiles. This is why these particular experiments typically employ iron particle projectiles, and why experiments with silicates and other interplanetary dust analogues are lacking. These limited launch capabilities have led to a paucity of data on various materials and impact conditions which are nonetheless critical to LDEF data analysis.

Analytical Calibration

Calibration is completed when analytical models have been checked to ensure they correctly reproduce impact phenomenology and once they include predictive capabilities of impact effects and damage. Analytical models can be in the form of either semi-empirical equations for first-order analysis or hydrodynamic computer codes for more precise analysis and a better understanding of the physical processes involved.

Semi-Empirical Equations

Semi-empirical equations can be curve-fits to limited experimental laboratory data sets or can be derivations from physical equations, but with empirical constants or exponents. Both approaches are highly dependent on the size and quality of the data set. In addition, the second type of equation is highly dependent on the assumptions which were used to perform the derivations. The derived equations can be much more accurate than pure curve fits, but can suffer due to the assumptions. For example, it is common practice to include only target material properties in these equations. This is a poor practice, because material properties of the impactor are just as important.

Many semi-empirical equations have been proposed. However, the equations which have been most widely used in analyzing space exposed surfaces include: Pailer and Grun (ref. 12) and Carey et al. (ref. 13) for marginal perforations; Cour-Palais (14) for cratering in metals, specifically in aluminum targets; and Gault (ref. 15) and Mandeville (ref. 16) for brittle glass or ceramics. With the increased data from the last several years, the semi-empirical equations have been improved somewhat, yet there is still no overwhelming concensus regarding improved utility to cases beyond those simulated in the laboratory, as discussed by Humes (ref. 17), for example.

Currently, the recommended equations are as follows. For marginal perforations of Al we use the McDonnell and Sullivan (M&S) equation (ref. 7):

$$f_{max}/d_P = 1.023 d_P{}^{1.056} (\rho_P/\rho_T)^{0.476} (\sigma Al/\sigma_T)^{0.134} V_p{}^{0.664}$$

where f_{max} is the equivalent thickness of foil for the ballistic limit, d is diameter (measured in cm), T stands for the target, P for the particle, ρ is density, σ is strength, and V is impact velocity (in km/sec). For craters in aluminum use the formula of Cour-Palais (ref. 14) as updated by Humes (ref. 17):

$$P = 0.42 m^{0.352}\, \rho_P{}^{1/6} V^{2/3} (\cos\theta)^{2/3}$$

where P is crater depth measured down from the ambient surface, m is particle mass, and θ is the impact angle. For craters in brittle materials use the equation of Mandeville (ref. 16):

$$\log D_c = 0.48 + 0.36 \log m$$

where D_c is crater diameter.

The biggest shortcoming of most of these equations is the limited data set used for derivation. Also, in many cases we are not yet smart enough to properly synthesize the data, and the processes are extremely complex, defying treatment via a few simple terms.

New efforts underway by LDEF PIs and SIG members will attempt to combine data sets and revise equations for marginal perforation and cratering based on the increased quantity of data. Of particular interest in their work is the transition from cratering to penetration, such that small craters and relatively large penetration holes from a single experiment surface may be converted to internally consistent distributions of projectile sizes; this is not currently the case, as described by Warren et al (ref. 18) for Solar Max and by Humes (ref. 17) for LDEF surfaces. In addition, McDonnell, Mandeville, Watts and Atkinson are continuing their individual developments of the current marginal perforation, cratering, and brittle cracking equations. Horz et al. (ft note 8) suggest that the marginal penetration limits can possibly be replaced by unique solutions for projectile size from the measurement of hole diameter and foil thickness (at unit velocity). Much more experimental data is still needed, particularly for the brittle cracking of ceramics and the behavior of composites in order to define good semi-empirical equations for major classes of materials employed in spacecraft.

Hydrodynamics Codes

Hydrodynamics codes are based on physical principles. These computer codes require long run times and large computer memories, and are typically used on computer workstations or supercomputers. These codes are very useful for predicting specific cases, or for looking at how impact phenomena vary with changes in material properties. However, their long run times (which lead to high costs) make them of little use for first-order predictions.

These codes are very dependent on the degree of characterization of the materials' equations of state, properties, property variations with temperature and pressure, and pre-impact states. If these are not known, then specific impact cases cannot be predicted. In addition, because of material variations, the codes require benchmarking against actual experiments. This benchmarking consists of making predictions, comparing the predictions against actual experimental data, and "tweaking" material properties within the acceptable physical ranges to consistently match the data.

Many hydrodynamics codes are currently in existence. In the past, HULL and CSQ were widely used for impact predictions. Currently, the best codes for impact predictions are the CTH code from Sandia National Laboratory and the MESA code from Los Alamos National Laboratory. All of these codes are undergoing continual improvements. In addition, a new Smoothed Particle Hydrodynamics (SPH) code is in development at the Phillips Laboratory in Albuquerque, NM.

The biggest drawbacks in using hydrodynamics codes are the lack of equation of state data for many of the materials of interest, and the codes' problems in modeling ceramics and composites. The latter problems will be slowly reduced with future codes and further code improvements. However, the lack of equation of state data can only be fixed by collecting additional data.

Example Of An LDEF-Related Calibration

The following is an example of a calibration performed for interpretation of LDEF cratering data and for selecting the "best" marginal perforation equation. First, the CTH code has been benchmarked against experimental data. Then the CTH code has been used to predict marginal perforations in typical satellite materials. These predictions have then been compared against predictions made using the Pailer and Grun or the McDonnell and Sullivan equations. We present here results of a preliminary study, which concentrates on the issue of marginal perforations (penetrations). The emphasis on aluminum for both impactors and targets is based upon the wide availability of data for this metal. Fortunately, both the frame of LDEF and most space debris are composed of aluminum. Because symmetric modelling avoids the issue of material strengths and densities this aspect was not well studied, except in the context of matching Horz's data.

A series of calculations have been made using the CTH code to investigate the penetration of typical satellite walls with typical space debris, which were then compared to LDEF observations. For these calculations the walls were assumed to be Al 6061-T6 alloy. For the CTH calculations, the impactors were spherical aluminum bodies, and both impact speed and size were varied to determined a matrix of penetration conditions. The matrix was bounded with the upper impact speed of about 20 km/s for debris (head-on collisions), and with a maximum particle size of 0.5 cm (the largest crater observed on LDEF about 0.5 cm diameter). Table 2 lists the results of these preliminary runs.

The first task with the CTH code was to perform some type of validation between experimental results and reproducible computer simulations. The data and results from a series of gas gun experiments was provided by Fred Horz (NASA JSC) (Table 3; also ft note 8).

The data provided by Horz contained many combinations of materials that were used for the impactor and the projectile. In order to get reasonably accurate results with the CTH code the materials chosen had to have material properties that were readily available and well characterized. Complex compound materials were ruled out, leading to a choice of an aluminum target and an impactor made of soda-lime glass.

Several models were available in CTH code to permit thermodynamic formulation of an equation of state; however, the one chosen was the Mie-Gruneisen. We caution that this is largely a thermodynamic parameter, related to shock isentropes, that may have little to do with affecting the material flow. The CTH code has an enormous number of options for both equations of state and constitutive relations. These calculations concentrated on simple elastic-plastic models and simple fracture (spall) models. The plastic compressive yield strengths were varied for both the soda lime impactors and the aluminum targets. The spall strengths were similarly varied. Yield and spall strength data were obtained from the literature and soda-lime manufacturers; for aluminum the data were based solely upon "best fit", since aluminum can have grossly varying properties depending upon composition and tempering history. By inspection of the literature we found that the closest fit for the aluminum targets of Horz was Al 1100 alloy with a temper of H16. The final best fit data and information entered into the code were the following:

Aluminum:

yield = 1.3 kbars, spall = 1.6 kbars; density = 2.70g/cm^3;
sound speed = 5.31 x 10^5 cm/sec; Gruneisen = 2.25; heat capacity = 1.04 x 10^{11} erg/cm^3/eV; constant in linear Hugoniot = 1.34

Soda-lime Glass (Horz Experiments):

yield = 10 kbars, spall = 1.2 kbars; density = 2.20g/cm^3; sound speed = 5.91 x 10^5 cm/sec; Gruneisen = 0.40; heat capacity = 8.744 x 10^{10} erg/cm^3/eV; constant in linear Hugoniot = 1.50

TABLE 2 Results of preliminary runs

Plate Thickness (mm)	Proj. Diam. (mm)	Proj. Veloc. (km/s)	Penetration	Comments
2.5	5.0	1.3	Yes	Spall
2.5	1.0	4.4	Yes	Spall
2.5	1.0	4.3	No	Spall
2.5	0.75	8.0	Yes	Spall
2.5	0.75	7.5	No	Spall Layers
2.5	0.50	17.0	Yes	Clean Hole
2.5	0.5	16.0	No	Spall Layers
2.0	1.0	3.5	Yes	Spall
2.0	1.0	3.0	No	Crater
2.0	0.75	5.3	Yes	Spall
2.0	0.75	5.0	No	Spall Layers
2.0	0.50	11.3	Yes	Spall
2.0	0.50	11.0	No	Spall Layers
2.0	0.25	20.0	No	Vapor Prob
1.5	1.0	2.2	Yes	Spall
1.5	1.0	2.0	No	Crater
1.5	0.75	3.2	Yes	Spall
1.5	0.75	3.0	No	Spall layers
1.5	0.50	7.0	Yes	Spall
1.5	0.50	6.5	No	Crater

TABLE 3: Data from F. Horz on Soda-Lime Glass Impact Experiments

Shot Number	Projectile Diameter (mm)	Aluminum Thickness (mm)	Velocity (km/s)	Hole Diam. (mm) Test	Hole Diam. (mm) CTH
786	3.175	9.02	5.8	3.62	10
787	3.175	8.64	5.81	7.31	12.5
788	3.175	7.62	5.79	10.19	12.5
789	3.175	1.6	5.87	8.76	10
791	3.175	10.94	5.84	13.73*	11.00*
785	3.175	9.525	5.91	2.24	9.8

*Crater diameter, not a penetration

Data/Model Fit

Workers at POD, Assoc., have tried to fit the penetration data with analytic equations. The CTH data is approximately fitted by the function:

$$V_P = k\, d_P^{\alpha}\, T^{\beta}$$

where k is a constant, V_P is the projectile velocity, d_P is the projectile diameter and T is the wall thickness. A large number of CTH runs were required to identify the actual penetration conditions. The resulting matrix of CTH data is, however, somewhat sparse. The best fits give:

$$\alpha = -1.5\ (\pm 0.2) \text{ and } \beta = 1.6\ (\pm 0.2)$$

Thus:

$$V_P = 1.4 d_P^{-1.5}\, T^{1.6}$$

with v_P in km/s when d_P and T are in cm. Rearranging, we have

$$T = 0.81 d_P^{0.9375}\, V_P^{0.62}$$

which should be compared to the Pailer and Grun (P&G) (ref. 12) equation:

$$T = m_P^{0.4}\, V^{0.833}\, \rho_P^{0.333}/(\varepsilon^{0.06} \rho_T^{0.5})$$

where ε is a material-specific strain value, ρ_T and ρ_P are wall and particle densities, m_P is the particle mass, and V is the normal impact speed. For a symmetric Al/Al impact this becomes:

$$T = 1.13 d_P^{1.2}\, V_P^{0.833}$$

We note that, although of similar form, the two equations differ in the values of the power indices. It is not clear whether these differences are real or merely a consequence of limited data. The Pailer & Grun formulation is not based on either theory or computation, but rather on experimental data for a variety of impactor and target materials, sizes or velocities; it is a "global" best fit for all their data.

Another equation utilized and compared is that of McDonnell and Sullivan (M&S) (see above). The M&S equation has power indices closer to those obtained from the CTH data, and lies between the CTH formulation and that of P&G. Again, the M&S equation is mostly derived from experimental data. For a symmetric Al/Al impact, the M&S formulation reduces to:

$$T = 1.023 d_P^{1.056}\, V_P^{0.644}$$

Taking a closer look at the three penetration equations quoted above, the following estimates are derived for predictions of penetrations as a function of satellite wall thickness. Although the CTH calculations were specific to only three wall thicknesses, extrapolations have been made using the derived equations. Each of the equations is inverted to give particle size. Thus we have:

CTH: $d_P = 1.2520 T^{1.067}\, V_P^{-0.666}$
P&G: $d_P = 0.9032 T^{0.833}\, V_P^{-0.6942}$
M&S: $d_P = 0.9769 T^{0.947}\, V_P^{-0.6288}$

Although the three equations differ in their constants and power indices, they predict very similar values of particle diameter for given values of T and V, as shown below in Table 4. We note that the predicted particle diameters agree within <17%, with the greatest errors occurring at the smallest sizes. These particles and wall dimensions, and the impact speed, are within the range of existing impact facilities, and experiments form part of the data base upon which scaling laws are founded. The above close agreements with differing laws illustrate why such differences exist, since unambiguous results are not easily obtained.

TABLE 4: Penetration Particle Diameters for Debris

Wall Thickness	d_P (mm)			Ratio
	P & G	M & S	CTH	max/min
1.0 mm	0.313	0.299	0.268	1.17
1.5 mm	0.439	0.438	0.414	1.06
2.0 mm	0.558	0.576	0.563	1.03
2.5 mm	0.672	0.711	0.713	1.06
3.0 mm	0.782	0.845	0.867	1.11
3.175 mm	0.819	0.892	0.92	1.12

Summary Of Future Requirements

Several requirements still exist in order to complete calibration for LDEF. Completing these requirements will also benefit other impact data calibration projects and any future flights of meteoroid and debris experiments. As previously stated, the current data sets need to be combined. This will allow refinement of semi-empirical cratering, marginal penetration, and brittle cracking equations. It will also allow identification of gaps in the data.

Much data still needs to be collected for use in developing semi-empirical equations. This is particularly true for impacts in brittle materials. Data also needs to be collected to better define equations of state for materials of interest to LDEF, other spacecraft, and future meteoroid and debris experiments. In addition, data needs to be collected on the total damage (e.g. spallation, delamination, and deformation) caused by impacts, not just cratering, cracking and perforation.

Currently, no good models exist for first-order total-damage prediction. These types of semi-empirical equations and models need to be developed. These models then need to be associated with environment models for complete calibration of the LDEF data.

Finally, while not previously addressed, there is a problem with calibration of the small crater (<100 μm diameter) data on anodized materials. The thickness of the anodization layer can be of great significance to the size of crater formed by different impactors, if the layer thickness is greater than ~20% of the crater diameter. The aluminum oxide in the anodized layer has a higher density and is much harder than Al 6061-T6 alloy. This can change the calibration of cratering and penetration equations, and alter the conclusions which will be made from subsequent analysis, such as environment model comparisons. This feature could also explain the trend, reported by several LDEF workers (see above), for cumulative impact feature number densities to "roll-off" at smaller sizes (e.g. <50 μm), and thus be well below the Kessler predictions and IDE results (ft note 4).

PARTICULATE FLUX ESTIMATES

Spacecraft in Earth orbit produce clouds of debris when they spontaneously explode or collide with one another. The first satellite explosion was observed by NORAD radar in 1961 and there have been over 90 satellite fragmentations since that time (ref. 19). That mutual collisions between spacecraft might produce a hazard to future space travel became clear in publications in the early 1970's (see ref. 20 for early work on collisions and for reference to yet earlier publications). Investigation of the space debris phenomenon has greatly intensified since that time to extend knowledge of the space debris population down to well below the 10 cm diameter objects that NORAD has been able to detect.

Meanwhile, meteoroid investigators attempted to determine the flux-versus-mass distribution of meteoroids by examining surfaces that had been exposed to space for extended periods (including lunar rocks) and then returned to Earth for laboratory examination; this determination was to be made by observing the number and size distributions of impact craters on the returned surfaces. By the mid 1970's these investigators started to detect, to their annoyance, impacts by aluminum and paint particles on the retrieved surfaces (ref. 18). That this was a problem meteoroid investigators would simply have to live with was shown quite clearly when about three square meters of the surface area of the Solar Max satellite was brought back to the Earth during a repair mission (see ref. 18 for some of this work and for references to earlier work). Hundreds of impacts by both meteoroids and orbital debris were detected on the Solar Max surfaces.

LDEF, because it was stabilized with its long axis continuously pointed radially to the Earth and fixed in rotational orientation about this axis so that one surface always faced in the direction of orbital motion of LDEF, is adding greatly to our knowledge of the flux of meteoroids and orbital debris. In addition to the large area-time of space exposure (two orders of magnitude greater than previously returned spacecraft surfaces), LDEF also affords the opportunity to obtain information about the directionality of the meteoroid and debris fluxes. This information can then be related, it is hoped, to the sources of meteoroids and orbital debris. Perhaps the asteroidal versus cometary abundance of impacting meteoroids can be deduced.

Well before LDEF recovery, Zook (ref. 21) theoretically deduced, under a "randomness" assumption, that from 6 to 9 times more meteoroids per unit area were expected to strike an LDEF leading edge surface than would impact a trailing edge surface; and, further, that this ratio depended on the velocity distribution with which meteoroids approached the Earth. These leading-to-trailing edge ratios of fluxes were due solely to LDEF orbital motion. When meteoroid impact velocities and a penetration equation are also taken into account, relative areal densities--leading to trailing edge--of meteoroid impact craters on LDEF can also be calculated (refs. 17 & 22); these ratios are found to range from 10 to 30, depending on the meteoroid velocity distribution and the meteoroid size distribution used. Kessler et al. (ref. 19) similarly deduced theoretical ratios to be expected for orbital debris.

LDEF Results To Date

We summarize here only the most salient findings concerning the separate meteoroid and debris impact populations, and their directionalities, that have been derived from LDEF investigations and published to date.

First there is clear evidence of impacts by both orbital debris and meteoroids on LDEF. By far the best means to separate the two populations is to determine the composition of the residue, if any, in the impact craters. Most spacecraft debris particles consist of aluminum fragments of spacecraft structures, of aluminum oxide from the burning of solid rocket fuel, or of paint particles (shown by the elements zinc, titanium, and aluminum, whose oxides commonly provide the white pigments in thermal paints). Impacts by organic particles--often human waste--are also seen quite often (usually dominated by the elements phosphorus, sodium, and potassium in EDX analyses). Such analyses are being carried out by several groups (see, especially, articles in "LDEF--69 Months in Space"). These analyses are far from completed and are essentially all still in progress; determining the composition of the residue in each of thousands of craters is no small task!

Analyses of residues in impact craters on gold surfaces that were facing the trailing direction of LDEF (refs. 1 & 3, ft note 8) have produced a very interesting result: Of 187 craters that had been analyzed for residue, 30 were found to result from impacting space debris while 57 were identified as of meteoritic origin; 111 craters had no identifiable residue in them and so an origin could not be assigned. This result was surprising because before LDEF recovery it had been predicted (ref. 19) that almost no debris would hit the backward-facing LDEF surfaces. The only way these surfaces can be struck is for particles to catch up to LDEF from behind. This, in turn, implies that LDEF must be near the perigee of particles in highly elliptical orbits; debris in geosynchronous transfer orbits would appear to be responsible.

On an aluminum surface facing about 50 degrees from the leading edge, Horz et al. (ref. 3, ft note 8) found that orbital debris impacts start to become more numerous than meteoroid impacts for impact craters smaller than about 100 microns in diameter. Below 50 microns in diameter, orbital debris appears to dominate the crater populations on leading-edge LDEF surfaces. Although several investigator groups (see LDEF-69 Months in Space) are doing compositional analyses, that by Horz et al. (ref. 3, ft note 8) is probably the most complete to date and is therefore quoted here.

Second, the time variation of the flux striking LDEF is also a strong indicator of the origin of the impacting particles. The only "active" meteoroid experiment on LDEF was the "IDE" experiment flown by Singer et al. (ref. 8, ft note 4) which electrically recorded when each impact occurred that penetrated one of many MOS detectors placed around LDEF. This experiment recorded over 15,000 impacts that penetrated either 0.4 μm or 1.0 μm thick dielectric layers of MOS capacitors.

The IDE sometimes sensed multi-orbit "streams" of particles, where the impact rate would greatly increase for a few minutes on every orbit. A very strong stream of this type was seen on June 4, 1984, where the stream was seen every orbit for about 25 orbits; 131 impacts occurred in 2 minutes on the first passage of this stream. The only reasonable interpretation of such a multi-event sequence is that LDEF was passing through the orbit plane of the debris cloud associated with some satellite (not yet identified). Also, the impact rate on IDE was elevated for the first few days of the mission. Presumably this was caused by contaminant particles from the Shuttle that had launched LDEF.

IDE also detected "beta meteoroids". These meteoroids are dust grains that are leaving the solar system on hyperbolic orbits to become interstellar grains, and their apparent flux should be at a maximum when a sensor faces toward the Sun. The beta's were best, and most clearly, detected by rearward-facing IDE sensors when they faced the Sun.

Third, the spatial density of impact craters is much greater on surfaces close to the leading edge of LDEF than it is on surfaces near, or at, the trailing edge. Leading edge-to-trailing edge ratios of spatial densities of craters depend on crater size and range from about 10 for craters smaller than about 50 microns in diameter (ref. 6) to about 20 for impact craters larger than about 500 microns in diameter (refs. 17 & 23). Although there are probably a number of debris impacts in the population of large (diameter >500 microns) impact craters, the ratio of leading-to-trailing crater spatial densities also appears consistent with meteoritic impacts alone (ref. 22). The best fit to the observed LDEF results is obtained when the meteor velocity distributions of Kessler (ref. 24) and of Erickson (ref. 25) are used to give particle velocities relative to the Earth.

In summary, analyses of impact craters (and holes in thin films and plastic) and the time history of impacts on LDEF are giving us a much better picture of both the meteoroid and space debris populations in near-Earth orbit. We have become especially aware of new features of the orbital debris populations: some debris clouds are concentrated into orbital planes and do not dissipate into the background as fast as one might have expected; more debris is impacting trailing-edge surfaces than was expected, probably implying that geosynchronous transfer orbits are well populated with debris.

Implications Of Results And Further Studies Needed

The largest impact crater on LDEF was 0.57 cm in diameter and was probably caused by an object about a millimeter, or a little less, in diameter. This is greatly helping to bridge the observational gap between the radar data (now estimated to reach down to about 1 cm diameter) obtained from ground stations and data returned from direct observations in space on orbital debris, or to make it possible to more confidently calibrate atmospheric meteor data. This means that shielding against meteoroids and debris to protect satellites from damage can now be better estimated; this is especially important for Space Station Freedom where many millions of dollars will be spent for impact shielding. It is also very important to establish an impact cratering rate at one point so that it may be compared with cratering rates at some time in the future; thus the growth of the orbital population with time can be monitored and compared with theoretical models and thereby validate (or invalidate) them.

Work for the future includes the following: 1) Much more needs to be learned about the chemistry of residues in impact craters--especially as it applies to separating the meteoroid and orbital debris populations into two distinct groups. 2) In theoretical modeling, all investigators need to understand the assumptions involved and what the implications are of changing the assumptions. That includes the "randomness" assumption for meteoroids, as well as trying out different meteoroid velocity distributions than the ones that have been tried. That is, how unique is the Erickson-Kessler distribution? Can we put in a larger asteroidal component and still fit the data?

LDEF METEOROID AND DEBRIS IMPACT DATABASE

The LDEF M&D database maintained at Johnson Space Center consists of five data tables containing information about individual features, digitized images of selected features, and inventory data for LDEF hardware controlled at JSC. About 4000 features were identified during the disassembly of the satellite at Kennedy Space Center, and an additional 4500 have subsequently been identified at Johnson Space Center. The database also contains a small amount of information which has been submitted by members of the PI community. Location information and other data for about 950 samples which are controlled by JSC are also included in the database.

Images for about 4500 features have been digitized. Although these images are not stored on-line because of the large amount of disk space required, the database contains the names (left and right image) and the removeable disk designation on which they reside. These images can be made available for downloading at the user's request.

Data Tables

The five data tables in the M&D database are named Primary Surfaces, Features, Cores, Digital Images, and Allocation History. The Primary Surfaces, Cores, and Allocation History tables are primarily used for keeping track of the samples controlled by JSC, although they do contain other information about the nature of the samples. The Features Table represents the focus of the database on which the other tables are based. It contains one record for every feature which has been identified either at KSC, JSC, or by contributing investigators. The Digital Images Table represents an index for retrieving digitized images of the features.

Sample Numbering Scheme

The feature numbers recorded in the database represent a combination of the surface ID and a unique feature number for that surface. The surface ID consists of four parts: the LDEF Bay and Row number, the component type, and the component number. The bay and row numbers are the same as those initially assigned to the satellite grids. The component type is a one-letter code which translates to a particular piece of hardware. Examples of common component-type codes are "E" for experiment trays, "C" for clamps and "F" for frame pieces (intercostals and longerons). The component number is a sequential number assigned to differentiate separate pieces of the same component type taken from the same bay and row. (NOTE: Subsequent divisions of components after the initial KSC scan are assigned 2-letter subsurface designations for purposes of maintaining uniqueness of individual surface pieces.) Specific feature numbers are assigned sequentially as they are identified; numbers begin with 1 for each surface.

Cores, which represent features that have been removed from a surface with part of the surrounding substrate, are numbered sequentially as they are removed regardless of the surface number. All cores taken from LDEF are prefixed with the characters "LD-" to differentiate LDEF cores from those taken from other satellites.

Primary Surfaces Table

The Primary Surfaces Table contains one record for each surface (and subsurface) on which features have been identified. The table contains fields for the origin, shape, orientation, surface area, substrate, location, and comments. These fields contain the following types of information:

Origin	LDEF Experiment Number, Intercostal, Longeron, Thermal Blanket
Shape	Rectangle, Dimensions
Orientation or Position	Left, Right, Center
Surface Area	Area of the surface in mm^2 (excluding overlaps and penetrations for bolts)
Substrate	Aluminum, Teflon, Steel, Gold
Location	JSC Location, PI (Locations are recorded only for those surfaces controlled by JSC)

Features Table

The Features Table contains one record for each feature which has been identified. It contains fields for the site of identification, X and Y coordinates, diameters, depth, impact type, and the presence of material. These fields contain the following types of information:

Site of Identification	KSC, JSC, or PI Name
X and Y Coordinates	Two sets of coordinates are recorded; one set represents the coordinates relative to an arbitrary origin assigned when the surface was originally scanned at KSC The other set represents the coordinates as recorded during any subsequent scanning of the surface at other facilities; offsets are calculated so that the data can be converted to the KSC values.
Diameters	Diameters for both major and minor axes are recorded for non-circular features. The diameters currently recorded in the database represent measurements made from lip to lip. Analysis of the digital images is now underway at JSC which will provide diameters of the features as determined at the original target surface.
Depth	Depth information is now recorded for only a very few features; this information was provided by Don Humes. Analysis of the digital images will also provide depth data for digitized features.
Impact Type	Crater, Hole or Penetration, Other (spray pattern, etc.)
Material Presence	Yes, No, and sometimes the quantity of material

Cores Table

The Cores Table contains one record for every unique Feature/Core combination. In some instances, there may be more than one feature present on a core because close proximity of the features makes it difficult to separate them. In such cases, there are two (or more) records entered; both records have the same core number but different feature numbers. Additionally, there may be several records for different core numbers with the same feature number. This situation usually arises when the surface is made up of more than one layer of material, and the feature is present on several layers.

This table contains fields for the core number, feature number, sub-surface, layer, substrate, and location. These fields contain the following types of information:

Core Number	Sequentially assigned unique integer, prefixed by the characters "LD-". Core numbers are assigned in order, regardless of the surface on which they were identified.
Feature Number	Corresponds to the number of the feature (or features) physically present on the core.
Sub-Surface	Additional designator for surfaces physically separated from original surfaces.
Substrate	Aluminum, Steel, Teflon, Gold
Location	JSC Lab or PI Name

Digital Images Table

The Digital Images Table contains one or more records for each left image filename. Duplicate records with the same image filename are allowed to accommodate images recorded at KSC and later recorded at JSC with the same name. It contains fields for left and right image filenames, feature number, magnification, station no., disk no., and image date. These fields contain the following types of information:

Left Image File and Right Image File	The names of the image filenames are constructed so that the feature number is contained in the name of the file and so that they conform to DOS file naming convention of an 8-character name followed by a 3-character extension. For the first image produced of a feature, the first character of the left image file is "L" and the first character for the right image file is "R". Subsequent files are identified by consecutive alphabetic characters; for example, the second set is prefixed by "A" and "B" for the left and right images respectively, the third set by "C" and "D", and so forth. Characters 3-5 of the filename represent the component and component number of the surface ID, characters 6-9 represent the specific feature number (with imbedded zero's for numbers less than 1000). The file extension represents the LDEF Bay and Row grid location.
Feature Number	The Feature Number is included for the convenience of the user. It corresponds to the feature number in the Features Table, and may be derived from the image filenames.
Magnification	This field represents the magnification at which the feature was imaged.
Station Number	There were several scanning and imaging stations set up at KSC, and each one was assigned a separate number. All images recorded at JSC are Station 7.
Disk Number	Represents the disk # on which the image resides. The characters A and B represent the front and back of the disk respectively.
Image Date	Represents the date the image was acquired.

Allocation History Table

The Allocation History Table is used for recording the history of the movement of primary surfaces and cores controlled by JSC. Every time a surface or core changes custody, an entry is made in this table. It contains fields for surface number, core number, investigator or site, and the date allocated. These fields contain the following types of information:

Surface Number	Corresponds to the surface ID recorded in the primary surfaces table. Data is contained in this field only if the sample represents a primary surface.
Core Number	Corresponds to the core number (not the feature number) recorded in the cores table. Data is contained in this field only if the sample represents a core.
Investigator/Site	Either a NASA site or an investigator's name.
Date Allocated	Date the sample was allocated or returned to JSC.

Database Access

The LDEF database may be accessed via SPAN, Internet, or modem. The capability for downloading results of searches to users' local computers via FTP, Kermit, or Mail is being developed and will be available within the next few months. Image files may be downloaded via FTP and, less efficiently, via Kermit. The image files do not stay on-line, but may be made accessible on request.

ACCESS VIA DECNET:

1) Log onto host computer.
2) Type SET HOST 9300.
3) Type PMPUBLIC at the Username: prompt.

ACCESS VIA INTERNET:

1) Type TELNET 146.154.11.35
   or
   TELNET CURATE.JSC.NASA.GOV
2) Type PMPUBLIC at the Username: prompt.

ACCESS VIA MODEM:
The modem may be 300, 1200, or 2400 baud; no parity; 8 data bits; 1 stop bit. The area code is 713 for long distance calls.

1) Dial 483-2500.
2) Type SN_VAX in response to the Enter Number: prompt.
3) Hit <CR> 2 or 3 times after the CALL COMPLETE message.
4) Type J31X in response to the # prompt.
5) Type C CURATE in response to the Xyplex> prompt.
6) Type PMPUBLIC at the Username: prompt.

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FOOTNOTES

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