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PENETRATION RATES OVER 30 YEARS IN THE SPACE AGE

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ABSTRACT

Experimental data from spacecraft providing impact penetration rates and cratering for metallic targets is reviewed. Data includes NASA Explorers 16 and 23 and the Pegasus series, the second US-UK satellite Ariel 2, Space Shuttle STS-3 (MFE), recovered surfaces on Solar Max Satellite, The Long Duration Exposure Facility (LDEF) and EuReCa TiCCE.

Factors concerning exposure to the environment are considered and, especially, material properties which affect the penetration resistance. Reference to a common material, Aluminium alloy 2024-T3, is effected and the data then compared to define firstly an average impact flux over the period. The data is examined, in the context of possible satellite and space debris growth rates, to determine the constancy of the flux. This also provides strong constraints on the current space debris component. It is found that the impact data are consistent with domination by natural meteoroid sources. Growth rates are not evident within the period 1980-1990 and Eureca TiCCE fluxes in 1993, for particles penetrating foils of around 10 microns thickness, supports the constancy of the flux. At larger dimensions the 1993 Eureca TiCCE fluxes show an 8-fold increase (McDonnell et al., 1994) but this is considered not inconsistent with the selective exposure to meteoroid streams of a satellite stabilised in heliocentric co-ordinates for an 11 month period.

1. INTRODUCTION

Experiments to assess hazards in space and to detect meteoroids have been one of the first priorities of exploration established in the USA and USSR. Various methods have been used but success was not always achieved. Early measurements on Explorer 8 reported in (McCracken et al.,1961) were proved to have been influenced by the high susceptibility of piezo - electric microphone detectors in Earth orbit to thermal changes or other factors (Nilsson, 1966). Later reviews (McDonnell 1978) swept much of this early unreliable data away, leaving a core of data from Explorers 16 and 23, and Pegasus 2 and 3 whose high reliability was not 'bettered' until the advent of data from recovered surfaces on Solar Max and LDEF. Penetration and cratering data are seen to offer the most comprehensive definition of the flux rate (i.e. from the same technique) over a wide range of masses. Differing techniques and, even within the penetration data, differing impact materials, can lead to flux differences which may be confused with, or even mask, temporal changes in flux. In this review, to which the latest data from the science experiment TiCCE on the EuReCa spacecraft has also been added, we have selected only penetration experiments, either of single metallic foil, or (with calibration factors), data from retrieved metallic semi-infinite targets. Relevant exposure factors to the space environment and Earth shielding have been presented. More especially, a comprehensive collation of the factors affecting the calibration of the different materials has been made, and an improved penetration formula derived from thin and thick target data, used to reassess the sensitivities of the experiments. This has led to the impact penetration rate for a randomly exposed object, corrected for Earth shielding, at the mean altitude of the experiment deployment, being derived.

2. KEY SPACE EXPERIMENTS IDENTIFIED.

Explorers 16 and 23

Both of these meteoroid satellites carried experiments comprising arrays of pressurised 'beer cans'; a pressure-sensing switch capable of measuring a "once only" leak was activated some short time after the first perforation of any can above the ballistic limit. Experimental details and data for Explorer 16 were presented by (Hastings, 1963 a, b & c ; Hastings, 1964) while those for Explorer 23 were presented by (O'Neal, 1965 & 1968). The data were analysed using chi squared tests regarding possible temporal changes and were found to be random over the exposure epoch. However, this did not preclude possible variations of short duration (e.g. within an orbit) or variations in flux beyond the observation period.

Ariel 2

Aluminium foils were used in a series of active in-situ sensors on board the second US-UK Ariel series; the experiments and analysis were reported by (Jennison et al, 1967). The data, which was analysed by one of the current authors (McDonnell, 1964) in support of his PhD thesis, showed that only one penetration was detected after a total of six months of exposure in space! Because this occurred at the edge of the detector corresponding to the region from which fresh foil was advanced during flight, it could not be ascertained if this was a true space impact perforation or an imperfection in the foil. We might note that the detection threshold for this (photometric) system is larger than that of the ballistic limit because of the need for a significant penetration area for the detection of light. The data nevertheless clearly demonstrated, by virtue of in-flight calibration, that the flux was some 3 orders of magnitude below the piezo-electric data acquired earlier by Explorer 8.

The Pegasus series

Three Pegasus satellites were flown (Naumann, 1965; Clifton & Naumann, 1966; Dozier, 1966). The meteoroid penetration detectors consisted of parallel plate capacitors formed by backing aluminium target sheets with a mylar trilaminate dielectric followed by a vapour-deposited layer of copper. In space, the capacitors were charged to 40 volts and penetrations were registered by discharges through the mylar layers.

It was noted that a penetration slightly larger than the ballistic limit for the thickness specified in Table 1 could be required because of the need to induce a discharge of the sensing capacitor behind the target. Two thicknesses of 2024-T3 aluminium detectors at 203 microns and 406 microns presented reliable data. This data furnished the best assessment of the milligram meteoroid flux until the advent of LDEF, and forms a critical overlap, in terms of sensitivity, with faint radar meteor data (10^{-6} g).

Solar Maximum Mission (Retrieved Louvres)

Repairs to the Solar Max spacecraft, recovered coincidentally at the same time as the launch of LDEF, led to the retrieval, for laboratory analysis, of multi-layer thermal insulation and, of more relevance to this particular study, aluminium louvres. This data (presented by Laurance and Brownlee, 1986) covered a range of crater diameters from sub-micron to millimetre dimensions. The pointing direction of the louvres was assumed to be random regarding the Earth orbital vector because of the dedicated solar pointing direction for spacecraft observations; it has been pointed out, however, (McDonnell, 1992) that the flux data derived in terms of particle **mass** by Laurance and Brownlee was in serious error because of the use of two quite different (and mutually inconsistent) penetration formulae on the same plot; this revised, quite drastically, the interpretation of their microparticle fluxes in terms of space debris. Nevertheless, the original source data, in terms of crater dimension, is incontrovertible and can now be related directly to other penetration data; we must take note of the possibility of some secondary cratering in the SMM data at the smallest dimensions. Although the chemical data of Laurance and Brownlee would seem to be especially relevant to the source of particles, it must be noted that, at very small dimensions, that space debris can be generated efficiently from impacts on surfaces local to the detector (e.g. from the extended SMM solar cell array which was within the acceptance angle for the louvre impacts).

STS-3 Microabrasion Foil Experiment (MFE)

As part of NASA's OSS Pathfinder Payload (OSS-1) an array approaching 1 m^2 in area was exposed for 8 days. Four hypervelocity perforations were detected (McDonnell, et al., 1984); chemical analysis showed silicon rich residues and the morphology was consistent with high velocity natural impactors. The low altitude of MFE (241 km) is of significance in the context of the poor access of microparticles which are in Earth orbit, since their lifetime in circular orbit is measured in terms of hours at this altitude. Access to unbound interplanetary particulates is, however, unabated at this altitude.

LDEF

LDEF's large area-time product and the wide range of materials deployed on it have elevated its importance to a very high level. Further, the many investigators involved have contributed a plethora of papers on the interpretation of the data obtained, in both the Proceedings of the three Post-retrieval Symposia held to-date and in many other journals.

We have chosen data from both experiments and the LDEF M-D Special Investigator Groups (M-D SIG). The small particle penetration data was best defined by the MAP experiment (McDonnell, 1992) for foil thickness and penetration in the range 2 to 30 microns, where detectors pointed in N,S,E,W and Space directions. For the larger impacts, data refers to thick target measurements (Humes, 1991) and data from the thermal control surfaces and the longerons and intercostals of the LDEF frame (See et al., 1993)

The directional stability of LDEF relative to the orbit vector was invaluable in understanding the dynamics of dust particles, but in the context of this survey, it has been "degraded" to imitate a randomly tumbling spacecraft to permit comparison with other data. Therefore, in this context, we have taken the 6-point average of the LDEF data, representing the average flux on the 6 faces of a cube at a given ballistic limit.

EuReCa Timeband Capture Cell Experiment (TiCCE)

Impact data is currently being analysed following the recovery in August 1993 of large areas of thermal blanket, the solar cell arrays and the Science experiment TiCCE (Timeband Capture Cell Experiment). The impact time resolution aspect of the experiment did not function correctly due to an overload in the first exposure epoch. Only flux data comprising thin foil surfaces (with capture cell) and other cratering data from the experiment is currently available, but later publications will extend to the publication of the data from impactor craters in the millimetre range and above on the MLI thermal blankets and the solar cell arrays.

3. EXPERIMENT PENETRATION SENSITIVITIES.

Material specifications for the meteoroid detectors employed on the selected satellites, together with their newly determined conversion factors to 2024-T3 aluminium (derived from our chosen penetration equation) are presented in Table 2. The Earth shielding, gravitational and sensitivity enhancement factors applicable to the data from these satellites are presented in Table 3.

Orbital Data

Orbital data (which is presented in Table 1) is used to find the mean altitude of the spacecraft; orbital parameters change during exposure due to orbit decay and there are also cases of differences between apogee and perigee.

Earth Shielding

The Earth shields an orbiting spacecraft from a proportion of the flux of extra-terrestrial particulate material arriving from 4P steradians of space. This proportion, known as the shielding factor, h , is given by:

$$\eta = \frac{1-\cos\theta}{2} \quad \text{(Cour-Palais, 1969)}$$

where q is the angle subtended by the spacecraft between the distance of the spacecraft from the centre of the Earth and the distance from the spacecraft to a point tangential to and 150 km above the Earth's surface which forms a normal to the Earth's radius.

Gravitational enhancement

As interplanetary particles approach the Earth from far away, their paths will be deflected towards the Earth because of its gravitational attraction. This effect is analogous of the focusing of a parallel beam of light by a convex lens and, because of this, has been termed gravitational focusing. The effect results in a gravitational enhancement of the particulate flux at and near the Earth relative to the flux at a great distance from the Earth. The gravitational flux enhancement factor, c, is given by:

$$\chi = 1 + \left(\frac{V_e^2}{V_\infty^2}\right) \quad \text{(Öpik, 1951)}$$

where V• is the approach velocity to the Earth and V_e is the escape velocity at the altitude of detection H and is given by $V_e(H)$ = +2GMe/(Re+H). Values for c are shown in Table 3.

Sensitivity enhancement

In addition to the increase of the flux of particles near the Earth due to the increase of velocity, we also experience enhanced sensitivity due to the increase of velocity. Thus smaller particles will be detected and hence (due to the size distribution of the particles) a larger number. We find from the LDEF data a cumulative flux index of alpha = 1.7 (mass index .57) between values of f_{max} = 10 microns to 100 microns; using the penetration dependence of f_{max}/dp µ $V^{.806}$ we find a sensitivity enhancement proportional to $(V_i/V_\infty)^{1.37}$ where V_i is the impact velocity increased by gravitational attraction relative to the interplanetary approach velocity to the Earth, V_∞. This enhancement is **additional** to the gravitational flux enhancement. Both factors are shown in Table 3. Accounting for Earth shielding, gravitational enhancement and sensitivity enhancement factors results in a mean total enhancement factor of 1.0279 for the whole data set. Although the differences between experiments are small, nevertheless, they are possibly significant, now that we have an accurate basis for such intercomparisons.

Earth shielding and gravitational enhancement are applicable, of course, only to the interplanetary component. For space debris in Earth orbit, Earth shielding is irrelevant by definition, but is replaced by much more significant factors, such as the altitude or inclination distribution of the space debris itself. Nevertheless, we see in the results of this comparison, that there is very strong evidence for space debris being a very minor component of the data set in the size ranges considered; our arguments regarding sensitivity to such effects as gravitational enhancement for the natural population are justified.

Penetration Formulae

Numerous formulae are available, the majority being derived from experimental hypervelocity penetration work dating from the beginnings of the space era (Fish & Summers, 1965) and with subsequent developments by many others continuing to the present day (e.g. Naumann, 1966, Frost 1970, McDonnell & Sullivan, 1992). References to many are contained for example in publications such as Proceedings of the Hypervelocity Impact Symposium, 1992. For the interpretation of the ballistic limit foil penetration data, we have used a formula which is based on the experimental calibration at hypervelocities of comparable foils:

$$\frac{f_{max}}{d} = 1.272\, d^{0.056} \left(\frac{\rho_P}{\rho_{Fe}}\right)^{0.476} \left(\frac{\rho_{Al}}{\rho_T}\right)^{0.476} \left(\frac{\sigma_{Al}}{\sigma_T}\right)^{0.134} V^{0.806}$$ (McDonnell & Sullivan, 1992)

where s = tensile strength in Mpa; r = density in g cm $^{-3}$; d= particle diameter in cm; and V = velocity in km sec $^{-1}$

This formula incorporates the tensile strength and density of target and in the absence of a true comparison in space, is the best a priori assumption. For aluminium targets the formula (McDonnell & Sullivan, 1992) extends from 4 to 16 km sec^{-1} based on micron impacts using a 2 MV microparticle accelerator (McDonnell, 1970); it incorporates, for larger dimensions, a dimensional scaling which ensures compatibility with light gun data and hence the valid interpretation of millimetre scale impact craters on LDEF and EuReCa. Other formulae have been presented recently (Watts et al., 1993) which offer promise of more comprehensive inclusion of a wider range of parameters. Current assessment of this formula leads to anomalous results and furthermore the formula is not based on actual penetration data of the type demanded for this comparison. One of us (J.M.Baron) is engaged currently in providing new experimental data towards his doctoral thesis which, it is hoped, will provide valuable penetration data for comparison with predictions from these formulae.

4. RESULTS

Shown in Figure 1 is the "raw" flux, representing the measured impact rate per m^2 referred to the detector thickness in microns or, in the case of impact craters on thick targets, the crater diameters converted to the equivalent marginal penetration thickness (f_{max}). Without sensitivity and exposure factors and conversion factors to a common material, we might have been tempted to consider the flux of LDEF, SMM and Eureca to be significantly higher than earlier satellite data . However, when the data is corrected for the appropriate factors (see Table 3 & Figure 2), it results in a considerable shift, both in the Explorer 16 and 23 sensitivities (as anticipated from the higher density and strength of their detector surfaces) and also between LDEF, Pegasus and SMM data. We have identified the following factors for consideration:

a). LDEF and the SMM (Louvre) data are in remarkably good agreement with the exception of:

(i) the flux below f_{max} = 2μm; where SMM flux increases to be one magnitude higher. This may be attributed to the 'contamination' from secondaries (possibly locally generated as has been observed even at LDEF at this dimension) or, alternatively, to a higher microparticle flux on SMM at these dimensions. Until the local secondary cratering hypothesis for SMM is disproved, we would place stronger emphasis on LDEF's 5.76 year 6-point flux measurement as being most representative, but note that the LDEF data at this value (f_{max} < 25μm) shows a high East to West ratio, which is attributed to orbital particulates (McDonnell, 1992).

(ii) The SMM flux above f_{max} = 128μm (as 2024-T3 aluminium) is lower than LDEF by a factor of ~ 1.5. Noting that the 158 μm flux point (as 2024-T3 aluminium) is the greatest thickness measured on SMM and hence statistically uncertain and, further, that the louvres do not represent a truly isotropic exposure, this is not considered significant. On very similar exposure conditions over 11 months on

Eureca, deployed in a similar sun pointing direction, the average flux varied by a factor of 4 in different pointing directions.

b). The Pegasus 400 μm data is lower by a factor of 1.5 than the LDEF point at f_{max} = 400 microns. This discrepancy could well prove significant and has, potentially, the possible interpretation that between Pegasus' 1965 exposure and LDEF's 1984-1990 epoch, the flux had increased by 50%. A space debris component of 50% on LDEF must therefore be considered at least as a possibility, if the natural particulates are assumed, otherwise, to be constant. But, we must first consider the variability of measurements of the natural flux before supporting this approach. We have emphasised the term *measurements* of the flux, rather than true variations in the flux, because, to date, the exposures have not been unbiased. Even within the LDEF data, the flux distribution at f_{max} = 100 μm is found to have minor irregularities; the average ratios of the North to South flux relative to LDEF's orbit over 5.76 years are not symmetrical, despite proper correction for LDEF's offset. The situation has been analysed (McBride et al., 1994) and is understood in terms of the non-random exposure to the crossing of meteoroid streams and cometary planes. It is found that, despite LDEF's fast precession, the yearly cycle is repeated almost on a heliocentric basis, and access to particular faces such as North and South is markedly anisotropic; in fact, access varies to the point of mutual exclusivity for most meteoroid steams. With the well accepted meteoroid steam anisotropies in both flux and direction at masses corresponding to f_{max} = 100 μm,we cannot say that the meteoroid flux will be measured consistently by any one surface on a satellite, **unless** it is truly randomly exposed from both the geocentric and heliocentric point of view, and, **further**, it is exposed for an integral number of years!

c). We see the MFE flux (at lower altitude) returning a flux at f_{max} = 5 mm, which is lower than LDEF by a factor of 4. If LDEF's flux at this dimension is considered to be partly space micro-debris (e.g. McDonnell, 1992), then this albeit short exposure, which returned only four impacts, could provide a useful figure for the orbital (and possibly debris) component, namely, a debris/natural ratio of 3:1. This can be inferred because orbital lifetime calculations for micro-debris at 241 km (Ratcliff et al., 1993) preclude MFE from seeing particles in orbit. The MFE flux is in good agreement with measures of the space pointing flux from LDEF. We cannot quantify the possible space debris components from flux alone, neither at the micron nor the millimetre range; chemical studies on residues are inconclusive, with about 50% being indeterminate and only some 15% of residues having the "debris" signature of typical elements used in spacecraft construction and operations (Bernhard, et al., 1993). Despite this, even from flux rates alone, we can certainly impose useful constraints on growth **rates,** because of the time difference between these different measurements. We have examined this in section 4.

5. FLUX COMPARISONS

Penetration Distributions

Data from all key LEO penetration experiments shown in Figure 2 may be examined in terms of the epoch of the experiment exposure (Table 1). In general,we can see only small flux differences which could be associated with the epoch. Because LDEF represents a very significant flux measurement at all dimensions, other experiments are compared to this penetration distribution. In Figure 3, the flux for different experiments is plotted to show, in more detail, the measured flux relative to the LDEF flux, but on a time axis. For comparison we also show the NASA + 2% and + 5% growth rate which would pertain to large and small space debris respectively.

We see no suggestion that the flux has changed significantly over 30 years, with one possible exception, namely for particulates corresponding to the penetration of aluminium of thickness f_{max} less than 25 microns (McDonnell, 1992). Although both SMM and LDEF are in good agreement (but with SMM showing a higher flux than LDEF at an earlier epoch and hence opposing a growth trend) it is still possible that these data have a significant orbital particulate component and, possibly orbital micro debris. The MFE data point, measured at an altitude below that where orbital particulates can be sustained, could well represent the "pure" interplanetary flux at the time of SMM exposure. It must be emphasised, though, that there are no reliable penetration flux measurements in the early 1960's to demonstrate that this is a true rate **increase** in the 1980's. The Ariel II upper limit is not below LDEF's 6-point average flux.

Space Activity Profiles

Consideration of the data, and changes in flux resulting from an increase in the space debris population may be examined in the light of space activity profiles. Shown in Figure 4 is the launch and in-orbit population over the period. Total launches have increased by only a small factor, but in-orbit objects and debris have increased by a factor of between 1 and 2 decades. In the absence of significant total impact flux rate changes except possibly at small dimensions, these trends in space traffic growth are not repeated in the data, and the dominance of the natural meteoroid population is strongly asserted even at the current epoch of 1993.

Deserving perhaps special attention, the GTO launch rate is worthy of special study (Figure 5). Analysis by Flury et al (1992) and by Kessler (1990, 1993) have drawn attention to a particular debris population which, being in eccentric orbit, impact on the pointing faces of LDEF. This debris could well be a relatively strong component on the trailing face but may be so only by virtue of the reduced flux of natural meteoroids on this face. This is especially relevant for the LDEF west fluxes below f_{max} = 25 microns, where the LDEF MAP data (McDonnell, 1992) has resulted in an East to West ratio of 20 to 50. However, these West low flux data are not confirmed by the Frecopa data of Mandeville and Berthoud. In questioning which data are more reliable, the LDEF MAP data should be accepted because 1) they were exposed all the time, compared to 11 months for Frecopa, and 2) in the (ubiquitous) presence of secondary ejecta as a contaminant, an experiment which measures the **lowest** flux (and very few MAP penetrations were recorded) must be considered the most significant.

It is from these East-to-West data and associated modelling, and from the IDE experiment that a microparticle orbital population is, indeed, inferred; but the delineation of the source of this data between natural and man-made orbiting remains yet unresolved.

We must caution against arguments considering all orbital particulates as debris and state that the 1993 Eureca TICCE penetration data at 8 microns (equivalent 2024-T3) is in near perfect agreement with LDEF 1984-1990 and Solar max 1980 - 1984 fluxes. If this **is** debris then any and all space debris growth must have taken place before 1980 in this size range! But further to this, orbital swarms and groups were seen in the mid 1970's on HEOS II.

6. MEASUREMENTS AHEAD

Considerable further data on Eureca will be available from the studies performed by ESA on the MLI and Solar Cell Arrays, and from the TICCE experiment. Preliminary data from large impacts on TICCE indicates an 8-fold or more increase for values of f_{max} in the millimetre region compared to LDEF's 6-point average, and the debate of "debris versus natural" particulates will be raised but with increased vigour.

Hubble Space Telescope Solar Array data will also be available under ESA studies currently being initiated. Though the Hubble arrays were returned more recently than Eureca, the mean epoch of exposure actually preceeds Eureca's by 11 months due to the 4 year exposure period! The Eureca data will therefore be the latest source in terms of mean epoch.

Although LDEF's 6-point average and 5.76 year exposure is apparently representative of the average natural meteoroid flux, we must acknowledge the modelling of meteoroid streams by McBride et al (1994); particular faces are prone to very selective exposure to particular, and to high activity meteoroid streams. Arguments will again centre on whether Eurecas's 8 fold increase be explained in terms of the quite natural and yet variable meteoroid streams or by space debris.

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Space-craft Name	Initial Altitude Perigee (km)	Initial Altitude Apogee (km)	Final Mean Altitude (km)	Orbital Inclin. (deg)	Launch Date	Exposure Time (secs)	Detector material	Detector Thick-ness (mm)	Detected Flux (no/m^2 sec^{-1})
Explorer 16	750	1180	965	52.0	16 Dec. 1962	1.88E+7 (0.60yr)	Annealed Berylco 25 alloy	29.2 54.9	1.99E-06 3.66E-06
Explorer 23	464	979	722	52.0	06 Nov. 1964	3.15E+7 (1.0yr)	302 Stainless steel (1/2hard)	25.4 50.8	2.4E-06 4.1 E-06
Ariel 2	289	1358	824	51.7	27 Mar. 1964	6.22E+6 (0.20yr)	1201-H6/H9 Al alloy	12 15	5.12E-05 for 15mm detector †
Pegasus 1	502	738	620	31.8	16 Feb. 1965	2.75E+7 (0.87yr)	1100-0 & 2024-T3 Al alloy	38 203 406	2.18E-06 (* see footnote)
Pegasus 2	512	742	627	31.8	25 May 1965	1.90E+7 (0.60yr)	1100-0 & 2024-T3 Al alloy	38 203 406	(* see footnote) 2.42E-07 5.64E-08
Pegasus 3	522	540	531	28.9	30 Jul. 1965	1.33E+7 (0.42yr)	1100-0 & 2024-T3 Al alloy	38 203 406	(* see footnote) 2.42E-07 5.64E-08
Solar Max (louvres)	575	575	533	28.5	14 Feb. 1980	1.31E+8 (4.16yrs)	1145-H19 Al alloy	125	7.85E-07
MFE on STS-3	241	241	241	38.0	22 Mar. 1982	1.53E+5 (0.01yr)	1201-H6/H9 Al alloy	5	2.60E-05
LDEF	476	476	463	28.4	06 Apr. 1984	1.82E+8 (5.77yrs)	1201-H6/H9 Al alloy	1.5 to semi - infinite	5.38E-05 for 4.83 micron detector
TICCE on EuReCa	508	508	508	28.4	01 Aug. 1992	2.83E+7 (0.90yr)	1201-H6/H9 Al alloy	9.2	5.41E-05 for 9.2 micron detector

† 50% confidence limit for Ariel 2. * The 38 microns flux quoted above for Pegasus 1 is the combined 38 microns flux for all three Pegasus satellites, while both the the 203 microns & 406 microns fluxes quoted above for Pegasus 2 & 3 are the combined fluxes for Pegasus 2 & 3 (as adopted by Clifton & Naumann, 1966)

Table 1. Key Satellite Experiments offering significant exposure of metallic surfaces in the LEO environment

Spacecraft detector material	Density (g cm-3)	Tensile strength (MPa)	Conversion factors* to 2024-T3 Aluminium
Beryllium-copper (Annealed Berylco 25) on Explorer 16	8.250	414	1.66
Stainless-steel (Half-hard 302) on Explorer 23	8.020	1030	1.85
Aluminium (1201-H6/9) on Ariel 2, LDEF (MAP), MFE, & TICCE	2.720	175	0.87
Aluminium (1145-H19) for SMM louvres	2.705	145	0.85
Aluminium (2024-T3) on Pegasus 1,2, & 3	2.770	459	1.00
Aluminium (6061-T6) on LDEF	2.700	310	0.94

*Derived from the chosen marginal penetration equation (McDonnell & Sullivan,1992)

Table 2: Target material specifications for penetration data used in Table 1.

Spacecraft name	Mean altitude, H (km)	Meteoroid velocity, Vp (km sec-1)* at H (km) altitude	Earth shielding factor (h)	Gravitational enhancement factor (c)	Sensitivity enhancement factor (S)
Explorer 16	965.18	22.555	0.7291	1.2719	1.1790
Explorer 23	721.79	22.638	0.6967	1.2812	1.1850
Ariel 2	823.50	22.603	0.7112	1.2772	1.1825
Pegasus 2 & 3	578.93	22.689	0.6929	1.2869	1.1887
Solar Max	532.75	22.706	0.6642	1.2889	1.1899
MFE on STS-3	241.00	22.818	0.5827	1.3016	1.1979
LDEF	458.00	22.733	0.6485	1.2920	1.1918
TICCE on EuReCa	508.00	22.715	0.6592	1.2899	1.1905

Table 3. Earth shielding, gravitational & sensitivity enhancement factors

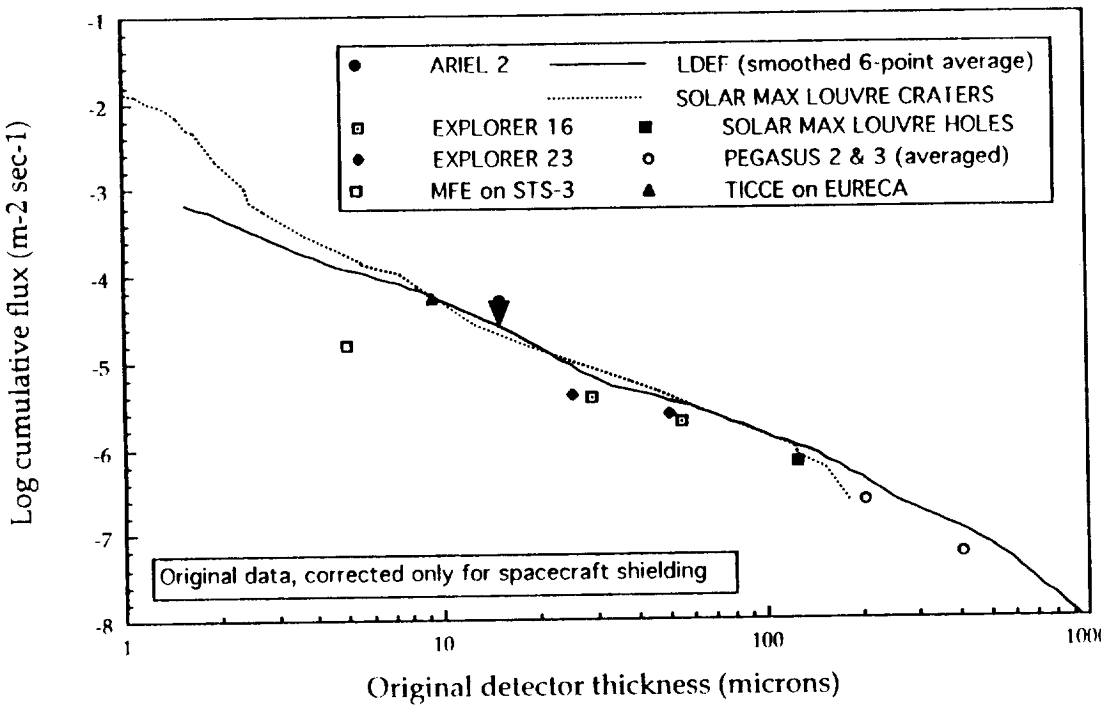

Fig.1: Selected meteoroid satellite data (1962 - 1993) plotted at the detector thickness irrespective at target material. It is corrected for (local) spacecraft shielding but not Earth shielding. (Note: the Ariel 2 datum point is an upper limit).

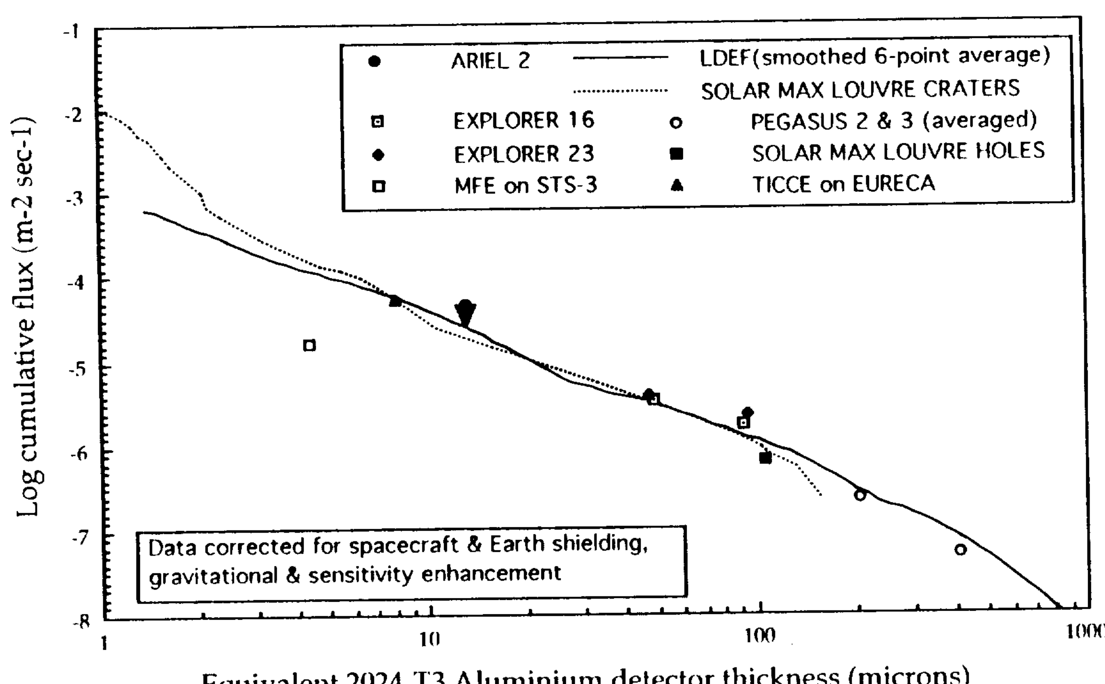

Fig. 2 Meteoroid satellite data (1962 - 1993). The data refer to unshielded exposure at 1 A.U. heliocentric distance at a velocity of 20 km sec $^{-1}$ The corresponding velocity at LDEF's altitude would be 22.3 km sec $^{-1}$ With the exception of data below f max=20 microns, no significant flux changes over the 30 year period are demonstrated. (Note: the Ariel 2 datum point is an upper limit).

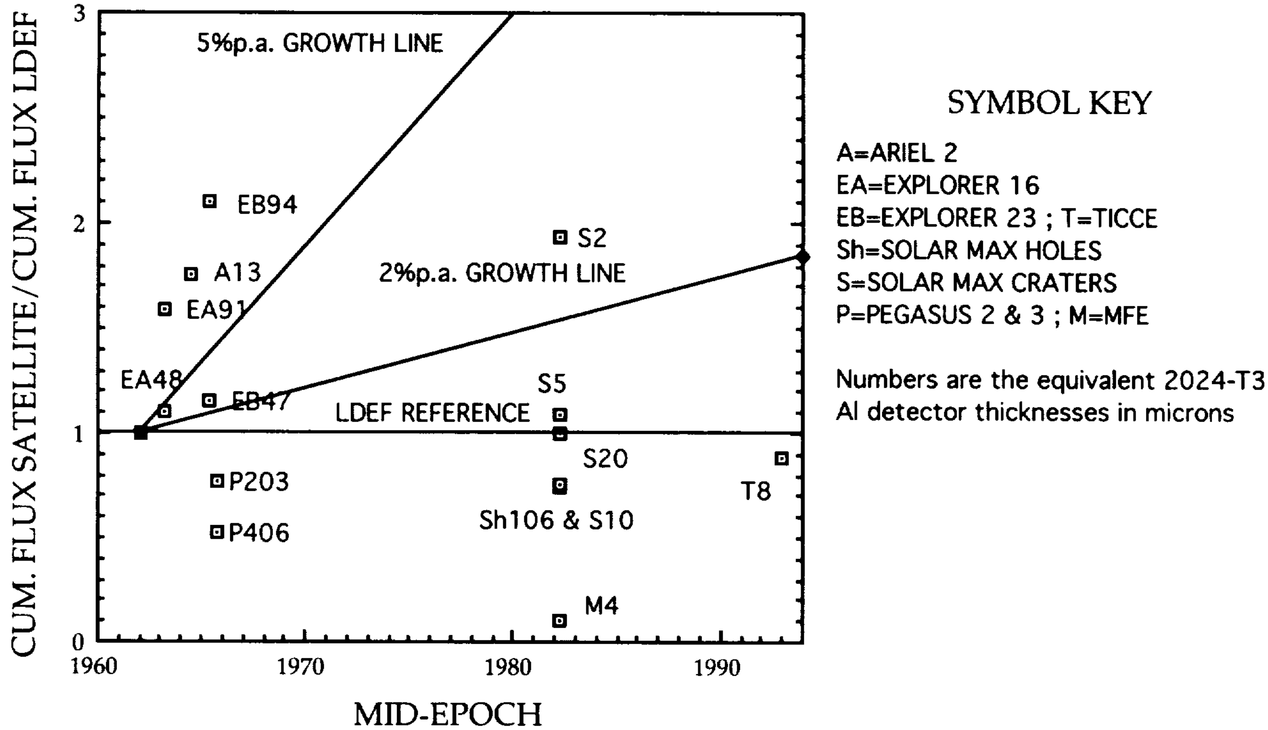

Fig. 3 Selected satellites flux data referenced to the LDEF 1984 - 1990 6-point average flux at the same detector thickness. Also shown for reference are the 2% and 5% per annum growth rates applicable respectively to large and small particles in the NASA Space Station Environmental Models.

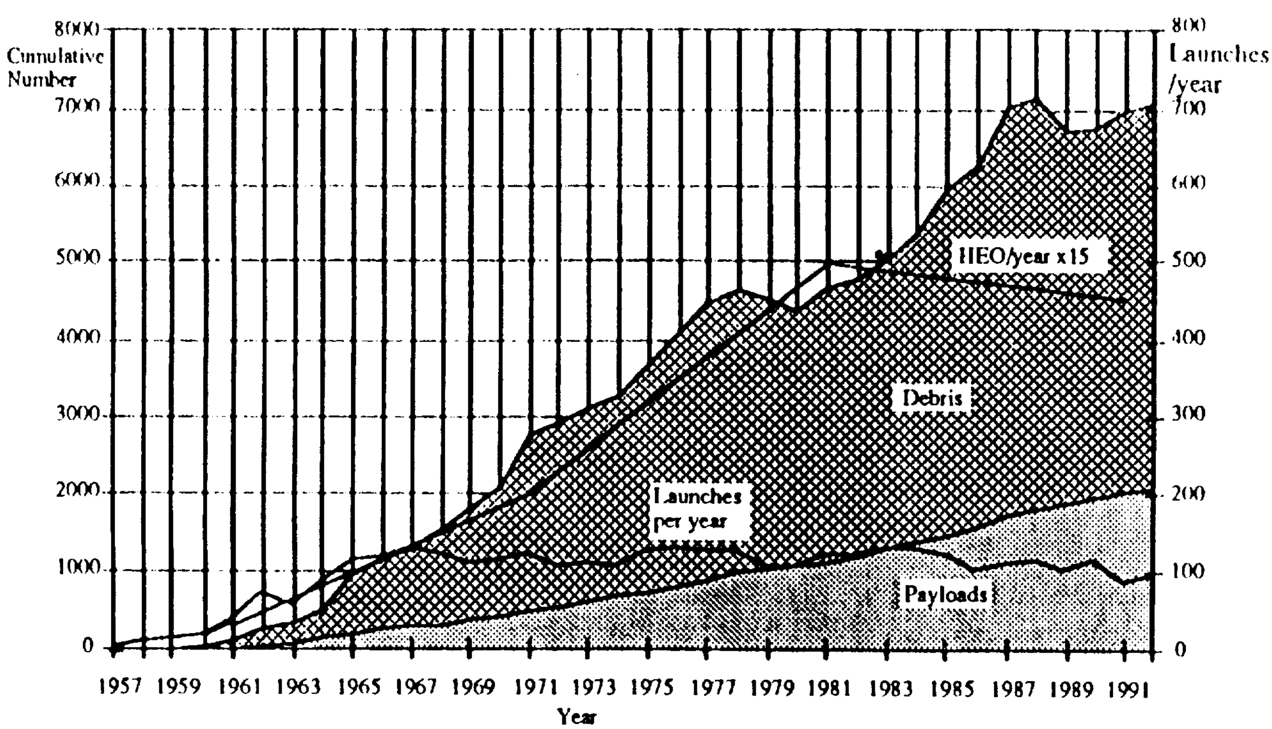

Fig. 4. Satellite launch rates and the in-orbit population of both satellites and space debris. Also shown for comparison is the high eccentric orbit launch rate which is shown in more detail in Fig. 5. Data courtesy S.P. Despande 1993.

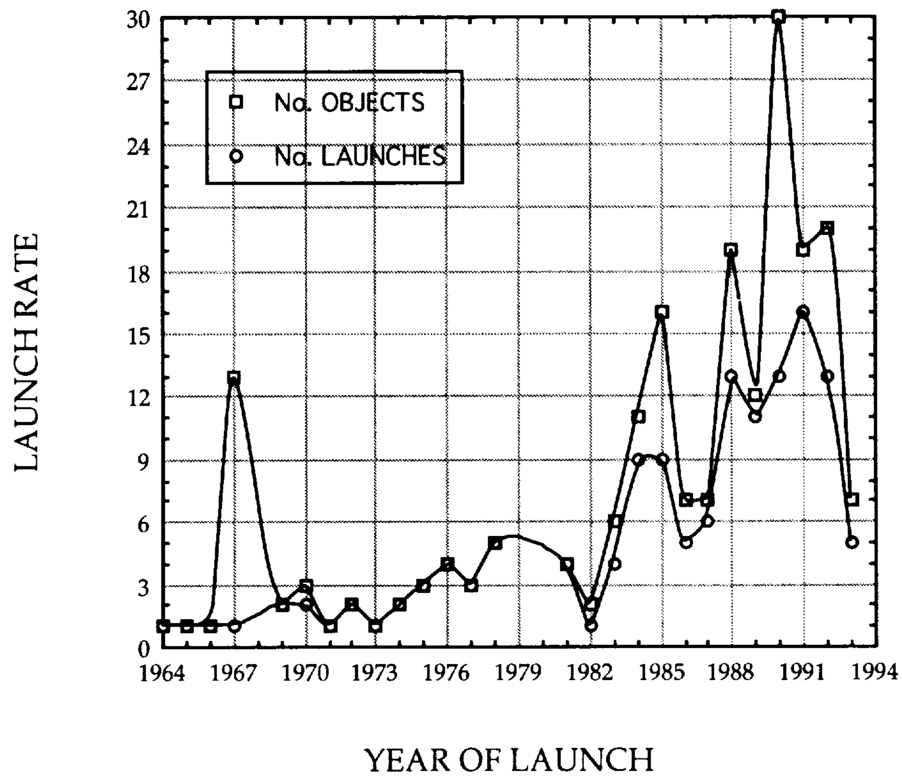

Fig. 5. Launch rate profile for GTO objects with eccentricities between 0.65 and 0.75 and inclinations to 60°. Data from the ESA DISCOS database, courtesy H Klinkrad, 1992.