ENHANCED METEOROID/DEBRIS 3-D ANALYSIS TOOL

H. Sdunnus[1], G. Drolshagen[2], C. Lemcke[1]

[1]HTS AG, Widenholzstr.1, 8304 Wallisellen, Switzerland
[2]ESA/ESTEC, 2200 AG Noordwijk, The Netherlands

ABSTRACT

ESABASE/DEBRIS is a unique tool to perform numerical impact analysis and risk assessment for orbiting spacecraft under consideration of their orbital evolution and attitude. It allows to predict the number of impacts from meteoroids and space debris and the resulting damage under consideration of realistic shielding and material characteristics.

Compared to its original version (Refs. 1,2) the tool has been considerably enhanced in several areas. The treatment of meteoroids has been improved and extended to account for directional effects like the Earth apex/antapex ratio, β-meteoroids, the full directional dependence of meteoroid streams and an altitude dependent velocity distribution. Latest space debris models such as the NASA96 model and the European MASTER96 debris model are available.

ESABASE/DEBRIS[1] now contains very flexible generic damage equations and the option also to incorporate new, user provided equations. The analysis of secondary ejecta is now possible. Further improvements address the analysis options and the user interface.

This paper presents the main features and capabilities of the enhanced tool.

1. INTRODUCTION

The steadily growing risk of being damaged by debris or meteoroid impacts has become a design criteria not only for manned missions, but also for unmanned spacecraft. Design engineers need tools to identify critical items on board of their spacecraft, i.e. tools which are able to reflect realistic mission scenarios, the spacecraft structure and directional and geometrical effects like shadowing. The sophisticated orbit propagation and spacecraft modeling background (geometry, materials, attitude) of the ESABASE framework enables the ESABASE/DEBRIS tool to fulfil not only the needs of the designer class users, but also of users with a more scientific background by providing sufficient flexibility of the models in the background.

[1] The enhanced ESABASE/DEBRIS tool is currently under development under ESTEC contract 11450/95/NL/JG. The final version will be available by end 1997.

2. USER INTERFACE

The ESABASE/DEBRIS user is able to specify the spacecraft geometry (reaching from simple plates to structures with a high level of complexity like Space Station), its attitude, mission parameters, and the shielding type and thickness of single spacecraft elements. For the actual impact study, the user can select between several 'state of the art' flux models and application options for meteoroids and debris and specify the particle size range, damage type (e.g. certain crater size or penetration) and design equations to be applied for analysis. Output parameters include the number of impacts for the selected size range, the average impact direction and velocity, and the number of impacts which cause the specified damage. The program is supported by 2-D and 3-D graphics and allows previewing and plotting of the selected environment and damage models.

On the input side, the user interface to ESABASE/ DEBRIS offers two alternatives, which both have been advanced with respect to user friendliness. Input values are either transferred to the program via editable ASCII input files or by stepping through an interactive 'point & click' menu facility based on OSF/MOTIF routines. Due to the now increased number of selectable parameters - especially in the damage and design section - the structure of the input files has been enhanced by introducing keywords, which represent a whole set of parameters. The program is provided with default options reflecting models and parameters for common applications. Figure 1 shows an example for the use of keywords to select ballistic limit equations under consideration of Single Wall structures.

```
#
# BALLISTIC LIMIT EQUATIONS
# - - - - - - - - - - -
#
# SINGLE WALL EQUATION
   Thick_Plate           2.5 0.33 ;  Parameters are Kf and K1
#  Thin_Plate                0.44 ;  Parameter is K1
#  Pailer-Gruen                   ;  No editable Parameters
#  McDonnell&Sullivan        69   ;  Parameter is Sigma_t [MPa]
#  Gardner                   69   ;  Parameter is Sigma_t [MPa]
#  Gardner_McDonnell_Collier 69  ; Parameter is Sigma_t [MPa]
#  Frost                          ;  No editable Parameters
#  Naumann_Jex_Johnson            ;  No editable Parameters
#  Naumann                        ;  No editable Parameters
#  McHugh_Richardson         0.54 ;  Parameter is Kf
#  Cour-Palais               0.54 ;  Parameter is Kf
```

Figure 1. Passage of an ESABASE/DEBRIS input file using keywords ('Thick_plate' Option is active)

A second, more intuitive solution to transfer the user input to the program is given by using the ESABASE/ DEBRIS menu tree. Figure 2 depicts the top level branches and shows that the core of the enhanced tool is represented by the following applications:

1) The interactive facility to prepare the input;
2a) A ground test option to analyse the damage of a single impact with well defined parameters;
2b) A non-geometrical tool to study impacts on a simple flat plate for a first risk assessment;
2c) The 3-D fully geometrical analysis module
3) On the output side the user interface is represented by a post-processor to extract the detailed results.

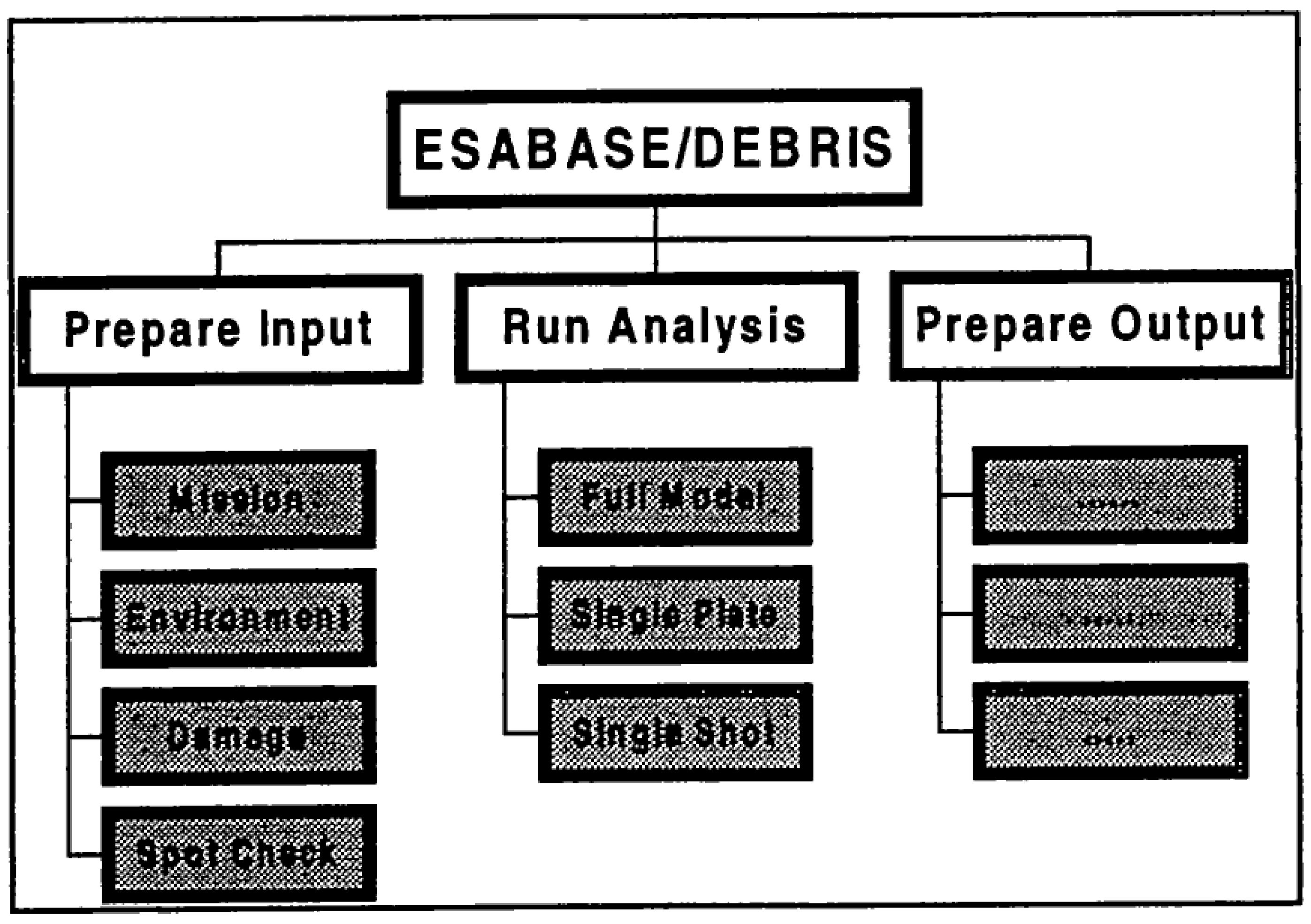

Figure 2. ESABASE/DEBRIS Menu Structure

3. FLUX MODELS (METEOROIDS)

The meteoroid model developed by GRÜN et al (Ref. 8) is a commonly adopted expression to describe the averaged flux resulting from meteoroids in terms of integral flux F(>m) (impacts per m^2 and year resulting from particles of mass m and larger) impacting a randomly oriented plate under a viewing angle of 2π in the ecliptic plane at 1 AU. This model represents the baseline meteoroid model for ESABASE/DEBRIS. It assumes an isotropic flux environment and does not give directional information. Contributions from streams or other sources are implicitly contained.

$$F(>m) = c_0 \left((c_1 m^{0.306} + c_2)^{-4.38} + c_3(m + c_4 m^2 + c_5 m^4)^{-0.36} + c_6(m + c_7 m^2)^{-0.85} \right) \quad (1)$$

m is the mass in grams, c_0 to c_7 are constants

$c_0 = 3.156 \cdot 10^7$	$c_1 = 2.2 \cdot 10^3$
$c_2 = 15$	$c_3 = 1.3 \cdot 10^{-9}$
$c_4 = 10^{11}$	$c_5 = 10^{27}$
$c_6 = 1.3\ 10^{-16}$	$c_7 = 10^6$

When applied to earth orbiting spacecraft, this flux is corrected with respect to the focusing and shielding effects of the Earth.

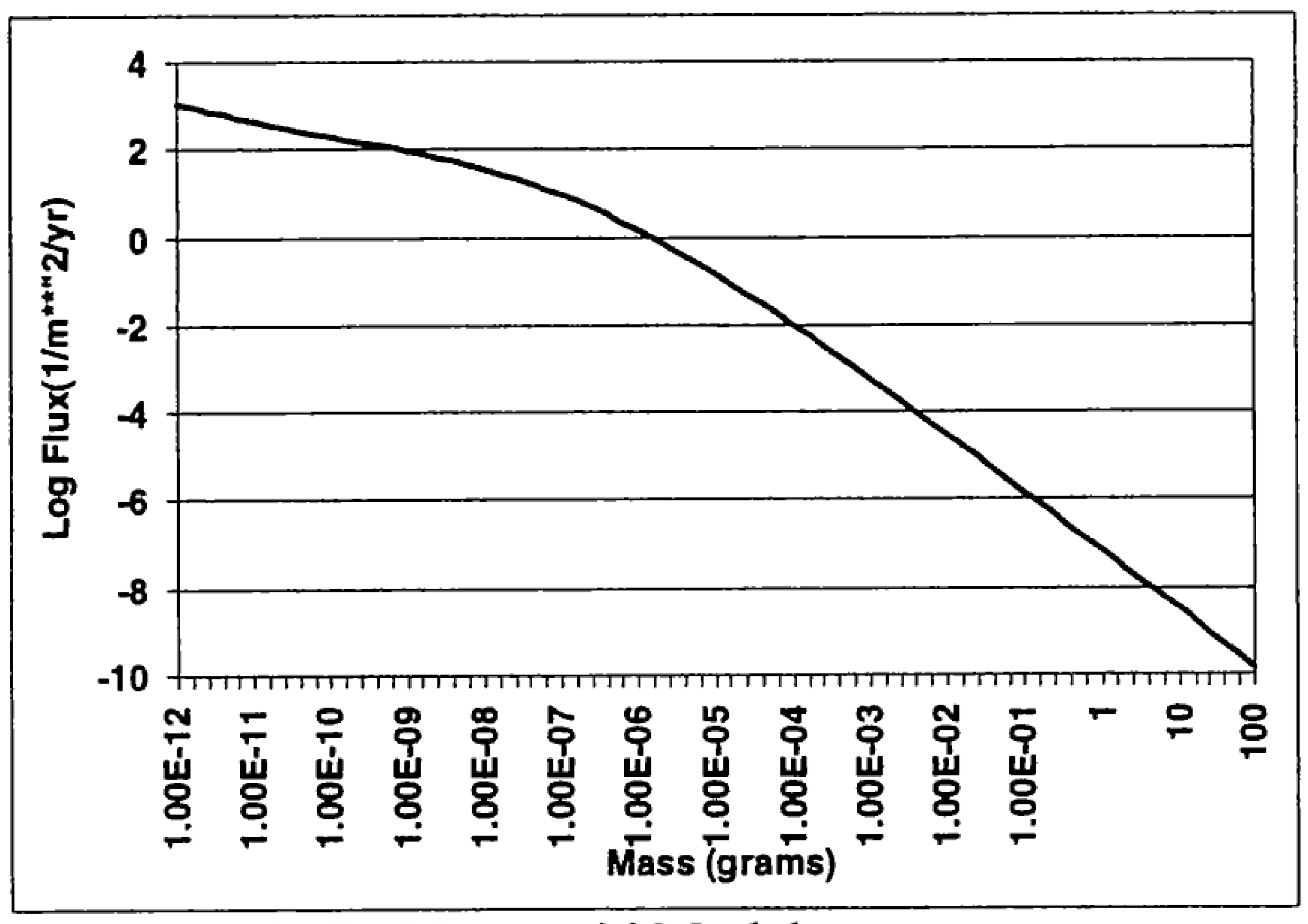

Figure 3. GRÜN Meteoroid Model
F(>m) impacting a randomly oriented plate in the ecliptic plane at 1 AU

In many cases a more detailed analysis is needed by the model user. A resolution of the meteoroid flux with respect to time is introduced by separating the overall meteoroid flux F_{tot} encountered by any detector in space into a 'sporadic' element F_{spo} (constant over the year) and a 'stream' element, -represented by the sum of N_{stream} single stream contributions- , which varies over the year. The total flux may be expresses as

$$F_{Tot} = F_{Spo} + \sum_{i=1}^{N_{Stream}} F_{Stream,i} \quad (2)$$

Before enhancement, the ESABASE/DEBRIS tool assumed the meteoroid flux according to GRÜN as the sporadic element and considered selected meteoroid streams according to COUR-PALAIS (Ref. 7) as the 'streams' component. Due to the simplicity of this model, directional effects could not be described and a re-normalisation to the exact value of the GRÜN flux had to be performed. The enhanced version deletes this shortcoming.

3.1 Directional effects of the streams component

In the enhanced version the streams element is described by a new approach developed by JENNISKENS (Ref. 6), which allows the determination of non-isotropic components at any given solar longitude (equivalent to mission time). It is based on observation data collected from sites around the world. Geometry and activity of about 50 single streams (e.g. Bootids, δ Leonids) are described by about 20 different parameters per stream (e.g. solar longitude at shower peak). This very detailed consideration of the streams component allows a full investigation of directionality effects as a function of mission time and spacecraft attitude. Figure 4 depicts the modulation of the meteoroid stream flux according to Jenniskens vs. solar longitude.(i.e vs. time in year)

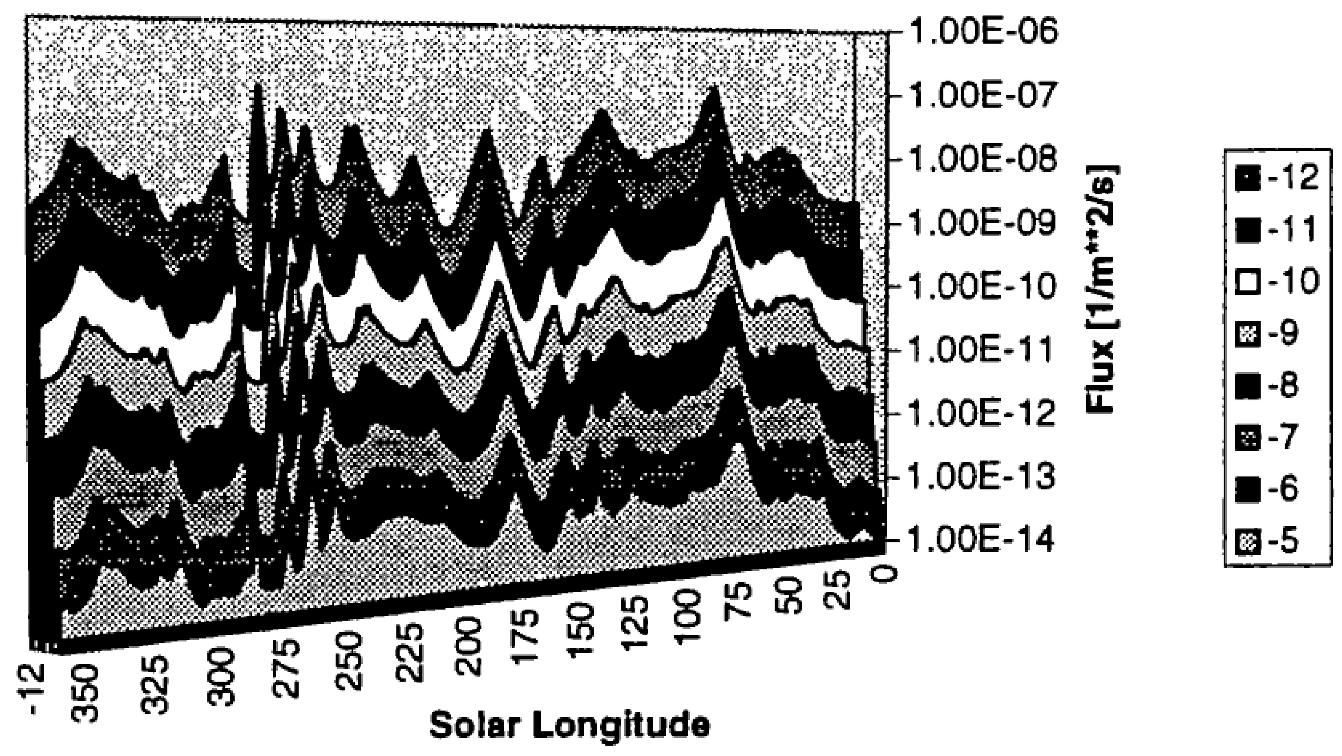

Figure 4. Meteoroid Stream Flux acc. to Jenniskens vs. Solar Longitude for 8 different mass regimes (colour code legend shows log(lower mass threshold))

The sporadic component now is represented by a derivative of the Grün model. The total fluence at 1 AU (accumulated over one year) of this sporadic component and the above described stream component is equal to the flux expressed by the original Grün model. A flux re-normalisation is not performed in this case

3.2 Directional effects of the sporadic component

The enhanced ESABASE/DEBRIS tool offers the option to consider three effects introducing a directionality of the sporadic meteoroid component.

3.2.1 Separation of α and β source

According to Ref. 3, the tool optionally offers the possibility to separate the sporadic meteoroid flux as described by the Grün model (Ref. 8) into an α population, representing the upper size regime above 10^{-11} g, and a β population, dominating the small size range below 10^{-11} g. While the α source is assumed to be isotropic, the β population comes from the Sun direction.

$$F_{\beta}(m) + F_{\alpha}(m) = F_{Grün}(m) \qquad (3)$$

3.2.2 Apex enhancement of the α source

Ref. 4 defines a modulation of the flux and velocity of the α source about the apex direction, i.e. with respect to the flight direction of the earth. The modulation of the α flux and velocity is a function of the angular deviation from the apex direction (denoted by t) and the parameter δ (describing a deviation from the measured peak value at about 10° off the apex direction). The modulated flux and velocity are defined as follows:

$$F_{\alpha}(t) = F_{\alpha}{}^{0}\left[1 + \Delta t \cos(t + \delta)\right] \qquad (4)$$

$$v_{\alpha}(t) = v_{\alpha}{}^{0}\left[1 + \Delta v \cos(t + \delta)\right] \qquad (5)$$

parameters are defined as

$$\Delta t = \frac{R_F - 1}{R_F + 1}, \quad \Delta v = \frac{V_A - V_{AA}}{V_A + V_{AA}}, \quad V_0 = (V_A + V_{AA}) / 2$$

(subscript A for apex and AA for antapex)

From the AMOR meteor data (Ref. 4) there are guesses for the maximum to minimum detection ratio, from which R_F and V_{AA} can be obtained. Recommended values are:

$V_A = 17.7$ Km/s , $V_{AA} = 8.3$ km/s , $R_F = 2$

3.2.3 Interstellar dust

The enhanced ESABASE/DEBRIS tool considers two components of interstellar dust particles, also introducing directional effects. According to Ref. 5 measurements on Ulysses and Galileo report particles of $3 \cdot 10^{-16}$ g at about 5 AU with heliocentric velocities of 26 km/s. The ecliptic longitude was 252° and the latitude 2.5°. The total particle flux at 1 AU is estimated to $5 \cdot 10^{-4}$ m^{-2} s^{-1}, the heliocentric velocity at 1 AU would be 47 km/s. The detected mean particle mass (Ulysses dust detector) was $3 \cdot 10^{-16}$ g. Further data stem from AMOR meteor data (Ref. 5), which indicate at least two other sources defined by their radiant direction and heliocentric velocity:

source 1: $\lambda = 243°$, $\beta = 50°$, $V_{\infty} = 40$ km/s
source 2: $\lambda = 347°$, $\beta = 60°$, $V_{\infty} = 80$ km/s

λ and β being the ecliptic longitude and latitude respectively. The diameter of these particles is estimated to be between 15 and 40 µm. As of today no definite flux values are known for these contributions.

3.3 Flux modulation-factor

Commonly used meteoroid flux models as the GRÜN Model consider the particle flux wrt. to a non-moving plate. The evaluation of orbiting structures requires the consideration of the spacecraft orbital velocity, shielding effects introduced by the earth, and the orientation of the satellite surface. In Ref. 13 an analytical expression has been derived to determine the flux modulation under consideration of constant impact velocities, but also under consideration of velocity distributions as they are applied in ESABASE.

4. FLUX MODELS (DEBRIS)

ESABASE/DEBRIS allows to select between three different debris models, representing the actual 'state of the art' in the field of debris modeling

4.1 NASA 90

The NASA 90 model defines debris fluxes and velocity by empirical functions which depend on the debris diameter, altitude, epoch, and on the inclination. For more detailed information on this widely used model the reader may refer to Ref. 9.

4.2 NASA 96

The recently published NASA96 model (Ref. 10) defines debris orbit numbers of circular and now also elliptical type with given particle size, altitude, and perigee altitude distributions for six different inclination ranges. It is meant to be applied for spacecraft design and observation in low earth orbit and incorporates a numerical collision analysis which yields the flux on a given target orbit by calculating the spatial debris densities along the target orbit. The model considers six different source components, the functional forms used to represent the number of particles consist of 12 sets of equations corresponding to the six inclination bands.

4.3 MASTER 96

The Meteoroid And Space Debris Terrestrial Environment Reference Model model (MASTER) (Ref. 11) has been developed as ESA's space debris reference model. In contrast to the above mentioned models it is based on semi-deterministic analysis and orbit prediction techniques. Fragmentation models have been applied to 127 known break-up events to generate a reference population at a given epoch. This results in a total of about 10^{11} objects above 100 μm in size which is reduced by sampling techniques to less than 250000 objects. Together with the trackable population, which is represented by the Two Line Element data set, the orbits of these objects are propagated to a common reference epoch. The resulting spatial density information, which later is retrieved for flux analysis is stored for discrete volume bins at this specific reference epoch. The lower mass threshold for MASTER is 0.1 mm. The altitude ranges from low Earth orbit (186 km) to geostationary altitude (36800 km). In order to meet the CPU and storage requirements of an enhanced ESABASE / DEBRIS implementation, an advanced MASTER engineering application was developed. Moderate eccentricity of the target orbit is possible, and a resolution of flux with respect to the orbital position of the spacecraft along its orbit is given. Figure 5 depicts a comparison (Sun Synchronous orbit) between the models available for ESABASE. In this case, the overall flux values agree reasonably, though the directional effects of the flux represented by the three models may differ.

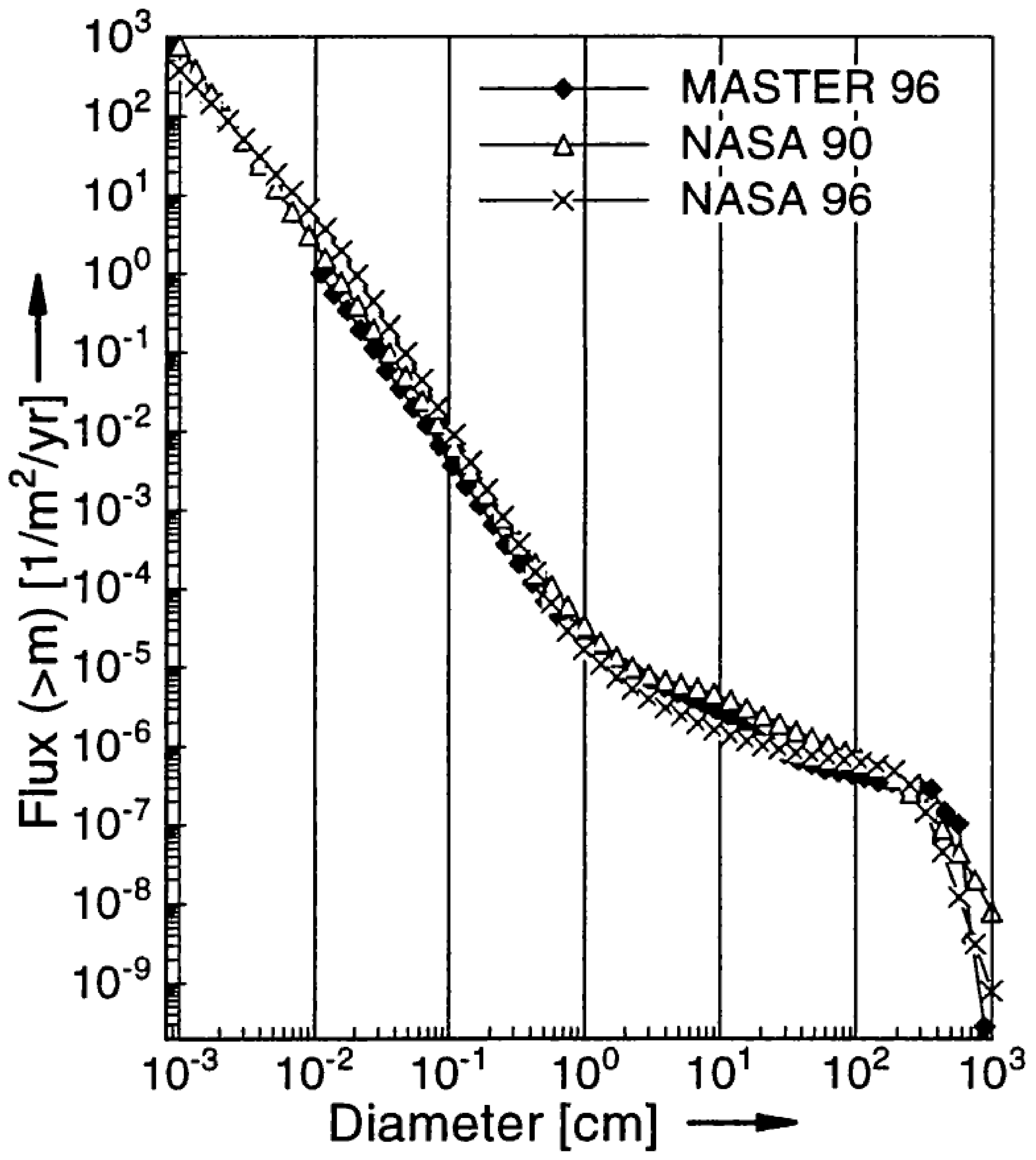

Figure 5. Comparison of Debris Models available in ESABASE . (Target Orbit : h = 780 km, i=98.5 deg) see Ref. 14

5. SECONDARY EJECTA

The consideration of a secondary ejecta model is one more of the innovative features of the enhanced ESABASE/DEBRIS tool. Post flight analysis of space hardware (EURECA, Hubble) indicated that this generation process may play a yet underestimated role. The implemented model (Ref. 12) is based on a thorough review of existing publications and experiments. The consideration of this model for ESABASE impact and damage analysis is optional. Its primary field of application are thick and homogenous surfaces on the investigated structure. For MLI blanket and solar cell type elements it should be considered only for small impacting particles. Under consideration of a given impactor mass and velocity vector the model renders fragment size and velocity per solid angle unit of the ejected particle cone and is thus able to trace particles until they impact other elements. Different ejection processes are considered, namely debris cone generation and spallation for brittle targets and debris cone generation for ductile targets. The jetting effect is neglected for all cases.

6. DAMAGE AND DESIGN EQUATIONS

Two parametric equations cover the computation of the ballistic limit of a spacecraft structure, three other parametric equations compute the effective damage (crater size). The input to the damage and design equations are impactor dependant parameters such as particle velocity, size (mass, diameter) and impact angle as well as design dependant parameters such as target properties (density, thickness, shielding spacing) expressed by material parameters.

6.1 Design equations

6.1.1 Single wall

The ballistic limit of a target represented by a single wall is expressed by

$$F_{mx} = K_1 \cdot K_f \cdot d_p^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_t^{\kappa} \tag{6}$$

ESABASE/DEBRIS allows a fast and effective selection of eleven commonly adopted equation types (e.g.THIN PLATE, PAILER & GRUEN etc.) represented by a certain set of parameters (K_f, $K_1,\lambda,\beta,\gamma,\xi,\kappa$), which are backed up by experimental values. For parametric studies the user is free to edit some of these parameters. Under consideration of the particle impact velocity and the particle size the software determines the ballistic limit and thus the wall thickness necessary for shielding.

6.1.2 Multiple wall

The multiple wall equation is a merger of the previous double wall and multiple wall equations. Its generalised form is :

$$\begin{aligned} F_{mx} = {} & K_1 \cdot d_p^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot [\cos\alpha]^{\xi} \cdot \rho_B^{\kappa} \cdot S^{\delta} \cdot \rho_s^{v1} \\ & - K_2 \cdot t_s^{\mu} \cdot \rho_s^{v2} \end{aligned} \tag{7}$$

Here the user may select between six commonly known equation types (e.g. MAIDEN-MCMILLAN, ESA DOUBLE, ESA TRIPLE), which are partially split into different velocity bands. Again, the user may edit the pre-defined parameters to create his 'own' damage equation. Within the software the ballistic limit equations have two forms: the first form computes the limit particle mass from impact velocity and failure criteria, the second form the limit particle velocity from the particle mass and failure criteria.

6.2 Crater and hole equations

Three equation types are used to express the damage size as a function of material and impactor characteristics

6.2.1 Crater equation

The general form of the crater equation is

$$D = K_1 \cdot K_c \cdot d_p^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_t^{\kappa} \tag{8}$$

Strictly speaking, the crater size equation is only valid when no failure occurs. For ductile targets, the crater is more or less spherical, and $K_c \approx 1$. For brittle targets, an interior crater with diameter D_h may form, the outer crater (with diameter D_c) being much larger. For brittle targets, K_c may be as high as 10. Nine pre-defined equations may be selected. Here, the user is able to edit the whole set of parameters ($K_c,K_1,\lambda,\beta,\gamma,\xi,\kappa$)

6.2.2 Clear hole equation

The clear hole equation is restricted to full perforations, i.e. it is mainly applicable for thin foils:

$$D = \left[K_0 \cdot \left(\frac{t_s}{d_p} \right)^{\lambda} \cdot \rho_p^{\beta} \cdot v^{\gamma} \cdot (\cos\alpha)^{\xi} \cdot \rho_s^{v} + A \right] \cdot d_p \tag{9}$$

Four pre-defined equations are available.

6.2.3 Advanced hole equation

The advanced hole equation is derived for the computation of the particle size from the impact velocity and the hole size on the back side of the target shield. The equation is only valid for ductile targets. Its general form is

$$d_p' = A \cdot \left(\frac{10}{9 + \exp\left[D_h' / B \right]} \right) + D_h' \left(1 - \exp\left[-D_h' / B \right] \right) \tag{10}$$

$$A = \frac{d_p}{F_{mx}} = 347 \cdot \left(\frac{V_n \cdot \rho_p}{\sqrt{\sigma_s \cdot \rho_s}} \right)^{-0.723} \cdot \left(\frac{\sigma_s}{\sigma_{Al}} \right)^{-0.578} \cdot t_s^{-0.053} \tag{11}$$

The determination of the parameters used in these equations require target material dependant calculations which will not be outlined here.

7. OVERVIEW

Table 1 gives a concluding overview of the differences between the old and the enhanced ESABASE tool.

	Old	New
Debris Models	NASA 84 NASA 89 NASA 90	NASA 90 NASA 96 MASTER 96
Meteoroid Models		
Sporadics	Cour-Palais Grün	Grün
Streams	Cour-Palais	Jenniskens
Advanced (directional effects of the sporadic component)	-	Apex Enhancement α,β separation Interstellar Sources
Velocity Distribution	Cour Palais Kessler	HRMP(also altitude dependant) Kessler
Secondary Ejecta	-	yes
Design Equations		
Single Wall **Multiple Wall**	Thick Plate Thin Plate Boeing ESA	Generic equations with user-editable parameters are applied. Commonly used equations are selectable via keywords such as THIN_PLATE or PAILER_GRUEN.
Damage Equations		
Craterisation **Clear Hole** **Advanced Hole**	Maiden Sawle	Generic equations with user-editable parameters are applied. Commonly used equations are selectable via keywords.

Table 1. Comparison between old and enhanced ESABASE tool

8. CONCLUSIONS

A survey of the features available for the enhanced ESABASE/ DEBRIS tool has been given. As a part of the versatile ESABASE framework, which allows a detailed spacecraft modelling under consideration of a 3D spacecraft geometry, materials, attitude and orbit propagation, ESABASE/DEBRIS becomes a valuable and powerful tool for damage and failure assessment due to particle impacts. The tool now offers a sophisticated treatment of directional effects from the meteoroid environment, a flexible and user friendly application of generic design and damage equations. Latest space debris, meteoroid, and secondary ejecta models are accessible.

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