THE COMPARATIVE ANALYSIS OF THE PROBABILITY OF SPACECRAFT PRESSURE WALL PENETRATION FOR DIFFERENT SPACE DEBRIS ENVIRONMENT MODELS

Andrey I. Nazarenko$^{(1)}$, **Vyacheslav G. Sokolov**$^{(2)}$, **Andrey V. Gorbenko**$^{(2)}$

(1) Space Observation Center, 84/32 Profsoyuznaya str, Moscow 117810, Russia, e-mail:nazarenko@iki.rssi.ru
(2) Rocket&Space Corporation "Energia", 4a Lenin str, Korolev, Moscow region, 141070, Russia

ABSTRACT

The paper is aimed at studying the dependence of probability of International Space Station modules penetration for different space debris environment models and the calculation techniques used in practice. Two techniques (software) were used for calculation of the penetration probability:

- The Russian «SDPA-PP» code [1, 2].
- The American «BUMPER» code [3, 4, 5].

The following models were used as the data sources on space debris environment:

- SDPA-2000 and ORDEM2000 for «SDPA-PP» software and
- SSP-30425, ORDEM96 and SDPA-2000 for «BUMPER» software.

The data on geometrical parameters as well as on wall and bumper parameters of modules play extremely important role in calculating the penetration probability. So, the coordinated unified data on aforementioned parameters and the coordinated equations for ballistic limit critical diameters (ballistic curves) were applied in all calculations.

The following issues are presented in the paper:

- The features of the applied methods of penetration probability calculation.
- The comparative characteristics of the used space debris (SD) environment data.
- The detailed analysis of penetration probability estimates.

1. INTRODUCTION

In 1999 the Space Observation Center (the former Center for Program Studies) carried out the work "The analysis of the probability and conditions of hitting and penetration of space debris particles and meteoroids into hermetically sealed modules and components of the ISS structure» under the contract with the Rocket-Space Corporation (RSC) «ENERGIA»[1]. The brief information about the results of this work was presented in the report [1] и paper [2]. The summary data on possible scattering of estimates of penetration probability (***PP***) of technogenous space debris into Russian module walls are presented in Table 1. The last column gives the NASA data (LMSMSS32823, Rev B, Table 3-2).

Table 1.

Summary ***PP*** estimates for various modules.

	Russian SDPA model		BUMPER
Module	Time interval, years	***PP*** values	***PP*** / Time interval
SM	15	0.0430 - 0.0965	0.133/14.6
SPP	14	0.0091 - 0.0397	0.067/13.5
DC 1	1	0.00052-0.00098	-
DC 2	14	0.00362-0.00836	0.011/13.5
Progress	1	0.00083-0.00177	0.100/14.6
UDM	14	0.01155-0.02523	0.021/13.5

The scattering of ***PP*** estimates my be caused by three factors:
a) the module's computational schemes,
b) shading conditions,
c) conditions of space contamination over the forecasting time interval.

In the majority of cases our ***PP*** values are more optimistic in comparison with the NASA data. For SM, SPP and DC 2 modules they are 2.0 - 2.5 times lower, than NASA's values.

In order to get more detailed data on the contribution of each above mentioned factor in ***PP*** estimates, a series of test ***PP*** calculations was performed using both Russian SDPA-PP technique and American BUMPER code. The results of this analysis of ***PP*** values are presented below.

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[1] The initial data for this work (the shape and sizes of modules, the structure of walls, the ballistic curve) were prepared by the experts of the RSC "ENERGIA".

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2. BASIC INFORMATION ON THE SDPA-PP ESTIMATION TECHNIQUE

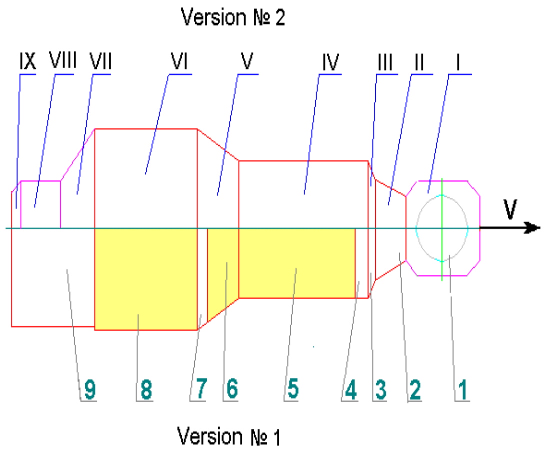

Fig. 1. Two versions of the SM surface partition into elementary components.

2.1. Initial data are:

- orbital elements of ISS;
- geometrical parameters of modules (Figure 1);
- wall and bumper parameters;
- equations for ballistic limit critical diameters (d_c) as functions of wall and bumper parameters, collision velocity and SD density;
- characteristics of SD flux based on the Russian SD model [6].

2.2. The penetration probability of particles

having size in the range of (d_j, d_{j+1}) is equal to

$$PP(d)_j = P_c(d)_j \cdot P(d_c < d | collision)_j . \qquad (1)$$

Here: $P_c(d)_j$ is the collision probability for the given module surface component (the SDPA model includes the software for these estimations);

$P(d_c < d | collision)$ is the conventional penetration probability, which takes into account statistical distributions of influencing factors:

$$P(d_c < d | collision)_j =$$

$$= \sum_k \sum_m \sum_i p(\rho_k, V_m, \cos\theta_i)_j \cdot P(d_c < d | \rho_k, V_m, \cos\theta_i)_j \quad ;(2)$$

ρ_k, V_m, θ_i are possible values of the specific weight of particles, of their relative velocity and the deviation of the velocity direction from the normal to the surface, $d_c = f(\rho_k, V_m, \cos\theta_i)$ is the ballistic limit for a given surface component, $p(\rho_k, V_m, \cos\theta_i)$ is the appropriate statistical distribution. The application of last formula is a feature of our technique. The other feature is the application of a cycle on probable directions of the relative collision velocity in the construction of the $p(V_m, \cos\theta_i)_j$ distribution (Figure 2).

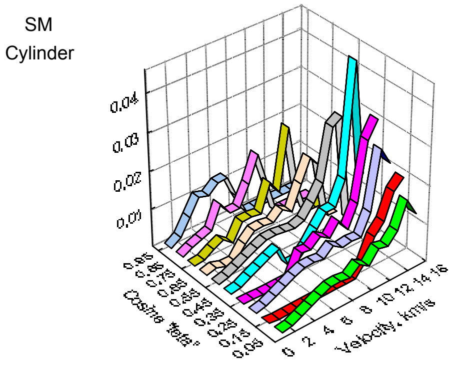

Fig. 2. Distributions of magnitude and direction of the velocity of possible SD impact on the SM surface.

3. CHARACTERISTICS OF THE SPACE DEBRIS FLUX RELATIVE TO ISS

Table 2 below presents the results of calculation of the flux of SD sizing larger than d_j by means of five different models: NASA-91 (SSP-30425), ORDEM96, MASTER'99, ORDEM2000 and SDPA2000. The results refer to the year 2000. The altitude of the orbit is 400 km.

Table 2.

Values of the cross-sectional area flux of SD sizing larger, than the specified value, $m^{-2}year^{-1}$.

	Lower boundary of sizes, cm		
Model	0.10	1.0	10
SSP-30425	3.58E-3	14.44E-6	9.18E-7
ORDEM96	4.91E-3	6.20E-6	2.16E-7
MASTER'99	2.34E-3	7.28E-6	5.73E-7
ORDEM 2000	3.56E-3	1.54E-6	2.90E-7
SDPA 2000	2.77E-3	10.90E-6	5.86E-7

The same data are presented below in Figure 3.

The comparison of cross-sectional area flux estimates by means of different models indicates, that the acceptable agreement between the ORDEM96, SDPA2000 and MASTER'99 models takes place in the range of SD sizes up to 1 cm only. The flux estimates by the ORDEM2000 model in the range of SD sizes from 0.25 cm to 2.5 cm are 2.5 – 6.5 times lower than the estimates by the other models. These distinctions also relate to the comparison with the data of former NASA models: SSP-30425 and ORDEM96. It is difficult to explain such a large differences between the estimates for SD size of about 1 cm. To clarify the reasons of these differences the extra analysis is required.

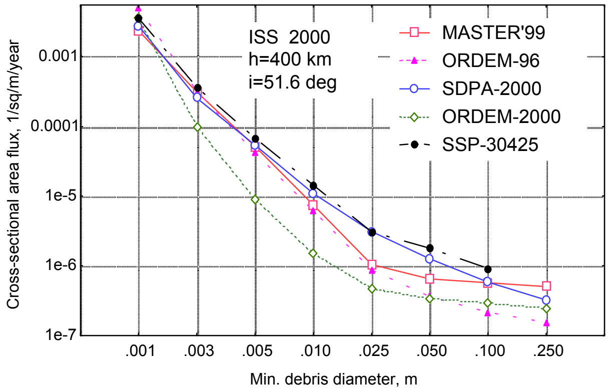

Fig. 3. Data on the cumulative flux of SD of different sizes relative to the ISS.

The ORDEM2000 model data well agree with other ones only for SD with minimal sizes lower than 0.25 cm и higher than 10 cm. Here the differences from the MASTER'99 and SDPA2000 models do not exceed 2 times.

The SDPA2000 and SSP-30425 models are in a rather good agreement throughout the SD size range under consideration. However, the estimates of the cumulative flux of SD sizing 2.5 - 5.0 cm in the SDPA model at least 2 – 3 times exceed the data of the other models. In the previous version of our model the distinctions in this size range were greater, however.

The value of the probability of collisions ($P_c(d)_j$) of spacecraft surface components with SD particles depend not only on the flux value (**Q**), but on possible directions of impact (the relative velocity) as well. It should be noted that the distribution of possible directions of the relative velocity $pV_{rel}(Az)$ and the distribution of directions of possible collisions $pQ_{rel}(Az)$ are not the same. They differ in the set of events, over which the averaging is carried out. In the first case the averaging is carried out over the set of particles, and in the second case – over the set of possible collisions. The $pQ_{rel}(Az)$ distribution is applied in the SDPA model. The relationship between these distributions is as follows:

$$pQ_{rel}(Az) = \frac{V_{rel}(Az)\cdot pV_{rel}(Az)}{\int V_{rel}(Az)\cdot pV_{rel}(Az)\cdot dAz}. \quad (3)$$

The data on the $pV_{rel}(Az)$ и $pQ_{rel}(Az)$ distributions, calculated in the SDPA model, as well as the dependence of the relative velocity on the direction are presented in Figure 4.

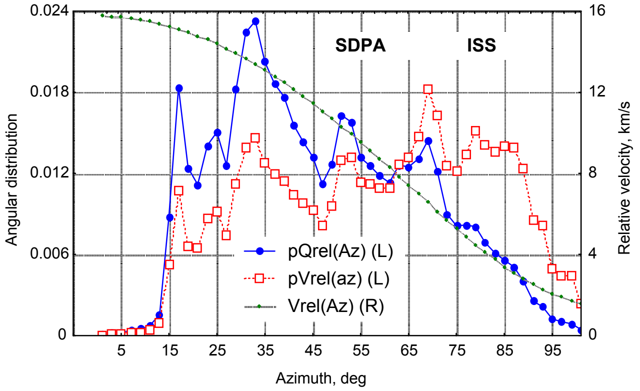

Fig.4. The distributions $pQ_{rel}(Az)$ and $pV_{rel}(Az)$, as well as the angular dependence of the relative velocity, for the SDPA2000 model.

4. COMPARISON OF THE DAMAGE PREDICTION CODES TEST RESULTS

As the simplest geometric model for test calculations we choose a cube with the side of 1 m and circular orbit parameters: altitude H = 400 km and inclination i=51.6° (the BOX model, [4]). The properties of all faces, each of which represents a double wall, are given in Table 3. In all cases the wall material and the shield material was the same, namely, – 6061-T6. The area of each of cube faces was 1 m^2.

Table 3.

Cube wall characteristics.

№	Side of cube	Area, m^2	Shield thick, cm	Stand off, cm	Wall thick, cm
1	Forward	1.0	0.30	12.0	0.25
2	Port	1.0	0.25	11.0	0.25
3	Aft	1.0	0.20	10.0	0.25
4	Starboard	1.0	0.25	9.0	0.25
5	Zenith	1.0	0.10	8.0	0.25
6	Nadir	1.0	0.05	7.0	0.25

Table 4 presents five basic calculation versions, which differ either in the model of environment, or in the analysis program itself. The cross-sectional area flux values, corresponding to these versions, were presented above in Table 2.

Table 4.
Basic calculation versions.

Used program code	BUMPER			SDPA-PP	
Versions	1	2	3	4	5
Orbital debris environment model	SDPA 2000	NASA 91	ORDEM 96	SDPA 2000	ORDEM 2000

Test calculations were carried out in two stages. At the first stage the collision probability estimates, and at the second stage – the estimates of the probability of wall breakdown were considered.

In analyzing the estimates of the probability of collisions of SC surface elements with particles of different sizes ($P_c(d)_j$) it is convenient to consider these estimates over a year interval, as well to calculate the ratio of obtained estimates to the cross-sectional area flux value:

$$A_{eff} = P_c(d)_j / \left[Q(d)_j \cdot 1year\right]. \qquad (4)$$

In the BUMPER program quantity A_{eff} denotes the "Effective Cross Section Area" of the oriented planar plate in the orbital debris environment and is calculated by formula:

$$A_{eff} = A \cdot \int_{\varphi} \cos[\beta(\varphi)] \cdot p(\varphi) \cdot d\varphi, \qquad (5)$$

where A is the upside surface area of the planar plate; $p(\varphi)$ is the approach angle probability density function; φ is the azimuth angle of approach; β is the angle between the normal to the plate and the direction of approach of orbital debris. This formula includes only positive values of cosine, i. e. the collision only with the facial side of a plate is considered.

In the SDPA model this quantity is calculated by formula:

$$A_{eff} = C_N \cdot A, \qquad (6)$$

where C_N is some dimensionless coefficient, which depends on the shape of a surface component (of different size) and on its orientation, A is the characteristic area of a surface component. In the given case the area of cube's faces is A=1 m^2. Therefore, the degree of proximity of estimates A_{eff} in calculations by means of the BUMPER and SDPA-PP programs is an indicator of concordance between the collision probability calculation techniques.

The results of determination of the probability of collisions of cube faces with SD sizing larger 0.1 cm, as well as the corresponding effective area estimates A_{eff}, are presented in Table 5. The upper line of this table presents the probability estimates $P_c(d)$ and the lower line – the area estimates A_{eff} for each face of a cube.

Table 5.
$P_c(d)$ (%) and A_{eff} (m^2) estimates

Cube face	Calculation version				
	1	2	3	4	5
For-ward	0.176	0.251	0.317	0.172	0.236
	0.635	0.701	0.645	0.638	0.662
Port	0.098	0.116	0.163	0.095	0.111
	0.355	0.324	0.331	0.344	0.332
Aft	0.001	0.0	0.004	0.001	0.000
	0.004	0.0	0.008	0.003	0.001
Star-board	0.092	0.116	0.163	0.095	0.118
	0.333	0.324	0.332	0.344	0.332
Sum	0.367	0.482	0.646	0.363	0.472
	1.326	1.349	1.316	1.328	1.326

The data of the two latter lines indicate that the differences between corresponding effective area estimates A_{eff} (do not exceed 2.5%) are much lower, than the differences between probability estimates, for which the maximum 1.80 times differs from the minimum. In accordance with the data of Table 2, the cross-sectional area flux estimates, calculated by the NASA91 and SDPA2000 models, differ 1.77 times, i.e. virtually to the same extent, as the collision probability estimates. This proves that the main source of differences between probability estimates are the differences between the cross-sectional area flux estimates. The differences between the techniques of calculation of collision probability and distributions of impact directions are considerably less significant.

In analyzing the penetration probabilities it is also convenient to consider not only the estimates of penetration probabilities themselves, but their ratio to the collision probability. In accordance with expression (1), this ratio has a meaning of the conventional penetration probability (under the condition of impact). However, in the BUMPER model the quantities of such a type are not calculated. For this reason Table 6 below presents the conventional penetration probabilities only for calculation versions 4 (the upper line) and 5 (the lower line).

Table 6.

Conventional probabilities of cube's faces penetration by particles of different sizes.

SD size	Cube faces			
	Forward	Port	Aft	Starboard
0.10-0.25	0.0000	0.0001	0.0000	0.0002
	0.0000	0.0001	0.0000	0.0001
0.25-0.50	0.1498	0.1038	0.0000	0.1383
	0.1154	0.0798	0.0000	0.1046
0.50-1.00	0.6913	0.7522	0.0057	0.8030
	0.6911	0.7356	0.0000	0.7850
1.00-2.50	0.8594	0.9816	0.0364	0.9818
	0.8727	0.9883	0.0623	0.9884

These data show, that the structure of walls provides, virtually, the complete protection against penetration of particles sizing smaller than 0.25 cm, and for the rear face - against particles of essentially larger size – up to 1 cm. It is seen also, that in application of the SDPA2000 model (version 4) the conventional probabilities of breakdown by particles sizing 0.25 – 0.5 cm are 30% higher, than in application of the ORDEM2000 model (version 5).

Table 7 presents the penetration probability estimates related to all versions under consideration.

Table 7.

Penetration probabilities PP (%) for cube walls.

Cube faces	Used program code and environment models				
	BUMPER			SDPA-PP	
	1	2	3	4	5
Forward	.00655	.00932	.0015	.00444	.00112
Port	.00311	.00326	.00392	.00221	.00048
Aft	.00001	0.0	.00015	0.0	0.0
Starboard	.00318	.00370	.00461	.00253	.00057
Sum	.01285	.01628	.01019	.00918	.00217

The comparison of the results of calculations for versions 4 and 5 indicates, that the penetration probabilities, corresponding to the application of the ORDEM2000 model, are 4.2 times lower, than the results of application of the SDPA2000 model. The analysis has shown, that in the test example under consideration the main contribution in the penetration probability (not lower, than 85-90%) is made by the particles sizing 0.25-1.0 cm. As follows from the data of Table 2 and Figure 3, the values of the flux of SDs of this size according to the SDPA2000 model data are 3 – 6 times greater, than those according to the ORDEM2000 model data. It is this circumstance, which represents the main reason of the difference between the penetration probability estimates considered above.

5. ESTIMATES OF PENETRATION PROBABILITY OF ISS SERVICE MODULE.

The configuration of Service Module, used in the BUMPER ***PP*** calculations, is represented in Figure 5.

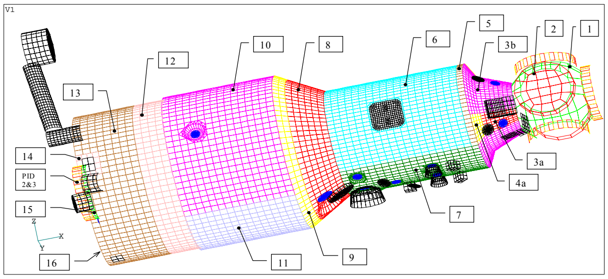

Fig. 5. The configuration of Service Module

The shielding properties of all module critical zones, depicted with their numbers in Figure 5, are presented in Table 8. All the shields as well as pressure walls of zones № 1, 2, 3a, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 3b are made of aluminum alloy AMg-6, but pressure walls of zones №14, 16 are made of stainless steel. Here t_b, t_w, S are thickness of shields, walls and a distance between them, respectively.

Table 8.

ID	Service Module critical item region	Thickness, cm		
		t_b	S	t_w
1	tranfer module "sphere"	0,20	2,0	0,60
2	transfer module "cover"	0,10	10,0	0,50
3a	transfer module "cone"	0,10	2,0	0,40
4	Working module "bottom"	0,10	2,0	0,35
5	Working module "fwd cyl"	0,10	2,0	0,16
6	Working module "radiator cyl"	0,10	5,0	0,16
7	Working module "nadir cyl"	0,10	5,0	0,16
8	Working module "cone w/shld"	0,10	2,0	0,23
9	Working mod. "cone w/o shld"	0,10	3,0	5,00
10	Working mod "radiator cyl"	0,10	5,0	0,20
11	Working module "nadir cyl"	0,10	5,0	0,20
12	power module "short s.o. cyl"	0,37	23,0	0,35
13	power module "long s.o. cyl"	0,37	23,0	0,35
14	prop tanks	0,37	8,0	0,12
15	Transverse chamber "cover"	-	-	0,35
16	power module aft	0,30	3,0	0,25
3b	thick plate@transfer mod. cone	0,10	2,0	2,60
	fwd docking mech	0,2	4,0/10	2,5/0,4

The estimates have been made on the basis of initial data, presented in section 2, for 5 variants of Table 4. The calculation results are presented in Table 9. They include the values of probability of ISS Service module penetration over a year time interval and its effective area, as well as probability of collision (impact) with particles sizing 0.1 cm and larger.

Table 9.

Calculation results for Service Module.

	Used program code and environment models				
	BUMPER			SDPA-PP	
	1	2	3	4	5
PP, %	0.560	0.704	0.826	0.362	0.136
PI, %	8.408	10.37	17.06	9.61	12.10
A_{eff}, m^2	31.74	30.55	30.59	34.70	34.00

The overall ISS Russian Segment configuration, used in the Service Module ***PP*** calculations, is represented in Figure 6.

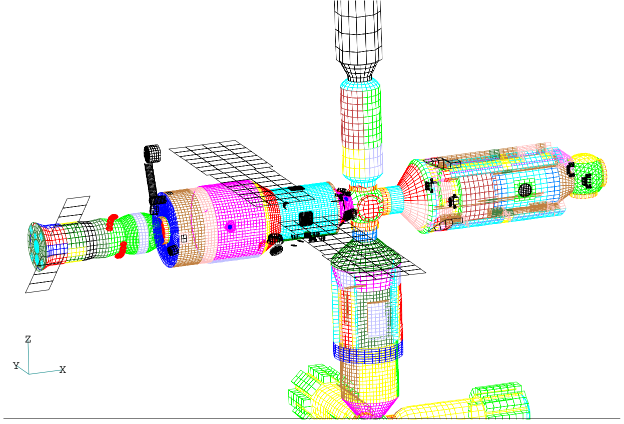

Fig. 6. Service Module in ISS Russian Segment configuration.

Let us consider also some additional ***PP*** calculation results featuring the influence of ISS orbit height. The probability of penetration of the Service Module over 2000 year with SPDA2000 environment model presented in Table 10.

Table 10.

PP of the Service Module over 2000 year with using SDPA2000 model.

Height of circuit orbit ***h***, km			
368	400	446	485
0.0031	0.0036	0.0042	0.0064

These results were obtained with SPDA2000 environment model using both SD specific flow values (see Table 3) and the distribution of directions of possible collisions $pQ_{rel}(Az)$. Obviously, the increase in orbit height gives rise 2 times in ***PP***.

6. CONCLUSIONS

The comparison of the probabilities of penetration calculated by different techniques using different environment models shows, that:

1. different calculation techniques results in scattering of ***PP*** estimates in the range of several tens of percent;
2. applying different environment models in ***PP*** calculations results in varying ***PP*** estimates in the range of several hundred percent;
3. the dependence of ***PP*** from SC orbit height requires to consider the SC orbit height time profile in ***PP*** calculations.

7. REFERENCES

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