IMPACT RISK ASSESSMENT FOR THE ATV USING ESABASE/DEBRIS

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1 ABSTRACT

The European Space Agency ESA participates in the International Space Station with various programs, one of them being the Automated Transfer Vehicle (ATV). The ATV is an unmanned servicing and logistics vehicle launched on Ariane 5 and designed to fulfil different roles like cargo transport, re-supply of fuel and consumables and orbit re-boost of the International Space Station (ISS). For this reason it is important that the risks imposed on these modules by meteoroids and orbital debris are calculated accurately. Following such calculations the Meteoroid and Orbital Debris Protection System (M/ODPS) can be optimised.

This paper presents the results of the risk assessment of meteoroids and space debris for the ATV spacecraft attached to the ISS using different shield configurations. The results are presented as the probability of no penetration (PNP) for each component and each configuration. They are compared to a target PNP requirement of 0.999 for 135 days and the weight penalty produced by the extra shielding is given.

2 INTRODUCTION

The ATV will be docked to the ISS for long periods, exposed to the space environment with almost no external protection and little servicing. It is therefore important that all critical elements are properly shielded against impacts from meteoroids and debris. On the other hand, any additional shielding requires additional weight, which reduces the payload capabilities and increases the launch costs. A careful trade-off between acceptable impact risk and extra shielding mass has to be made.

The impact risk assessment tests various configurations and analyses the best shielding possibilities for the ATV. The aim is to adapt the existing design of the ATV in order to achieve a specific level of protection. The actual design of the ATV includes a Whipple shield in all its modules. The option selected to increase the level of protection was adding a Kevlar/Nextel Layer between the bumper and the backwall of the Whipple shield (WS), transforming it into a Stuffed Whipple shield (SWS), similar to the advanced shield used in the Columbus module. This implies an increase in weight that has to be traded off against the increase in protection

This assessment was realised with the ESABASE/DEBRIS tool. This is a software tool for analysing the interaction between a spacecraft and the space environment. ESABASE allows the creation of a 3D model of the spacecraft and includes various environment models and tools for calculating the effects of meteoroids and space debris.

The main objective of these calculations was to study the effects of the stuffed Whipple and of non-conformal shields (augmentation wings) installed on the Russian Service Module (RSM). A Multi-Layer Insulation (MLI) added on top of the bumper shield is also considered. Studied is the feasibility of the different configurations to achieve a target PNP of 0.999 for 135 days and the weight increase resulting from the extra shielding.

3 THE ESABASE/DEBRIS TOOL

The ESABASE/DEBRIS impact assessment tool [2] was used to perform the analysis. This tool allows to create a geometry model of a spacecraft and analyse it with a number of applications. It includes various debris and meteoroids models and based on them calculates the fluxes on the spacecraft. The tool also calculates the number of particles that are capable of penetrating the spacecrafts shields.

The meteoroid and space debris flux models applied are the applicable models for design of the International Space Station as specified in SSP 30425 [1]. The full velocity and impact angle distribution, as implicit to the flux models, was considered. The debris flux model used for the calculations does not consider flux from elliptical orbits and assumes that all debris moves in circular orbits. The meteoroid model assumes an isotropic flux.

4 THE AUTOMATED TRANSFER VEHICLE

The ATV is one of the most important contributions from the European Space Agency to the International Space Station. It is an unmanned resupply vehicle launched by Ariane 5 carrying propellant, equipment for onboard systems and experimental facilities and

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general supplies. It will also be responsible for reboosting the ISS into orbit using its own engines. It will automatically rendezvous and dock with the Space Station and its first test flight is scheduled for 2003.
A risk analysis for the ATV is important because of its long exposure to the space debris and meteoroids environment. The ISS, being a manned program, has much higher safety requirements than other programs and requires a high level of protection from particle impacts.

4.1 The ATV's Mission

The ATV will provide the following services to the International Space Station:

- Delivery of cargoes to the Station such as experiments, food, compressed air and water
- Refuelling of the Station i.e. the transfer of propellant to the Zarya Russian Service Module
- Reboost and attitude control during the reboost operation of the whole Station, i.e. orbit correction using the ATV propulsion system to compensate for the continuous loss of altitude by the Station.
- Removal of waste from the Station followed by a controlled reentry of the ATV into the Earth's atmosphere. The ATV will be safely consumed during reentry.

4.2 Mission Parameters

The analysis was done for the ATV/ISS attached phase using the following mission Parameters:

Mission duration: 135 days attached to the Russian Service Module of the ISS

Orbital Altitude: 400 km
Inclination: 51.6°
Year: 2008

The following parameters were used by ESABASE:

Solar activity parameter, S: 70
Debris Mass growth rate: 0.05
Small debris growth rate: 0.02
Meteoroid material density: 1.0 g/cm^3
Space debris material density: 2.8 g/cm^3

Attitude of ATV/ISS
Roll: 0°
Pitch: -11.2°
Yaw: -6.1°

4.3 ATV model geometry

Figure 1 shows the ESABASE model used in the calculations, including the Russian Service Module and the four augmentation wings attached to the RSM. All elements excepting the Avionics Module have an MLI layer added on top of the bumper shield. This figure also shows the vectors corresponding to the tilted attitude described in section 4.2

Table 1 shows the corresponding geometry parameters for the baseline ATV configuration. Note that the Spacecraft part (modules 1 to 6) have a higher backwall yield strength of 57000 psi compared to 47000 psi in the cargo carrier (modules 7 to 9).

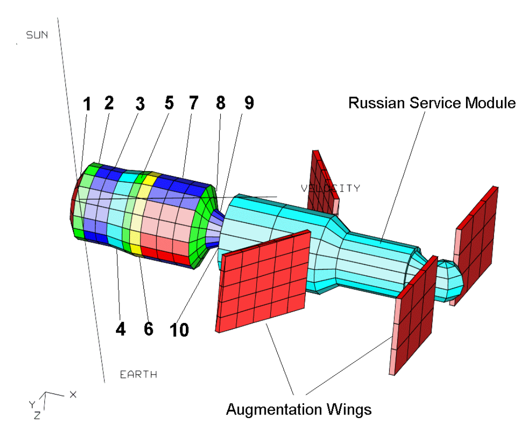


Figure 1 – ATV Geometry

	ATV element	Area [m^2]	Bumper thickn. [cm]	MLI thickn. [cm]	Rear Wall thickn. [cm]	Spacing bump.-wal [cm]	Back-wall Yield Strengh [ksi]
1	**Thruster cone (TC)**	14.0	0.08	0.022	0.25	4.0	57
2	**Lower Thruster Cyl. (LTC)**	7.7	0.08	0.022	0.42	9.66	57
3	**Upper Thruster Cyl./ Cylindrical panels (UTC)**	16.8	0.08	0.022	0.33	9.66	57
4	**Lower Avionics module (LAM)**	12.1	0.20	-	0.34	10.4	57
5	**Upper Avionics Module (UAM)**	6.2	0.10	-	0.34	10.4	57
6	**Ext. Cylind. (EC)**	8.4	0.12	0.022	0.30	12.8	57
7	**Pressur. Module Cyl. (PM)**	38.3	0.12	0.022	0.30	12.8	47
8	**Cone 2 (C2)**	13.2	0.12	0.022	0.25	12.15	47
9	**Cone 1 (C1)**	5.0	0.12	0.022	0.30	12.8	47
1	**Russian Docking System (RDS)**	Included in model but not used for risk assessment. The NASA Allocation of PNP = 0.99995 is used instead					

Table 1 – ATV Geometry

4.4 THE ATV SHIELDING

The original design of the ATV is equipped with a Whipple shield in all its modules. A Whipple shield consists of an exterior bumper spaced at a given stand-off distance from the inner wall (or back-up wall). It is the standard means for providing protection to critical spacecraft systems from meteoroid and orbital debris impacts. However, the spacecraft volume and weight available for shielding is often severely constrained, resulting in short stand-off distances below the optimum. This fact substantially decreases the protection performance and/or increases the weight of the Whipple shield.

In order to improve the protection of the modules, an extra layer is added between the bumper shield and the backup wall of the Whipple shield, transforming it so into a Stuffed Whipple shield.

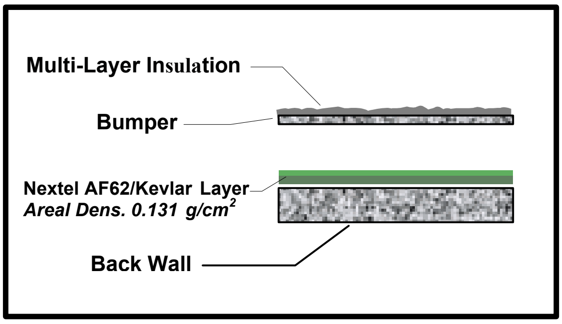


Figure 2 - Configuration of the stuffed Whipple

Figure 2 shows the configuration of the Stuffed Whipple Shield used in the calculations. A Multi-Layer Insulation sits on top of the bumper shield. The stuffing consists of two layers, one of Nextel AF62 and one of Kevlar, installed close to the backup-wall. The areal density of the stuffing is 0.131 g/cm2.

5 EQUATIONS USED IN THE COMPUTATION OF THE PNP FOR THE ATV

Following tests performed on the different shield configuration of the ATV, various damage equations where developed to calculate the minimum particle diameter (d_c) capable of penetrating the shields for a given impact angle and impact velocity (see [[3]] and [4]). These equations where used for the ESA-BASE/DEBRIS calculations. The same Equations (eq. 1 and eq. 2) were used for the Whipple Shield with MLI on top, Whipple Shield without MLI and Stuffed Whipple Shield with MLI on top, using a different factor for each type.

The Whipple Shield (WS) equation was used for all subsystems with an MLI layer on top, this being the M/OD shielding in the baseline configuration. The thickness of the MLI is added to the bumper thickness. A slightly different Whipple Shield equation is used for those modules not equipped with an MLI (the Avionics module).

The Stuffed Whipple Shield (SWS) equation, which consists of the Whipple shield equation with a higher pre-factor, is used for those elements reinforced with a layer of Nextel and Kevlar with a total area density of 0.131 g/cm^2. For this calculation, the thickness of the intermediate Kevlar/Nextel layer is added to the thickness of the back-up wall. The thickness of the MLI is added to the bumper.

The Multi-Shock (MS) equations where used to asses the effect of particles penetrating the Service Module augmentation wings. For this analysis a constant stand-off distance of 40 cm, a total shield areal density of 0.63 g/cm2 and the real ATV rear wall thickness is used.
The three-step approach described by E. Christiansen in [5] was used to calculate the contribution from those particles that penetrate the augmentation wings attached to the Service Module. This contribution is added to the results as a “Correction Factor” (NP_{corr}).

The following variables are used in the equations:

d_c	Critical diameter for penetration[cm]
C	Speed of sound in target [km/s]
t_w	Thickness of back-up wall [cm]
t_b	Thickness of bumper/shield [cm]
ρ_p	Particle density [g/cm^3]
ρ_w	Back-up wall density [g/cm^3]
ρ_b	Bumper density [g/cm^3]
H	Brinell hardness of target [BHN]
V	Impact Velocity [km/s]
S	Space between bumper and back-up wall [cm]
P	Penetration depth [cm]
q	Impact angle [deg]
V_n	Normal component of impact velocity $V_n = V\cdot \cos q$ [km/s]
s	Yield Strentgh of back-up wall [ksi]

5.1 <u>Whipple Shield and Stuffed Whipple Shield equation:</u>

<u>Low velocity region</u>

For $V_n \leq 3$ km/s

$$d_c = \left[\frac{t_w (s\ /40)^{1/2} + t_b}{0.6(\cos q)^{5/3}\cdot r_p^{1/2}\cdot V^{2/3}}\right]^{\frac{18}{19}} \quad (1)$$

Linear interpolation is used between low and high velocity regions.

High velocity region

For $V_n \geq 7$ km/s.

$$d_c = \left[\frac{A \cdot t_w^{2/3} (s/70)^{1/3}}{(\cos q)^{2/3} \cdot r_p^{1/3} \cdot r_b^{1/9} \cdot V^{2/3} \cdot S^{-1/3}} \right] \qquad (2)$$

where A depends on the shield Type:

Whipple Shield with MLI on top: A = 2.9754
Whipple Shield without MLI: A = 3.918
Stuffed Whipple Shield with MLI on top: A = 5.2002

5.2 Multi-shock Equation (for calculations with augmentation wings)

High velocity region:

For $V_n \leq 2.4/(\cos q)^{1/2}$ km/s

$$d_c = 2 \cdot \left[\frac{t_w (s/40)^{1/2} + 0.37 m_b}{(\cos q)^{4/3} \cdot r_p^{0.5} \cdot V^{2/3}} \right] \quad \text{with} \quad m_b = t_b \times r_b \qquad (3)$$

Linear interpolation is used between low and high velocity regions.

Low velocity region:

For $V_n \geq 6.4/(\cos q)^{1/4}$ km/s

$$d_c = \left[\frac{0.358^3 \cdot t_w (s/40)^{1/2}}{(\cos q) \cdot r_p \cdot r_w^{-1} \cdot V \cdot S^{-2}} \right]^{\frac{1}{3}} \qquad (4)$$

6 TOTAL FLUXES ON THE ATV

The first step in the Analysis was calculating the impact fluxes to the ATV in its baseline configuration (see Table 1). Figure 3 and Figure 4 show the distribution of the total impact flux for meteoroids and debris over the surface of the ATV in impacts/m^2/year for

The reason for the majority of the debris impacts coming from the sides is that the debris model only includes circular orbits. Because of this, the wings receive the highest impact fluxes. The shadowing effect of the augmentation wings attached to the Service Module can be clearly seen.

The pitched attitude of the ISS produces an asymmetric flux on the second pair of wings, with the top of the wings receiving a higher flux than the bottom part.
The wing attached to the left side of the ISS presents a higher impact flux than the right side wing due to the yaw angle of the ISS.

The rear part from the Spacecraft section from the ATV (Upper and lower Avionics Module and Thruster Cylinder) gets hit from the sides by those objects not hitting the wings. These figures do not include the effects of any particles that get through the augmentation wings and hit the ATV, although this was included in the calculations.

Because of the tilted attitude, some objects also hit the upper (spaceward) side of the ATV, specially the Cone 2 and the Pressurised Module.

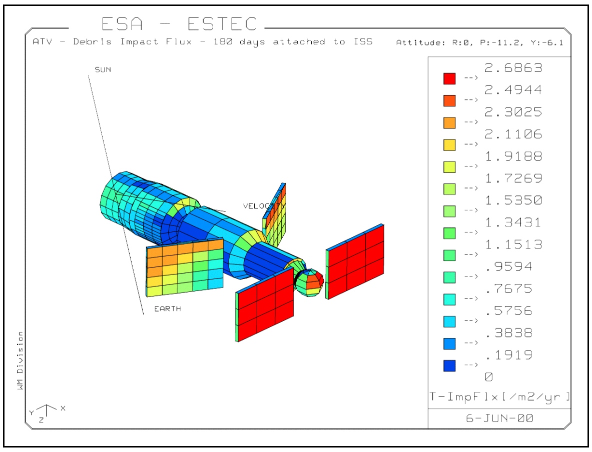


Figure 3 – ATV Debris impact flux

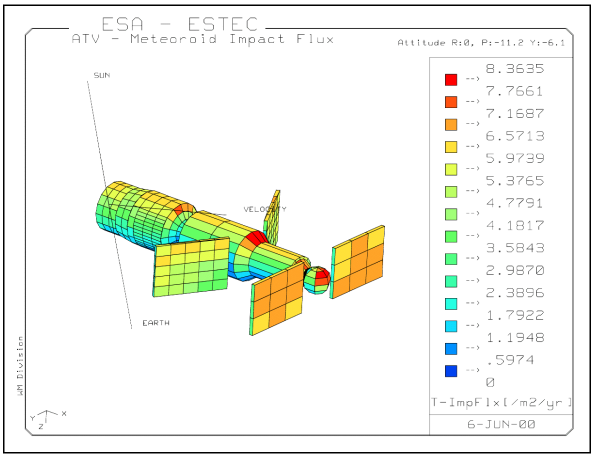


Figure 4 – ATV Meteoroid impact flux

The distribution of the Meteoroid Flux is very different, with most of the objects hitting the upper an frontal side of the ATV, while the lower, earthward looking side has almost no flux.

The maximum flux for space debris is 2.67 impacts/m^2/yr for an object size of D > 0.01 cm. For meteoroids, the maximum flux is 8.36 impacts/m^2/yr for the same minimum object size. It should be noted that, although the meteoroid impact flux is higher at the minimum size shown of D > 0.01 cm, the number of failures caused by debris impacts is much larger than that caused by meteoroids (a factor of 10 or more) for the given shielding. The reason is that for sizes critical for penetration of the ATV shields, debris fluxes are dominating. According to the reference flux models, the directional distribution of impacts, as seen in Figure 3 and Figure 4, is the same for all sizes.

7 DAMAGE ANALYSIS

Ten different ATV shielding configurations where investigated, using the WS configuration as a baseline and equipping different modules with a SWS. Separate calculations where performed for the ATV equipped completely with either WS or SWS. Then the contributions for each module were added together depending on the type of shield used. This allows to analyse a large number of configurations by combining the contributions of the desired modules. Table 2 summarises all the configurations presented in this report.

PNP Analysis shielding configurations	
Configuration 1	Baseline – WS in all modules
Configuration 2	SWS in Cone2 and ½Pressurised module
Configuration 3	SWS in Cone2 and ¾Pressurised module
Configuration 4	SWS in Cone2 and Pressurised module
Configuration 5	SWS in Cone2, Pressurised module and External Cylinder (full Cargo Carrier)
Configuration 6	SWS in Cone2, ½Pressurised module and Cylindrical Panels
Configuration 7	SWS in Cone2, Pressurised module, External Cylinder and Thruster Cylinder
Configuration 8	SWS in Cone2, Pressurised module and Cylindrical Panels
Configuration 9	SWS in all modules excepting the Avionics module
Configuration 1	SWS in all modules

Table 2 – Summary of all shielding configurations

Note that the pressurised module was divided into four parts. This way it was possible to analyse some configurations where only part of it was shielded. Figure 5 shows an example corresponding to configuration 2, where only the Cone 2 and ½ of the Pressurised Module are equipped with the SWS.

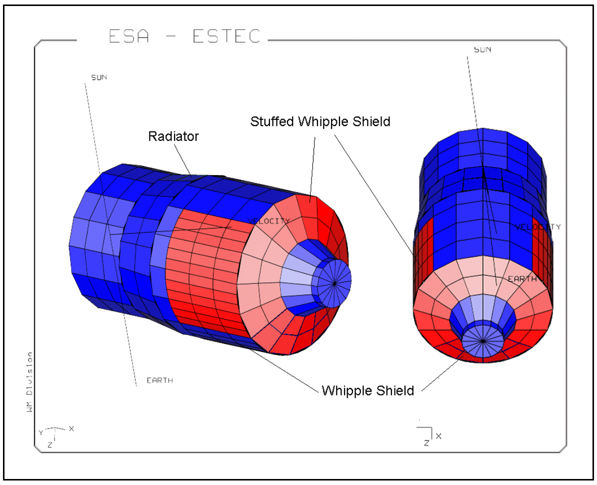


Figure 5 – Example of ATV shielding configuration

The output from ESABASE/DEBRIS delivers the number of penetrations NP in [1/m^2/yr]. Then the Probability of No Penetration is calculated by the following equation:

$$PNP = e^{-NP} \qquad (5)$$

The considered failure mode is the penetration of the inner wall.

For each configuration the results for a 180 and a 135 days mission was reported. No allocations for external items or rear flux were included. All calculations were done with the augmentation wings attached to the Service Module and with the ATV in the tilted attitude given in section 1. Sigma refers to the yield strength of the back-up wall. The aim of the analysis was to determine what level of protection is necessary to achieve the target requirement of PNP = 0.999 for 135 days and what weight increase this would produce for the M/OD Protection System.

ATV + Wings WS/SWS in C2+3/4PM
New equation with high vel. factor WS => 2.9754 SWS => 5.2002
ESA tilt - 135 days - No rear flx. No ext. items

ATV Item	MLI Outside	Shield type	Backw. yield strenght [ksi]	Extra Weight inc 30% Conting. [kg]	**Debris**	**Meteoroids**	NP corr	NPTot	PNPtot
Thruster Cone	Yes	WS	57		.156E-5	.446E-4	.000E+0	.462E-4	0.99995
Thruster Cylinder	Yes	WS	57		.890E-4	.851E-5	.908E-6	.984E-4	0.99990
Cylindrical Panels	Yes	WS	57		.276E-3	.364E-4	.359E-5	.316E-3	0.99968
Lower Avion. Module	No	WS	57		.824E-4	.580E-5	.307E-5	.913E-4	0.99991
Upper Avion. Module	No	WS	57		.496E-4	.296E-5	.000E+0	.526E-4	0.99995
Ext m cylinder	Yes	WS	57		.116E-3	.165E-4	.344E-5	.136E-3	0.99986
-Y PM (Left)	Yes	SWS	47	16.3	.737E-4	.184E-5	.138E-4	.893E-4	0.99991
-Z PM (Up)	Yes	SWS	47	16.3	.456E-4	.329E-5	.000E+0	.489E-4	0.99995
+Y PM (Right)	Yes	SWS	47	16.3	.487E-4	.151E-5	.138E-4	.640E-4	0.99994
+Z PM (Down)	Yes	WS	47		.159E-4	.124E-5	.000E+0	.171E-4	0.99998
Cone2	Yes	SWS	47	22.5	.813E-4	.564E-5	.273E-4	.114E-3	0.99989
Cone 1	Yes	WS	47		.943E-5	.669E-5	.793E-6	.169E-4	0.99998
RDS cylinder	NASA allocation							.375E-4	0.99996
Total				71.2	.889E-3	.135E-3	.667E-4	.113E-2	0.99887

Table 3 – Results Table for configuration 3

The results are summarised in tables (see Table 3) including the contributions from each module. The correction factor NP_{corr} represents the number of objects that penetrate the augmentation wings and are then capable of penetrating the shields.

7.1 Configuration results

Configuration 1 - Baseline configuration (Whipple shield)

The baseline configuration with a simple Whipple shield in all modules. All modules except the Upper and Lower Avionics module have an MLI on top. The PNP is 0.99815 for 135 days, well below the target PNP of 0.999for 135 days.

Configuration 2 - Stuffed Whipple shield in Cone 2 and ½Pressurised Module

In this configuration the Cone 2 and the +Y and –Y sides of the Pressurised Module were reinforced with a SWS. The PNP is 0.99877 clearly showing the improvement provided by the stuffing. The weight increase for this configuration is 55 kg including 15% for attachments and 15% for contingencies ($0.131\ g/cm^2 \times 32.2\ m^2 + 30\ \%$).

Configuration 3 - Stuffed Whipple Shield in Cone 2 and ¾of the Pressurised Module

This configuration is very similar to configuration 2, with the stuffed Whipple shield added in the most exposed parts of the cargo carrier. The upper quarter (-Z) of the Pressurised Module also has a Stuffed Whipple shield, so that all upper ¾ of the Pressurised Module and the complete Cone 2 have an increased protection. The aim is to protect the upper part of the pressurised module from meteorites and from those objects that are not stopped by the augmentation wings because of the tilted attitude of the ATV. This extra protection provides a PNP of 0.99887, with weight increase of approximately 71 kg including 15% for attachments and 15% for contingencies ($0.131\ g/cm^2 \times 41.9\ m^2 + 30\ \%$).

Configuration 4 - Stuffed Whipple Shield in Cone 2 and Pressurised Module

In this configuration, the complete Cone 2 and Pressurised Module were equipped with SWS resulting in a PNP of 0.99888, almost the same as configuration 2. The weight of the extra Kevlar/Nextel Layer is 87.7 kg ($0.131 g/cm^2 \times 51.5\ m^2 + 30\%$).

Configuration 5 – SWS in Cone 2, Pressurised Module and External Cylinder

This configuration represents a reinforcement of all modules corresponding to the Cargo Carrier and results in a PNP of 0.99897. The Weight increase is 102 kg including 15% for Attachments and 15% for contingencies. This configuration does not reach the target by a light margin, so that the shielding of some modules of the Spacecraft would be required.

Configuration 6 - SWS in Cone 2, ½Pressurised Module and Cylindrical Panels

This configuration is similar to configuration 2, but also adds SWS to the Cylindrical Panels. This results in a PNP of 0.99898 and implies a weight increase of 87 kg

Configuration 7 – SWS in Cone 2, Pressurised Module. External Cylinder and Thruster Cylinder

This configuration represents one of the possibilities of achieving the target PNP, by adding extra shielding to the Spacecraft (C2, PM, EC) and the Thruster cylinder. This result has an extra weight of 115 kg including 30% for attachments and contingencies and achieves a PNP of 0.99903.

Configuration 8 – SWS in Cone 2, Pressurised Module and Cylindrical Panels

This configuration represents a second and more effective possibility of achieving the target PNP, adding extra shielding to the Cone 2, ¾ of the Pressurised Module and the Cylindrical Panels. This results in an extra weight of 100 kg including 30% for attachments and contingencies and achieves a PNP of 0.99908 days. This result is slightly better than that of configuration 7, weights 16 kg less and only three modules are equipped with SWS instead of four.

Configuration 9 – SWS in all modules except the avionics module

In this configuration the complete ATV except the Avionics module was reinforced with a Stuffed Whipple Shield. The PNP is 0.99929, having a high margin above the target PNP. The weight of the extra Kevlar/Nextel Layer is 167 kg.

Configuration 10 – SWS in all modules

In this configuration, all modules of the ATV were equipped with a Stuffed Whipple Shield. This configuration shows the maximum PNP possible with the actual SWS. The PNP achieved is 0.99934.
The weight of the extra Kevlar/Nextel Layer is almost 200 kg.

7.2 Result Conclusions

Figure 6 shows a diagram with the PNP results and weight penalties for all the configurations described above. The configurations where selected in such a way that the extra shielding was progressively increased and applied only to the most exposed areas. The mass penalties for the various configurations with extra shielding range from 55 to 200 kg including 15 % for attachments and 15% for contingencies. Comparing configurations 2 and 3 shows that a reinforcement of the upper side of the Pressurised module is important, in order to protect the ATV from meteoroids and from those debris particles not stopped by the augmentation wings.

A comparison between configurations 3 and 4 shows that a reinforcement of the Earth- looking side (-Z) of the ATV modules produces almost no improvement of the PNP. This is because with the modelled attitude of the ISS, almost no particles hit the lower side of the ATV. By leaving the Earth-looking side of the ATV without SWS, 25 % of the extra weight could be spared.

Configuration 5 represents the stuffing of the full Cargo Carrier and shows that a stuffing of some parts of the Spacecraft are also needed if the target PNP of 0.999 for 135 days is to be achieved.

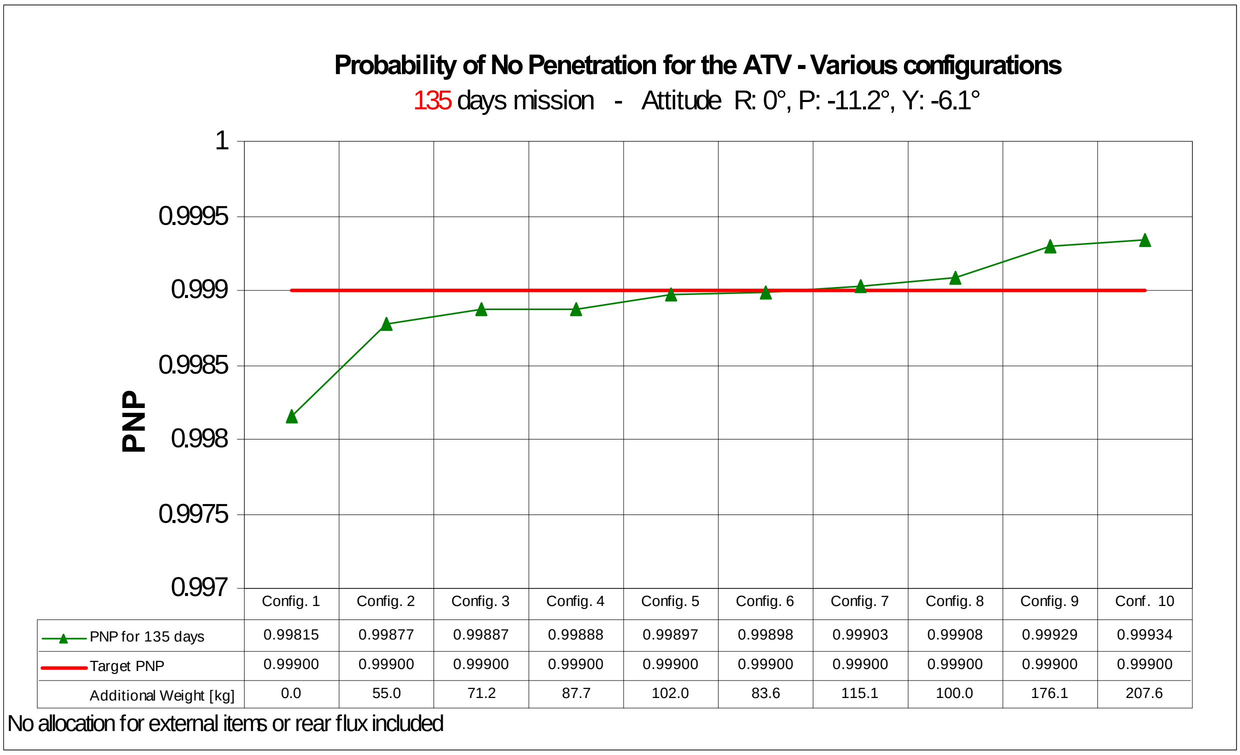
The calculations where done without including the contributions from the external items and the rear flux and with the augmentation wings attached to the Service Module. These wings have a significant effect on the protection of the ATV although their effectiveness is greatly reduced if the pitch or roll attitude of the ISS is further increased.

The presented results have to be seen as preliminary but they can support the decision for potential ATV shielding augmentations. For the final ATV configuration, some wall thickness might be different and the extra protective layers could be optimised. If the present stuffing is replaced by several thinner layers with the same combined Arial density the protection should be more effective for the same mass penalty. For such an improved shielding design, the analysed configurations 3 to 10 are believed to all meet the target PNP of 0.999 for 135 days.

7.3 Analysis Conclusions

- The contribution to number of penetrations from debris objects is a factor 10 or more greater than that of meteoroids
- It is important to shield the upper part of the modules
- Shielding of the Cone2 and the Pressurised Module offer the highest protection
- The augmentation wings offer a high level of protection, but their effectivity would be reduced if the pitch off the ISS is further increased.
- The weight increase necessary to achieve acceptable levels of protection ranges between 71 and 115 kg.

It should also be pointed out that the “old” debris flux model from ref. [1] was used for this analysis. This is the applicable model for the design of ISS elements. It is well known that this model is outdated and conservative. Newer debris models would predict a much smaller number of failures for the baseline ATV shielding.



	Config. 1	Config. 2	Config. 3	Config. 4	Config. 5	Config. 6	Config. 7	Config. 8	Config. 9	Conf. 10
PNP for 135 days	0.99815	0.99877	0.99887	0.99888	0.99897	0.99898	0.99903	0.99908	0.99929	0.99934
Target PNP	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900	0.99900
Additional Weight [kg]	0.0	55.0	71.2	87.7	102.0	83.6	115.1	100.0	176.1	207.6

No allocation for external items or rear flux included

8 SUMMARY AND CONCLUSION

The Automated Transfer Vehicle, being a very important contribution to the ISS needs to fulfil high safety requirements regarding space debris and meteoroids impacts. The risk analysis performed is this study shows the shielding enhancements providing by adding a layer of Kevlar-Nextel to the Shield.

Those configurations shielding the frontal and spaceward looking parts of the ATV are the most effective, and the weight increase for the enhanced shielding ranges between 71 and 115 kg. The augmentation wings provide a high level of protection, but only if the pitch of the space station is not further increased.

The analysis of different ATV shielding configuration performed in this study provided an efficient way of analysing the weight and protection requirements for the ATV, showing the effectivity and possibilities of the enhanced shielding.

ABBREVIATIONS

ATV	Automated Transfer Vehicle
C2	Cone 2
ISS	International Space Station
M/OD	Meteoroids and Orbital Debris
M/ODPS	Meteoroids and Orbital Debris Protection System
MLI	Multi-Layer Insulation
MS	Multi-Shock
NP	Number of Penetration
PM	Pressurised Module
PNP	Probability of No Penetration
RSM	Russian Service Module
SW	Single Wall
SWS	Stuffed Whipple Shield
WS	Whipple Shield
EC	External Cylinder

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