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THE DEVELOPMENT OF THE COLUMBUS SPACE DEBRIS PROTECTION

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1. Introduction

The first investigation into a manned space flight programme called Columbus were initiated by Germany and Italy in 1982. This was ten years before 1992, the 500th anniversary of Columbus discovery of America, hence the name Columbus for the project, chosen in the expectation that Columbus would fly in 1992.

In 1984 the United States of America proposed to Europe to participate in the International Space Station programme, later called Freedom. The respective agreements in the form of the Intergovernmental Agreement and the Memorandum of Understanding (MOU) were signed in 1988.

The Columbus programme paused in its progress in 1991/1992 as a consequence of the European Space Agency reviewing its major programmes. In November 1992 the Ministerial Council at their meeting in Granada confirmed to execute the Columbus Attached Pressurized Module (APM). In March 1993 NASA started a Space Station Redesign effort following a White House directive to half the cost for the International Space Station.

At the Columbus Programme Baseline Review (PBR-1) in 1987 the issue of protection against space debris caught ESA programme management attention for the first time. Also from that time onwards, a very intensive cooperation between ESA and NASA followed on the subjects of protection requirements, shielding design and testing and risk analysis.

2. Status of Protection in 1987

The protection requirement was totally crew-related and was expressed as the minimum probability of 0.9995 per year of no pressure wall penetration by meteoroids and space debris resulting in a pressure drop to 700 mbar in less than 2 minutes.

Following an agency requirement to build the APM from a Spacelab-type pressure shell for cost saving reasons, the module wall had a thickness of 1.6 mm. A single Aluminium shield of also 1.6 mm thickness with a spacing of 150 mm from the module wall formed the protection.

Programmatics related:

1982-1984	Phase A investigations (D, I)
mid 1984	COL programme proposal to member states; US proposal for participation in Space Station Programme
Jan. 1985	Ministerial Council at Rome approves a 2 year preparatory Col programme
Nov. 1987	Ministerial Council at The Hague approves Col programme to be performed in 2 phases: Phase 1 from Jan. 1988 to end 1990, Phase 2 from 1991 to 1998, (Phase 1 was later extended to end 1992)
Dec. 1987	1st meeting with NASA on requirements
Sep. 1988	IGA signature MOU signature
Sep. 1990	Joint ESA/NASA requirements agreed (JPDRD signature)
Nov. 1992	Ministerial Council at Granada confirms Col programme (APM)
Mar. 1993	Space Station Redesign

Space Debris related:

15. Sep.1987	MBER, MDPS Mtg., AI from PBR-1
29/30 Sep.1987	MSFC, informal M/OD protection Mtg.
June 1989	Col PRR Part 1, Departure from Spacelab pressure shell design
6-9 Feb. 1990	MSFC, rack I/F, enlarged module ø
23-26 Sep.1990	MSFC, M/OD TIM CR 869 Shield Augmentation
18/19 Apr.1991	JSC, M/OD TIM
July 1991	CR 883 M/OD Environment Update followed by APM shield design update
Dec. 1991	IMR: CR 869 withdrawn, RISK Study implemented with final report in March 1993
14-16 Jan.1992	JSC, M/OD TIM on RISK Study
17 Jan.1992	JSC, briefing to Kohrs
6 May 1992	ESA burst test
May 1992	APM SRR data package contains waiver request against M/OD requirements
13/14 July 1992	SRR Board requests no-burst tests
28 Jan. 1993	receipt of ECOL M/OD no-burst test proposal

Table 1: Programmatics and Space Debris related Events and Involvements of Columbus

The Columbus Programme Baseline Review Board found that the risk to the crew and the station was possibly more encompassing than envisioned by the pressure loss requirement, that a detailed risk analysis was missing and that shielding test evidence was not broad enough.

The ESA project team tackled these issues and proposed the following concepts and plans:

- Penetration / Catastrophic Events

In contrast to NASA thinking the view was developed that not ary wall penetration by a debris particle should be considered a critical event. With the currently available computer codes it was easy to evaluate the probability of a wall failure, but not the severity of the damage. However, in order to keep the probability figure of a catastrophic event at least in the vicinity of the requirement, severe but not catastrophic events were to be discounted. In order to assess the over-all station risk, a risk analysis was to be performed, a task, which ESA as the provider of a single module could not perform.

- Effect Tree for Risk Analysis

The team developped an effect tree for the performance of a risk analysis for the Columbus module and its crew.

- Module related Safety Concept

A detection system consisting of some 20 ultrasonic sensors spread over the module skin was to alert the crew of a debris impact. By triangulation the impact location can be determined down to a third or quarter of a metre. By impact calibration the severity of the damage was to be assessed. This system was complemented by a crew warning and information system. A prototype of the detection system from Norske Veritas is working.

For cost reasons the NASA Program Definition and Requirements Document (PDRD) does not contain a requirement for a crew alert function against space debris impact.

- Proposal for a Test Programme

Since the knowledge of shielding design was scarce, a test programme was proposed which covered

- improvement of sabot design
- impact test with Aluminium shield
- impact test with Kevlar/Aluminium composites
- impact test of sandwich panel
- impact test of pressurised samples
- oblique impacts.

All of these tests were finally executed, albeit the tests of pressurized samples only as late as summer 1992.

This programme was discussed in September 1987 with NASA-MSFC personnel responsible for the US pressurized module design.

3. Steps in the Shielding Design Development

At the Columbus Preliminary Requirements Review in June 1989 it was decided to no longer require a module pressure shell design based on the Spacelab design. In order to meet the requirement of no catastrophic consequences in case of a debris impact by non-penetration, a shell thickness requirement of 3 mm was identified. In order to avoid arguments later on design verification, the Boeing measure of 1/8th of an inch (3.2 mm) was finally chosen.

In order to fill the MOU agreement of joint space station utilisation with life, the space station partners NASA, NASDA and ESA agreed on the concept of the International Standard Payload Rack (ISPR), which can be accommodated in all partners'pressurized modules. This agreement necessitated the adoption of a common module diameter. For the reason of maximum payload volume the largest of the three existing module diameter was chosen, which happened to be the Boeing module diameter.

The APM diameter had to be increased, as a consequence of which the spacing between the Columbus shield and the back wall had to be reduced from 150 mm to 120 mm. Spacing is the only commodity in shielding which comes free of mass and other design effort.

The loss of shielding effectiveness was compensated by splitting the former 1.6 mm shield into two of 0.8 mm thickness at 50 % spacing each, i.e. two times 60 mm. In fact, this new shield arrangement was even slightly superior in performance. The particle sizes which would be defeated increased from 3.5mm at 2 km/sec and 6.8 mm at 7 km/sec velocity to 4.2 mm and 8.1 mm respectively.

The concept of shielding is to defeat particles up to a certain size (as a function of particle velocity). From the critical particle diameter/velocity onwards, the cloud of fragmented particles and shield will knock a sizeable hole into the pressure wall. As the energy of the incoming particle grows, the hole will become larger. At even higher energy, the shield will no longer be able to fragment the particle, and the particle will go through the pressure wall causing a hole only slightly larger than the particle, and a lot smaller than the holes caused by a fragment cloud.

4. The International Space Station Protection Requirement

The PDRD protection requirement is as follows:

From SSP 3000, Section 3:
The Space Station Protection Requirement
3.1.3.1.1.2.2 CRITICAL SPACE STATION CORE EQUIPMENT METEOROID/DEBRIS REQUIREMENTS
The design goal for each SSCE classified as being critical is to have a minimum probability value of 0.9955 of experiencing no failure due to meteoroid and debris impact that would endanger the crew or space station survivability for the 30-year life of the space station. However, due to uncertainties both in the meteoroid and debris environment and the behavior of materials in

this environment, the initial space station design requirements shall use a 10-year exposure time period with a minimum probability value of 0.9955.

ESA has made this requirement applicable to the APM design in September 1990, with a slight rewording replacing "space station"by "APM"

However, ESA assessed the requirement as follows:

- The (1-0.9955) per 10 year risk level has not been rationalized by NASA. This risk level represents much more than a technical performance parameter.
- the protection requirement is expressed as per "critical element". The resultant risk for the crew and the station thus depends on the definition of what constitutes a critical element and on how many critical elements the station consists of (i.e. the design implementation of the station). The probability will then have to be taken to the power of 20 (0.9137) or 30 (0.8734), increasing the risk by a factor of 19 or 28 compared to the original number.
- The no-burst requirement (related to pressurized modules) is added to the Columbus System Requirements Document.

5. NASA Shield Augmentation Concept

In order to make the space station elements launchable mass-wise and yet accomplish an effective ultimate shielding, NASA introduced in 1990 the concept of shield augmentation. For example, the habitable modules were to be launched with a shield providing only a moderate probability of experiencing no failure endangering crew or station survivability. Later the shield was to be augmented in two 5 year intervals, see table 2.

Time Period (Years from 1st element launch)		
1 - 5	6 - 10	11 - 30
0.9972	0.9995	0.9996

Table 2: Required average annual probabilities for habitable modules exposed to meteoroids and space debris.

ESA proposed an averaged constant probability level of protection of 0.99918 per year, according to the following definition:

$$(0.9972^{5} \times 0.9995^{5} \times 0.9996^{20})^{1/30}$$

$$= 0.99918$$

A course evaluation of the required shield masses for the APM resulted in the following figures:

B/L MASS INCLUDING SHELL	2.500 KG
AUGMENTATION MASS AFTER 5 YEARS	5.000 KG
AUGMENTATION MASS AFTER 10 YEARS	2.500 KG
TOTAL SHIELDING MASS	10.000 KG
"CONSTANT" SHIELD MASS INCL. SHELL	8.000 KG

It is evident from this rough assessment that it is very uneconomical mass-wise to not launch space station elements adequately shielded right from the beginning. Considering the EVA and robotics effort to put the additional shielding in place on-orbit makes this concept even less attractive. In December 1991 NASA withdrew this concept.

6. Computer Tools

Computer tools have been developed by NASA and by ESA for two basic applications:

- Numerical simulation of the physical process of a particle breaking through shields.

- Probability assessments of a body in a given orientation, altitude and inclination and year being hit by meteoroids and space debris particles of a given size on upwards.

For the first application, ESA had hydrocodes developed by ESI, France. Ballistic limit curves, developed from impact tests carried out by Ernst-Mach Institut, Germany, under MBB-ERNO management for Columbus, matched with the ballistic limit curves derived from the hydrocode, when extrapolated to a velocity region of 8 km/sec to 20 km/sec, well above the region accessable by test.

For the second application, ESA had a code ESABASE developed. ESA and NASA agreed in a Technical Interchange Meeting (TIM) in April 1991, to compare this code with the NASA developed "Bumper" code. ESA proposed two simple test cases, a box and a space station configuration consisting of four cylinders and a box (the truss) for a comparison run, which was performed by SSEIC (Grumman). Reasonable agreement was achieved.

7. Station-Level Meteoroid / Orbital Debris Risk Study

In December 1991 the Space Station Program was directed to perform a station-level M/OD risk study, to be completed by March 1992. At last the failure definition of "wall penetration" (PNP = probability of no penetration) was replaced by "catastrophic failure", but only for this study. The PDRD requirements baseline continues to carry the definition "that penetration of the pressure vessel shall be deemed a "critical" failure" (PDRD Section 3, 3.1.3.1.1.3.1).

Since impacts with pressure wall penetration are to be expected in the 30 year operational period of the space station, ESA proposed to extend the scope of the M/OD Risk Study to also analyse design measures for crew survivability rather than relying on shielding and debris avoidance manoeuvres of the total station as the only countermeasures against space debris.

The design features for assurance of crew survivability encompassed the following:

- impact sensing system for locating the impact and reporting its severity (prototype from Norske Veritas developed for Columbus),
- crew alert system, driven by the impact sensing system,
- crew support features like floor lighting for marking escape path, signal lights above all hatches to mark escape direction, translation aids for rapid module egress, motorized hatches to have crew time available exclusively for rescue,
- dumping of additional air into crippled module to extend time for excape.

The analyis of these items was not included in the risk analysis.

8. First No-Burst Test Results

Between 1985 and 1988 ESA had Columbus industry perform impact tests talked about earlier in this paper. These tests were continued in order to obtain a better understanding of the triple wall concept (a double shield and the pressure wall). While analytical and test procedures related to the quasistatic load condition (module wall loaded by air pressure) are established since decades in the form of classical fracture mechanics tools, the behaviour of a pressurized structure under hypervelocity impact is widely unknown and not yet assessible by verified analytical techniques.

Six tests were performed on pressurized samples in order to simulate the load conditions of the back-up wall representing the hull of the Columbus module wall. Because of the limited volume of the test chamber and the necessity to achieve a failure of the test article in order to be able to study the burst phenomenon, which was expected, the test article was scaled to a thickness of 1.6 mm and a pressure of 2.8 Bar and only a single shield.

The test is presented in detail in other papers in this ymposium (see "Meteoroid and Debris Simulation at EMI - experimental methods and recent results "by E. Schneider, K. Kitter, A. Stilp and "Ballistic limit equations for the Columbus double bumper shield concept" by H.G. Reimerdes, K.H. Stecher, M. Lambert).

Three test panels burst, and a first, but very dramatic result is that the critical defect size caused by a hypervelocity impact is only about 30 % to 50 % of the critical defect size under quasi static pressure.

In order to be able to control the "module un-zip" phenomenon adequately, more tests are required on pressurized samples and also in a velocity regime of 11 km/sec, unexplored so far. Scaling problems can be avoided by shooting on full scale test coupons. This is all under investigation.

9. Conclusion

The threat of space debris to the crew and the space station has been fully recognized by now, by both ESA and NASA. Great effort has been spent on a proper requirements formulation. Numerous tests have been performed to establish and compare ballistic limit equations and with it shield performance. The protection achieved thus far does not meet the required protection level. The module burst ("unzip") phenomenon poses a new problem for the shield design which is not yet understood and can only be solved by large scale (preferrably full scale) testing of pressurized test coupons. Such tests are currently under consideration by ESA to be executed.