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IMPACT OF METEOROIDS AND ORBITAL DEBRIS ON HERMES DESIGN†

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Abstract—The purpose of the paper is to illustrate the impact of space debris and meteoroids on the Hermes design. The models used for characterizing the population of particles, and the safety requirements to be fulfilled will be presented. Then will be detailed the risk analysis performed on Hermes configuration, with description of methods, test campaigns and results. Operational and design solutions for a better safety will be discussed. Specific contribution of space debris to the risk will be analysed in order to emphasize the necessity of establishing space rules for no-creation of debris.

1. MODELIZATION OF THE ENVIRONMENT

1.1. Meteoroids model

The model used for characterizing the population of meteoroids is fully described in [1]. The total accumulated number of particles with mass m or larger, per m^2 and per year, impacting a randomly oriented flux plate under a viewing angle of 2π is:

$$F_0(\mathrm{m}) = 3.15576 \times 10^7 \times [F_1(\mathrm{m}) + F_2(\mathrm{m}) + F_3(\mathrm{m})]$$

where:

$$F_1(\mathrm{m}) = (2.2 \times 10^3 \times \mathrm{m}^{0.306} + 15)^{-(4.38)}$$

$$F_2(\mathrm{m}) = 1.3 \times 10^{-9} \times (\mathrm{m} + 10^{11}\,\mathrm{m}^2 + 10^{27}\,\mathrm{m}^4)^{-(0.36)}$$

$$F_3(\mathrm{m}) = 1.3 \times 10^{-16} \times (\mathrm{m} + 10^6\,\mathrm{m}^2)^{-(0.85)}$$

with m in grams.

The shielded flux to be taken into account is:

$$F = Ge \times B \times F_0$$

where Ge is gravitational defocusing factor

$$Ge = 1 + \frac{\mathrm{Re}}{r}$$

and B is earth shielding factor

$$B = \frac{1 + \cos\theta}{2}, \text{ with } \sin\theta = \frac{\mathrm{Re}}{\mathrm{Re} + h}$$

r = orbit radius
Re = Earth radius + Earth atmosphere (100 km)
h = altitude above Earth atmosphere (100 km).

The density of meteoroids depends on particle mass[1] but, for our purpose, an average density of 1 g/cm^3 has been considered. The meteoroid particles have a velocity that can range from 11 to 72 km/s[1]. In addition, the actual impact velocity v_i has to be calculated taking into account the spacecraft velocity v_s and the meteoroid velocity v_m relative to the Earth:

$$\mathrm{v}_i = \mathrm{v}_m - \mathrm{v}_s.$$

When necessary, an average impact velocity of 20 km/s has been considered.

1.2. Orbital debris model

The debris model considered is the Kessler model used for designing the Space Station[2]. The cumulative flux of orbital debris of diameter d and larger is:

$$F(d, h, i, t, s) = k \times H(d) \times \phi(h, s) \times \Psi(i) \times [F_1(d) \times g_1(t) + F_2(d) \times g_2(t)]$$

where

F = number of impacts per m^2 of surface area per year
d = orbital debris diameter in cm
h = altitude in km
i = inclination in degrees
t = date (year)
s = solar radio flux $F_{10.7}$ for $t - 1$ year
k = ratio of the flux against an oriented surface to the flux against a randomly tumbling surface[2]
$\Psi(i)$ = inclination-dependant function[2]
$H(d)$ = diameter-dependant function[2]
$\phi(h, s) = \phi_1(h, s)/(\phi_1(h, s) + 1)$
$\phi_1(h, s) = 10^{(h/200 - s/140 - 1.5)}$

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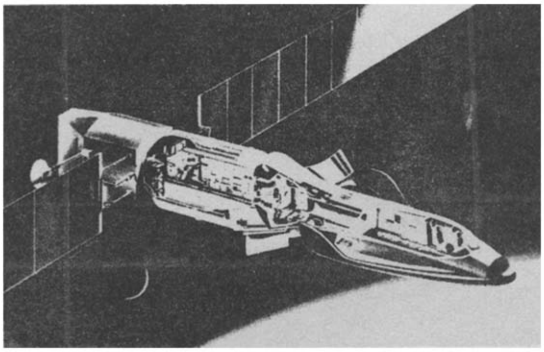

Fig. 1. Hermes docked to MTFF.

$$F_1(d) = 1.22 \times 10^{-5} \times d^{-2.5}$$
$$F_2(d) = 8.1 \times 10^{10} \times (d + 700)^{-6}$$
$$g_1(t) = (1 + q)^{(t-1988)}$$
$$g_2(t) = 1 + p \times (t - 1988)$$

q, the estimated growth rate of fragment mass; $q = 0.02$ until the year 2010; $q = 0.04$ after the year 2010; p, the assumed annual growth rate of mass in orbit; $p = 0.05$.

Density for space debris depends on particle diameter[2]; for our study, an average density of $4\ g/cm^3$ has been considered. Distribution of impact velocity for orbital debris depends on inclination and altitude[2]; an average value of 10 km/s has been assumed, when necessary.

2. MISSION REQUIREMENTS

The risk analysis that will be presented in this paper has been performed for the servicing mission to the European Free-Flyer station (MTFF), that was, until the Munich Conference of November 1991, the nominal Hermes mission (see Fig. 1). That leads to the following set of parameters:

Altitude = 460 km
Inclination = 28°5
Duration = 12 days (8 days docked to MTFF)
Year for dimensioning = 2015

Following the Munich Conference, new ESA strategy for mastering manned space and in-orbit servicing consists in a progressive approach, that leads to a three-step scenario for the Hermes program.

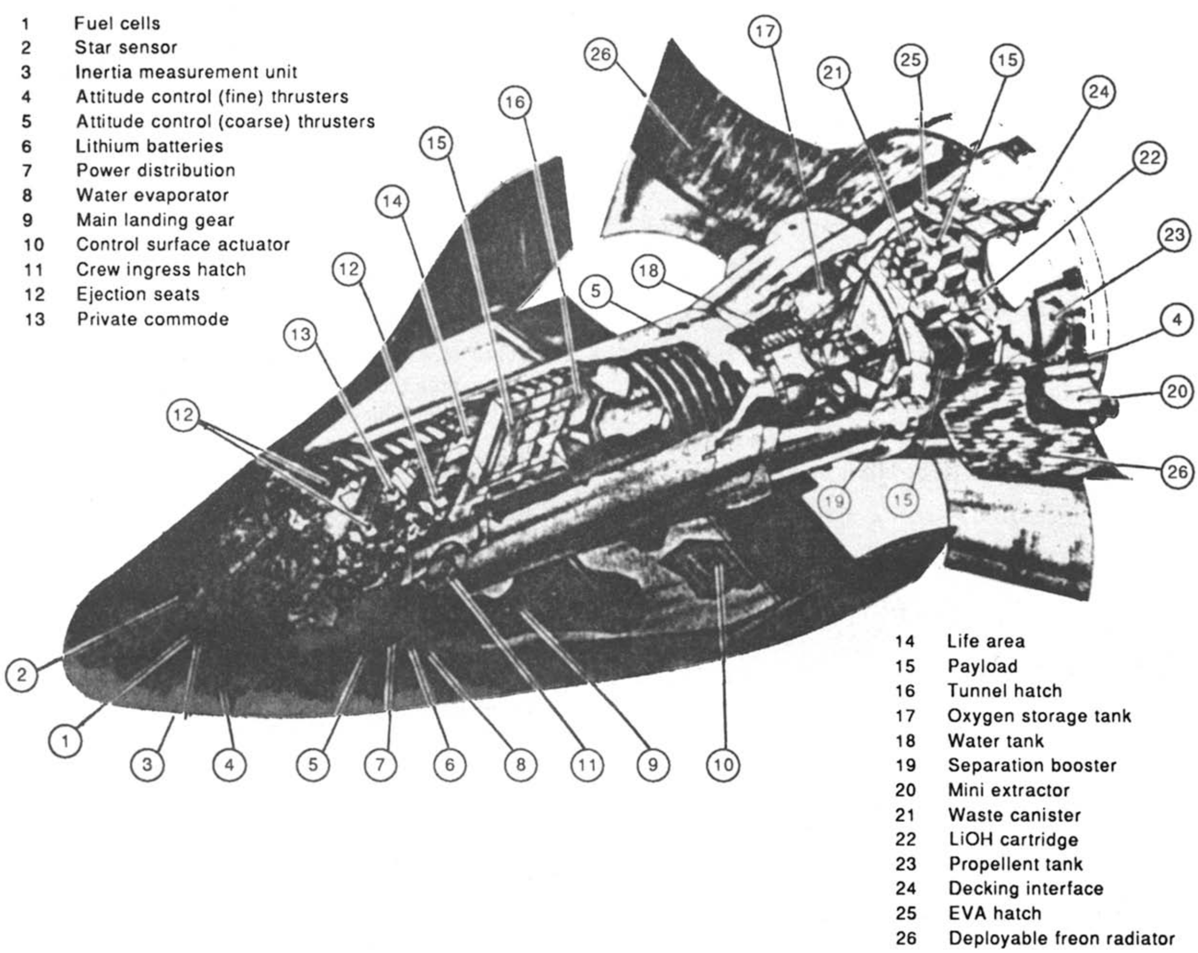

Fig. 2. Configuration used for M/D risk analysis.

Step 1 will concern the development of an unmanned demonstrator (X-2000) with the objectives of validating launch and atmospheric re-entry phases. This X-2000 flight must allow the following flights to be performed with man on-board[3]. Within this logic, meteoroids and debris impacts have still to be considered for X-2000 design, due to their heavy consequences on structural design. As a conclusion, risk analysis performed for the mission to MTFF will have to be reviewed in the frame of the X-2000 scenario but it nevertheless keeps its entire interest.

3. SAFETY AND RELIABILITY REQUIREMENTS

The space vehicle must be designed in such a way that the probability of catastrophic (serious, major) consequences due to meteoroids and debris impacts is less than 10^{-5} (10^{-4}, 10^{-3}). Catastrophic consequences refer to the loss of crew, serious consequences to the loss of spaceplane, major consequences to the loss of mission.

4. RISK ANALYSIS—METHOD

Risk analysis was performed on the configuration shown in Fig. 2. The space vehicle is constituted of two main parts: spaceplane (front part) and Hermes Resource Module (rear part).

The method consists, firstly, in making a partition of the configuration into a list of items, and for each item, to process through three steps.

First step: evaluation of criticality of damage (catastrophic, serious or major). The work was focused on items of main interest, i.e. pressurized areas, tanks, thermal protection, radiators.

Second step: evaluation of damage created by meteoroids and debris impacts, using:

- empirical formulae based on experiments; they can be considered as reliable for single wall structure; they are much more questionable for double or triple wall (for damage size determination) and request assessment based on real tests.
- hydrocodes
- tests on representative samples of materials; a first set of 20 tests was already performed at EMI (Freiburg) on shingles, FEI (Flexible External Insulation) system, nose, winglet. Additional tests are under preparation in order to validate laws of damage for double and triple walls.

At the end of this second step, it is possible to determine the size of the critical particle both for meteoroids and debris.

Third step: evaluation of meteoroids and debris impact probability using the environment models described above, the spaceplane configuration, the

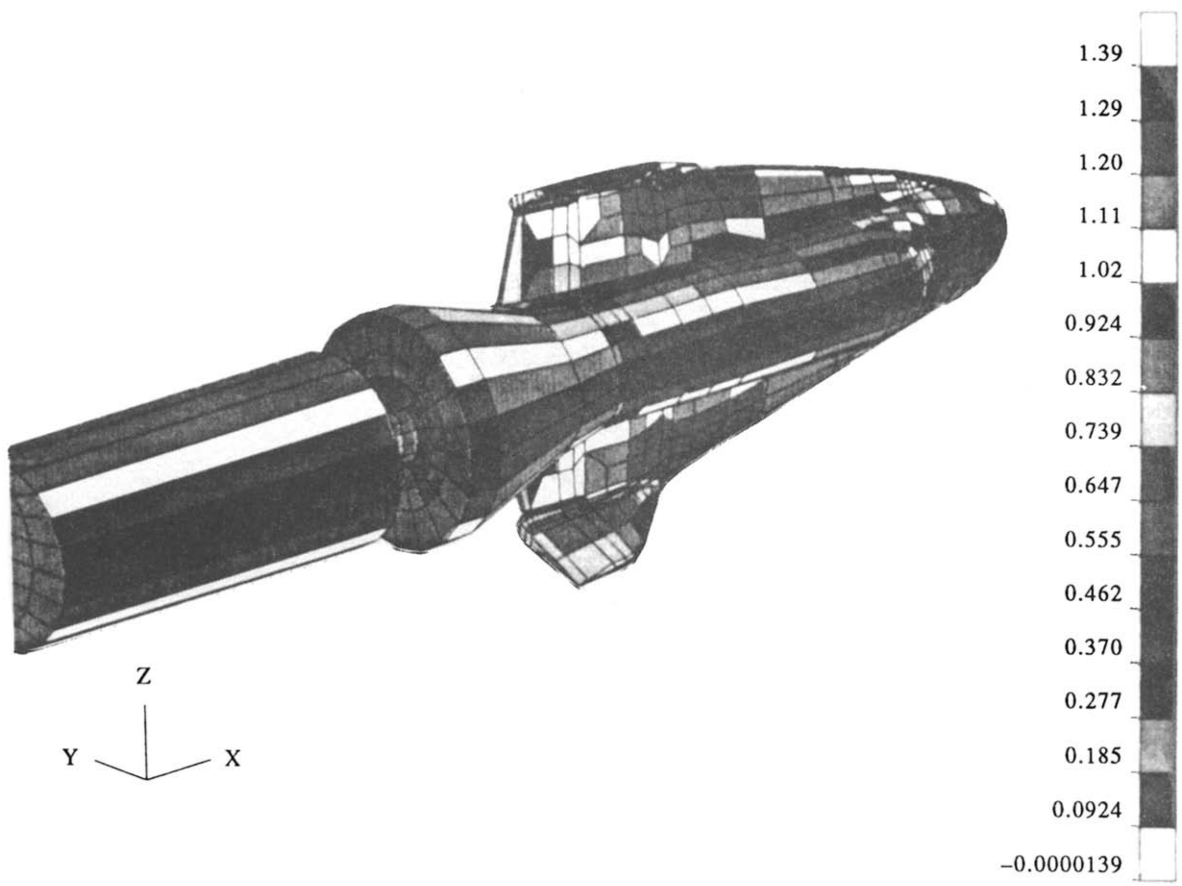

Fig. 3. Hermes docked to MTFF. Viewing factor k-orbital debris sun-pointed attitude.

mission parameters (sun-pointed attitude, etc.) and taking into account all the possible shielding effects. As part of this process, MBB–ERNO computed precise zonal impact probabilities taking into account directional effects. Two examples of this work are presented here.

Figure 3 shows the viewing factor k (see Section 1 on models and Ref.[2] for additional information) here computed for orbital debris. Figure 4 shows the average meteoroid velocity vector over the surface area.

5. RISK ANALYSIS—RESULTS

Risk analysis identified two main problems:

- cabin depressurization
- loss of propellant tanks

5.1. Depressurization

A hole of ϕ 14 mm in the pressurized cabin produces a fast decompression leading to the loss of the crew, and was considered as having catastrophic consequences. This hole dimension corresponds to the time necessary for the crew to dress with IVA (intra vehicular activity) suits.

Mainly constituted with double or triple wall structures, space vehicle configuration showed a good general behaviour towards depressurization, except for one weak point: the single skin of cabin extrados (see Fig. 2). A meteoroid of ϕ 2.8 mm and a debris of ϕ 7.1 mm impacting this area were calculated as leading to catastrophic damage. Tests performed on a representative sample of this area led to consider a value of ϕ 2.5 mm for the debris critical size. This reduction from ϕ 7.1 mm to ϕ 2.5 mm is due to the presence of the FEI, that was not considered in the theoretical calculation.

In the same way, any impact resulting in a leakage in the wall of the pressurized areas was considered as a major risk (interruption of mission). The same area of cabin extrados resulted in a high figure for loss of mission probability.

5.2. Propellant tanks

Any impact resulting in a leakage in the propellant tanks was considered as functionally catastrophic, as the loss of propellant makes the re-entry impossible. Most of the tanks were naturally protected by HRM (Hermes Resource Module) structure, except propellant tanks situated at HRM rear (see Fig. 2)

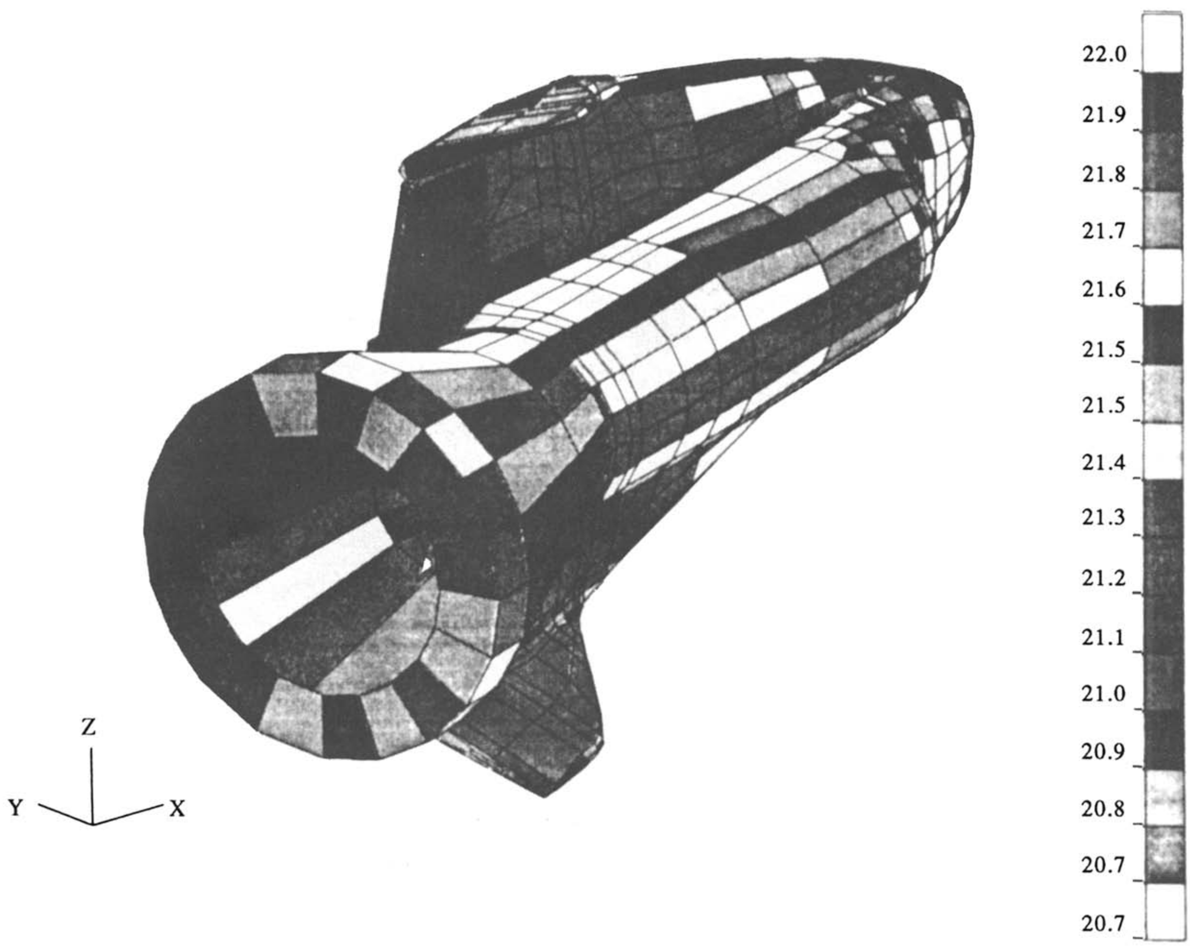

Fig. 4. Average meteoroid velocity sun-pointed attitude.

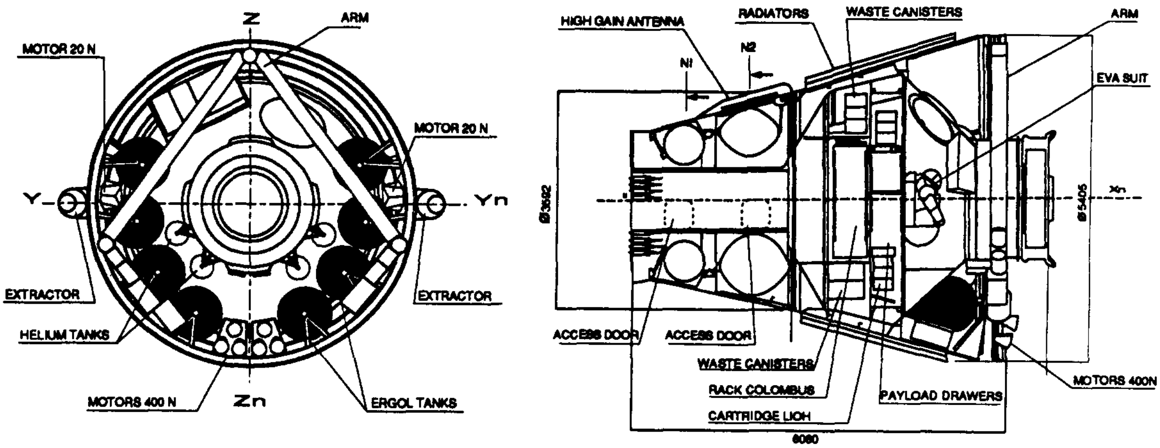

Fig. 5. HRM first configuration.

which were directly exposed to space and which constituted the most sensitive point. A meteoroid of ϕ 0.29 mm or a debris of ϕ 0.15 mm were found to perforate such a tank.

5.3. Global results

The design of other considered areas (windshield, radiators) was found to be consistent with the risk allocated to a failure due to meteoroid and debris impact.

Some aspects of the risk analysis request additional investigation:

- in addition to the functional risk, an impact on any pressure vessel may result in an explosion
- the risk of an impact on the thermal protection is not yet completely quantified due to the difficulty of evaluating the criticality of damage, for thermal re-entry phase.

The main conclusion is that the figures resulting from risk analysis have shown no compliance with safety and reliability requirement, for the two items mentioned above. An important finding is that contributions to the risk of meteoroids and orbital debris were found to be approximately equivalent; it means that this first considered configuration was not adapted to the reality of the environment, even for the natural part of it, i.e. meteoroids population.

6. MODIFICATION OF DESIGN

Starting from these findings, a set of actions was undertaken in order to get a space vehicle design consistent with the particles population. This work is under way and the new modified configuration will be finalized by November 1992.

6.1. Propellant tanks

A trade-off between redundancy of the propellants, shielding of tanks and change in the HRM layout has been performed; the solution consists in a modification of the HRM layout so that propellant tanks are situated in a naturally shielded area.

Figure 5 shows HRM first configuration; propellant tanks are shown shaded. Figure 6 shows the new HRM layout. In addition to the displacement of tanks, a provision has been made in the mass budget allowing to add a shield for pressurized tanks

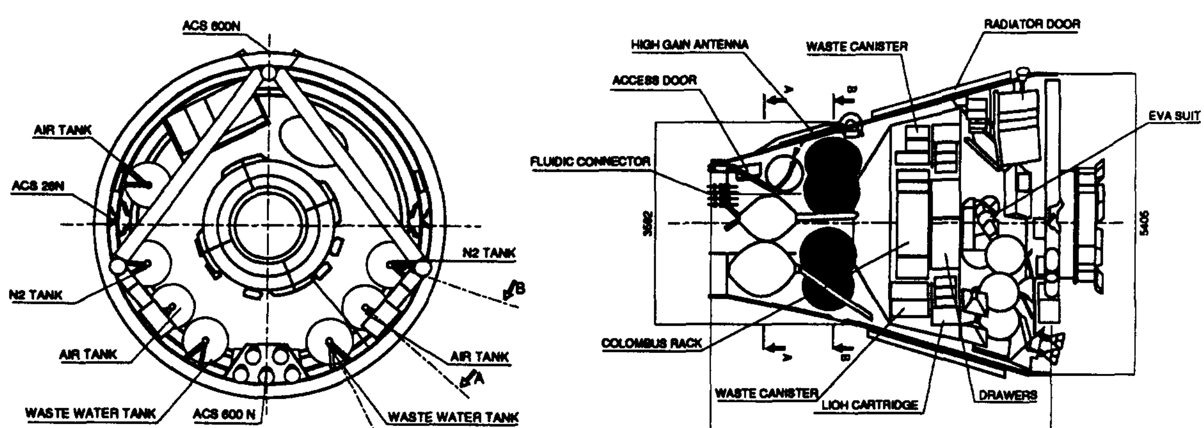

Fig. 6. HRM new configuration.

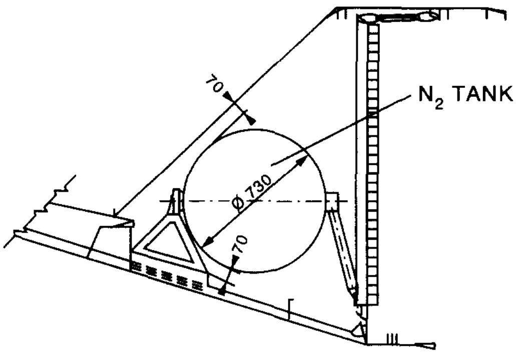

Fig. 7. Section BB of Fig. 6.

remaining at HRM rear (see Fig. 7 relative to Fig. 6), if the on-going studies identify a risk of explosion for these pressure vessels.

The HRM may be very simplified in the X-2000 scenario; anyway, the work performed shows, for the future, that the concept is feasible.

6.2. Depressurization

A trade-off between the solutions presented in Fig. 8 is underway taking into account:

- efficiency of meteoroids and debris shielding
- delta mass
- delta internal/external volume
- structural feasibility and interfaces with other areas (shingles)
- other constraints like thermal control.

The first drawing represents the initial configuration design.

The first solution consists in a load carrying double skin; the main characteristics are:

- inner skin with external frames
- fastening of a second skin on these frames and on which FEI is bonded
- the two skins are load carrying skins.

The second solution consists in large panels FEI—aluminium–honeycomb:

- design is the same as for the previous solution
- the second skin does not participate in the general loads and is made rigid with honeycomb panels.

The idea, for the third solution, is to have a FEI–Kevlar multi-walls; the thickness of FEI is determined by the thermal insulation necessary to protect Kevlar material; the inter-layer is spaced enough to permit the spreading of the shattering of the particles.

Solution No. 4 consists in replacing FEI with shingles.

Solution No. 5 would lead to add an external protection to the FEI, made with a C–Sic material.

7. CONCLUSION

With this new improved configuration, the risk resulting from meteoroids and orbital debris impacts will be compatible with safety and reliability requirements. The corresponding calculations are not detailed here but it appears clearly that the contribution from meteoroids becomes negligible with this modified design; as a consequence, the design and the resulting increase of weight are now directly related to the population of debris the spaceplane will encounter.

As regards to spacecraft shielding, maximum effort has been made with the modifications described above. It is not easy to go further without suffering an unrealistic mass penalty. The debris environment, resulting from manned space activity, is now the only parameter which can still be influenced.

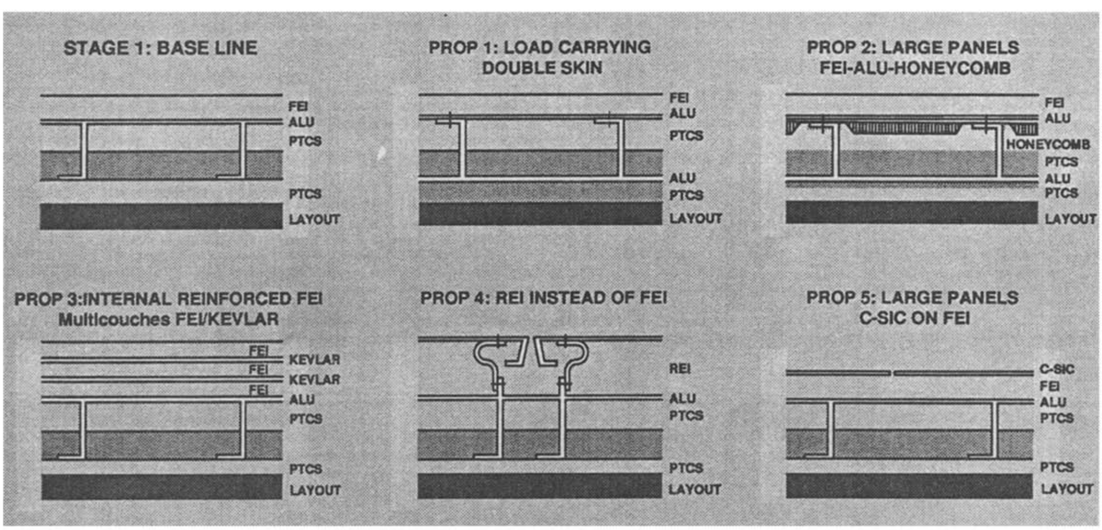

Fig. 8. Structural design modification trade-off.

More generally speaking, aside from Hermes, the shielding problem will become even more difficult for spacecraft to be designed in the year 2020 and after. That could be considered as very distant but, in space like on Earth, environment is a parameter with a very long time constant.

For these reasons, it is of the highest importance to take now the appropriate measures to avoid the proliferation of small debris: retrieval of satellites after end of life, passivation of stages, etc.

That seems to be a *sine-qua-non* condition for the feasibility of future spacecraft.

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