HIGH PRESSURE COMPOSITE TANK BEHAVIOUR UNDER AN HYPERVELOCITY IMPACT

Roland SALOME (1) , **Vincent ALBOUYS** (1) , **Christian LE FLOC'H** (2)
Didier SORNETTE (3) , **Jean Paul VILA** (4)

(1) Centre National d'Etudes Spatiales, 18 Avenue Edouard Belin, 31401 TOULOUSE CEDEX 4
e-mail : roland.salome@cnes.fr
e-mail : vincent.albouys@cnes.fr
(2) EADS Launch vehicules, BP 11 – 33165 Saint Medard en Jalles Cedex, France
e-mail : christian.le-floch@lanceurs.aeromatra.com
(3) Centre National de la Recherche Scientifique – Université de Nice, France
(4) Institut National des Sciences Appliquées, Toulouse, France
e-mail : jean-paul.vila@gmm.insa-tlse.fr

ABSTRACT

Space debris represent a threat to spacecrafts in near earth orbits and protection against them is a key requirement for the Space Station. Thus, regulations are being issued in order to prevent new debris generation from a spacecraft which can be impacted by a debris. Due to their risk of burst, pressurized vessels are classified as critical components, and high pressure composite overwrapped vessels are considered as specially critical. Furthermore, the design of a protection device is closely depending of the behaviour of the vessel under impact.

CNES has started a R&D action in order to characterize the behaviour of a high pressure composite vessel under an hypervelocity impact.

This study is managed by EADS / Launch Vehicles in collaboration with Nice Sciences University and INSA Toulouse.

The pressure vessel considered is an over-wrapped carbon fibre on a titanium liner loaded with Xenon or Helium under high pressure (15Mpa or 31Mpa).In a first phase, the theoretical approach to predict the tank behaviour consists in a 2D and 3D simulation using a SPH code (Smoothed Particle Hydrodynamics).

An experimental validation of the numerical model will be conducted in the future.

1. INTRODUCTION

Space debris represent a threat to spacecrafts in near earth orbits and the protection against an impact is a key requirement for manned vehicules and specially for the International Space Station.

Thus, regulations are being issued in order to prevent new debris generation. Launch vehicule upper stages and spacecrafts at end of life shall be reorbited. But they have also to be passivated, this is mainly applicable to their propulsion subsystem, in order not to present a risk of explosion under uncontrolled environmental conditions or under an hypervelocity impact.

Due to their risk of explosion, pressurized vessels are classified as critical components, and specially high pressure composite overwrapped vessels.

The aim of the CNES research action, managed by EADS in collaboration with Nice University and INSA in Toulouse, is to characterize the various mechanisms involved by the hypervelocity impact on a pressurized vessel and to check what is its structural behaviour.

As experimental studies need many samples with regard to the variety of parameters to be investigated, and therefore would be expensive, the first phase consists in doing a numerical simulation applicated to a specific test vessel. An other task is to identify the test parameters and the test set-up and prepare the test procedure. The experimental phase and the numerical model validation will be conducted further.

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2. THE HIGH PRESSURE TANKS

High pressure tanks are used in spacecraft propulsion subsystem to store Helium gas to pressurise the propellant tanks (chemical propulsion) or Xenon as the propellant for electric propulsion.

For these space applications the tank must be of high performance, lightweight, and designed to withstand severe launch and operational loads. It consists of a thin titanium liner (0.9 mm thickness), overwrapped with a carbon fibre (or Kevlar) epoxy resin composite. The usefull volume is typically in the range from 50 to 180 litres.

For a typical Helium application on telecommunication spacecrafts, the tank is pressurized up to 30 MPa. The pressure decreases as the gas is consumed during the tranfer operations of the spacecraft to its geostatonnary orbit. The remaining pressure during all the in-orbit life is around 3 MPa.

In the Xenon case, the pressure is slowly decreasing from 15 MPa down to near 0 during the operational life (15 years).

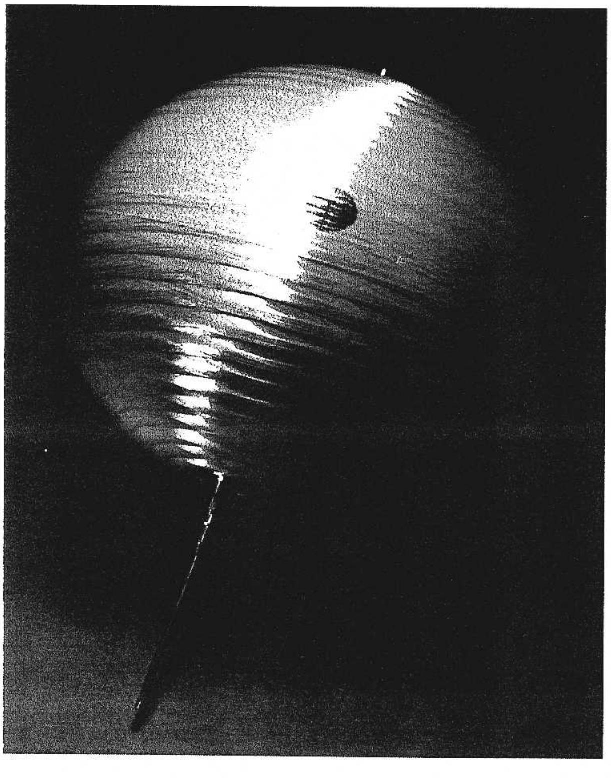

Fig 1 – 35.5 litres

Titanium / Kevlar – Eurostar type tank

3. NUMERICAL SIMULATION

3.1. Definition of the projectile

The characteristics of the projectile are :

- aluminium material
- spherical shape $0.1 < \phi < 5$ mm
- velocity range : $5 < V < 20$ km/s

3.2. Definition of the target

For the cost reasons mentioned above, the target will be an existing 7 liters tank with a stainless steel liner.

- spherical shape
- liner thickness : 1 mm
- carbon composite thickness : 3.4 mm

This tank will be used for the code validation test plan.
Three configurations for the gas storage are considered :

- Helium at 30 MPa and 3 MPa
  (begin and end of life conditions respectively)

- Xenon at 15 Mpa

The tank is unshielded

3.3. Numerical simulation

As already presented in the literature, very accurate Finite Elements or Finite Differences methods exist but they are considered not very suitable for hypervelocity impact simulation. They are not well adapted to the description of large deformations and fragmentations and to follow the interfaces (border between the composite shell and the metal liner). Thus, our analysis uses a SPH method with coupling between the tank and the gas.

The preliminary analysis has shown the influence of two main parameters which are :

- the modelisation of the composite and its damaging under high deformation.
- the effect of the pressurized gas into the tank.

3.4. Composite modeling

The composite material is manufactured by filament winding, therefore it is considered as a transverse isotropic composite material.

Consequently, the stiffness matrix contents only five independent coefficients :

- the in-plane Young modulus longitudinal (l)
- the Young modulus through the thickness transverse (t)
- the shear modulus in the (t,l) plane
- the two Poisson coefficients

To take into account the large deformations, a transfer matrix from the local frame to the laboratory reference has been determined.

The data on mechanical properties of composite materials are available in the open literature for static conditions, but they are difficult to obtain under hypervelocity conditions. Thus, we have simulated the sensitivity of the code to the parameter values.
Additional experimental work on real samples under hypervelocity impact are necessary and will be performed further in order to calibrate and test the SPH code outputs.

4. RESULTS

4.1 Damage scenarii

Four damage scenarii which can lead to the burst rupture of the tank are identified.

(1)- Shock wave in the pressurized gas :
The pressure peak of this strong shock wave is proportional to the initial pressure in the tank and can reach up to 1 Mbar (10^{11} Pa).
Starting from the impact area, the shock wave is transmitted to the gas by the fragment cloud and propagates into the fluid and can reach the opposite side of the tank. It also goes along the tank wall.

Thus, all the structure is submitted to very high loads which can be higher than the design burst characteristics of the tank.

(2)- Compressive and shear waves in the tank shell
Upon impact, the liner and the composite shell are subjected to large deformations and high stresses. These lateral compression waves can be damped in the liner. However, they may reach the opposite side and result in locally exceeding the material strength by a resonance process. Moreover, interference phenomenon can occur into the composite and induce detrimental damage whereas the composite material has low performance in compression.

(3)- Damage of the rear side by fragments
A fragments cloud is generated by the impact from the projectile, the metallic liner and the composite shell.
The cloud propagates with a velocity up to 1.4 times the initial velocity of the projectile. The fragments are decelerated in the gas and in some conditions their kinetic energy can be decreased down to 0. However some of them can reach the opposite side of the tank with sufficient energy to induce cratering and perforation with generation of new debris and possible catastrophic failure.

(4)- Fatigue failure
In the three cases above with tank shell perforation, we consider that there is a leak and a very rapid depressurization of the tank. However, if the impact is not detrimental by itself, the tank is damaged and it shall sustain remaining high pressure loads. Then, we are facing a fatigue crack propagation like process which leads in a short delay (about 1s) to the rupture of the tank.

4.2. Results

Various simulation cases were done and the analysis has been performed in 5 steps :

- determination of the perforation threshold
- estimation of the hole diameter and of the residual energy transmitted to the gas
- determination of the energy threshold beyond which the critical pressure is reached (80 Mpa in our case)
- determination of the angle of the pressure cone (piston effect)
- evaluation of the damages on the opposite side of the tank

4.2.1. Sensitivity of the model

The sensitivity of the model to several parameters (pressure loads in the shell before impact, characteristics of the composite) has been studied. This shows that :

- the hole and the damaged area diameters are not very dependent of the initial loads in the shell.
- the damaged area diameter can be increased of about 30% with respect to the limit load characteritics of the composite.

4.2.2. Helium tank

Fig.2 and 3 are cross sections of the tank showing the propagation of the debris and the shock wave within the helium gas at 20 μs and 100 μs after the impact at a pressure level of 30 Mpa.

Fig.4 corresponds to 10 μs at 3 Mpa pressure

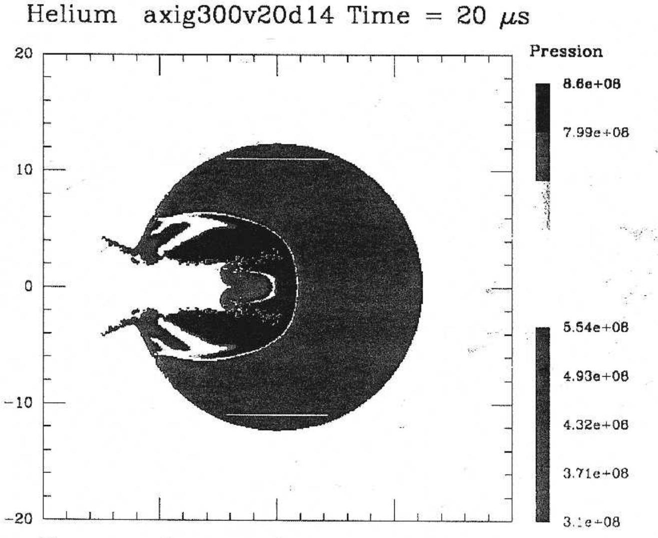

Fig.2 - Pressure field – Helium 30 MPa, V=20km/s
Φ=14mm, t=20µs

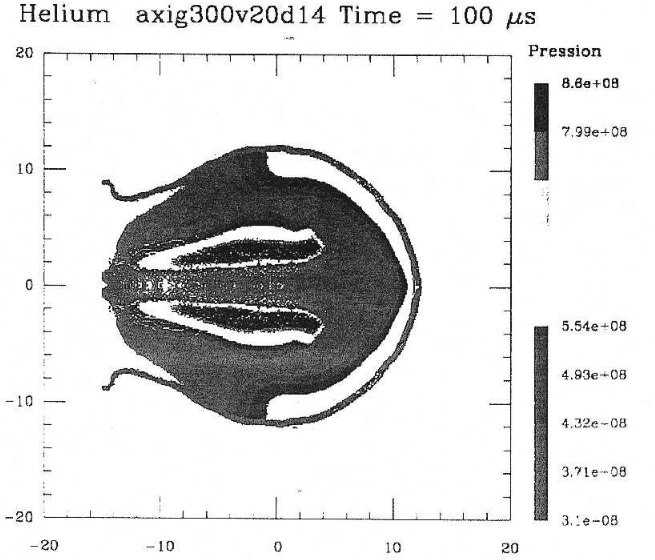

Fig.3 - Pressure field – Helium 30Mpa, V=20km/s
Φ=14mm, t=100µs

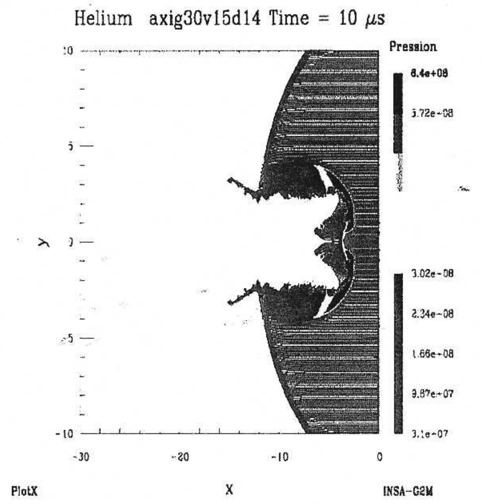

Fig.4 - Pressure field – Helium 3 MPa, V=20km/s
Φ=14mm, t=10µs

Figures 5 and 6 give the diameter of the damaged area which is presented in a phase diagram (velocity / size) of the projectile.

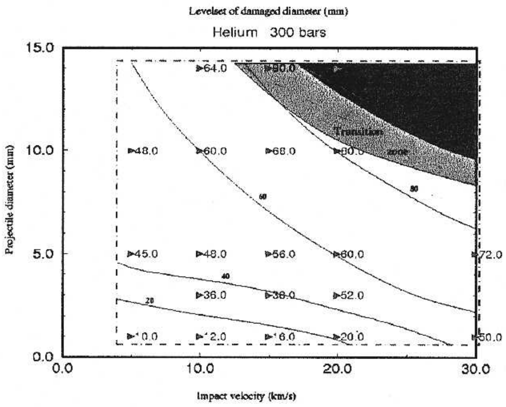

Fig 5 – Phase diagram – Helium 30 Mpa

This shows that the explosive domain is reached for projectile with a diameter above 10 mm. The failure scenario is the scenario (1) due to the pressure shock wave in the gas. The pressure value of 80 MPa corresponding to the limit load characteristic of the composite seems to be representative of the rupture threshold of the tank.

The scenario (2) is obtained for smaller projectiles with slower velocity.

This figure also shows a transition zone where the effects of the pressure shock wave going along the internal face of the tank are important.

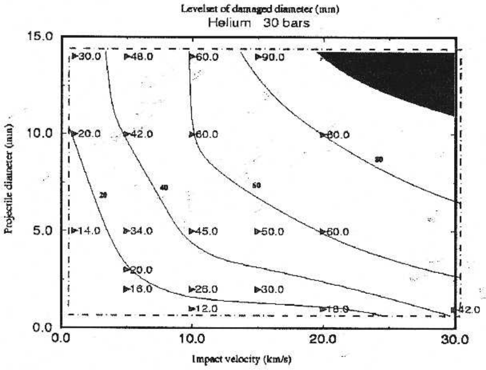

Fig.6 – Phase diagram – Helium 3 MPa

The explosive zone is shifted out of the operational diagram and the effects of the shock wave along the wall are significantly lowered.
Scenario (2) is not critical in this 3 Mpa case

Table 1 gives typical values observed for various impact conditions in the Helium tank.

Test	t_1	V_1	P_1	t_2	V_2	P_2	P_{max}	D_E	D_T	$\frac{E_{gaz}}{E_p}$
v10d3	10	0.2	30	20	0	30		8	36	1.4
v20d3	10	0.28	40	20	0.1	30		16	52	2
v10d5	5	2	130	10	0.5	50		18	48	6.4
v20d5	5	2.2	350	10	0.8	90	1800	27	60	14
v10d10	5	6.0	1600	10	3.0	780	2400	32	60	29
v20d10	5	8.0	2700	10	2.6	600	8000	36	80	42
v10d14	5	7.0	2600	10	5.0	1700	3000	32	64	39
v20d14	5	11.5	5000	10	8.0	2000	11000	40	110	59

Table 1 – Helium at 30 MPa

V..d.. = impact Velocity [km/s] and projectile Diameter [mm]

t1 and t2= time after impact [µs]

V_1 and V_2 = shock wave velocity at time t1 and t2 after impact respectively [km/s]
P_1 and P_2 = pressure in the wave [Mpa]
Pmax is the maximum pressure value in the gas at t = 2 µs [Mpa]

D_E and D_T = hole and damaged area diameter respectively [mm]

E_{gas}/E_p = kinetic energy ratio transmitted to the gas [%]

Table 2 gives similar data for 3 Mpa case

Test	t_1	V_1	P_1	D_1	t_2	V_2	P_2	D_2	D_E	D_T	$\frac{E_{gaz}}{E_p}$
v20d5	5	5.0	50	2	10	1.7	30	1	22	60	
v20d10	5	9.0	600	9	10	5.0	200	4	39	80	12
v10d14	5	7.0	300	12	10	5.5	150	6	40	60	3
v15d14	5	10.0	700	12	10	7.0	200	7	42	90	9
v20d14	5	13.0	1100	8	10	8.0	300	6	42	100	16

Table 2. – Helium at 3 MPa

Same is given in Table 3 for a tank loaded with Xenon

Test	t_1	P_1	t_2	P_2	P_{max}	D_E	D_T	$\frac{E_{gaz}}{E_p}$
v20d5	5	1200	15	80	$1.8\ 10^4$	26	70	36
v20d10	5	4500	15	400	$1.6\ 10^5$	40	110	62
v20d14	5	11000	15	110	$2\ 10^5$	48	120	68

Table 3 – Xenon at 15 MPa

4.2.3. Xenon tank

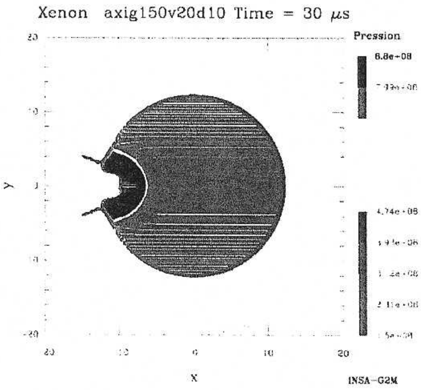

Fig 7. - Pressure field – Xenon 15Mpa, V=20km/s
Φ=10mm, t=30μs

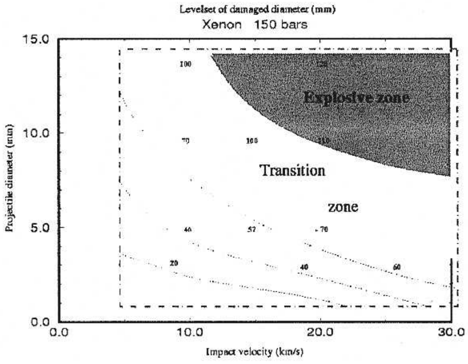

Fig.7 – Phase diagram – Xenon 15 MPa

In comparison to the Helium case, the two first scenarii are more critical with Xenon due to its higher specific mass (30 times) and its equation of state which allow a higher energy transfer from the projectile to the gas.

The third one appears to be not critical. The kinetic energy of the fragments seems to be too low to create a hole in the back wall of the tank, nevertheless they can damage it.

5. CONCLUSION

The first results obtained by the numerical modelling performed with SPH code provides a good idea of the high pressure composite tank under hypervelocity impact.

The bigger the tank is, the lower are the effects of the internal shock wave in the gas. The effects of the fragments on the rear wall of the tank will decrease too.

The initial gas pressure is of a major importance. The higher the pressure is, the more important the kinetic energy transfer is. Then, the risk of over-pressure in the tank is increased. Nevertheless, the fragments are slowed down and the risk of damaging the back wall is reduced.

The use of Xenon leads to possible explosive regime more critical compared to the helium case. But the effect of the fragments cloud is less dangerous.

No detrimental effect has been foreseen due to Xenon loading in a super critical state.

We have to carefully consider the forth scenario which takes place during a lapse of time not covered by the runs performed. After the tank shell is punched, the gas pressure will decrease slowly, typically in few seconds, which is a long time compared to the duration of the phenomenons in the tank (up to few tens of microseconds). Thus a punched tank shall withstand a pressure close to its initial value before the impact.

The higher the pressure is the more critical this scenario is.

The next step of the study will be to perform hypervelocity impacts on real samples to get improved input data related to the composite. Further on, the SPH code will be used to simulate the behaviour of the 70 litres test pressure vessel. In parallel, test facility will be defined and a test plan will be issued.

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