# A NEW DIMENSIONLESS NUMBER FOR TYPE IV COMPOSITE PRESSURE VESSEL DESIGNER TO INCREASE EFFICIENCY AND REDUCE COST

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## ABSTRACT

A new dimensionless number (DN) is proposed in order to evaluate the performance of a high-pressure vessel composite structure. It shows that very few composite part is used at its maximum loading potential during bursting. Today, for 70 MPa on-board type IV composite tanks, DN values close to 20%. The suggested DN will be a useful indicator for an industrial application. By maximizing the DN at the design phase, it is possible to minimize the mass of the composite structure of a CPV, to reduce the manufacturing time and cost. To increase the DN as close as possible to 100%, it is necessary to succeed in increasing the overall loading of the composite structure, to have better oriented fibre. For this, it seems necessary to find new processes which make it possible to better orient the fibre.

## 1.0 INTRODUCTION

In response to problems related to energy, climate and health [1], hydrogen is an increasingly used energy vector. The use of hydrogen energy is the subject of national plans in many countries around the world. This is particularly the case for the transport sector, specifically truck, train and car manufacturers. Since the end of 2015, car manufacturers have introduced the first homologated electric vehicles (FCEV: Fuel Cell Electric Vehicle). These FCEVs run on a fuel cell that uses hydrogen. Through an electrochemical reaction, hydrogen reacts with oxygen from the air to produce electricity and water. For these mass-produced vehicles, hydrogen is stored in gaseous form at 700 bar in on-board Composite Pressure Vessels (CPV). For light vehicles, 1 kg of hydrogen makes it possible to travel approximately 100 km. At 700 bar, considering that 1 kg of hydrogen occupies 25 litres, the on-board storage volume of a FCV needs to be at least 125 litres to provide a travel distance of more than 500 km. In order for the industry to fully develop and reach the general public, an improvement of this technology is necessary in order to make it more reliable, more acceptable and above all less expensive.

Indeed, the first mass-produced vehicles are today offered at prices higher than 60,000 euros excluding VAT. The hydrogen storage system is still highly expensive (10,000-15,000€ for 5kg of $H_2$). The aim is therefore to reduce the cost of these tanks while increasing reliability and safety. For pressures of 700 bar, the structuring material best suited to meet the performance objectives of the tanks is high-strength carbon fibre deposited by filament winding around a liner. For large mass-production series (several tens of thousands of tanks per year), the carbon fibre represents the major cost of the storage system [2]. It is therefore important to be able to optimize the use of carbon fibre. In order to monitor the performance of the tanks, there are a number of simple indicators that can be used. Nevertheless, these indicators are not sufficiently representative of the actual performance of the composite structuring of the tank. This paper proposes a new indicator based on a dimensionless number for a simple evaluation of the mechanical performance of the composite structure of high-pressure tanks.

## 2.0 700-BAR TYPE-IV COMPOSITE PRESSURE VESSEL

There are five types of tanks for high-pressure storage (Figure 1). Type-I tanks are completely made of metal. Type-II tanks are metallic with an additional composite structuring in the cylindrical part (circumferential composite). Type-III tanks are also metallic with composite in total surface of the metallic liner (circumferential and helical composites). Type-IV tanks (Figure 3, 4 & 5) consist of one or two metal bosses to ensure the connection with the storage system, a polymer liner for gas tightness and a circumferential and helical composite structuring which makes it possible to cover the entire surface of the ferrule and the domes. Type-V tanks are Type-IV tanks without the liner. Today, for better integration, the conformable vessels are developed like snake tanks, under body tanks…

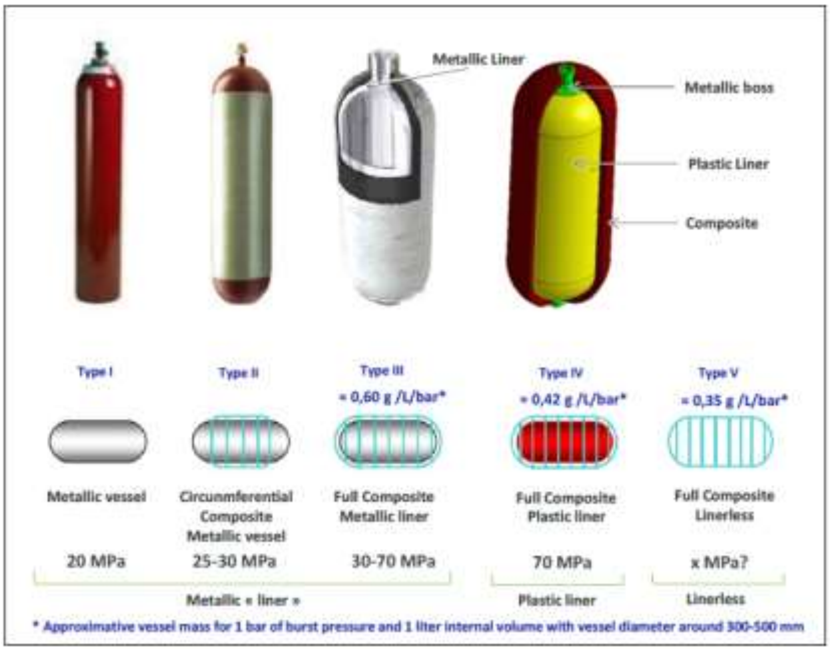



Figure 1. Pressure Vessel types

Composite laminate is manufactured by filament winding process, Figure 2. During the process, continuous reinforcements (filament, wire, yarn, tape, or other) impregnated of resin are wounded around a rotating plastic liner in a prescribed way. When the required number of layers is applied, the resin of the wound form is cured following a temperature transient.

Figure 2. CEA Robotic Filament Winding Machine with On-board rotational delivery system

The materials used commonly for 70 MPa type IV pressure vessel (Figure 3) are:

- For the composite
  - Toray T700 carbon fibre
  - Epoxy resin
- For the liner
  - Poly-ethylene
  - Poly-amide
- For the boss
  - Aluminium 6061

Figure 3. CEA 62L 700 bar Type IV $H_2$ Composite Pressure Vessel before burst test

Figure 4. CEA 62L 700 bar Type IV $H_2$ Composite Pressure Vessel after 1800 bar burst test


Figure 5. CEA 36L 700 bar Type IV $H_2$ Conformable Composite Pressure Vessel prototype

Today, the value of the burst pressure ratio ($P_{burst}/P_{working}$) is equal to 2.25 [3][4][5], Figure 6, for on-board carbon composite $H_2$ pressure vessels at initial life. For a 70 MPa pressure vessel, the minimum burst pressure at initial life is 157.5 MPa. In general, to take into account the composite mechanical distribution, the composite is designed for 175 MPa. The pressure operational range is from 2 MPa to 87.5 MPa. 87.5 MPa is the value of the maximum pressure during the filling at the hydrogen refilling station (HRS). The value of the safety factor (SF) can be defined as the value of the minimal burst pressure (157.5 MPa) divided by the value of the maximum pressure allowed during operational life of the vessel (87.5). The value of SF is 1.8, Figure 3. The level of composite porosity can reach 4% to 8%.

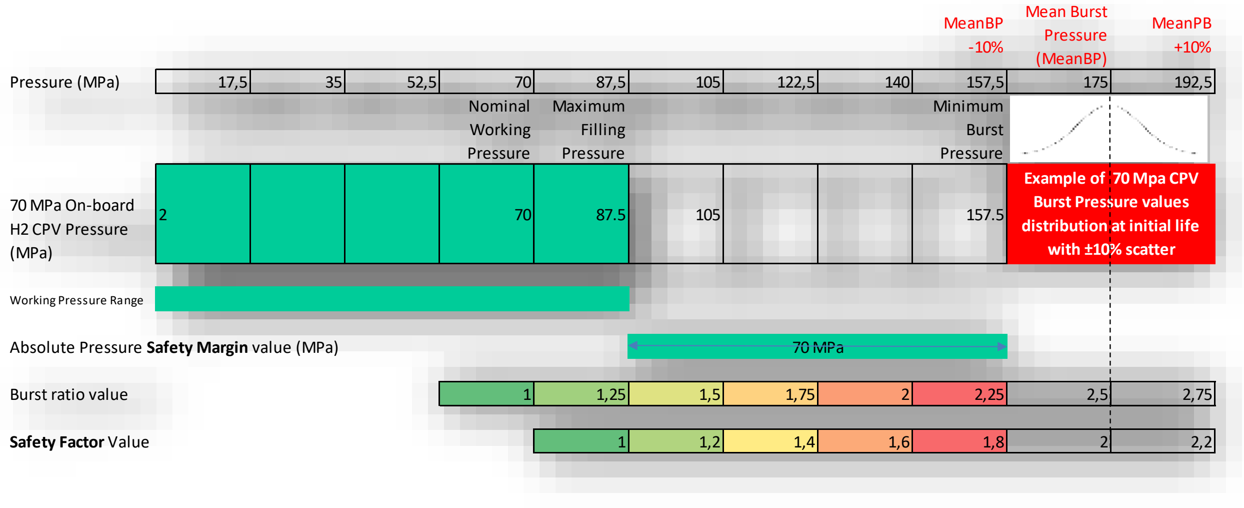



Figure 6. 70 MPa safety margin of composite material for 70 MPa on-board $H_2$ carbon CPV

## 3.0 EXISTING PERFORMANCE INDICATORS

For high-pressure 700-bar composite tanks, for example an on-board tank for hydrogen storage, carbon fibre is most often used. Carbon fibre accounts for 50 to 70% of the tank price, especially for high production rates. It is therefore important, in order to minimize the storage cost of the tank, to have a composite with a high mechanical performance. Today, to simply evaluate the mechanical performance of a high-pressure composite tank (CPV), there are indicators that can be considered such as:

- Burst pressure of the tank
- Gravimetric capacity of the storage system
- Volumetric capacity of the storage system
- Specific cost of the storage system
- Tank performance index

Table 1. European FCH-JU targets.

| Application | Parameter | Unit | | FCH-JU target | | |
|---|---|---|---|---|---|---|
| | | | 2012 | 2017 | 2020 | 2023 |
| Hydrogen Storage | Hydrogen storage system cost | €/kg $H_2$ | >3000 | 800 | 600 | 500 |
| | Volumetric capacity ($H_2$ tank system) | kg/L | 0.02 | 0.022 | 0.023 | 0.025 |
| | Gravimetric capacity (H2 tank system) | % kg $H_2$/ total kg | < 4 | 4 | 5 | 6 |

### 3.1 Burst pressure of the tank

The composite structure of the vessel is designed with respect to the burst pressure target value. The average burst pressure of a tank and its distribution are intensive values that do not really give the efficiency of the composite laminate since they disregard the volume of the tank and thus the quantity of fluid that the tank stores, its total mass and, in particular, its composite mass. As an example, the minimum burst pressure of a composite tank using carbon fibres for automotive applications is 2.25 times the nominal operating pressure, i.e., a pressure of 1575 bar for a 700-bar tank. Generally, manufacturers design the tanks for average pressure that is several hundred bar higher than the minimum burst pressure, in order to take into account the performance distribution and maintain a safety margin. Usually, manufacturers do not communicate these results but the value is around 1750 bar, Figure 6.

### 3.2 Gravimetric capacity of the storage system

$$Gravimetric\ capacity = Gravimetric\ Storage\ Density = \frac{H_2 mass}{H_2 mass + Storage\ System\ Mass}$$

The gravimetric capacity of a high-pressure composite tank is the ratio of the mass of the fluid stored in the tank to the total mass of the storage system. For FCEV applications, the mass of the storage system corresponds to the sum of the mass of the stored hydrogen, to which the mass of the tank is added, and the mass of all the elements of the storage system enabling the fuel cell to be powered in order to carry out the filling and other functions including safety functions (BOP: balance of plant). In Europe and North America, there are performance targets related to the gravimetric capacity of the tank [6] (see Table 1), but this criterion is not sufficient to determine the mechanical performances of the composite at burst level (ultimate resistance level). This indicator doesn't take into account the intrinsic performance of the fibre (ultimate strength). Tank manufacturers tend to give a gravimetric capacity in which the mass of the storage system is not fully considered. As a result, the gravimetric capacity is greater than that initially defined. The gravimetric capacity of the tank is an indicator used for automotive integrators to assess the impact of the storage system in terms of mass on the vehicle.

### 3.3 Volumetric capacity of the storage system

$$Volumetric\ capacity = Storage\ Volumic\ Mass = \frac{H_2 mass\ (g)}{Storage\ System\ Volume\ (L)}$$

The volumetric capacity of a tank is another indicator used by FCEV automotive integrators because it makes it possible to measure the volumetric impact of the tank for a better integration in the vehicle. The volumetric capacity for FCEV applications corresponds to the mass of on-board hydrogen divided by the volume of the storage system. Tank manufacturers also use a volumetric capacity that considers only the volume occupied by the tank regardless of the volume occupied by the storage system. This gives higher values but they do not really correspond to the expectations of automotive integrators. This indicator could be interesting for measuring the efficiency of the composite structure of a tank, but it depends on the stored fluid and its density as a function of the pressure. Consequently, depending on the nature of the stored fluid, this indicator may have different values for the same mechanical performance of the composite structure. Moreover, this indicator does not take into account the burst pressure of the tank and therefore the ultimate mechanical performance of its structure and also the intrinsic performance of the fibre.

### 3.4 Specific cost of the storage system

The specific cost of the storage corresponds to the manufacturing cost of the tank in relation to the mass of the stored hydrogen. This value is important for automotive integrators because it is presently too high (> 1000 €/kg H2) to permit a rapid deployment of hydrogen vehicles. It is an economic indicator and the mechanical performance of the composite structure is not accessible. This indicator may vary considerably depending on the volume of the tank, the storage system, the price of the carbon fibre used and the annual production rate.

### 3.5 Tank performance index

$$Performance\ Index = \frac{Nominal\ Working\ Pressure\ (bar)\ .\ Vessel\ Internal\ Volume\ (L)}{Tank\ mass\ (kg)}$$

This indicator is the one that is presently the closest to evaluate properly the mechanical performance of a composite structure. Indeed, the performance index is defined as the ratio of the nominal working pressure multiplied by the volume of stored fluid and divided by the mass of the empty tank. But the nominal operating pressure is not the image of the ultimate performance of the tank to withstand the greatest pressure possible. Moreover, this indicator does not take into account the intrinsic performance of the fibre. Consequently, this indicator is not yet sufficient to evaluate the performance of the composite structure of a tank.

## 4 A DIMENSIONLESS NUMBER TO EVALUATE CPV EFFICIENCY AT BURST

The next indicator, called DN (Dimensionless Number), is a dimensionless number used to measure the mechanical performance of the composite structure of a tank from the design phase or after the test phase. This number is dimensionless because it is the ratio between two energies.

The assumptions that have been taken into account are that:

- the carbon fibres are working in tension, in the same direction, along the longitudinal fibre axis
- all the fibres are loaded at the same level
- the mechanical energy reached in the fluid at the time of bursting is entirely taken up by the fibre of the composite.

DN is the ratio of the average burst pressure of the high-pressure composite tank multiplied by the volume of stored fluid divided by the ultimate tensile strength in the axis of the UD carbon ply and divided by the volume of structuring carbon composite. The volume occupied by the composite structure can be estimated simply by dividing the mass of the composite structure by its density (1.5 in general for 60% carbon fibre with epoxy matrix).

$$DN_{laminate} = \frac{\overline{P_{burst}} \cdot V_{fluid}}{\sigma^{l}_{UD\ ply} \cdot V_{laminate}}$$

The numerator evaluates the maximum energy that the tank can accept. It is the energy evaluated at the bursting pressure.

The denominator evaluates the energy that the composite material of the tank can accept when all the material is charged at 100%.

This number makes it possible to evaluate the efficiency of the composite structure of a high-pressure tank. By maximizing the DN, it is possible to minimize the mass of the composite structure of a CPV.

## 5 COMPARISON OF THE DIFFERENT INDICATORS WITH THE DIMENSIONLESS NUMBER

The purpose of this chapter is to quantify the values of the dimensionless number to evaluate the mechanical performance of the composite and to determine bounds that indicate whether the composite structure is optimized or not.

The results presented in Tables 2 and 3 are realistic data derived from the analysis of tanks that have been designed, manufactured and tested at CEA as part of national or european collaborative multi-stakeholder research projects such as OSIRHYS IV [7], STORHY, COPERNIC. An analysis of the current market has also made it possible to complete this table.

Table 2. 70 MPa H2 Type IV CPV description.

| Vessel n° | Project | Comment | nominal working pressure (NWP) | internal volume | fluid stored | Volumic mass at Tamb and NWP | vessel total length | vessel external diameter | BOP length with On Tank Valve | mass of fluid at nominal presure | empty vessel total mass | Carbon Laminate mass | Cabon fiber composite volumic mass | Volumic fibre ratio in composite | Carbon Fiber mass | kind of carbon fibre | fiber stress at rupture | laminate stress at rupture |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | MPa | L | - | kg/L | mm | mm | mm | kg | kg | kg | kg/m3 | % | kg | - | MPa | MPa |
| 1 | STORHY | reference | 70 | 37 | H2 | 0.04 | 958 | 301 | 50 | 1.48 | 33 | 26.9 | 1500 | 60% | 16.1 | T700 | 4900 | 2100 |
| 2 | COPERNIC | optimized composite | 70 | 37 | H2 | 0.04 | 958 | 301 | 50 | 1.48 | 27 | 21 | 1500 | 60% | 12.6 | T700 | 4900 | 2100 |
| 3 | - | CNG | 70 | 37 | CH4 | 0.45 | 958 | 301 | 50 | 16.65 | 33 | 26.9 | 1500 | 60% | 16.1 | T700 | 4900 | 2100 |
| 4 | COPERNIC | High volume<br>High production rate | 70 | 150 | H2 | 0.04 | 952 | 631 | 50 | 6 | 125 | 108 | 1500 | 60% | 64.8 | T700 | 4900 | 2100 |
| 5 | - | reference with coatings | 70 | 37 | H2 | 0.04 | 958 | 301 | 50 | 1.48 | 37 | 26.9 | 1500 | 60% | 16.1 | T700 | 4900 | 2100 |

Table 3. 70 MPa H2 Type IV CPV indicators and Dimensionless Number.

| Vessel n° | Project | Comment | nominal working pressure (NWP) | internal volume | fluid stored | Volumic mass at Tamb and NWP | *burst pressure* | *vessel gravimetric capacity* | *vessel volumetric capacity* | *Storage system gravimetric capacity* | *Storage system volumetric capacity* | *Hydrogen Storage system cost* | *performance index (based on nominal working pressure)* | *$DN_{laminate}$* | *$DN_{fiber}$* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | MPa | L | - | kg/L | *MPa* | *kg H2/kg* | *kg H2/L* | *kg H2/kg* | *kg H2/L* | *€/kg H2* | *Bar.L/vessel kg* | - | - |
| 1 | STORHY | reference | 70 | 37 | H2 | 0.04 | *175* | *4.29%* | *0.022* | *3.95%* | *0.021* | *2944* | *785* | *17.2%* | *12.3%* |
| 2 | COPERNIC | optimized composite | 70 | 37 | H2 | 0.04 | *180* | *5.20%* | *0.022* | *4.70%* | *0.021* | *2299* | *959* | *22.7%* | *16.2%* |
| 3 | - | CNG | 70 | 37 | CH4 | 0.45 | *175* | *33.53%* | *0.244* | *31.62%* | *0.232* | *262* | *785* | *17.2%* | *12.3%* |
| 4 | COPERNIC | High volume<br>High production rate | 70 | 150 | H2 | 0.04 | *175* | *4.58%* | *0.020* | *4.48%* | *0.019* | *722* | *840* | *17.4%* | *12.4%* |
| 5 | - | reference with coatings | 70 | 37 | H2 | 0.04 | *175* | *3.85%* | *0.022* | *3.57%* | *0.021* | *2944* | *700* | *17.2%* | *12.3%* |

The purpose of this chapter is to quantify the values of the dimensionless number to evaluate the mechanical performance of the composite and to determine bounds that indicate whether the composite structure is optimized or not. The computed values of the dimensionless number (DN on table 3) are low (<23%) even if the vessel is optimized.

Figure 7 shows a finite element calculation of a 700 bar pressure vessel at 1750 bar (burst) from European Copernic project. The fibre stress field is shown. The figure indicates that a large part of the carbon fibre is not fully loaded.

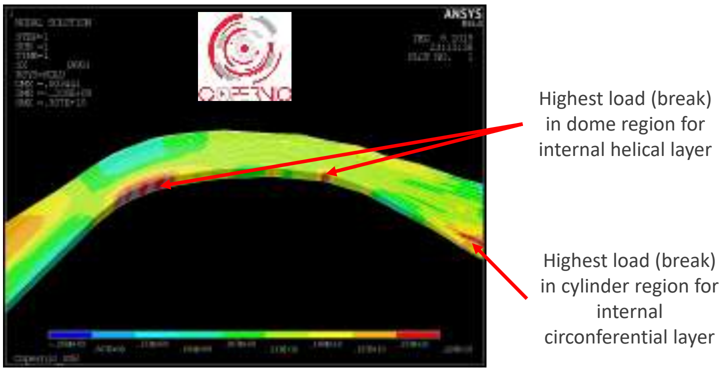



Figure 7. Finite Element calculation at burst level, large part of carbon fibres not fully loaded

### 5.1 Comparison of the burst pressure of the tank with the dimensionless number

As can be seen in Table 2 & 3, Tank n°2, defined within the framework of the OSIRHYS IV project [7] and manufactured under the COPERNIC project [5], has a burst performance that is 50 bar higher than that of Tank n°1, from the STORHY project. One might think that the mass of carbon composite used for Tank n°2 would be greater than that of Tank n°1. In reality, it is the opposite. The mass value of the carbon composite of Tank n°2 is 21 kg compared with 27 kg for Tank n°1. This is due to a numerical optimization of the composite architecture of the tank which has led to a better utilization of the potential of the composite structure. The composite of Tank n°2 is used in a better way than that of Tank n°1. Indeed, the proposed dimensionless number goes in this direction. According to this number, upon rupture, DN=17.2% of the potential of the composite of Tank n°1 is used, compared with DN=22.7% of the potential of Tank n°2. The burst pressure is thus not a sufficient parameter to evaluate the effectiveness of the composite structure of a tank.

### 5.2 Comparison between the gravimetric rate and the dimensionless number

Tank n°3 (Table 2 & 3) is similar than Tank n°1 but the stored fluid is methane. The burst performances can be estimated as strictly identical. Nevertheless, the density of methane is approximately 10 times higher than that of hydrogen. As a result, the value of the gravimetric rate of Tank n°3 is 33.53% while that of Tank n°1 is 4.29%. On the other hand, the value of DN is the same for both tanks. The gravimetric rate is thus not a sufficient parameter to evaluate the effectiveness of the composite structuring of a tank.

### 5.3 Comparison between the volumetric capacity and the dimensionless number

As for the gravimetric rate, the comparison of Tank n°3 and Tank n°1 leads to the same conclusion concerning the volumetric capacity. Indeed, the value of the volume capacity of Tank n° 3 is 0.244 kg/L while that of Tank n° 1 is 0.022 kg/L. The volumetric capacity is thus not a sufficient parameter to evaluate the effectiveness of the composite structuring of a tank.

### 5.4 Comparison between the specific cost of a storage system and the dimensionless number

The data that make it possible to estimate the values of the storage system are derived from the European project Copernic. The volume of the tank and the annual production rate have an important influence on the reduction of the specific cost of the storage system. For a tank of 150 litres (Tank n°4) manufactured at 100,000 items a year, the specific cost of the storage system is estimated at 722€ per kilogram of stored hydrogen, whereas for Tank n°1, manufactured at 1000 items per year, the value is 2944€ per kilogram of stored hydrogen. It is therefore difficult to determine with this indicator whether the composite structure of Tank n°4 is more efficient than that of Tank n°1. The values of the non-dimensional number show that, between the two tanks, the efficiency is close to 17%. The specific cost of a storage system is not a sufficient parameter to evaluate the effectiveness of the composite structure of a tank.

### 5.5 Comparison between the performance index of the tank and the dimensionless number

The performance index of the tank takes into account its total mass. Therefore, it considers not only the mechanical performance of the composite but also the other materials of the tank such as the bases, the liner and any other additional elements such as, for example, coatings for protection against impact or fire. To illustrate this, Tank n°5 is identical to Tank n°1 but has an additional mass of 4 kg which is not linked to its structuring composite. The performance index drops by 10% while the tank's mechanical performances at burst are identical. The performance index of the tank is thus not a sufficient parameter to evaluate the effectiveness of the composite structure of a tank.

## 6 REFERENCE VALUES FOR $DN_{LAMINATE}$

When considering the laminate, the DN values of a 700-bar type-IV tank for on-board storage of hydrogen (safety factor 2.25 for bursting) found in the state of the art are around 17%. This means that 17% of the total energy capacity of the laminate is involved (Tank n°1) at the time of the burst. When the composite structure is optimized for the burst test (Tank n°2), the composite mass decreases from 26.9 kg to 21 kg and the DN increases from 17% to 22.7%.

In the first approach, it is possible to propose, in an absolute manner, an estimation of the tank performance according to the following.

- $DN_{Laminate}$ < 15%: tank inferior to the state of the art
- 15% < $DN_{Laminate}$ < 20%: tank with a composite matching the state of the art
- $DN_{Laminate}$ > 20%: tank with an optimized composite

This proposal should be validated by a further study.

In parallel, $DN_{Laminate}$ can be used in a relative manner to compare the tanks to each other.

Today, with the table below, you can see what should be the mass of composite you need for a $H_2$ 700 bar composite pressure vessel with a mean burst pressure value equal to 1750 bar and a $DN_{laminate}$ value equal to 22% (actual optimized level).

Table 4. Optimal Composite Mass for 700 bar type IV vessels (1750 bar burst) with $DN_{laminate}$=22% (filament winding, optimized design / SOA).

| burst pressure (Mpa) | Fibre strength (Mpa) | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 175 | Composite strength (Mpa) | 1286 | 1500 | 1714 | 1929 | 2143 | 2357 | 2571 | 2786 | 3000 | 3214 | 3429 | 3643 | 3857 | 4071 | 4286 |
| Vessel Inner Volume (L) | $H_2$ mass at 700 bar (kg) | Optimal Composite Mass (with $DN_{Laminate}$ = 22%) (kg) | | | | | | | | | | | | | | |
| 1 | 0.04 | 0.93 | 0.80 | 0.70 | 0.62 | 0.56 | 0.51 | 0.46 | 0.43 | 0.40 | 0.37 | 0.35 | 0.33 | 0.31 | 0.29 | 0.28 |
| 10 | 0.4 | 9.3 | 8.0 | 7.0 | 6.2 | 5.6 | 5.1 | 4.6 | 4.3 | 4.0 | 3.7 | 3.5 | 3.3 | 3.1 | 2.9 | 2.8 |
| 25 | 1 | 23.2 | 19.9 | 17.4 | 15.5 | 13.9 | 12.7 | 11.6 | 10.7 | 9.9 | 9.3 | 8.7 | 8.2 | 7.7 | 7.3 | 7.0 |
| 37 | 1.48 | 34 | 29 | 26 | 23 | 21 | 19 | 17 | 16 | 15 | 14 | 13 | 12 | 11 | 11 | 10 |
| 50 | 2 | 46 | 40 | 35 | 31 | 28 | 25 | 23 | 21 | 20 | 19 | 17 | 16 | 15 | 15 | 14 |
| 63 | 2.52 | 58 | 50 | 44 | 39 | 35 | 32 | 29 | 27 | 25 | 23 | 22 | 21 | 19 | 18 | 18 |
| 75 | 3 | 70 | 60 | 52 | 46 | 42 | 38 | 35 | 32 | 30 | 28 | 26 | 25 | 23 | 22 | 21 |
| 100 | 4 | 93 | 80 | 70 | 62 | 56 | 51 | 46 | 43 | 40 | 37 | 35 | 33 | 31 | 29 | 28 |
| 125 | 5 | 116 | 99 | 87 | 77 | 70 | 63 | 58 | 54 | 50 | 46 | 44 | 41 | 39 | 37 | 35 |
| 150 | 6 | 139 | 119 | 104 | 93 | 84 | 76 | 70 | 64 | 60 | 56 | 52 | 49 | 46 | 44 | 42 |
| 175 | 7 | 162 | 139 | 122 | 108 | 97 | 89 | 81 | 75 | 70 | 65 | 61 | 57 | 54 | 51 | 49 |
| 200 | 8 | 186 | 159 | 139 | 124 | 111 | 101 | 93 | 86 | 80 | 74 | 70 | 66 | 62 | 59 | 56 |
| 225 | 9 | 209 | 179 | 157 | 139 | 125 | 114 | 104 | 96 | 89 | 84 | 78 | 74 | 70 | 66 | 63 |
| 250 | 10 | 232 | 199 | 174 | 155 | 139 | 127 | 116 | 107 | 99 | 93 | 87 | 82 | 77 | 73 | 70 |
| 300 | 12 | 278 | 239 | 209 | 186 | 167 | 152 | 139 | 128 | 119 | 111 | 104 | 98 | 93 | 88 | 84 |
| 600 | 24 | 557 | 477 | 418 | 371 | 334 | 304 | 278 | 257 | 239 | 223 | 209 | 197 | 186 | 176 | 167 |
| 700 | 28 | 650 | 557 | 487 | 433 | 390 | 354 | 325 | 300 | 278 | 260 | 244 | 229 | 217 | 205 | 195 |
| 1000 | 40 | 928 | 795 | 696 | 619 | 557 | 506 | 464 | 428 | 398 | 371 | 348 | 328 | 309 | 293 | 278 |

## 7 IMPROVING DN

The proposed dimensionless number can be refined. Indeed, it is possible to integrate:

- several structuring fibres in the case of a hybrid composite structure of a tank by modifying the denominator into a series that gives the sum of the contribution of each fibre

$$DN_{laminate} = \frac{\overline{P_{burst}} \cdot V_{fluid}}{\sum_1^n \sigma^l_{UD\ ply,\ n} \cdot V_{laminate,\ n}}$$

- the contribution of the liner for tanks of type 2 and 3 by subtracting from the numerator the mechanical energy contained in the liner at the time of bursting. This energy remains to be defined.

$$DN_{laminate} = \frac{\overline{P_{burst}} \cdot V_{fluid} - E_{liner}}{\sigma^l_{UD\ ply} \cdot V_{laminate}}$$

- the mechanical contribution of the fibre instead of the contribution of the composite and consideration of the fibre volume rate

$$DN_{fibre} = \frac{\overline{P_{burst}} \cdot V_{fluid}}{\sigma^l_{fibre} \cdot v_f \cdot V_{laminate}}$$

When comparing the DN values for laminate and fibre in Table 3, the values of $DN_{fibre}$ are still much lower than $DN_{laminate}$. Indeed, the resistance properties of the UD ply are always inferior since there is a translation factor in order to consider phenomena that degrade the expected performances (shaping, composite architecture, flexural work, etc.).

## 8 REFERENCE VALUES FOR $DN_{FIBRE}$

When it comes to the fibres, the value of $DN_{fibre}$ of Tank n°1 (state of the art) is 11%. This value can be compared with the percentage of broken fibres in finite element calculations taking into account the damage of the fibres, of the matrix and delamination. This value seems consistent with simulation results. Indeed, for a calculation carried out on a 2L 700-bar tank bursting around 1750 bar (Figure 8) (Osirhys project [4]), the percentage of broken fibres was estimated to no more than 8%.

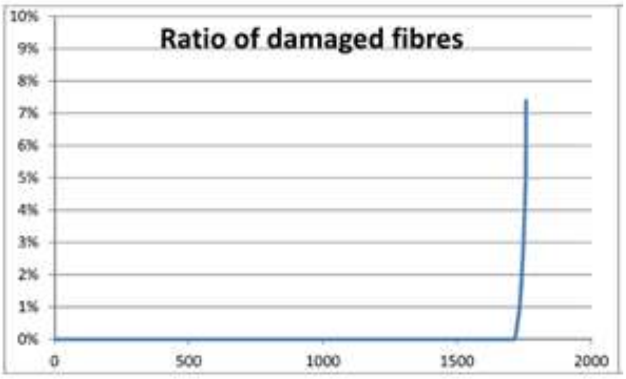


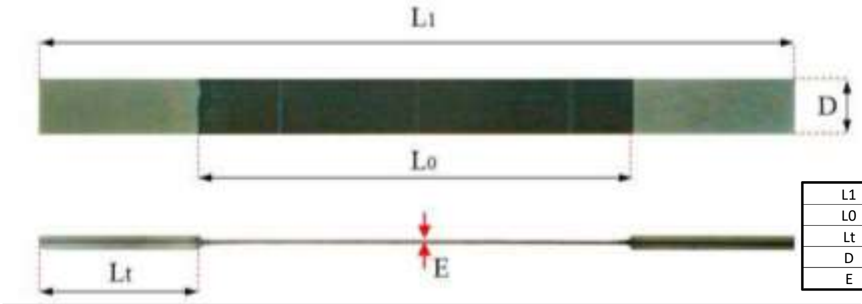

Figure 8. Numerical evolution of the fibre content in the tank as a function of pressure (bar)

Tank n° 2 was optimized and the $DN_{fibre}$ value is equal to 15%. As for $DN_{laminate}$, it is possible to propose, in an absolute manner, an estimate of the tank performance according to the following.

- $DN_{fibre}$ < 8%: tank inferior to the state of the art
- 8% < $DN_{fibre}$ < 13%: tank with a composite matching the state of the art
- $DN_{fibre}$ > 13%: tank with an optimized composite

## 9 APPLICATION FOR 0° COMPOSITE SAMPLE

The dimensionless number defined in this paper can be used to estimate composite efficiency during UD 0° sample tensile test (Figures 9 & 10). Experimental results from OSIRHYS IV project are considered [4]. The fibre is carbon T700 and the matrix is epoxy family. The fibre volume fraction is equal to 60%.




| | |
|---|---|
| L1 | 260 mm |
| L0 | 150 mm |
| Lt | 55 mm |
| D | 17.5 ± 0.3 mm |
| E | 2 ± 0.1 mm |

Figure 9. 0° Composite sample geometry for traction test from Osirhys IV project

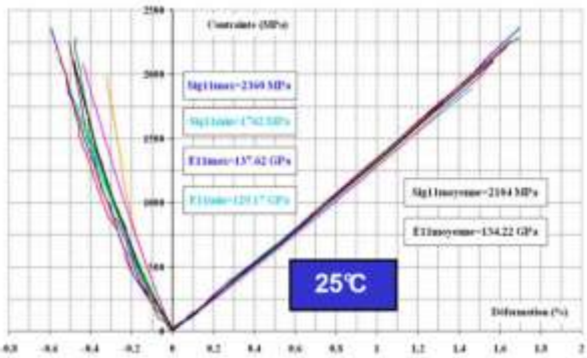



Figure 10. Compression & Tensile tests on 0° T700/Epoxy samples from Osirhys IV project

The maximal strength of the fibre value is 4900 MPa. So for a 0° UD sample at 60% volumic fibre ratio, the maximal strength of the sample is computed at 2940 MPa ($\sigma_{11}^{R\ ideal}$). The mean value obtained during the traction tests is 2104 MPa ($\sigma_{11}^{R\ sample}$). In this case, DN number can be calculated as follow.

$$DN_{0°\ UD\ sample} = \frac{\sigma_{11}^{R\ sample}\ .\ V_{sample}}{\sigma_{11}^{R\ ideal}\ .\ V_{sample}} = 72\%$$

As we expect, the mechanical efficiency of the composite from a sample is higher than composite from pressure vessels. The reasons are well known as quasi perfect fibre alignment, stress field in the same direction than fibre length, thin composite, very low porosity, quasi no 3 D effects…

## 10 IDEAL SOLUTION FOR A $H_2$ 700 BAR TYPE IV COMPOSITE PRESSURE VESSEL

Using DN number, it is easy to determine the ideal solution. The ideal solution is the solution where the minimum mass of composite (or fibre) is used but today, in this case no process is existing to manufacture the ideal structure. The ideal solution is obtained with a DN number equal to 100%. The table below shows what is the ideal solution ($DN_{laminate}$=1) depending of the strength of the carbon used for a 700 bar type IV composite pressure vessel where the fibre volumic ratio is equal to 0,6. and the mean burst pressure is equal to 1750 bar.

Table 5. Ideal Composite Mass for 700 bar type IV vessels (1750 bar burst) with $DN_{laminate}$=100%

| burst pressure (Mpa) | Fibre strength (Mpa) | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 175 | Composite strength (Mpa) | 1286 | 1500 | 1714 | 1929 | 2143 | 2357 | 2571 | 2786 | 3000 | 3214 | 3429 | 3643 | 3857 | 4071 | 4286 |
| Vessel Inner Volume (L) | $H_2$ mass at 700 bar (kg) | Ideal Composite Mass (with $DN_{Laminate}$ = 100%) (kg) | | | | | | | | | | | | | | |
| 1 | 0.04 | 0.20 | 0.18 | 0.15 | 0.14 | 0.12 | 0.11 | 0.10 | 0.09 | 0.09 | 0.08 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 |
| 10 | 0.4 | 2.0 | 1.8 | 1.5 | 1.4 | 1.2 | 1.1 | 1.0 | 0.9 | 0.9 | 0.8 | 0.8 | 0.7 | 0.7 | 0.6 | 0.6 |
| 25 | 1 | 5.1 | 4.4 | 3.8 | 3.4 | 3.1 | 2.8 | 2.6 | 2.4 | 2.2 | 2.0 | 1.9 | 1.8 | 1.7 | 1.6 | 1.5 |
| 37 | 1.48 | 8 | 6 | 6 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| 50 | 2 | 10 | 9 | 8 | 7 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 3 | 3 |
| 63 | 2.52 | 13 | 11 | 10 | 9 | 8 | 7 | 6 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 4 |
| 75 | 3 | 15 | 13 | 11 | 10 | 9 | 8 | 8 | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 5 |
| 100 | 4 | 20 | 18 | 15 | 14 | 12 | 11 | 10 | 9 | 9 | 8 | 8 | 7 | 7 | 6 | 6 |
| 125 | 5 | 26 | 22 | 19 | 17 | 15 | 14 | 13 | 12 | 11 | 10 | 10 | 9 | 9 | 8 | 8 |
| 150 | 6 | 31 | 26 | 23 | 20 | 18 | 17 | 15 | 14 | 13 | 12 | 11 | 11 | 10 | 10 | 9 |
| 175 | 7 | 36 | 31 | 27 | 24 | 21 | 19 | 18 | 16 | 15 | 14 | 13 | 13 | 12 | 11 | 11 |
| 200 | 8 | 41 | 35 | 31 | 27 | 25 | 22 | 20 | 19 | 18 | 16 | 15 | 14 | 14 | 13 | 12 |
| 225 | 9 | 46 | 39 | 34 | 31 | 28 | 25 | 23 | 21 | 20 | 18 | 17 | 16 | 15 | 15 | 14 |
| 250 | 10 | 51 | 44 | 38 | 34 | 31 | 28 | 26 | 24 | 22 | 20 | 19 | 18 | 17 | 16 | 15 |
| 300 | 12 | 61 | 53 | 46 | 41 | 37 | 33 | 31 | 28 | 26 | 25 | 23 | 22 | 20 | 19 | 18 |
| 600 | 24 | 123 | 105 | 92 | 82 | 74 | 67 | 61 | 57 | 53 | 49 | 46 | 43 | 41 | 39 | 37 |
| 700 | 28 | 143 | 123 | 107 | 95 | 86 | 78 | 71 | 66 | 61 | 57 | 54 | 50 | 48 | 45 | 43 |
| 1000 | 40 | 204 | 175 | 153 | 136 | 123 | 111 | 102 | 94 | 88 | 82 | 77 | 72 | 68 | 64 | 61 |

The table below shows what is the ideal solution ($DN_{fibre}$=1) depending of the strength of the carbon used for a 700 bar type IV composite pressure vessel where the fibre volumic ratio is equal to 0,6. and the mean burst pressure is equal to 1750 bar.

Table 6. Ideal Composite Mass (kg) for 700 bar type IV vessels (1750 bar burst) with $DN_{fibre}$=100%

| burst pressure (Mpa) | Fibre strength (Mpa) | 3000 | 3500 | 4000 | 4500 | 5000 | 5500 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500 | 9000 | 9500 | 10000 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 175 | Composite strength (Mpa) | **1800** | **2100** | **2400** | **2700** | **3000** | **3300** | **3600** | **3900** | **4200** | **4500** | **4800** | **5100** | **5400** | **5700** | **6000** |
| Vessel Inner Volume (L) | $H_2$ mass at 700 bar (kg) | Ideal Composite Mass (with $DN_{Fiber}$ = 100%) (kg) | | | | | | | | | | | | | | |
| 1 | 0.04 | 0.15 | 0.13 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 |
| 10 | 0.4 | 1.5 | 1.3 | 1.1 | 1.0 | 0.9 | 0.8 | 0.7 | 0.7 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
| 25 | 1 | 3.6 | 3.1 | 2.7 | 2.4 | 2.2 | 2.0 | 1.8 | 1.7 | 1.6 | 1.5 | 1.4 | 1.3 | 1.2 | 1.2 | 1.1 |
| 37 | 1.48 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 50 | 2 | 7 | 6 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 |
| 63 | 2.52 | 9 | 8 | 7 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| 75 | 3 | 11 | 9 | 8 | 7 | 7 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 3 |
| 100 | 4 | 15 | 13 | 11 | 10 | 9 | 8 | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 5 | 4 |
| 125 | 5 | 18 | 16 | 14 | 12 | 11 | 10 | 9 | 8 | 8 | 7 | 7 | 6 | 6 | 6 | 5 |
| 150 | 6 | 22 | 19 | 16 | 15 | 13 | 12 | 11 | 10 | 9 | 9 | 8 | 8 | 7 | 7 | 7 |
| 175 | 7 | 26 | 22 | 19 | 17 | 15 | 14 | 13 | 12 | 11 | 10 | 10 | 9 | 9 | 8 | 8 |
| 200 | 8 | 29 | 25 | 22 | 19 | 18 | 16 | 15 | 13 | 13 | 12 | 11 | 10 | 10 | 9 | 9 |
| 225 | 9 | 33 | 28 | 25 | 22 | 20 | 18 | 16 | 15 | 14 | 13 | 12 | 12 | 11 | 10 | 10 |
| 250 | 10 | 36 | 31 | 27 | 24 | 22 | 20 | 18 | 17 | 16 | 15 | 14 | 13 | 12 | 12 | 11 |
| 300 | 12 | 44 | 38 | 33 | 29 | 26 | 24 | 22 | 20 | 19 | 18 | 16 | 15 | 15 | 14 | 13 |
| 600 | 24 | 88 | 75 | 66 | 58 | 53 | 48 | 44 | 40 | 38 | 35 | 33 | 31 | 29 | 28 | 26 |
| 700 | 28 | 102 | 88 | 77 | 68 | 61 | 56 | 51 | 47 | 44 | 41 | 38 | 36 | 34 | 32 | 31 |
| 1000 | 40 | 146 | 125 | 109 | 97 | 88 | 80 | 73 | 67 | 63 | 58 | 55 | 51 | 49 | 46 | 44 |

## 11 CONCLUSION

A new dimensionless number (DN) is proposed in order to evaluate the performance of a high-pressure vessel composite structure. It shows that very few composite part is used at its maximum loading potential during bursting. Today, for 70 MPa on-board type IV composite tanks, DN values close to 20%.

The suggested DN will be a useful indicator for an industrial application. By maximizing the DN at the design phase, it is possible to minimize the mass of the composite structure of a CPV, to reduce the manufacturing time and cost.

To increase the DN as close as possible to 100%, it is necessary to succeed in increasing the overall loading of the composite structure, to have better oriented fibre. For this, it seems necessary to find new processes which make it possible to better orient the fibre.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