ROAD TRHYP

Clean Hydrogen Partnership

Co-funded by the European Union

WORKSHOP

Trailer design to maximise amount of gH_2 transported using Type V tubes

« ROADTRHYP »

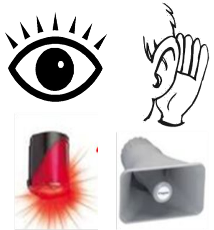
ROAD trailer design – use of **T**ype V the**R**moplastic tube with light composite structure for **HY**drogen trans**P**ort

ICP

March 4th, 2025

Air Liquide | COVESS Thermoplastic Tank Technologies | ARKEMA | Wrocław University of Science and Technology | Efectis | SEGULA Technologies | ENVITEST | Institut Pprime

Safety moment : What should I do if an alarm goes off ?

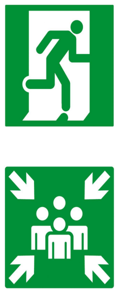


1/ I HEAR OR SEE A BUILDING ALARM

2/ I am OUTSIDE the building:

**3/ I DO NOT ENTER,
I go to the closest
meeting point.**

2/ I am INSIDE the building:



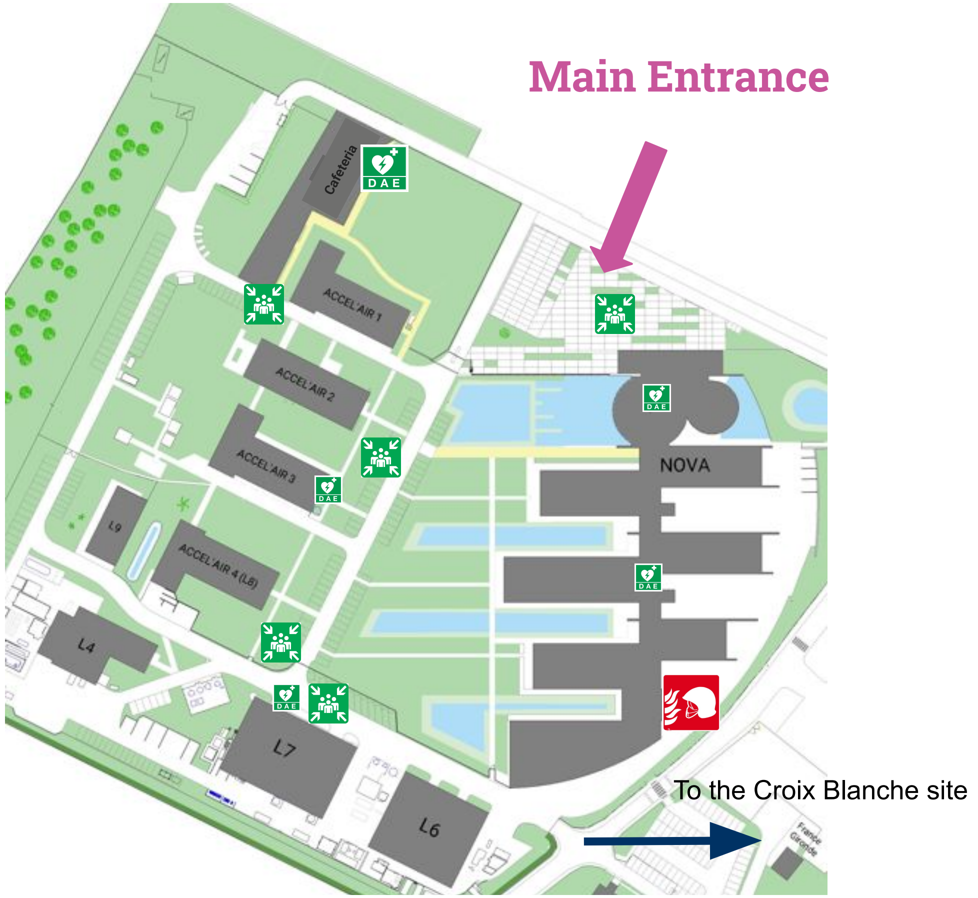
3/ I go to the closest meeting point calmly, I do not run, I hold the handrail when using the stairs. (I do not take the elevator).

I look after the visitors for whom I am responsible.

4/ I RE-ENTER the building only if the Meeting Point Coordinator invites me to do so.

Safety moment : What should I do if an alarm goes off ?

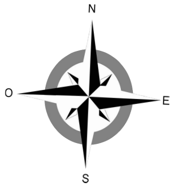
ASSEMBLY POINTS - Innovation Campus Paris



Main Campus: 5 assembly points

In case of emergency:
Call the internal first aid team

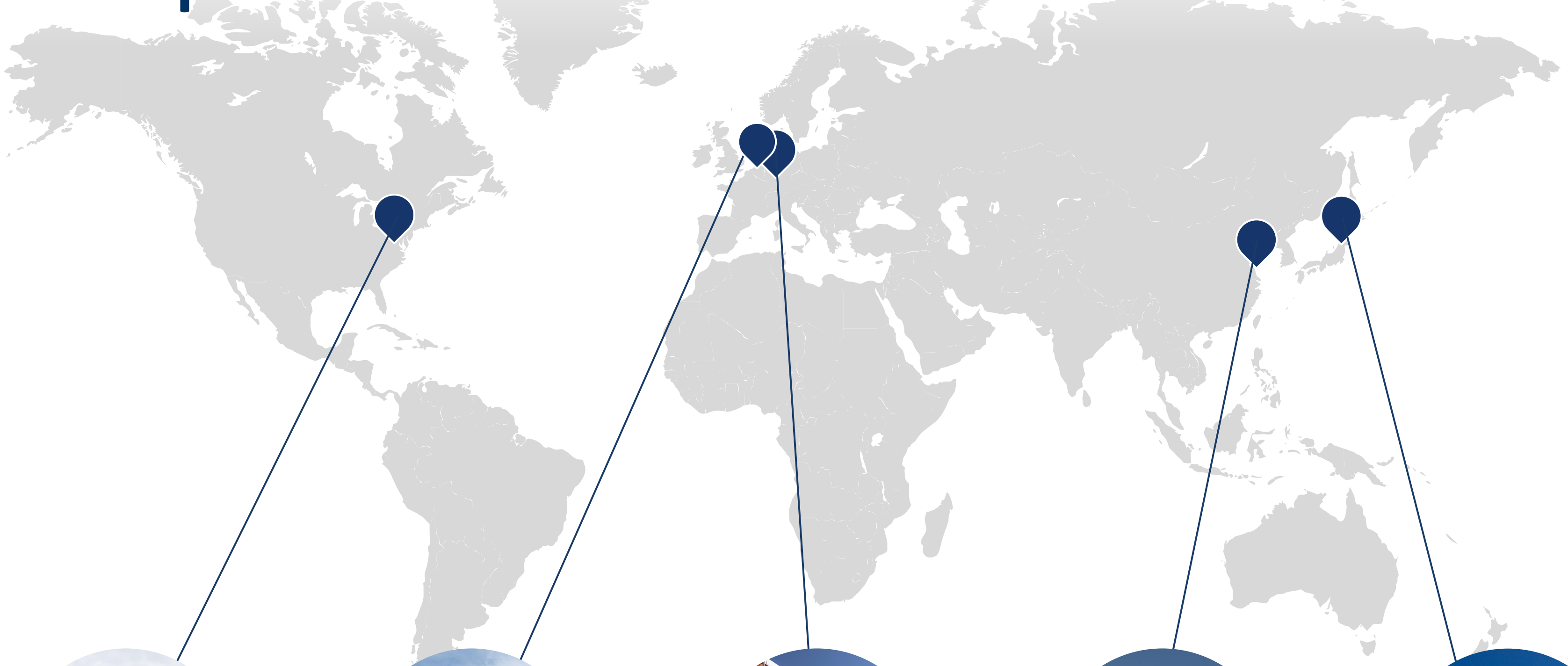
French phone: 01 39 56 38 82
Foreign phone: +33 1 39 56 38 82



WELCOME !

Key Figures

Campuses around the world



Innovation Campus Delaware (2007)

Innovation Campus Paris (1970)

Innovation Campus Frankfurt (2008)

Innovation Campus Shanghaï (2005)

Innovation Campus Tokyo (1986)

~ 500
R&D employees

+ 300
Academics & Industrial Partners

> 50%
R&D projects conducted in partnerships

5
Campuses

©CAPA

INNOVATION CAMPUS **PARIS**

59 Laboratories

8 Technical platforms

Gas Safety - Process Engineering - Computational and Data Science - Material Qualification - Combustion, Food processing - Additive Manufacturing - Gas Analysis

400 people on the Campus

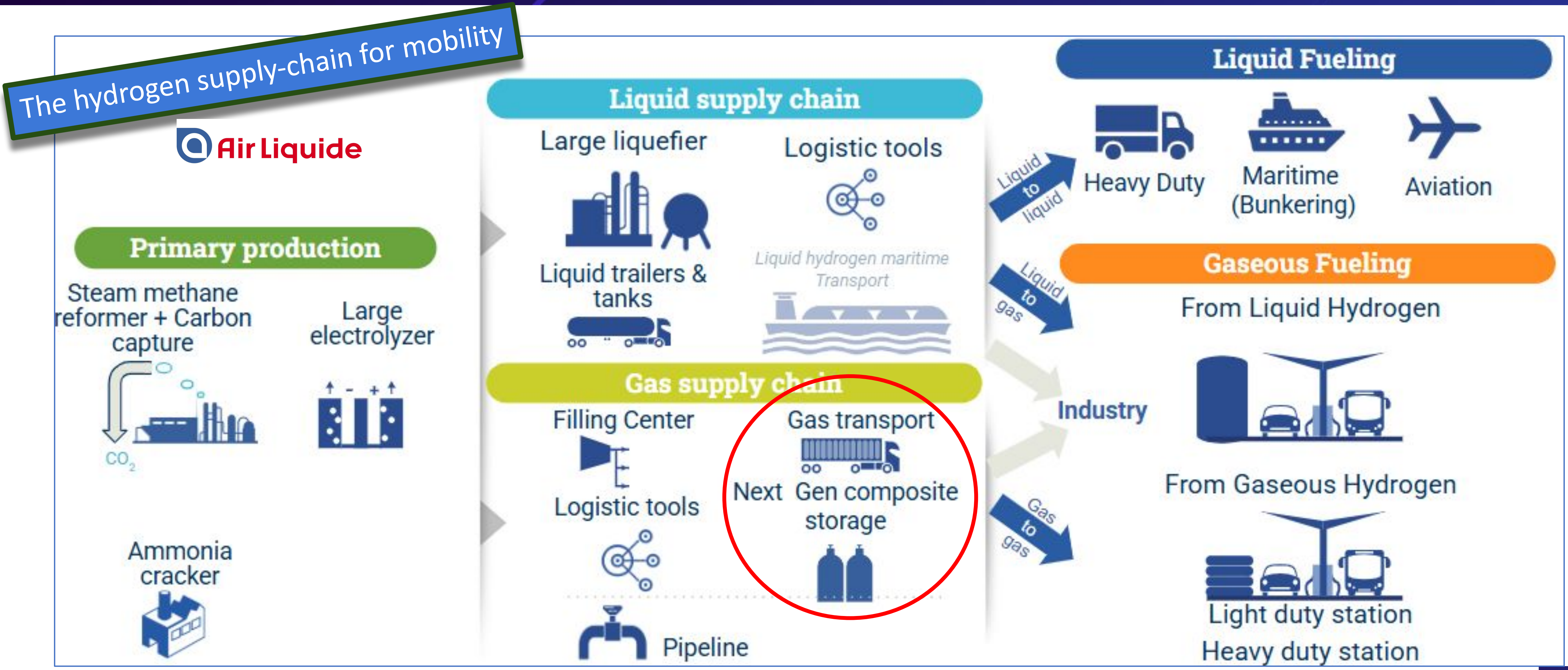
Discover the campus in video

The campus also relies on a team based in Krefeld (Germany).

Agenda

10.00 – 10.30 am	Welcome
10.30 – 10.50 am	Presentation of ROAD TRHYP : origin and objectives
10.50 – 11.00 am	Partnership – Role of each partner
11.00 – 13.00 am	Preliminary results :
	- Type V cylinder development / performances *(including usage)* *Materials, Processing (equipment, energy, waste, ...), Weight saving, Gravimetric index, Recyclability*
	- Trailer / Demonstrator concept
	- Safety & Fire behaviour
	- Regulation aspects
	- Life Cycle Analysis Type I, IV
13.00 – 13.30 pm	Q & A session
13.30 pm	Lunch – Networking – Parts displayed

Origin of the project : Why did we start ROAD TRHYP ?



Origin of the project : Why did we start ROAD TRHYP ?

Metallic tubes trailer

Challenges

Composite tubes trailer

Regulation, standards	Use of EN 17339 Transportable gas cylinders - Hoop wrapped and fully wrapped carbon composite cylinders and tubes for hydrogen 1,5 T of Hydrogen at 700 bar	
Hydrogen purity	**ISO 14687 / SAE J2719** compliance: *< 5 ppm water content*	➢ Polymer absorption ➢ Drying feasibility ➢ Vacuum/collapse resistance
Safety	Composite tube & trailer behavior in fire	➢ Fire: damage, Leak before burst ➢ TPRD ➢ Leak management & mitigation
Usage	Type V: smooth the differences with metallic behavior	➢ Filling/emptying + drying SOP ➢ Damage detection & inspection

Scope of the CH JU Call and objectives of ROAD TRHYP

Scope of the call :

- To develop and validate a solution to store in a trailer a **minimum payload of 1.2 ton** of compressed Hydrogen
- Working pressure **above 500 bar**
- The **solution should be cost competitive** compared to existing solutions reaching at least a cost of 600-650 €/kg of Hydrogen stored

Objectives of the project :

- # 1: Design *Type V tubes* according to EN 17339 and key performance & usage (filling/unfilling, drying, …) tests
- # 2: Elaborate a *decontamination methodology* to ensure H_2 purity → key parameters to have less than 5 ppm H_2O
- # 3: Demonstrate the *safety of Type V tubes* → Upfire test & modelling of tube behavior in fire - Safety aspect
- # 4: Demonstrate that a trailer made with Type V tubes will achieve the *expected KPIs in 2030* (*350* €/kg of GH_2 stored, > 500 bar WP, GC > 5 - 5,3 %) & *improved environmental impact*
  - → Trailer & demonstrator design
  - → Demonstrator testing to validate key features & modelling validation (filling/unfilling & upfire)
  - → TCO & LCA Type I, Type IV and Type V comparison
- # 5: *Formulation of the regulatory regulations* aiming at faster deployment of the technology

The Partnership

COVESS	Development of Type V tubes (330 l)
ARKEMA	Tape optimisation & manufacturing
SEGULA TECHNOLOGIES	Design of trailer & manufacture demonstrator, participates to the regulation study, the eco-design and the LCA
INSTITUT P'	Study the mechanical behaviour of tubes exposed to fire
Wrocław University of Science and Technology	Cylinder testing
ENVITEST	Is in charge of drying & filling/unfilling tests
Efectis	Is in charge of large scale fire tests and fire modelling
Air Liquide	Filling/unfilling tests & modelling, drying tests, standard and regulation study, TCO

ROAD TRHYP :

Technical Presentations

ROAD TRHYP

ROAD TRHYP
Mid Term Review

Type V composite tubes optimisation

« ROADTRHYP »

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Clean Hydrogen Partnership

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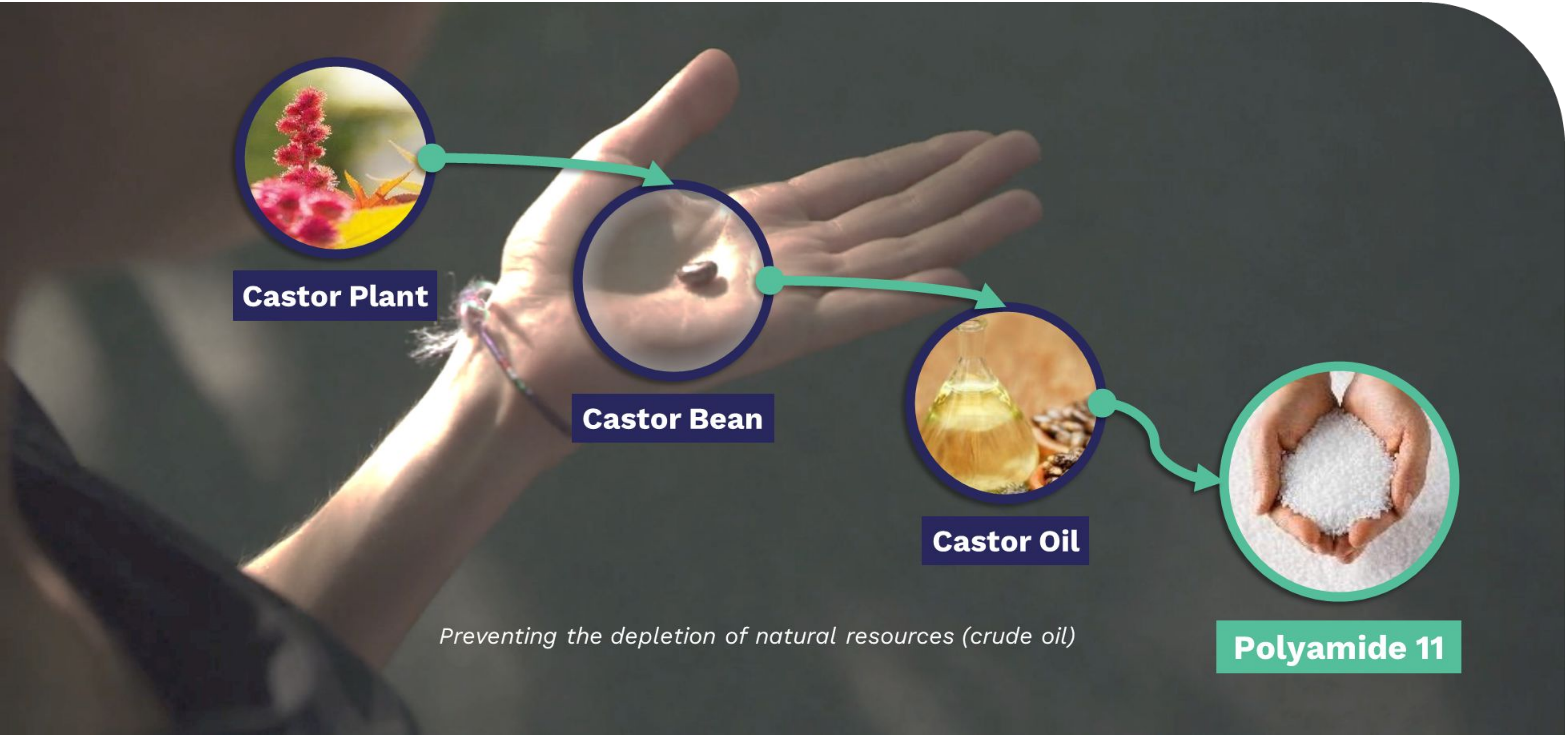
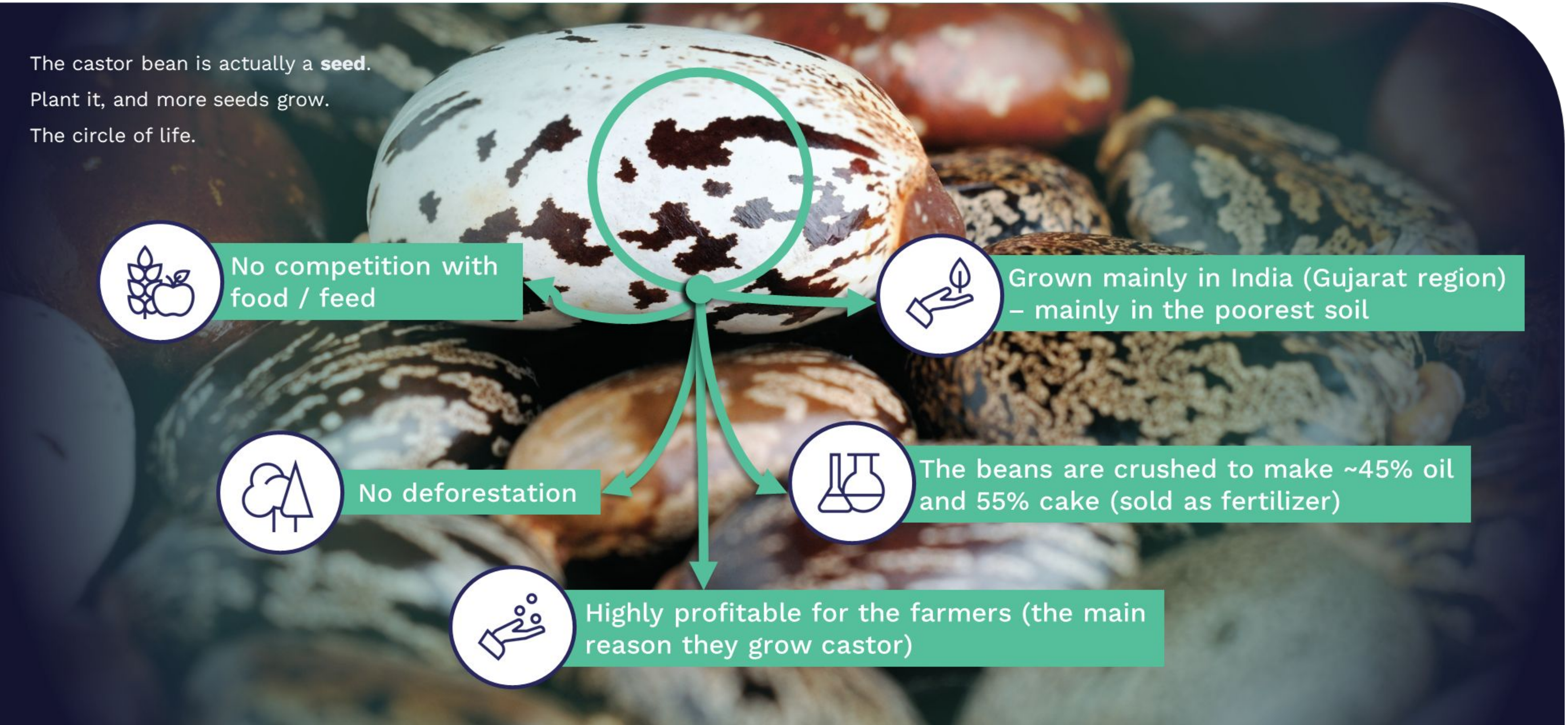
Air Liquide · Covess · Arkema · Wrocław University of Science and Technology · Efectis · Segula Technologies · Envitest · Institut Pprime

From castor bean to advanced polymers – A miracle of science



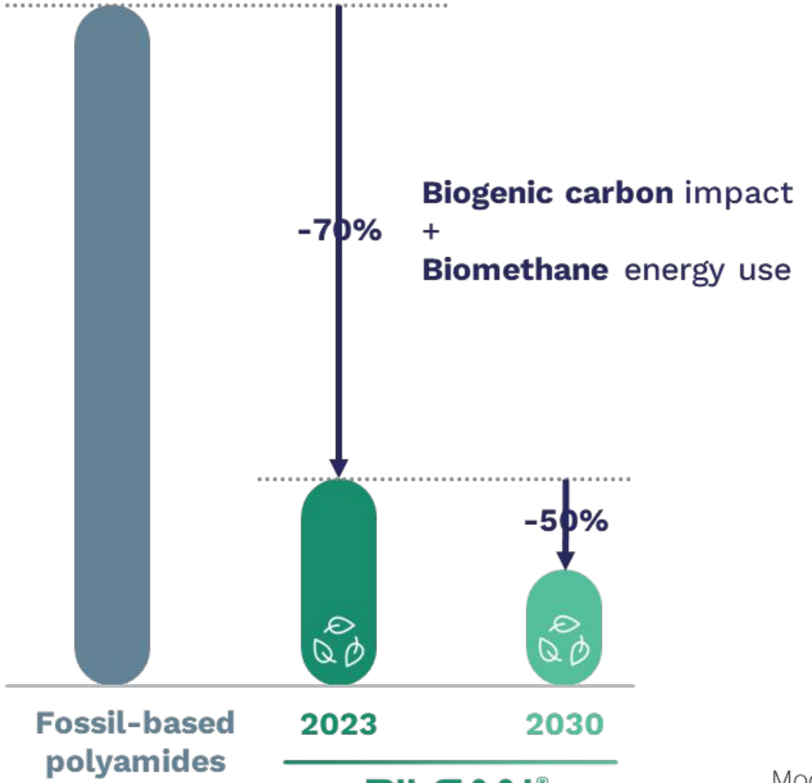
Castor – The magic bean



Climate Change Impact Reduction and Other LCA Benefits

Carbon footprint

(comparative data vs standard fossil-based polyamides)
Standard ISO 14040/44 (kg eq. CO_2/kg)



RILSAN®
Bio-based PA11

Model for Fossil Materials Based on use of Traditional Energy Sources

Rilsan® PA11's carbon footprint reaches < 2 kg CO2e/kg
- Applies to the entire global production (not limited to a selection of grades)
- Continuous action plan for further reduction by 2030

Agricultural land use
Castor grows best in marginal soils

Water depletion
Castor takes advantage of the natural rainy seasons

[1] **Sources:** Arkema internal LCA (Rilsan® PA11, PA12) and Plastics Europe (PA6.6, PA6)
[2] **Arkema also participates in driving the Pragati sustainable farming initiative which teaches efficient targeted irrigation methods**

Circular – “cradle to cradle”

UDX® tapes: High Performance Unidirectional Tapes for demanding Applications

UDX®

UDX® tapes by Arkema are **lightweight high-performance materials** made of unidirectional **continuous reinforcing fibers** and **thermoplastic polymers**

Thermoplastic

The polymer is bringing thermal and chemical resistance to the composite and is chosen among **Rilsan® PA11, Rilsan® Matrix, Kepstan® PEKK or Kynar® PVDF**

60%+ Fiber content

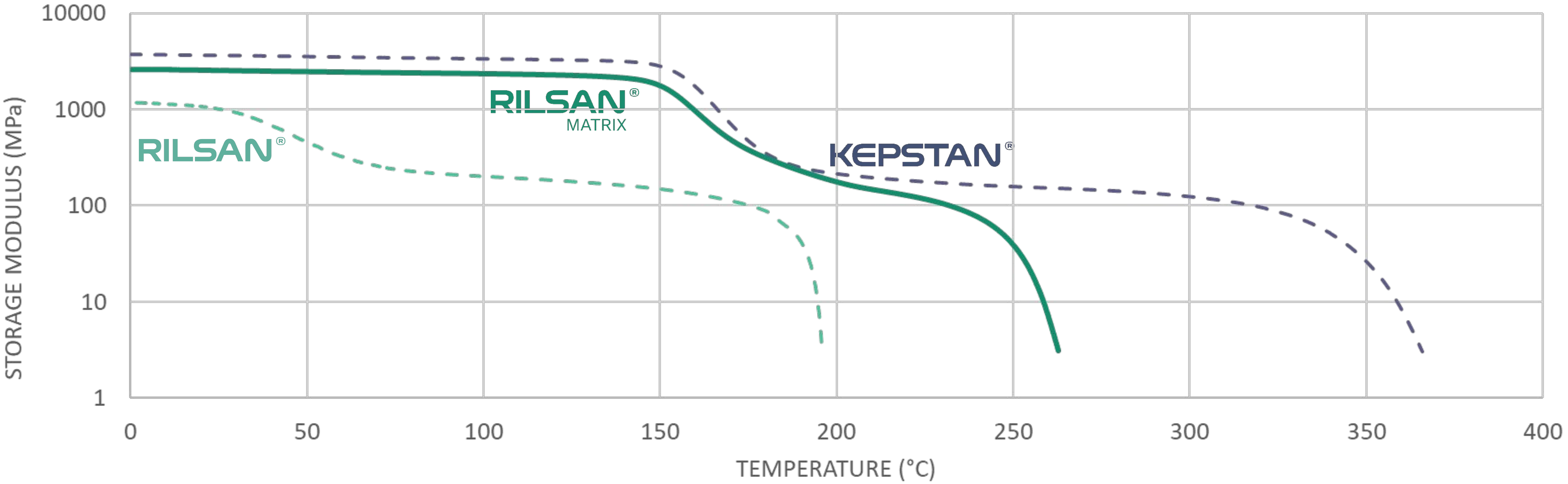
A high ratio of carbon fiber can be obtained (50% to 60%+ in volume) as well as very low areal weight depending on applications

Productive

High spools length and no slitting allows high deposition rates with limited losses

RILSAN® RILSAN® MATRIX

Our Very Unique Polymers for UDX® tapes



Rilsan® PA11

RILSAN®

- Biobased
- High chemical resistance
- Low melting point (< 190°C)
- High performance even at low temperature (<0°C)
- Low moisture uptake (2% at saturation)

Rilsan® Matrix PPA

RILSAN® MATRIX

- Partially biobased
- High glass transition temperature
- Low melting point (< 260°C)
- High mechanical performance
- Low moisture uptake (2,6% at saturation)

Arkema's Innovative Impregnation Process for UDX® tapes

→ Arkema has developed a very unique manufacturing method for UDX® tapes based on

- One tow = One tape technology
  - No slitting : No cut fibers, no material lost, higher performance
  - No splicing : Longer continuous spools
- The use of dry coarse powder
  - No water/solvent ≠ slurry process
  - Coarse powder ≠ slurry process
- High impregnation speed
- The use of highly performant polymers
  - Not impacted by high viscosities ≠ melt impregnation
  - Not limited in terms of fiber content ≠ melt impregnation

Arkema impregnation process for manufacturing UDX® tapes

Continuous 3500m / 10kg UDX® PA11 spool

→ Thanks to this technology, our UDX® tapes are meeting the technical and economic needs of our customers even using performant carbon fibers associated with high performance polymers

Mechanical Performance of UDX® PA11 tapes

UDX® PA11 COMPOSITES

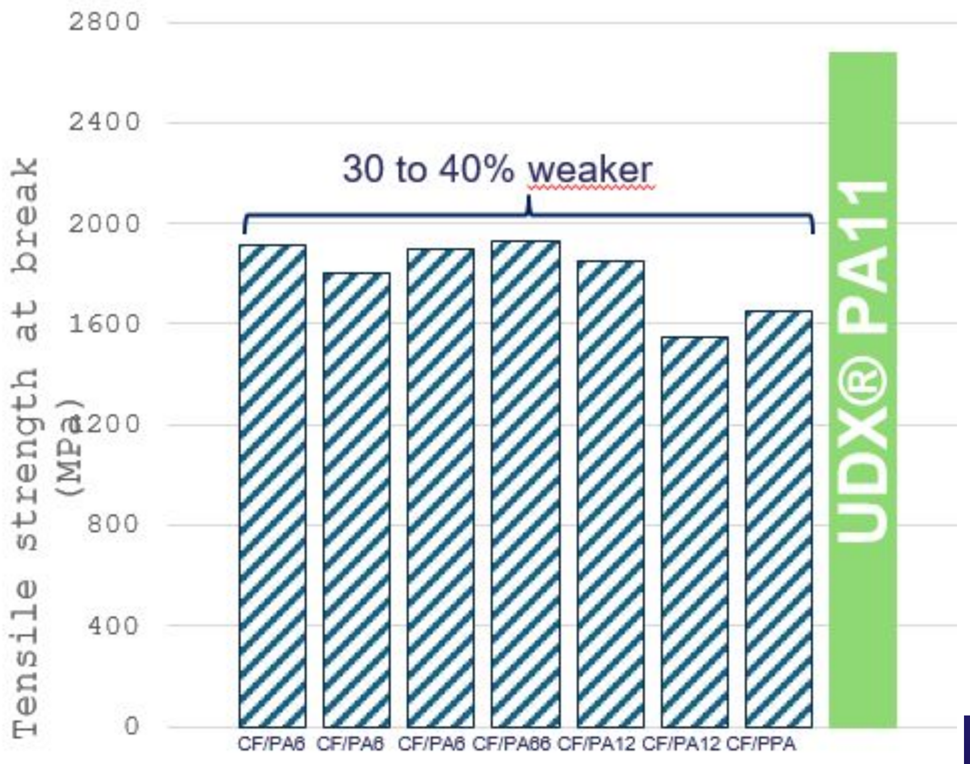
UDX® PA11 composites have been manufactured using tapes made of 57%vCF of 24k carbon fiber calibrated at 12.7mm in width deposited using ATL processing and autoclave post-consolidation.

All these mechanical data are highly dependent on the fiber volume content, fiber type, deposition and consolidation medias as well as the testing method.

UDX® PA11 TAPES	CONDITION	TEST METHOD	UNIT	MEAN VALUE
Glass Transition Temperature (Tg)	Dry	DMA	°C	50
Fiber content	From process quality control		%vCF	57
Tensile modulus (0°)	23°C, Dry	ISO 527-5	GPa	146
Tensile strength (0°)	23°C, Dry	ISO 527-5	MPa	2677
Flexural modulus (0°)	23°C, Dry	ISO 14125	GPa	121
Flexural strength (0°)	23°C, Dry	ISO 14125	MPa	1047
Shear modulus (45°)	23°C, Dry	ISO 14129	GPa	2.22
Maximum shear strength (45°)	23°C, Dry	ISO 14129	MPa	199
Shear strength at 5% shear strain (45°)	23°C, Dry	ISO 14129	MPa	35
Tensile modulus (90°)	23°C, Dry	ISO 527-5	GPa	5.93
Tensile strength (90°)	23°C, Dry	ISO 527-5	MPa	49
Flexural modulus (90°)	23°C, Dry	ISO 14125	GPa	5.73
Flexural strength (90°)	23°C, Dry	ISO 14125	MPa	108

High mechanical performance at 57%vol CF

- Tensile strength/modulus in fiber direction
- Higher than other tapes solutions



Other standards available (fiber type, content etc.)

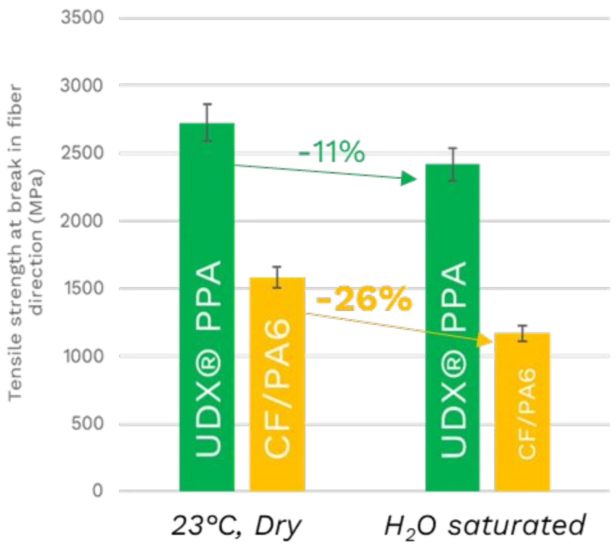
Mechanical Performance of UDX® PPA tapes

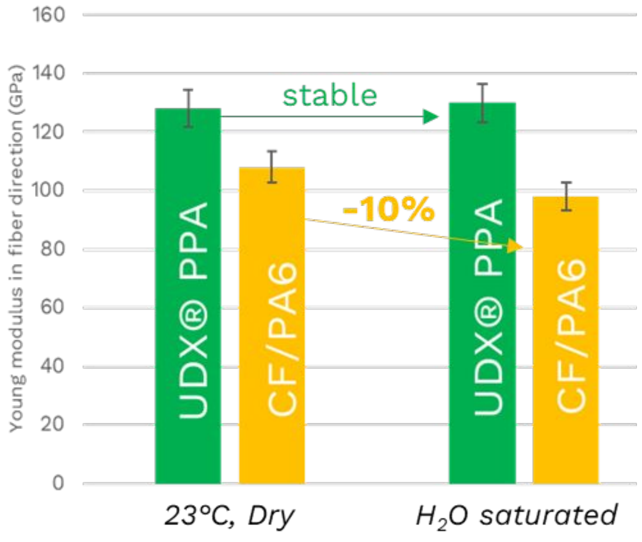
UDX® PPA TAPES	CONDITION	TEST METHOD	UNIT	MEAN VALUE
Glass transition temperature (Tg)	Dry	DMA	°C	163
Fiber content (%vCF)	From process quality control		%vCF	53
Tensile modulus (0°)	23°C, Dry	ISO 527-5	GPa	128
Tensile strength (0°)	23°C, Dry	ISO 527-5	MPa	2728
Tensile modulus (0°)	85°C, Dry	ISO 527-5	GPa	130
Tensile strength (0°)	85°C, Dry	ISO 527-5	MPa	2370
Tensile modulus (0°)	23°C, H_2O @70°C	ISO 527-5	GPa	130
Tensile strength (0°)	23°C, H_2O @70°C	ISO 527-5	MPa	2420
Flexural modulus (0°)	23°C, Dry	ISO 14125	GPa	110
Flexural strength (0°)	23°C, Dry	ISO 14125	MPa	1410
Shear modulus (45°)	23°C, Dry	ISO 14129	GPa	4.51
Maximum shear strength (45°)	23°C, Dry	ISO 14129	MPa	169
Shear strength at 5% shear strain (45°)	23°C, Dry	ISO 14129	MPa	48
Shear modulus (45°)	85°C, Dry	ISO 14129	GPa	2.7
Maximum shear strength (45°)	85°C, Dry	ISO 14129	MPa	135
Shear stress at 5% shear strain (45°)	85°C, Dry	ISO 14129	MPa	36
Flexural modulus (90°)	23°C, Dry	ISO 14125	GPa	6.21
Flexural strength (90°)	23°C, Dry	ISO 14125	MPa	65

Autoclave consolidated panels of UDX® PPA tapes

High mechanical performance at 53%vol CF

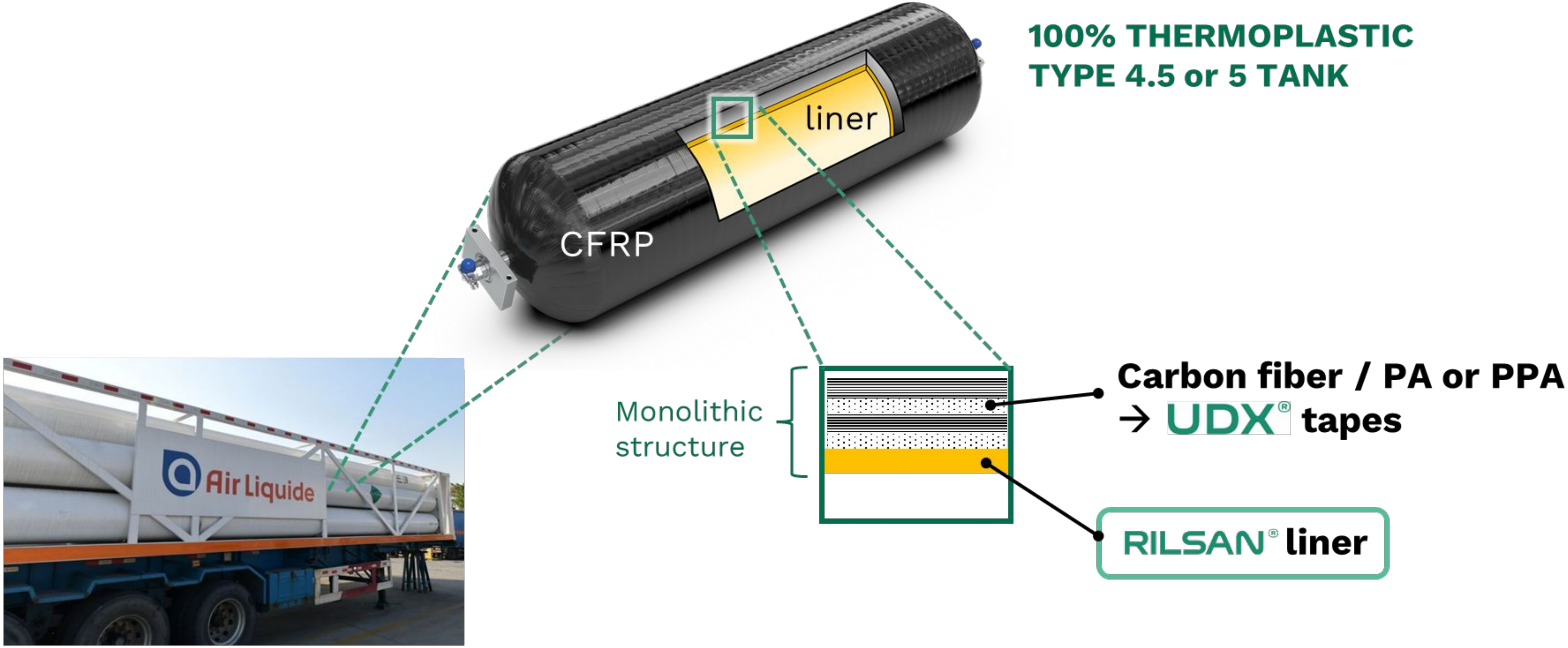
- Tensile strength/modulus in fiber direction
- Higher than other tapes solutions
- Less impacted by moisture uptake than other tapes





Other standards available (fiber type, content etc.)

Our Thermoplastic Solutions for Type 4.5 & 5 tank manufacturing



H_2 powered vehicle and/or for H_2 transportation

Type V cylinder development / performances (including usage)

Materials, Processing (equipment, energy waste,..), weight saving , Gravimetric index , Recyclablity

Content

- The Principal of the type V developed.
- The Unique Selling points (USP's) identified for the current commercial applications
- The production process
- Major developments which have taken place in covess in this project.
- Major USP's in use of a type 5 and a 4.5 compared to the state of the art.
  - Monolithic structure hence vacuum resistance.
  - Safety benefits with future development possibilities.
  - Fatigue performance
  - Barrier performance
  - Low Ecological footprint - Recyclability

ROAD TRHYP

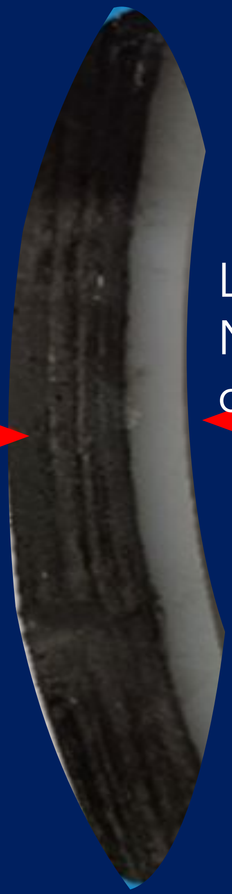
COVESS THERMOPLASTIC TANK TECHNOLOGIES

Clean Hydrogen Partnership

Co-funded by the European Union

Type 4 | Type 4.5 | Type 5

Outer reinforced layer



Liner No cohesion

Co-melted Liner

Similar base polymer for both layers cohesively "bonded/melted" into a unique thermoplastic monolytic composite structure

Co-melted barrier

Relevant unique selling points (USP's) of covess commercial type 5 low pressure applications.

- Unique safety behaviour
  - Leak before burst e.g : runaway heating installations
  - Safer failure mechanisme compared to thermoset
- Outstanding fatigue resistance (low variability) for thin glass fibre polyolefin reinforced structures with safety factor of 2.78 (**porosity level < 2%)**
  - After 300.000 cycles full retention of burst strength levels after cycling
- Vacuum resistance.
- Light e.g. usually even 30 -50% lighter compared to the composite cold water counter part mainly due to our monolytic structure
- Recyclable

The production process

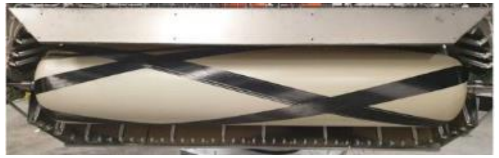
The process can be best described as a 3D composite printing process

A 3D composite printing process

- Covess process is a thermoplastic (TP) Unidirectional (UD) tape winding process with **a direct consolidation no post curing step** needed for a thermoset solution

- Over the years a significant Patent portfolio has been developed and is further expanding all the time covering all parts of this process.

The production process cntd.



Infrared oven multi feedback loop with camera's

Preheating the tape into melt

UD tape bobbin tensioning device

Detailed tension control for every bobbin

- Detailed temperature control is present, for **each layer of the tank**, over **multiple zones.**
- Current winding speed for the prototype line is in average 15 m/min - industrialisation will increase the tape laying speed upto 60 m/min.

Past en recent high pressure developments

In the period 2014- 2016 similar technology, first high-pressure achievement with type 5/60liter based on PA

During the Roadthryp-project 2023 -2025 below vessel of 330liter was produced as a type 4.5 structure

Failure at 444 Bar

G.I = 3.2%

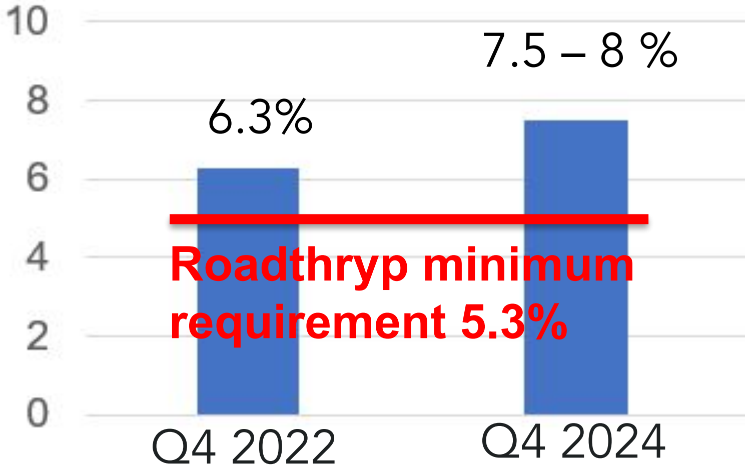
Weight 27 kg

Mid-long term true potential.

G.I. > 10

Increased Storage efficiency (G.I. index times 2.34

Gravimetric Index (G.I.)



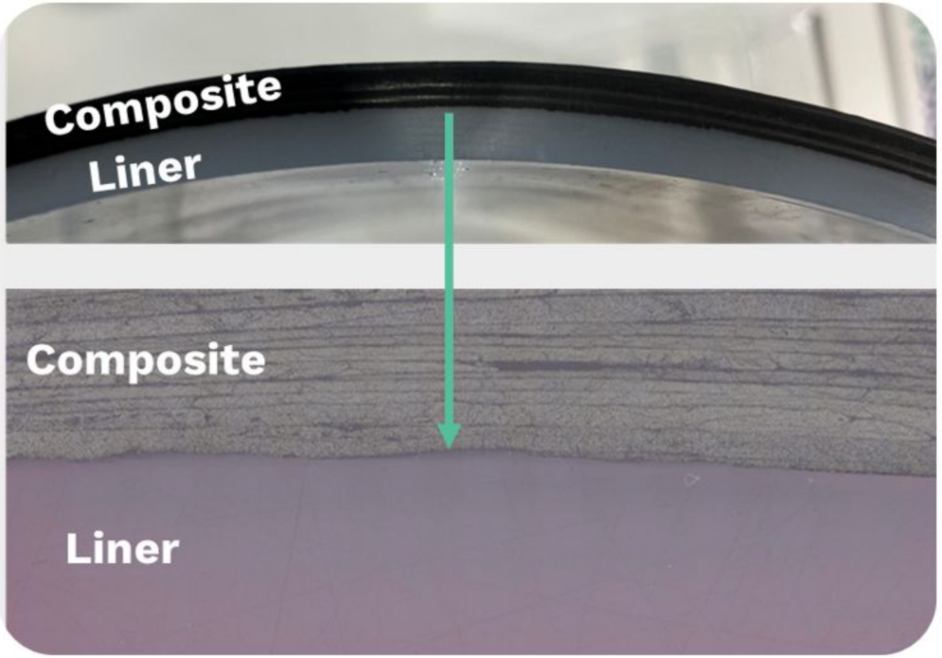
Latest failure at 733 Bar

G.I = 7.5 – 8,0 %

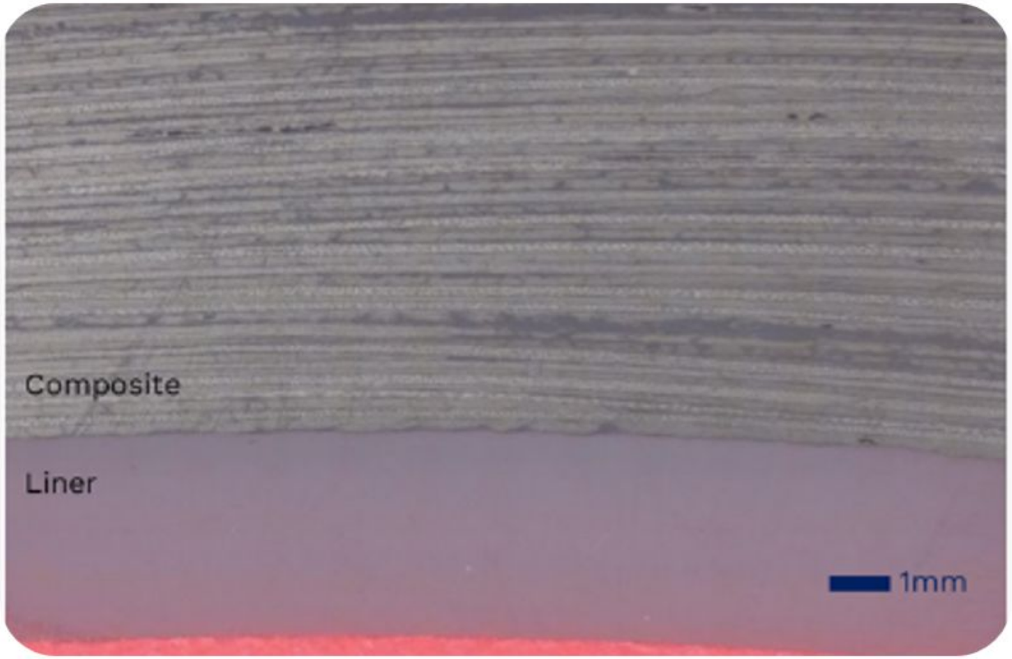
Monolythic structure for 4.5 and 5

→ Type 4.5 tank example - PA 11 based

- Cohesion remains even after burst test performed : **Strong cohesion**
- High UDX® PA11 tapes **in-situ consolidation level**
- **Low void content**



No burst test performed



Burst test performed (700bar)

First surprising bonfire testing results

It was always believed that a thermoplastic structure would not survive a bonfire experiment

Temp., pressures monitored internally and externally

First bonfire testing

Before

Initial start up

TPRD start up

Tank after test still gas tight

Second bonfire testing same tank

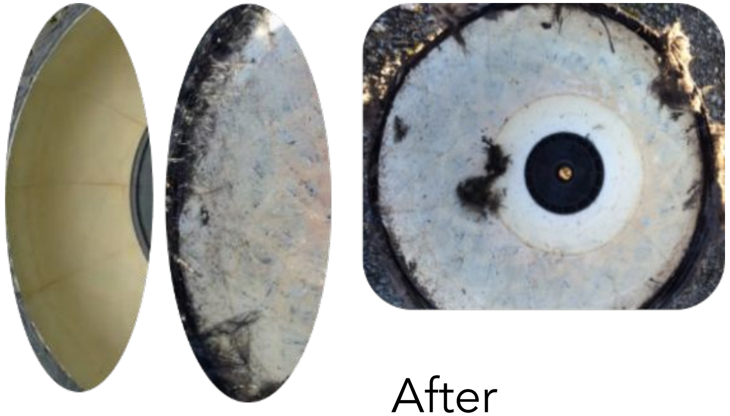
7 additional min. no safety valve

No explosion observed

Observations

- Internal temperature reached the melting temperature of the inner barrier
- Unique monolithic structure delivered Isotropic multi gas leakages popping up - preventing an explosive situation

Before



After

USP identified for our high pressure type 5 applications and some consequences in use.

USP's of the COVESS tank process technology compared to Type 4:

- No curing process
  - No curing means no additional micro-voids introduced in the structure.
  - No issues like a curing gradient over the cross section of the reinforced tank structure

Consequences:

- A low void structure < 3 %
- Lower variability in performance + better expected fatigue performance.
- Better barrier performance very low permeation rate
- Higher impact performance

Consequences for the transportation application

- Longer live time expected in use. For the current low-pressure type 5 commercial applications 150.000 pressure cycles and full retention of the burst pressure after cycling is really basic performance.

USP identified for our high pressure type 5 applications and some consequences in use.

- Monolithic structure

Consequences:

- Integrated fused inner liner (type 4.5) barrier (type V) – no collapse / blistering possible
- Better barrier performance very low permeation rate
- Vacuum resistance
- Higher reliability because less assembly arrangement

Consequences for transportation en production:

- Faster decontamination\drying possibilities.
- Opportunities for faster filling and emptying (higher then 85 degC)
- Vessels do need only a very low pressurization level when not in use.

i.e. behaving much more like steel tanks, but 5 times lighter.

Other USP 's cntd.

- Light weight result (Gravimetric index (G.I.) 7.5 – 8.0%). Burst pressure data are now fully validated. Next step cycle testing and getting certified asap. A very low ecological footprint solution - recyclability + e.g. use of Biobased polymers like PA 11

Outlook for the near future:

- Potential further improvement areas for the following generation tanks are already identified.
- Our Type V tanks have the definite potential to become the lightest compressed gas tank in the market with a G.I. > 10%
- Very high safety features possible i.e. explosion proof design possibilities also referred to as self-venting tanks

Consequence for the transportation market:

- Faster acceptance in the market for the use of Hydrogen as an Energy carrier

Trailer Design & Demonstrator

Participants:

AIR LIQUIDE
SEGULA
ARKEMA
EFECTIS
ENVITEST
COVESS

AGENDA

1. Technical Requirements
2. Concepts
3. Ventilation & Fire Protection
4. Trailer Design
5. FEM/FEA
6. Manufacturing
7. Demonstrator Status

1. Technical Requirements

- Trailer + Tractor max. weight = 40t
- Hydrogen tubes in vertical position
- Hydrogen weight - 1.2T, 500 bar and a cost of 400 €/kg H2 – end of project
- Target hydrogen weight - 1,5t/700 bar/2030
- MEGC - 40 ft long container
- Sections with a maximum capacity of 5 000 L
- Gas cabinet at the back of trailer
- Max. height of system - below 4m
- Nominal temperature range of +45°C ... -20°C
- 316L or 316 quality stainless steel for MEGC construction

2. CONCEPTS - 2 base approaches

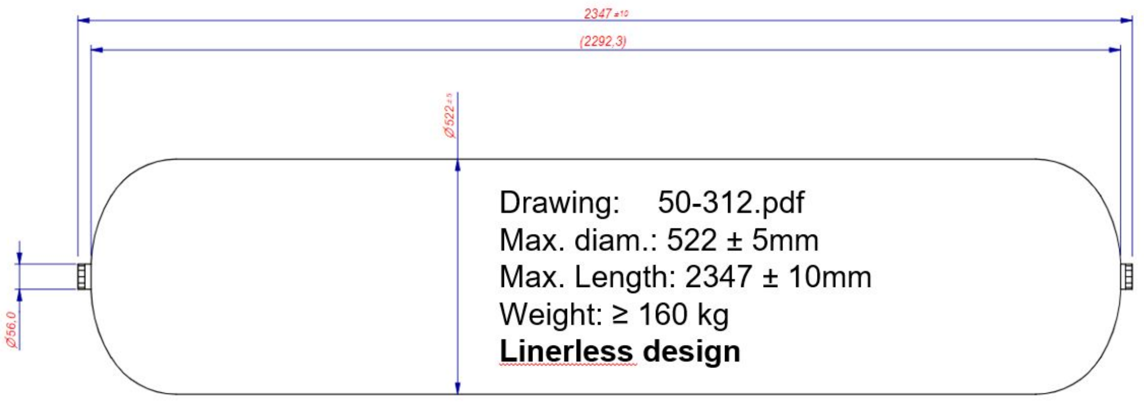
OPEN FRAME STRUCTURE - elements of the structure are loaded in tension-pressure, torsion is transmitted by diagonal reinforcements

PRO	CONS
Simple, cheap & light design	Protection of tubes (stones, etc.)
No ventilation needed	Protection against fire
Good inspection possibility	Tubes are in outdoor conditions

CLOSED, SHELL STRUCTURE - bending is transmitted through the walls, floor and ceiling, torsional stress is transmitted by the shear flow in the walls of the structure

PRO	CONS
Better protection against fire	Ventilation needed
Better protection against stones	Bad inspection of systems
Tubes are in indoor conditions	More complicate design

2. CONCEPTS - Hydrogen Tubes - MEGC Type ?



Used for Trailer Design Nr.: I. – V.

Material: Carbon Fibre/PA11

This data means higher protection of hydrogen tubes, which is why it was decided to use a closed MEGC and not an open frame system. Advantages:

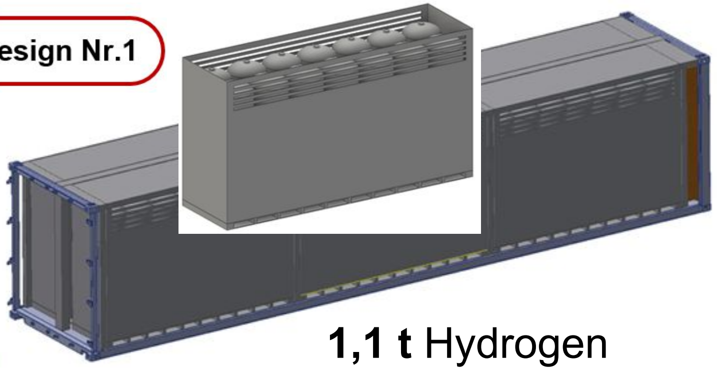
- Closed box as a sunshield (white outer paint w/ good ventilation)
- Reduced exposure to water, snow, dirt, stones and UV radiation
- Ablative layer (fire protection) is a good thermal insulation - smaller thermal gradient on the tubes
- Light-weight design of metal structure

Used for Trailer Design Nr.: VI.

- Wall thickness: 50mm
- Length: 2581 mm
- 533 mm O.D.

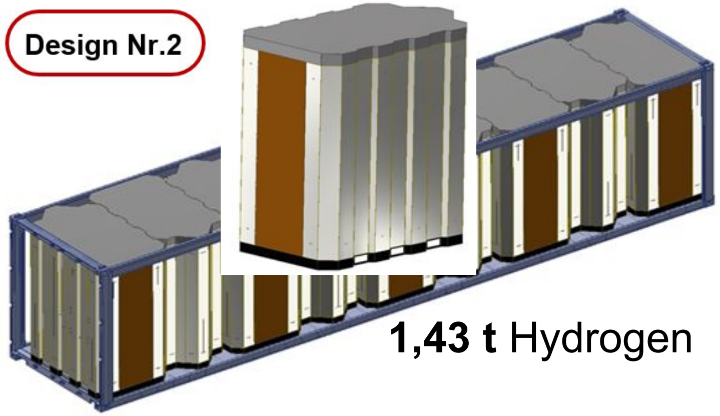
2. CONCEPTS - 40 ft MEGC/700 bar

Design Nr.1



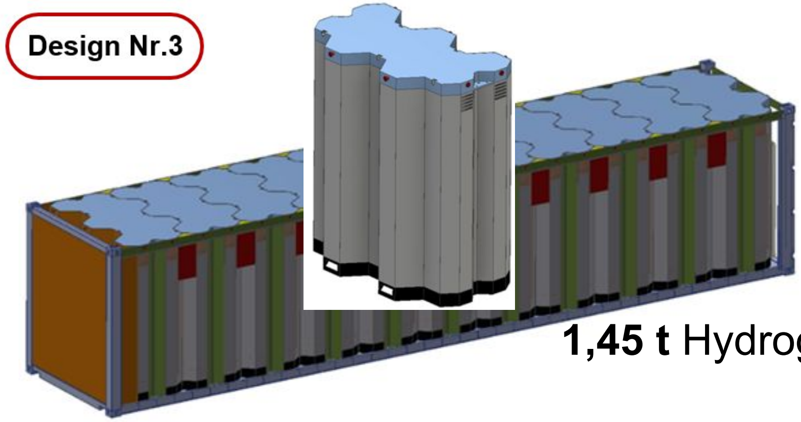
1,1 t Hydrogen

Design Nr.2



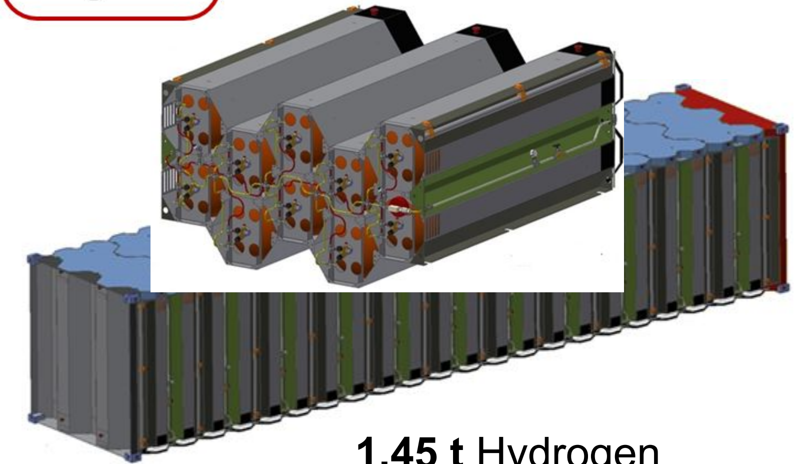
1,43 t Hydrogen

Design Nr.3



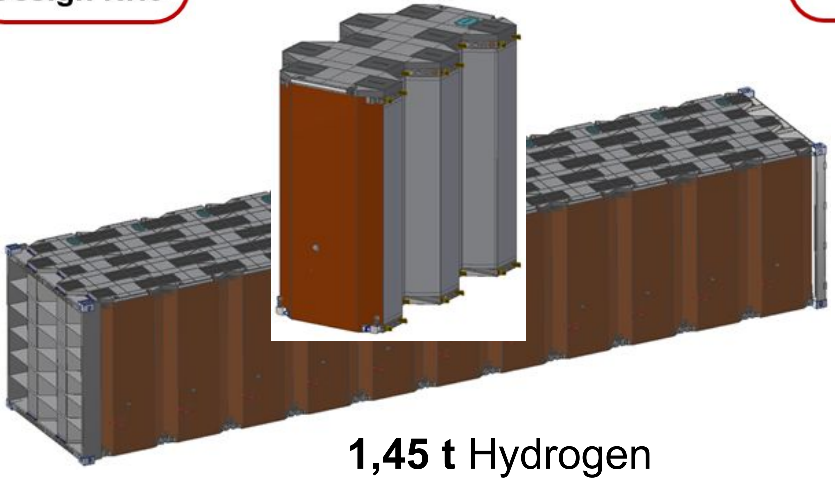
1,45 t Hydrogen

Design Nr.4



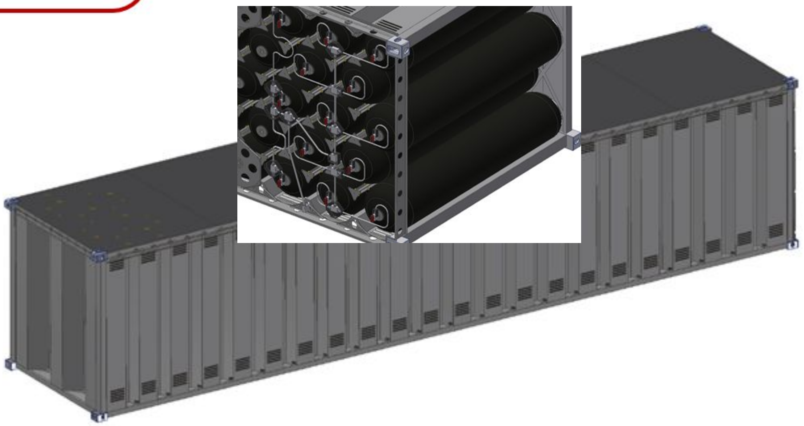
1,45 t Hydrogen

Design Nr.5



1,45 t Hydrogen

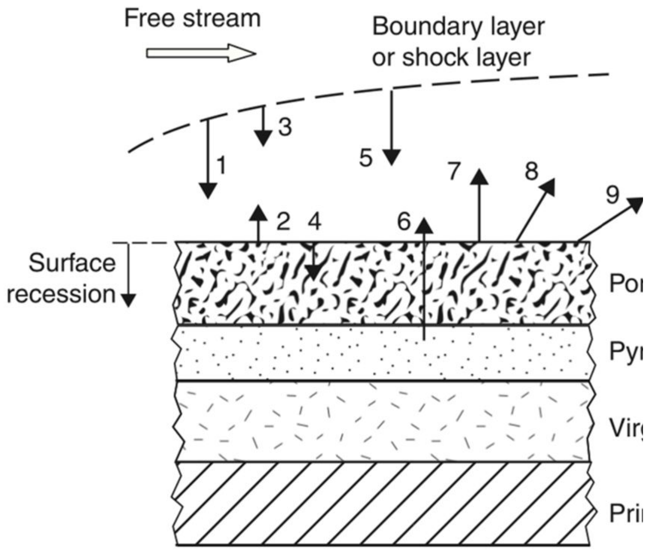
Design Nr.6

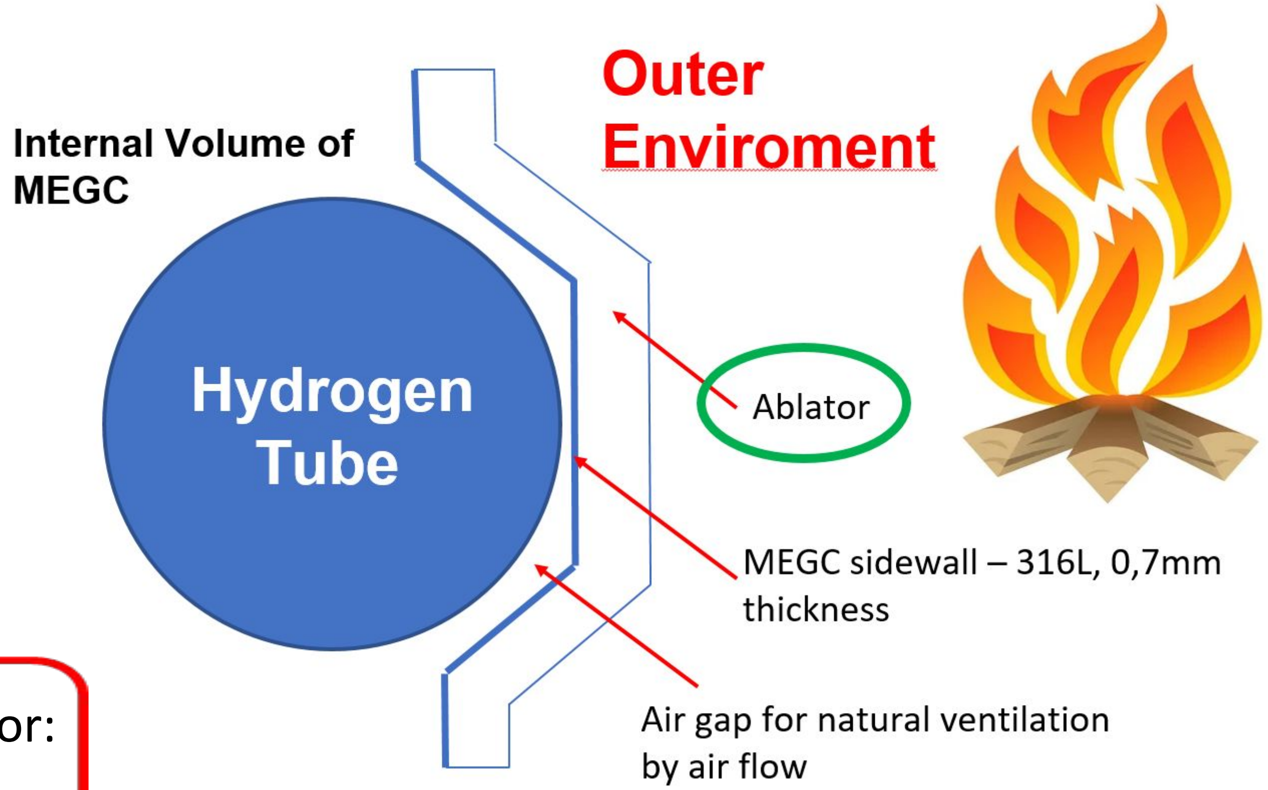


1,48 t Hydrogen

3. VENTILATION & FIRE PROTECTION - ABLATORS

- A resinous matrix that forms the char layer. Silicone, epoxy resins and phenolic resins
- A gas-generating component such as nylon, cork, etc.
- A reinforcement component, like fibres, microballoons, silica & alumina
- Fillers, like silicon dioxide, carbon black and expanded perlite





Characterization of critical properties:

- Char yield (high)
- Thermal conductivity (low)
- Glass transition temperature (high)
- Mechanical property (high)

Weight of Ablator: **353 kg**

evaporation rate of about **0.02 mm/s** in order to have the duration of protection for at least another 10 minutes.

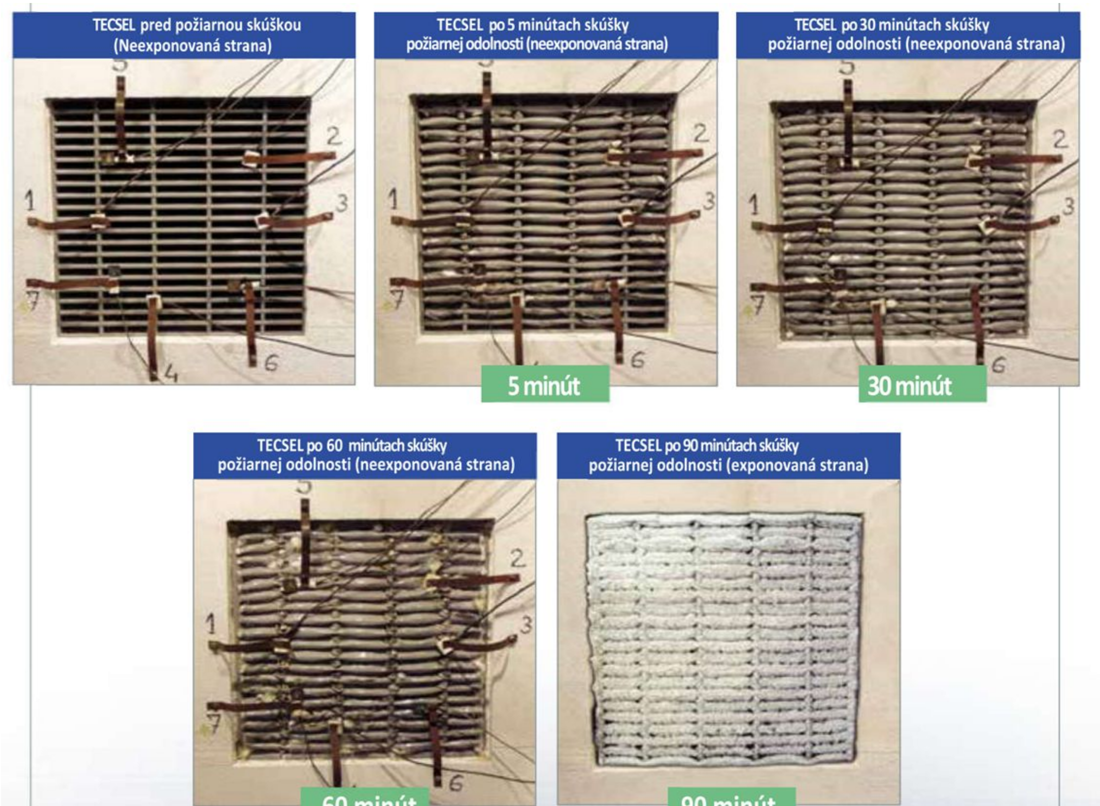
additional **7€** on 1 kg of transported gaseous hydrogen

Commercial Products
Passive

WING fire damper

- Not allowed to dust, gases, caustic vapors and other aggressive chemical
- are not affected by direct sunlight and UV radiation
- No vibrations allowed

Expandable foam system



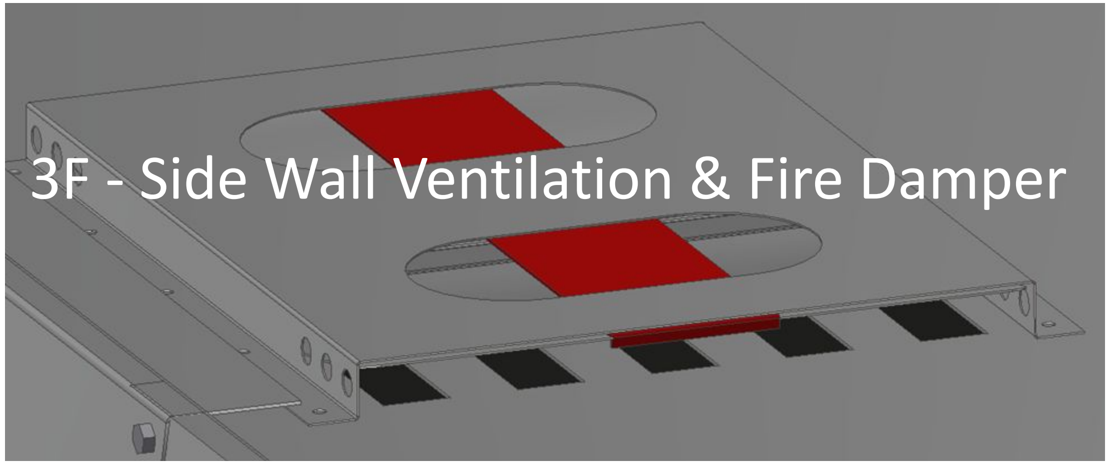
- For indoor use only
- avoid contact with water and sustained temperatures above 40°C
- Very slow reaction time

3. VENTILATION & FIRE PROTECTION - FIRE DAMPERS

NEW, Innovative Aproach

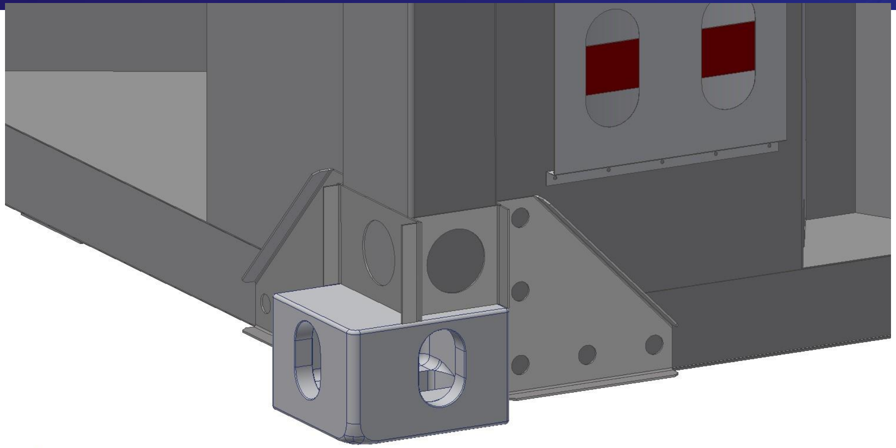
Passive

But lower TRL (=2)

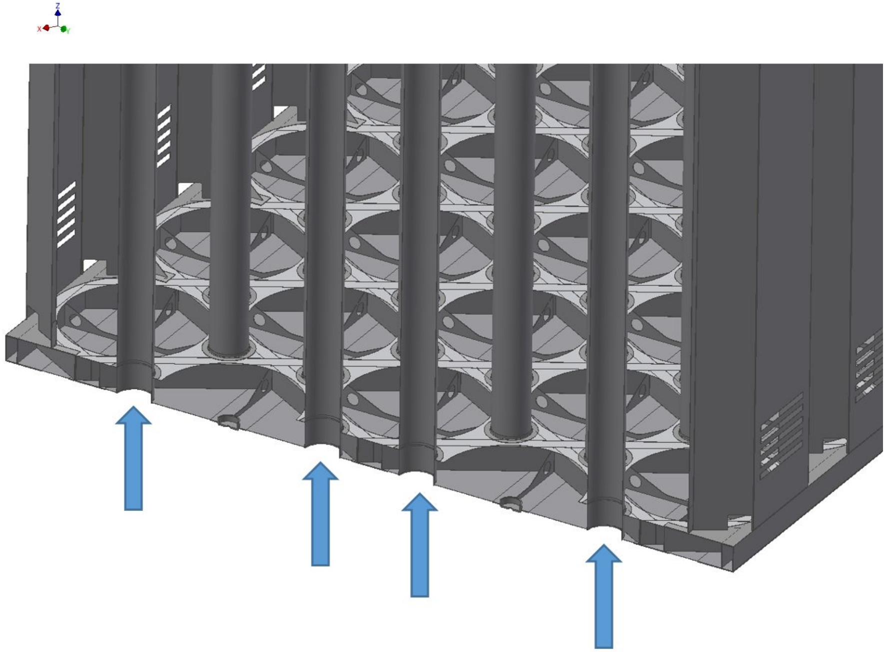


3F - Side Wall Ventilation & Fire Damper

- Allowed to dust, gases, caustic vapors and other aggressive chemical
- Can affected by direct sunlight and UV radiation
- Vibrations allowed
- Cheap product



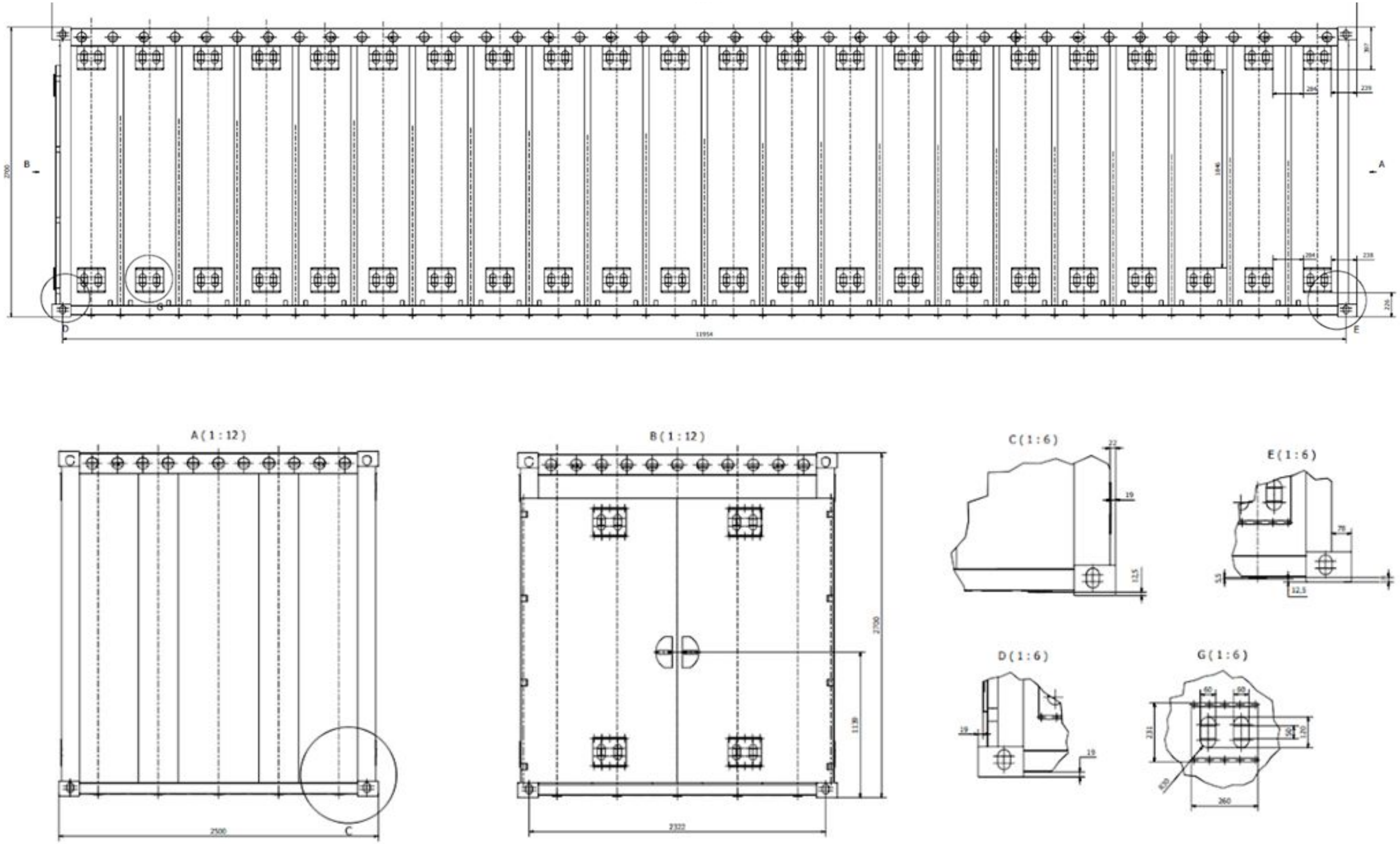
250 fire dampers

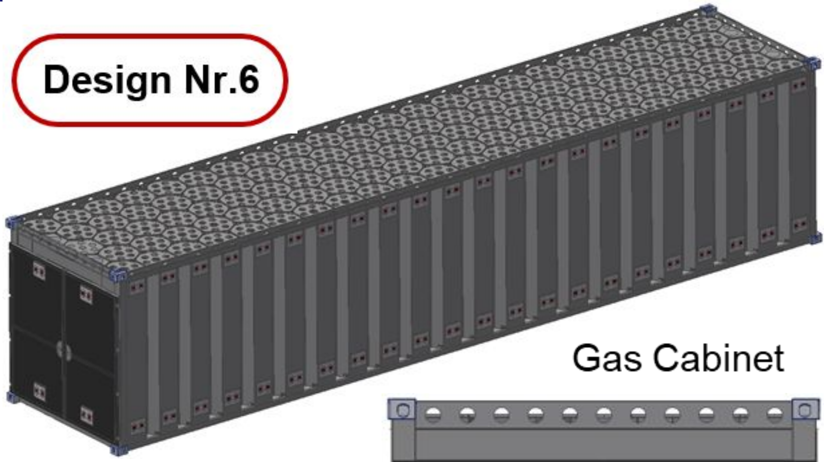


Bottom Ventilation & Fire Damper

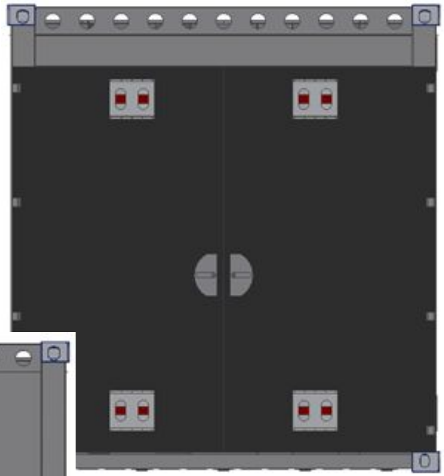
- For indoor/outdoor applications
- Operational temperature: -70 to +60°C(or more)
- Shorter reaction time
- Cheap product

4. Trailer Design - MEGC Structure

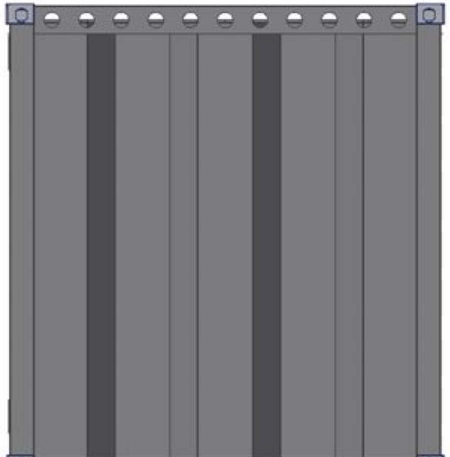




Gas Cabinet



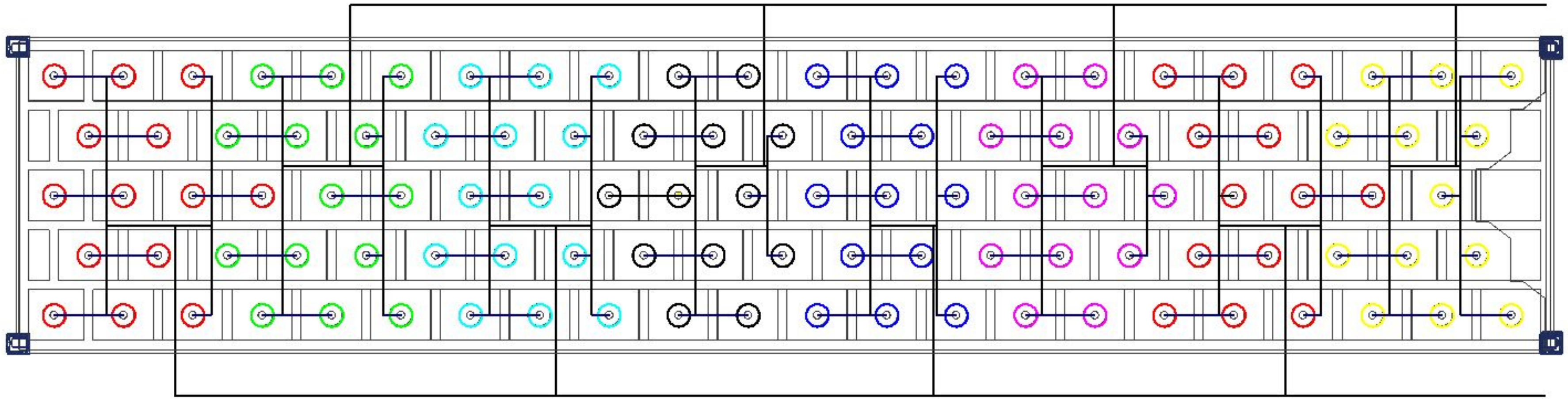
Front Side



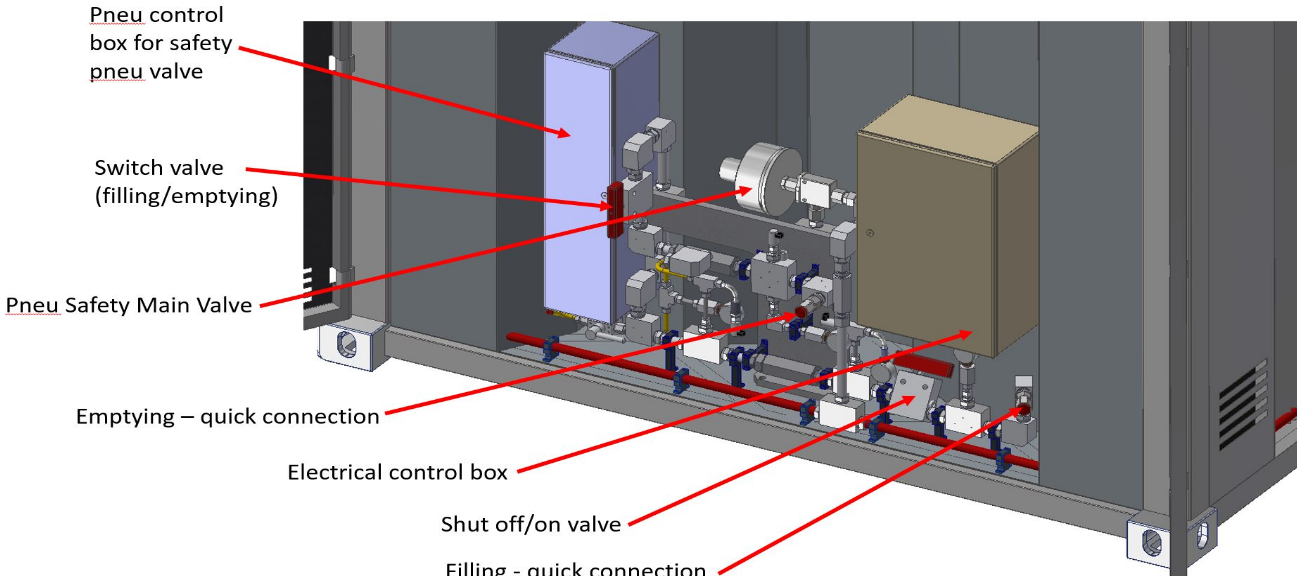
Pallet-Size Container - 40 ft length

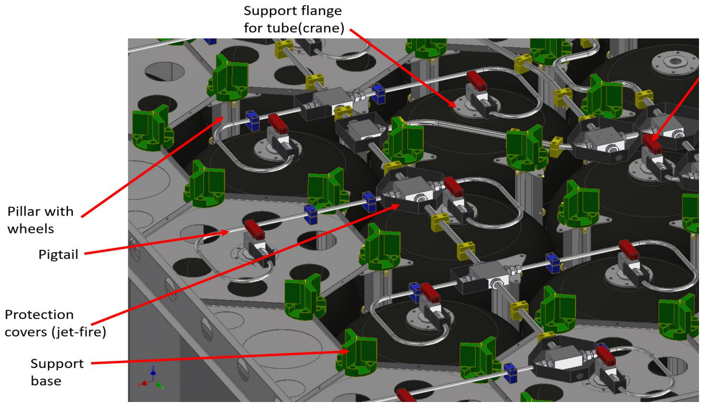
4. Trailer Design - gH2 Distribution

MEGC sectioning (Pneu system):



- Total weight of gH2 distribution system is estimated on **650 kg** (Swagelok systems w/ jet-fire protection on each joints, piping)
- Significant weight reduction is potentially achieved by using welded elements (with the removal of the jet-fire protection system)

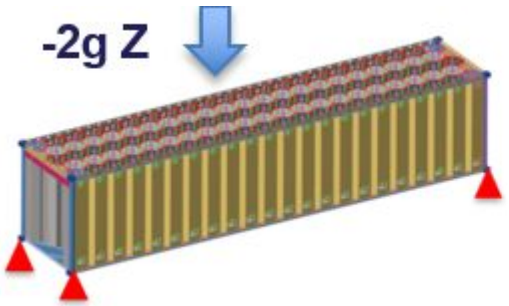


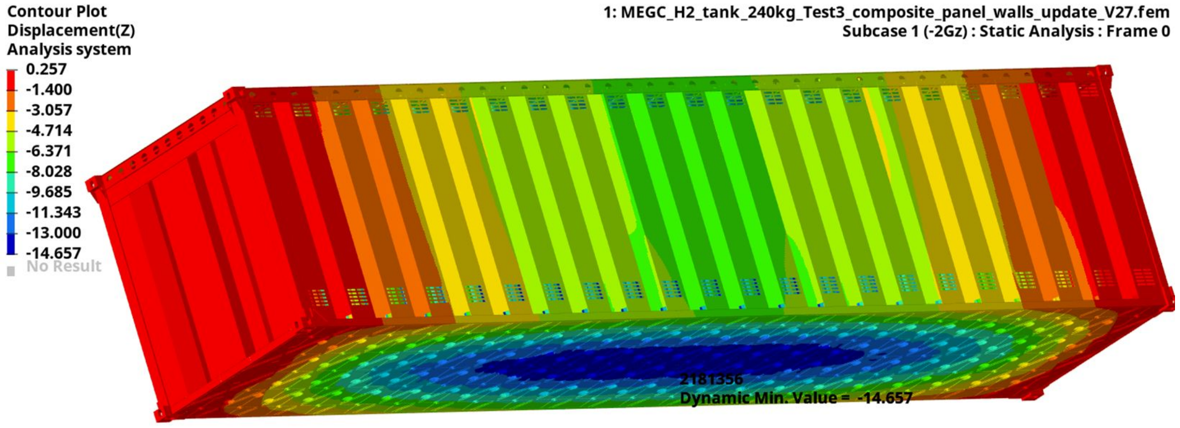


107 tubes

5. FEM/FEA - Displacements: ISO – 1496-1(2013E)

2g Vertically Upward



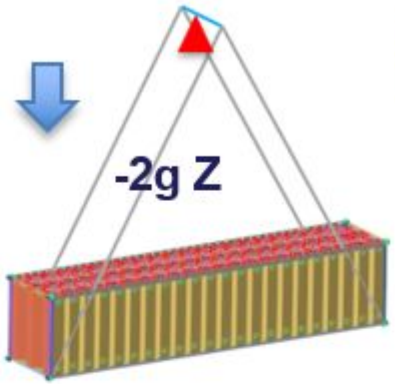


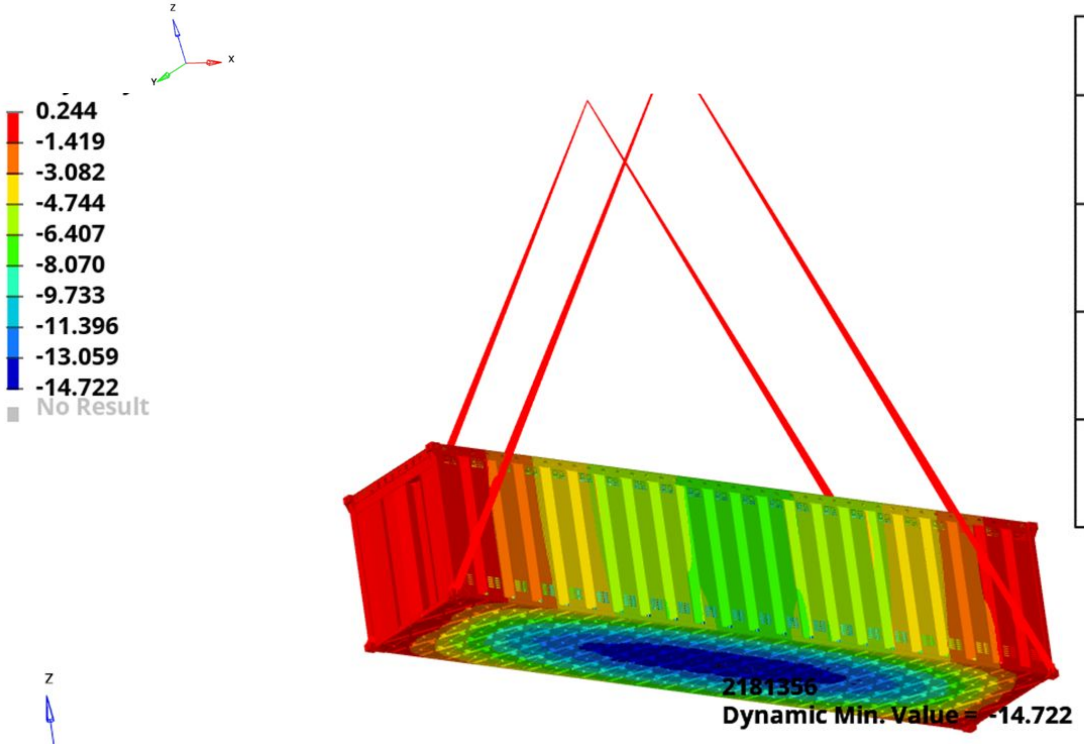
Max. displacement = **14,657 mm**

ADR2023:

Requirements	To Simulation
2g longitudinally	-2Gx
2g vertically upward	+2Gz
1g laterally	+1Gy
1g vertically downward	+1Gz

Crane - bottom clamp



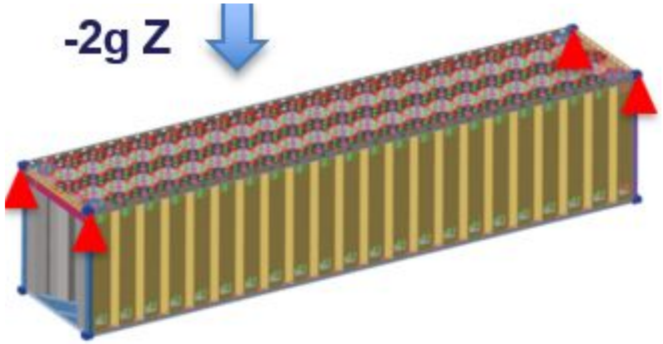


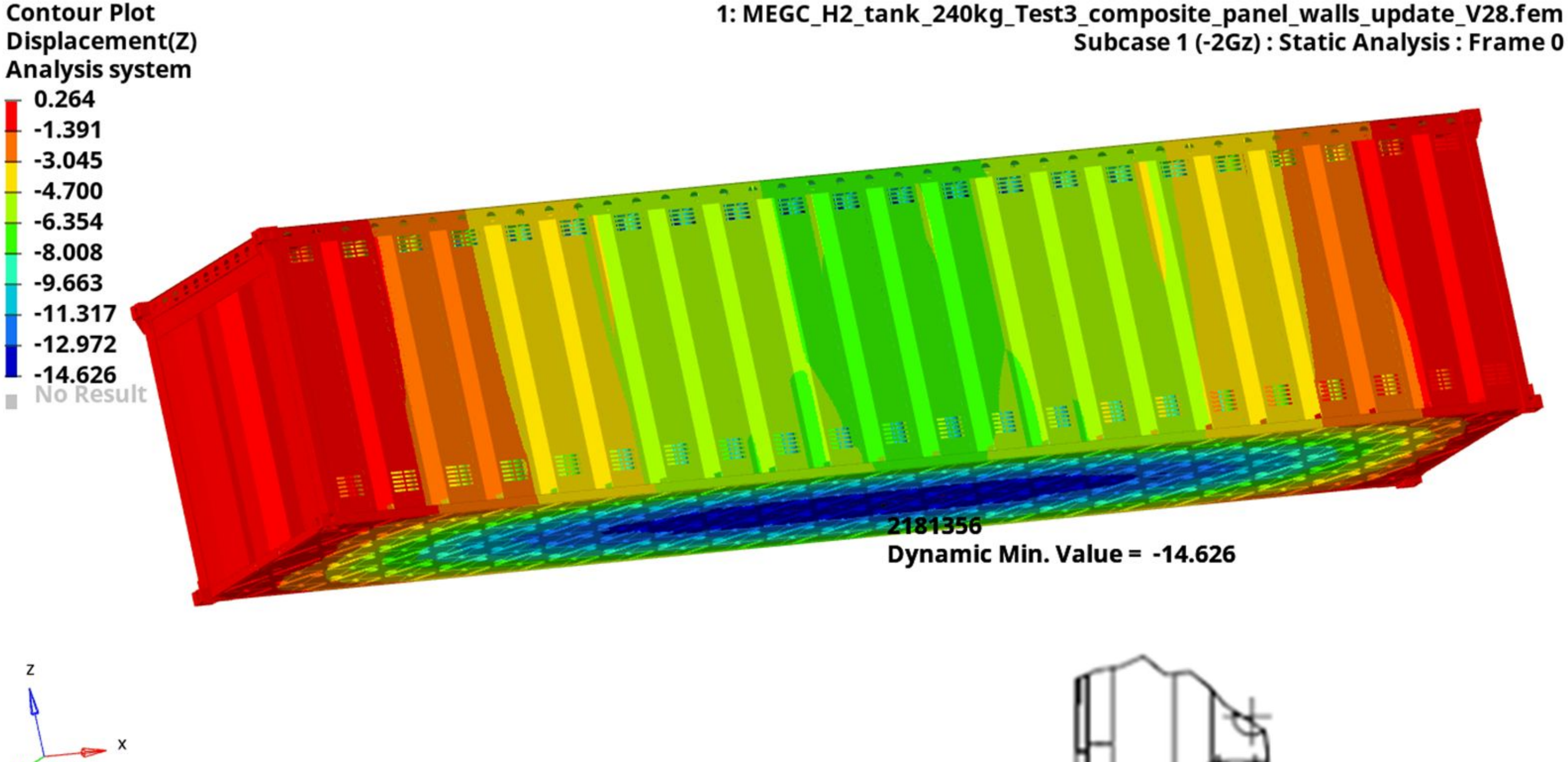
Max. displacement = **14,722 mm**

5. FEM/FEA - Displacements: ISO – 1496-1(2013E)

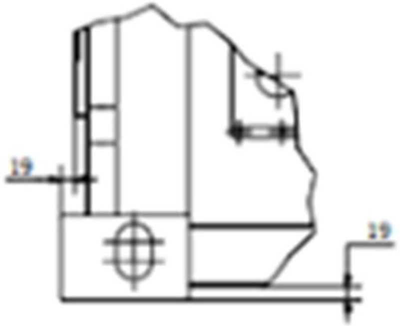
Crane - upper clamp

Max. displacement = **14,62 mm**

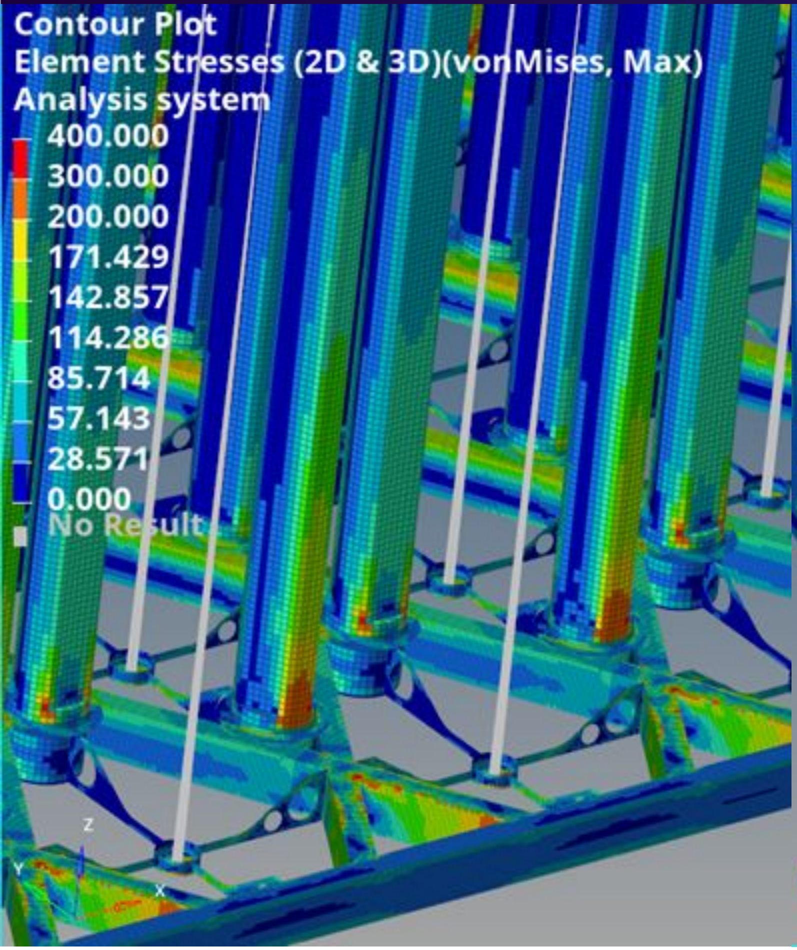


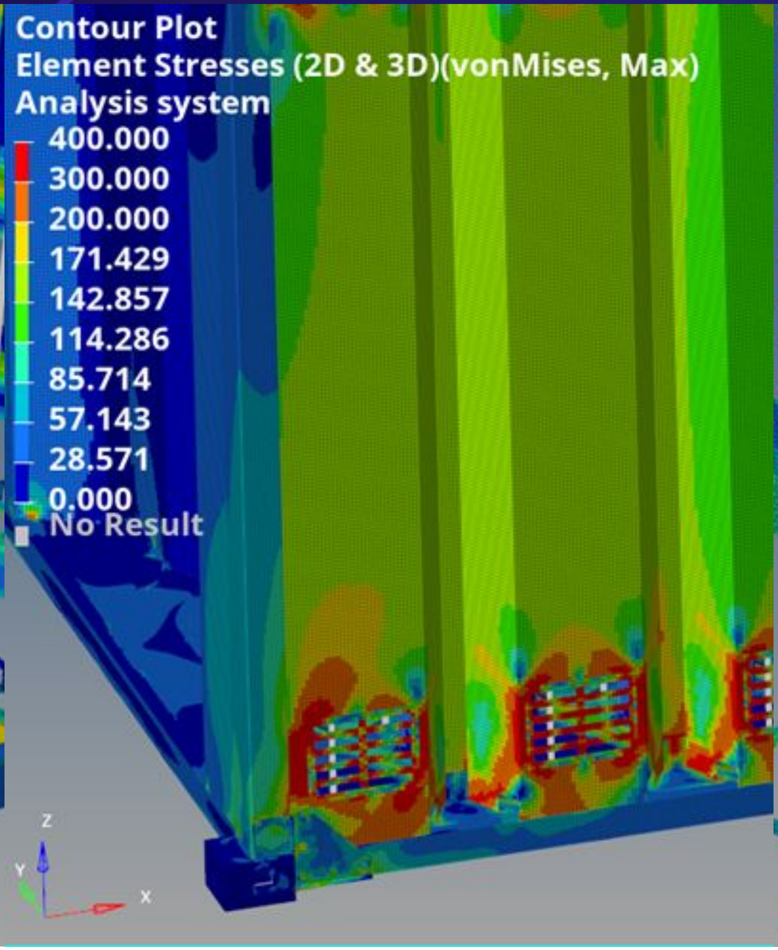


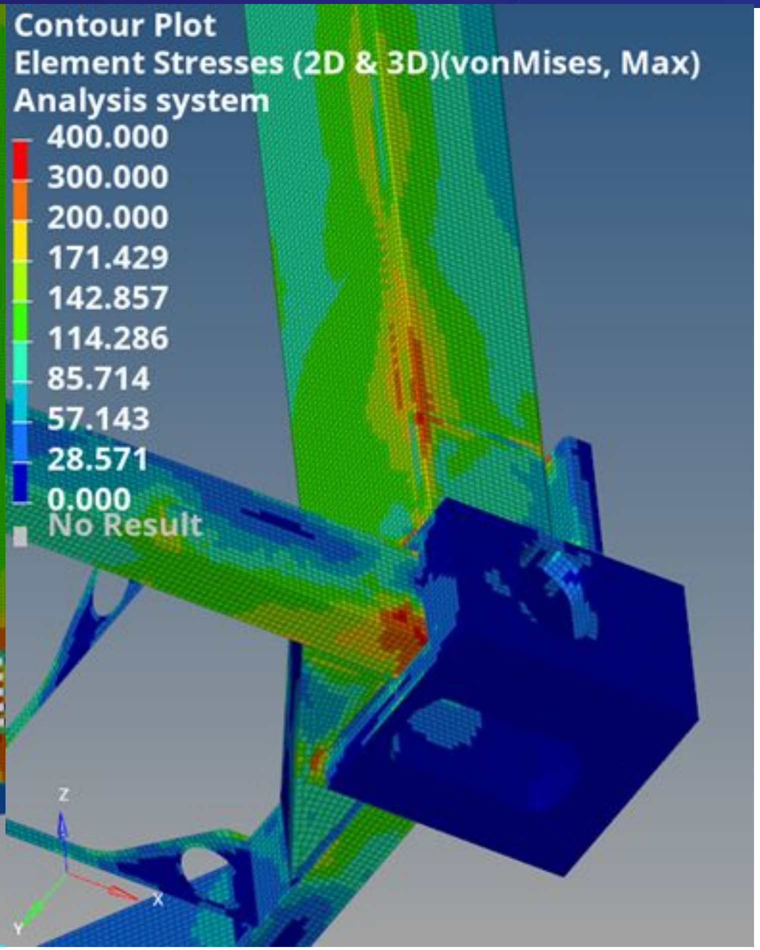
The container bottom floor plate can deflect not more than **6 mm** below the base plane (bottom faces of the lowe cube corner) - max. allowable deflection is 19+6=**25 mm** (standard).



5. FEM/FEA - Stresses





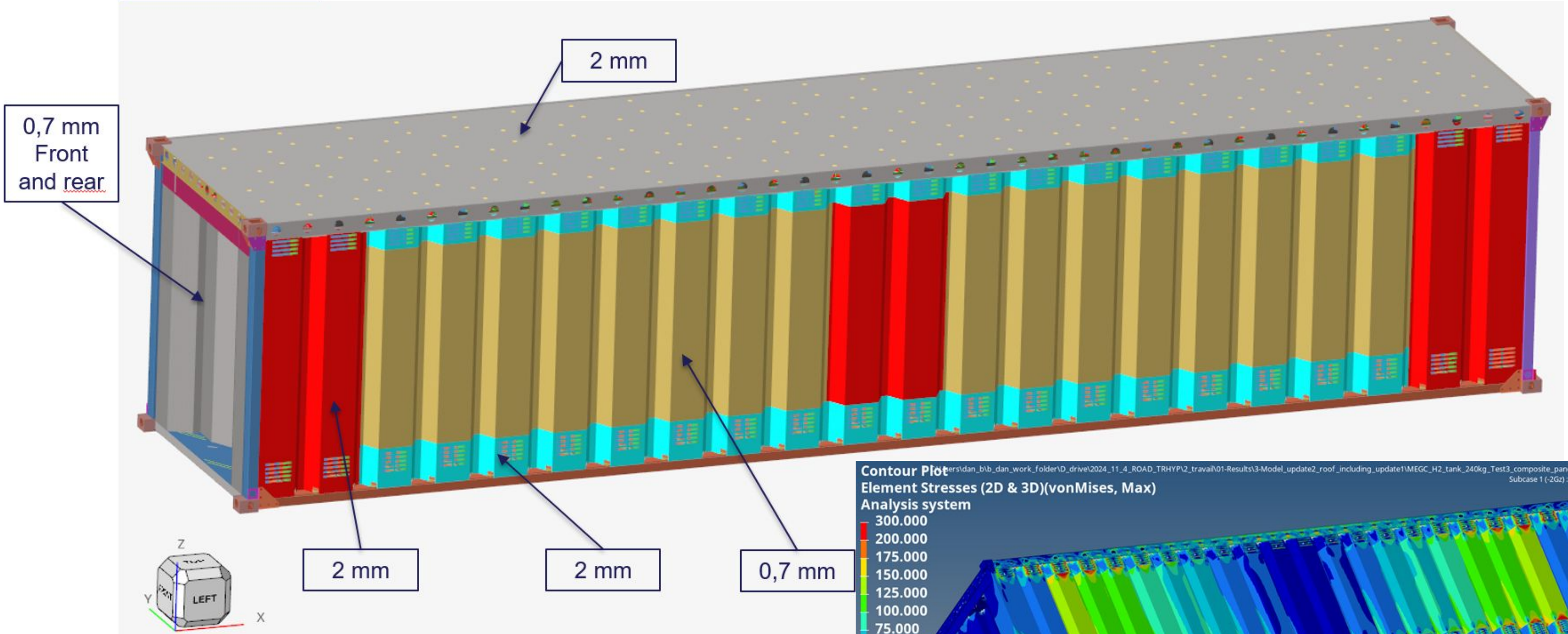


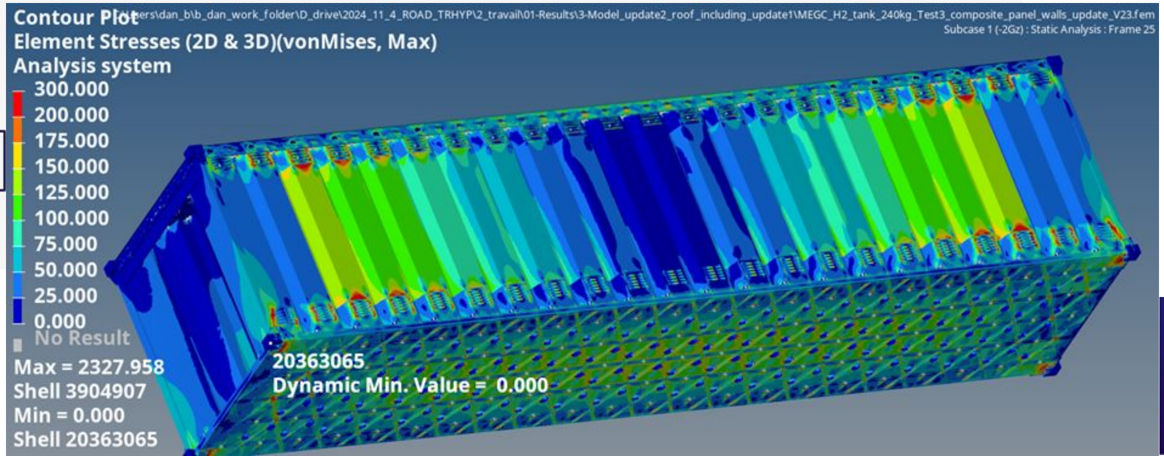
The main problem: Coefficient of safety for **yield strength = 1.5**

- Stainless steel 316L - Yield strength -Re= 300 MPa , using safety factor 1,5 - the allowed max value is **200** MPa
- The only way to deliver a MEGC that has at least no issues on the main structure (small issues on panels to be addressed later with the manufacturing process for industrialisation) is to limit the tanks weight to **200 Kg**

5. FEM/FEA - Recommendations

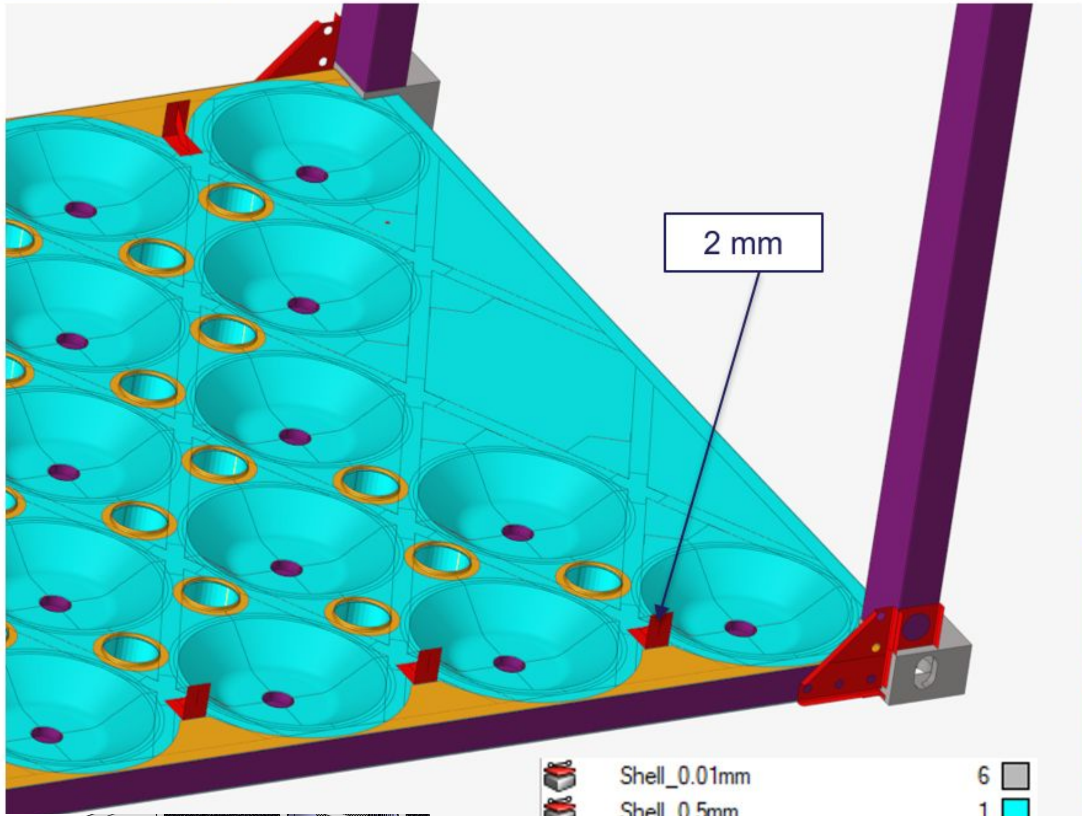
Component view

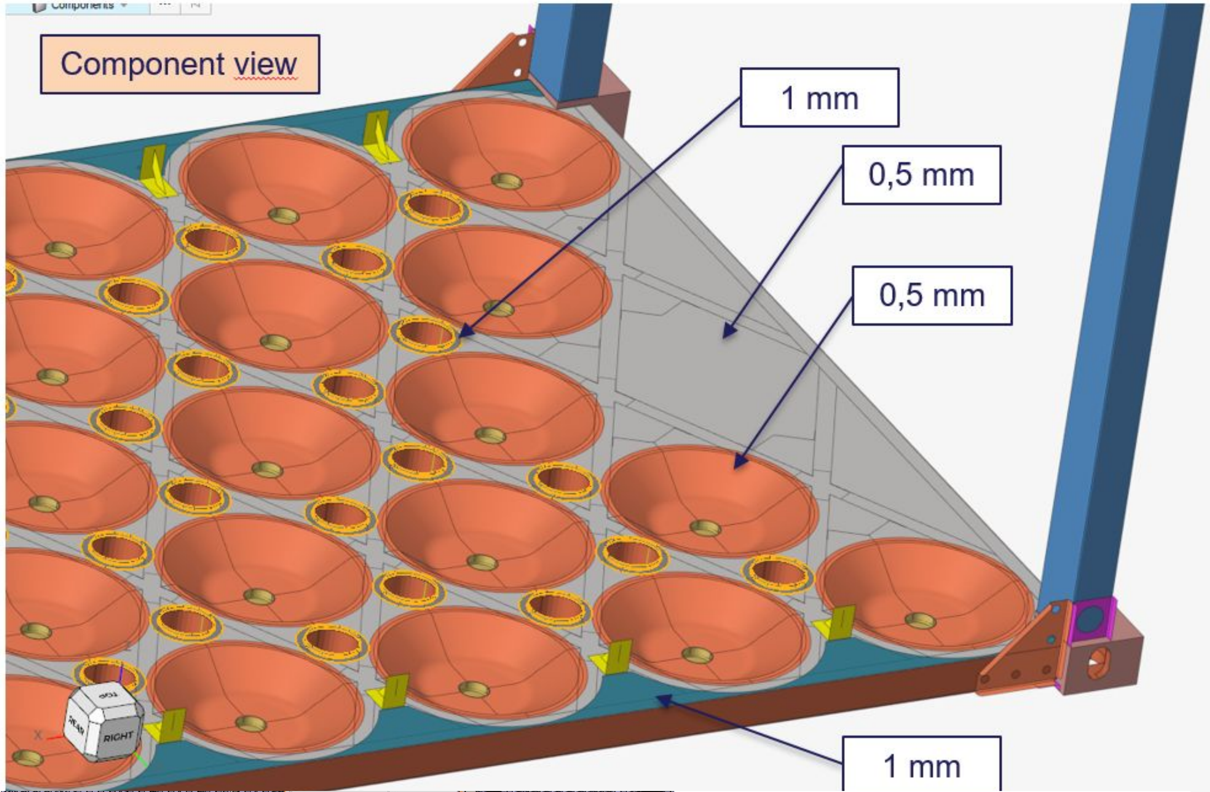


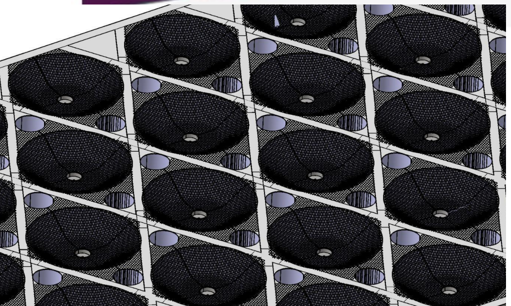


5. FEM/FEA - Recommendations

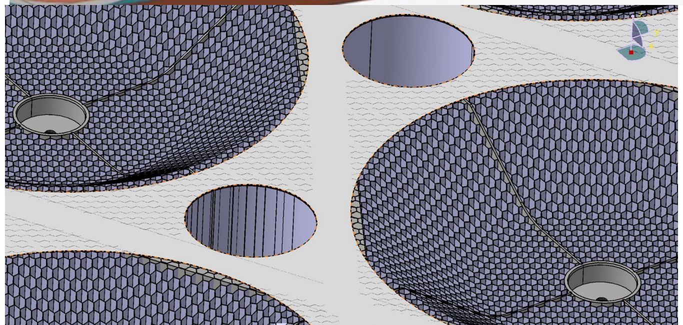
property view

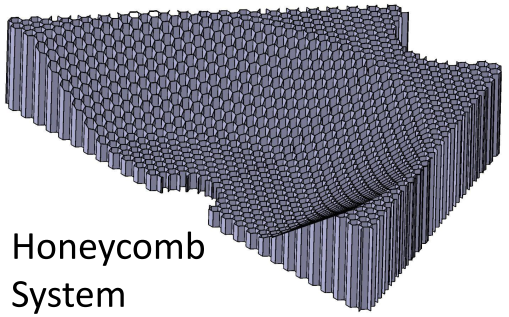






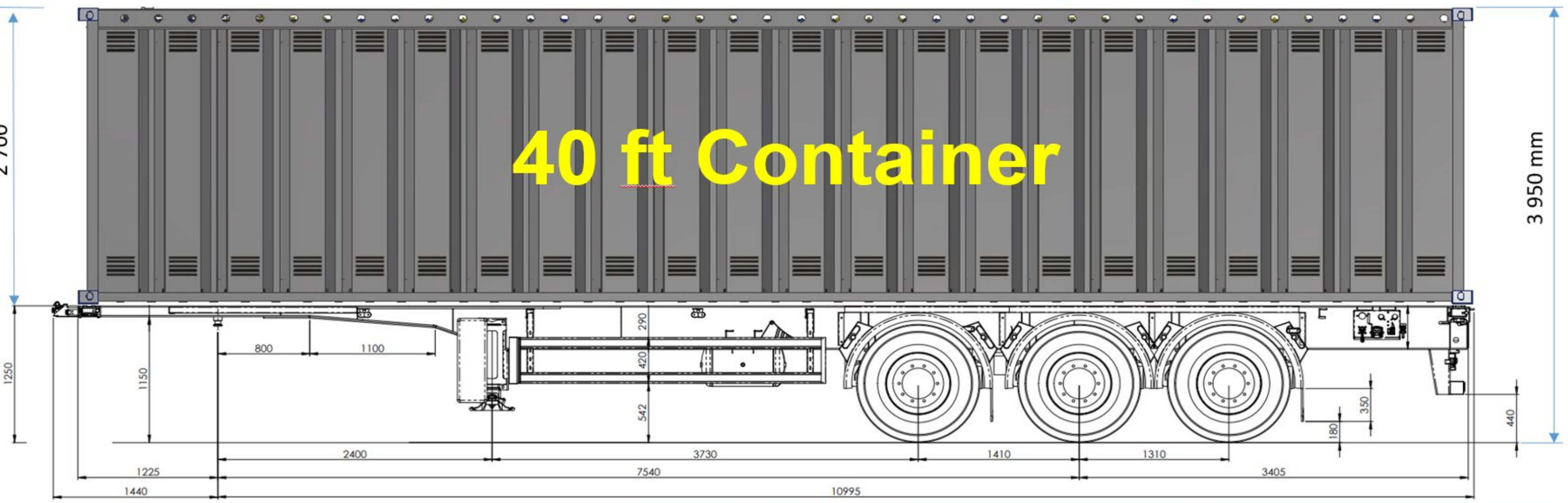
Shell_0.01mm	6
Shell_0.5mm	1
Shell_0.7mm	14
Shell_1.5mm	3
Shell_1mm	2
Shell_2mm	13
Shell_2mm_Simplified_composite	11
Shell_3mm	5





Honeycomb System

5. FEM/FEA - Conclusion

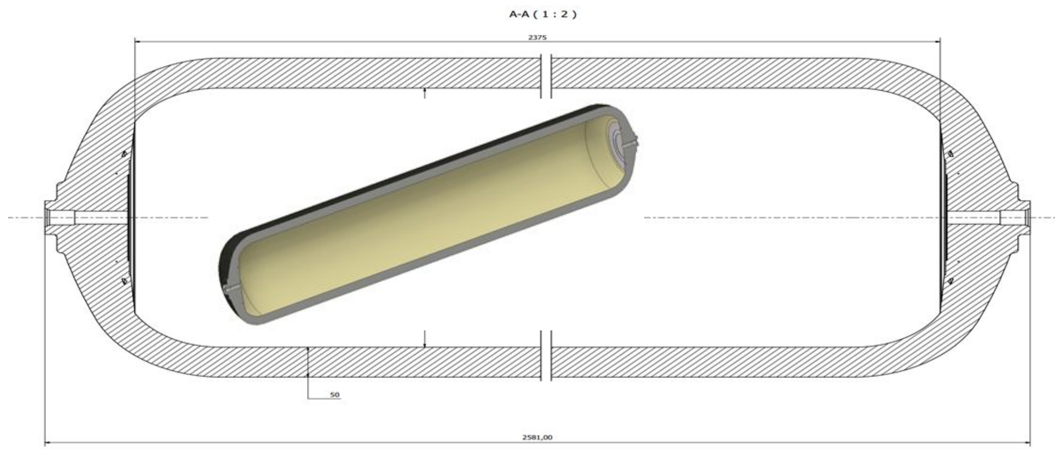


Hydrogen Tube:

- Wall thickness: 50mm
- Length: 2581 mm
- 533 mm O.D.
- 200 kg weight

All Tubes Weight [kg]	Pneu Systems Weight [kg]	MEGC Container Weight [kg]	Fire Plates Protection Weight	Gaseous Hydrogen Weight [kg]	Chassis Weight [kg]	Sum Trailer Weight [kg]
21 400	650	3 700	353	1 481	3 112	30 696

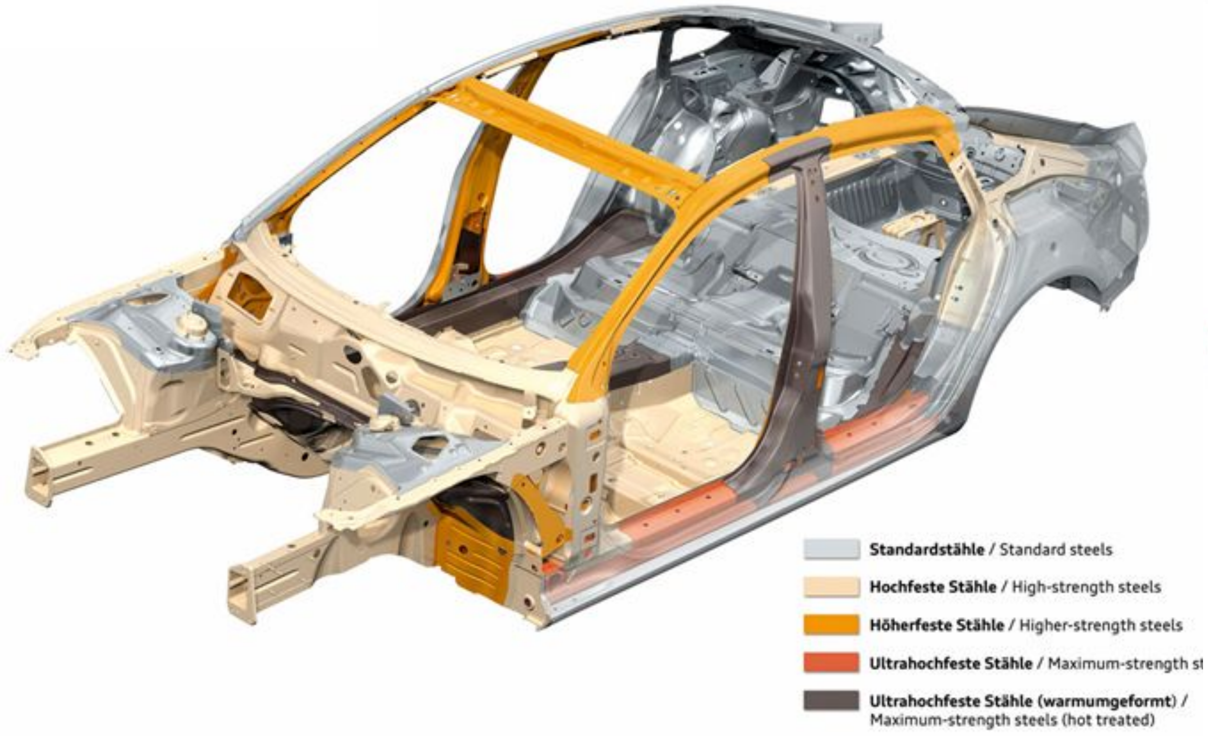
Sum Truck Weight: 40 000 – 30 696 = 9 304 kg and included:
Tractor (2-axle) weight = 7 500 kg
Fuel (+other medium) = 1000 kg
Crew (2 people w/ baggage) = 300 kg
This means, that we have margin now:
9 304 – 7 500 – 1000 – 300 = 504 kg

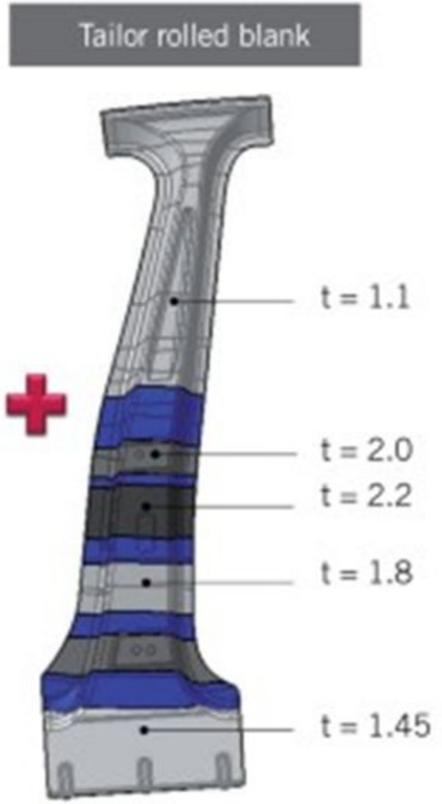


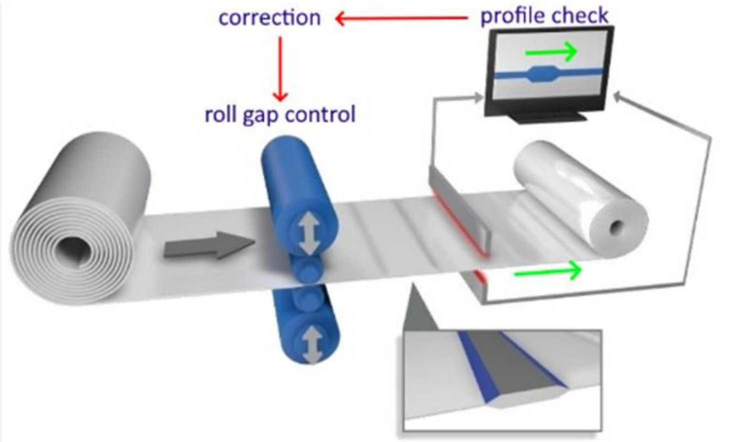
It should be noted that these figures represent worst case scenarios, so we have the option to further reduce the mass of the MEGC (further redistribution of material according to more FEA simulations, using only the ablator in the wheel - chassis - location only). It is possible to save up to **1t of material in total !**

6. MEGC Structure - Manufacturing

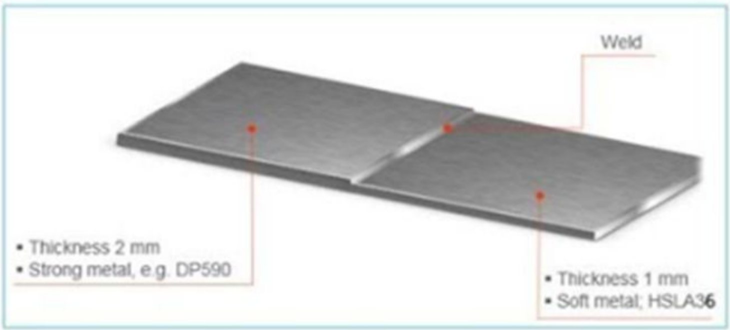
Multi material example





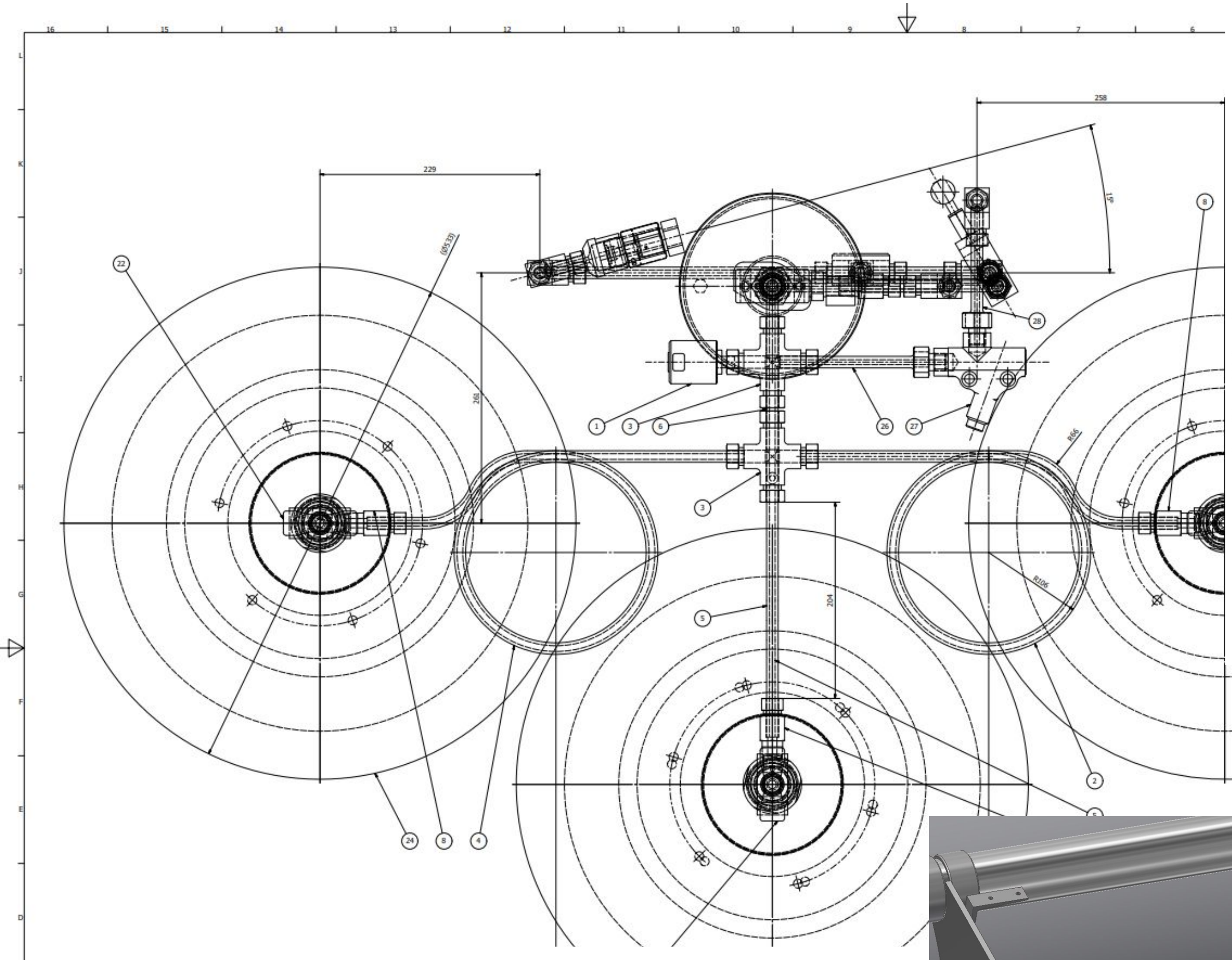


Tailor Welded blank (TWB)

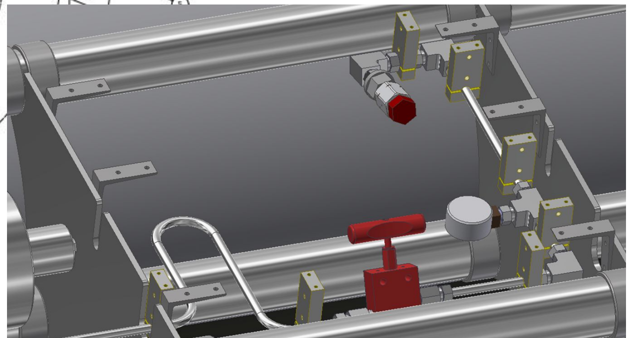


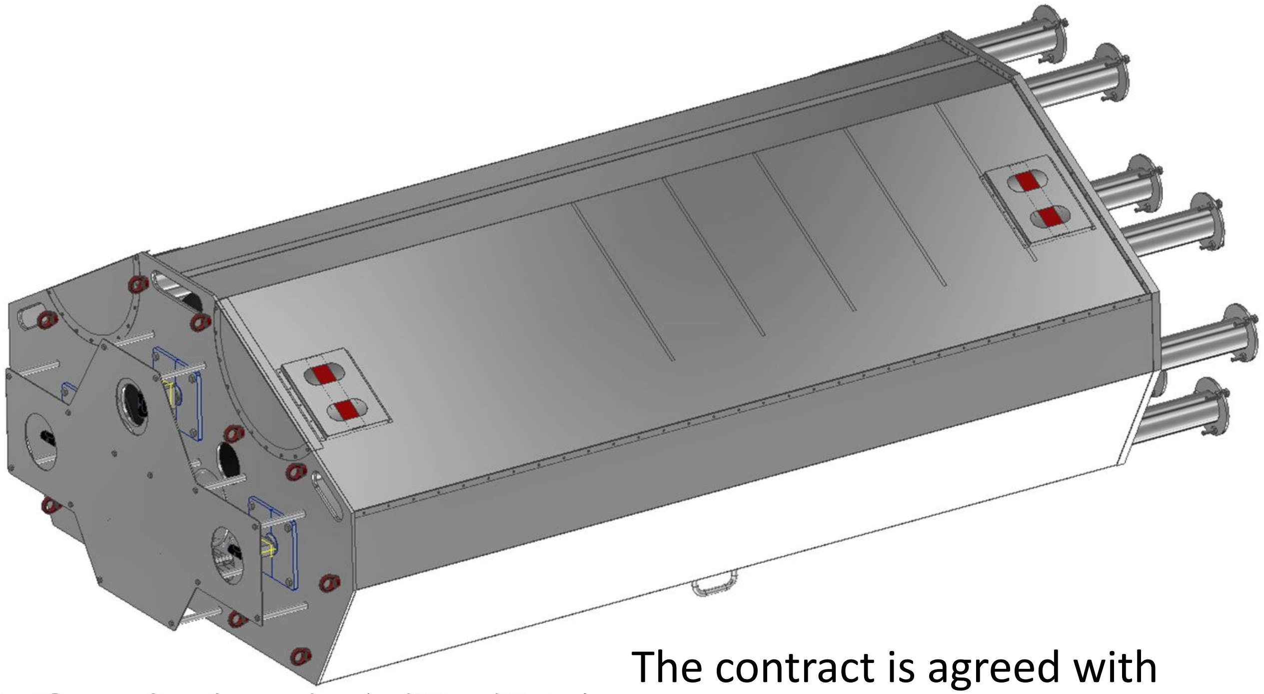
- The ROAD THRYP project is situated, in terms of manufacturing, <u>between the industry of industrial containers and automotive</u>. A high-performance structure is needed for a reduced price of fabrication.
- A multi material approach would be preferred in detriment to the cost. So, to maintain a reduce price we can use as inspiration the technologies of tailor rolled blanks and tailor welded branks that allows us to use the material

7. Demonstrator - Status



FABER INDUSTRIE SPA
Cap. Soc. € 5.000.000 i.v.
Reg. Imprese di UD n° 00168400307
Cod. Fisc. e Part. IVA 00168400307
Cod. Identif. CEE IT 00168400307





		70MPa	version
8	7	SS-8FKD-1-8-SwagelokCompany-3D-08-28 70 MPa-2023	the same for 32MPa
9	5	SS-8FKD-9-SwagelokCompany-3D-08-28-2023 70MPa	L-armature SS-12M0-2-Swagelok for 32MPa
10	1	Tube_10	Drawing: SEG-THRYP-Demo-10-10
11	1	SS-8FKD-3-SwagelokCompany-3D-08-28-2023 70MPa	SS-12-M0-3 - Swagelok for 32MPa
12	1	Pressure Gauge 8008S-fy ASHCROFT for 70 MPa	the same for 32 MPa
13	1	NVT8N1VB15-N50-SwagelokCompany-3D-08-30 70MPa-2023	the same for 32 MPa
14	1	Reduction_1	Drawing: SEG-THRYP-Demo-10-14
15	1	RU3512	M/F W30x2LH -12MF, Set: ENS RAC+BOUCHON W30x2.00 LH -JT(fy CAHOUET ref. RX3159)
16	1	Special_Cap_1	fy CAHOUET
17	1	Tube_17	Drawing: SEG-THRYP-Demo-10-17
18	1	Tube_18	Drawing: SEG-THRYP-Demo-10-18
19	1	Tube_19	Drawing: SEG-THRYP-Demo-10-19
20	1	Tube_20	Drawing: SEG-THRYP-Demo-10-20
21	1	Tube_21	Drawing: SEG-THRYP-Demo-10-21
22	3	Isolation valve -NVT8N8VE15-N50-Swagelok Co. for 70MPa	BOWN12/8 - 25E-TEKNO Co. for 36MPa
23	1	533mm O.D. Hydrogen tube_2581mm Length_346L_v05 for 70MPa/32 MPa	Open question - development ot tube is ongoing (fy COVESS). Ist step - tube w/ 32MPa
24	1	Like Pos.23	Detto. Given tube is equipped with thermocouple tree
25	2	Like Pos.23	Detto. Only Plug on bottom.

The contract is agreed with **FABER** company , after small adjustments the contract can be agreed so that the demonstrator will be ready in **<u>August-September this year.</u>**

Safety - Fire behavior

Participants:
- Efectis France
- Air Liquide
- Pprime Institute

Aim and Objectives

- **Safety aspects** of the new high-pressure type V tubes trailer developed during ROAD TRHYP

- To do this, 4 distinct but interdependent tasks:

1	Identify the main failure scenarios of the new trailer type
2	Assess the consequences of these scenarios
3	Lab scale tests of the mechanical behavior of tanks
4	Large-scale fire tests for a tube and of a set of type V

Identification of the main failure scenarios for the new trailer type

- Shortlist of dimensioning failure scenarios identified
  - Scenarios n°1, 2 and 3 to be considered
    - Envelope of the other ones
    - Leak before burst expected instead of burst for Scenario 5

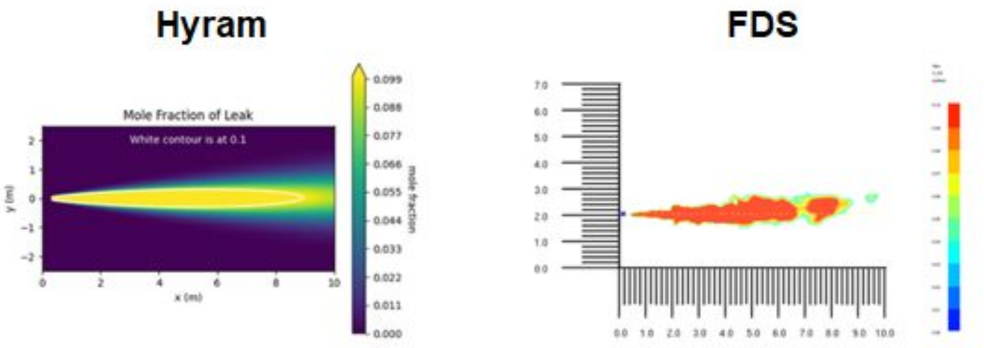
Scenario n°	Type of Failure	Basis / Envelope
1	Full bore rupture of the filling hose of the trailer	Full rupture Envelope based on an analysis of the components
2	Leak on the filling hose of the trailer	Partial rupture
4	TPRD opening following a thermal aggression	The thermal aggression includes / covers : tire fire, vehicle fire (heavy/light), hydrocarbon pool fire under the vehicle (petrol), criminal act
5(?)	Burst of one tube	Full rupture of the tube Representative of: collision / impact, over filling
3	Leak on the pipings of the trailer	Partial rupture on the pipings

Assessment of the severity of consequences of these scenarios

- From the shortlist of dimensioning failure scenarios defined

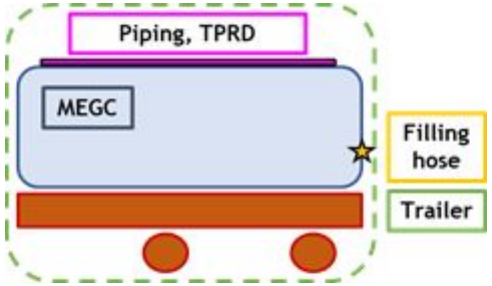
- Evaluation of the consequences
  - In terms of distances of effects (flame length, thermal thresholds)

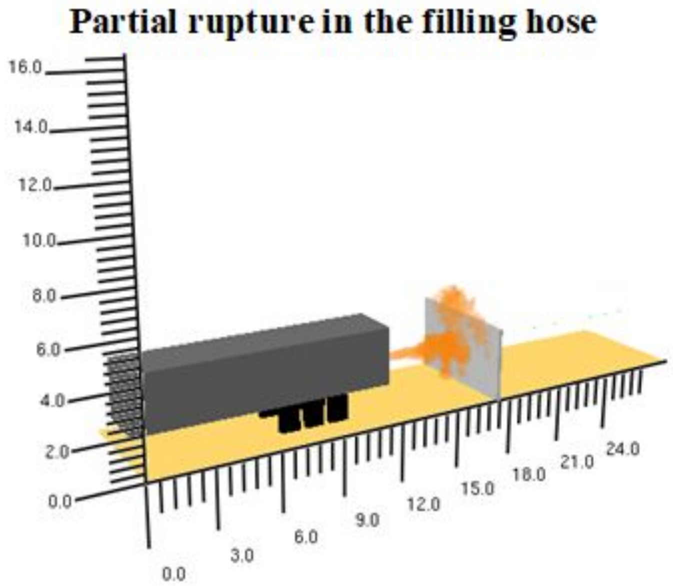
- Using different methods and tools
  - Depending on abilities - complexities - applications
  - To verify that simplified tools (Aldea & Hyram) are sufficient to assess quickly the consequences
  - To validate complex CFD tools (FDS - Fire Dynamics Simulator) to further refine the scenarios taking into account mitigation barriers, environment, etc.



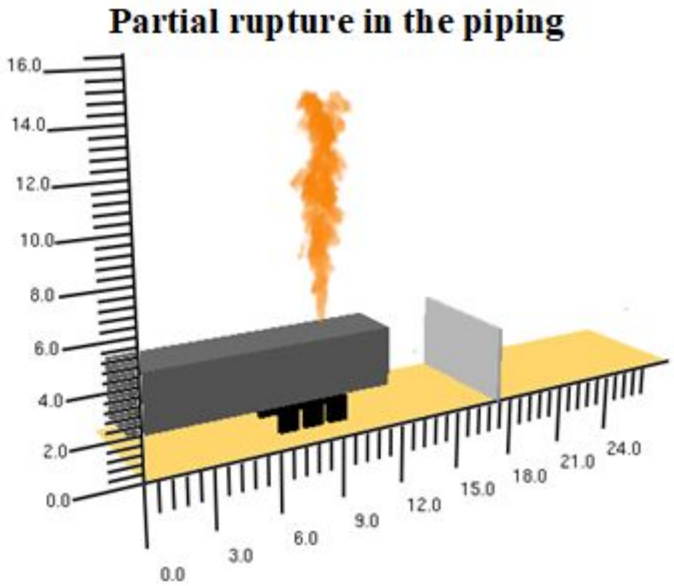
Thresholds for:
- Irreversible effects - 3 kW/m²
- Lethal effects - 5 kW/m²
- Significant lethal effects - 8 kW/m²

- Complex CFD tools to further refine the scenarios taking into account mitigation barriers, environment, etc.





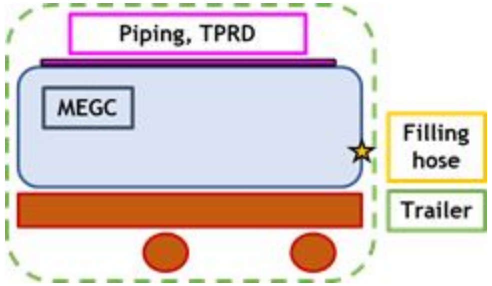
Scenarios n°1-2

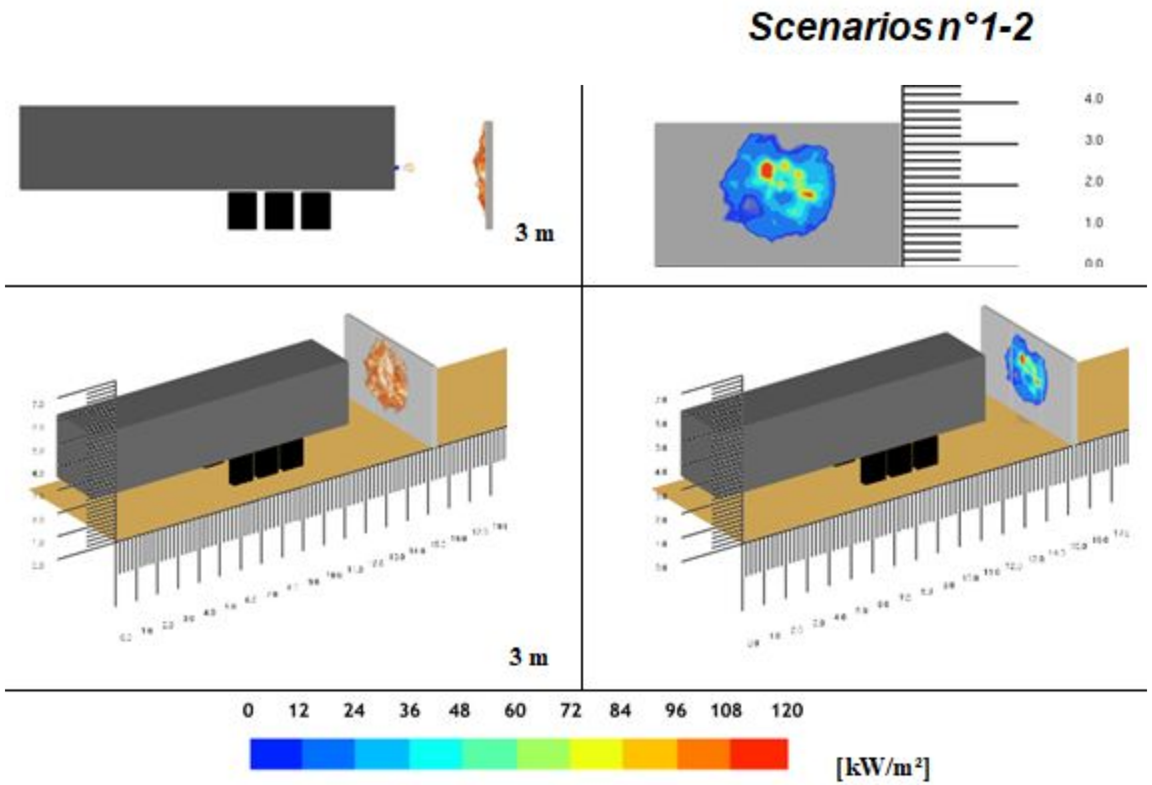


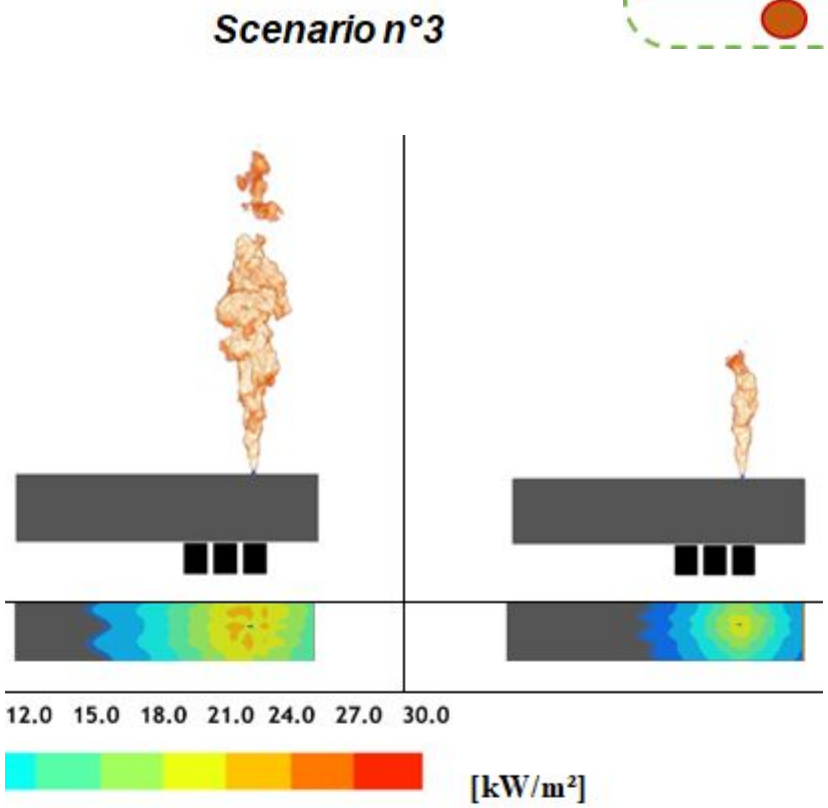
Scenario n°3

Assessment of the severity of consequences

- Complex CFD tools
  - Evaluation of the heat fluxes on the elements / environment







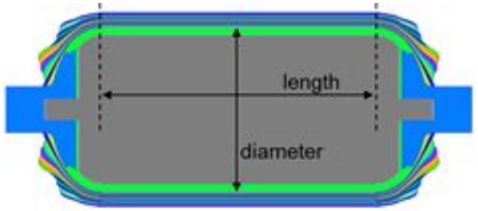
Lab scale tests of the mechanical behavior of tanks

Safety concern: How would a single composite tank for gH2 storage react when it is engulfed by fire ?

To answer this question, we need to:

- **Understand the material behavior**:
  - Measure the performance of the composite material.
  - Assess the benefits of such composite material compared to previous/common technologies.
- **Understand the structural behavior**:
  - Develop a numerical tool capable of accurately representing the geometry and the in-situ conditions of a storage tank engulfed by fire.
  - Predict the tank failure and propose reliable burst/leak criteria.

Numerical model for the tank composite lay-up



Lab scale tests of the mechanical behavior of tanks

- **Understanding the material behavior**
  - Identify the thermophysical properties of the (thermoplastic) composite.
    - *Important to understand the **heat transfer** within the composite shell due to the heat flux emerging from the engulfing fire.*
  - Determine the thermomechanical properties of the composite.
    - *Important to understand the complex (temperature-dependent) **mechanical behavior** of the composite maintaining the structural integrity of the storage tank.*
  - Analyze the thermal degradation of the material.
    - *Important to understand the **decomposition steps** of the thermoplastic resin at very high temperatures.*
  - Examine the coupled behavior of the material undergoing degradation.
    - *Important to understand how **degradation weakens the material**'s thermophysical and mechanical properties, a necessary step to understand the tank's behavior as well.*

Lab scale tests of the mechanical behavior of tanks

Understanding the material behavior

- Characterization through an experimental campaign with different measurements/techniques…

The mechanical behavior also depends on temperature!

- Measure Tg and identify key temperature changes from viscoelastic properties.
- Identify T-dependent mechanical properties before decomposition (test in a climate chamber)
- Expose samples to heat fluxes (different degradation levels) and test them to identify the residual mechanical properties.

thermophysical properties

Non-linear heat equation must be solved!

$$\rho(T)c_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q$$

How to determine T-dependent properties of the composite undergoing decomposition?

- Measure the T-dependent properties (if possible)
- Determine the mass loss curve → decomposition ratio as a function of temperature
- Simulate a real-test (cone calorimeter test) with a kinetic model (decomposition) and thermal model (heat transfer) and identify the missing properties through inverse analysis.

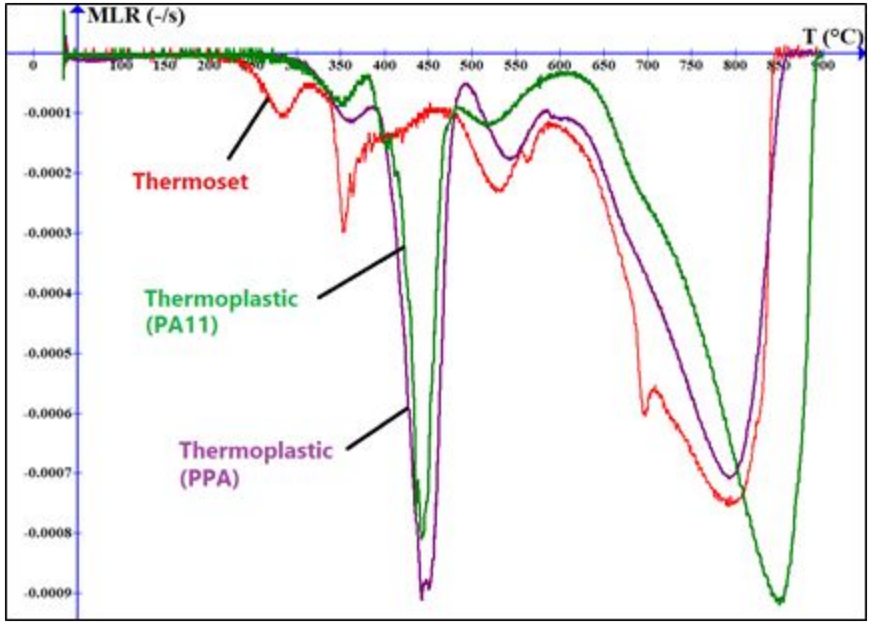
thermomechanical properties

Lab scale tests of the mechanical behavior of tanks

- **Understanding the material behavior**
  - **How does the thermoplastic-based composite compare to thermoset composites (epoxy)?**

❖ *Higher decomposition temperature:* ***200-250°C*** *for epoxy vs.* ***300-350°C*** *for PA11/PPA (pyrolysis peak: ~100°C difference).*

❖ *Comparable melting and crystallization temperatures (low temperatures = better processability).*



Lab scale tests of the mechanical behavior of tanks

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❖ *Comparable melting and crystallization temperatures (low temperatures = better processability).*

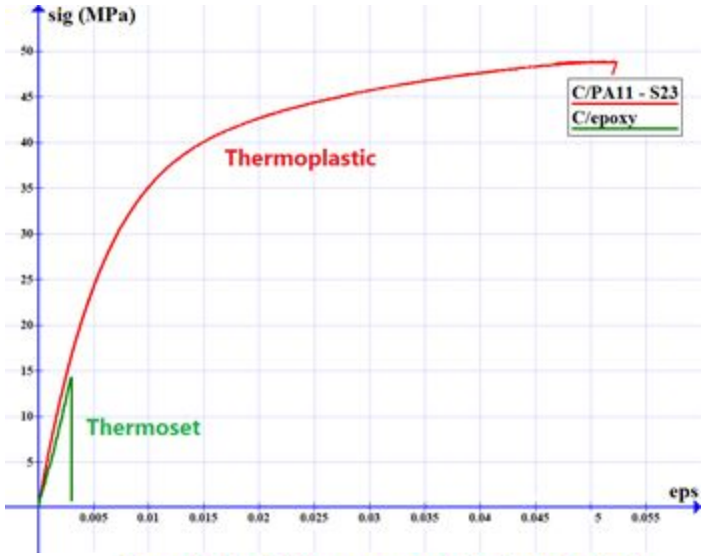
❖ *Considerably high mechanical performance for a comparable fiber ratio:*

➢ *Increase in material stiffness*

➢ ***3x** the matrix (transverse) strength and **4x** the shear strength*

➢ *More elongation before the breaking point (2x to 10x)*

➢ *4-5x the strength in quasi-isotropic fiber orientations*



Strength (matrix / transverse-dominated behavior)

Elongated sample (45°) after tensile testing

Lab scale tests of the mechanical behavior of tanks

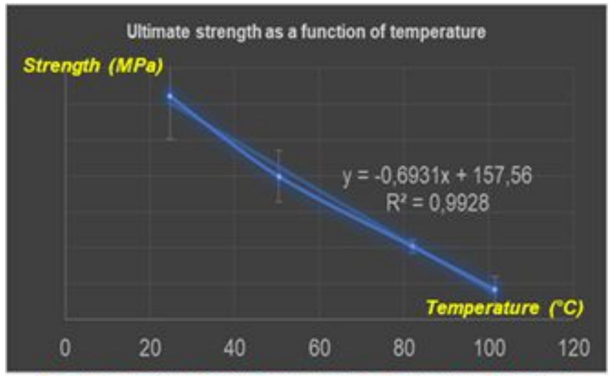
- ## Understanding the material behavior
  - **How does thermal degradation affect the properties of the material ?**

C/PA11 results

★ *<u>Main takeaway for C/PA11 composite</u>:*

- *Stiffness drops significantly around the glass transition temperature and decreases slowly as the temperature of the material rises.*
- *Only ~1/3rd of the room-T stiffness is kept at 100°C*
- *Strength gradually decreases (linearly) with the temperature rising.*
- *Only ~1/3rd of the original strength remains at 100°C*
- *Thermal degradation is relatively small for a low heat flux (20 kW/m²)*
- *Thermal degradation is correlated to the amount of heat energy to which the material is exposed: after a certain threshold (4 MJ/m²), the properties are much more affected by the thermal decomposition.*

Tensile testing on 45° sample at 25°C *at 50°C*



Tensile strength (matrix / transverse-dominated behavior)

The influence of temperature and the thermal degradation on the composite behaviour will be used for large-scale simulations

Simulation of the thermomechanical behavior of tanks

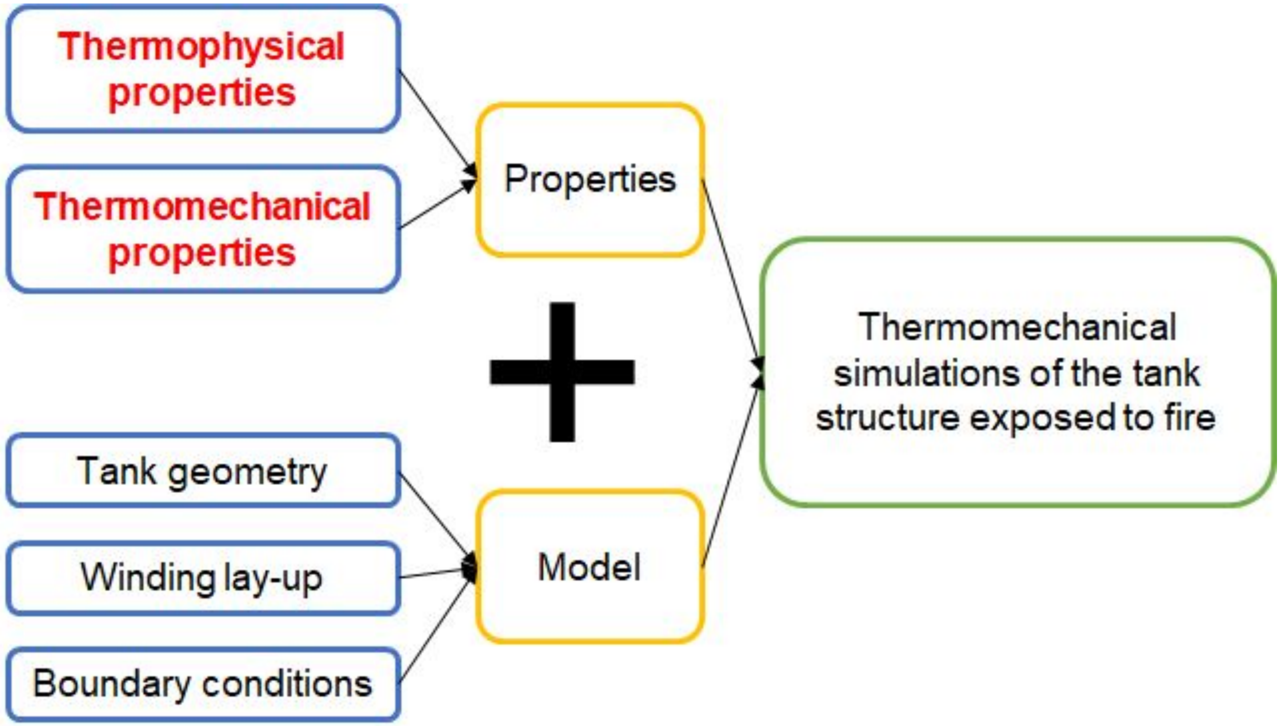
- **Understanding the structural behavior**

❖ *Data collected from the experimental campaign aiming to identify key properties of the material as well as how these properties are affected by the thermal degradation emanating from the fire that engulfs the structure.*

❖ *Obtained directly from TCM code developed by PPRIME*

❖ *Obtained directly from winding process by COVESS*

❖ *Obtained directly from CFD simulations by Efectis (see next)*



Simulation of the thermomechanical behavior of tanks

- **Understanding the structural behavior**

❖ ***FEM simulations*:**

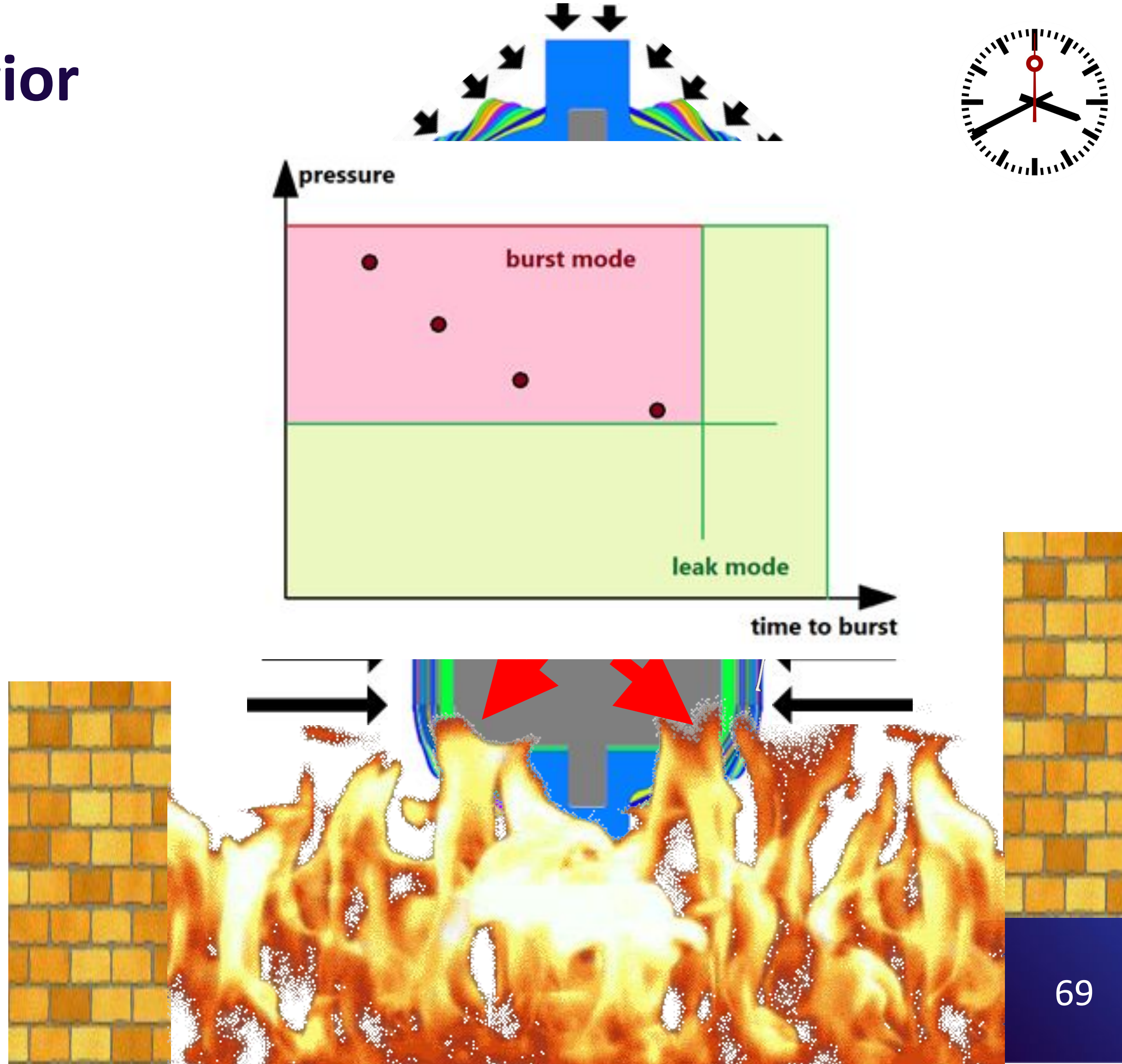
➢ *Entire geometry is modeled (composite lay-up, metallic bosses, etc.) and the model parameters / properties are assigned.*

➢ *Internal pressure is applied in a first step. The tank is in mechanical equilibrium and the internal pressure is maintained constant afterwards.*

➢ *Asymmetric external heat flux | adiabatic temperature, obtained from CFD simulations, is applied in a second step.*

➢ *Outer layers start to decompose. Load is transferred to inner layers. Burst criterion is used to determine the time-to-burst for a given internal pressure.*

➢ *Different internal pressures can be applied. Then a leak criterion can be proposed to delimit the "safety curve" (whether burst or leak occurs first for any type of heat flux or pressure applied).*

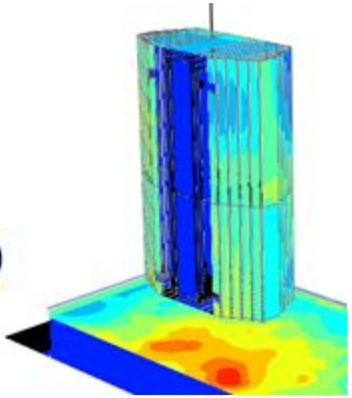


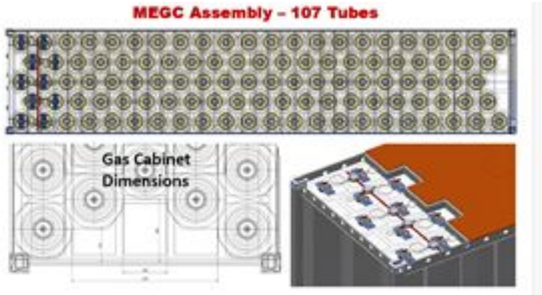
Large-scale fire tests for a tube and of a set of type V

- Numerical simulation of the planned fire tests using FDS code
  - To design the fire tests & optimize the instrumentation

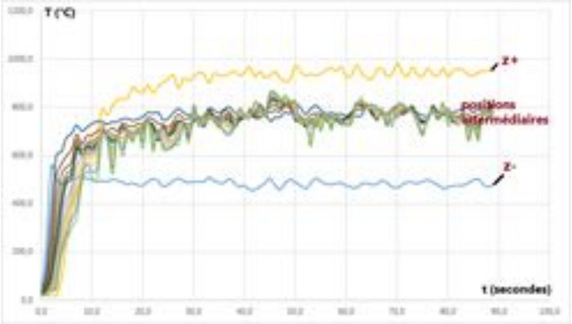
On a single type V tube

On a set of 3 tubes in a gas cabinet (final demonstrator)





  - To serve as inputs for thermomechanical simulations (boundary conditions necessary for the lab-scale simulations)



Perspectives and progress

- Large scale fire tests planned:
  - Single type V tube: autumn 2025
  - Set of 3 tubes / demonstrator: spring 2026
  - Safety analysis of the fire tests in progress (HAZID review)
    - Considering preparation, performance and after test stages

- Numerical simulations of these tests in progress

Regulation aspects

Participants:

AIR LIQUIDE

EFECTIS FRANCE

SEGULA

Aim and Objectives

ROAD TRHyP project

⇒ Development of a new technology of trailer

⇒ New risks faced (greater operating pressure and amounts of transported H2)

⇒ New potential designs of the equipment and ancillary components

Crucial need for a mapping of the current Regulations, Codes and Standards [RCS] to ensure that:

→ The concept can rapidly get its certification once implemented

→ The concept is suitable with the actual industrial/regulatory environment

→ Be aware and share good practices of trailer operation

Identify potential and actual gaps/grey areas in the regulations and formulate recommendations to allow dedicated working groups filling them

Final interest of the approach : be ready for a fast and safe deployment of the technology

Reminder RCS

RCS stands for Regulations, Codes and Standards

→ Several levels of rules that must be dealt with in the project

Mandatory

Regulations	Legislation issued by local institutions, dealing with the authorization for installation and usage. ➔ Mandatory compliance	**Local/national legislation, permitting**
Standards	Sets of recommendations, good practices or guidelines written by technical experts. ➔ Not mandatory, but more and more used as a support by the legislation	**ISO/IEC** (international), **EN** (European)
Codes	Sets of guidelines, relative to a given sector, written by governmental bodies and/or technical groups. ➔ Aim : ensure public safety and welfare	**EIGA/CGA documents, NFPA**
Company internal rules	Set of rules internally defined, based on good practices or experience, to ensure safety and quality of the company's projects, processes or products.	**Internal documentation**

Voluntary

Reminder: technical specificities of the developed trailer

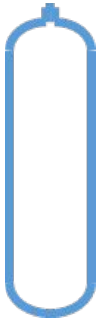
- **Type V cylinder technology**
  - Unknown behavior for authorities;
  - Compatibility with trailer equipment to be ensured;
  - Leak-before-burst behavior under fire expected;
  - Strategy of risk management to be approved.
- **Water capacity of an individual tube 330 L**
  - Common for trailers with vertically-oriented cylinders.
- **Operating pressure of the trailer 700 bar**
  - Greater than for current applications;
  - Mechanical resistance to be confirmed.
- **Overall mass transported 1.5 t of GH_2**
  - Enhanced capacity compared to current transport vehicles;
  - Safety distances to be adapted.

Adopted approach

2 sources of information identified :

- **Identification of the existing recommendations and requirements related to the application with special focus on:**
  - Technical limitations (ex.: size);
  - Safety (ex.: safety elements);
  - Tests to pass.
- **Interviews of stakeholders of the application (manufacturers and users):**
  - Vision of the market evolution;
  - Current needs;
  - Other applicable codes;
  - Opinion on the new technology;
  - Identified gaps and points of attention in the RCS.

Subjects of interest - Gaseous hydrogen cylinders



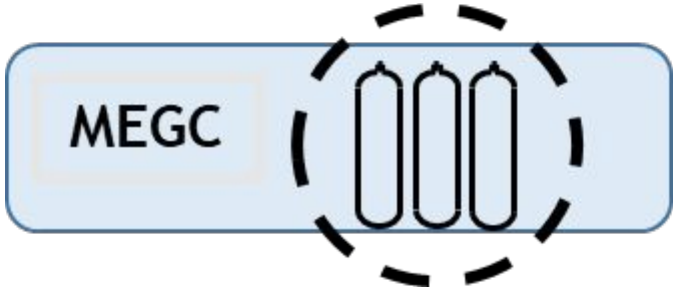
GH_2 cylinder

Regulations → One section in the *Agreement Concerning the International Carriage of Dangerous Goods by Road* (ADR) dedicated to the "requirements for the design, construction, inspection and testing of portable tanks with shells made of fibre-reinforced plastics materials" **basically written for cylinders up to type IV technology** (but not fully adapted for type V).

ISO standards → Several existing standards dealing with the minimum requirements for the material, design, construction, manufacturing processes, examination and/or testing of refillable composite tubes (*TS 17159:2019, 11119-3:2020, 11515:2022*), but **none of them matches all the specificities of the project.**

EN standards → Two standards identified defining the minimum requirements for the materials, design, construction, testing and inspections for fully-wrapped composite cylinders (*EN 12245:2022, EN 17339:2020*), both being **potentially well-suited for the current application despite some limitations.**

Subjects of interest - Cylinder ancillary components



MEGC → Multiple Element Gas Container

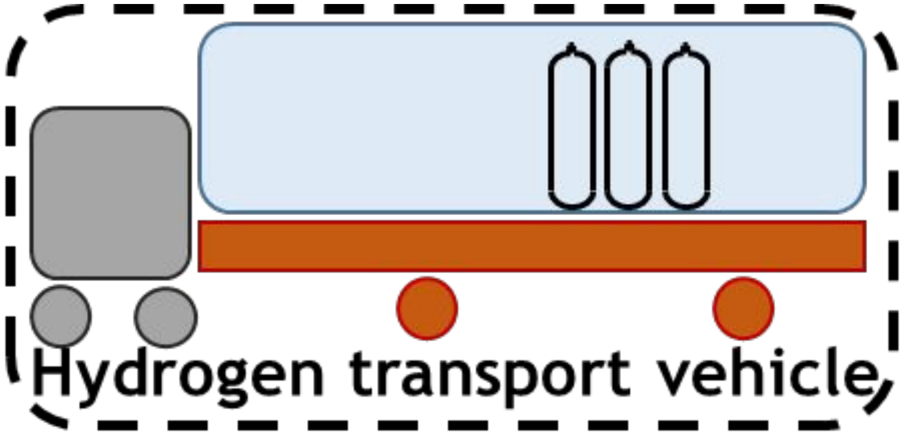
Regulations → Sections in the *Agreement Concerning the International Carriage of Dangerous Goods by Road* dedicated to the "requirements for the design, construction, inspection and testing of MEGCs" are not applicable for the current application (UN MEGC or MEGC with metal cylinders).

ISO standards → Several existing standards about the general requirements (design, testing, sizing and marking) of safety devices and equipment (*4126:2013* for safety valves, *4126:2018* for bursting discs, *23826:2021* for ball valve devices, *10297:2024* for ball valves), but specificities of the cylinder are not considered (type of cylinder, compatibility with the product, the cylinder material or the other components).

→ One guidance standard (*11114-2:2021*) for the selection and compatibility evaluation between non-metallic materials and the carried gas, approving the choice of PA11 as tube material/liner with compressed GH_2.

EN standards → No standard identified

Subjects of interest - Hydrogen transport vehicle

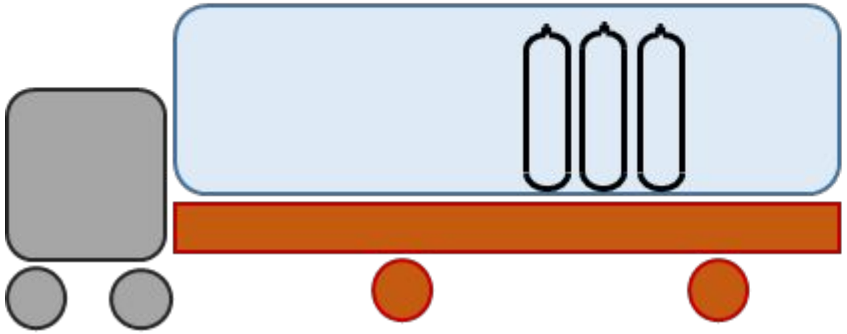


Regulations → Annex B of the *Agreement Concerning the International Carriage of Dangerous Goods by Road* (encompassing both last parts of the document) focuses on the vehicle, with special concern on its construction and approval ; no special issue has been found (ex.: general safety recommendations). Transcripted in the European directive *2008/68/CE*, considered as a minimum in Europe, being aware that more stringent provisions can be locally requested.

→ European directives (*96/53/CE, 2015/719*) providing features of the road vehicles authorized on European roads ; no issue although it must be kept in mind that some regions may have more restrictive requirements.

Standards → No standard noticed (ISO, EN)

Subjects of interest - Hydrogen Refuelling Station



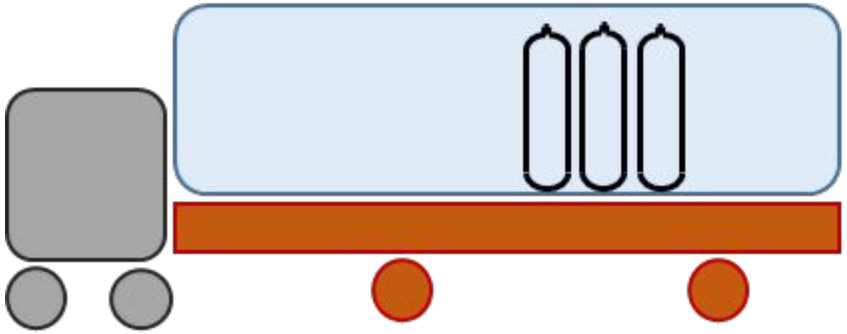
Regulations → **Common basis for the safety requirements and environmental assessment with European regulations (ex.: *ATEX Directive, SEVESO Directive, Strategic Environmental Assessment, Industrial Emissions Directive*).**

→ **Local authorities have the lead to elaborate their own decrees and permitting processes, being potentially more stringent and variable depending on the country/region/…**

Example in France, HRS submitted to both *ICPE 4715* and *1416* for installations subject to declaration, dealing with the risk management, safety requirements (separation distances, emergency device, safety systems), operational and monitoring rules and environment.

No current incompatibility, but the features of the filling trailer are never mentioned (possible upcoming evolutions with the more severe operation conditions)

Subjects of interest - Hydrogen Refuelling Station

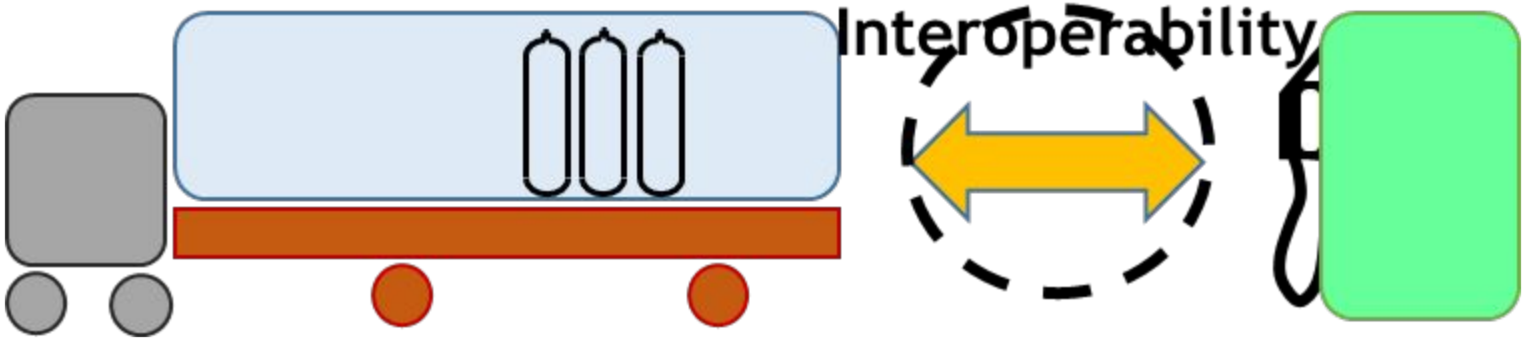


Regulations → Common basis for the safety requirements and environmental assessment with European regulations (ex.: *ATEX Directive, SEVESO Directive, Strategic Environmental Assessment, Industrial Emissions Directive*), but potential variability in the application between geographies.

ISO standards → gathered in the *19880 series*, here mainly *19880-1* for fuelling stations, to define the minimum design, installation, commissioning, operation, inspection and maintenance requirements for the safety and the expected performance of fuelling stations. Not incompatible with the new trailer concept, despite warnings in case of specific trailer designs or applications.

EN standards → No standard identified.

Subjects of interest - Operations between vessels



Regulations → No regulation identified

ISO standards → gathered in the *19880 series*, other than -1, to focus on the safety requirements related to the station components. No details related to the filling operation.

EN standards → One standard (*EN 17127:2024*) dealing slightly with the refuelling protocols between the trailer and the station (no safety nor performance aspects mentioned). Not incompatible with the new trailer concept as long as it is considered as a specific design (would require a dedicated risk analysis on the safety hazards if so).

Codes → functional requirements provided by EIGA in terms of functioning and safety of the interface between the GH_2 trailer and the HRS, but not up to expected operating pressures.

Main identified gaps

- **Lack of harmonized regulation or permitting process across geographies:**
  ⇒ Potential differences in the HRS designs between geographies (required equipment, imposed safety distances) and the accepted trailer designs.

- **In the existing RCS, the technology of the trailer is never mentioned:**
  ⇒ Potential differences in the interpretation of the risk analysis regarding the local regulations.
  ⇒ Possible evolutions of regulations with the new operating conditions, which increase the severity of the consequences of potential accidents.

- **Standardization of the safety strategy to be improved:**
  ⇒ Identifying the minimal technical solutions for safety
  ⇒ Defining ways to determine adapted safety distances (considering the operating conditions and the implemented barriers).

- **Missing standardization for the interoperability between trailers and HRS:**
  ⇒ Need for standardized equipment at the interface and transfilling protocols (maximum admissible transfer rate).

- **Lack of solution to exchange data between the trailer and HRS (amount and quality of GH_2 delivered).**

Next steps

- Identify potential solutions to fill the identified gaps
- Identify working groups in touch with the concerned topics
- Share propositions of evolutions
- Enhance the market for this solution

Life Cycle Assessment Type I, IV & V

Work Package Leader WP8: SEGULA

Participants: Air Liquide, ARKEMA, COVESS

AGENDA

I. Introduction, Goal & Scope of the Study

II. Life Cycle Inventory (LCI)

III. Life Cycle Inventory Assessment (LCIA)

IV. Interpretation of the Results

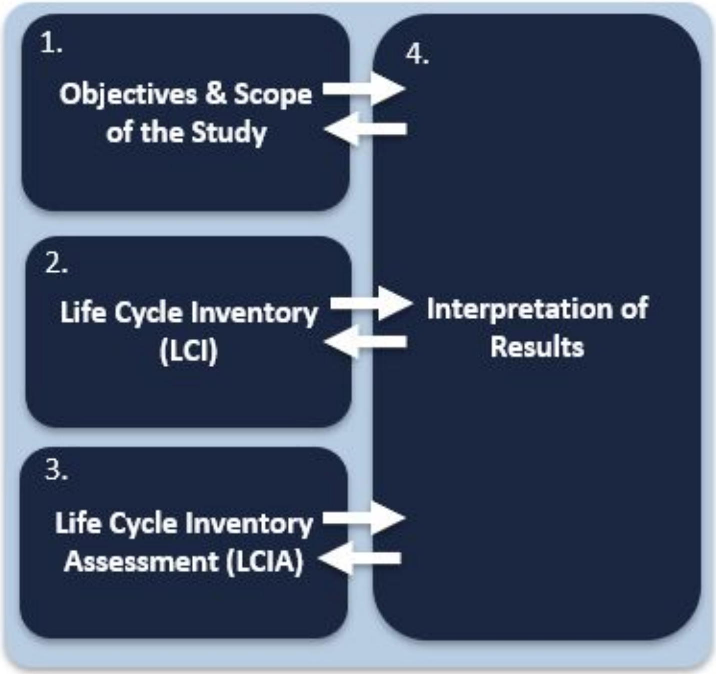
V. Conclusion and Next steps

I. Life Cycle Assessment (LCA) - Definition

Life cycle assessment:

- Most **Advanced tool** for the **evaluation of environmental impacts**.
- This is a standardized method for measuring the **quantifiable effects** of products or services on the **environment**.

Multi-stage - Multi-criteria - Systemic



LCA Study

LCA FE (GaBi)

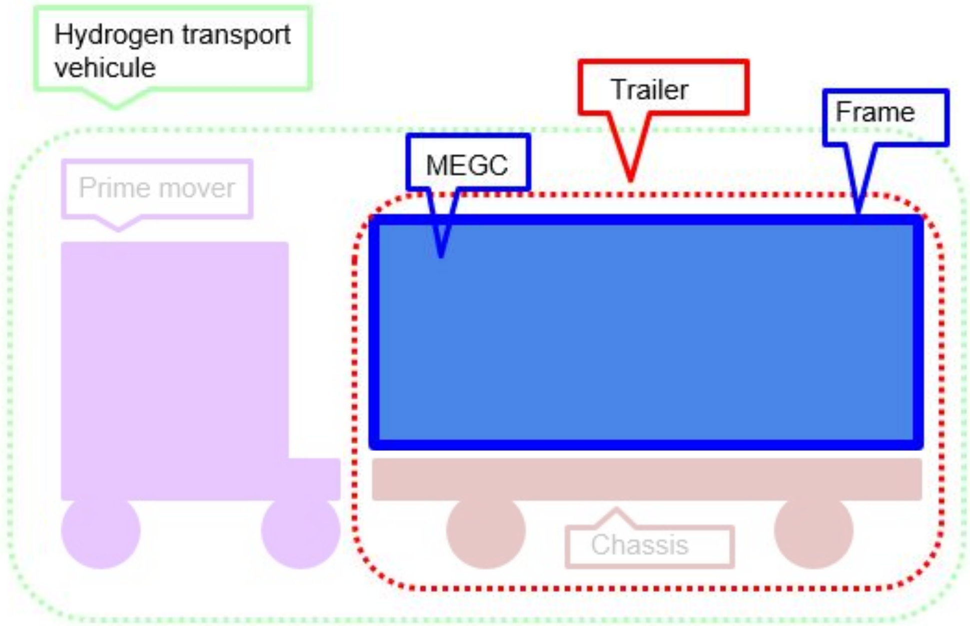
SimaPro

LCA Software's

I. Work carried out – Goal & Scope of the Study

Goal of the Study: Analyse and compare the environmental impacts of Hydrogen transport for different tubes technologies.

Product:

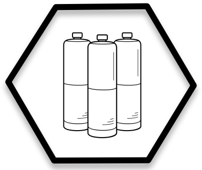


Functional Unit: The functional unit chosen to quantify the main function is the transport of **1 kg of hydrogen over 100 km distance** with a defined standard itinerary. The following tables shows the basic conditions of the functional unit.

Characteristic	Value
Number of journeys	• 1 return trip a day (with empty return) • 5 days a week • During 40 years
Distance travelled (one way)	150 km
Total distance covered	3,120,000 km

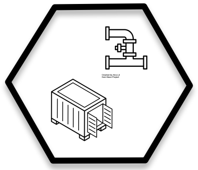
II. Life Cycle Inventory (LCI)

1. Production Phase



Tubes Production

	Type I	Type IV	Type V
Materials	Chrome Molybdenum Steel	HDPE liner + **Epoxy Carbon fibres** composites	**Carbon Fibres PA11 Tapes**
Manufacturing Process	Forging	Filament Winding + Composite Curing Oven	Filament Winding
Unit mass (kg)	2,481	95	200
All tubes mass (kg)	24,810	10,830	21,400
Quantity	10	114	107
Lifespan	**40 years**	**30 years**	**30 years**



Frame & Piping System Production

	Type I	Type IV	Type V
Materials	Galvanised Steel & Stainless Steel 316 (Piping)		Mostly Stainless Steel 316
Frame Mass (kg)	3,726	6,040	4,053 (including Fire Plates protection)
Piping System Mass (kg)	/	528	650
Assembly	Welding	Welding	Welding
Lifespan	**40 years**	**40 years**	**40 years**

- **Assumptions** have been made about tube manufacturing processes.
- The **frame & the piping system** were modelled using only the **main materials**.
- **Specific data** with the BOMs of these modules containing a large amount of data are necessary for a **complete LCA**.

II. Life Cycle Inventory (LCI)

2. Use Phase & Maintenance

<u>Use phase</u>: Daily transport of hydrogen between a filling centre and one of Air Liquide's client sites during 40 years.

<u>Maintenance</u>: Different process during the life cycle (part replacement, painting…)

<u>Use phase is almost the same for both trailers</u>. The only variable that changes is the quantity of transported hydrogen.

GLO: Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity Sphera <u-so> p

Key Data	Type I (200 bar)	Type IV (300 bar)	Type V (700 bar)
Hydrogen mass (per tube) **[kg]**	32.82	7.40	13.90
Hydrogen Mass (total) **[kg]**	328.2	843.95	1 487.26
Hydrogen transported (Life cycle) **[kg]**	3,413,586	8,777,126	15,467,454
Gas losses during Use Phase **[%]**	0.2	0.4	0.4
Energy required to compress hydrogen to 200/300/700 bar **[kWh/kg]**	2.2	2.2	3.6
Hydrogen compression Country	FRANCE		

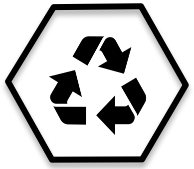
Truck-Trailer parameters	Type I (200 bar)	Type IV (300 bar)	Type V (700 bar)
Payload **[kg]**	328.2	843.95	1 418.48
Utilisation	1	1	1
Driving Share Motorway **[%]**	70	70	70
Driving Share Rural **[%]**	15	15	15
Driving Share Urban **[%]**	15	15	15

II. Life Cycle Inventory (LCI)

3. End-of-Life

<u>End-of-life consideration method</u>: **Substitution method** / avoided impacts method

 Method that involves allocating all impacts and benefits of recycling to end-of-life



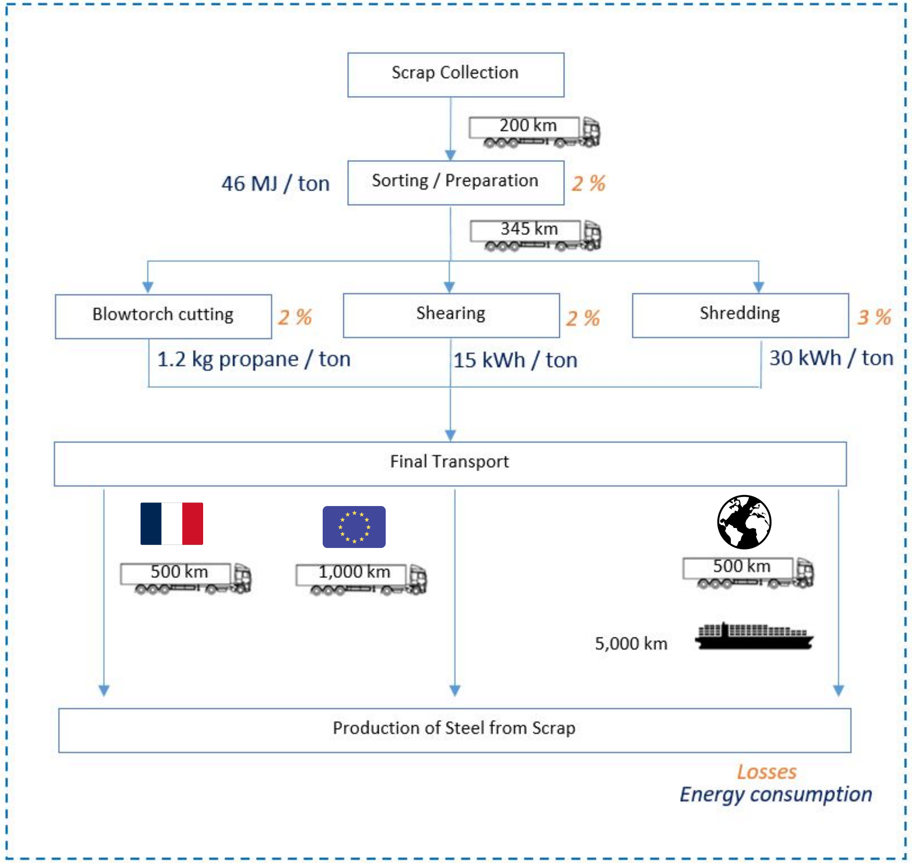
Metal Recycling :
- Type I tubes
- Type I, IV & V Frame
- Type I, IV & V Piping system

Landfilling:
- Type IV Tubes

RER: Commercial waste (AT, DE, IT, LU, NL, SE, CH) on landfill Sphera <p-agg>

For Type V (Waiting for further information)
- Current Scenario Landfilling (<u>Worst case</u>)
- Further Work Recycling

<u>3 important points to consider</u>:
- Determine the **recycling rate**.
- Possible **change in properties** of the secondary material.
- Identifying **substituted processes**.



III.1. LCIA – Selection of environmental indicators

Normalization & Weighting (EF 3.1)

- **Normalization** allows to express the results of different impact categories in the same unit by relating them to a reference system.
- **Weighting** involves assigning a factor to this value based on the **current importance** of the represented environmental issues and its **robustness.**

kg CO_2 eq

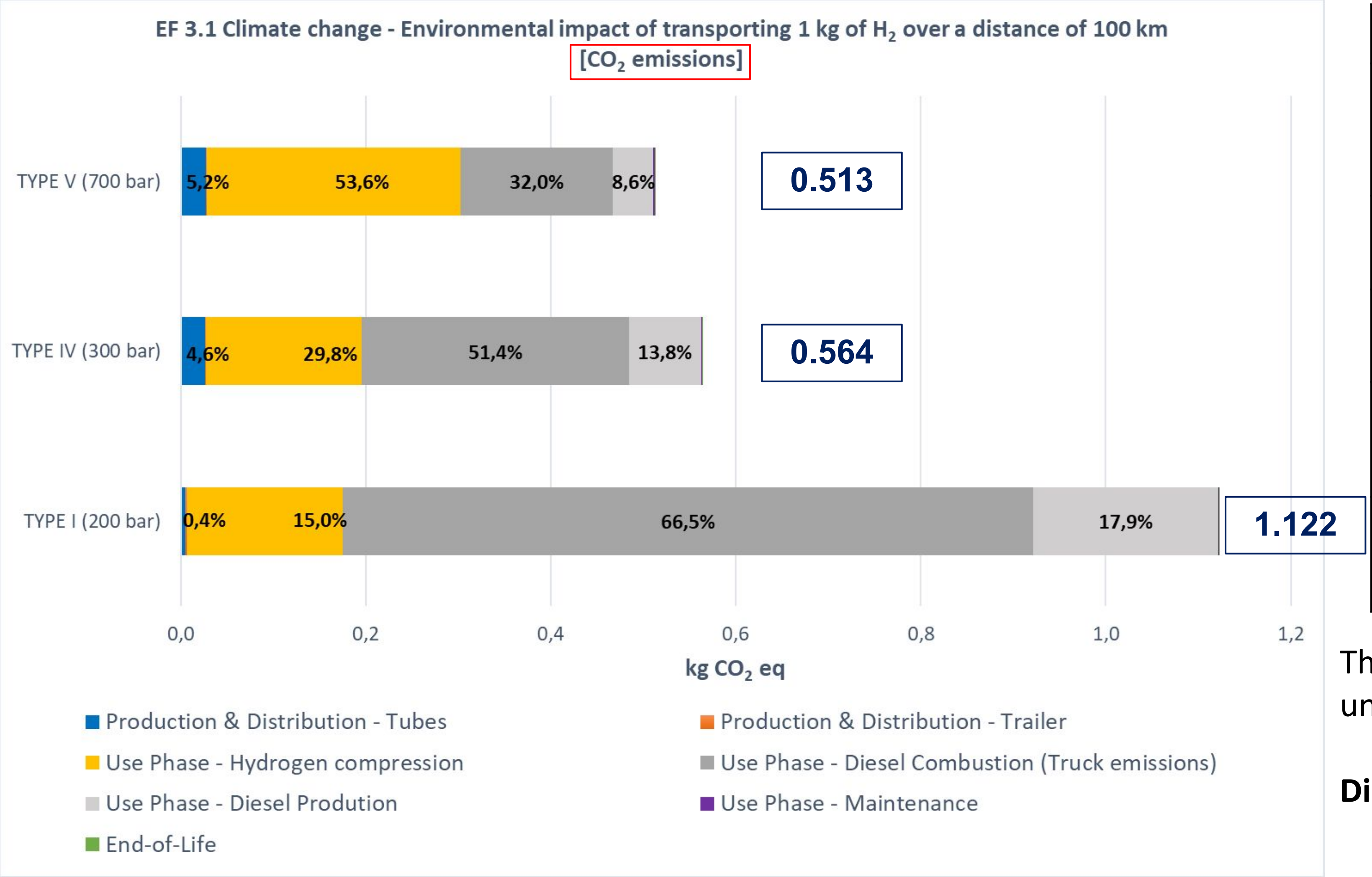
kg Sb eq / MJ

Disease incidences

kBq U235 eq

III.2. LCIA – Comparison between TYPE I, TYPE IV & TYPE V for transporting 1 kg of hydrogen over a distance of 100 km.

The results for all systems must be reported in a common unit: transport of **1 kg of hydrogen over 100 km distance**



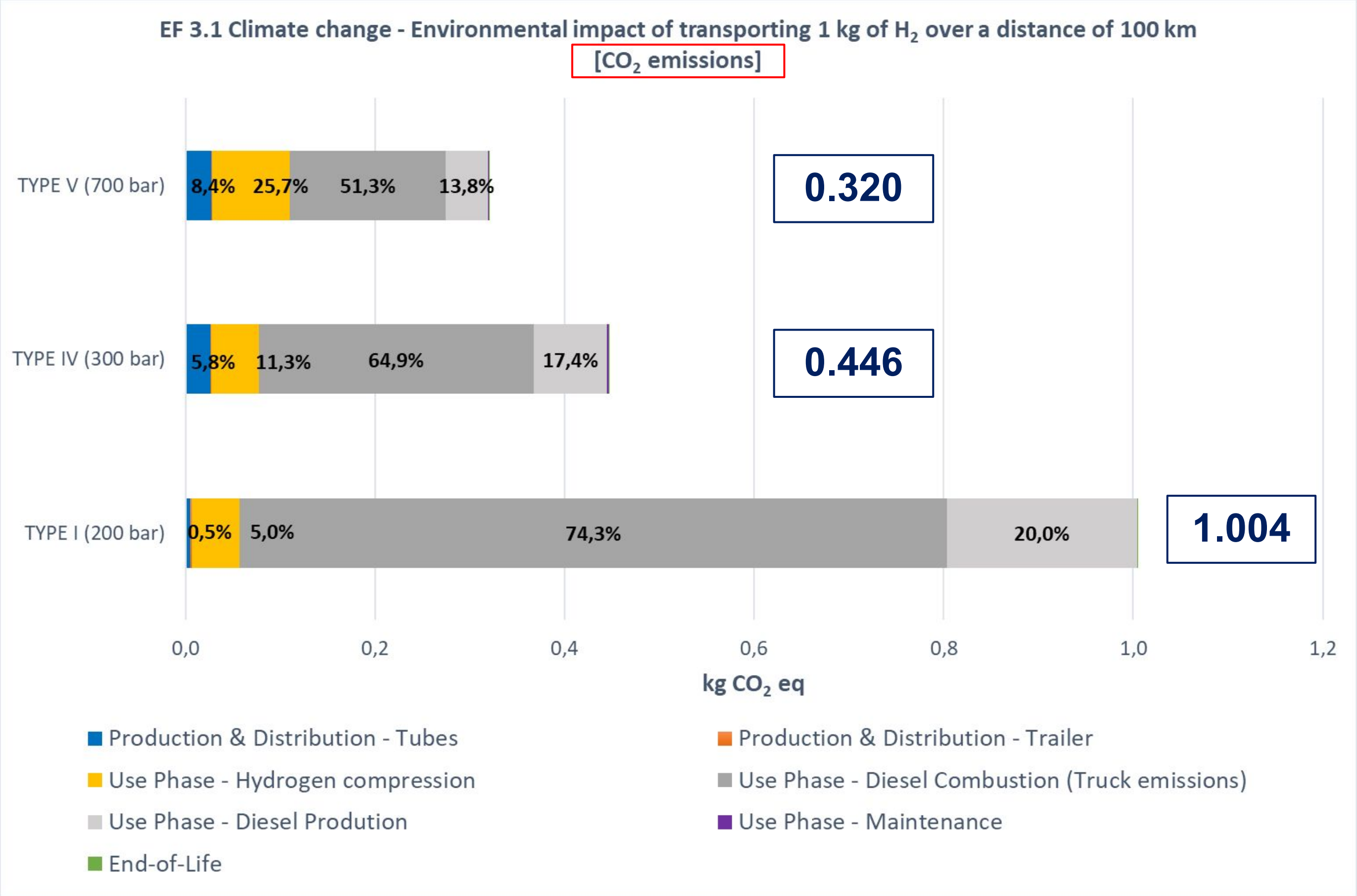
Evolution between type IV and type V trailers	
EF 3.1 Climate Change - total (kg CO_2 eq.)	- 9 %
EF 3.1 Resource use, fossils (MJ)	+ 41 %
EF 3.1 Resource use, mineral and metals (kg Sb eq.)	+ 11 %
EF 3.1 Particulate matter (Disease incidences)	+ 8 %
EF 3.1 Ionising Radiation, human health (kBq U235 eq)	+ 64 %

These results are valid only for the functional unit with the following standard itinerary:

Distance Supplier – Customer =150 km

III.2. LCIA – Comparison between TYPE I, TYPE IV & TYPE V for transporting 1 kg of hydrogen over a distance of 100 km.

Transport of **1 kg of hydrogen over 100 km** distance with a defined standard itinerary (distance Supplier-Customer = 500 km)

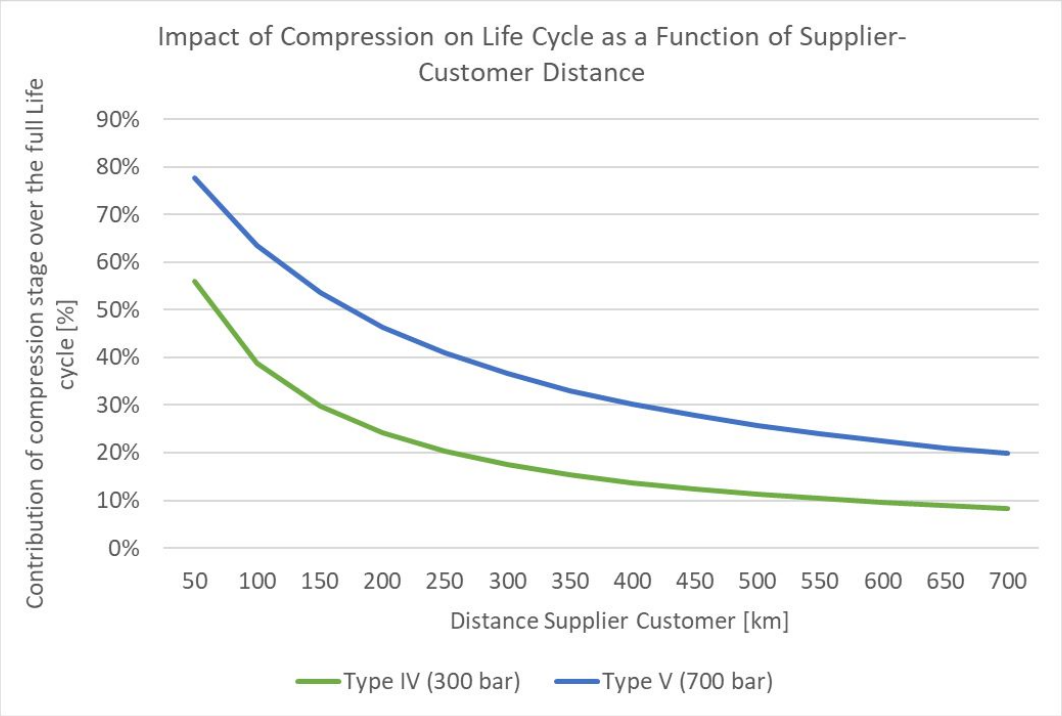


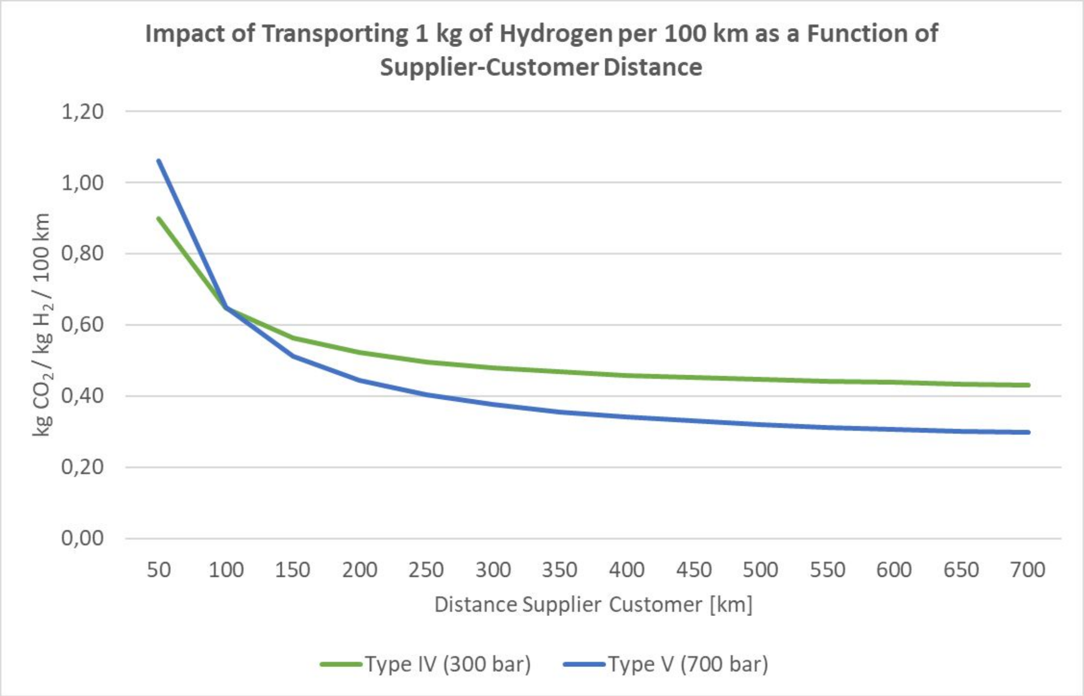
Evolution between type IV and type V trailers	
EF 3.1 Climate Change - total (kg CO_2 eq.)	- 28 %
EF 3.1 Resource use, fossils (MJ)	+ 14 %
EF 3.1 Resource use, mineral and metals (kg Sb eq.)	- 6 %
EF 3.1 Particulate matter (Disease incidences)	- 15 %
EF 3.1 Ionising Radiation, human health (kBq U235 eq)	+ 64 %

Distance Supplier – Customer = ~~150 km~~ 500 km

⚠ A longer delivery distance favors type V hydrogen tanks because the **fixed energy cost of compressing** hydrogen to 700 bar **is better amortized** over **more kilometer**.

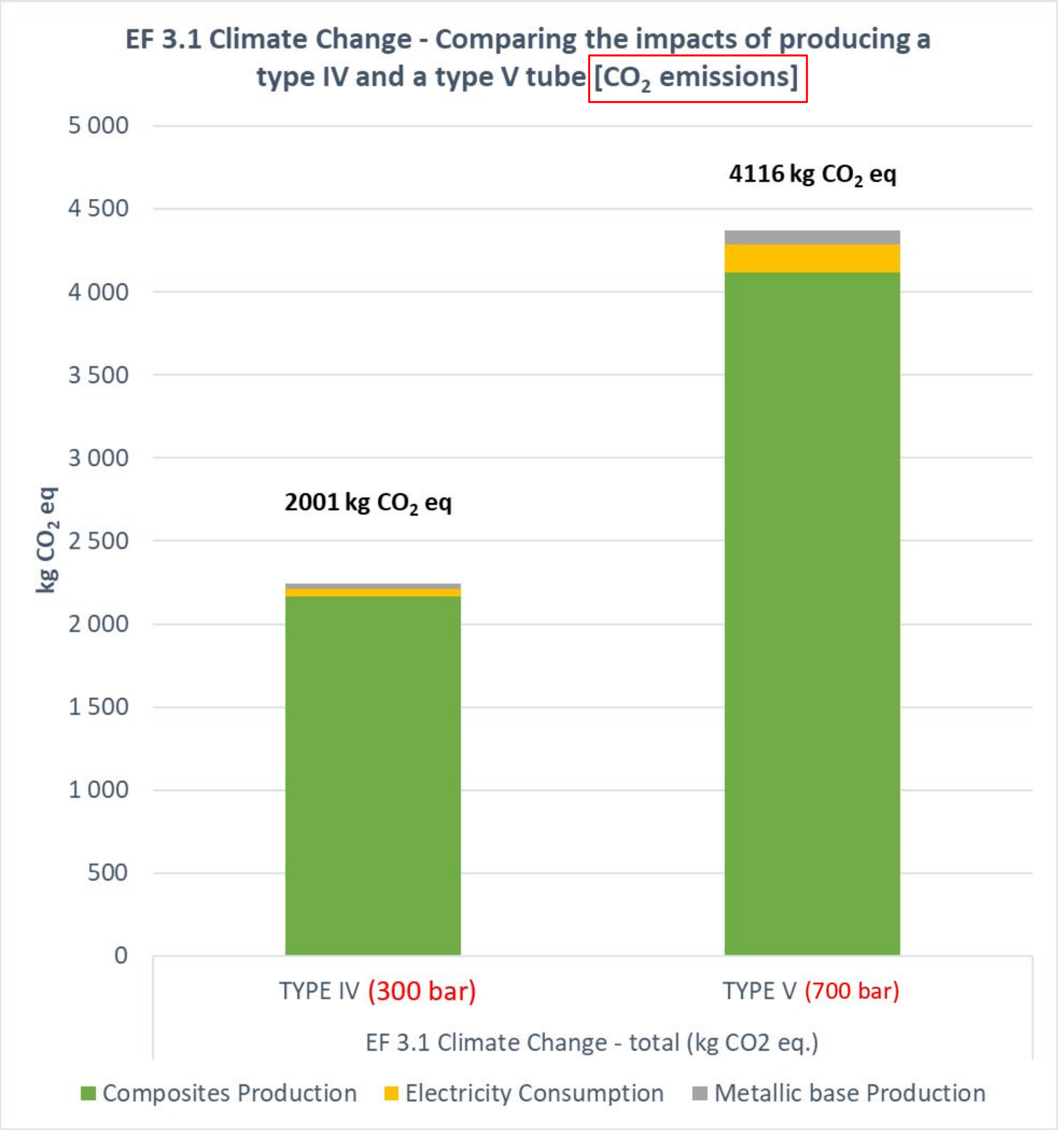
III.2. LCIA – Comparison between TYPE I, TYPE IV & TYPE V for transporting 1 kg of hydrogen over a distance of 100 km.





- Increasing the distance between the supplier and the customer significantly reduces the share of the 700-bar compression stage in the overall life cycle.
- The cost of compressing hydrogen to 700 bar is much higher than to 300 bar.
- The supply chain must be adapted
- Adjust the operating pressure based on the number of customers served, the total distance traveled, and the quantity of hydrogen is paramount to lower CO2 footprint

III.3. LCIA – Production of TYPE IV & TYPE V tubes



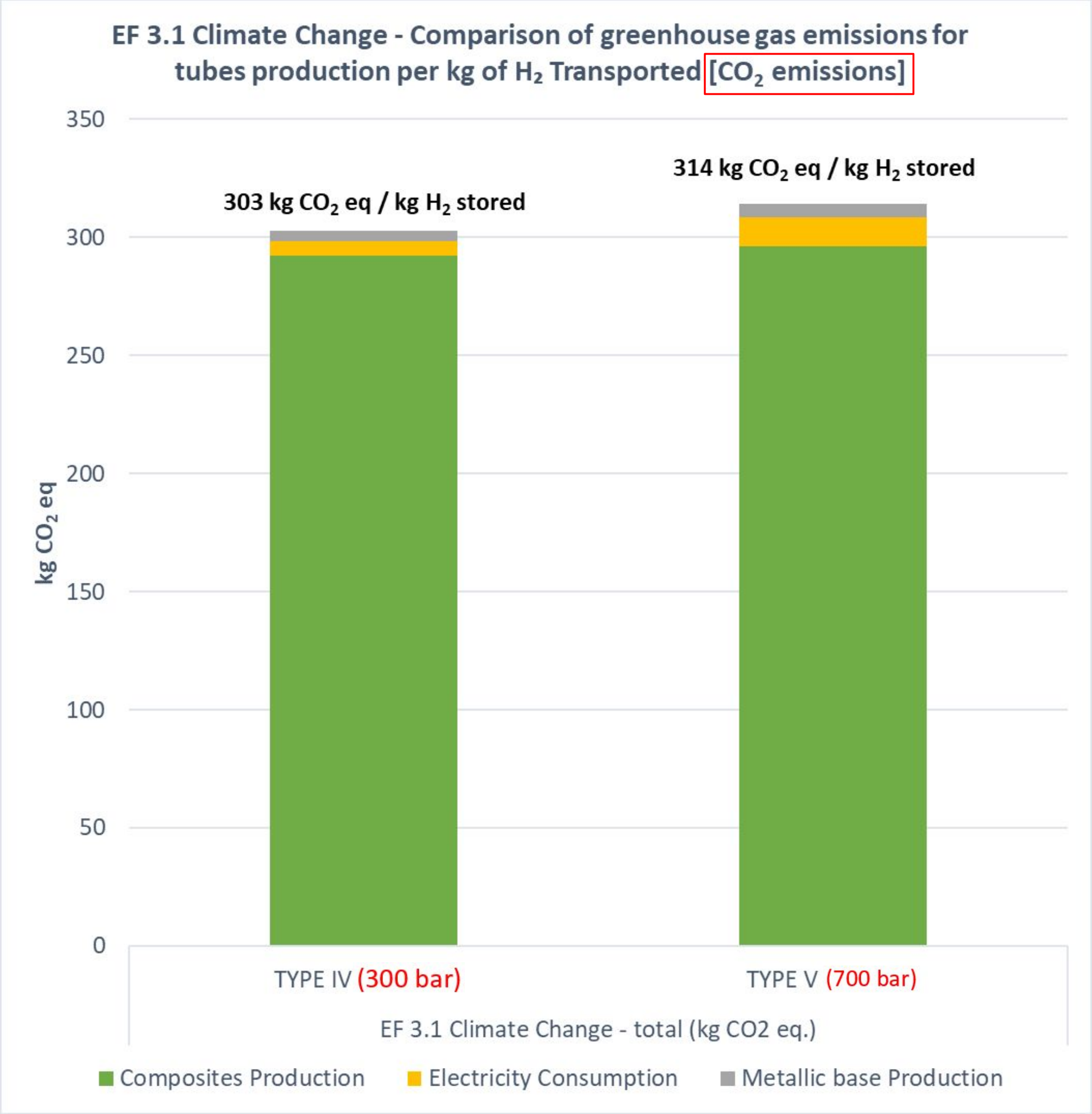
- Type V tube mass = **2.1 x** Type IV tube mass
- Type V tube CO_2 emissions = **2 x** Type IV tube CO_2 emissions
- Almost the same number of tubes and the same volume
- Higher quantity of material for the production phase and therefore higher quantity of carbon fibre

	Hydrogen storage capacity (kg H2 per tube)
TYPE IV	7,40
TYPE V	13,90

Interesting to look at the impact in terms of hydrogen transport capacity:

$$\frac{CO_2 \; emissions \; to \; produce \; 1 \; tube}{Hydrogen \; Storage \; capacity}$$

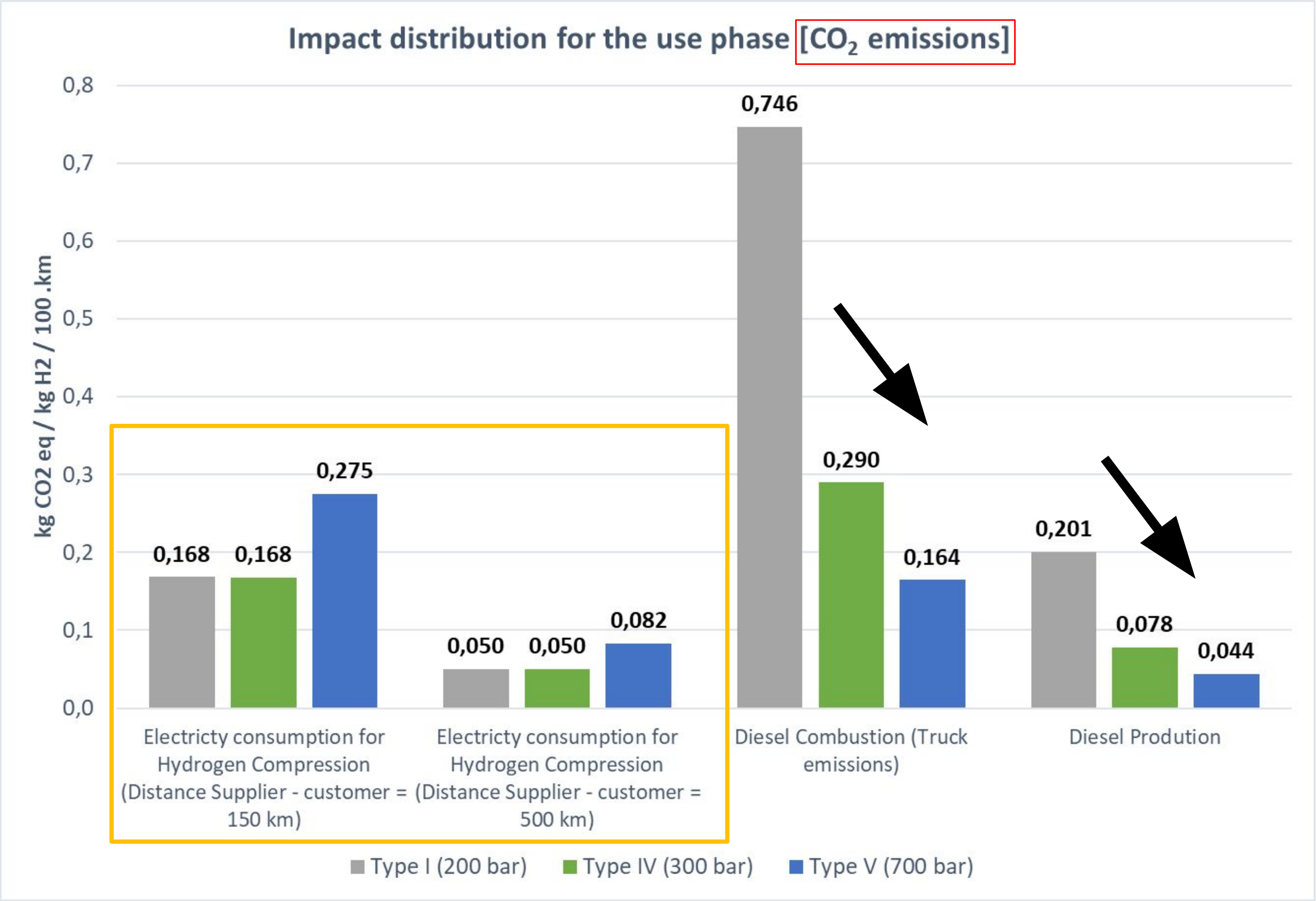
III.3. LCIA – Production of TYPE IV & TYPE V tubes



Contribution of the tubes manufacturing phase to the entire life cycle:

Impact Categories	TYPE IV	TYPE V
EF 3.1 Climate Change - total (kg CO_2 eq.)	4,60%	5,20%
EF 3.1 Resource use, fossils (MJ)	2,00%	1,90%
EF 3.1 Resource use, mineral and metals (kg Sb eq.)	29,70%	17,20%
EF 3.1 Particulate matter (Disease incidences)	6,90%	9,30%
EF 3.1 Ionising Radiation, human health (kBq U235 eq)	0,20%	0,40%

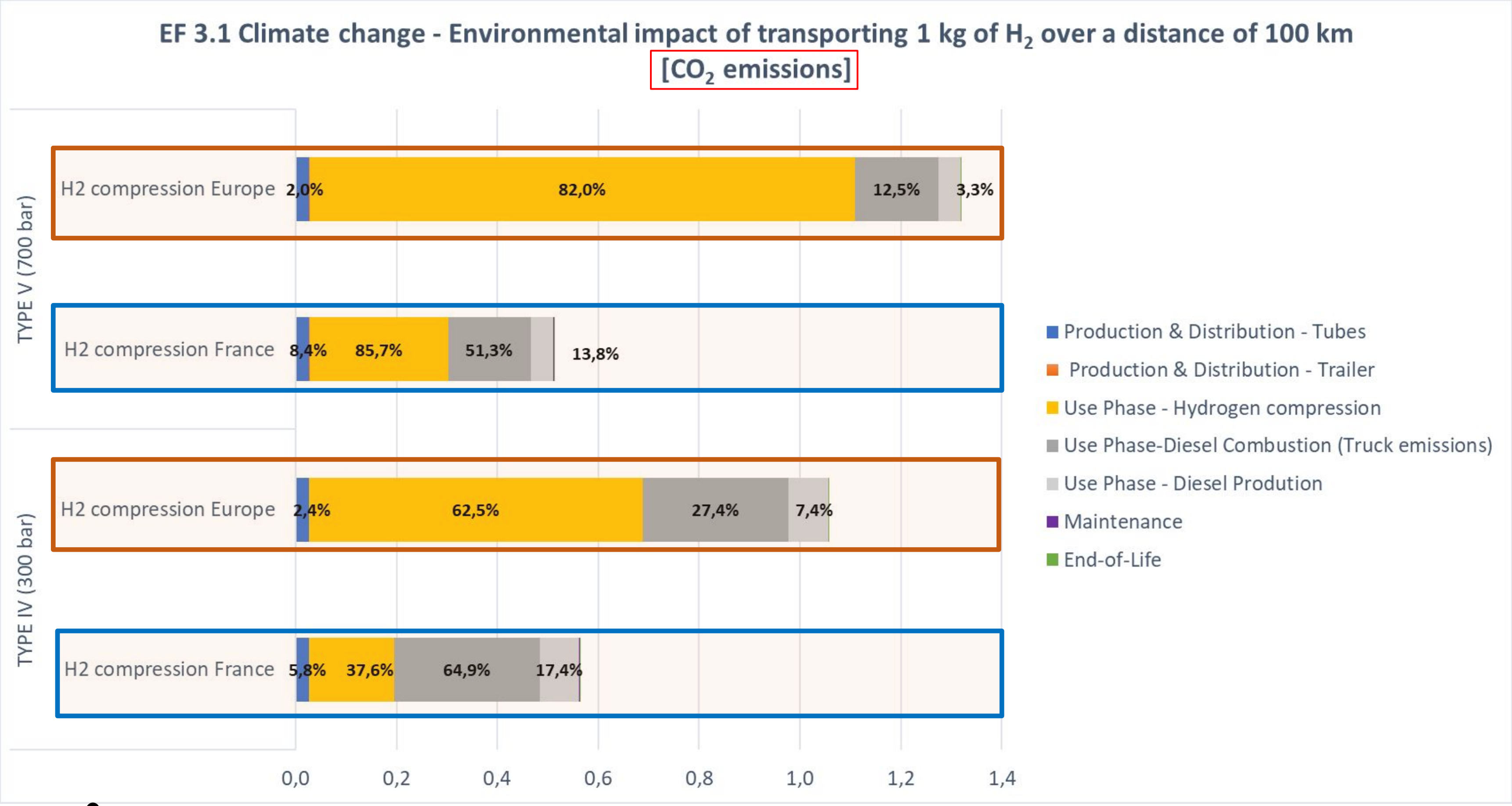
III.4. LCIA – Impact distribution for the use phase



- Compressing hydrogen to 700 bar significantly **reduce diesel consumption** (more hydrogen transported)
- The cost of **compression** at 700 bar is **energetically high**

IV. Interpretation of the Results – Hydrogen compression country

Transport of **1 kg of hydrogen over 100 km** distance with a defined standard itinerary (distance Supplier-Customer = 150 km)



Reduced impacts between type IV and type V trailers		
Compression Country	**France**	**Europe**
EF 3.1 Climate Change - total (kg CO_2 eq.)	- 3 %	+ 25 %
EF 3.1 Resource use, fossils (MJ)	+ 45 %	+ 37 %
EF 3.1 Resource use, mineral and metals (kg Sb eq.)	+ 13 %	+ 25 %
EF 3.1 Particulate matter (Disease incidences)	+ 14 %	+ 33 %
EF 3.1 Ionising Radiation, human health (kBq U235 eq)	+ 64 %	+ 64 %

Since hydrogen compression has a significant impact across all impact categories, it is crucial to perform this process using a **low carbon intensity electricity mix**.

IV. Interpretation of the Results– Hydrogen Trucks for use phase

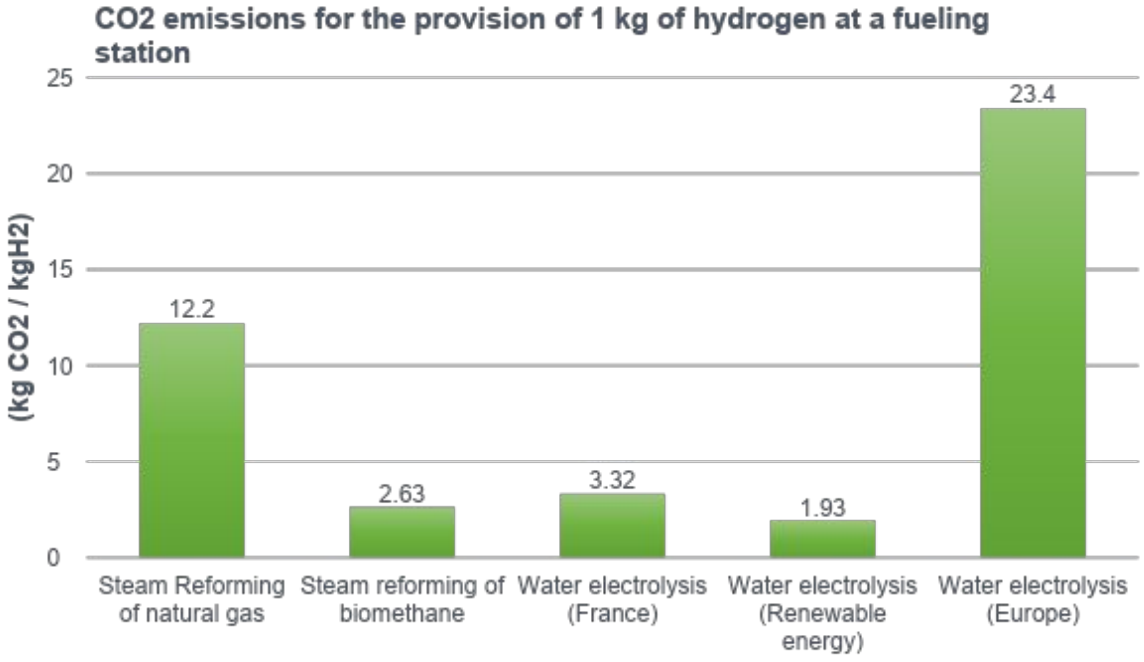
Use phase is the one that **contributes the most** to the environmental impacts of the studied system. Therefore, it is interesting to investigate the feasibility of using **hydrogen-powered trucks** for the daily transport of hydrogen.

Important Data:

Truck's hydrogen consumption

Truck Model	Hydrogen Consumption (kg H_2/100km)
NIKOLA TRE FCEV	8.7
HYZON HYMAX 46 T	8.8
Mercedes-Benz GenH2	8

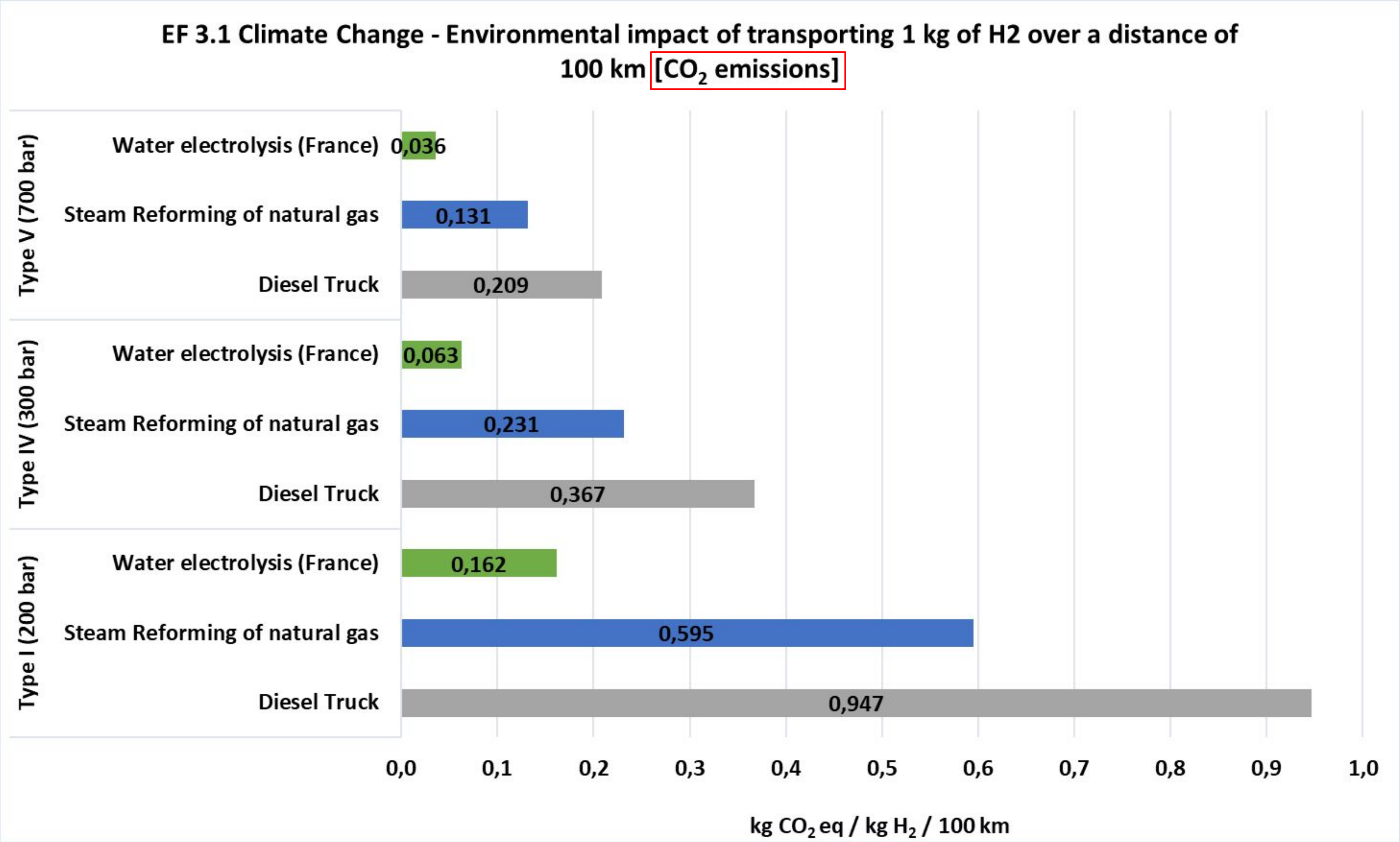
Hydrogen Production



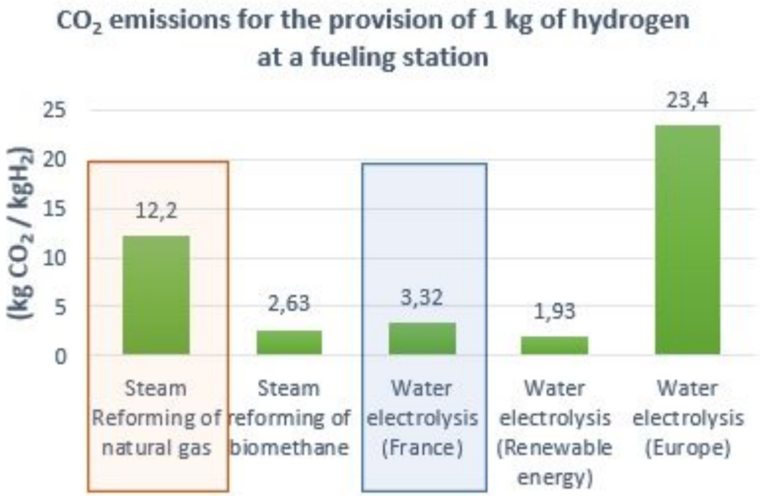
***References:* Mobilité France Hydrogène**: *Quelles perspectives pour le poids lourd électrique à hydrogène pour le transport de marchandises ? (2022)*

Truck-Trailer (gross weight = 32-44 T) **7-9 kg H_2 / 100km**

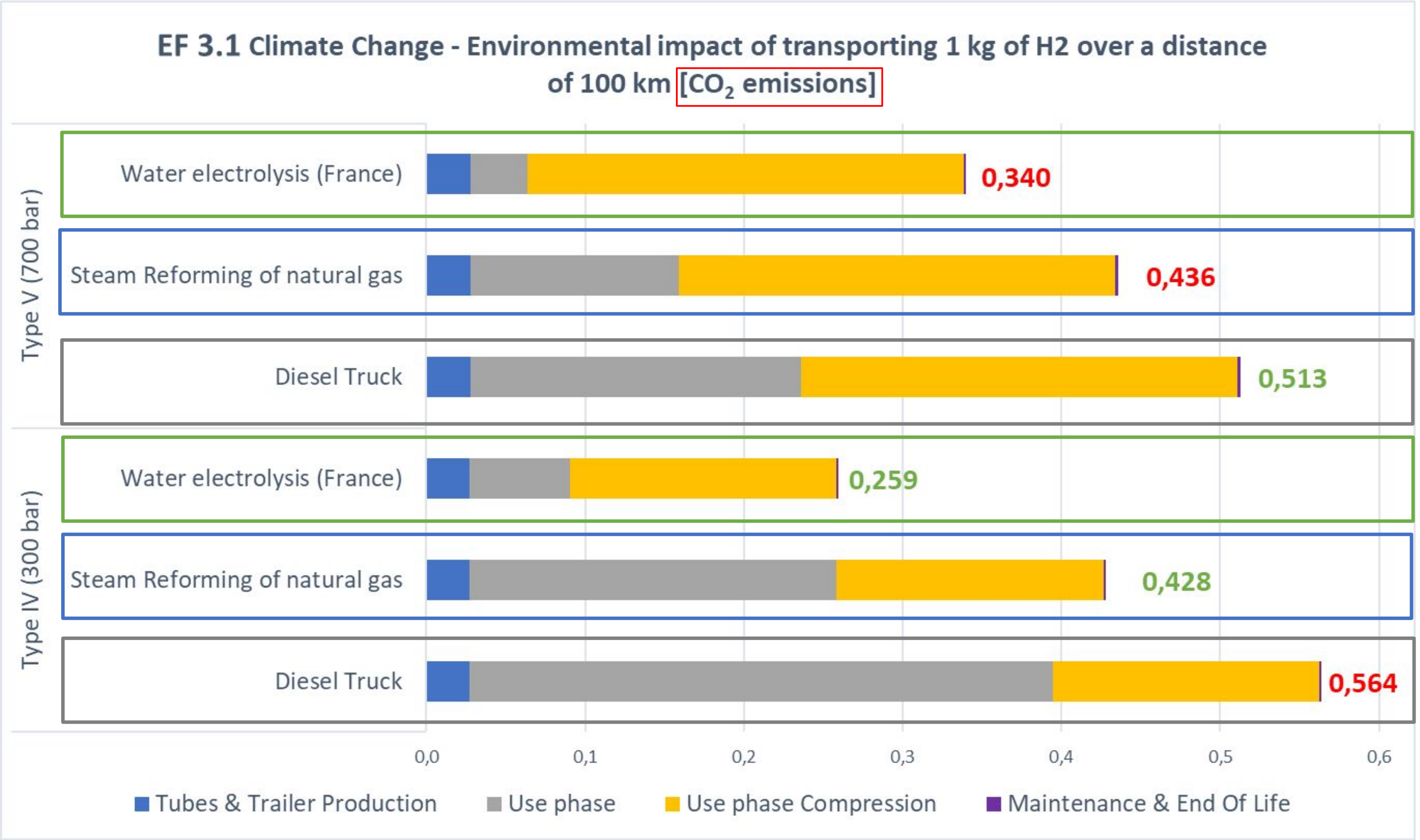
IV. Interpretation of the Results– Hydrogen Trucks for use phase



To reduce the impact of use phase, **hydrogen production must be decarbonized**.



IV. Interpretation of the Results– Hydrogen Trucks for use phase

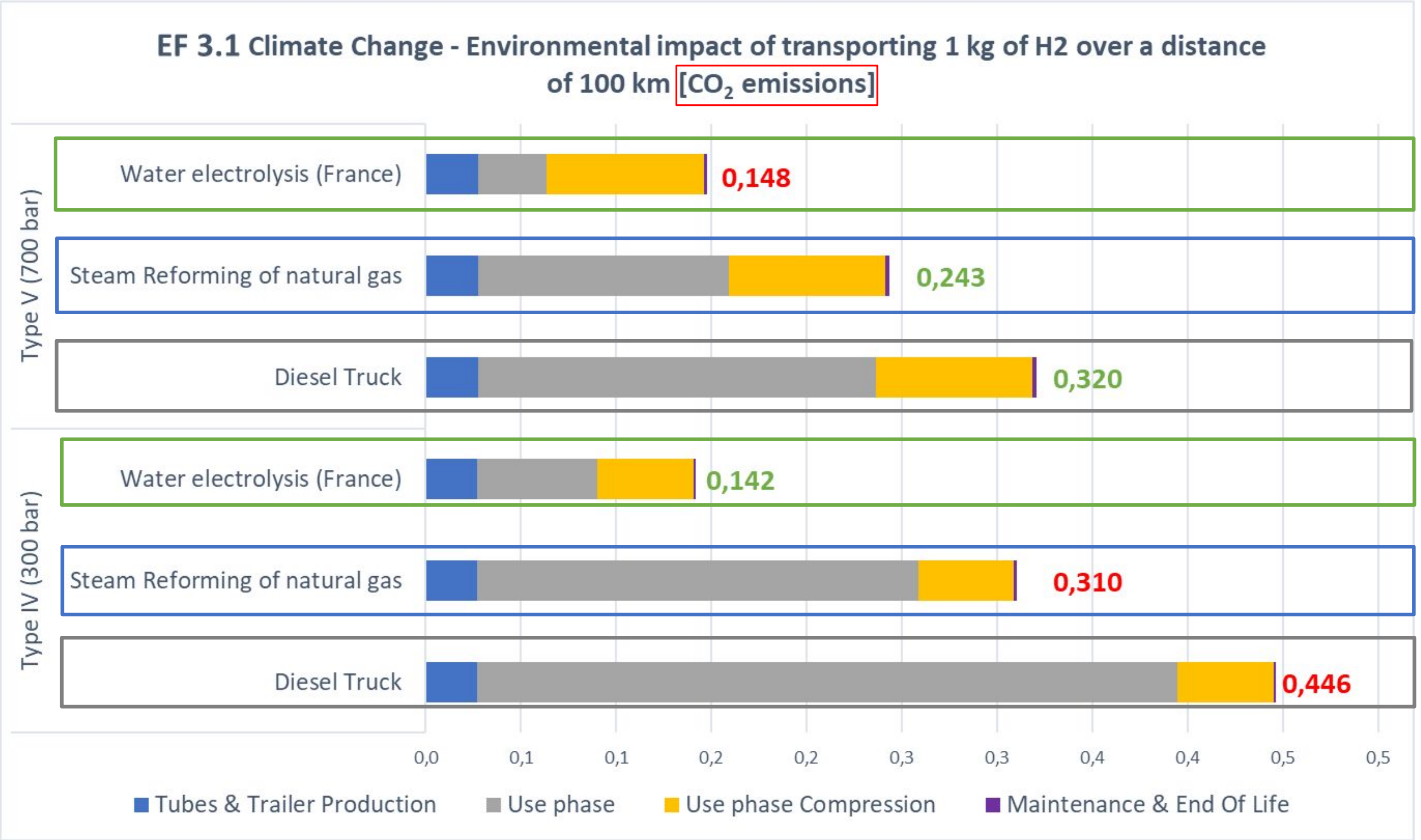


Distance Supplier – Customer =150 km

- The use of **hydrogen-powered trucks reduces emissions** during use phase and therefore the impacts over the entire life cycle.
- Impact of hydrogen compression remains fixed and therefore takes up a **larger share** of the overall life cycle
- For a Supplier - Customer distance of 150 km, **type IV is more advantageous** in this scenario.

How can Type V tubes be made more advantageous?

IV. Interpretation of the Results– Hydrogen Trucks for use phase



- Increasing the distance improves the results of type V.
- The **results are better for type V** if the hydrogen is produced through **natural gas steam reforming.**
- The results are better for type IV if the hydrogen is produced through water electrolysis.

Adapt Supply Chain to maximise benefit of 700 bar Type V storage

Distance Supplier – Customer = ~~150 km~~ 500 km

Increase the distance Supplier - Customer

V. Conclusion

Transport in **Type IV** tubes significantly **reduces CO2 emissions** compared to Type I.

- 50 % for the reference case

More generally, transport in **Type IV** tubes **reduces impacts in all categories** compared to type I.

Type V allows for a reduction of impacts compared to Type IV, but to a **smaller degree** and for more **specific cases**.
To maximise CO2 reduction at high pressure with Type V tubes, adapt supply chain.

On-site Hydrogen **production** / **Adapting** hydrogen **pressure** based on the **distance** traveled.

The hydrogen mass transported is larger with Type IV, and increasing compression from 200 to 300 bar does not lead to a significant rise in impacts.

Compared to Type I, when using Type IV the impacts are significantly reduced **for transporting 1 kg of hydrogen**.

The Type V results show the significant impact of **increasing compression from 300 bar to 700 bar.**

Therefore, the **operating pressure** must be **adjusted** based on the number of customers served, the distance, and the quantity of hydrogen to be delivered.

Supply chain must be adapted !

V. Conclusion

Key levers for reducing environmental impact

- Significant influence of the **electricity mix** used.
- Transport with **hydrogen-powered trucks** or **hydrogen internal combustion engine.**
- Hydrogen delivery based on customers through **intermodal transportation**.
- Investigate the **recycling and reuse of type V tubes**. Work on decreasing CO2 impact of Carbon fibre by using **better electricity mix** and/or use **low impact precursor**

→ For electricity consumption during hydrogen compression
→ For carbon fibre manufacturing
→ For hydrogen production, if hydrogen-powered trucks are used for its delivery

VI. Next steps

- Analyze the **different supply chain possibilities** in greater depth.
- Compare the type IV and type V at **equivalent service pressure**.
- Determine the **optimal operating pressure** based on the situation.
- Possibility of using **carbon fibers with a cellulose-based precursor** instead of PAN.

HIGH PAYLOAD HYDROGEN TRAILERS WITH NEW COMPOSITE CYLINDERS

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