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NoTank

NOVEL COMPOSITE PROPULSION TANK ARCHITECTURE FOR SMALL SATELLITES

NOTANK - NOvel composite propulsion TANK architecture for small satellites

esa

Final presentation

25 | March | 2024

Subcontractor

Frezite High Performance

U.PORTO

CONTENTS

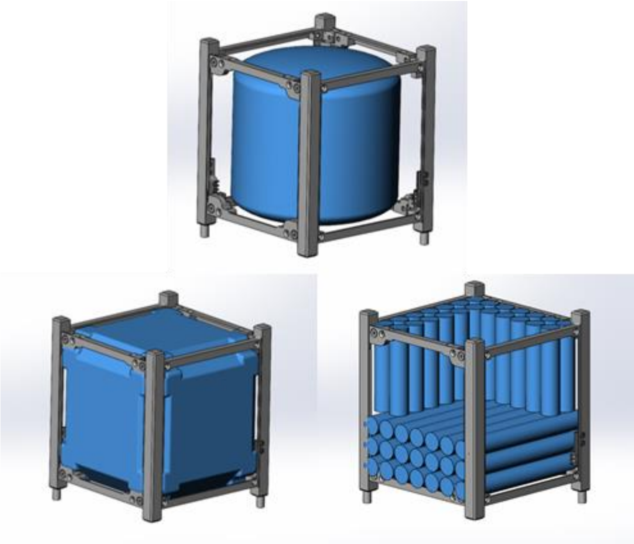
Since 1986

1.

Project overview

GSTP Element 1

The main technical objective is to develop **propulsion tanks** with **non-conventional architectures** that maximize the **volume storage ratio** inside small satellites while being suitable for **mass production** with **reduced costs.**



- Maximization of storage volume ratio in small satellites using propulsion tanks (thus, minimizing the overall satellite volume).
- Suitability for high pressure (200 – 300 bar) propellants.
- Reduce production cost (aimed at a reduction of 30% to 50%, roughly).
- Suitability for mass production (small to medium series).
- Efficient customization for different small satellite series.

Status of current activities – Gantt Chart

Code	Task	Resp.	06-23 M1	07-23 M2	08-23 M3	09-23 M4	10-23 M5	11-23 M6	12-23 M7	01-24 M8	02-24 M9
WP1000	**Benchmarking and preliminary solution definition**	**FHP**									
WP1100	Preliminary definition of alternative concepts	INEGI									
WP1200	Identification of design and production drivers	FHP									
WP1300	Geometries vs. manufacturing processes trade-off	INEGI		**TN1**							
WP1400	Definition of requirements	FHP		**TN2**							
WP2000	**Conceptual design of storage system**	**INEGI**									
WP2100	Definition of topological concepts to be studied	INEGI									
WP2200	Materials preliminary selection and characterisation	INEGI									
WP2300	Preliminary design of alternative concept	INEGI					**TN3 TN4**				
WP3000	**Manufacturing process conceptual definition**	**INEGI**									
WP3100	Preliminary definition of manufacturing processes for conceptual designs	INEGI									
WP3200	Tooling, equipment and process design	INEGI									
WP3300	Manufacturing plan definition	INEGI									
WP3400	Manufacturing process implementation plan for prototypes production	FHP						**TPc**			
WP4000	**Design and manufacturing concepts validation**	**FHP**									
WP4100	Laboratory scale trials for geometries and manufacturing conditions	INEGI									
WP4200	Breadboards manufacturing in semi-industrial facilities	FHP									
WP4300	Validations tests	FHP							**TN5**	**TN8 | HW1**	
WP4400	Correlations of validation results with design concept	INEGI									
WP5000	**Recommendations for future work**	**INEGI**									
WP5100	Future evolutions of proposed designs	INEGI									
WP5200	Needs for manufacturing processes development and implementation	INEGI									
WP5300	Technology adjustment to market trends and opportunities	FHP									
WP5400	Roadmap developmentation and implementation plan	FHP									**TN4v2**
WP6000	**Project management**	**INEGI**									
WP6100	Management and technical coordination	INEGI		IM1			IM2			IM3|4	
WP6200	Technical coordination of application and industrial implementation	FHP	M					MS1			MS2 | 3

INEGI
FHP

Outputs List.

Documents:
- **TN1:** State-of-the-art (M2) (Delivered to ESA)
- **TN2:** Requirements List (M2) (Delivered to ESA)
- **TN3:** Design Justification file (M5)
- **TN4:** Design Development and Verification Plan_v1(M5)
- **TPc:** Test Plan Contributes
- **TN5:** Test Plan (M7)
- **TN6:** Test Report (M8)
- **TN4v2**: design development and verification plan_v2 (M9)

Prototypes:
- **HW1:** Laboratory scale prototypes (M8)

Milestones:
- **MS0** - Kick-off (Closed)
- **IM1** - RR -Requirements Review (TN1 | TN2) WP1000
- **IM2** - PDR - Preliminary Design Review (TN3 | TN4) WP2000
- **MS1** - MRR - Manufacturing Readiness Review WP3000
- **IM3** - TRR - Test readiness Review (TN5) WP4000
- **IM4** - PTR - Post-Test Review (TN6 / HW1)) WP4000
- **MS2** - FR -Final Review (TN4_v2) W5000
- **MS3** - FP -Final Presentation (FP) W6000

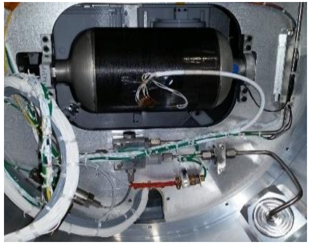
On-going
Pending of approval
Closed
Not-started

State-of-the-art

Overview of storage tanks concept

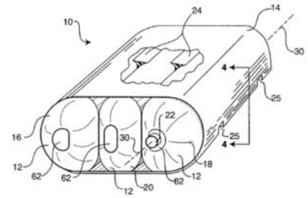
Classical designs

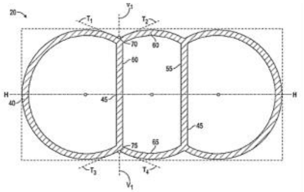
Sphere/cylinder



Alternative design concepts

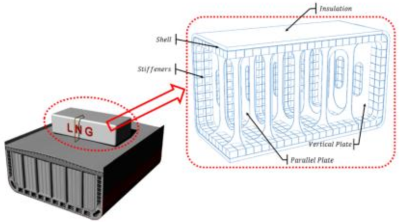
Conformable





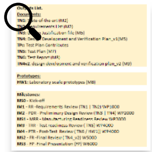
Cylinder array

Rectangular

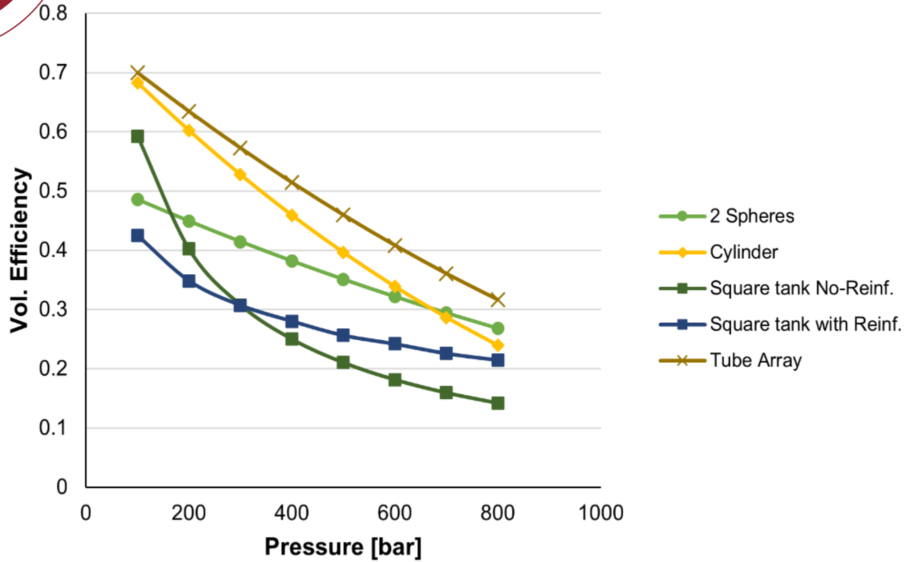


Toroidal

State-of-the-art



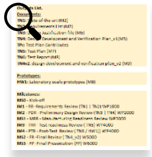
Preliminary volumetric efficiency assessment



Based on parametric assessments, and literature overview, the main findings regarding storage system geometries are:

- The **cylindrical design** shows an **average performance** over the entire range of pressures.
- The **square design is mostly efficient for small service pressures**, as its efficiency drastically reduces over the service pressures span.
- The **conformable cylinder array consistently outperforms the conventional cylindrical**, since smaller wall thicknesses can be used.

State-of-the-art



Geometries Vs Manufacturing

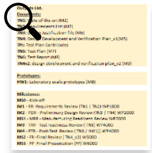
Manufacturability assessment of each tank geometry

		Tank geometry						
		Sphere	Cylinder	Conformable	Toroid	Rectangular	Cylinder array	**Total**
Manufacturing process	Filament winding	3	3	2	1	2	2	**13**
	Resin transfer moulding	2	2	2	2	3	2	**13**
	Roll Wrapping	1	3	1	1	2	2	**11**
	Hot-stamping	1	1	1	1	2	1	**7**
	Braiding	1	1	1	1	1	3	**8**
	Total	**9**	**11**	**9**	**7**	**11**	**12**	

• **Score 1:** Manufacturing process is hardly applicable; • **Score 2:** Manufacturing process is applicable; • **Score 3:** Manufacturing process is ideal

Filament winding, resin transfer moulding and roll-wrapping are the most flexible processes, taking the span of considered geometries. Analogously, the cylinder array tank geometry allows the most flexibility manufacturing-wise.

State-of-the-art



Conclusions

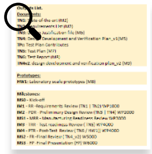
The current trend of **new pressure vessel designs aims to enhance volume efficiency and customizability**, ultimately trying to contribute to greater compactness of spacecraft systems by optimizing space utilization;

On preliminary evaluations of volume efficiency (i.e. ratio between storage volume and bounding box volume), **the cylinder tube array storage system has demonstrated superior performance**, particularly when considering higher service pressures;

Focus on the conceptualization of a system that aligns with both mission objectives and system requirements;

A selection of the most suitable candidate technologies for each storage system has been proposed with a focus on identifying the best candidates that align with the global objectives of this activity – increased customizability and reduced manufacturing costs;

Requirements Definition



For the requirements definition, a series of design and manufacturing drivers have been taken into account.

Design:

- **Propellant**: Guarantee chemical compatibility.
- **Pressure**: Capability to hold fluids at high pressure.
- **Temperature**: Able to comply with temperature range.
- **Volume**: Efficient storage of required propellant quantities.
- **Mass**: Low mass for high mass-to-storage ratio
- **Costumizability**: Allow for quick rearangement to different requirements

Manufacturing:

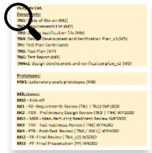
- **Production Volume:** Be able to supply and supress market needs for smallsatellites.
- **Lead Time:** Be able to quickly adapt manufacturing process to possible design changes.

Requirements Definition

Design requirements

Category	Requirement ID.	Requirement
General	REQ-GEN-01	The storage system shall be designed considering electric propulsion.
	REQ-GEN-02	The storage system shall be **compatible with either Xe, Ar or Kr.**
	REQ-GEN-03	The associated systems shall be compatible with communication requirements.
	REQ-GEN-04	The storage system shall be designed considering adequate sensors and monitorization systems.
	REQ-GEN-05	The storage system shall **provide a mechanical interface to the satellite**.
Design	REQ-DES-01	The storage system shall survive in space environment a minimum of the design lifetime.
	REQ-DES-02	The storage system shall be designed considering its demisability upon re-entry.
Structural	REQ-STR-01	The Maximum Expected Operating Pressure of the storage system **shall be 300 bar**
	REQ-STR-02	The storage system shall be designed for a **Burst Pressure equal to 1.5xMEOP**.
	REQ-STR-03	The storage system shall be designed considering the influence of vibration and shock loads expected during a typical launch.
	REQ-STR-04	The structure fundamental frequency shall be higher than 50 Hz (to be confirmed).
Material	REQ-MAT-01	The materials selected shall be in agreement with ECSS-Q-ST-70C.
	REQ-MAT-02	The materials selected shall have a shelf-life compatible with the manufacturing process.
Thermal	REQ-THE-01	The storage system shall not be **exposed to temperatures** outside the range **of -20°C and 60°C**.
Environmental	REQ-ENV-01	The system shall be compatible with the expected radiation environment.

Requirements Definition



Conclusion

Summary of the design critical requirements

Requirement ID.	Requirement
REQ-GEN-02	The storage system shall be **compatible with either Xe, Ar or Kr.**
REQ-STR-01	The Maximum Expected Operating Pressure of the storage system **shall be 300 bar**
REQ-STR-02	The storage system shall be designed for a **Burst Pressure equal to 1.5xMEOP**.
REQ-STR-04	The structure fundamental frequency shall be higher than 50 Hz.
REQ-THE-01	The storage system shall not be **exposed to temperatures** outside the range **of -20°C and 60°C**.

Commercial and technological interest of using electric propulsion has motivated the **selection of Xe, Kr, and Ar as the propellants to be considered** during the concept generation stage;

It was found to be inefficient from a design point of view to store these gases past the 300bar pressure range. For this reason, this value was chosen as the design

The range of operating temperatures has been selected based on previous missions, and led to **the definition of -20°C to 60°C**;

9.

Questions and Discussions

4. Design Development

Material selection

An extensive review of different resin and fiber technologies was made, to select the most appropriate for the current application considering material properties and availability.
A high strength carbon fiber Toray T700
Toughened epoxy resin

Resin Type	Product	Company	T_g (°C)	Carbon Fibre Type			Tensile Modulus (GPa)	Tensile Strength (MPa)	Strength and Stiffness ratio (MPa/GPa)	Confirmed Application in Space
				IM	HS	SM				
Polyimide	RS-8HT	Toray	314			T300	124	1738	14.0	Yes
Epoxy	FRVC411	SHD	160		T700		100	2000	20	Yes
	MTM 441	Solvay	190	IM5	HTS	HTA	129	2159	16.7	Yes
	TC275-1	Toray	183		TR505		146	2892	19.8	Yes
	EX-1522	Toray	180	IM7			172	2689	15.6	Yes

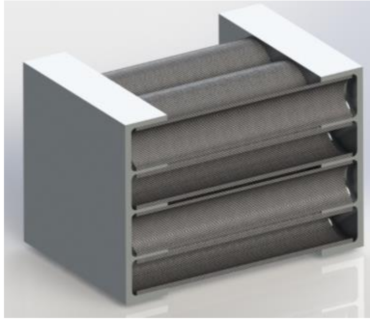
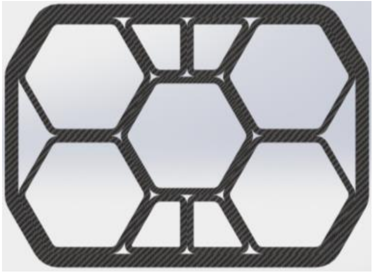
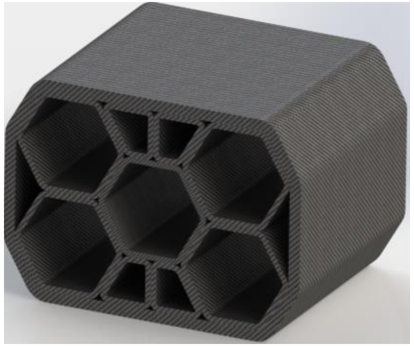
Characterization

A mechanical characterization test campaign was performed to measure the required properties for design.
Layer thickness is 0.16mm

Property	Value	Std. Dev.	Unit
E_{11}	102.33	6.11	GPa
E_{22}	6.38	0.23	GPa
ν_{12}	0.29	0.04	-
G_{12}	3.38	0.06	GPa
X_T	2002.12	173.5	MPa
Y_T	40.78	2.53	MPa
S_L	54.98	1.39	MPa

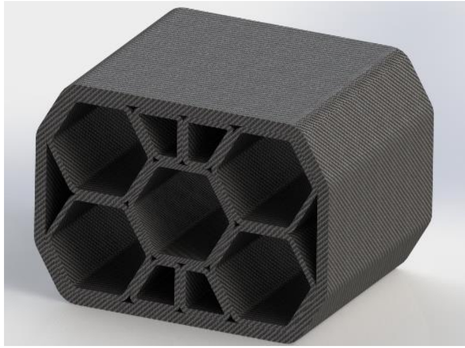
Design Development

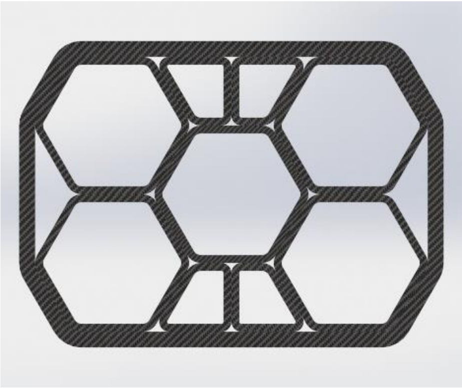
Two concepts were initially proposed:

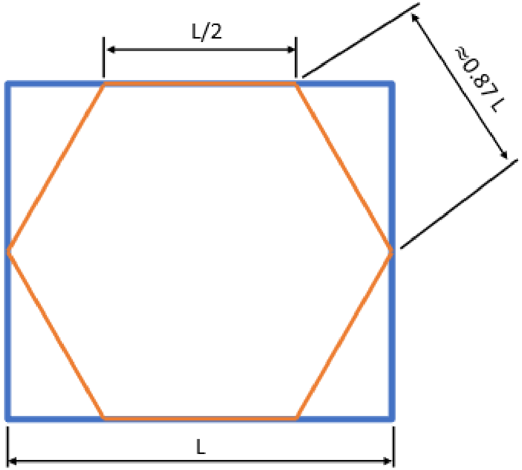
	1st	2nd
Concepts	 	 
Manufacturing process (WP3000)	- **Filament winding** (wet-winding) - Filament winding (tow-preg) - Hand lay-up / roll-up	
Experimental tests (WP4000)	- **Non-destructive testing** (Ultra-sound, Ray-x, eddy-current); - **Geometrical inspection** (geometric distortions compared to the nominal shape); - **Mass evaluation**; - Volume-to-weight ratio evaluation.	

Modular hexagonal concept

The first design iteration was based on a packing of hexagonal lobules, resembling a honeycomb structure



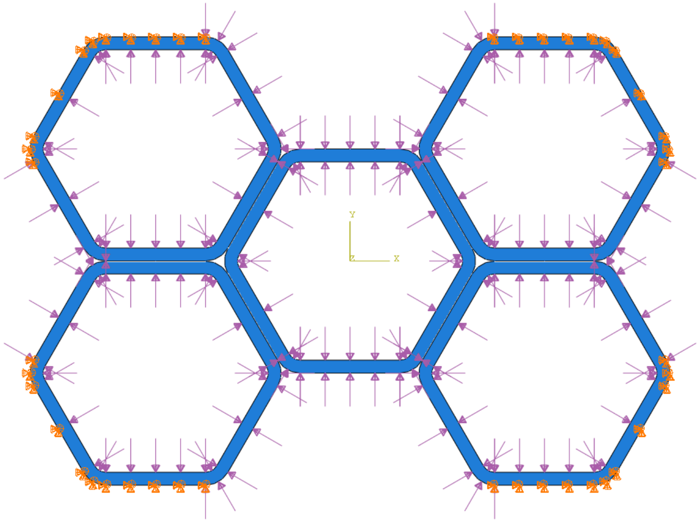


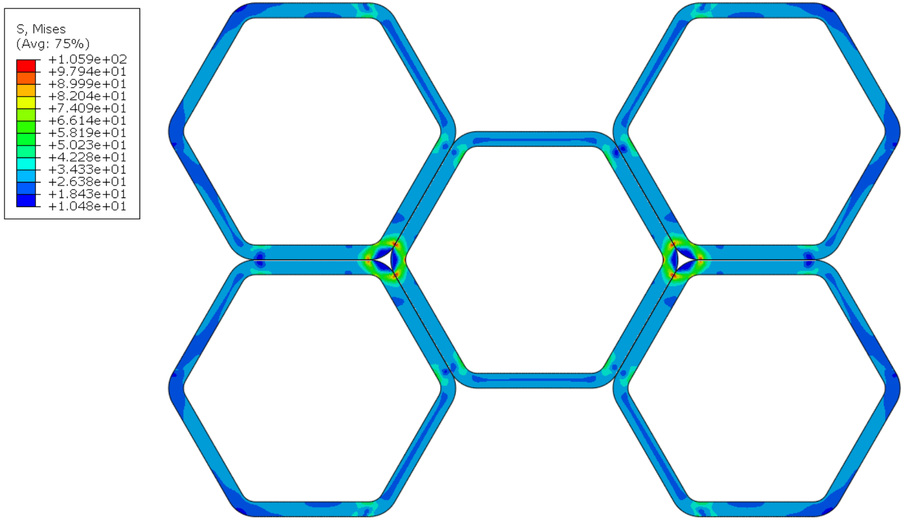


Modular hexagonal concept

The first design evaluation was conducted considering an infinitely stiff overwrapping structure, and cells composed by aluminum walls (composite approximation).

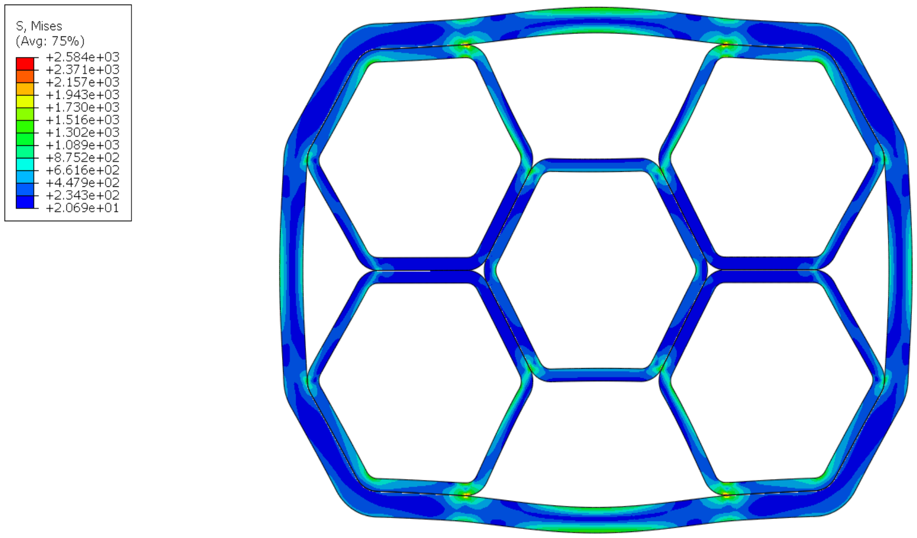
The results give a good indication of the feasibility of this solution, as long as the overwrapping structure maintains stiffness.





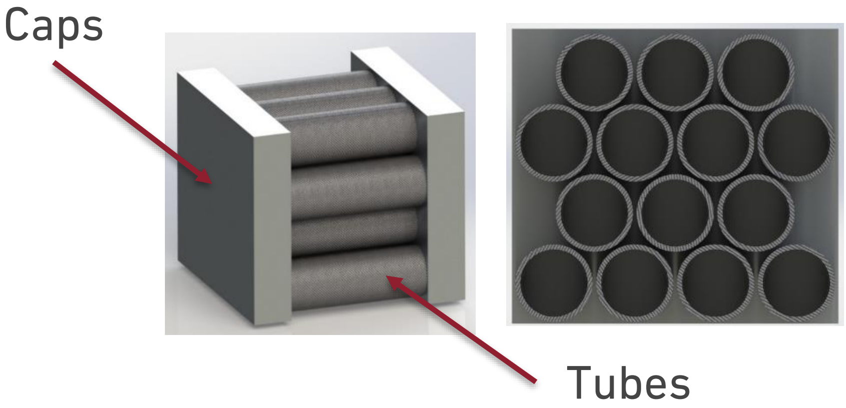
Modular hexagonal concept

- The overwrapping structure needs an increased stiffness compared to the hexagons.
- Analyses show that the **high stiffness dependence makes the design inadequate**.
- The **design failed due to high bending stress and stress concentrations** at the hexagon-overwrapping interface.



Tube array concept

- This alternative concept corresponds to an array of cylindrical tubes, packed in an hexagonal configuration to achieve maximum volumetric efficiency;
- Cylindrical configurations are the optimal shape to sustain internal pressure loading, minimizing wall thickness;
- The concept is formed by two major elements: Composite Tubes and Metallic Caps.
- Design focus: Composite laminate sequence, metallic caps detail dimensions and interfaces



Design Development

Metallic caps

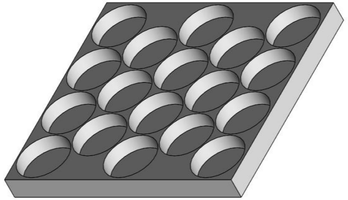
The cap functions are:

- Support and join the tube array;
- Enclose the internal storage volume;
- Inter-connect the internal volume.

Material

The material chosen for the caps are metallic alloys. Aluminium alloys are the preferred choice because of their lower weight and costs.

Material	Young's modulus [GPa]	Poisson's coefficient	Yield strength [MPa]
Aluminium alloy	71	0.33	700
Titanium alloy	96	0.36	930



The tubes

The tube functions are:

- The main storage component;
- Support the caps.

Main characteristics

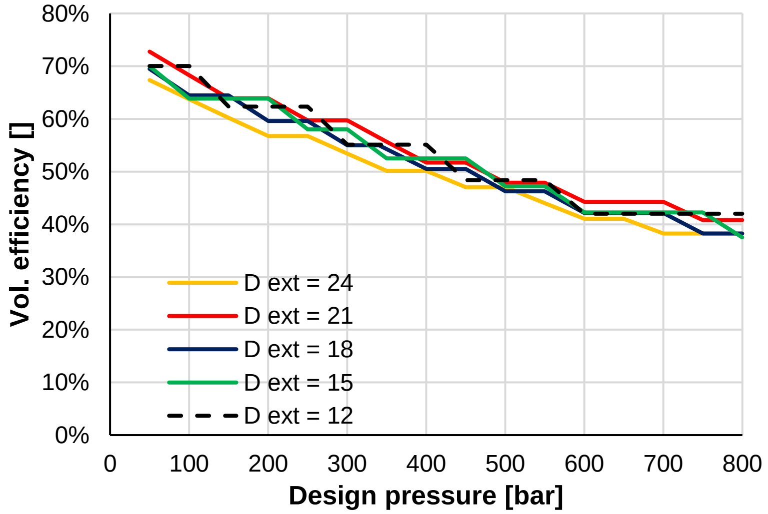
- High strength CFRP.
- Linerless construction.

Tube preliminary design

An analysis of the volumetric efficiency and weight are analyzed to define tube size, considering the internal pressure as the only relevant design load.

A non-optimized laminate sequence was used to kick-start the design process:

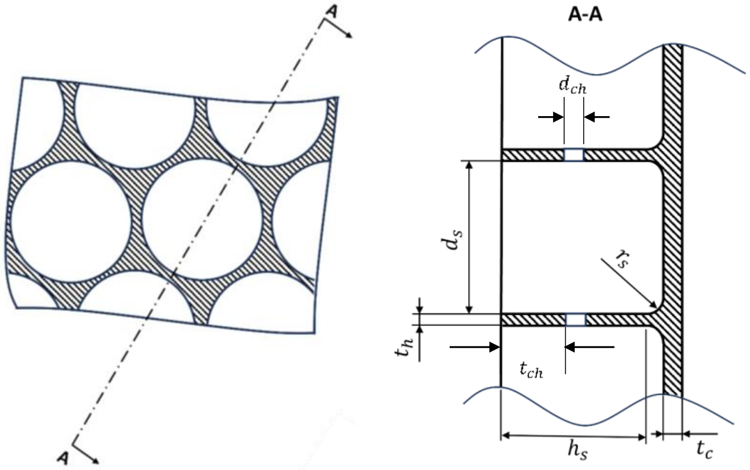
The best performant solution corresponds to a **tube with an external diameter of 20mm**.



External diameter	Design pressure	Horizontal length	Vertical length	Tube number	Thickness	Storage area	Vol. efficiency	Dry area
[mm]	[bar]	[mm]	[mm]	[u]	[mm]	[mm²]	[n.d]	[mm²]
12	300	89.00	95.93	59	0.96	4708.3	55%	1964
...								
17	300	89.00	90.37	26	1.28	4257.9	53%	1644
18	300	94.00	97.82	26	1.28	4868.1	53%	1748
19	300	99.00	88.26	23	1.28	4882.3	56%	1639
20	300	83.50	85.40	18	1.28	4299.9	60%	1355
21	300	87.50	92.00	18	1.28	4807.1	60%	1427
22	300	91.50	98.38	18	1.6	4996.6	56%	1846
...								
30	300	93.00	82.65	8	1.92	4299.9	56%	1355

Metallic caps parametrization

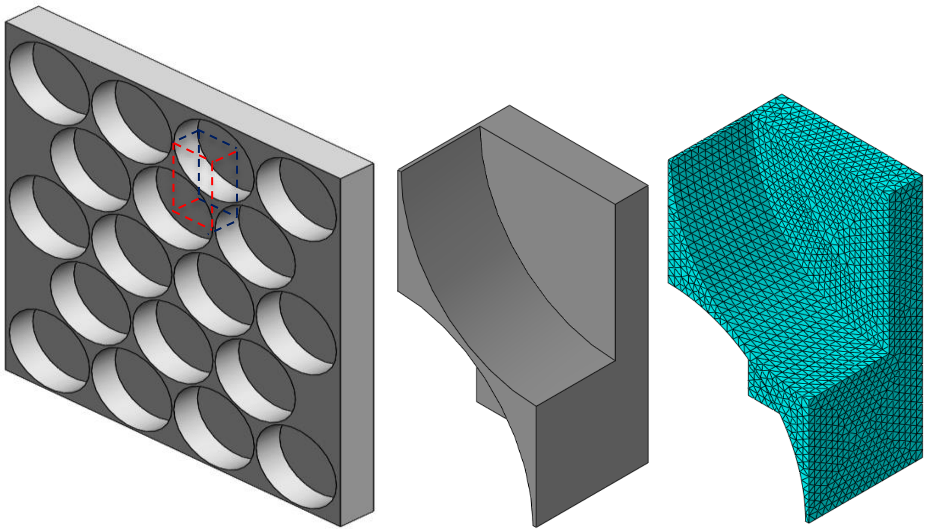
The cylinders are assembled onto two metallic cap structures positioned in both ends of the tank. The relevant parameters were identified to be further analyzed.



Finite element model

A simplified model of the cap is used to analyse and define the relevant parameters.

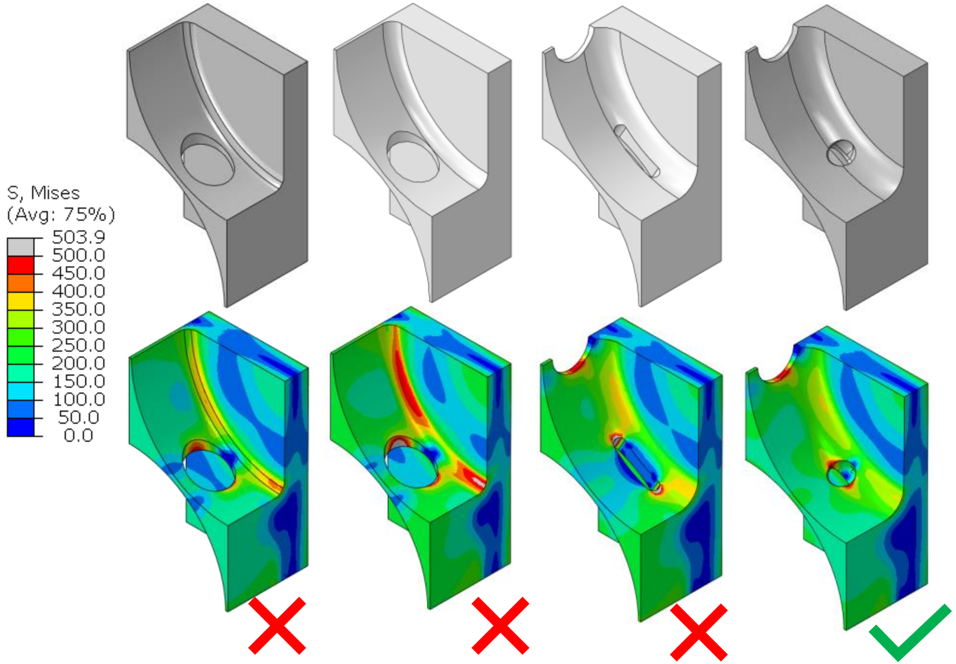
From the tube preliminary analysis, slot diameter shall be around 20mm (d_s)



Design Development

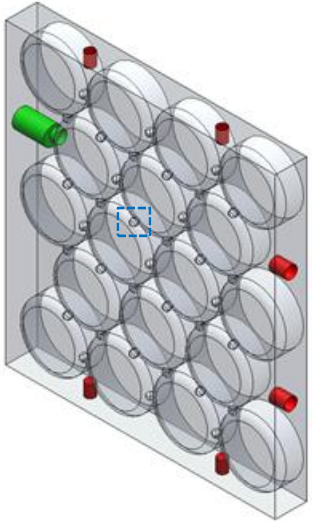
Metallic Caps Design evolution

Some design iterations…



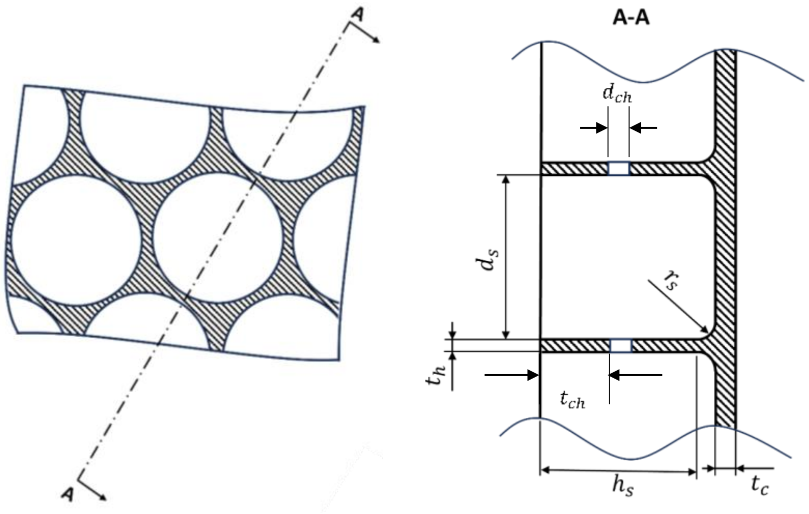
Added Features

- External perforations for inlet and outlet fittings;
- Fixture holes to secure the tank to the satellite platform;
- Internal slots for fluid communication;



Design Development

Final Metallic Caps Specifications



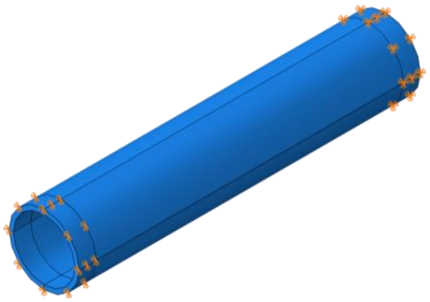
Design parameter	Symbol	Value [mm]
Slot diameter	d_s	20.6
Cap depth	h_s	5.5
Channel 1 diameter	d_{ch1}	4.0
Channel 2 diameter	d_{ch2}	2.0
Wall thickness	t_h	0.5
Fillet radius	r_s	2.0
Slot thickness	t_c	2.5
End wall	t_{ch}	1.0

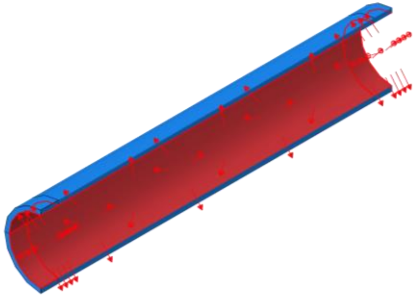
Preliminary design : Tubes

Design considerations

- Internal diameter is set to 18mm;
- Internal pressure primary load;
- Cap interface must be included.

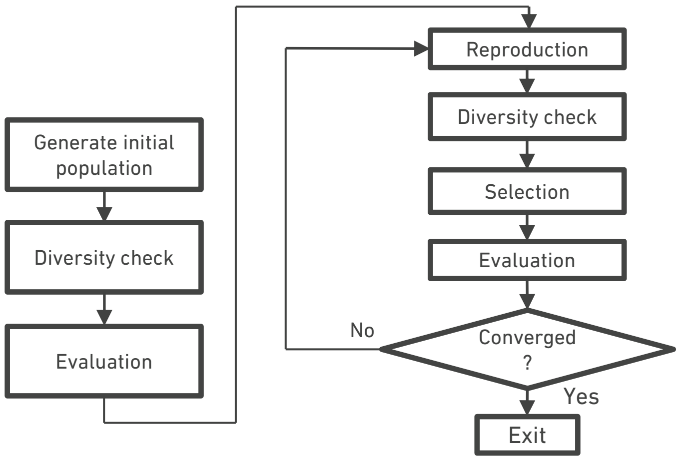
To account for the cap-tube interface FEM analyses are required.





Laminate design

- Further design to reduce wall thickness and failure indexes (Hashin criteria);
- Optimization through modified Genetic Algorithm.

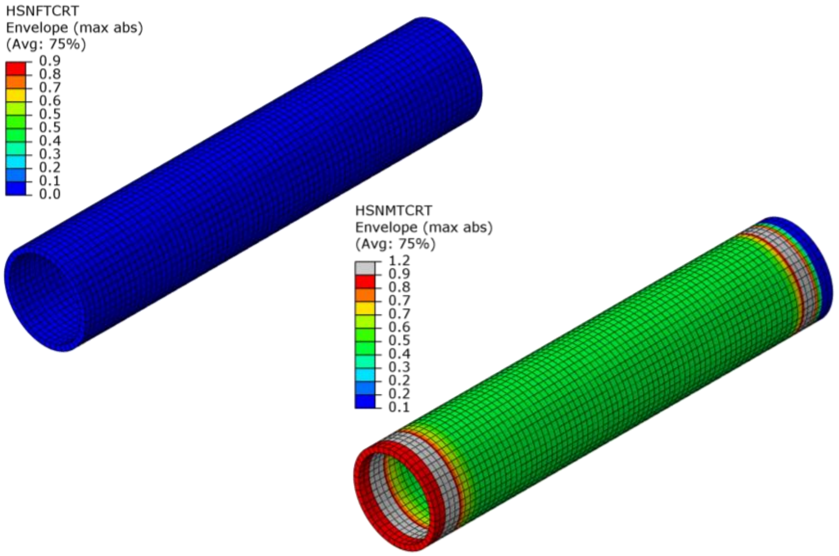


4.

Preliminary design : Tubes

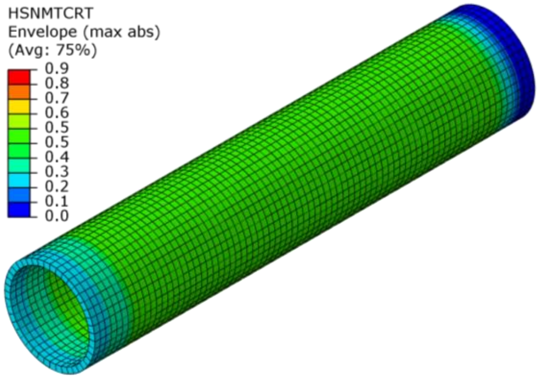
First design

- Fails at cap interface because local stresses;



After laminate optimization.

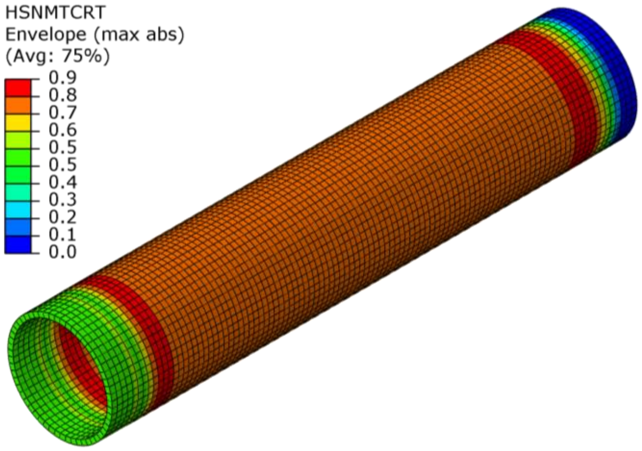
- Performing the laminate optimization including the bending stresses.
- New sequence: $[\pm 20; \pm 85; \pm 85; \pm 20]$



Preliminary design : Tubes

Additional solutions

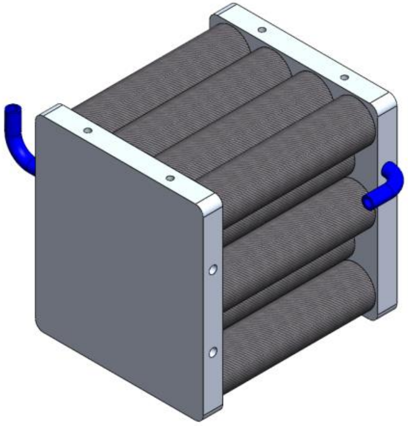
- Releasing the double laminate constraint;
- Is possible to reduce thickness: $[+15; \pm 60; \pm 85; -15]$



Performance summary

- Considering a 1U cell tank

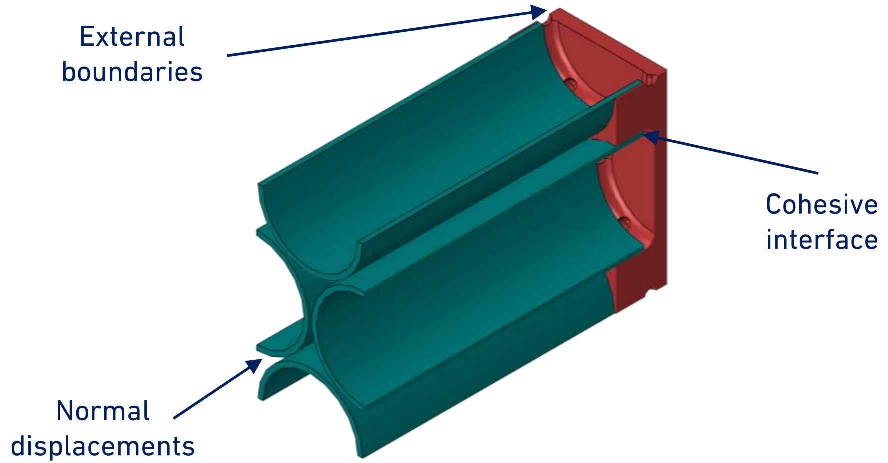
	Lay-up	Tube number	t	Vol. efficiency	Dry area	Tank weight
	[deg]	[u]	[mm]		[mm^2]	[g]
L8	±20; ±85; ±85; ±20	18	1.28	55%	1396	362.6
L6	+15; ±60; ±85; -15	18	0.96	58%	1029	313.9



Design verification: assembly simulation

Design considerations

- Internal pressure is the primary load;
- Cap interface is included as a cohesive interface

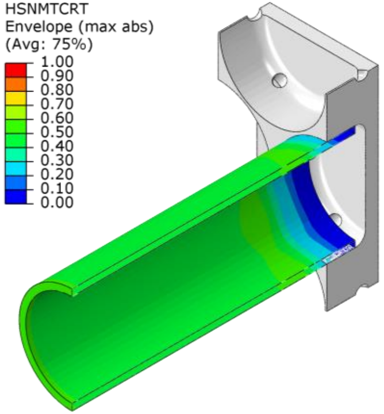


Design verification: assembly simulation

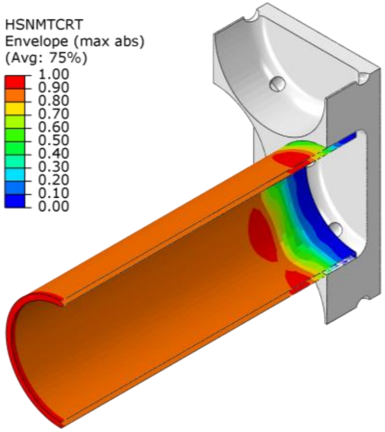
Internal pressure results: tube component

- No damage initiation is triggered
- L6 laminate is closer to damage initiation

L8 ±20; ±85; ±85; ±20



L6 +15; ±60; ±85; -15

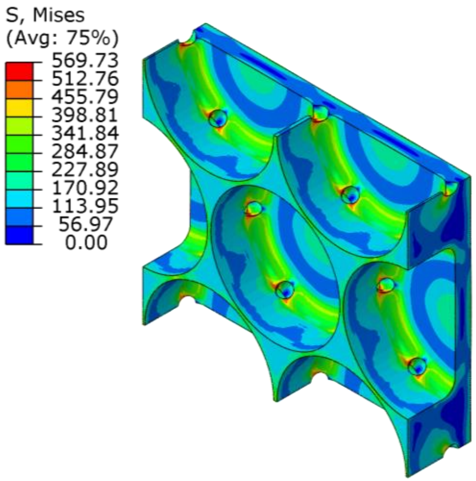


Design verification: assembly simulation

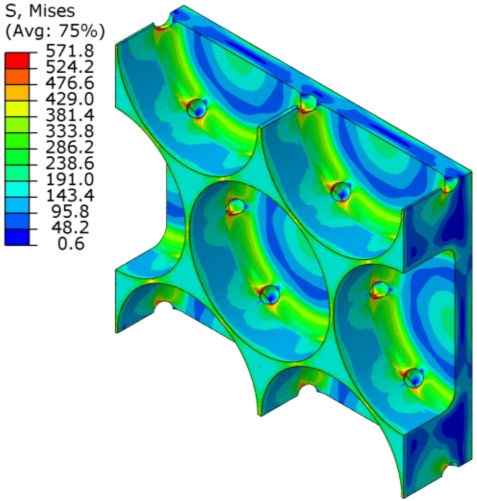
Internal pressure results: cap component

- Installed stresses well below the yield stress

L8 ±20; ±85; ±85; ±20



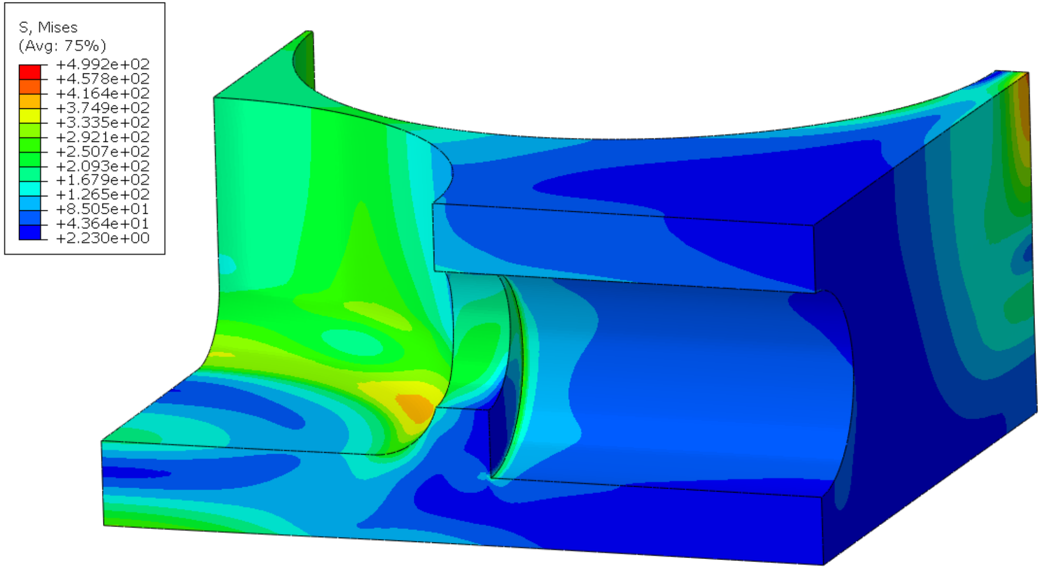
L6 +15; ±60; ±85; -15



Design verification: assembly simulation

Internal pressure results: cap component (fitting connection slot)

- Introduction of fitting details does not add relevant stress concentrations



Design verification: assembly simulation

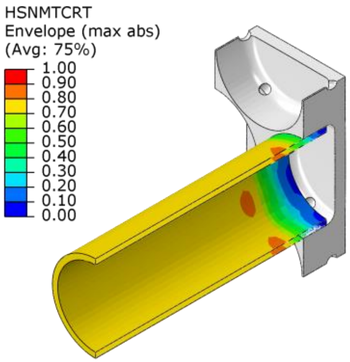
Combined pressure & temperature results: tube component

- No damage initiation is triggered in the L8 laminate
- **Damage initiation is triggered in the L6 laminate at 60°C – unfeasible design**

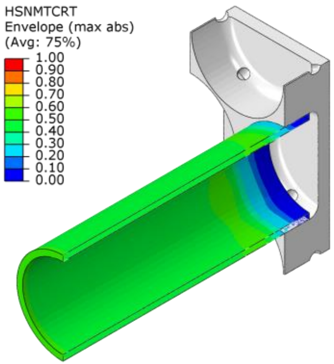
L6 **+15; ±60; ±85; -15 @ 60°C**

L8 **±20; ±85; ±85; ±20**

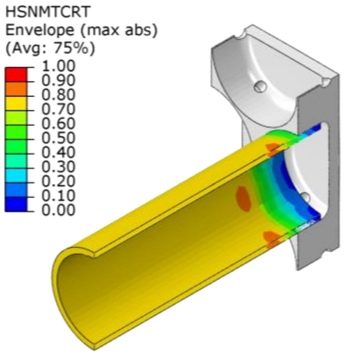
-20°C

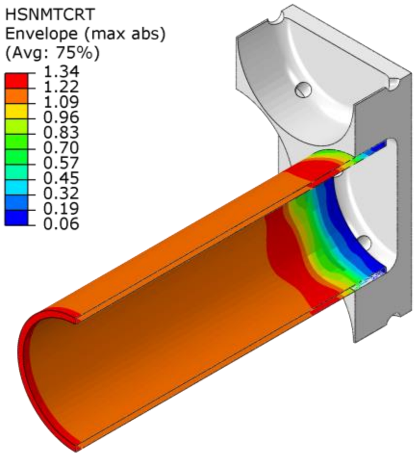


20°C



60°C





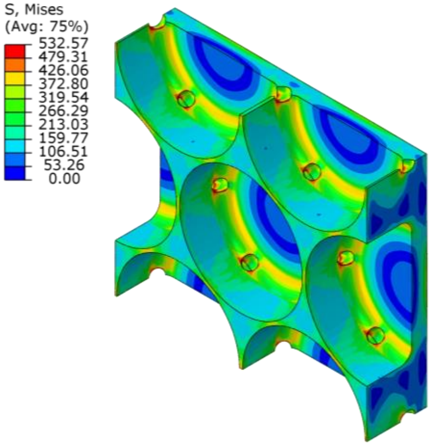
Design verification: assembly simulation

Combined pressure & temperature results: cap component

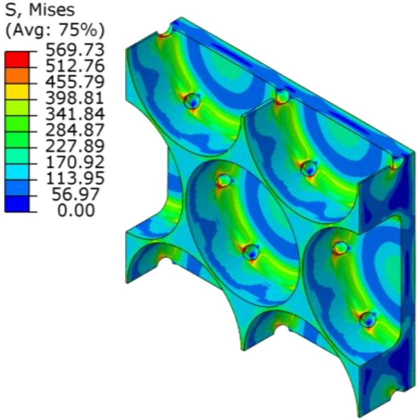
- Installed stresses below the yield stress

L8 ±20; ±85; ±85; ±20

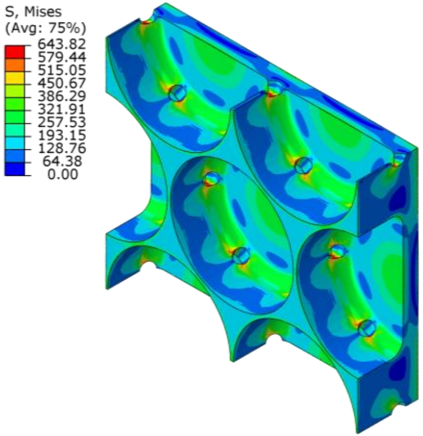
-20ºC



20ºC



60ºC



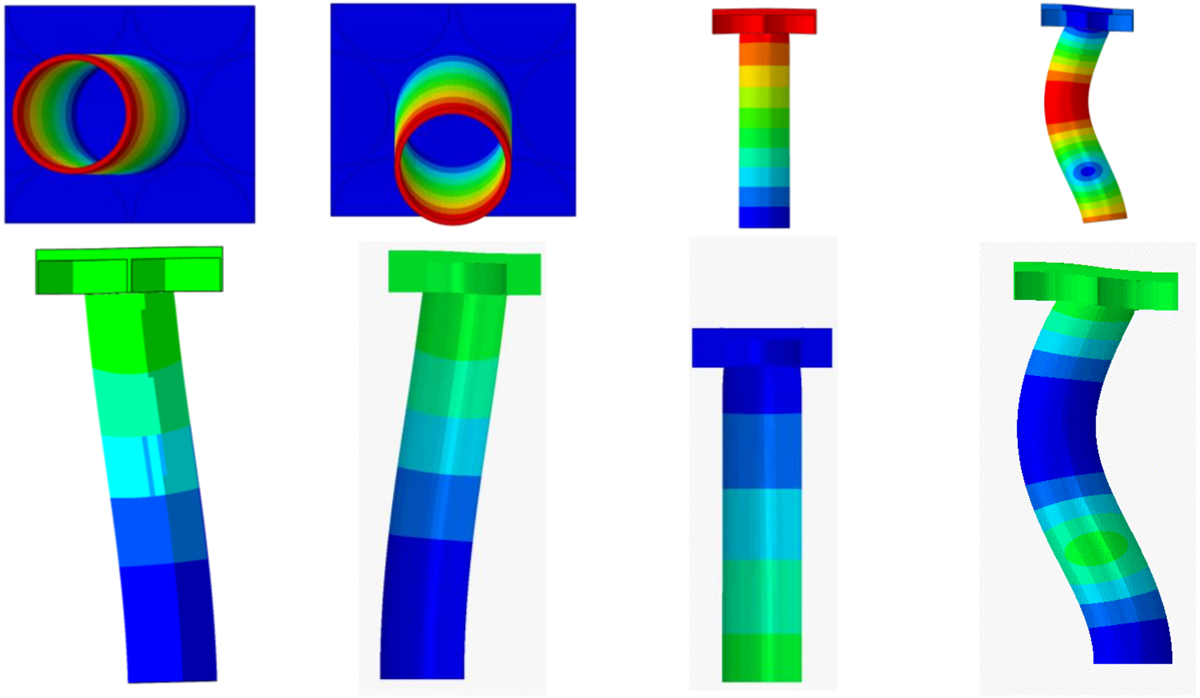
Design verification: assembly simulation

Vibration analysis

- Lowest natural frequency at 2435Hz (scales with $1/L^2$)

L6

+15; ±60; ±85; -15



f1=2435 Hz

f2=2442 Hz

f3=5217 Hz

f4=10435 Hz

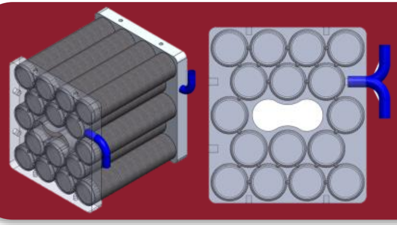
Design Development

Final remarks – Technical Remarks

- Expected cost reduction – 20%
- Minor loss in mass-volume-fraction and volumetric efficiency
- Independent customization in any principal direction was achieved.
- Modular design – allows for removal of "storage units"

KPI	Baseline (2U) [1]	NoTank (2U)	Change
Mass volume fraction (kg/L)	0,625	0,67	+ 6,72%
Volumetric-efficiency (%)	59	55	-4%
Manufacturing Cost* (€)	827€	662€	-20%
Customizability	Limited	Free	N/A

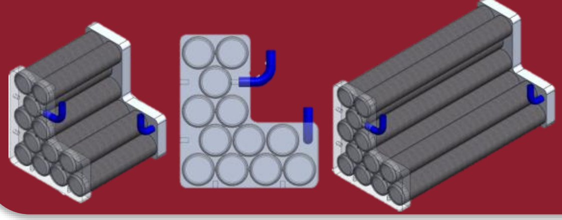
*estimated cost based on cost modeling tool and Granta EduPack® cost references



1U Hollowed Configuration

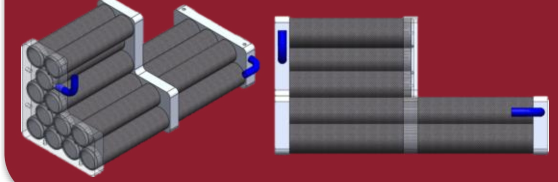
Removal of modules to facilitate wiring communication between payload

1U/2U L-Shaped Configuration



L-Shaped configuration that could be fitted into irregular physical space

2U Tailored Configuration



Tailored configuration that is arranged around other payloads and ensures satellite maximum volumetric efficiency

Manufacturing process definition

Product Specifications (Composite Tube)

Tube	Lay-up [deg]	Internal Diameter D_i (mm)	ǂ External Diameter D_e (mm)	Length (mm)
L8	[±20; ±85; ±85; ±20]	18	$\mathrm{D_i} + 16\mathrm{t}$	90

ǂ D_e *is dependent on achieved layer thickness* (t)

- ✓ Constant circular cross section composite tube:
  - ➢ L8: Balanced lay-up, pair-wise inverse orientation – Best suited for Filament Winding process

Inefficient to manufacture a single composite tube. The envisaged process shall be able to produce an oversized tube (length-wise) that is later sectioned to the desired length.

Tooling Selection (Mandrel)

- Low CTE material
  - ➢ Reduces cure induced residual stresses
  - ➢ Geometric accuracy
- Good stiffness
  - ➢ Reduced bending during filament winding

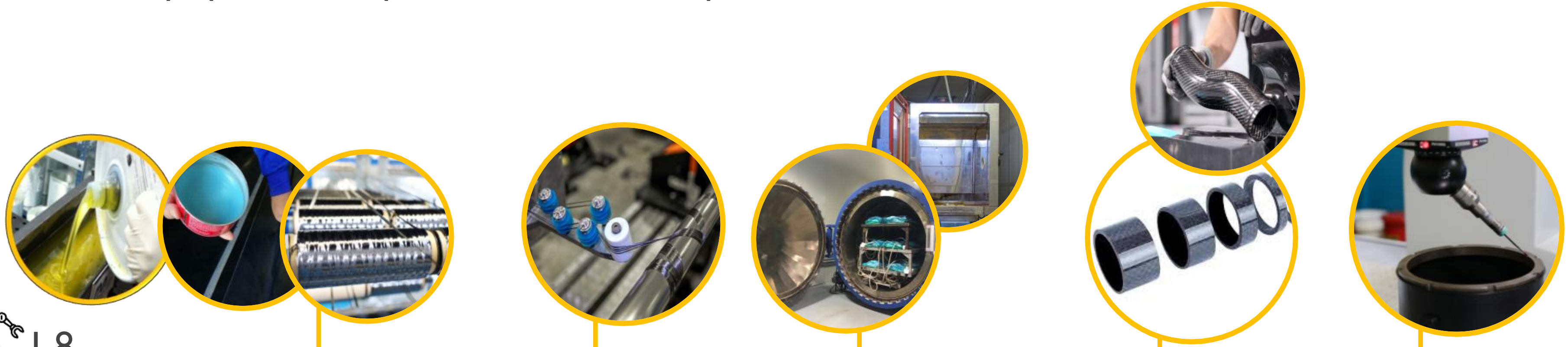
Requirement	Specification
REQ-MAN-001	The mandrel shall have a length of 2500 mm
REQ-MAN-002	The mandrel shall be a solid round bar with an outer diameter equal to 18 ± 0.011 mm
REQ-MAN-003	The chosen material for the mandrel shall be a low CTE stainless steel. (TBD on suppliers' availability)
REQ-MAN-004	The mandrel average surface roughness (Ra) shall be 0.8 μm.
REQ-MAN-005	The mandrel shall exhibit a circularity/roundness geometrical tolerance of at least $IT8$ (0.033) mm
REQ-MAN-006	The mandrel shall exhibit a general-purpose straightness geometric tolerance according to ISO 2768-mH.

5.

Manufacturing process definition

Manufacturing Plan Macro-Stages

- ❑ Bill of material definition (BOM)
- ❑ Equipment requirements and capabilities



L8

PREPARATION → LAY-UP → CURE → POS-PROCESSING → QI

Manufacturing process definition

Manufacturing Plan Detailed Steps

Operation Number	Operation Name	Process Description	Duration (min)
FW-0010	Manufacturing Order	Elaboration of the manufacturing order (including all manufacturing details, for example materials, layup, winding parameters, tube drawing)	5
FW-0020	Mandrel Assembly and Preparation	Assembly the mandrel in the filament winding machine and apply at least 3 layers of release agent.	15
FW-0030	Winding Program	Program the winding program according to the Manufacturing Order details. The program is done using the machine Supplier software (Winding Expert)	10
FW-0040	Resin Preparation	The resin is prepared according to the quantities estimated and reported in the MO. The percentage of each component is also specified in the MO	10
FW-0050	Winding process	The winding is made according to the specified winding program in FW-0030.	5
FW-0060	Peel Ply Application	After winding the peel ply is wounded.	5
FW-0070	Shrink-Tape Application	After winding the peel ply the shrink-tape is wounded.	5
FW-0080	Labelling	After winding the CFRP tube is labelled with a unique serial number.	1
FW-0090	Cure	The tube is transferred to the curing oven and the curing cycle is performed.	480
FW-0100	Demoulding	The mandrel is extracted from the tube, typically, by hand typically or if needed by the demoulding machine.	2
FW-0110	Shrink tape removal	Remove the tube from the oven, and un-wrapping the peel ply and the shrink tape;	5
FW-0120	Tube Grinding	To improve the outer surface geometry the tube is grinded;	10
FW-0130	Sections Labelling	Each section of the tube to be cut is labelled in order to guarantee full traceability	1
FW-0140	Quality control	Measure tube dimensions, control the mass of each section and for each manufactured batch control FVF and Porosity	15
FW-0150	Tube Sectioning	Cut 22 tubes of the specified length (90mm), from the originally manufactured tube. Discard resulting excess.	8

Manufacturing process definition

Manufacturing Implementation

Manufacturing @ FHP

Assembly @ FHP

Prototype

Manufacturing process definition

Quality Inspection

- **Mass:** Used for the assessment of FVF.
- **Length:** Check if tube sectioning methods are appropriate or need to be refined.
- **Avg. Diameter:** Consistency of shape and if an external moulding process needs to be considered; May influence adhesive joint configuration.
- **Avg. Thickness:** Indirectly measures avg. layer thickness. In turn, influences structural performance.
- **Fiber volume fraction (FVF):** Determine if processed material properties are in line with standards, and process quality
- **Void Content:** Assess material, and process implementation quality
- **NDT (Termography):** Assess material quality in machined zones for delamination or chipping.

Operation Number	Criteria	Description
QA-FW-MSS	Mass	The measured mass of a single tube must not deviate more than 1,0 g, across the batch average.
QA-FW-LEN	Length	The measured length of the composite tube must be within 0.1 mm range from the targeted length.
QA-FW-AVD	Avg. Diameter	The average measured external diameter of the composite tube must be within a + 0 mm to -0.05 mm tolerance of the targeted diameter.
QA-FW-AVT	Avg. Thickness	The average measured thickness of the composite tube must be within a +0 mm to -0.025 mm tolerance of the targeted thickness.
QA-RW-FVF	FVF	The tube shall have a FVF 67 ± 3%
QA-RW-VDC	Void Content	The tube shall have a Void Content ≤ 3%
QA-FW-NDT	NDT	No thresholds were defined regarding the NDT (Tomography)

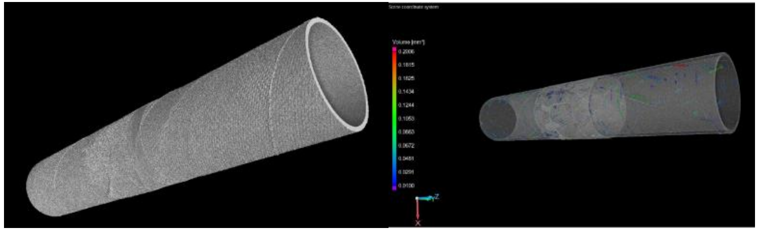
Manufacturing Implementation and Testing

Quality Inspection

Mass measurements

Geometric measurements

Requirement	Threshold	Result	Compliant
QA-FW-MSS	Deviation <1g	< 0,02g	YES
QA-FW-LEN	90 ± 0,1 mm	90,04 mm	YES
QA-FW-AVD	$19{,}6\ ^{+0.00}_{-0.05}$ mm	19,73 mm	NO
QA-FW-AVT	$0{,}8\ ^{+0.000}_{-0.025}$ mm	0,854 mm	NO
QA-FW-FVF	67 ± 3%.	65,83%	YES
QA-FW-VDC	<3%	<1,7%	YES
QA-FW-NDT	Noticeable concentration of delaminations in tube sectioning zones?	No noticeable concentrations of delaminations via tomography NDT	YES



Tomography scans

The average layer thickness was outside projected values, leading to non-compliance in thickness and OD.

This can be corrected by doing some process parameter adjustments in the future.

Manufacturing Implementation and Testing

Testing – out of scope

A low-fidelity model was manufactured to evaluate adhesive joint leak tightness

The test was conducted on a pressure test rig, using water at 5 bar.

Over the test duration, no noticeable leak was detected.

Future Activity Planning

Main Objectives:

- Raise to **TRL 6**
- Identify commercial prospects
- Develop model detail features (e.g. adhesive joint, external fittings)
- Qualification tests
- Identify and plan future development needs

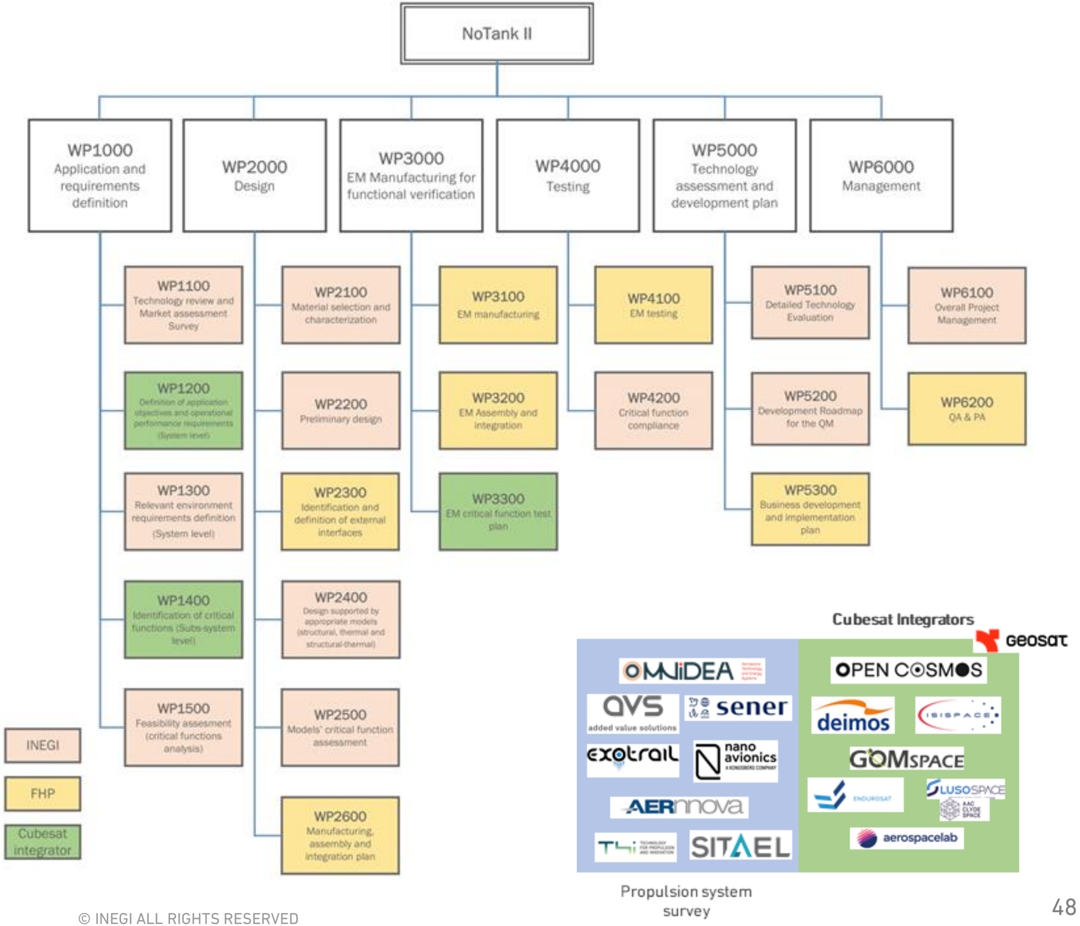
ID	Description	Technical Outcomes
1	Application and requirements definition	• Technology review and market assessment survey • Definition of application and operation performance requirements (system level) • Relevant environment requirements definition (system level) • Identification of critical functions (sub system level) • Feasibility assessment
2	Design	• Preliminary design • Materials selection and characterization • **Oriented design, considering external interfaces**, supported by appropriate models (structural, thermal, and structural-thermal) • Models' critical function assessment • Manufacturing assembly and integration plan
3	EM Manufacturing	• EM Manufacturing • EM assembly and integration • EM critical function test
4	Testing	• EM testing • Critical function compliance
5	Technology assessment	• Detailed technology evaluation • Development roadmap for the QM

Future Activity Planning

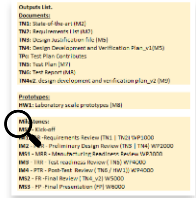
Main Objectives:

- Raise to **TRL 6**
- Identify commercial prospects
- Develop model detail features (e.g. adhesive joint, external fittings)
- Qualification tests
- Identify and plan future development needs

Budget: ~412k EUR



Next Steps - MILESTONES | PLANNED REVIEWS


Outputs List.
Documents:
TN1: State-of-the-art (M2)
TN2: Requirements List (M2)
TN3: Design Justification file (M5)
TN4: Design Development and Verification Plan_v1(M5)
TPc: Test Plan Contributes
TN5: Test Plan (M7)
TN6: Test Report (M8)
TN4v2. design development and verification plan_v2 (M9)

Prototypes:
HW1: Laboratory scale prototypes (M8)

Milestones:
- Kick-off
-Requirements Review (TN1 | TN2) WP1000
IM2 - Preliminary Design Review (TN3 | TN4) WP2000
MS1 - MRR - Manufacturing Readiness Review WP3000
IM3 - TRR - Test readiness Review (TN5) WP4000
IM4 - PTR - Post-Test Review (TN6 / HW1)) WP4000
MS2 - FR -Final Review (TN4_v2) W5000
MS3 - FP -Final Presentation (FP) W6000

Milestones	Planned Reviews	Format	Due Date
MS0 - Kick-off		Video Conference	M0
	IM1 - RR -Requirements Review	Video Conference	M2
	IM2 - PDR - Preliminary Design Review	Video Conference	M5
MS1 - MRR - Manufacturing Readiness Review		FHP Premises	M6
	IM3 - TRR - Test readiness Review	Video Conference	M8
	IM4 - PTR - Post-Test Review	Video Conference	M8
MS2 - FR -Final Review		Video Conference	M9
MS3 - FP -Final Presentation (FP)		ESTEC Premises	M9+1

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