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Durable Low-Cost Pressure Vessels for Bulk Hydrogen Storage

DE-FE-0032002

Project Duration: 3/1/2021-8/31/2023

WireTough Cylinders, LLC

and

Siemens Energy Corporate Technology Center

Project Review: April 19, 2023

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ACKNOWLEDGEMENTS

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TENARIS USA (VENDOR)

PAOLO BERTOT, SANTIAGO BORREO

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Presentation Outline

- Background
- Project Objectives
- Potential Project Benefits
- Tasks, Deliverables and Status
- Results
- Concluding Remarks

BACKGROUND

- Capital intensive equipment in fossil-fuel electricity generating plants are required to shut-down frequently and ramp-up rapidly to manage variable energy demands within a single day.
- Damage to plant equipment/components due to such thermal cycling causes reduced life and unplanned outages.
- One solution is to store excess energy in the form of hydrogen at high pressures during low demand periods.

Project objectives

- To design and build a prototype of a Type II-S, low-cost and durable pressure vessel with a capacity between 1,500 to 2,000 liters to safely store 40 to 50 KG hydrogen.
- The design must comply with ASME-BPVC Section VIII-Division 3 requirements.
- The pressure vessel must have the ability to withstand deep pressure cycles ranging from the maximum operating pressure to ambient pressure for 20+ years of service.
- Demonstrate feasibility of manufacturing the storage vessel by building a prototype and obtaining necessary certifications to offer it commercially

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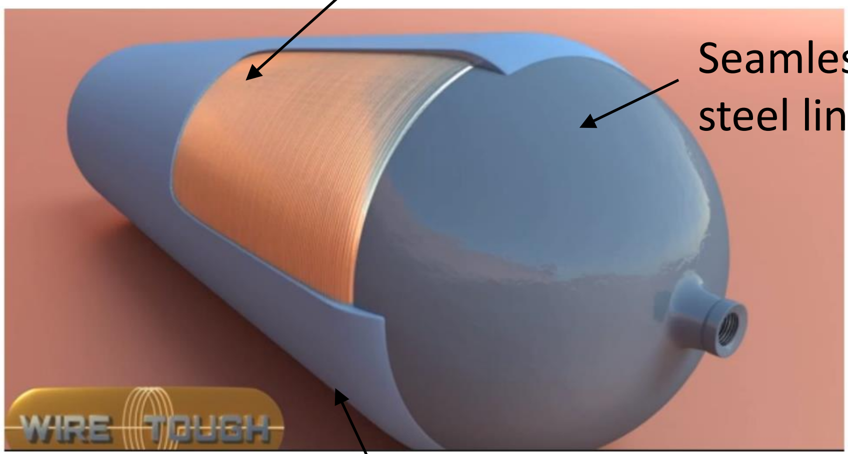
Potential Project Benefits

- A new product for bulk storage of hydrogen will be developed and will be ready for commercialization. The solution will be suitable for storing excess energy in
  - ✓ Fossil-fuel power plants
  - ✓ Nuclear energy generation plants
  - ✓ Renewable solar/wind energy generation plants
- It can also be used for ground storage of hydrogen in fueling stations

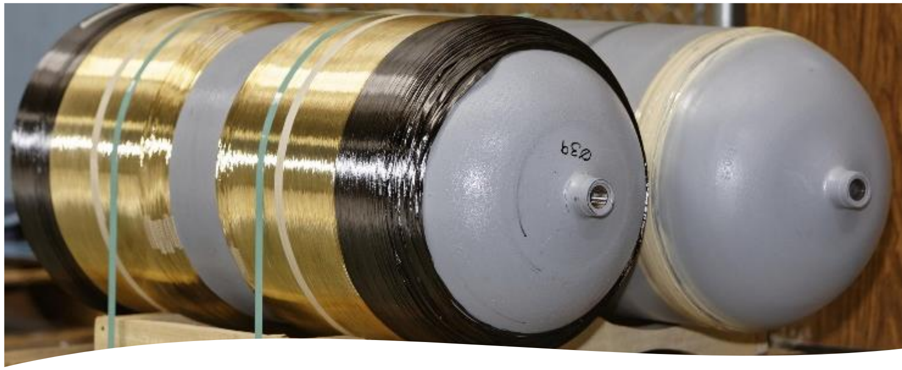
Pressure Vessel Construction Materials

High Strength steel Wire Wrap consisting of several layers of wire



Seamless steel liner

UV Protective skin



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TASKS , DELIVERABLES, & STATUS

Task Description	Schedule
Task 1.0 – **Project Management and Planning (WTC)**	
• Project management plan	Continuing
• Technology maturation plan	Completed
Task 2- Design Optimization and Selection of Preliminary Design (WTC)	
• Prepare user design specification	Completed
• Preliminary cylinder design	Completed
Task 3 –Design Analyses (Siemens/WTC)	
• Analysis of the liner	Completed
• Analysis and assessment of the wire wrapped vessel	Completed
• Fatigue crack growth analysis during service loading	Completed
Task 4 – Liner Selection and Manufacture (WTC/Vendor)	Completed
Task 5 – Building a Prototype of the Cylinder (WTC)	Completed
• Wire wrapping and inspection	May 15,2023
• Autofrettage and final finishing	June 2023
• Cylinder cost analysis	Ongoing
Task 6. 0 – Manufacturing Design Report (3rd Party Verification)	Completed
Task 7.0 – Task 7.0 – Technoeconomic Assessment (TEA)	July 2023
Contract Final Report	August 2023

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Design Optimization Studies

Nominal OD (mm)	Minimum Wall thickness, mm	Estimated Liner Burst Pressure, MPa	Maximum Allowable Pressure, MPa	Maximum Operating Pressure, MPa	Water Capacity Liters	KG of H_2 Stored
610	22.9	60.8	50	35.0	1715	40
610	25.2	68.1	56	39	1687	43
508	22.9	74.4	62	43.4	1380	38
508	25.2	82.4	68	47	1350	40
406	22.9	94.2	78	55	840	28
406	25.2	102.14	85	60	817	29

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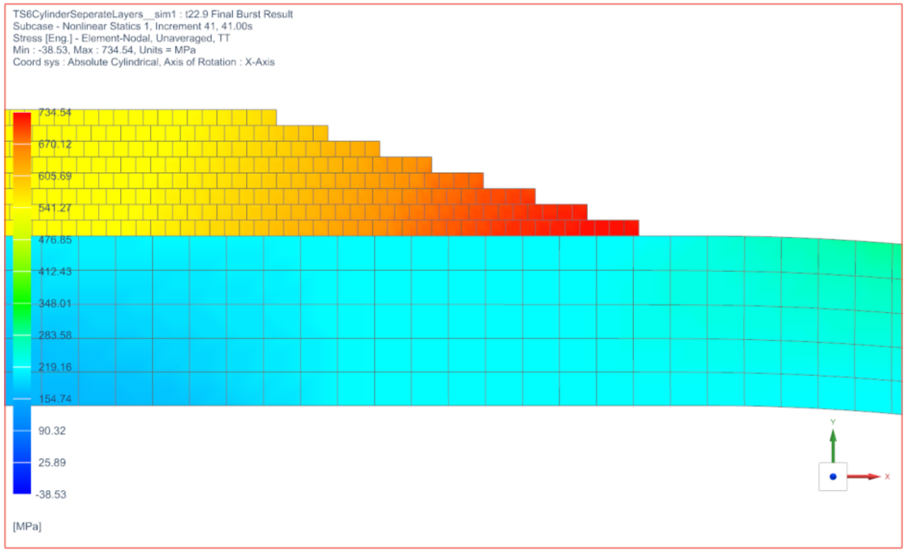
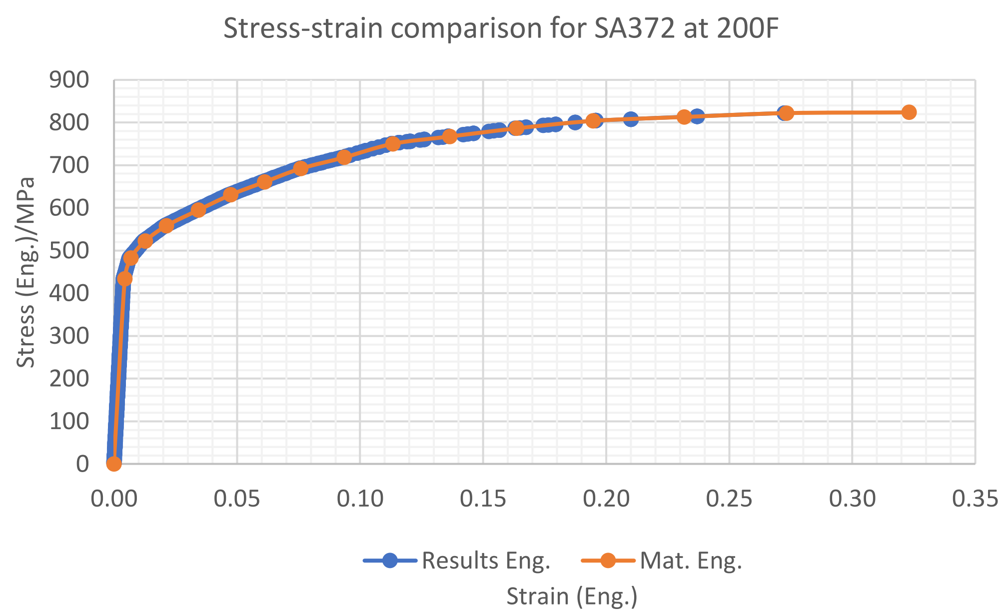


Finite Element Modeling

Loading Sequence During FE Analysis

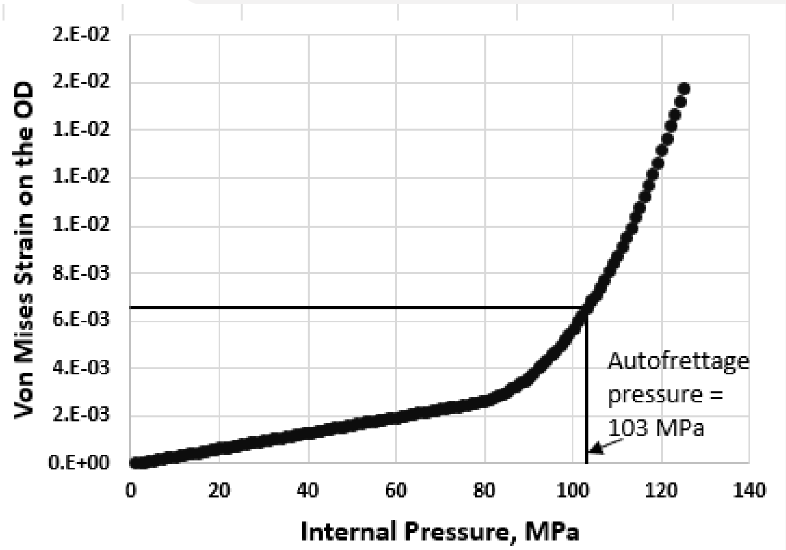
- Wire wrapping
- Autofrettage Pressure and releasing the pressure
- Service loading to MOP
- Identify regions of high stress for the fracture mechanics analysis

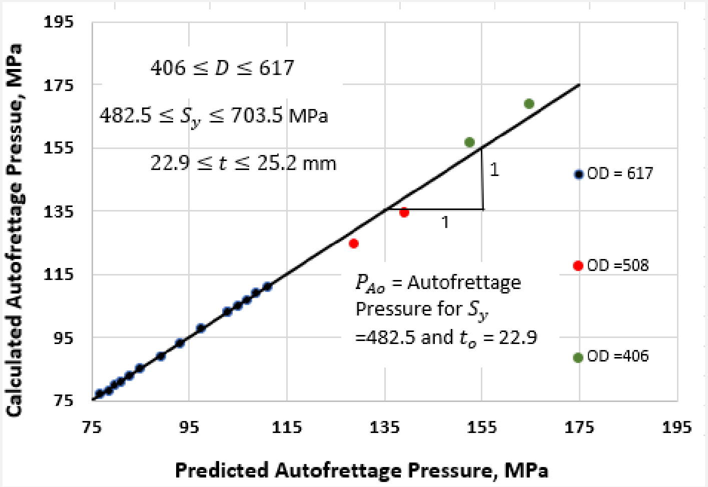


Matrix of cases analyzed by FEA

OD, mm	S_y, MPa	Wall Thickness, mm					Wrap thickness, mm
610		22.9	23.5	24.0	24.5	25.2	17.06
	482.5	x	x	x	x	x	
	517	x					
	552	x					
	587	x					
	622	x					
	658	x					
	703.5	x	x	x	x	x	
610	703.5	x				x	14.22
508	703.5	x				x	17.06
508	703.5	x				x	14.22
406	703.5	x				x	17.06
406	703.5	x				x	14.22

ESTIMATION OF AUTOFRETTAGE PRESSURE



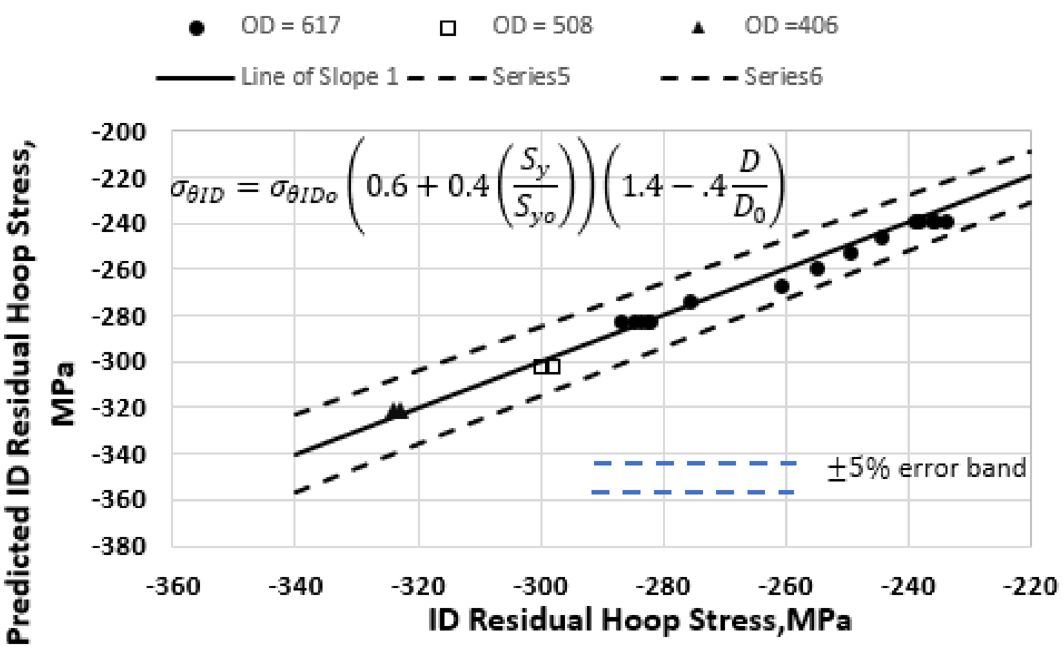


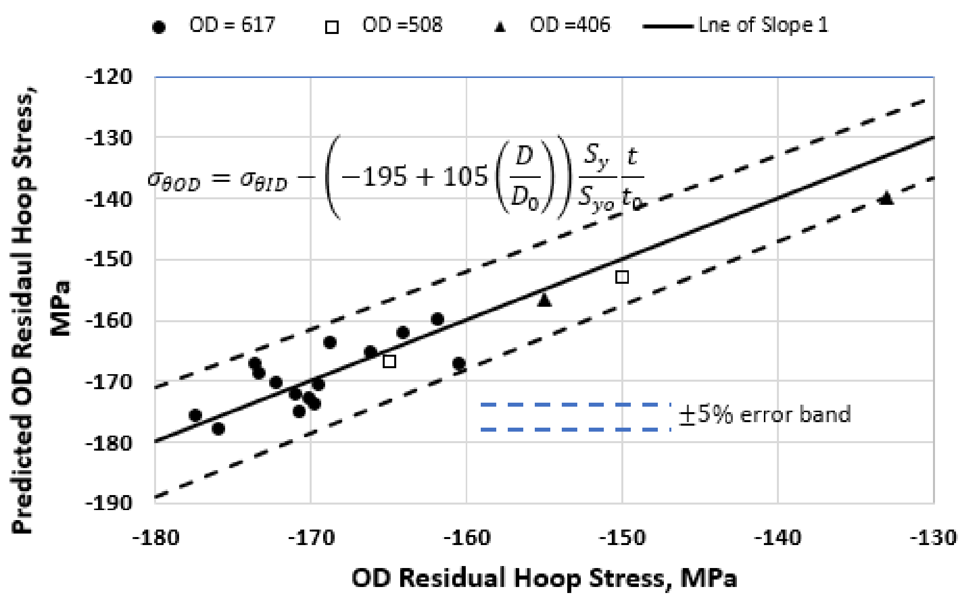
$$\frac{P_A}{P_{A0}} = f\left[\frac{S_y}{S_{yo}}, \frac{t}{t_o}, \frac{D}{D_o}, \frac{t_w}{t_{w0}}\right]$$

$$\frac{P_A}{P_{A0}} = \left(0.26 + 0.74\frac{S_y}{S_{y0}}\right)\left(.206 + .794\left(\frac{t}{t_0}\right)\right)\left(2.4 - 1.4\frac{D}{D_0}\right)$$

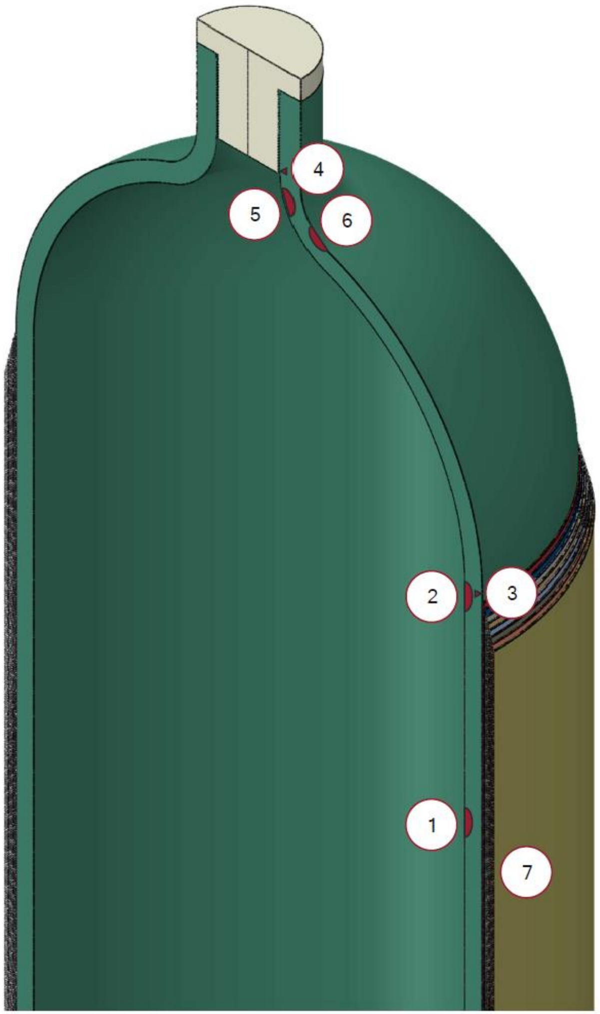
Tsz L. “Elaine” Tang, Letchuman “Sri” Sripragash, Santosh B. Narasimhachary, and Ashok Saxena, “Models for Estimating Autofrettage Pressure and Residual Stresses in Walls of Type 2 Pressure Vessels”, ASME PVP2023 -105506, Atlanta , GA, July 11 – 16, 2023

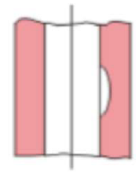
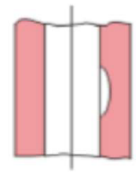
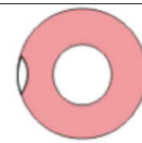
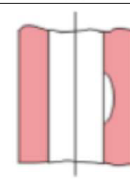
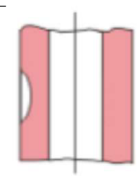
PREDICTED AND FE ESTIMATE OF RESIDUAL STRESS





Fracture Mechanics Cases Analyzed



	Flaw Evaluated (Figure 4-2)	Crack Model Used		Initial Flaw Size (Depth, a x Length, 2c)
1	Longitudinal Crack at ID of Liner Shell		Semi-Elliptical Longitudinal Crack in Cylinder on the Inside Surface	0.039 in [1mm] x 0.197 in [5mm]
2	Longitudinal Crack at ID of Liner Shell (near end of wire wrap)		Semi-Elliptical Longitudinal Crack in Cylinder on the Inside Surface	
3	Circumferential Crack at OD of Liner Shell (near end of wire wrap)		Semi-Elliptical Circumferential Crack in Cylinder on the Outside Surface	
4	Circumferential Crack at First Thread		Semi-Elliptical Circumferential Crack in Cylinder on the Inside Surface	
5	Longitudinal Crack at ID near Top of Vessel Nozzle Knuckle		Semi-Elliptical Longitudinal Crack in Cylinder on the Inside Surface	
6	Longitudinal Crack at OD near Top of Vessel Nozzle Knuckle		Semi-Elliptical Longitudinal Crack in Cylinder on the Outside Surface	
7	Fatigue in Wire Wrap	N/A	Fatigue of Wire	N/A

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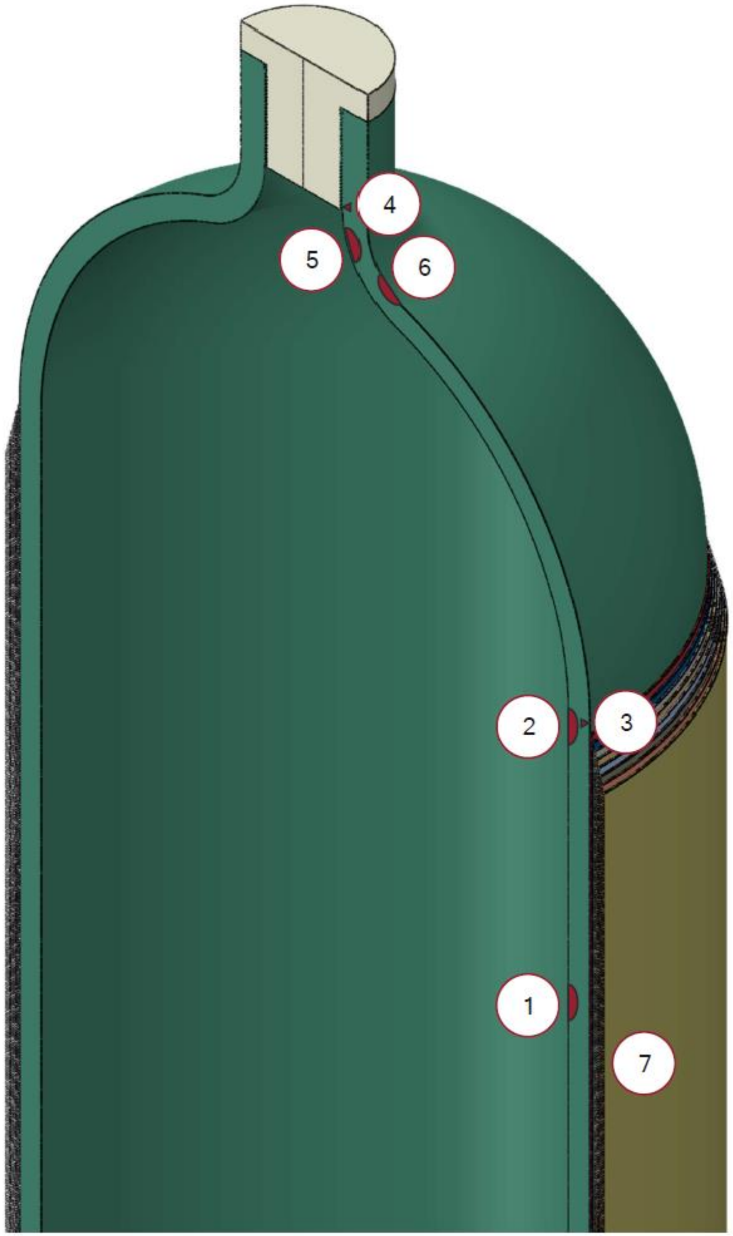
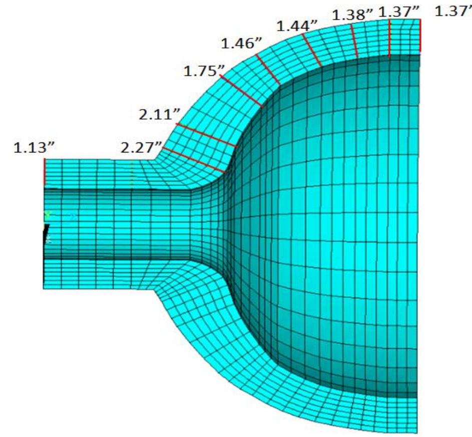
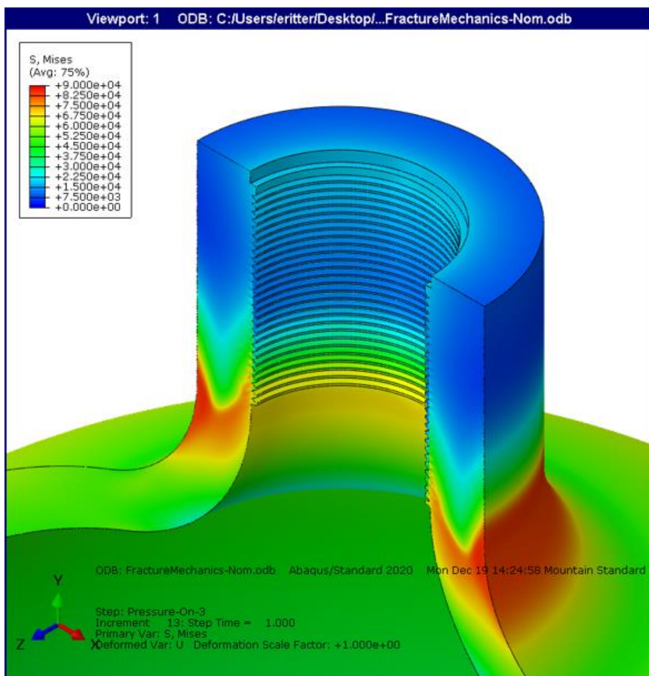
Design Life as per ASME Section VIII-Division 3 Method

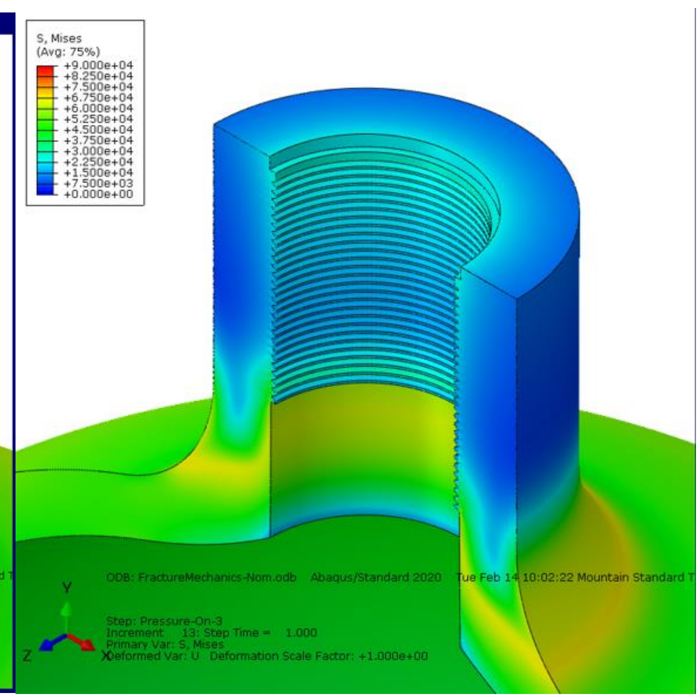


Crack Location	Life (cycles) $P_{max} = 350\ bar, P_{min} = 35\ bar$	
	t = 22.9 mm	
	Cycles	Years
1	$55.8\ x\ 10^6$	279,000
2	13,300	66.5
3	57,000	285
4	5,500	27.5
5	3,000	15
6	50,000	250

Stresses at the ID near Top of the Vessel Nozzle Knuckle





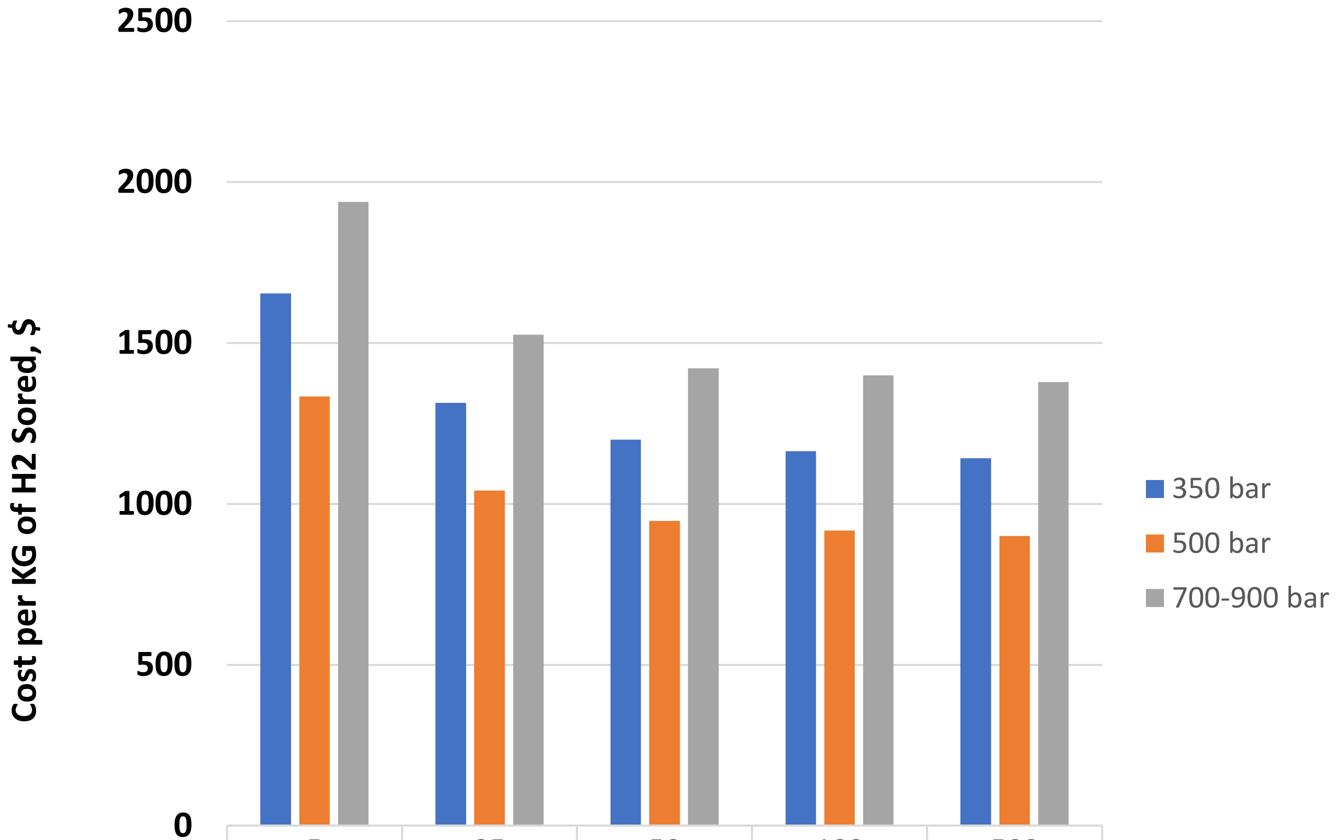


Guidance from Design Optimization Studies

- To achieve maximum operating pressures of 700-900 bar, the liner OD must be ≤ 406 mm
- To achieve maximum operating pressures of 50 MPa, the liner OD must be ≤ 508 mm
- To achieve maximum operating pressures of 350 MPa, the liner OD must be ≤ 610 mm
- Autofrettage significantly enhances fatigue crack growth life in hydrogen environment
- To keep autofrettage pressures low, a lower yield strength to ultimate tensile strength ratio is beneficial
- Increasing liner material yield strength without enhancing hydrogen assisted fatigue crack growth behavior is not useful for improving design life.

610 mm OD Liners Being Delivered to the WireTough' Plant

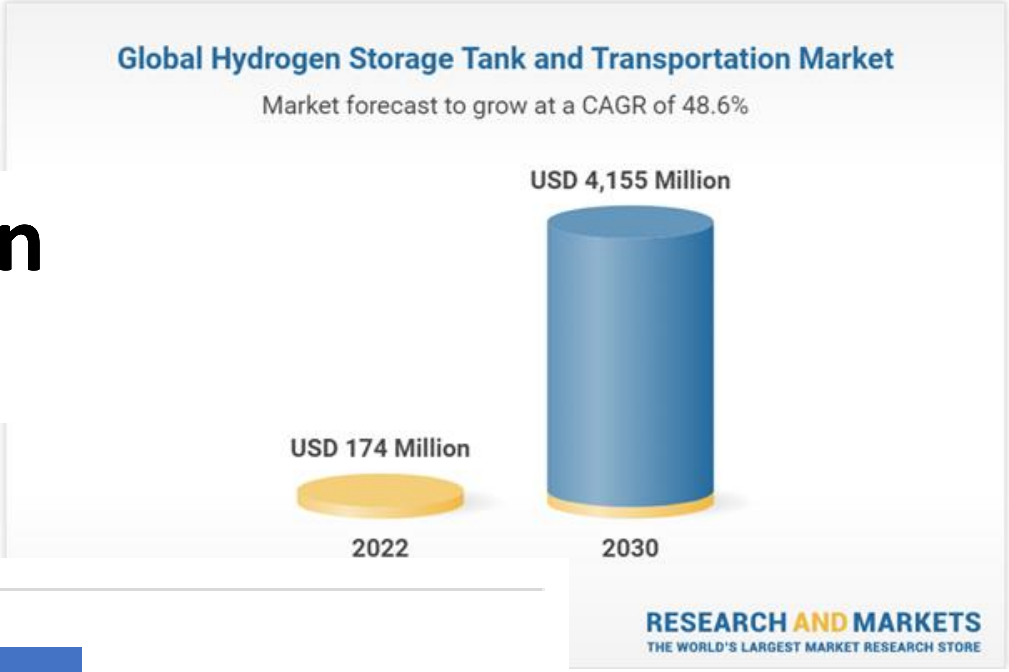
Cylinder Costs for Producing 100 Cylinders per Batch

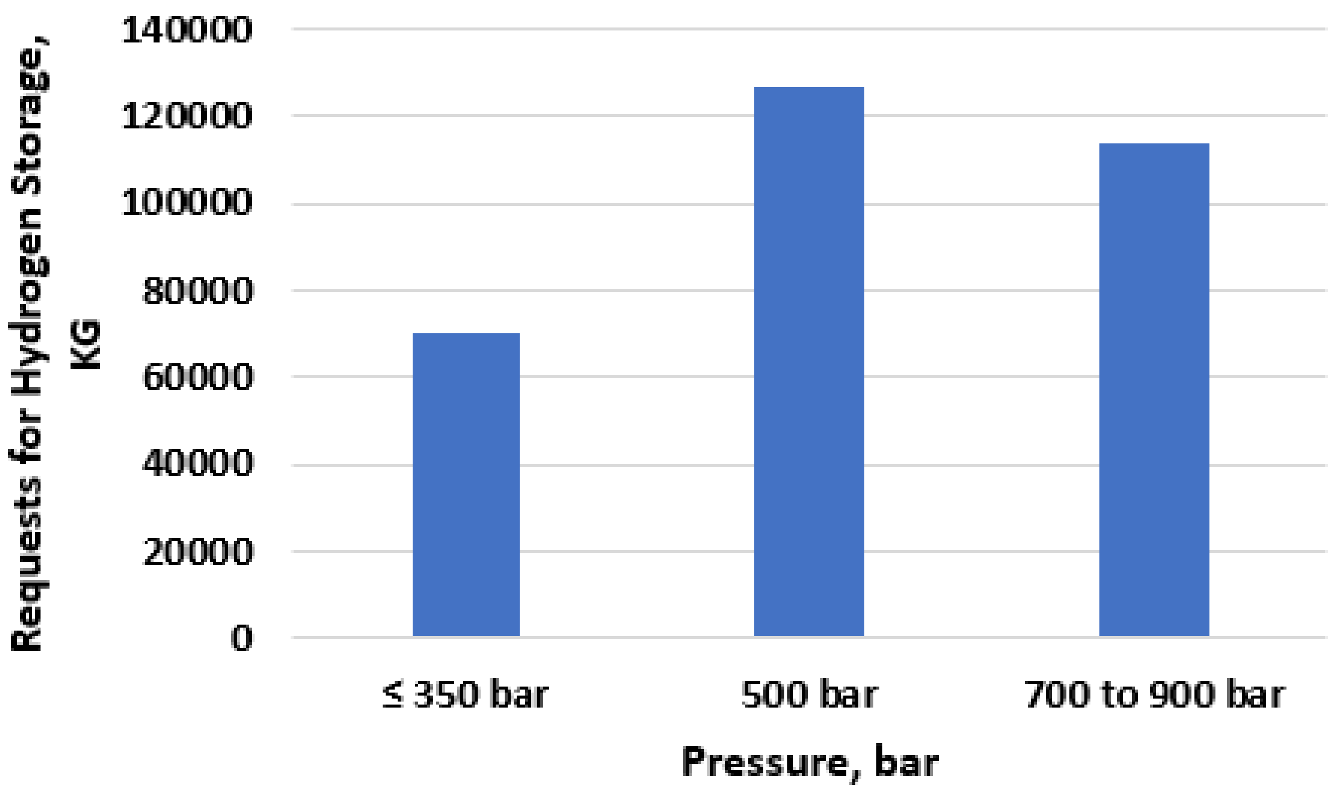


	5	25	50	100	500
350 bar	1654	1314	1199	1163	1142
500 bar	1334	1041	947	917	901
700-900 bar	1939	1525	1422	1400	1378

Number of Cylinders per Year

Commercialization Plan - Markets





Commercialization

- 350 bar MOP and 500 bar MWAP, 1715 L certified hydrogen storage vessel that can store 40 KG of hydrogen is expected to be available for production in August 2023 (end of this program)
- 500 bar MOP and 650 bar MWAP, 1500 L design able to store 44 KG of hydrogen is available for certification.
- 700 - 900 MOP and 1000 bar MWAP, 750 L design able to store 30 KG of hydrogen is available for certification.
- WireTough is actively seeking production partners who can produce these cylinders on a large scale

WireTough's Products Ready for Certification

Product	Description						
	Capacity, L	OD, mm	Length, mm	H_2 Stored, at MOP, KG	MOP, bar	MWAP, bar	Cylinder Weight, KG
HSA 700	765	440	8500	35	700 - 875	1000	3,700
HSA 500	1500	545	8000	45	500	650	4,572
HSA 350	1715	645	8000	40	350	530	4,600

350 Bar Type II-S Cylinder Compared with Type 1

Metric	Type II-S	Type 1
OD, mm	610	350
Wall Thickness	25.4	38
Capacity	1800	425
H_2 Weight, KG	40	10
Cylinder Weight	4550	2300
Cost/KG of H_2,$	1163 +x (cost of 1 set of safety device)	1400 + 4x cost of gages and safety devices and connections
Weight/KG of H_2, KG	113.75	240

- Both Type I and Type II-S are designed by Division 3 Rules
- Similar comparison at 500 bar will be much more in favor of Type II-S cylinders