

Executive Summary



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1. Title of the Project: Development of composite structures for the application in hydrogen storage and distribution integrated with sensor

2. Date of Start of the Project: 25th September 2023

3. Aims and Objectives:

- (i) Develop a virtual platform to design, manufacture, and performance testing of the composite structures such as vessel, tubes, pipelines for the storage and distribution of hydrogen at high pressure.
- (ii) Develop sensor technology and methodology to integrate with composite structure
- (iii) Manufacture prototype of composite structures integrated with sensor based on the design and manufacturing technology obtained using the virtual design and manufacturing platform for a given fluid volume, working pressure and performance requirement.
- (iv) Performance testing of the composite structures relevant for commercial application

4. Significant achievements (not more than 500 words to include List of patents, publications, prototype, deployment etc)

- i. Patent filed or commercialized:
 - a) Sharma, Pranjali, Bera, T., Semwal, K., Badhe, R.M., Sharma, A., Ramakumar, S.S.V., & Neogi, Swati. (2021) Development of High Performing Type 3 Composite Cylinders for Compressed Hydrogen Gas Storage. Indian patent (Submitted application no. 202221004254).

- b) Neogi Swati, Chugh Parivesh “Development of Lightweight, Type 4 Cng Pressure Vessel Of 70 Litre Capacity”. Indian Patent, November 2019, **Patent No. 481628**.
- c) Guha Probin Kumar, Siwajek Michael J, Hiltunen Michael J, Pflughoeft Scott Eldor, Neogi Swati; Continental Structural Plastics Inc, assignee. “Enhanced thermoset resins containing pre-treated natural origin cellulosic fillers”. United States patent, 2014, **US 9,676,942**.
- d) Guha Probin Kumar, Siwajek Michael J, Hiltunen Michael J, Neogi Swati, Dunagan Jack Douglas, Burley Adam Craig, “Energy cell temperature management”. United States patent, December 2017, **US 9,843,076**.
- e) Guha PK, Siwajek MJ, Neogi Swati. “Long fiber thermoplastic formed with recycled and renewable content” United States patent, November 2016, US 9,499,688.
- f) Neogi, Swati, Ledbetter J, and Shacklady A, “Low temperature Dry Loose Tube Fiber-Optic Cable” United States Patent, August 2006, US 7,099,542
- g) Neogi, Swati. Risch, B.G and Coat, P “Hydrogen-absorbing composition and optical fiber cables incorporating same” European Patent, June 2004, **EP 1426804**
- h) Neogi, Swati. Risch, B.G and Coat, P “Fiber optic cables with hydrogen absorbing material”, United States Patent, June 2004, **Publication no US2004/0109652A1**.

ii. List of peer reviewed publications in last 5 years (authors, journal, reference) with impact factor (as per JCR):

1. Sankhla, Sangeeta, and Swati Neogi. "Ambient-dried, scalable and biodegradable cellulose nanofibers aerogel for oil-spill cleanup." *Journal of Environmental Chemical Engineering* 12, no. 3 (2024): 112745.
2. Sankhla, Sangeeta, Monika Jindal, and Swati Neogi. "Ultraviolet shielding composites of different cellulose/aramid nanofibers." *Materials Chemistry and Physics* 317 (2024): 129199.
3. Mondal, Sourav, Swati Neogi, and Saikat Chakraborty. "Optimization of reactor parameters for amplifying synergy in enzymatic co-hydrolysis and microbial co-fermentation of lignocellulosic agro-residues." *Renewable Energy* 225 (2024): 120281
4. Sharma, Pranjali, Akash Kumar Buroolia, Ananya Mandal, and Swati Neogi. "Commercially available resources for physical hydrogen storage and distribution." In *Towards Hydrogen Infrastructure*, pp. 225-256. Elsevier, (2024).
5. Mondal, Sourav, Swati Neogi, and Saikat Chakraborty. "Experimental and kinetic analyses of delignification of lignocellulosic grass with minimal holocellulose loss during pretreatment." *Bioresource Technology Reports* 23 (2023): 101549.
6. Warhekar, Pooja, Amitabha Bhattacharya, and Swati Neogi. "Design of Carbon Black Reinforced Composite RAM Using Mixing Model Assisted-Methodology." *IEEE Transactions on Electromagnetic Compatibility* (2023).

7. Sankhla, Sangeeta, Pooja Warhekar, Amitabha Bhattacharya, and Swati Neogi. "Effective electromagnetic interference shields based on cellulose nanofibers-carbon nanotubes layered composites." *Materials Chemistry and Physics* 310 (2023): 128483
8. Yadav, Rahul, Sangram K. Rath, Sangeeta Sankhla, Swati Neogi, and Nikhil K. Singha. "Polymer nano-biocomposite based on poly (ethylene-co-methyl acrylate) (EMA)/cellulose nanocrystals (CNC); preparation and properties." *Journal of Macromolecular Science, Part A* 60, no. 9 (2023): 618-627.
9. Pramanick, Rinku, Sanjeev K. Verma, Pal Dinesh Kumar, Sirshendu De, Sudarsan Neogi, and Swati Neogi. "Quantification of time-dependent deterioration in mechanical property and ballistic performance through Cunniff Number of poly (p-phenylene terephthalamide) fibers under UV irradiation." *Materials Today Communications* 36 (2023): 106614.
10. Sankhla, Sangeeta, Sourav Mondal, and Swati Neogi. "Pyrolysis of cellulose nanofibers: detailed assessment of process kinetics and thermodynamic parameters." *Cellulose* 30, no. 12 (2023): 7695-7712.
11. Sankhla, Sangeeta, Aparna Nath, and Swati Neogi. "Preparation of Aramid–Cellulose Nanofiber Films with Improved Mechanical and Dielectric Properties Utilizing Environmentally Friendly Hydrothermal Treatment for Electrical Insulation." *ACS Sustainable Chemistry & Engineering* 11, no. 23 (2023): 8420-8430.
12. Sharma, Pranjali, Akash Kumar Buroolia, Nitai Chandra Adak, Jigyasa Daiya, Hafijul Hossain Sardar, and Swati Neogi. "Effect of tension on liner buckling and performance of a type-4 cylinder for storage of compressed gases with experimental validation." *Thin-Walled Structures* 189 (2023): 110928.
13. Sharma, Pranjali, and Swati Neogi. "Performance-based design and manufacturing of filament wound Type-4 cylinders for compressed gas storage." *Composite Structures* 309 (2023): 116710.
14. Pramanick, Rinku, Sanjeev K. Verma, Rajesh Kumari, Sirshendu De, Sudarsan Neogi, and Swati Neogi. "Effect of thermally induced microstructural changes on the mechanical properties and ballistic performance of poly (p-phenylene terephthalamide) fibers." *High Performance Polymers* 35, no. 5 (2023): 519-532.
15. Kuppusamy, Raghu Raja Pandiyan, Anita Zade, and Swati Neogi. "Kinetics development for controlled mono-methyl amine-ethoxylation reaction using laboratory scale autoclave experiments and process plant reactor data simulations." *Chemical Papers* 77, no. 4 (2023): 1887-1906.
16. Sharma, Pranjali, Hafijul Hossain Sardar, and Swati Neogi. "Thermomechanical processing of Type-4 composite cylinders under static load." *Journal of Energy Storage* 55 (2022): 105465.
17. Sharma, Pranjali, Shubhangi Sharma, Tapan Bera, Kaladhar Semwal, Rajesh M. Badhe, Alok Sharma, Gurpreet Singh Kapur, S. S. V. Ramakumar, and Swati Neogi. "Effects of dome shape

- on burst and weight performance of a type-3 composite pressure vessel for storage of compressed hydrogen." *Composite Structures* 293 (2022): 115732.
18. Kuppusamy, Raghu Raja P., Swati Neogi, Santoshi Mohanta, Moganapriya Chinnasamy, Rajasekar Rathanasamy, and Md Elias Uddin. "Mechanical, Thermal, and Ablative Properties of Silica, Zirconia, and Titania Modified Carbon-Phenol Ablative Composites." *Advances in Materials Science and Engineering* 2022, no. 1 (2022): 7808587.
 19. Zade, Anita, Swati Neogi, and Raghu Raja Pandiyan Kuppusamy. "Design of effective injection strategy and operable cure window for an aircraft wing flap composite part using neat resin characterization and multi-physics process simulation." *Polymer Composites* 43, no. 6 (2022): 3426-3445.
 20. Kuppusamy, Raghu Raja Pandiyan, Santoshi Mohanta, and Swati Neogi. "Molding of Carbon-Epoxy Composite Prepregs for Applications in Aerospace Industries." In *Advanced Composites in Aerospace Engineering Applications*, pp. 303-318. Cham: Springer International Publishing, 2022.
 21. Sankhla, Sangeeta, Santoshi Mohanta, Karthika K. Namboothiri, Raghu Raja Pandiyan Kuppusamy, and Swati Neogi. "Altered rheokinetic and mechanical behavior of anhydride cured epoxy resin due to addition of cellulose nano-crystals." *Carbohydrate Polymer Technologies and Applications* 2 (2021): 100124.
 22. Mohanta, Santoshi, Yashwanth Padarathi, Jeetendra Gupta, and Swati Neogi. "Insight into the nondestructive performance evaluation of fiber-reinforced polymer composite laminate immersed in produced water using embedded fiber Bragg grating sensor." *Polymer Composites* 42, no. 9 (2021): 4717-4727.
 23. Sharma, Pranjali, Parivesh Chugh, and Swati Neogi. "Study to methodize the design of a safe Type-4 CNG storage vessel using finite element analysis with experimental validation." *International Journal of Pressure Vessels and Piping* 192 (2021): 104425.
 24. Padarathi, Yashwanth, Santoshi Mohanta, Jeetendra Gupta, and Swati Neogi. "Quantification of swelling stress induced mechanical property reduction of glass fiber/epoxy composites immersed in aqueous 10% sulphuric acid by instrumenting with distributed optical fiber sensors." *Fibers and Polymers* (2021): 1-10.
 25. Padarathi, Y., S. Mohanta, J. Gupta, and S. Neogi. "Assessment of transport kinetics and chemo-mechanical properties of GF/Epoxy composite under long term exposure to sulphuric acid." *Polymer Degradation and Stability* 183 (2021): 109436.
 26. Chatterjee, Victor Avisek, Sanjeev Kumar Verma, Debarati Bhattacharjee, Ipsita Biswas, and Swati Neogi. "Manufacturing of dilatant fluid embodied Kevlar-Glass-hybrid-3D-fabric sandwich composite panels for the enhancement of ballistic impact resistance." *Chemical Engineering Journal* 406 (2021): 127102.

27. Sankhla, Sangeeta, Hafijul Hossain Sardar, and Swati Neogi. "Greener extraction of highly crystalline and thermally stable cellulose micro-fibers from sugarcane bagasse for cellulose nano-fibrils preparation." *Carbohydrate polymers* 251 (2021): 117030.
28. Sharma, Pranjali, Tapan Bera, Kaladhar Semwal, Rajesh M. Badhe, Alok Sharma, S. S. V. Ramakumar, and Swati Neogi. "Theoretical analysis of design of filament wound type 3 composite cylinder for the storage of compressed hydrogen gas." *International Journal of Hydrogen Energy* 45, no. 46 (2020): 25386-25397.
29. Bej, Barnali, N. C. Pradhan, and Swati Neogi. "Production of Hydrogen by Steam Reforming of Methanol Over Novel Nano-Nickel Oxide-Based Catalyst." In *Advances in Bioprocess Engineering and Technology: Select Proceedings ICABET 2020*, pp. 405-414. Springer Singapore, 2021.
30. Chatterjee, Victor Avisek, Ramakant Saraswat, Sanjeev Kumar Verma, Debarati Bhattacharjee, Ipsita Biswas, and Swati Neogi. "Embodiment of dilatant fluids in fused-double-3D-mat sandwich composite panels and its effect on energy-absorption when subjected to high-velocity ballistic impact." *Composite Structures* 249 (2020): 112588.
31. Maji, Prosenjit, Arpit Jain, Nibedita Dutta, Ahmed Ovais Siddiqui, Debdarsan Niyogi, and Swati Neogi. "Characterization of effective permeability of prepreg fibers under autoclave molding process conditions using process model simulations." *The Journal of The Textile Institute* 112, no. 1 (2021): 1-7.
32. Manukonda, Balasubrahmanya Harish, Victor Avisek Chatterjee, Sanjeev Kumar Verma, Debarati Bhattacharjee, Ipsita Biswas, and Swati Neogi. "Rheology based design of shear thickening fluid for soft body armor applications." *Periodica Polytechnica Chemical Engineering* 64, no. 1 (2020): 75-84.
33. Mohanta, Santoshi., Yashwanth. Padarthy, S. Chokkapu, Jeetendra. Gupta, and Swati Neogi. "Ultra-violet health monitoring of smart composite laminate using embedded fiber Bragg grating sensors." *Journal of Composite Materials* 54, no. 22 (2020): 3143-3158
34. Mohanta, Santoshi, Yashwanth Padarthy, Jeetendra Gupta, and Swati Neogi. "In-situ determination of degree of cure by mapping with strain measured by embedded FBG and conventional sensor during VIM process." *Fibers and Polymers* 21 (2020): 2614-2624.
35. Chatterjee, Victor Avisek, Sanjeev Kumar Verma, Debarati Bhattacharjee, Ipsita Biswas, and Swati Neogi. "Enhancement of energy absorption by incorporation of shear thickening fluids in 3D-mat sandwich composite panels upon ballistic impact." *Composite Structures* 225 (2019): 111148.
36. Chatterjee, Victor Avisek, Puja Dey, Sanjeev Kumar Verma, Debarati Bhattacharjee, Ipsita Biswas, and Swati Neogi. "Probing the intensity of dilatancy of high-performance shear-thickening fluids comprising silica in polyethylene glycol." *Materials Research Express* 6, no. 7 (2019): 075702.

iii. Technology adopted or transferred

1. Development of Light-Weight CNG Pressure Vessel of 70 Litre Capacity

Transferred to: Gas Authority of India Limited (GAIL)

Year of transfer: 2019

Development of Type-4 CNG Pressure vessel of 70 litre capacity.



Figure: Type-IV CNG Pressure vessel

- Developed Type-4 pressure vessel is manufactured of carbon fiber overwrapped on a polyamide based polymeric liner.
- Characteristic of developed technology is higher strength to weight ratio.
- Vessel is 30-50% light weight than conventional pressure vessel.
- Vessel is capable to sustain internal pressure of fluid up to 800bar.

Reference: Neogi S., & Chugh P. (2019) Development of Light-Weight, Type 4 CNG Pressure Vessel of 70 Litre Capacity. Filed for Indian patent, filing number: IN201711023929A

2. Development of Type 3 Hydrogen Pressure Vessel of 70 Litre Capacity

Transferred to: Indian Oil Corporation Limited (IOCL), Year 2022



Figure: Type-IV H₂ Pressure vessel

- Developed Type-3 pressure vessel is manufactured by carbon fiber overwrapped on Aluminum based metallic liner.
- Characteristic of developed technology is higher strength to weight ratio.
- Vessel is developed based on ISO 15869.
- Developed pressure vessel is capable to sustain internal pressure of fluid up to 800 bar.
- Life expectancy is more than 15 years.

3. Development of optical fiber embedded smart composite pipe for Offshore and Onshore Applications



Figure: FBG Sensor based smart composite pipe

- Developed smart composite pipe with optical fiber sensor (FBG) in distributed form as well as localized sensor
- Embedded FBG sensor is capable to monitor the pipe health such as temperature and stress under extreme process conditions.

iv. Industry participation or sponsorship

Gas Authority of India Limited (GAIL), Oil and Natural Gas Corporation (ONGC), Indian Oil Corporation Limited (IOCL), Indian Space Research Organization (ISRO), and Defence Research and Development Organization (DRDO)

5. Concluding remarks

Returning to India, Prof. Neogi has created a facility, Composites Applications Laboratory, in the Department of Chemical Engineering, IIT Kharagpur with the sponsorship of TIFAC, DST, Govt. of India, intending to advance the composite technology and cater the need of small and medium scale industries in India. Such facility is unique in the country. Currently, her research group consists of more than 10 Research Scholars and 2 PD associates who work on the development of advanced composites for various applications including defence, oil and gas sector, marine, and composite pressure vessels for chemical and energy storage. Most of these projects are sponsored by various medium and large-scale industries as well as defence organizations, such as, Gas Authority of India Limited (GAIL), Oil and Natural Gas Corporation (ONGC), Indian Oil Corporation Limited (IOCL), Indian Space Research Organization (ISRO), and Defence Research and Development Organization (DRDO). Recently her research group has developed an indigenous manufacturing technology for Type 4 filament wound composite vessels for the storage of compressed natural gas, for applications in the transport sector with the sponsorship of GAIL. She is also working to develop a filament wound Type 3 vessel for the storage of compressed hydrogen gas with the sponsorship of IOCL. Her group is the sole developer of the first indigenously manufactured commercial storage cylinders of compressed hydrogen gas. Her invention can instill significant reformations in hydrogen energy utilization and reduce our dependence on foreign sources for meeting the current power demand.