EVALUATION AND APPLICATION OF A SUSTAINABLE NYLON RESIN – A CASE STUDY ON COMPONENTS IN TRANSPORTATION REFRIGERATION SYSTEMS

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Abstract

Companies worldwide are increasingly recognizing the reduction of embodied carbon as a crucial strategy to achieve Net Zero emissions, and as a growing priority to address global climate change. The heating, ventilation, and air conditioning (HVAC) original equipment manufacturers (OEMs) are part of the industry that utilizes a large volume of plastic components. As a global climate innovator, Trane Technologies has set a sustainability goal to reduce embodied carbon emissions by 40% and design systems for circularity by 2030. To support these objectives, a cross-functional team collaborated on a project to evaluate and implement recycled nylon resins in multiple components on the Precedent® transportation refrigeration units offered by Thermo King®, one of Trane Technologies' strategic brands.

Two types of recycled nylon resins were evaluated as alternatives to the incumbent resins made from 100% virgin nylon. These alternative resins, sourced from various suppliers, are composed entirely of either post-industrial or post-consumer recycled nylon. This paper provides a detailed discussion on the alignment with Net Zero targets, the evaluation process, including assessments of resin performance, and support of circular business models and supply chain resiliency. The investigated recycled resins demonstrate comparable properties in terms of functionality and processability. By transitioning from virgin nylon to recycled nylon, Trane Technologies expects to achieve at least 50% reduction in total embodied carbon. Additionally, Trane Technologies estimates that over 350,000 pounds of recycled resins repurposed from scrap can be reused within our supply chain annually.

Introduction and Motivation

Extensive discussions have linked the increased presence of greenhouse gases in the atmosphere to global warming and climate change. If appropriate measures are not implemented, it is anticipated that global temperatures could rise to 1.5 degrees Celsius above pre-industrial levels by 2050[1]. For this reason, the Paris Agreement on climate change dictates the global responsibility of reducing greenhouse gas emissions. One of the major contributors to greenhouse gas emissions is material extraction and manufacturing, with plastic resins being one impact category. In the case of the HVAC industry, a significant amount of nylon resins is used for Thermo King® plastic components. This paper discusses the use of recycled nylon in place of prime nylon, which reduces the embodied carbon in transport refrigeration products, thereby helping to lower greenhouse gas emissions and reduce the impact on climate change.

Nylon is considered one of the highly valuable material resources in the modern world due to its moderate cost, high strength, excellent durability, and thermal stability. Its good thermal stability enables the material to maintain its strength and stiffness at the elevated temperatures found in demanding environments, such as engine bays and areas near exhaust systems. Consequently, nylon resins are widely used in various industries such as automotive, packaging, and electronics for semi-structural components. In the HVAC industry, nylon resins are commonly used for brackets, enclosure for electrical components, blowers, and fans. Additionally, nylon resins are recyclable, meaning they can be melted down and reused without adversely impacting on their physical and mechanical properties. This recyclability makes nylon resins a crucial role in achieving sustainability goals throughout the value chain.

Current State of the Technology Industry Uses

Pathways to net-zero solutions - HVAC OEMs are evaluating approaches to achieve net zero emissions associated with plastics, which can only be accomplished by actively engaging the broader supply chain. Existing literature on the circularity of nylon resins outlines two parallel approaches to address the relevant areas in the pursuit of net zero emissions for plastic use. These two pathways include:

- Forming a closed loop within the supply chain for internal scrap utilization
- Engaging with the resin manufacturers who supply recycled nylon that meets the physical and mechanical properties of prime resin

Closing the loop within the Supply Chain - Scrap generated from the trim-off from thermoforming process or from sheet manufacturing processes like cutting and slitting has the potential to be reused in a close loop. Many facilities are implementing recycling programs to reprocess scrap, reducing waste and promoting sustainability. Advancements in manufacturing technologies are also being explored to minimize scrap generation and improve material efficiency.

Currently, most scrap is sold to third-party recyclers, leading to limited visibility in its downstream processing. Only a small portion of recycled thermoplastic material is reused in a “closed loop” within the HVAC supply chain. To close the loop, HVAC OEMs need to collaborate with raw material suppliers and recyclers, redirecting scrap back to suppliers' mills and ensuring recycled material meets quality standards. Addressing end-of-life waste from HVAC products also requires new technologies to sort and segregate plastic waste, and a sufficient/consistent supply of recycled feedstock for reuse within the HVAC industry.

Engaging with the resin manufacturers - Another approach is to leverage expertise from the resin suppliers, particularly those with extensive experience and technical know-how in resin recycling, whether for PIR (Post-Industrial Recycled Resin) or PCR (Post-Consumer Recycled Resin) resins. The goal of resin suppliers is to maintain the resin and fillers ratio equivalent to that of prime resins to avoid shrinkage differences and to understand the degradation of physical and mechanical properties due to the recycling process compared to prime versions. Additionally, it is necessary to review the feed stream process used for recycling resin to ensure that the process starts with a high-quality feed stream to achieve high retention of properties. The supply chain associated with the feed stream of recycled resin manufacturing is also evaluated to ensure supply continuity for business needs.

One challenge of implementing these pathways is being able to meet the part or product performance currently achieved with virgin materials. For example, with respect to HVAC equipment blowers and fans, two of the physical properties are especially critical: airflow capacity to ensure that unit performance and efficiency of the fan. Achieving these necessitates demanding material-related properties, including robust strength, durability, and dimensional stability. Due to these stringent requirements, the nylon resins that are used to manufacture the HVAC parts are prime resins, containing more than 60% base nylon resin, with the remaining being fillers and other additives. It has been considered difficult to add more recycled resin beyond a certain limit due to the degradation of mechanical and physical properties. In addition, in general, only the recycled resin repurposed from scrap from the same pure prime resin scrap to ensure that the mechanical properties of the final product are maintained.

To increase recycled content and achieve sustainability benefits in plastic resins for HVAC application, equivalent performances of recycled resins can also be achieved only if the feedstock is from consistent high-quality sources, and/or the recovery process is advanced. This ensures that the recycled resin can replace existing prime resin without impacting the stringent physical and mechanical requirements. In general, OEMs do not have the capabilities to develop recycled nylons from scrap material. Therefore, progress is possible only through collaboration with the recycled resin manufacturers and suppliers.

Technology Approach and Discussion

Three recycled nylon resin samples, under evaluation, originate from various sources: one derived from PCR sources and two derived from PIR sources. Both the incumbent resin and the three recycled resin samples use approximately 60-65% of nylon-6,6 as the base polymer, and all contain similar percentages of glass fiber, fillers, and other additives. In the recycled materials, the base polymer is sourced entirely from either PCR or PIR streams. Considering Trane Technologies currently uses around 550,000 lb nylon resins annually on a specific transport refrigeration product, a successful transition from virgin to recycled material would enable the annual reuse of roughly 350,000 lbs of recycled polymers.

While the specific sources of the base polymer of the two PIR recycled resins are proprietary to suppliers, PIR sources, are generally understood to originate from clean, factory-generated plastic scrap, such as trimmings, excess material from manufacturing processes, or out-of-spec products. The base resin in the PCR resin originates from recycled carpet. After collection, the carpet is ground into particulates that are sorted, and the base polymer is isolated from other components using a patented wet-separation process.

Table 1 summarizes the embodied carbon values for two recycled resins (PCR-based and PIR-based) and their virgin counterparts, as provided by the suppliers. Raw-material values were obtained from the GaBi database, and transportation and processing inputs (energy and water) were added to determine the final cradle-to-gate results. This transition can reduce embodied carbon by up to approximately 70%, resulting in an estimated greenhouse gas reduction of 600–800 tons per year based on current annual resin usage.

Table 1. Embodied carbon of the PCR resin and its virgin counterpart

	Embodied carbon (kg CO_2e/kg)		Reduction in greenhouse gas emissions (kg)
Material	Recycled resin	Virgin Equivalent	
PCR Nylon-6,6 resin	1.09	3.41	578,783
PIR Nylon-6,6 resin	1.1	4.4	823,269

A preliminary evaluation will be conducted using the resins' technical data sheets and a series of performance-based testing to assess the recycled resins. Resins that meet the pre-screening criteria will be further evaluated through molding trials, followed by a full PPAP submission from the component manufacturer to fully approve the resin change. The whole validation process recommended is outlined below:

- Comparison of physical, mechanical and thermal properties between virgin and recycled resins
- Comparison of Gardener impact properties between virgin and recycled resins
- UV weatherability test to compare UV stability between virgin and recycled resins
- Spiral flow testing and molding trial
- PPAP Submission (including dimensionals and supporting qualification data)

Physical, Mechanical and Thermal Properties Comparison

The mechanical properties of the recycled resins were originally expected to reach at least 80% of those of the virgin resin. Following the suppliers' extensive formulation of the recycled resins and comprehensive lab testing, experimental results were gathered and compared with the incumbent virgin resin (Table 2). The results show that the recycled nylon resins retain the majority of the properties of the virgin resin. The property degradation, whether from PCR or PIR sources, is negligible. Following the review of the resin TDS documents, the materials engineering team and the product team agreed to advance all three recycled resins to the next phase of testing and evaluation.

Table 2. Physical property comparison between prime and recycled nylon resins

	Prime Resin (Sample 1)	Recycled Resins		
		Sample 2 (PIR)	Sample 3 (PCR)	Sample 4 (PIR)
Density (g/cc)	1.40	1.41	1.46	1.42
Tensile strength (MPa)	128	125	111	121

Tensile elongation (%)	2 – 4	2 – 4	3	2.33
Tensile Modulus (GPa)	8.2	-	-	9.0
Flexural Strength (MPa)	186	186	170	212
Flexural Modulus (GPa)	8.2	8.3	8.1	9.7
HDT (1.80 MPa, ˚C)	207	207	205	-

Gardner Impact Test

Some of the plastic components made with the incumbent resin serve as a protective shield for the components behind them in the transportation refrigeration units. These shields help prevent damage caused by hail, road rocks kicked up by passing vehicles, or branches from roadside trees. The Gardner impact test method[2] involves dropping a weight from a specified height onto flat, rigid plastic specimens. This test is more suitable than other impact testing methods, such as the Charpy or Izod methods, because it can better simulate road impacts. This method was chosen to evaluate the strength of the incumbent resin and candidate recycled resins.

Four batches of plaques with a thickness of 1/8 inch were made with either the incumbent resin or one of the three recycled resins. A minimum of 40 2"x2" specimens were prepared from each batch for Gardner impact testing. Prior to testing, all the specimens were preconditioned in an environmental chamber for at least 72 hours, at 23°C and 50% relative humidity. The Bruceton staircase method was employed to calculate the mean failure energy (MFE) and its standard deviation (S_{MFE}). Gardner impact properties of all samples are summarized in Table 3. The desired recycled resins are expected to achieve at least 80% of the incumbent resin's lower bound of Gardner impact properties, estimated by the Mean-3S_{MFE}, to qualify. Based on the test results, Samples 2 and 3 closely meet this requirement. Sample 4 exhibits inferior impact performance compared with Samples 2 and 3.

Table 3. Garnder impact properties comparison between samples with prime and recycled nylon resins

	MFE	S_{MFE}	Mean-3S_{MFE}
Sample 1	7.6	0.3	6.7
Sample 2	5.8	0.2	5.2
Sample 3	9.3	0.7	7.2
Sample 4	5.0	0.3	4.1

UV Resistance Test

Specimens prepared from all four resins underwent extensive UV testing in a Xenon arc chamber in accordance with the SAE J2527 standard, with exposure levels tested up to 2500 kJ. Figure 1 below displays the Delta E (color shift) versus the amount of energy exposure for specimens made with each resin. The specific weathering requirement target was not provided to the supplier. As a result, the suppliers applied their standard UV package (proprietary information). Additionally, the color of these parts is designed to be generic black, so all these resins contain certain percentages of carbon black. Both the UV package and the carbon black contribute to a certain level of UV resistance in these resins. After UV exposure, most of these resins exhibit Delta E values close to or less than 5.

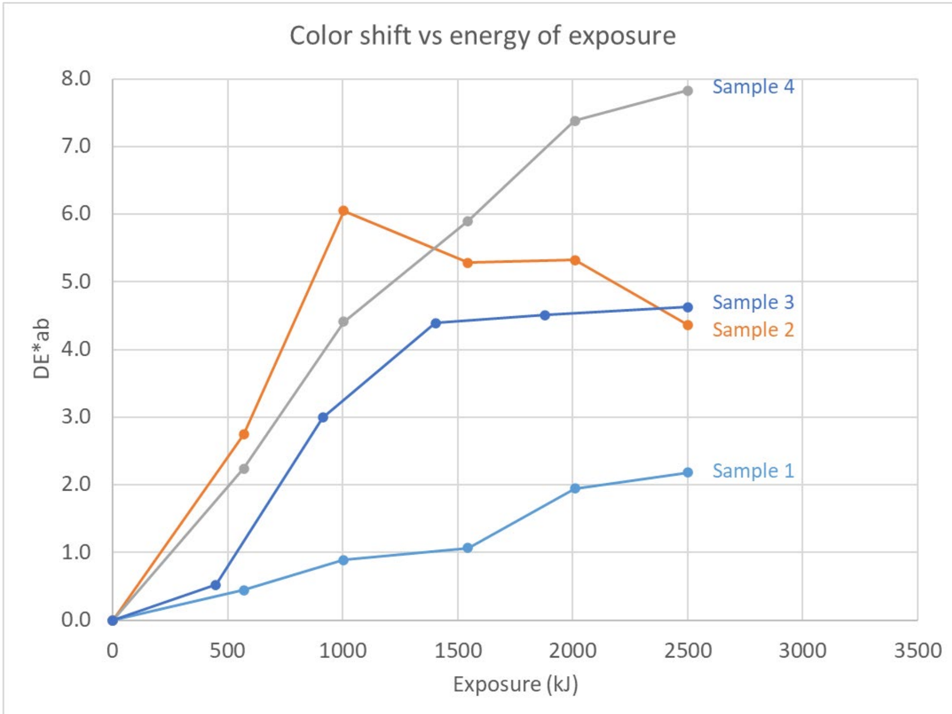

Figure 1. Color shift vs. energy of exposure of samples with incumbent (virgin) resin and recycled nylon resins

Spiral flow length testing and molding trial

Because Sample 4 exhibited sub-par impact performance and a higher color shift in preliminary testing, it was excluded from further evaluation. Samples 2 and 3 were then carried forward for processability and molding trials. Spiral flow testing of the two recycled resins and the incumbent material was conducted on a JSW Model J110 injection-molding machine. The barrel temperature was maintained at roughly 275 °C, and with mold cooling turned off, mold temperatures remained between 5 and 10 °C above room temperature. Figure 2a shows a representative spiral flow length test part molded using resin sample 3. The spiral flow lengths of 3 resins are summarized in Table 4. The two recycled resin demonstrated slightly greater flow lengths as compared to the incumbent resin, possibly due to polymer degradation associated with multiple additional thermal cycles in the PIR source or the extended aging of carpet in the PCR source.

Table 4. Spiral flow lengths of incumbent resin and 2 recycled nylon resins

	Spiral flow length (inch)
Sample 1	34.8 (±0.50)
Sample 2	34.9 (±0.53)
Sample 3	36.4 (±1.23)

Molding trials with both recycled resins were conducted at the supplier's facility immediately after a production run using the incumbent resin. All parts could be molded successfully with each recycled resin, requiring only minimal processing adjustments. No short shots were observed on the largest part (~25" × 14" × 5") for either recycled resin (Figure 2b).

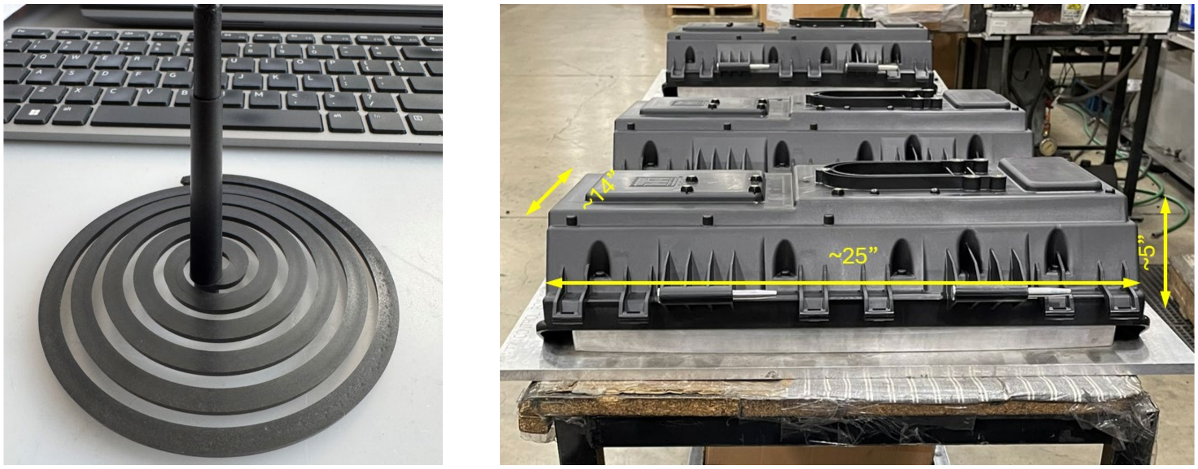

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Figure 2. a: One representative spiral flow sample with resin Sample 2; b: one part (control box) molded with resin Sample 3

Screw boss stripping torque testing

Before moving on to the final step (PPAP submission and approval), samples made from the two recycled resins went through a 3F (form, fit, function) assessment at the final manufacturing plant. The screw drive holding force (stripping torque) for six self-tapping screw bosses on the control box (1-6 shown in Figure 3a) was tested as part of this 3F assessment. Torque was applied in 0.5 Nm increments from 2.5 Nm to 5 Nm to install the #8 Trilobular Pan Head Thread-Rolling screws into the bosses as demonstrated in Figure 3b, and binomial pass/fail outcomes (stripped/not stripped) were recorded at each corresponding torque level. For each of the three resin formulations, five parts (replicates) were tested, and in total, data was collected from 30 bosses.

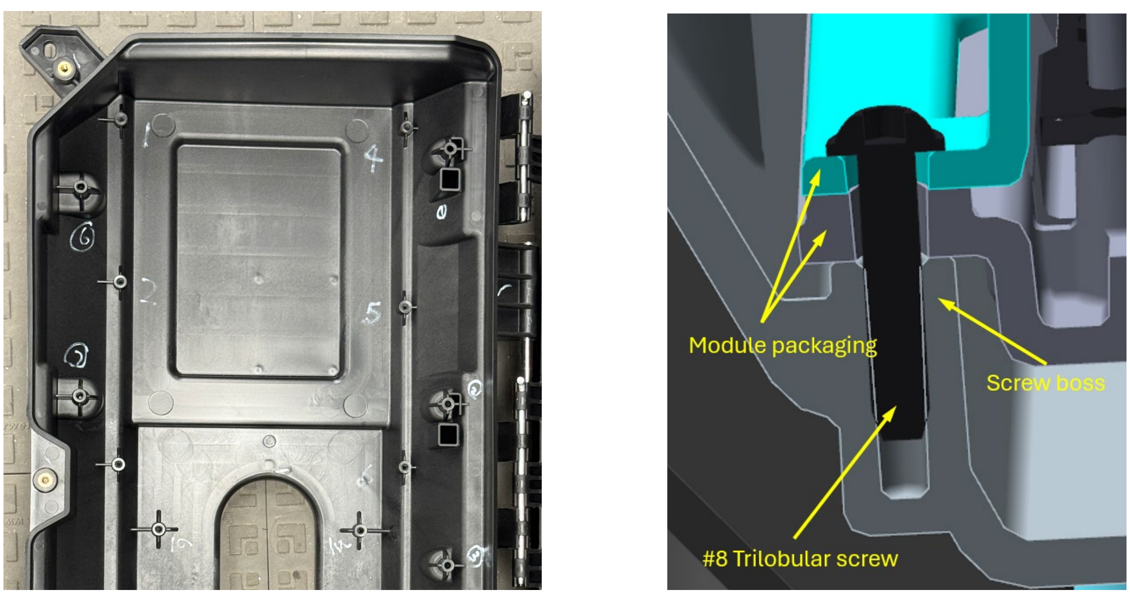

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Figure 3. Six self-tapping screw bosses (1–6) for stripping torque testing

The number of screw bosses that stripped at each applied torque level is presented in Table 4. For the production parts, boss stripping initiated at 4.0 Nm, and all remaining bosses failed at 4.5 Nm. In the trial parts fabricated with Sample Resin 2, stripping initiated at 3.5 Nm, with the majority of bosses failing at 4.0 Nm. The trial parts produced with Sample Resin 3 demonstrated the highest resistance to stripping, with initial failures observed at 4.0 Nm and most bosses failing at 4.5 Nm. The stripping resistance of 3 resin samples aligns with the order of Gardner impact strength results presented in Table 3. Resin sample 2 showed slightly lower screw-boss strip torque, but it remained above the design guideline. Therefore, both recycled resins are considered to have passed this test.

Table 4. Number of bosses stripped at each torque

	Stripping torque (Nm)			
Part	3.5	4.0	4.5	5.0
	Quantity of bosses that stripped			
Production part (Resin sample 1)	0	16	14	
Trial part (Resin sample 2)	4	22	4	
Trial part (Resin sample 3)	0	1	22	7

Conclusions & Closing Remarks

Through close collaboration with select resin suppliers that have strong ownership and awareness of the recycled resin markets, we were able to finalize two recycled resins that demonstrated equivalent performance. A business analysis incorporating part weight, sales volume, and resin pricing from the two suppliers realized that a cost savings would be achieved by adopting these recycled materials. Other benefits of implementing this initiative are as follows:

- A cost reduction in resin price compared to the incumbent virgin material
- A reduction of up to ~70% in total embodied carbon (varied by sources)
- Annual reuse of 350,000 lbs of recycled resin within the existing supply chain

Trane Technologies uses a circular economy as a business model by integrating sustainability into its entire value chain, from product design to end-of-life management. Trane Technologies remains at the forefront by setting an example in reducing carbon emissions, water, waste, and energy use within its operations[3]. They are adopting circular business models by moving beyond the linear take-make-waste approach, and a $4.5trillion potential to be unlocked or a value at stake by 2030 through the circular economy[4].

Waste is produced at various points throughout the product life cycle. Industries can work to create value from materials discarded during production and use them in new products, allowing them to reduce investment. Where possible, scrap and end-of-life products are transformed back into their base materials and reprocessed into new products, minimizing waste, maximizing material quality and lowering the embodied carbon of our product inputs.

Testing the use of recycled resins on multiple plastic components within Thermo King® Trailer Refrigeration products with the goal of reducing the carbon footprint and saving on procurement costs. Trane Technologies expects to reduce the embodied carbon by at least 30%, by reusing the scrap and recycled material within our supply channels. By decreasing the dependency on virgin materials, we are able to foster a more resilient supply chain. By accessing closed loop scrap materials, we are able to mitigate the need to landfill and extract new virgin natural resources. By incentivizing a reuse economy, we are supporting growth in these markets with the hope to reduce costs as demand increases over the long term. We are designing new solutions that would not have been an option in the past.

Addressing all aspects of material circularity is becoming increasingly crucial for OEMs seeking to achieve net zero emissions in the near future. HVAC OEMs are actively working toward this goal for plastics commodities by collaborating with resin manufacturers to obtain recycled resins that match the physical and mechanical properties of prime resin. This approach enables OEMs to maintain product performance and quality while reducing reliance on virgin materials. By prioritizing high-quality recycled inputs, HVAC OEMs can significantly lower their environmental impact and advance their sustainability objectives. Furthermore, OEMs should extend the concept of circularity beyond plastics and explore similar solutions for other key materials, such as aluminum, steel, and copper, to further enhance their progress towards sustainable operations.

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