Enclosure (A) to:
10-FLFW-2018-000049

PROJECT ACFJ17PV19 - Demonstration and Validation of Uncured, Scrap Composite (Prepreg) Reuse, F-35 Composite Manufacturing

Prepared for
AFLCMC/WNVK
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TABLE OF CONTENTS

Table of Figures

List of Tables

Enclosure (A) to:
10-FLFW-2018-000049

Demonstration and Validation of Uncured, Scrap Composite (Prepreg) Reuse, F-35 Composite Manufacturing

1.0 SUMMARY

Feasibility of the Direct Recycling (DR) method of reusing waste, uncured composite prepregs was validated. High rates of fabrication via DR and good to excellent quality of the composites were able to satisfy the requirements of several different reuse applications achieving the 1135 lbs. of waste reductions and $108k of cost savings shown in Table 1 and Table 3 (167 lbs supported AFRL/ AFLCMC efforts). DR methods use existing facilities, materials and training reducing startup barriers and achieved 85% to 100% of nominal properties with the economically recyclable feedstocks. While recycling is still only 20% of the waste stream, payback for this work is now estimated to be ~1.5 years.

Table 1: Waste and cost savings from recycling of uncured composite prepregs in 2017

Composite Prepreg (2017 lbs.)	Prepreg Waste(lb) (Hazard)	Carrier Weight (lb.)	Carrier Paper Waste(lb.)	Paper Waste(lb., recycled)	Machining Waste (lb.)	Total Composite Waste (lb.)	Disposal Cost ($)
27750	5550	17147	8,072	(12,488)	4163	34932	
[% of PP #s]	20%	62%	29%		15%	**126%**	
Recycled - 2017	1135	lbs.	Cost Savings Estimate		Material* - recycle labor		
					Disposal savings		
					Labor/Tooling Savings		
						Total	$ 107,567

Table 2: Categories of reuse applications served in 2017 for recycled composite prepreg waste.

Re-used by application	Lbs.	Cost Savings
Demos/Development	110.4	$ 7,438
ManTech	370.4	$ 54,279
Composite Testing	21.9	$ 2,607
Program tooling	632.1	$ 43,243
Totals	**1135.0**	**$ 107,567**

2.0 INTRODUCTION

Fifth generation aircraft composite part fabrication produces at approximately 35% scrap, much of it is uncured prepreg which is dispositioned as hazardous waste. Recycling of uncured material into manufacturing aides, training, and engineering products, instead of expensive disposal, eliminates this waste stream, its costs and can recapture some or all of the original value of the material. While others have developed commercial products based on discontinuous forms (random chips), LM developed 'Direct Recycle' (DR) of scrap composite materials delivering maximum reuse value to the end-user creating a self-funding reuse path for this waste stream.

Successful reuse of uncured composite materials requires consistent, known performance for the end user. The non-virgin, possibly un-documented, feedstock requires receiving evaluation to target a processing 'Norm' and consistent fabrication. Air Force Plant #4 has a limited number of waste chemistries (resin systems) at present – this project verified and documented the QA evaluation techniques required. These efforts validated and documented prior LM ESH funded process development supporting expanded end-user acceptance; these goals include:

• In-coming Quality Assurance/Blend: Measure cure state and flow to quantify variability and impact on processing characteristics.

• Recycle Intermediates Database: Characterize recycle laminate variability for aging, fiber orientation (random) and areal uniformity to support acceptance decisions.

• Joining methodologies: Demonstrate designs and fabrication techniques for efficient joints, expanding the utility of the recycle materials and maximizing use of waste materials.

Demonstrating these technologies increases opportunities to use recycled waste as Department of Defense (DOD) manufacturing support articles as a low/no cost material substitute (Figure 1). Recycling costs were tracked, compared to the cost of the manufacturing support articles from virgin stock or commercial sources, and these values were used to calculate cost savings via recycle of waste materials.

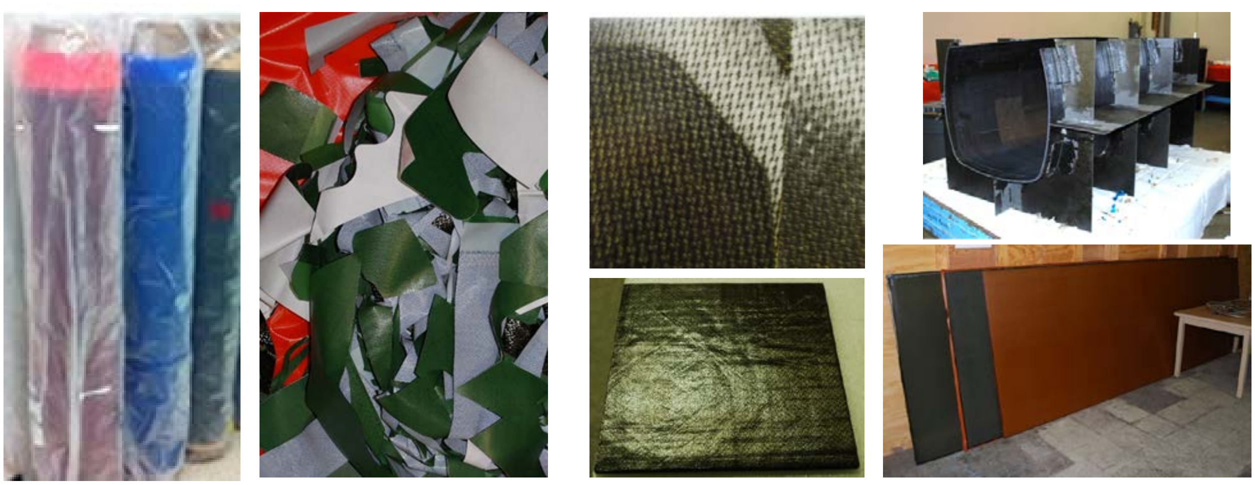


Figure 1: Recycling of composite prepreg wastes into panels and manufacturing aides

3.0 RECYCLING CANDIDATE MATERIALS

3.1 Recycle materials considered

All varieties of uncured composite prepreg materials which can be converted to value-added articles should be considered. Prepreg material consist of some form of reinforcement fiber or carrier textile which is wetted with a viscous resin system. These materials include prepreg tape, fabric, and non-woven scrims which are used to build, bond and add functionality to structural parts.

3.2 Recycle materials manufacturer contact information

Cytec Aerospace Materials – Carbon fiber composite prepregs, adhesives and scrims
1440 N. Kraemer Blvd
Anaheim, CA 92807
Tel: +1.714.630.9400

1300 Revolution Street
Havre De Grace, MD 21078
Tel: +1.410.939.1910

Hexcel – Carbon fiber composite prepregs, adhesives and scrims
Shelby Thacker – Texas & Ohio
shelby.thacker@hexcel.com
(801) 508-8355

3M – Composite adhesives and scrims
Customer Service
1-888-3M HELPS; (1-888-364-3577)
3M Corporate Headquarters
3M Center
St. Paul, MN 55144

3.3 Current use of recycle materials

The composite prepreg materials are the feedstock for composite structure for fighter aircraft, specifically F-35 variants A, B, and C. The prepreg is cut into patterns, arranged at controlled orientations to carry specific loads, consolidated, cured and machined to final shape to be assembled into the airframe. The prepreg materials are reactive and have a finite working life, usually 30 days, in which they must begin cure into the pre-machined part in order to satisfy processing requirements. Material performance requires that the final parts have the maximum number of continuous fibers across the part to optimally carry the loads. Thus, irregular pattern off-cuts and materials which can no longer meet manufacturing certification requirements are disposed of as waste.

3.4 Recycle materials information

A wide variety of composite prepreg materials are used in AFP#4; the material systems which have sufficient volume and will support value-added recycling are included in Table 3. The bulk of the prepreg materials are Hexcel IM7 carbon fiber fabrics and tapes with Solvay 977-3 epoxy or 5250-4 bismaleimide resins. More information for these material systems are available from links in section 6.2 for the main composite systems and a link to informational material and fabrication brochure from Hexcel® which concisely describes composites and the processing required to make high quality parts.

Table 3: Recyclable Prepreg Materials at Air Force Plant No. 4

Manufacturer	Reinforcement	Matrix System	Form	Other
Solvay (Cytec)	IM7 carbon fiber	Epoxy 977-3 (EP)	4HS Fabric	0/90 4HS
Solvay (Cytec)	IM7 carbon fiber		4HS Fabric	Bias weave
Solvay (Cytec)	IM7 carbon fiber		Tape- 5mil	49” wide
Solvay (Cytec)	Glass (S and E)		4HS Fabric	Various
Solvay (Cytec)	IM7 carbon fiber	Bismaleimide 5250-4 (BMI)	4HS Fabric	0/90 4HS
Solvay (Cytec)	IM7 carbon fiber		Tape- 5mil	49” wide
Solvay (Cytec)	Glass (S and E)		Fabrics	Various
Hexcel®	IM7/ M65 (High Temperature)	Bismaleimide M65 HT	4HS Fabric	0/90 4HS
3M	AF – 191; 563	Mod. Epoxies	Scrim	Wide Film
Hexcel, Solvay	Surface veils	Various	Scrim	Wide Film

Table 4 is the list of recycling runs completed in 2017 and summarized in Table 2. The table includes applications, material type recycled, product size and quantity, value attributes and the number of pounds reused. This information is used when matching waste streams to applications and determining cost savings potential.

Table 4: Detailed list of recycled material and the applications served

Recycled Composite Materials - 2Q, 2017									
Date	Enduse	Description	Material	Cost/Value Description of Matl	Qty	in2	Source; Piece Sizes	Actual (Lbs.)	Number of Coupons /Panels
Demonstrations									
1/9/2017	Recycle demo	Flat Plate Core (no scrap)	Graphite /Epoxy - old	Small Proc. Panels	2	225	Fines/Sm.	3.8	1
1/16/2017	Recycle demo	Flat Plate Core (no scrap)	Graphite /Epoxy-new	Small Proc. Panels	2	225	Mix	4.8	1
2/28/2017	Reuse CRAD	Test panels; Batch 1,2	Graphite /Epoxy	1 sq. ft. test panels	7	144	Mix	10.5	7
2/28/2017	Reuse CRAD	Test panels; Batch 1,2	Graphite /BMI	1 sq. ft. test panels	7	144	Mix	10.5	7
4/20/2017	Reuse CRAD	Test panels; Batch 3	Graphite /BMI-Epoxy	1 sq. ft. test panels	7	144	Mix	10.5	7
5/12/2017	Reuse CRAD	Test panels; Bonding	Graphite/Glass; Film	Lap shear w/tabs	21	36	BG	0.5	21
5/12/2017	Reuse CRAD	Test: Bonding substrate	Graphite/Epoxy	Lap shear panel & tabs	21	96	BG	24.2	4
11/10/2017	Recycle demo	Press shim -0.25x51sq	Peel Ply/Epoxy	Shim - commodity	1	2304	BG	30.0	1
12/14/2017	Texas A &M FSAE	Sub-scale race car	IM7/Epoxy	Raw Matl - Ext. Use			BG	40.0	PP reuse
ManTech / Training									
3/6/2017	ManTech - JC	AGM Process trials	Graphite /Epoxy Roll	Raw Matl - Ext. Trial			BG	20.0	PP reuse
3/20/2017	ManTech - JC	Tooling supports	Graphite /Epoxy	Raw Matl - Internal			Mix	20.2	1
4/12/2017	AFLCMC - WRAP1	Test coupons	Graphite /Epoxy	ManTech Test substrate	1	18	BG	20.2	1
5/1/2017	AFLCMC - WRAP1	Test coupons	Graphite /Epoxy	ManTech Test substrate	1	18	BG	10.0	1
5/18/2017	AFLCMC - WRAP2	Test coupons	Graphite /Epoxy	ManTech Test substrate	210	18	BG	9.0	210
7/17/2017	Mfg. Support: QA	Robo-drill panel 2	Graphite /Epoxy	ManTech QA substrate	16	144	BG	73.0	16
7/25/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training panels	16	144	BG	35.0	177
9/6/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training coupons	184	12	BG	35.0	184
9/8/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training panels	16	144	BG	35.0	16
11/10/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training coupons	184	12	BG	35.0	184
11/15/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	13.5	3
11/15/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	13.5	3
11/15/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	13.5	3
12/11/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	13.5	3
12/11/2017	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	13.5	3
2017 - 2018	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG	Values to be captured in 2018	
2017 - 2018	Training - Assembly	Fab. coupons	Graphite /Epoxy	F35 Training - Curved	3	323	BG		
Characterization / Composite Testing									
2/14/2017	AFRL Fastener Test	Coupons: 5"x6" (64)	Graphite /Epoxy	ManTech substrate	64	30	BG's	21.9	64
Program/ Tooling / Misc.									
1/17/2017	Dream Chaser -MS	Flat tool plate, 1/4"	Graphite /5250-4	High Temp tool plate	1	1152	BG/Trim	16.1	1
2/17/2017	Glass Caul - Recycle Fab.	Flat plate	Glass Peel/ 977-3	Commodity	1	6912	BG - Dry	72.0	2
3/3/2017	CF/Ep Tooling Stock - AFRL	Flat plate: 4x 12 x 0.312	Graphite /977-3	ManTech/Training	1	6912	BG - Dry	137.0	36
3/15/2017	CF/Ep Tooling Stock -Trng	Flat plate: 4x12x 0.256	Graphite /977-3	Training Panels	1	6912	BG - Dry	110.0	48
3/23/2017	CF-Gl/Ep Caul -AFRL	Flat plate: 4x12x 0.16	IM7-Gl Peel /977-3	Commodity	1	6912	BG - Dry	80.0	32
4/2/2017	CF-Gl/Ep Caul - PDC	Flat plate: 4x12x 0.16	IM7-Gl Peel /977-3	Commodity	1	6912	BG - Dry	80.0	34
11/10/2017	Dream Chaser -MS	Flat tool plate 1/8"	Graphite /5250-4	High Temp tool plate	1	2304	BG/Trim	18.2	1
12/13/2017	Dream Chaser -MS	Flat tool plate 0.1"	Graphite /5250-4	High Temp tool plate	1	2304	BG	14.0	1
12/13/2017	Dream Chaser -MS	Flat tool plate 0.15"	Graphite /5250-4	High Temp tool plate	1	2304	BG	21.0	1
12/13/2017	Dream Chaser -MS	Flat tool plate 0.1"	Graphite /5250-4	High Temp tool plate	1	2304	BG	14.0	1
12/13/2017	Dream Chaser -MS	Flat tool plate 0.15"	Graphite /5250-4	High Temp tool plate	1	2304	BG	21.0	1
12/13/2017	Dream Chaser -MS	Flat tool plate 1/4"	Graphite /5250-4	High Temp tool plate	1	2304	BG	35.0	1
Totals								**1135**	**1072**
			Piece Sizes: Fines/Small; Med-lg; BG - Broadgoods Mix - all sizes						Total Articles
		*Other: Includes fabrication labor savings; reuse of tooling and fabrication materials.							

4.0 RECYCLING EVALUATION PLAN - PERFORMANCE TESTING

Recycling success for uncured composite waste streams is measured by the amount of material that can be cost effectively converted to useful products. The ability of those products to repeatedly satisfy the customer requirements builds long-term waste stream reuse (reduction). Increasing scale/volume makes recycling operations more profitable by permitting the best fit of material type and form to the needs.

Figure 2 is a flowchart of the recycling material process. Production broadgoods waste is sorted by reinforcement, resin system and evaluated for processability before use or storage. Trimmings, pattern off-cuts, are available daily and are not stored as their generation rate exceeds our use rate. Applications are evaluated for suitability with these materials; available materials are pulled from room temperature (RT) or refrigeration; and parts are fabricated. Cost avoidance is maximized by matching high rate waste feedstocks and methods to the product reducing labor costs for the volume of reuse applications presently available.

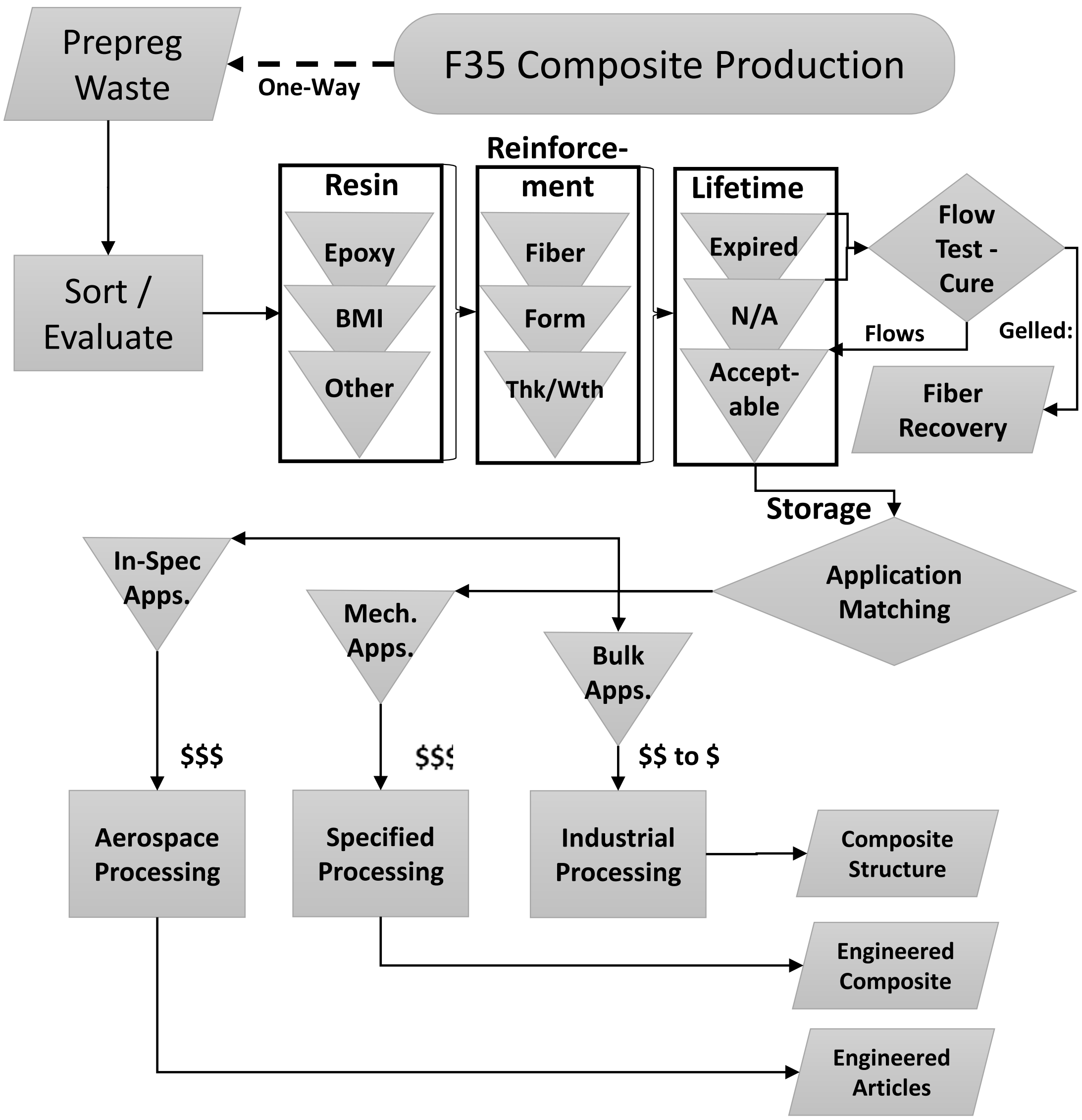


Figure 2: Flowchart for Direct Recycling of Uncured Composite Wastes

The test plans below evaluate the manufacturability, performance and variability of the AFP#4 prepreg waste streams to facilitate the recycling product flow and capture the highest value applications to make waste reuse as attractive as possible.

4.1 Fabrication economics - Processability

The value of the reuse application minus the cost of the conversion from waste to usable product determines whether recycling will succeed and persist. The 'Direct Recycling' method is a manual process reconfiguring waste materials to make product as close to the virgin material as possible. The robustness of the resin systems impacts its manufacturability and was characterized using the test matrix of Table 5, which includes extent of reaction, viscoelastic behavior, processing (flow) and evaluates handling and the laminate variability in thickness and orientation. This project determined the rates of conversion that are needed to enable cost savings and how much of the waste stream fits within those constraints.

Table 5: Aging characterization matrix for uncured waste prepregs.

Resin types	Epoxy			Bimaleimide			Epoxy/Bismaleimide Mix		
Outtime (70F)	<10 days	> 30 days	> 60 days	<10 days	> 30 days	> 60 days	<10 days	> 30 days	> 60 days
Layup Eval.	1	1	1	1	1	1	1	1	1
DSC	2	2	2	2	2	2		2	
DMA	2	2	2	2	2	2		2	
Flow	1	1	1	1	1	1	1	1	1

The test procedures / methods / sample definitions used are:

- Epoxy – Solvay/Cytec 977-3 toughened system
- Bismaleimide - Solvay/Cytec 5250-4 toughened system
- Epoxy/Bismaleimide – 50/50 mix of resin system; interleaved plies
- Layup evaluation – Tack/stickiness, ease of forming, prepreg defects/anomalies.
- DSC – Differential Scanning Calorimeter: Measures heat absorption/generation to determine extent of cure, maximum reaction rate and heat capacity. (equipment/method)
- DMA – Dynamic Mechanical Analysis: Measures stiffness and plasticity to quantify softening, gelation response, phase changes and glass transition temperature. (equipment/method)
- Flow – Prepreg resin flow: Measures % resin flow out of prepreg at maximum cure pressure and temperature. Modified ASTM – D3531-16: shortened 5 minute test.

4.2 Properties – Performance

Customer acceptance is based on satisfactory performance at reduced costs vs. using virgin material. This waste stream has been 'discarded' for exceeding its specified lifetime or being cut-up into irregular shapes in standard manufacturing processes. Random material batches were collected, aged as needed, fabricated into small test panels, cut into coupons and tests. A reduced test matrix was used to evaluate a 50/50 mixture of the main resin systems. Measuring the in-plane and interlaminar properties and processing responses provides Quality Assurance (QA) data defining the quality of laminates and the suitability to applications. The recycled laminate product characterization matrix is shown in Table 6.

Table 6: Mechanical performance validation test matrix

Run Number	Resin System	Prepreg Outtime	Recycle Piece Size	Tensile Strength	Tensile Modulus	Flex Strength	Shear Strength
1	Ep/BMI	10+ days	Med-Lg	X	X	X	X
2	Ep/BMI	30+	Med-Lg	X	X	X	X
3	Ep/BMI	60+	Med-Lg	X	X	X	X
4	Epoxy	10+ days	Sm-Med	X	X	X	X
5	Epoxy	30+	Sm-Med	X	X	X	X
6	Epoxy	60+	Sm-Med	X	X	X	X
7	Epoxy	10+ days	Med-Lg	X	X	X	X
8	Epoxy	30+	Med-Lg	X	X	X	X
9	Epoxy	60+	Med-Lg	X	X	X	X
10	Epoxy	10+ days	Broadgoods	X	X	X	X
11	Epoxy	30+	Broadgoods	X	X	X	X
12	Epoxy	60+	Broadgoods	X	X	X	X
13	Bis-MaleImide	10+ days	Sm-Med	X	X	X	X
14	Bis-MaleImide	30+	Sm-Med	X	X	X	X
15	Bis-MaleImide	60+	Sm-Med	X	X	X	X
16	Bis-MaleImide	10+ days	Med-Lg	X	X	X	X
17	Bis-MaleImide	30+	Med-Lg	X	X	X	X
18	Bis-MaleImide	60+	Med-Lg	X	X	X	X
19	Bis-MaleImide	10+ days	Broadgoods	X	X	X	X
20	Bis-MaleImide	30+	Broadgoods	X	X	X	X
21	Bis-MaleImide	60+	Broadgoods	X	X	X	X

The test procedures / methods / sample definitions used are:

- Flex – Flexural Strength: Three point test at 0.12"/min. with 2.5" span (ASTM –D7972-14)
- SBS – Short Beam Shear: Three point test at 0.05"/min. with 0.4" span (ASTM - D2344)
- Tensile/Mod. – Tensile Strength/Modulus: Dogbone tensile coupon tested at 0.05"/min. with 3" gauge section, ASTM – D3039-17 with extensometer.
- Small – prepreg trim pieces; less than 1 ft2 area; approximately 8 pcs per ply were used to ensure multiple butt splices in the test. samples
- Medium – prepreg trim pieces; 1 to 3 ft2 area; approximately 4 pcs per ply used.
- Large – broadgoods; approximately 1.2 pcs per ply; small, but not zero chance of butt splice.
- Outtime – Number of days at room temperature: Fresh ≈ 10 days; >30 days, Specification outtime; >60 days – Double Specification outtime.

Some applications require more than laminates. To expand the reuse applications, structural testing, bonded joints, were also characterized to validate their performance. Table 7 lists evaluation testing of the surface mechanical preparations and chemical treatments, the type of adhesives agents available in the recycle stream and two cure methods. Because recycling applications may not employ the well-defined specifications for bonding for aerostructure, a robust look at the possible outcomes was desired to inform potential applications of the range of performance possible. All substrate materials used were recycled by the DR methods. Lap shear coupons with a 1 inch nominal gage area were tested using ASTM 5868 at 0.5 "/min. load rate.

Table 7: Recycled material bonding evaluation matrix

Surface Preparation	Surface Treatment	Adhesive	Bond Pressure
Solvent Wipe	None	FM 300	Vacuum Bag
Solvent Wipe	None	Prepreg	Vacuum Bag
Scuff- Scotchbrite	None	FM 300	Vacuum Bag
Scuff- Scotchbrite	None	Prepreg	Vacuum Bag
Abrade - 60 grit	None	FM 300	Vacuum Bag
Abrade - 60 grit	None	Prepreg	Vacuum Bag
Abrade - 60 grit	LICA 38; 0.25%	FM 300	Vacuum Bag
Abrade - 60 grit	LICA 38; 0.25%	Prepreg	Vacuum Bag
Abrade - 60 grit	LICA 38; 0.5%	FM 300	Vacuum Bag
Abrade - 60 grit	LICA 38; 0.5%	Prepreg	Vacuum Bag
Abrade - 60 grit	NZ 97; 0.25%	FM 300	Vacuum Bag
Abrade - 60 grit	NZ 97; 0.25%	Prepreg	Vacuum Bag
Abrade - 60 grit	NZ 97; 0.5%	FM 300	Vacuum Bag
Abrade - 60 grit	NZ 97; 0.5%	Prepreg	Vacuum Bag
Abrade - 60 grit	LICA&NZ 0.25%	FM 300	Vacuum Bag
Abrade - 60 grit	LICA&NZ 0.25%	Prepreg	Vacuum Bag
Solvent Wipe	LICA&NZ 0.25%	FM 300	Vacuum Bag
Solvent Wipe	LICA&NZ 0.25%	Prepreg	Autoclave - 90 psi
Scuff- Scotchbrite	LICA&NZ 0.25%	FM 300	Vacuum Bag
Scuff- Scotchbrite	LICA&NZ 0.25%	Prepreg	Autoclave - 90 psi

The test procedures / methods / sample definitions used are:

- Solvent wipe: Acetone wipe; ambient dry
- Scuff – ScotchBrite light scuff, remove surface shine, leave resin surface
- Abrade – 60 grit surface removal exposing fibers
- None – solvent wipe only
- LICA38: Ken-React Titanium IV 2,2(bis 2-propenolatomethyl)butanolato, tris(dioctyl)pyrophosphato-O in Isopropyl Alcohol coupling agent brushed on; dried.
- NZ97: Ken-React Zirconium IV 1,1(bis-2-propenolatomethyl)butanolato, tris(2-amino)phenylato in NMP solvent
- Prepreg – 38% resin content IM7/977-3 epoxy prepreg (recycle) used as film adhesive
- FM-300 – 3M epoxy film adhesive, nominal 0.015" thick
- Vacuum Bag – Cure pressure limited to vacuum inside bag; typically 25 to 27 in. Hg.
- Autoclave – Cure pressure in autoclave of 90 psi in addition to vacuum inside bag.

In addition to the lap shear testing, Tee joints from a test panel and the 2016 cure tool demo article were tested using the LM Tee (Pi preform) setup to evaluate a typical joint used for this application.

5.0 TEST RESULTS

Material Characterization: Table 8Table 15 summarizes the results of 441 fabrication/chemistry and mechanical property tests used to determine both nominal performance of this recycled product and the variability that may be encountered. These performance ratings are organized by the M&P parameter, calculating relative ranking by feedstock size, resin differences, and prepreg outtime. The performance rankings in this report are internal to this study, they are not compared to the F35 design allowables.

Table 8: Performance differences between virgin and recycled composite prepreg materials

Property Evaluated		Tensile Strength	Tensile Modulus	Tensile Strain	Flexural Strength	Short Beam Shear	Resin Flow Test	Reaction Onset Temp.	Heat of Reaction Change	Summed Effect
Piece Size; No hybrids	Broadgoods	100%	100%	100%	100%	100%	100%	NA	NA	100%
	Med/Lg	87%	100%	89%	102%	100%	100%	NA	NA	96%
	Sm/Med	73%	100%	79%	89%	94%	99%	NA	NA	89%
	Delta	27%	0%	21%	13%	6%	2%			
								Deg. C	J/g	
Resin Type	BMI	86%	98%	89%	96%	96%	100%	122	132	94%
	Epoxy	88%	99%	90%	98%	100%	99%	147	214	96%
	Ep/BMI	100%	100%	100%	100%	100%	100%	105	140	100%
	Delta	2%	1%	1%	3%	4%	1%	42	82	
								% of Nom.	% of Nom.	
Out-time	10 days	89%	100%	90%	96%	98%	99%	97.7%	97.7%	96%
	30 days	86%	97%	90%	98%	98%	100%	103.4%	98.4%	96%
	60 days	91%	99%	93%	99%	98%	101%	85.2%	84.1%	94%
	Delta	5.0%	2.8%	3.4%	3.0%	0.7%	2.0%	18.3%	14.3%	
	Tests	105 coupons each; Tensile/Flex				126 cpns	63 cpns	42 samples		441

The upper group ranking show there is a clear advantage to using broadgoods (continuous) prepreg in the part; small/medium pieces-based parts are 27 percent lower in in-plane tensile strength and medium/large pieces have 13 percent lower performance. Tensile strain reductions are slightly less, but flexural strength reduction for smaller pieces in minimal. Modulus and interlaminar shear strength are not affected by piece size. For this trial set, the incorporation of piece-size effects into the test matrix was aggressive in order to capture some impact – medium/large pieces requiring splicing were preferentially selected to differentiate them from single-piece broadgoods layups for these small test panels. When economic feasibility with respect to piece size is determined, small pieces, and possibly a significant portion of the medium size pieces, may not be viable. The remaining waste stream will have performance of 85 to 100% of virgin properties, depending on the property of interest.

The remaining two lower data sets, Resin Type and Outtime, list the averages of the category which. The highly sensitive tensile strength/strain averages of the Resin Type show the averaged reductions of the upper data group; the remaining values provide little impact. The 100% values for the Ep/BMI in the Resin Type group are an artifact of the single Piece Size category. The Outtime data show similar averages – no visible impact of prepreg aging to twice the specified outtime before layup and cure. These resin systems are very stable when frozen; the extreme RT outtime exposure 'freezes' the resin via advancement, extending the time usable flow for cure is possible. Prepregs of 977-3 epoxy resin have been cured successfully with over one year of RT exposure.

Table 9 recalculates the rankings versus the maximum performance material. The broadgoods /BMI is the 100% system, a high temperature, highly toughened matrix system, Solvay 5250-4, delivers 8 to 11% higher mechanicals and at least 50F higher service temperature use. The 977-3 epoxy system is also toughened, but its mechanical and thermal capabilities are lower in both virgin and recycled material. Mixing these two resin systems further degrades performance 6 to 14%. Lower performance is expected as one resin system or the other would not receive its recommended cure processing. The hybrid system used the epoxy cure schedule; 355F maximum cure temperature rather than 375F initial cure plus a 440F post cure for the BMI. Hot/wet performance might be compromised due to incompletely cured BMI resin, but post curing the mixture to 440F would significantly degrade the epoxy, reducing performance more severely.

Table 9: Performance differences between resin types, mixtures in DR materials

Resin Type	Outtime (days)	Piece Size	Resin Type Basis	Fiber Basis
Epoxy	10	Mix	86%	76%
Epoxy	30	Mix	87%	77%
Epoxy	60	Mix	90%	80%
Epoxy	10-60 day	S-M	75%	66%
Epoxy	10-60 day	M-L	88%	78%
Epoxy	10-60 day	BG	100%	89%
BMI	10	Mix	89%	
BMI	30	Mix	81%	
BMI	60	Mix	88%	
BMI	10-60 day	S-M	71%	
BMI	10-60 day	M-L	86%	
BMI	10-60 day	BG	100%	
Ep/BMI	10	M-L	101%	72%
Ep/BMI	30	M-L	97%	70%
Ep/BMI	60	M-L	102%	73%

Note: 977-3 Epoxy products exposed to repeated 355F cures as a caul plate (near its Tg, glass transition temp.) exhibited discoloration and some warpage; it may have a limited lifetime for 350F cures. The 5250-4 BMI materials would be recommended for application fabrication cycles exceeding 10 repetitions.

Overall, aerospace composite systems have the characteristics to deliver value-added products and the extended-life processing characteristics which support Direct Recycling. Properties nearly match virgin materials for much of the waste stream for at least twice as long as the standard M&P specification limits; the recycling process is quite forgiving. Because aerospace composites use IM (Intermediate Modulus) with high strength and stiffness, they exceed the performance of most commercial and industrial market offerings.

Because they possess the specified chemistries and lamina configurations of the aerospace and DOD material systems, they have increased value for DOD applications.

Joining evaluation was conducted to determine suitability for a large application market, tool mold surfaces made with irregular pieces as shown in the 2016 LM ESH demo article. To increase acceptance of recycled composite materials for tooling structure, joining strength was verified. Organometallic coupling agents (Kenrich Petrochemicals) and a range of standard bond preparations methods were evaluated for joint strength improvements (Table 10: Lap Shear joint performance was impacted by preparation, adhesive and cure methods. Shear strengths were greatest with use of film adhesive, autoclave cure and the mixed coupling agent surface treatment. Not removing the glossy as-cured surface and use of composite prepreg as the adhesive showed the lowest strengths. Heavy abrasion produced internal fiber exposure decreasing strength due to loss of the fiber vendor's surface treatment by abrasion. Using coupling agents can restore some of the surface adhesion. All of the strengths measured, 1780 to 3040 psi, greatly exceed the structural loads expected in a tool support structure (eggcrate). Additional tests of split-T joints yielded pull off strengths up to 517 pli (lbf/lin. inch). This value is also greater than required to restrain tooling structures to tolerances and should be sufficient to resist bagging/autoclave induced forces with standard joining techniques.

Table 10: Lap Shear joint performance was impacted by preparation, adhesive and cure methods

Mechanical Preparation	Solvent wipe	82.8%
	Scuff (abrasive pad)	104.1%
	Abrade (60 grit disc)	95.3%
Surface Modifier (abraded)	Ken-React LICA 38	96.5%
	Ken-React NZ 97	99.5%
	LICA + NZ 97	108.8%
Cure Pressure	Vacuum bag	91.8%
	Autoclave (90 psi)	125.2%
Bonding Resin	Matrix - 977-3	85.3%
	FM-300 adhesive	110.4%

Overall, evaluation of mechanical strengths showed that piece size is important, but the knockdowns are mild. Commercial recycling products such as Hexcel HexTool® sheet molding compound (chipboard), lists a tensile strength of 37.7 ksi and modulus of 5.95 msi on its datasheets, about 1/3rd the strength of the Direct Recycling product with ≥ 94 ksi tensile strength at 7.4 msi modulus. Flex strength averages are much higher at 129 ksi (100% of virgin at all conditions). DR's high performance opens up many applications; the low variability at these knockdowns also improves acceptability. Direct Recycling products are competitive with most systems and outperform many commercial/industrial materials.

5.1 FABRICATION TESTING

Processability evaluation examined prepreg handleability, chemical advancement and resin flow. The evaluation matrix of Table 5 was used to determine these attributes, the methods and results follow:

5.1.1 Layup evaluation

Direct Recycle cost effectiveness requires a high rate of prepreg layup which is dependent on both material shape (area and regular shape) and condition. The fabrication of test panels with differing piece sizes and outtime verified 2016 experience with small to medium sized pieces, Figure 3. Prepreg tack and drape are required to build up complex, 3D shapes, but can interfere with efficient fabrication of large panels. The high layup rates are possible with large pieces (broadgoods), but these rates can be reduced up to an order of magnitude when using virgin, high tack or distorted materials.

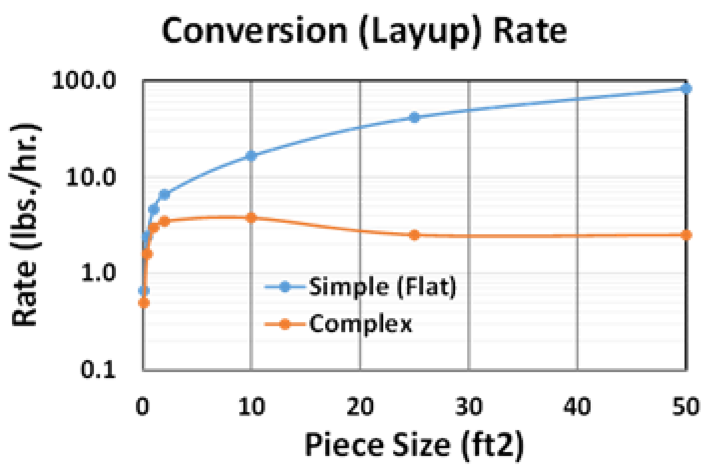


Figure 3: Recycling rate with Direct Recycling is dependent on piece size

The amount of tack/drape is controlled by aging (outtime at room temperature, temperature and humidity in the layup room and the amount of residual solvent in the prepreg. Tack and drape slowly decrease with outtime, but some prepregs with over 60 days at RT did have sufficient tack for complex parts with slight heating or when exposed to higher RT/humidity. Solvent retained in bagged or tightly rolled prepregs increased the relative tack of prepregs until the solvent was allowed to volatilize with exposure to air. Up to 120 days layup life for complex parts may be possible with gentle heating of the prepreg or part. Transient heating of the prepreg is preferred to minimize resin advancement. Heating the part may work better for some applications, but compaction must be controlled with intermittent hot debulk cycles to ensure good consolidations before the resin gels.

Aged, low or no tack, prepreg broadgoods is preferred for large, flat panel fabrication. Low tack plies can be easily positioned at rates over 100 lbs. /hr. making the cost of recycling extremely low. 2017 recycling fabrication data recorded layup speeds of 10 to

125 pcs. /hr. For large panels, 4 ft. x 12 ft., each ply is about 3 lbs. With low tack prepregs, up to 50 plies/hr. can be applied for 150 lbs. /hr. High tack, limp plies must be applied with the same methods as complex parts, adhering central axes under tension and incrementally working the remaining perimeter – reducing the ply rate to ~ 10/hr., or 30 lbs. /hr. While Direct Recycling accepts less critical defects of M&P specification compliant fabrication, wrinkles are avoided as they introduce uncontrolled fiber orientations. Wrinkles are also created when the waste prepregs are stored in an un-controlled manner and laid flat without tension. Collection and storage methods which employ flatness or tension attributes are preferred.

Figure 4 shows the laydown rate for the section 5.0 trial panels. Regularly shaped pieces lay up quickly, but the maximum rate is limited by the panel size. The 6.4 lbs. /hr. layup rate for 12 inch square plies equals 78 pieces /hr. layup rate, vs a range of 50 to 120 pcs. /hr. for all panels. For broadgoods, panel sizes up to 4 or 9 ft2 can be assembled at similar rates with pre-cut plies yielding >30 lbs. /hr. conversion rates. As discussed in section 7.2, the minimum conversion rate considered economical is about 4 lbs. /hr. At a nominal 16 ft2. /lb. areal weight, 64 ft2 must be laid up per hour, indicating pieces must average 0.5 ft2 to 1.25 ft2. to achieved viability. Thus, aside from cosmetic fill-in of the layup pattern, small pieces - 10 to 15% of the waste stream, are not economically viable for the Direct Recycling method. Likewise, small panel sizes should be avoided.

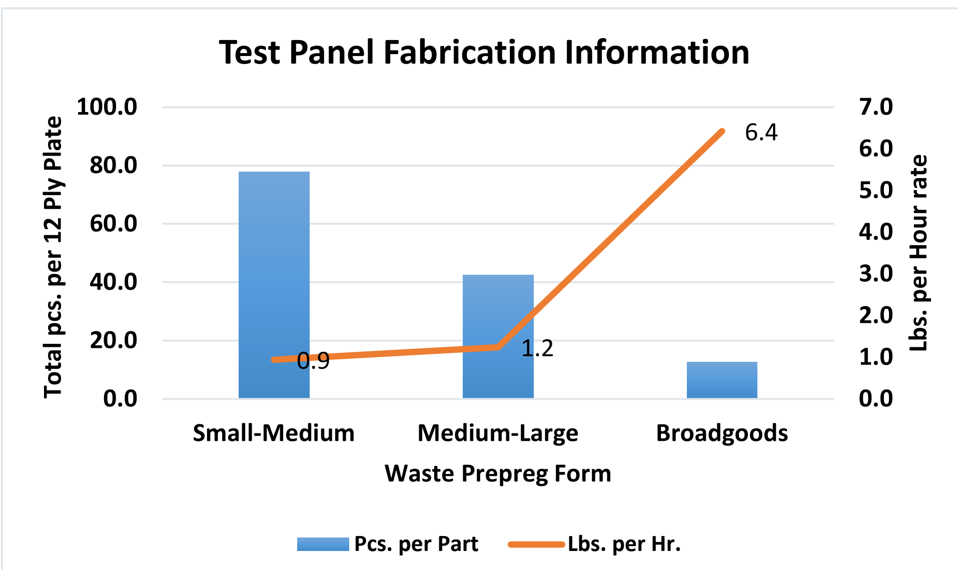


Figure 4: Mechanical evaluation (small) panel fabrication rates vary with piece quality

5.1.2 DSC discussion and results

Differential Scanning Calorimetry, DSC, measures the heat flow into or out of a material sample yielding heat capacity, phase change thermal impacts and heats of reaction. DSC can measure the temperature of the onset of reaction and, with a calibration sample, estimate the percent completion of the resin system reaction. The measurements were taken with a TA Instrument Q2000 system at a 5°C/min ramp rate to 300-350°C with a sample size of 8-12 mg in a nitrogen atmosphere. A typical plot is Figure 5 displaying temperature vs. heat flow and the four main features of the reactive material:

1. Reactivity onset – start of gelation reaction. (deg. Celsius)
2. Main Reaction onset – initiation of main cross-linking activity. (deg. Celsius)
3. Total heat of reaction – Integrated heat flow for cure
4. Maximum reaction rate – Temperature of the highest heat flow for the ramp rate used (deg. Celsius); usually not observed in long cure schedules designed to control the maximum exotherm and enhance cure quality.

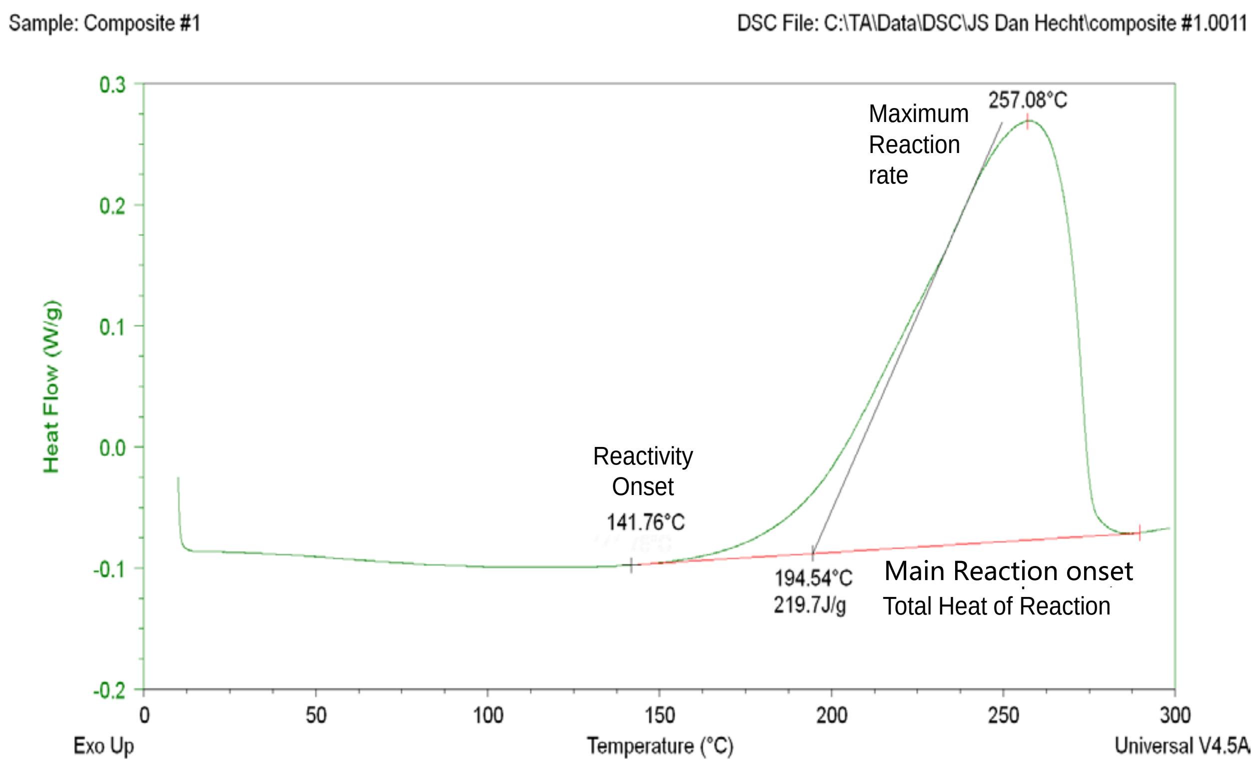


Figure 5: Typical epoxy prepreg trace in Differential Scanning Calorimetry

These DSC data for the prepreg evaluation matrix are presented in Table 11. The top three rows show the prepreg system DSC data for each resin system with their standard deviation in the next three rows. The 977-3 epoxy has the highest onset and peak reaction temperatures as well as the highest heat of reaction. The mixed EP/BMI system had the lowest onset and reaction temperatures. The BMI system had an intermediate onset and reaction temperature and the lowest heat of reaction. Variability as measured by the standard deviations are low for reaction temperatures and moderate for heat of reaction.

Mixed hardener/catalyst packages can either accelerate (fire hazard) or prevent reaction – this should be checked with small amounts of material if there is any likelihood of mixing.

The lower two sections of the table present the data for RT advancement. These test values are very consistent and show little effect of extended outtime. The variability is probably caused by variation in local resin content for the small sample sizes required.

Table 11: DSC reactivity information for fresh and aged composite prepreg systems

DSC	Days Outtime	Onset Temp °C	Enthalpy J/g	Enthalpy Tmain °C	Peak Rx °C
AVG.	EP/BMI	104.8	140.4	151.2	222.3
	Epoxy	146.5	214.4	190.7	256.0
	BMI	120.6	139.8	176.3	244.2
Std. Dev.	EP/BMI	4.6	13.5	1.2	1.2
	Epoxy	2.9	12.4	2.5	0.7
	BMI	10.4	27.1	6.0	0.9
Epoxy	10	148.5	213.5	192.8	256.5
	30	147.2	220.8	190.3	255.8
	60	143.8	208.8	189.0	255.7
BMI	10	115.3	135.0	181.0	244.3
	30	129.5	131.3	179.0	244.5
	60	116.8	153.2	169.0	243.7

5.1.3 DMA disc/results

Dynamic Mechanical Analysis testing on the evaluation matrix uncured panel material in a 4 ply quasi-isotropic layup with the tension fixture of a TA Instrument: DMA RSA G2 at 3°C/min from 0°C to 100°C. While advancement and cure features of the resin system were detected, the data was highly variable and did not provide insight into the usability of the prepreg waste. The start-up of the flow test provided a user-friendly and efficient method to test processability and this evaluation method was dropped.

5.1.4 Flow test results

An effective, low cost ASTM-D3531-16 Standard Test Method for Resin Flow of Carbon Fiber-Epoxy Prepreg capability was assembled using a Hotronix XRF-TT Table Top Air Fusion 16"x20" (Tee Shirt Press). The computer controlled temperature, time, pressure press was set up to test a 0.1m x 0.1m test coupon. The setup pre-heated a lower platen and used a 0.1m x 0.1m Viton pad to control press area (Figure 6Figure 6).

Laminate resin loss into glass bleeders through porous Teflon cloth was measured after the sample cooled. The test schedule was set to nominal 350F at 90 psi applied pressure for 5 minutes. This quick test completes most of the flow possible. Samples tested during warm-up, approximately 30 minutes, experienced 25% reduced flow values as some reaction occurred before reaching minimum viscosity. The full test method is attached in Appendix D. While initial trials were completed measuring ply stack thickness changes and calculating a resin flow via volume reduction. The addition of a Veritas L1501i 0.01 gram balance provided similar, but more consistent results.

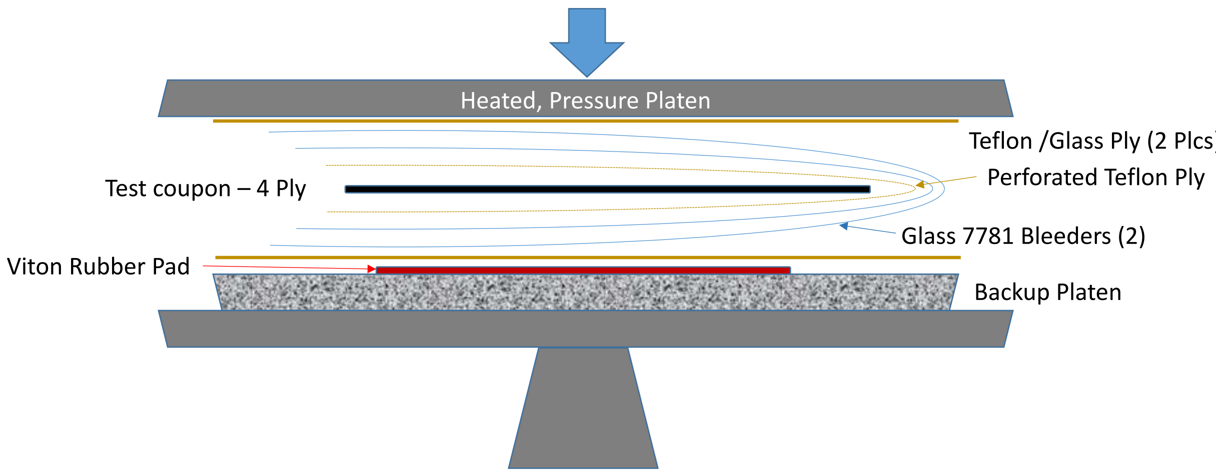


Figure 6: Resin flow test sample and press setup

Table 12 lists the resin flow values for the evaluation matrix. Minimal change is seen in the flow numbers for up to 60 days of room temperature advancement. Flow does vary with resin system and mixing of resin systems. A very old, heavy resin peel ply prepreg tested just short of one year old had 75% of the flow of the fresh material.

Table 12: Waste prepreg processability as measured by ASTM- D3531 test method for prepreg resin flow

Sample Description				dWt./ply (g/m2)	% Flow of resin	% Flow of prepreg ASTM #	% Flow of Resin (average)			Prepreg Flow % Avg. ASTM Flow Value			Outtime Days
Run	Matl	Outtime	Size				Resin	+ Size	Outtime	Resin	+ Size	Outtime	
1	Ep/BMI	10	Med-Lg	81.0	65.1%	24.7%			65.1%			24.7%	10
2	Ep/BMI	30	Med-Lg	73.3	58.9%	22.4%	61.6%		58.9%	23.4%		22.4%	30
3	Ep/BMI	60	Med-Lg	75.8	60.9%	23.1%			60.9%			23.1%	60
4	Epoxy	10	Sm-Med	68.0	54.7%	20.8%			53.9%			20.5%	10
5	Epoxy	30	Sm-Med	68.0	54.7%	20.8%		56.2%	55.5%		21.4%	21.1%	30
6	Epoxy	60	Sm-Med	73.8	59.3%	22.5%			53.6%			20.4%	60
7	Epoxy	10	Med-Lg	65.0	52.2%	19.9%							
8	Epoxy	30	Med-Lg	67.2	54.1%	20.5%	54.3%	52.0%		20.6%	19.8%		
9	Epoxy	60	Med-Lg	62.0	49.8%	18.9%							
10	Epoxy	10	Broadgoods	68.3	54.9%	20.8%							
11	Epoxy	30	Broadgoods	71.8	57.7%	21.9%		54.8%			20.8%		
12	Epoxy	60	Broadgoods	64.5	51.8%	19.7%							
13	BMI	10	Sm-Med	72.3	58.1%	22.1%			64.0%			24.3%	10
14	BMI	30	Sm-Med	77.8	62.5%	23.7%		62.6%	65.5%		23.8%	24.9%	30
15	BMI	60	Sm-Med	83.7	67.3%	25.6%			68.9%			26.2%	60
16	BMI	10	Med-Lg	87.3	70.1%	26.6%							
17	BMI	30	Med-Lg	83.3	66.9%	25.4%	66.1%	69.8%		25.1%	26.5%		
18	BMI	60	Med-Lg	90.0	72.3%	27.5%							
19	BMI	10	Broadgoods	79.3	63.7%	24.2%							
20	BMI	30	Broadgoods	83.5	67.1%	25.5%		65.9%			25.0%		
21	BMI	60	Broadgoods	83.3	66.9%	25.4%							
Old	**977-3**	**350**	**BG**	**62.0**	**42.2%**	**17.7%**	Approximately 1 year old prepreg (RT) has 75% flow in fast test.						

If QA equipment is not available, processing the test coupon/bleed sample through a representative ramp to temperature in the fabrication equipment will give a good indication of the flow potential by the number of glass bleeders fully wetted. Processable prepregs at 38% resin content fully wetted one ply of 7781 glass per ply of 0.0083" thick prepreg. Visual estimates of flow are sufficient to tell if the prepreg will consolidate well.

Note: These tests were made with fabrics made via solvent prepreg lines which fully wet out the tow fibers. Unidirectional tapes at AFP#4 have only 32% resin content and purposely leave some of the central fibers dry to provide a vapor path for off-gassing during consolidation. Tape prepreg test samples should be bent after flow testing to determine if they are fully wetted – the inside diameter surface fiber will pucker up off the tape surface if it is not fully bonded into the prepreg. The low resin content will also reduce handleability; i.e. the amount of time this product form can be laid up into complex parts.

5.1.5 Laminate variability - fiber orientation and thickness

Direct Recycling's use of irregular pieces adds variability to laminate quality. Ply orientation and local ply count is affected by the imperfect fit-up mandated by economic layup rates. The evaluation test panel coupons supplied thickness variability data and the large plates of 2016's demo tool support plates were examined by Computed Tomography (CT) for orientation.

5.1.5.1 Thickness variability:

Physical tolerances – Test coupons thickness measurements provided hundreds of data points for laminate thickness for panels fabricated on a flat tool, with autoclave cure pressure applied with a vacuum bag over breather materials. The summary data presented in Table 13 show that panel and Per-Ply Thicknesses (PPT) are relatively stable. Prepreg material or lot appears to have the most impact on thickness, i.e. standard prepreg manufacturing tolerances.

Table 13: Panel thickness variability for a range of recycle feedstock materials and qualities

Per Ply Thickness Variation	Panel Thickness (inch)	Per Ply Thicknes s (inch)	Ply thk. Std. Dev. (inch)	Ply Thk. COV (%)
Ep/BMI	0.1028	0.00857	0.000068	0.80%
Epoxy	0.1016	0.00847	0.000114	1.34%
BMI	0.0995	0.00829	0.000105	1.27%
Grand Avg.	0.1009	0.00841	0.000138	1.64%

Piece Size Variation (Ep; BMI)	Panel Thickness (inch)	Per Ply Thicknes s (inch)	Ply thk. Std. Dev. (inch)	Ply Thk. COV (%)
Sm-Med	0.100067	0.00834	0.000113	1.36%
Med - Lg	0.10043333	0.00837	0.000085	1.02%
Broadgoods	0.10113333	0.00843	0.000097	1.16%
Grand Avg.	0.10054	0.00838	0.000099	1.18%

Table 14 has detailed thickness data, the only anomalous recycling thickness data are from panels 4 & 5, Small-Medium piece/Epoxy panels which show what looks to be a few placement overlaps in panel 4 and more than one double ply in panel 5. Double plies are a part of the feedstock waste stream as some patterns are cut from dual ply material. 2016 experience showed that overlaps tended to produce a more uneven bag side surface then slightly larger gaps between pieces patched into a ply. Overall, recycling can increase the standard COV of Per Ply Thickness from 1.16% with broadgoods to 1.36% for the smallest pieces with some layup discipline – not a significant effect. However, some applications rely on 'flat' surfaces and will require broadgoods feedstocks, post cure machining or a caul plate to force resin flow to achieve the flatness desired.

Table 14: Detailed panel thickness data for recycled materials made into test panels.

Run	Matl	Outtime	Size	As Fabricated Thickness - Fabrication errors							Corrected Thk. for extra ply --> Lot Impact						
1	Ep/BMI	10	Med-Lg	0.1035	0.102	0.103	0.1035	0.1045	0.1033		0.1035	0.102	0.103	0.1035	0.1045	0.1033	
2	Ep/BMI	30	Med-Lg	0.1025	0.103	0.1025	0.1025	0.102	0.1025		0.1025	0.103	0.1025	0.1025	0.102	0.1025	0.1028
3	Ep/BMI	60	Med-Lg	0.1025	0.103	0.103	0.1035	0.101	0.1026		0.1025	0.103	0.103	0.1035	0.101	0.1026	
4	Epoxy	10	Sm-Med	0.1095	0.1155	0.1015	0.102	0.102	0.1061	Doubled	0.10117	0.09884	0.1015	0.102	0.102	0.101102	
5	Epoxy	30	Sm-Med	0.117	0.1185	0.1155	0.1185	0.118	0.1175	plies?	0.1004	0.1019	0.0989	0.1019	0.1014	0.1009	
6	Epoxy	60	Sm-Med	0.1015	0.1	0.1	0.1	0.1	0.1003		0.1015	0.1	0.1	0.1	0.1	0.1003	
7	Epoxy	10	Med-Lg	0.101	0.1015	0.102	0.1	0.101	0.1011		0.101	0.1015	0.102	0.1	0.101	0.1011	
8	Epoxy	30	Med-Lg	0.1015	0.102	0.1015	0.102	0.105	0.1024		0.1015	0.102	0.1015	0.102	0.105	0.1024	0.1016
9	Epoxy	60	Med-Lg	0.1035	0.1025	0.102	0.102	0.102	0.1024		0.1035	0.1025	0.102	0.102	0.102	0.1024	
10	Epoxy	10	Broadgoods	0.101	0.1	0.1	0.101	0.1	0.1004		0.101	0.1	0.1	0.101	0.1	0.1004	
11	Epoxy	30	Broadgoods	0.103	0.1025	0.1035	0.1035	0.103	0.1031		0.103	0.1025	0.1035	0.1035	0.103	0.1031	
12	Epoxy	60	Broadgoods	0.1025	0.1035	0.1025	0.102	0.1045	0.103		0.1025	0.1035	0.1025	0.102	0.1045	0.103	
13	BMI	10	Sm-Med	0.099	0.097	0.1	0.099	0.0985	0.0987		0.099	0.097	0.1	0.099	0.0985	0.0987	
14	BMI	30	Sm-Med	0.1015	0.101	0.102	0.1005	0.1015	0.1013		0.1015	0.101	0.102	0.1005	0.1015	0.1013	
15	BMI	60	Sm-Med	0.0985	0.097	0.0985	0.0985	0.098	0.0981		0.0985	0.097	0.0985	0.0985	0.098	0.0981	
16	BMI	10	Med-Lg	0.099	0.098	0.0985	0.099	0.0985	0.0986		0.099	0.098	0.0985	0.099	0.0985	0.0986	0.0995
17	BMI	30	Med-Lg	0.1005	0.0985	0.0995	0.101	0.0995	0.0998		0.1005	0.0985	0.0995	0.101	0.0995	0.0998	
18	BMI	60	Med-Lg	0.098	0.098	0.099	0.0985	0.098	0.0983		0.098	0.098	0.099	0.0985	0.098	0.0983	
19	BMI	10	Broadgoods	0.1	0.1	0.0995	0.098	0.0995	0.0994		0.1	0.1	0.0995	0.098	0.0995	0.0994	
20	BMI	30	Broadgoods	0.1015	0.101	0.1015	0.101	0.1	0.101		0.1015	0.101	0.1015	0.101	0.1	0.101	
21	BMI	60	Broadgoods	0.0995	0.1	0.1	0.1	0.1	0.0999	Ply values	0.0995	0.1	0.1	0.1	0.1	0.0999	Ply values
						Grand Average (inches)			0.101895	0.00849			Grand Average (inches)			0.100867	0.00841
						Std. Deviation (inch)			0.004103	0.00034			Std. Deviation (inch)			0.001658	0.00014
						Coefficient of Variation			4.0%				Coefficient of Variation			1.6%	

]

5.1.5.2 Orientation variability:

Lamina tolerances – Sections of four demonstration panels with differing Materials & Processing (M&P) tolerance criteria were cut into 6” x 6” squares; stacked in groups of 6 (24 total) and secured to form a block ~4” high. This block was scanned by Computed Tomography (CT) at North Star Imaging and GE Inspection Technologies. The scans had a 68um resolution, which was just adequate to determine tow angles from a random selection of scans through the horizontal planes of the stack. Broadgoods are expected to achieve nominal aerospace angular tolerances as they can easily define a reference edge and can be cut with standard equipment and templates. Figure 7 shows the patchwork of smaller recycled pieces. Figure is a sample of the scans and angles measured for broadgoods (Panel l) and tight layup tolerancing (Panel 3).

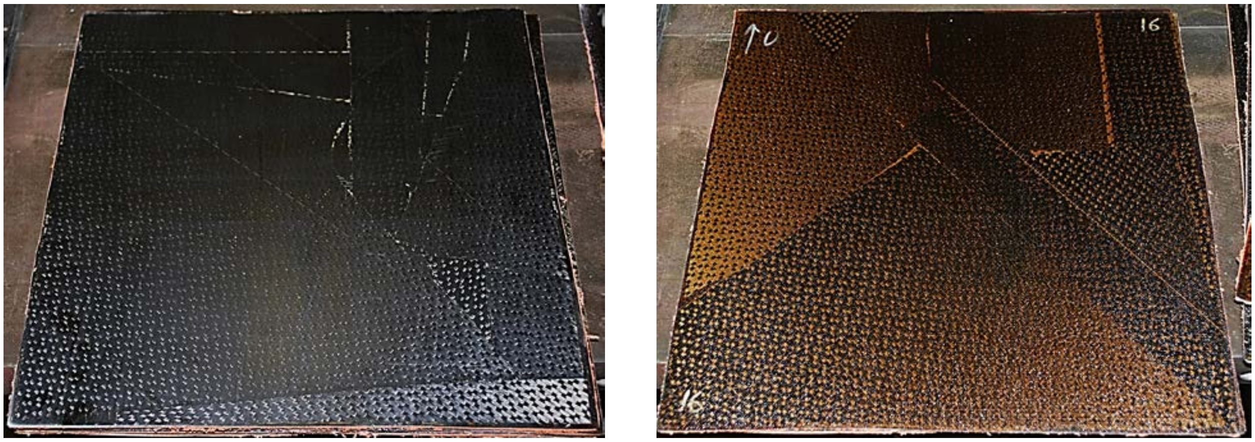
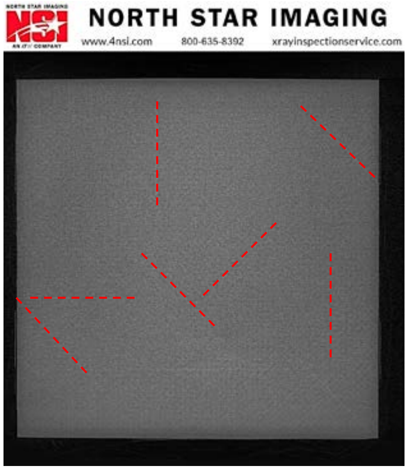


Figure 7: Direct Recycling patchwork panels ply construction, Small – Medium pieces.



360

Angles - Panel 1				
45	90.5	90	90	90
0	-45	-46	-45	-47
-2	42	45	44	44
90	-45	42	90	-45
45	45	91	0	47
-45	0	0	47	0

Angles - Panel 3				
46	98	-47	89	87
1	46	85	-2	86
134	45	139	88	44
-44	-43	37	-2	0
2	50	-3	-1	-1
90	-41	-3	-1	42
2	1	90		
90		28		

839

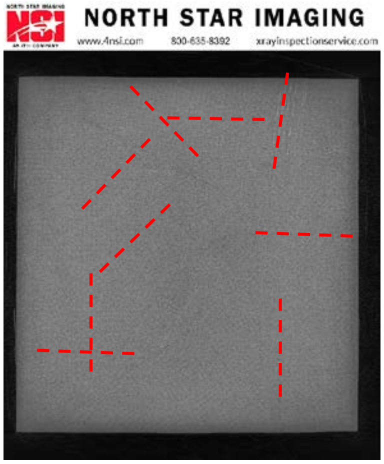
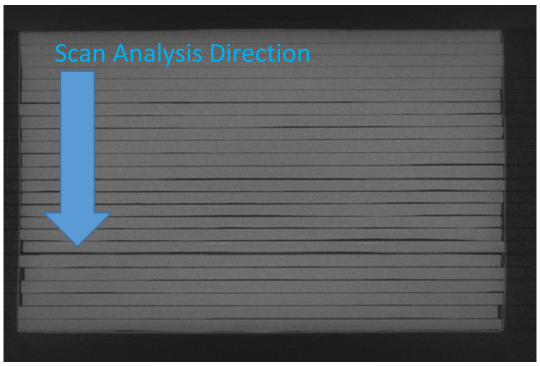


Figure 8: Fiber orientation variability in recycled laminates with various M&P tolerances

Orientation variability is summarized in Figure 9. Broadgoods and Double-Ply layup was most accurate. High rate, Loose Tolerance layup did result in higher ply angle deviation, the Tight Tolerance layup and the extra operator effort for irregular pieces did yield tighter angle alignment. The double-ply, 2 plies of the same angle to cover up gaps which may exist, had better results, but was difficult to distinguish whether the layup had 1, 2 or 3 layers of the same orientation. Only the loose tolerance panel had mis-alignments outside aerospace specifications. Fabric prepregs will not be affected significantly by these mis-alignments as confirmed by the evaluation panels, but mis-orientations will be much more important with unidirectional tape prepregs.

Figure 9: Ply orientation summary based on computed tomography data of varied M&P standards



Panel	Σθ Offset	S.D. θ/Ply	Max Δ
1 - BroadGoods	-0.3	1.3	3.0
2 -Loose Tolerances	5.0	7.8	20.0
3 - Tight Tolerances	2.5	1.5	17.0
4- Double Ply	-0.1	1.5	5.0
Average	**1.8**	**3.0**	**NA**

Note for Sections 5.1.5.1and 5.1.5.2: One significant tensile break showed another aspect of the DR recycling technique; clusters of prepreg selvage edges in the panel were present in the weakest of the coupons. Selvage areas only have 90 degree fibers for approximately one-half inch width. The gage area of coupons from small-medium piece panels were observed to have up to three selvage edges in the failed gage section reducing tensile strength to 61 ksi; approximately 10% weaker than the panel as a whole. These panels averaged eight pieces per one square foot ply, with certain plies having twice that number. Besides requiring more labor to layup small pieces, they also detract from performance.

5.2 MECHANICAL TESTING

Evaluation of direct recycle composite material included mechanical and element testing. Tensile tests looked at in-plane performance loss due to discontinuous fiber reinforcement of the irregular feedstock. The flexural test was included as an excellent Quality Assurance (QA) test which evaluates tensile and compressive performance along with general laminate quality. Short Beam Shear (SBS) tests directly evaluate interlaminar ply strength, a good indication of composite quality. Combined, these tests provide a good basis for judging composite quality. Table 15 defines the test matrix executed for the laminate mechanical evaluation with test details listed below it. Element testing included lap shear bond testing and limited testing of Tee joints typically used for simple structures. The test coupons cut from the test panels are displayed in Figure 10. Table 16 defines the lap shear evaluation matrix with details below, the Tee joint testing is described in section 5.2.5.

Table 15: Laminate Characterization Matrix for Uncured Recyclable Composite Prepregs

Resin type	Epoxy								
Remnant Size	Small			Medium			Broadgoods		
Outtime	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days
Tensile/Mod.	5	5	5	5	5	5	5	5	5
Flexural	5	5	5	5	5	5	5	5	5
Short Beam Shr	6	6	6	6	6	6	6	6	6
Resin type	BMI - Bismaleimide								
Remnant Size	Small			Medium			Broadgoods		
Outtime	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days
Tensile/Mod.	5	5	5	5	5	5	5	5	5
Flexural	5	5	5	5	5	5	5	5	5
Short Beam Shr	6	6	6	6	6	6	6	6	6
Resin types	Epoxy/BMI Hybrid								
Remnant Size				Medium					
Outtime	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days	Fresh	>30 days	>60 days
Tensile/Mod.	Reduced Matrix			5	5	5	Reduced Matrix		
Flexural				5	5	5			
Short Beam Shr				6	6	6			

The mechanical test procedures / methods / sample definitions used are:

- Flex – Flexural Strength: Three point test at 0.12”/min. with 2.5” span (ASTM –D7972-14)
- SBS – Short Beam Shear: Three point test at 0.05”/min. with 0.4” span (ASTM - D2344)
- Tensile/Mod. – Tensile Strength/Modulus: Dogbone tensile coupon tested at 0.05”/min. with 3” gauge section, ASTM – D3039-17 with extensometer.
- Epoxy – Solvay/Cytec 977-3 toughened system
- Bismaleimide - Solvay/Cytec 5250-4 toughened system
- Epoxy/Bismaleimide – 50/50 mix of resin system; interleaved plies
- Small – prepreg trim pieces; less than 1 ft2 area; approximately 8 pcs per ply were used to ensure multiple butt splices in the test. samples
- Medium – prepreg trim pieces; 1 to 3 ft2 area; approximately 4 pcs per ply used.
- Broadgoods (Large); approximately 1.2 pcs per ply; small, but not zero chance of butt splice.

- Outtime – Number of days at room temperature: Fresh ≈ 10 days; >30 days, Spec. outtime; >60 days – double Spec. outtime.

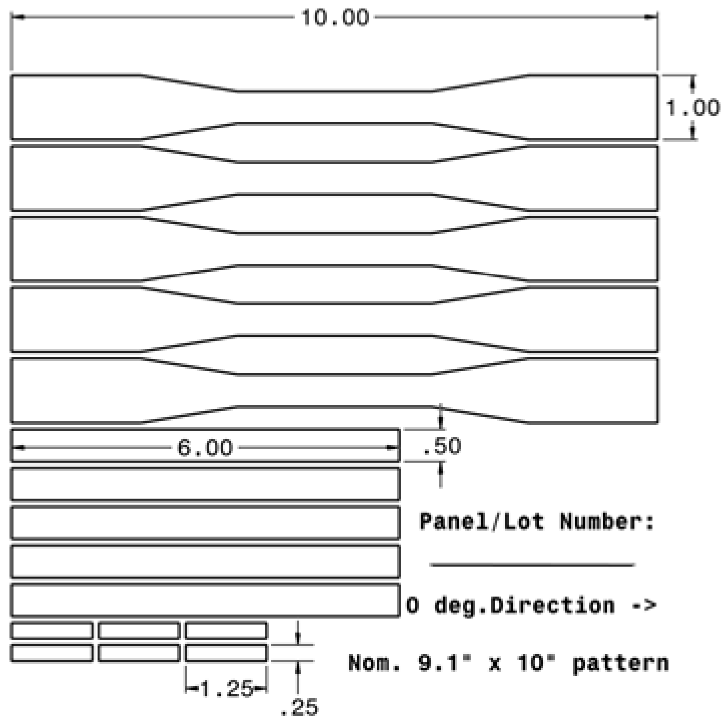


Figure 10: Cut pattern for test coupons for mechanical characterization

For the laminate mechanical testing, the 12” x 12” trial panels were waterjet cut into the test coupons in Figure 10. No post-machining edge treatment to smooth out machining damage was done. The coupon cut pattern was sufficiently far enough from the edges that coupons were nominal thickness and variability.

The mechanical performance results for recycled materials is summarized in Table 17 for easy comparisons of the various properties. Because the composite systems themselves have differing levels of performance, the data is grouped by the test parameters which to be evaluated individually or compared to the grand average. The details of each test series are discussed in the following sections.

Table 16: Surface preparation and processing parameter matrix to investigate lap shear bond strength

Sample ID No.	Mechanical Preparation	Adhesive	Coupling agent	Cure Pressure	Test Samples
TSPP	None - Tool Surface	None- Prepreg	None	Vacuum	5
TSFA	None - Tool Surface	FM-300	None	Vacuum	5
SCPP	Scuff (ScotchBrite)	None- Prepreg	None	Vacuum	5
SCFA	Scuff (ScotchBrite)	FM-300	None	Vacuum	5
ABPP	Abrade - 60 Grit disc	None- Prepreg	None	Vacuum	5
ABFA	Abrade - 60 Grit disc	FM-300	None	Vacuum	5
ABL38.25PP	Abrade - 60 Grit disc	None- Prepreg	Ken-React LICA38-0.5% wipe	Vacuum	5
ABL38.5PP	Abrade - 60 Grit disc	FM-300	Ken-React LICA38-0.5% wipe	Vacuum	5
ABL38.25FA	Abrade - 60 Grit disc	None- Prepreg	Ken-React LICA38-0.5% wipe	Vacuum	5
ABL38.5FA	Abrade - 60 Grit disc	FM-300	Ken-React LICA38-0.5% wipe	Vacuum	5
AB97.25PP	Abrade - 60 Grit disc	None- Prepreg	Ken-React NZ97-0.5% wipe	Vacuum	5
ABN97.5PP	Abrade - 60 Grit disc	FM-300	Ken-React NZ97-0.5% wipe	Vacuum	5
ABN97.25FA	Abrade - 60 Grit disc	None- Prepreg	Ken-React NZ97-0.5% wipe	Vacuum	5
ABN97.5FA	Abrade - 60 Grit disc	FM-300	Ken-React NZ97-0.5% wipe	Vacuum	5
ABL+N.25PP	Abrade - 60 Grit disc	None- Prepreg	0.25% NZ97 + 0.25% LICA38 wipe	Vacuum	5
ABL+N.25FA	Abrade - 60 Grit disc	FM-300	0.25% NZ97 + 0.25% LICA38 wipe	Vacuum	5
L+N:TS - VB	None - Tool Surface	FM-300	0.25% NZ97 + 0.25% LICA38 wipe	Vacuum	5
L+N:TS - Auto	None - Tool Surface	FM-300	0.25% NZ97 + 0.25% LICA38 wipe	Autoclave	5
L+N:SC - VB	Scuff (ScotchBrite)	FM-300	0.25% NZ97 + 0.25% LICA38 wipe	Vacuum	5
L+N:SC - Auto	Scuff (ScotchBrite)	FM-300	0.25% NZ97 + 0.25% LICA38 wipe	Autoclave	5

Trial parameters definitions are:

- Mechanical abrasion –
  - None: Smooth tool surface with solvent wipe to clean surface
  - Scuffed: ScotchBrite removal of surface sheen followed by solvent wipe
  - Abraded: Right-angle rotary air sander with 60 grit sandpaper with solvent wipe
- Adhesive –
  - None- Use the recycle prepreg material to form co-bond panels
  - Film Adhesive – Recycled 3M FM-300; still within fabrication outtime limits
- Coupling Agent – Organometallic agents recommended by Kenrich Petrochemicals, Bayonne, NJ. Coupling agents can react with application solvents as evidenced by

precipitation of the reagent; isopropyl alcohol was compatible with LICA 38, but not NZ97. NP97 required a different solvent (N-Methyl-2-Pyrrolidone). Solutions of the coupling agents were prepared, painted on the panels, dried and the lap joint assembled.

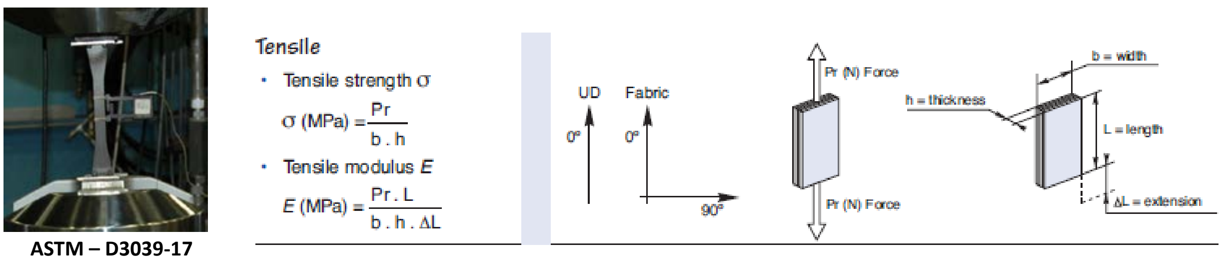
- None- Surface as prepared and wiped clean
- Ken-React LICA38: •LICA 38 Titanium IV 2,2(bis 2-propenolatomethyl)butanolato, tris(dioctyl)pyrophosphato-O in Iso-propyl Alcohol
- Ken-React NZ97: NZ 97 Zirconium IV 1,1(bis-2-propenolatomethyl)butanolato, tris(2-amino)phenylato in NMP solvent

Table 17: Recycled composite mechanical properties – Averaged and variability results

Run	Material	Outtime	Size	Tensile Strength	CoV	Tensile Modulus	CoV	UltimateTensile Strain	CoV	Flexural Strength	COV	Short Beam Shear	COV
				(ksi)	*(%)*	(msi)	*(%)*	(%)	*(%)*	(ksi)	*(%)*	(psi)	*(%)*
1	Ep/BMI	10	Med-Lg	84.3	*4.0%*	7.31	*2.0%*	1.15	*4.1%*	115.5	*2.8%*	10112	*5.2%*
2	Ep/BMI	30	Med-Lg	81.3	*4.2%*	7.08	*2.3%*	1.23	*5.8%*	122.7	*2.8%*	10274	*3.5%*
3	Ep/BMI	60	Med-Lg	84.8	*7.2%*	7.28	*5.8%*	1.24	*4.7%*	127.1	*7.0%*	10905	*3.0%*
	Ep/BMI	Med-Lg	Average	83.5	*5.1%*	7.22	*3.4%*	1.21	*4.9%*	121.8	*4.2%*	10430	*3.9%*
4	Epoxy	10	Sm-Med	67.0	*7.9%*	7.16	*6.3%*	0.98	*6.0%*	101.0	*4.5%*	10781	*6.0%*
5	Epoxy	30	Sm-Med	80.9	*12.4%*	7.32	*7.9%*	1.10	*9.9%*	117.4	*6.6%*	11747	*4.5%*
6	Epoxy	60	Sm-Med	83.9	*5.9%*	7.32	*4.0%*	1.21	*2.2%*	122.7	*5.7%*	11663	*5.7%*
	Epoxy	Sm-Med	Average	77.3	*8.7%*	7.26	*6.1%*	1.09	*6.0%*	113.7	*5.6%*	11397	*5.4%*
7	Epoxy	10	Med-Lg	90.7	*2.6%*	7.50	*1.5%*	1.21	*5.5%*	133.3	*4.3%*	11407	*5.9%*
8	Epoxy	30	Med-Lg	88.0	*7.6%*	7.31	*1.8%*	1.18	*8.6%*	125.8	*4.9%*	11350	*3.4%*
9	Epoxy	60	Med-Lg	93.9	*7.9%*	7.30	*1.3%*	1.28	*12.1%*	126.5	*8.3%*	12028	*3.2%*
	Epoxy	Med-Lg	Average	90.9	*6.0%*	7.37	*1.6%*	1.22	*8.7%*	128.5	*5.9%*	11595	*4.2%*
10	Epoxy	10	Broadgoods	108.3	*2.0%*	7.76	*1.9%*	1.37	*3.6%*	131.2	*1.7%*	11825	*1.8%*
11	Epoxy	30	Broadgoods	100.0	*3.9%*	7.22	*0.7%*	1.38	*4.9%*	121.2	*3.2%*	11200	*5.7%*
12	Epoxy	60	Broadgoods	101.2	*3.5%*	7.46	*2.9%*	1.33	*2.6%*	121.6	*5.1%*	11596	*6.6%*
	Epoxy	Broadgoods	Average	103.1	*3.1%*	7.48	*1.8%*	1.36	*3.7%*	124.6	*3.3%*	11540	*4.7%*
13	BMI	10	Sm-Med	87.1	*4.2%*	7.32	*4.8%*	1.21	*10.2%*	119.9	*11.5%*	11018	*6.0%*
14	BMI	30	Sm-Med	79.0	*15.2%*	7.20	*13.5%*	1.24	*7.9%*	126.2	*2.3%*	10198	*4.9%*
15	BMI	60	Sm-Med	81.4	*8.8%*	7.11	*6.7%*	1.16	*6.2%*	127.2	*13.6%*	9793	*3.7%*
	BMI	Sm-Med	Average	82.5	*9.4%*	7.21	*8.3%*	1.20	*8.1%*	124.4	*9.1%*	10336	*4.9%*
16	BMI	10	Med-Lg	105.1	*5.2%*	7.63	*5.1%*	1.42	*4.3%*	145.8	*5.0%*	11297	*3.5%*
17	BMI	30	Med-Lg	88.9	*9.6%*	7.16	*3.3%*	1.26	*9.8%*	147.8	*3.1%*	12146	*4.5%*
18	BMI	60	Med-Lg	107.4	*2.7%*	7.67	*3.3%*	1.42	*5.2%*	142.9	*3.2%*	10777	*2.5%*
	BMI	Med-Lg	Average	100.5	*5.8%*	7.49	*3.9%*	1.37	*6.4%*	145.5	*3.7%*	11407	*3.5%*
19	BMI	10	Broadgoods	118.5	*2.9%*	7.65	*2.2%*	1.54	*3.1%*	139.9	*5.0%*	11537	*3.3%*
20	BMI	30	Broadgoods	113.8	*2.4%*	7.54	*1.2%*	1.51	*3.7%*	147.9	*1.5%*	11469	*1.7%*
21	BMI	60	Broadgoods	117.3	*4.2%*	7.55	*1.4%*	1.55	*4.9%*	145.7	*1.8%*	11722	*4.1%*
	BMI	Broadgoods	Average	116.5	*3.2%*	7.58	*1.6%*	1.53	*3.9%*	144.5	*2.8%*	11576	*3.1%*
		Grand Average of all runs		93.5	*5.9%*	7.37	*3.8%*	1.28	*6.0%*	129.0	*5.0%*	11183	*4.2%*
		Max-Min delta of all runs		43.5%	*87%*	8.8%	*95.0%*	*36.9%*	*82.1%*	31.8%	*88.9%*	19.4%	*73.7%*

5.2.1 Tensile Strength/ Modulus

In-plane laminate performance was tested using a dog bone coupon with a gage section three inches long by ASTM – D3039-17 on a hydraulic test frame at 0.05”/min. (Figure 11). A 1 inch extensometer (#10118609) was attached to capture strain and calculate modulus between 0.1% and 0.3% strain. The samples failed at a variety of locations which included recycling type defects, butt-lines and selvage clusters, the taper-gage section discontinuity and random gage section locations. The strength and modulus averages and coefficients of variation (COVs) are listed in first data columns of
Table **17**, followed by the ultimate strain value. The values for the highest performing variants are within family for the virgin material database and the predominately low COVs indicate reasonable results. The ultimate strain varied from about 1% to just over 1.5%, provide sufficient strain to failure for the manufacturing aide applications pursued.

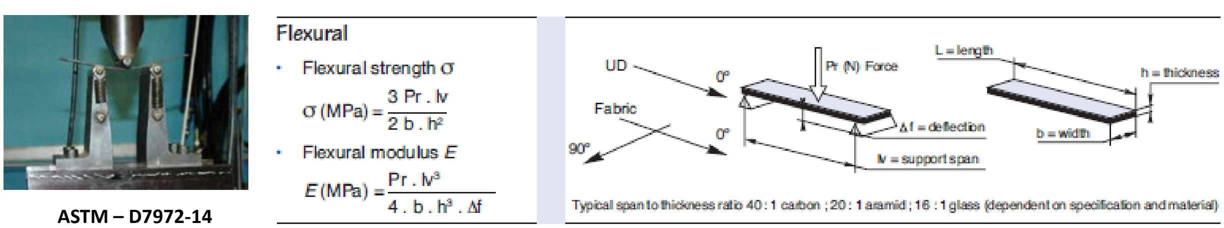


ASTM – D3039-17

Figure 11: Dog bone tensile specimens used to measure strength and modulus via extensometer

5.2.2 Flexural Strength

Flexural strength was characterized for use as a low cost, quality assurance dataset. The coupons and setup require the lowest degree of capability and provides indications of tensile, compressive and interlaminar composite quality. ASTM – D7972 test methods used a 2.5” span and 0.12”/min. loading rate (Figure 12. All failures were compressive, no tensile or interlaminar failures were noted. The averages and COVs in Table 17 show that flex testing yielded the highest strengths at typical variability. The failure zone is concentrated below the load introduction point reducing the amount of material at maximum stress and the likelihood of defect clusters in that area. The quality of recycled panels can be confirmed quickly with off-cuts using these values and the feedstock information.

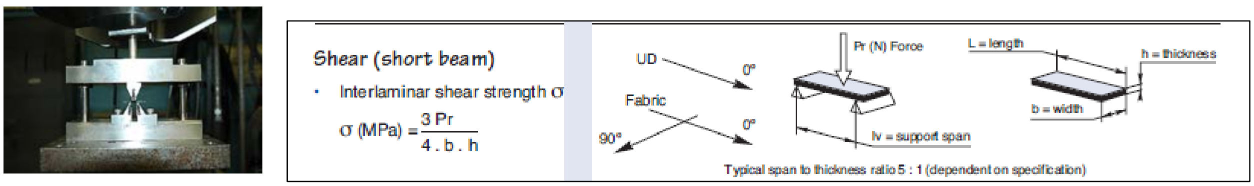


ASTM – D7972-14

Figure 12: Flexural strength measured with 3 point bend setup; coupon tool side down

5.2.3 Short Beam Shear Strength

Short Beam Shear (SBS) testing was used because tensile and flexural testing was not expected to provide useable interlaminar strength information for higher quality recycled laminates. Three point SBS testing using ASTM - D2344 at 0.4” span (4:1) and 0.05” min. rate (Figure 13) yielded uniform values for all variations with a light decrease for the hybrid resin system. No discernable difference in all test configurations and prepreg ages was shown.



ASTM - D2344

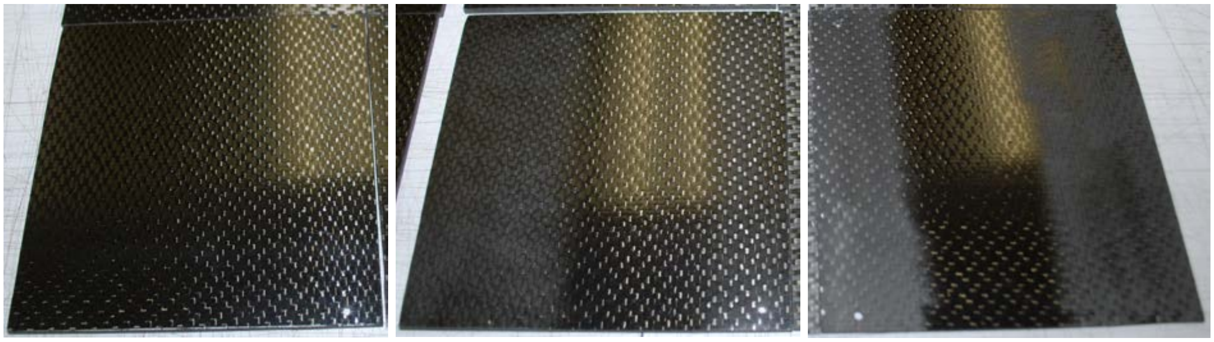
Figure 13 Short Beam Shear strength measured with 3 point bend setup; coupon tool side down

The total of the in-plane mechanical testing shows that laminates fabricated with recycled prepregs by the DR method yield reproducible performance with small knockdowns for piece size used and resin mixing (Solvay 977-3/5350-4). Overall, the DR recycling method is robust for laminate performance.

5.2.4 Lap shear joint testing

Shear joints are the preferred load transfer configuration for adhesively bonded structures. Because bonded joints can have high variability; the response to typical preparation methods, adhesion promoters and variability with respect to recycled materials was investigated. Single lap shear testing (ASTM – D5868-01 @ 0.5”/min) with added end doublers to center the load path were used to measure shear strength of an approximate 1 sq. inch bond area. Table 16 detailed the trial parameters. After the results of the initial sixteen trials of the bond parameters, another four trials were added to fully explore the capabilities of no or light abrasion of the surface.

The fabrication of the lap shear test elements panels is documented in Figure 14, Figure 15 and Figure 16. Figure 14 shows the mechanical preparations; the original, smooth surface finish (left); a scuffed surface using ScotchBrite abrasive non-woven which just removed the surface sheen without exposing the fiber (center); and the 60 grit sandpaper abraded surface which exposed the fiber (right), including fiber interiors which are not surface treated. The lap shear pre-cured assemblies are shown in Figure 15, the main bond panels are registered by riveting and the grip doublers are visible at the top of the picture. Figure 16 shows the resulting bondlines of the prepreg and film adhesive bonds in the vacuum bag cure. The prepreg resin flowed well and filleted the lap joint while the FM -300 appeared to have minimal flow on most of the joints.



Tool Surface – Solvent Wipe | Scuffed – Scotchbrite / Solvent Wipe | Abrade -60 Grit / Solvent Wipe

Figure 14: Surface appearances of lap shear test panels with different abrasion levels

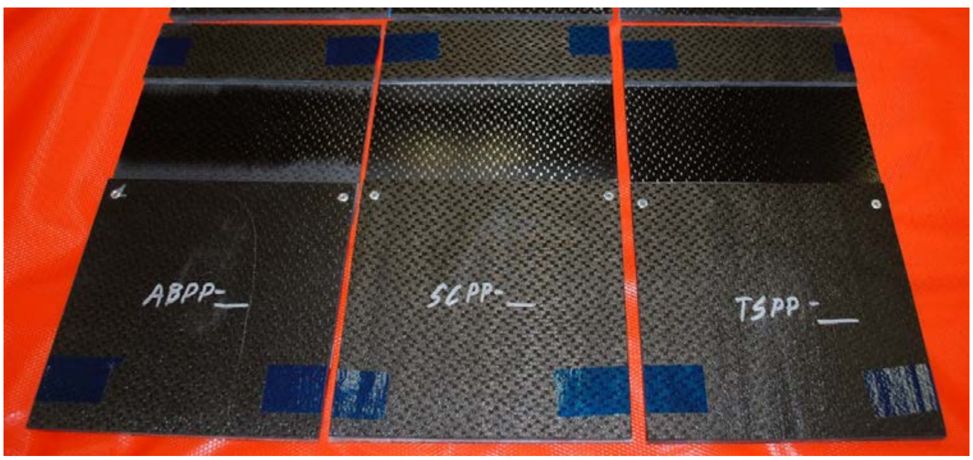
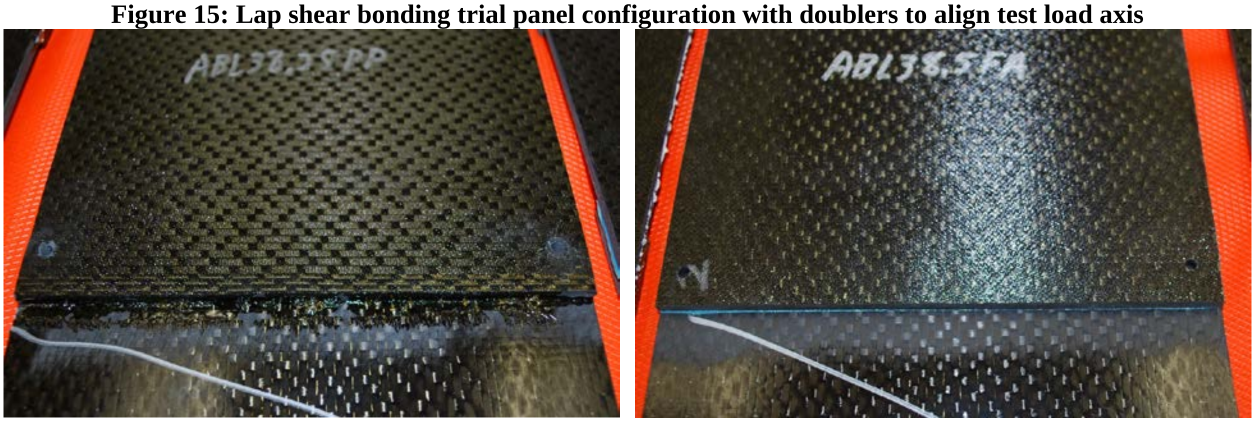


Figure 15: Lap shear bonding trial panel configuration with doublers to align test load axis



Prepreg "Adhesive" – Vacuum Bag Cure | Film Adhesive – Vacuum Bag Cure

Figure 16: Lap joint bonds after vacuum bag cure with prepreg and film adhesive bond materials

The results of the testing show that lap shear strength varied by 71% in this study. Multiple factors have an impact as shown in Table 10 and Table 10. Smooth, inert tool surfaces are shown to bond poorly. Because surface preparation for this class of structures is expected to be severe, most of the conditions used a fully abraded surface to ensure a 'fresh' surface was available for bonding. This choice yielded moderate strength bonds with the favored film adhesive, high or mixed coupling agents improved strengths modestly. The un-treated, scuffed resin surface of the first trial set yielded the highest strength, showing that freshly exposed and roughened resin can be acceptable. The last four test sets (right side of Figure 17) explored vacuum bag vs autoclave pressure cures along with coupling agents on resin rich surfaces. The data scatter is high, but the value of chemical surface treatments is verified on the original, low strength tool surface which demonstrated the highest performance.

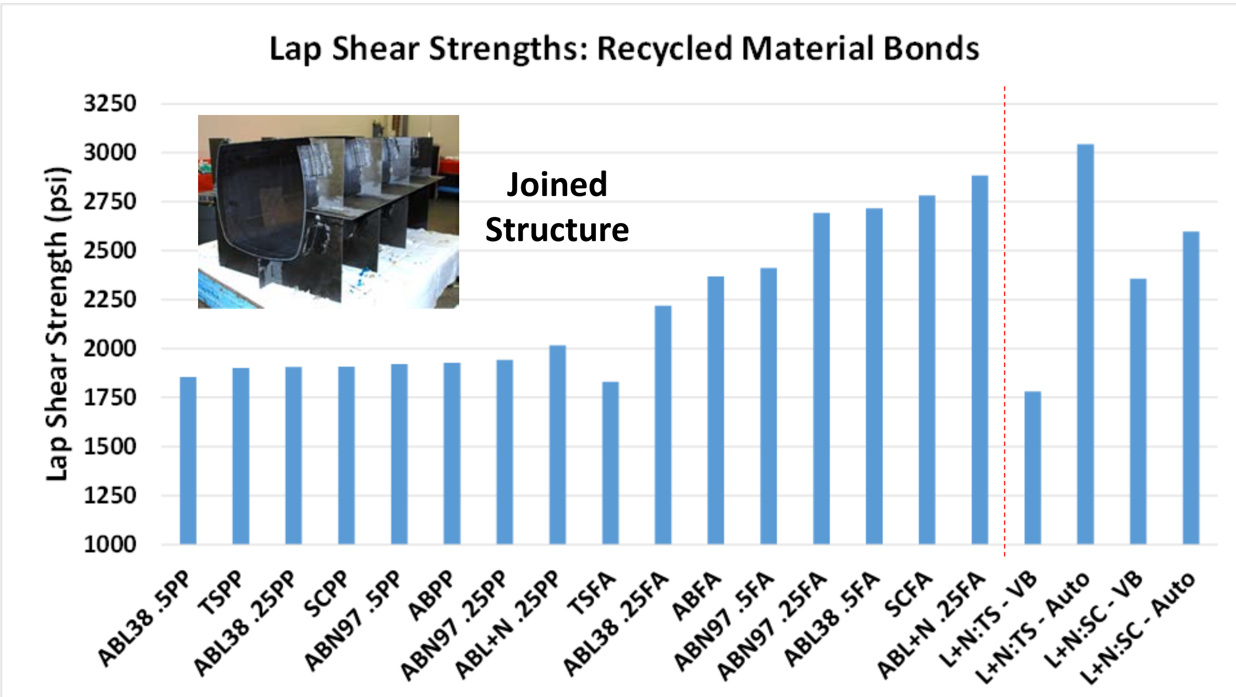


Figure 17: Lap shear results determining range of joint strengths of likely processing variability

The 2016 medium size tool demo shown in Figure 17 re-used a thin wall, prototype tool to make a sturdy manufacturing tool (thick wall) resulting in high deflection forces to remedy thermal warpage. The tool required approximately 500 lbf to pull the edges back to model contour, rather than the <50 lbf of the thin wall part. The eggcrate support structure’s role is to correct and stabilize the final tool surface contour. The joints must carry these loads and any additional cure bagging or autoclave pressure effects. The four, transverse eggcrate panels most support a minimum of 125 lbf each; which is well below the 14,000 psi (2 sided joint x >4 inch length x 1750 psi minimum) of the Tee joint discussed in section 5.2.5. While these strengths are variable and lower than fully optimized aerospace manufacturing techniques, they should easily suffice for manufacturing support structures.

5.2.5 Tee joint testing

The Tee joints for recycled prepreg were fabricated using a finger joint design which wrapped interlocking, one-inch wide fingers on the cut pattern in Figure 20 (left side) around the center web section. The assembled joint is shown on the right side, the upright leg plies wrapped around a web template covered with a release carrier (green poly) enhancing peel resistance versus a simple 'L' over-wrap joint. The joint has at least 3 layers of prepreg to form the upright legs and 2 for the base. The orientation of the plies can be controlled by the cut pattern (0/90 or bias ply) to harden or soften the joint. The finger joint can be assembled, warmed and formed to shape or built-up in-situ with tooling aides to improve compaction control of the joint.

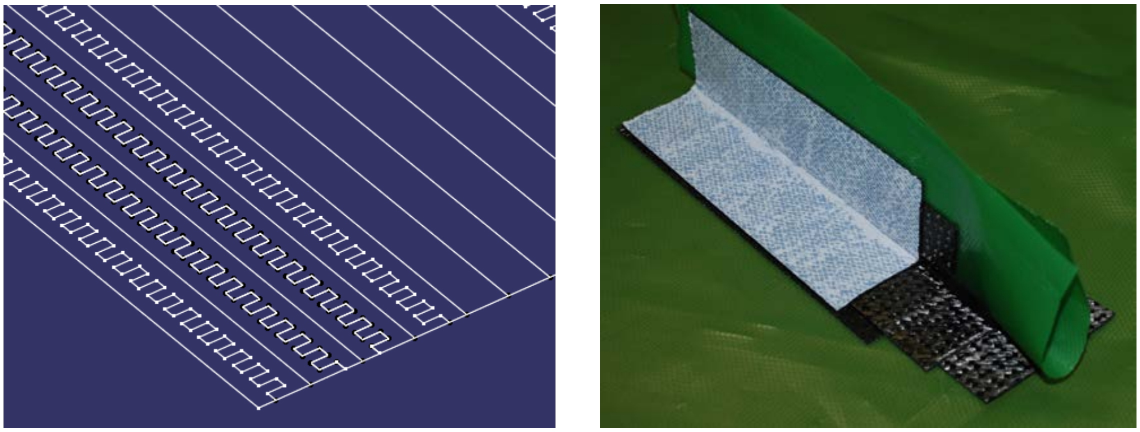
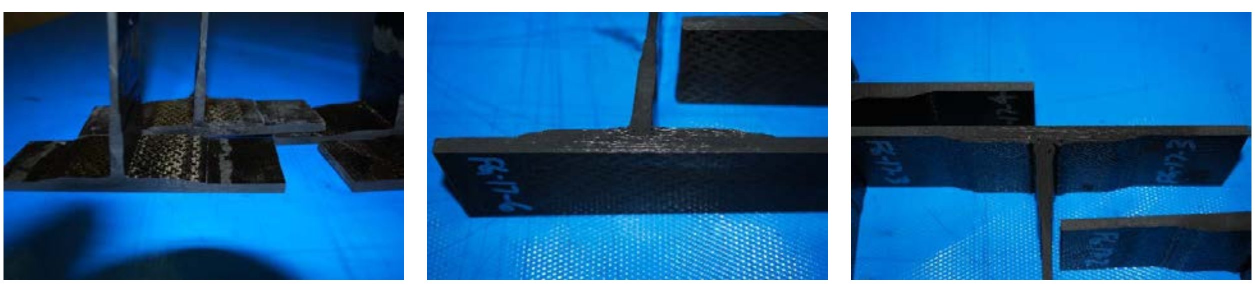
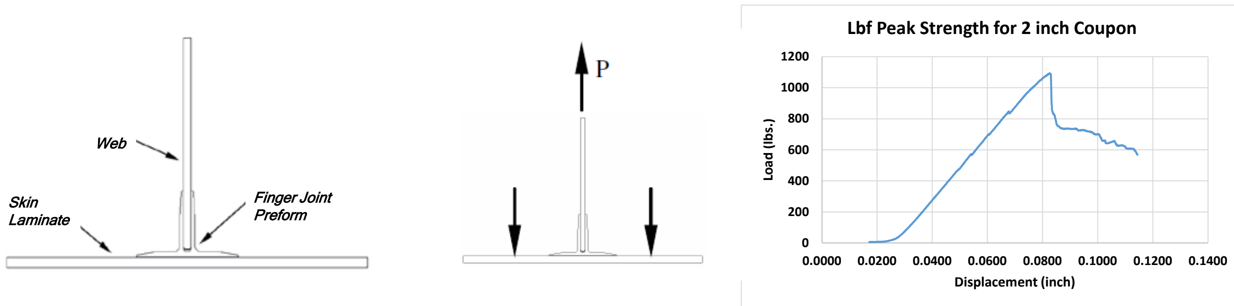


Figure 18: Construction and feedstock pattern for finger joint Tee joint using recycled prepregs

Test joints were taken from two articles; the 2016 tool demo and a fabricated test T panel. The 2016 tool preformed the finger joint and vacuum bag cured the entire, complex tool with 22 joints at one time, the eggcrate support maintaining geometry. The T panel used metallic, extruded Tee stiffeners on a flat tool and auxiliary bagging devices for 3D woven joints to reduce the forming time for the finger joints. The demo tool's preformed joints compacted better, but still exhibited some ply misorientation and voids. The in-situ compaction with aides results were sub-standard, but were tested to determine the impact. Several Tee joints are shown in Figure 20 and the LM joint pull-off strength test configuration is shown in Figure 20 with a typical load vs. displacement chart shown.

Figure 19: Finger joint coupons taken from 2016 demo tool (right, center) and 2017 T panel (left)





Tee Finger Joint **Pull-off Test** **Load – Displacement Chart**

Figure 20: Tee element, Pull-off test configuration used to evaluate joint strength

The results of these tests are listed in Table 18. The 37% higher pull-off strength and higher quality of the bagged demo tool finger joint vs the autoclave cured Tee panel shows the impact of poorly controlled forming. The 350 – 550 pli (lbf/lin. inch) load capability is sufficient for tooling and support aides, but does not have the huge margin of the shear joints. Using the lessons learned from the lap shear joint work, coupling agents and film adhesives may provide a path to ~750 pli, joints.

Table 18: Tee element pull–off strength for finger-lock joint: test panel and tool samples

Tee Panel	P max	PLI	Tool Joints	P max	PLI
FG-17-1	851	425.5	FG-17-6	976	488
FG-17-2	693	346.5	FG-17-7	1095	547.5
FG-17-3	780	390	FG-17-8	957	478.5
FG-17-4	829	414.5	FG-17-9	1109	554.5
FG-17-5	630	315			
	Avg.	**378**		**Avg.**	**517**
	S.D.	**47**		**S.D.**	**39**

The economic driver behind this intermediate quality joint is the poor performance of simple ‘L’ overwrap joints typically used on tools and the expense of 3D woven joints which have stellar performance and flexibility. This joint may be several times the effort of a simple overwrap, but should be about one-tenth the cost of a 3D woven joint. L overwrap joints fail in peel at 20 to 60 pli per side, yielding about one-fifth the strength of the finger joint. The expensive 3D woven is expected to be up to several times stronger, depending on the configuration of the joint, but this performance level is not required for many manufacturing structures. This preliminary data shows this type of joint has an intermediate performance and cost position, but needs specific forming tooling to achieve consistently, acceptable results. This recycle application will need both a motivated, volume user with access to a cutting table to develop this low cost, intermediate performance joint.

6.0 PROCESS IMPLEMENTATION PLAN

Direct Recycling (DR) itself requires only modest actions to implement. AFP#4’s fabrication capabilities are sufficient to carry out recycling. Modifications to standard practices have been, and continue to be, made to increase productivity and reduce costs.

Maximum recycling value requires an internal marketing effort to inform potential users of the products and an engineering effort to match applications with the products of the waste stream. An important requirement for the recycling process is material control – this material cannot be allowed to re-enter the production system as it has been scrapped because it no longer satisfies production requirements. Overall, DR is not difficult to initiate, but it will require knowledgeable personnel to keep it successful.

This project provides the validation data showing that DR of aerospace composite prepregs into reliable, value-added articles delivers acceptable return on investment. The tasks shown in Figure 21 support continued growth in DR waste reduction by:

- Documenting the methods and techniques used for Direct Recycling along with a viable database to match waste prepregs to applications, including:
  - In-coming Quality Assurance/Blend: Cure and flow testing to quantify variability due to feedstock characteristics. This task demonstrated blending to ensure high quality laminate as processed.
  - Recycle Intermediates Database: Characterize recycle laminate performance and variability with respect to virgin material and M&P specifications for fiber orientation (random) and areal uniformity to maximize acceptance.
  - Joining methodologies: Characterize standard and unique joints to expand the utility of the recycle materials, maximizing use of waste materials.

- Evaluating the application and manufacturing parameters needed to achieve value-added recycling of composite prepreg materials.

An important component of recycling success is developing reuse applications; so far, the following markets have been served:

- Training –
  - Raw materials – small coupons for destructive operations (drilling)
    - Generic carbon fiber composite
  - Machining blanks – Representative articles which allow advanced training techniques to be taught.
    - Generic carbon fiber composite fabricated to part dimensions
  - Formed articles – Representative parts/ assemblies to teach advanced finishing techniques (these articles require further fabrication work after receiving recycled products)
    - Generic composite part dimensions with supplemental features added by training group
  - Local training / education – Training facilities and institutions which are feeder paths to AFP#4 manufacturing personnel.
    - Mixture of raw and fabricated materials per curriculum
- Testing –

- Controlled materials – Non-expired materials which can be processed within the M&P specifications can be fabricated into test coupons if their quality trail was maintained. This is possible due to the rapid fabrication for simple panels allowing use of the limited lifetime of nearly expired material.
  - Composite laminates made to requirements of program specifications
- Chemical / Physically representative substrates – Coating, corrosion, sealing tests
  - Composite laminates made to requirements of program specifications

- Validation & Verification –
  - Process studies – cutting and coating trials
    - Representative materials; possibly program compliant processing
- Manufacturing support–
  - Engineering development and program assembly tooling
  - Quality assurance - Automated drilling machine QA panel qualification for new sensor
    - Physical property compliant laminates

6.1 Schedule

Figure 21 is the planned schedule for the project. The work went smoothly, requiring less effort than projected for the fabrication and testing tasks. Analysis and documentation are done, completing the work scope.

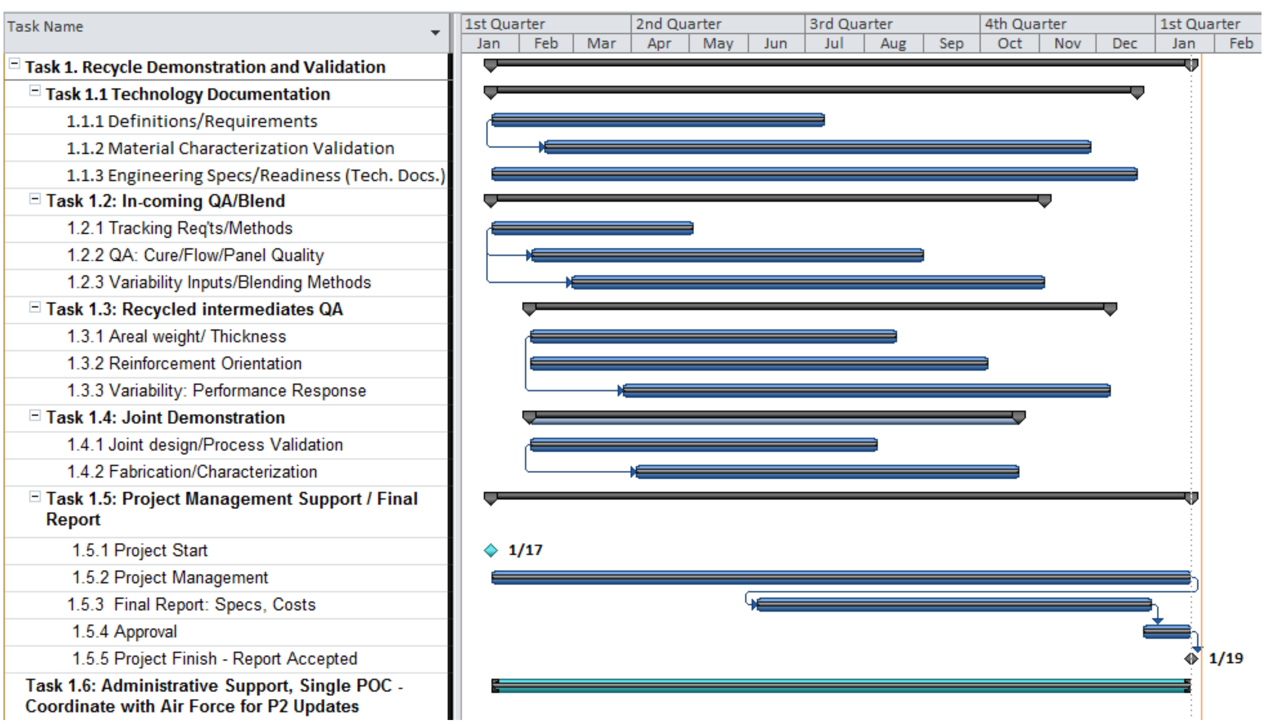


Figure 21: PROJECT ACFJ17PV19 schedule to validate Direct Recycling of waste composite prepregs

6.2 Technology documentation

The methods and validation information for recycling are documented for continued use in AFP#4 and other locations. Description and appendix location of documents attached:

A. Cost/Benefit decision – layup planning sheet: Nominal cost/value estimate built into fabrication sheet (MS Excel® file) template. (App. A)
B. M&P Guidelines - Direct Recycling (App. B): A concise document is attached covering the basics of composite fabrication with additions for using recycling streams. Recyclers are assumed to be in production of composite articles and know the M&P requirements of their material systems.
    a. Recycled prepreg evaluation: Flow test – Modified ASTM D3531 method
    b. Blending – Ages and resins: No documentation – use recommendation (always test small quantity on large heat sink when unsure to verify acceptable reactivity).
    c. Cure: Generic and vender specific. Use with flow test to verify schedule.
    d. Environmental, Safety & Health: Precautions for Direct Recycling
    e. Machining: Recommendations for typical finishing of recycled coupons/panels.
C. Prepreg flow test method based on ASTM-D3531 (End of App. B)
D. Material Handling / Storage recommendations. (App. C)
E. Reference links from Hexcel and Cytec (Solvay) below give generic, concise information which may be useful for simplified fabrication methods to reduce costs.
    a. http://www.hexcel.com/user_area/content_media/raw/Prepreg_Technology.pdf
       A good educational article with standard materials and processing information.
    b. https://www.cytec.com/sites/default/files/datasheets/CYCOM_977_3.pdf
       Specific recommendations for AFP#4's 977-3 epoxy system.
    c. http://www.cytec.com/sites/default/files/datasheets/CYCOM_5250-4_032012.pdf
       Specific recommendations for AFP#4's 5250-4 Bismaleimide (BMI) system.

7.0 ACTUAL COST SAVING BENEFITS

The ACFJ17PV19 program validated the effectiveness of "Direct Recycling", taking pattern cutting off-cuts and expired broadgoods materials and reusing them in non-certified, production and technology support applications at Air Force Plant No. 4 (AFP#4) and associated responsibilities. Lockheed Martin Aeronautics (LM Aero) ESH and business recycling efforts reused 1135 lbs. of composite materials in 2017 for a cost savings of $108k (Table 19). This amount represents only 20% of the estimated uncured composite prepreg waste stream and a much smaller percentage of the non-hazardous waste; but captures significant cost savings via high value reuse applications.

Table 19: 2017 composite prepreg recycling validation results

Composite Prepreg (2017 lbs.)	Prepreg Waste(lb) (Hazard)	Carrier Weight (lb.)	Carrier Paper Waste(lb.)	Paper Waste(lb., recycled)	Machining Waste (lb.)	Total Composite Waste (lb.)	Disposal Cost ($)
27750	5550	17147	8,072	(12,488)	4163	34932	
[% of PP #s)	20%	62%	29%		15%	**126%**	
Recycled - 2017	1135	lbs.	Cost Savings Estimate		Material* - recycle labor		
					Disposal savings		
					Labor/Tooling Savings		
						Total	$ 107,567

7.1 Financial analysis introduction

Recycling feasibility is dependent on creating more value from waste stream management than the cost of the effort. Persistent success comes from diverse reuse applications which can recapture the value of this expensive material, augmenting the cost savings for disposal and fabrication efficiency. The 2017 applications shown in Table 4 describe many of the high value uses pursued. These applications and the effort required to execute will be summarized in this section and discussed in more detail in in section 7.2.

There are at least three possible cost savings models:

1. Cost savings = cost of raw materials not purchased
2. Cost savings = cost of raw materials minus cost of recycling effort
3. Cost savings = cost of raw materials plus differential cost of recycling

The cost savings for 2016 were calculated using definition No. 1. While analyzing the 2017 data, two things become clear. There are subjective inputs to the financial calculations and the operations inputs have a large impact on costs. In order to reduce the uncertainty, method 3 was pursued with the premise that a single analysis path would be created and the remaining uncertainty accepted as part of a fluid operational system. This allows applications to be judged on a consistent basis to determine which actions will be cost effective. More data collection and analysis may improve the model, but it may be just as effective to arbitrarily select a minimum, acceptable cost savings value and use that value to mitigate remaining uncertainties.

The methodology used to determine the overall economic impact follows the following steps:

- Determine the value of the products that recycled material competes against.
    - Survey commercial, industrial and internal sources of composite laminates
        - Materials, forms, scale, complexity
    - Build a value model which reflects that data
- Determine the costs of recycled products

  - Collect and analyze the information available to build an agile, uncomplicated cost model for fabrication within the engineering lab environment with relaxed M&P methodologies for recycle applications.
- Verify the models: adjust data inputs/ process impacts in order to handle discontinuous model outputs without distorting the decision making process.

These financial model development efforts yielded an initial model used for 2017 results and were iterated for future use. Periodically, the analysis should be reviewed for fidelity of inputs, interactions and changes to the competitive market which is the basis for cost savings.

7.2 Analysis and explanation

Cost savings was determined by **Value** minus **Cost**.

Value:

Case 1: One small category of recycling is reuse of un-expired materials with an intact material pedigree and specified M&P engineering for fabricating certified laminates. The value is simply the cost avoidance of not buying the prepreg required. AFP#4 nominal costs were used in Table 1, extra material was included for complex articles which would have significant pattern cutting scrap rates. Specialty materials, such as the bias weave epoxy prepreg, are included as standard weave costs because the products can be fabricated with standard weave. The extra effort is likely to balance out the extra cost of the specialty weave.
Case 2: All other categories included the total cost impact of materials, labor, disposal and auxiliary items required in recycling to estimate cost savings. Internal costs are known, but external, competitive laminates may not use the same materials and their disposal costs are included in their procurement costs. For the commercial class of reuse applications, the list price of a satisfactory product was used to establish 'value'. Commercial and industrial supplier product value information was surveyed for a valid economic analysis basis. [No detailed proprietary cost information is included in this document version – analyses will be based on publicly assessable market values and a nominal $100/hr. labor cost which can be ratio'd for quick estimates.]

Table 20 contains list price (4Q, 2017) data from several commercial (Dragonplate, Hillside), and industrial (McMaster-Carr, Hexcel) outlets for the variety of composites of interest. The commercial materials do not have the premium raw materials of aerospace, but they satisfy some reuse requirements. Premium products at commercial outlets have smaller volumes and costlier materials; the survey results showed products with aerospace-like characteristics also have aerospace pricing for equivalent forms. The italicized data in the table is interpolated using the low/medium/high price points of the other categories which have more complete data. This data is relatively complex, so it was condensed into the lookup tables of the working model based on the data of Figure 22 with incremental definitions to estimate a value (Table 21).

Table 20: Survey of recycle composite reuse application pricing; internal and external sources

Value Points	12 x 12 x 0.25" panels	Source	Low		*Medium*		High		MSI
			$/panel	$/Lb.	*$/panel*	*$/Lb.*	$/panel	$/Lb.	
Commodity	Gl/Ep	McM-Carr	$ 13.00	$ 4.81	*$ 25.00*	*$ 9.26*	$ 37.00	$ 13.70	2.50
	CF-Gl/Ep	McM-Carr	$ 30.00	$ 12.00	*$ 40.00*	*$ 16.00*	$ 50.00	$ 20.00	5.00
	SM (30) fiber (Flat)	DragonPlate	$ 90.00	$ 45.00	*$113.00*	*$ 56.50*	$ 136.00	$ 68.00	7.43
	SM (30) fiber (Flat-Large)	DragonPlate	$ 70.00	$ 33.30	*$ 87.00*	*$ 43.50*	$ 105.00	$ 52.50	7.43
Industrial	SM (30) fiber	Hillside	$108.00	$ 54.00	*$121.50*	*$ 60.75*	$ 135.00	$ 67.50	7.43
	Specialty (HexTool®, IM CF)	Hexcel		*$ 65.45*		*$ 81.82*		$ 112.00	5.50
Aerospace	IM (40) composite/Ep,BMI	DragonPlate	*$232.20*	*$ 116.10*	*$309.60*	*$ 154.80*	$ 387.00	$ 193.50	9.00
Equivalents	IM (40) composite/HT(BMI)	DragonPlate	*$281.45*	*$ 140.73*	*$375.27*	*$ 187.64*	$ 469.09	$ 234.55	9.00
	Non-recycle application - Certified			*Italics - Estimated value*					

Definitions used in the table are included in section 8.0.

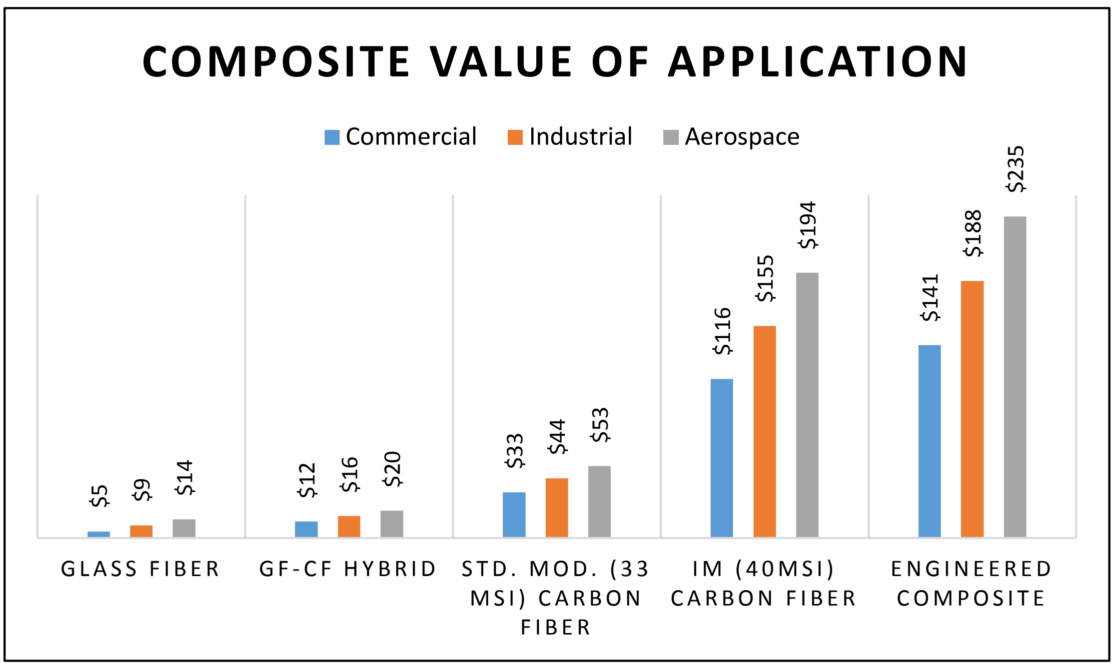


Figure 22: Composite laminate values used for material types and applications

Table 21: Composite value lookup table used for cost recycling model

Material/Market	Commercial	Com./ Industrial	Industrial	Ind./Aero	Aerospace
Glass fiber (GF)	$ 4.81	$ 7.04	$ 9.26	$ 15.00	$ 30.00
GF/Carbon Fiber (CF) Hybrid	$ 12.00	$ 14.00	$ 16.00	$ 20.00	$ 35.00
Std Mod 33 msi Carbon Fiber	$ 33.30	$ 38.40	$ 43.50	$ 48.00	$ 52.50
IM 40msi Carb Fiber	$ 116.10	$ 135.45	$ 154.80	$ 174.15	$ 193.50
Engr'd Composite	$ 140.73	$ 164.18	$ 187.64	$ 211.09	$ 234.55

Aside from the wide range of material types and qualities above, the pricing of the delivered parts is highly dependent on scale as defined by lbs. / panel or coupon size (square inches). Some price lists contain enough information to curve fit the cost/size relationship as shown in Figure 23. For the smallest articles, coupons, the price can more than double versus a large ¼" thick laminate. This curve fit value correlation is critical as most reuse applications require their product be rough cut to size. Combining a lookup table of composite value and the impact of product size, the value of a competitive, commercial laminate can be estimated. This information is embedded into the "Air force Plant #4 Composite Recycling" run sheet (App. B) allowing the application requested to be quickly appraised for cost effectiveness.

Quasi-Isotropic plate		
in2	Price	Cost $/lb.
36.00	$ 40.00	$ 80.08
144.00	$ 136.00	$ 68.07
288.00	$ 259.75	$ 65.00
576.00	$ 495.25	$ 61.97
1152.00	$ 805.00	$ 50.36
2304.00	$ 1,610.00	$ 50.36
4608.00	$ 2,897.80	$ 45.32
22800.00	$ 11,900.00	$ 37.62

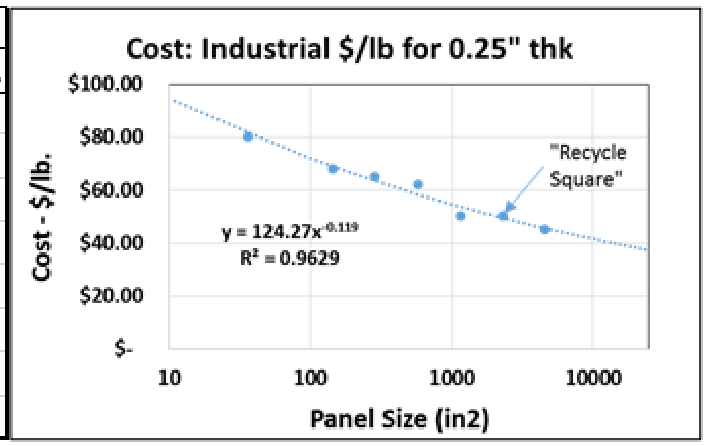


Figure 23: Determination of cost correlation with panel/coupon size of product required.

Cost:

The effort to determine a differential cost of recycled vs. standard AFP#4 related articles is the mostly a labor requirement calculation. In order to estimate the nominal labor requirement, recycling fabrication hours were compared to historical fabrication quotes.

An estimate of nominal hours required to fabricate engineering-type, ¼" thick panels of different sizes in the engineering lab is detailed in Table 22. The top row provides various levels of scale, area of the panel, and the subsequent rows list tasks required to complete the job. Labor estimates are increased by the setup and material handling requirements of small orders; actual cutting, layup and debulk hours which are part of the recycling tasks represent less than a third of the total. Thus, per part labor requirements favor larger panels by diluting the total laminate processing hours per pound as shown by the bottom line lbs. /hr.

The highlighted row, Labor Ratio value, was plotted and curve fitted (Figure 24) to estimate labor/cost requirements for any size panel in cost savings calculations. The use of a 16 ft2 panel as the basis was chosen as that size is typical for recycling efforts.

Table 22: Labor estimate vs panel size to fabricate ¼" thick recycled composite laminates

Sq. Ft panel	1	4	9	16	48	158
Panel in2	144	576	1296	2304	6912	22791
Collection	0.5	0.5	0.5	0.66	0.75	1
Mgmt/Engr	0.5	0.5	0.5	0.66	0.75	1
Cutting	1.5	2	2.25	2.5	3	3.5
Layup/Debulk	1.5	2	3	4	7	12
Tool Prep/Bag	2	2.5	3.25	4	5	5.5
Cure	2.5	2.6	2.65	2.7	2.8	3
De-bag	0.5	0.6	0.7	0.8	1	1.25
Cutting	0.25	0.66	1	2	5	8
Labor Hrs.	9.25	11.36	14.34	17.32	25.3	35.25
Labor Ratio	0.53	0.66	0.83	1.00	1.46	2.04
Lbs.	2.0	8.0	20.0	32.0	95.9	316.2
Lbs./Hr.	0.22	0.70	1.27	1.85	3.79	8.97

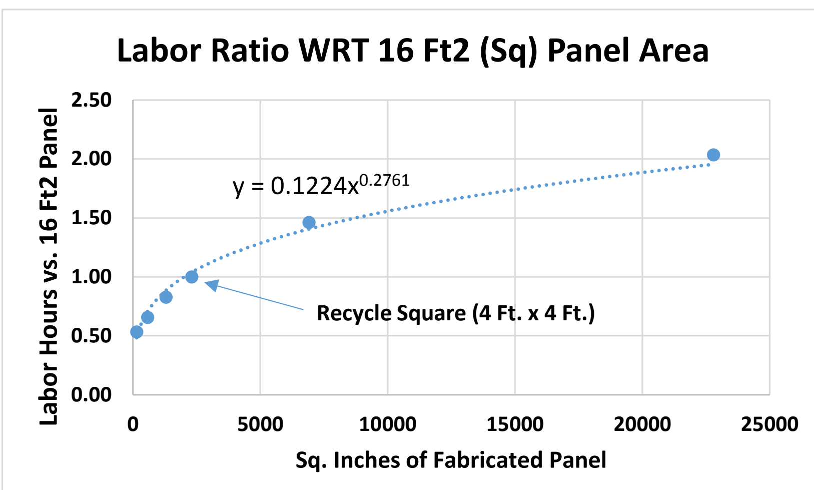
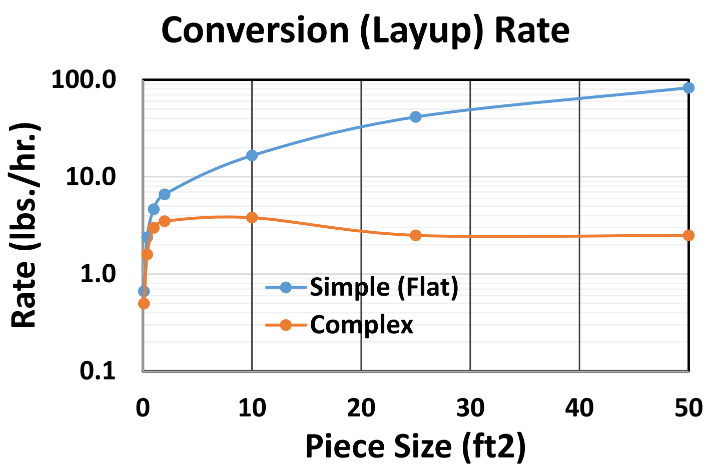


Figure 24: Plot and curve fit of recycling labor required to fabricate laminates – Engr. Lab

The physical conversion recycling rate vs waste prepreg piece size was estimated in 2016 and is shown in Figure 25. This relationship can vary considerably for any single action, but the general trends were confirmed by 2017 results. Simple, large flat plate can be converted at very high rates; larger plates were laid up (DR converted) at over 100 lbs. /hr. However, as the complexity of the part layup increases, the conversion rate falls dramatically. Large decreases are also seen for small items for which the overall lay-down rate is greatly reduced by the minimal mass of each piece handled. The 2017 ACFJ17PV19 characterization panels were small and despite the high rate of prepreg pieces laid up, the mass rate was low, one to seven lbs. /hr. For very large plates made with fresh broadgoods, the high tack and low stiffness of the huge sheets prevent quick location of the sheet or correction of fiber orientation anomalies, resulting in an order of magnitude slower rate than possible with aged, stiff and low tack material. The resulting rates for large, tacky feedstock are only slightly higher than the complex shape rate curve. Thus, this graph provides guidance for the feasibility of recycling, but cannot predict actual cost savings.

Figure 25: Recycling rate of waste composite prepregs in relation to size and shape



2017 actual cost for recycling of the materials can be estimated in two ways. The first method shown, Table 23, uses market value to determine the majority of the cost savings. An additional cost savings for two tools re-used was included as this expense was required for a complex part application. The second method tracks fabrication and machining hours of internal recycling. Recycling cost savings by the second method include labor and material costs (included in the LMPI version) plus the auxiliary cost items. Table 23 has the records-based 2017 labor calculations; these values were curve fit to generate predictive cost tables (Table 24, Table 25). A predictive capability may be sufficient for cost savings tracking, but is essential for economic decision-making when marginal feedstocks are evaluated for large applications.

Table 23's 2017 results from first iteration of the cost model defines the following values and calculations listed by (columns numbers):

- Application information: Date(1), Use(2), Lbs. recycled(3), No. of Coupons/Panels(4)
- Material value – Nominal prepreg cost, F35 (5) – LMPI – Not Listed
- Market value – Cost model value based on material type (Table 21) (6)
- Cost scale factor – coupon/panel size effect (multiplier from Figure 23) (7)
- Recycle fabrication labor – actuals, not model value (8)
- Standard labor estimate – cost model estimate (Figure 24) (9)

- Layup/Recycle Labor Saved: Std. Labor minus Actual hours for recycling portion only.
- Total labor hours saved – Standard Fabrication vs Recycle total fabrication hours (11) This value is not included as the total exceeds the method including
- Waste disposal costs are not included using this market-based basis.
- Market Value of Recycled Material – No. of lbs. x Market value/Lb. (12). Labor savings are listed, but the savings versus the market rate are assumed to be included in the Market value calculation as no fabrication is required. The labor information is useful for estimates of cost savings using the facility rates.

The relationships and calculations within this table are explained below:

1. The recycle runs in Table 23 are organized by reuse application with column totals at the bottom.
2. Columns 1 through 8 have raw data inputs from internal/external markets and fabrication records. Column 6 and 7 uses the market value lookup Table 21 and size effects (Figure 23) which will have to be updated periodically.
3. Column 9 lists estimated fabrication labor hours (fully loaded costs) for potential users/recyclers to use for comparison. The costs are calculated at a nominal $100/hr.; other labor rates can be ratio'd from this value.
4. Column 10 lists hours saved solely in the recycle conversion step as a way to gage recycling productivity during cutting, layup, debulk. Note: Broadgoods recycling requires cutting, trim piece reuse does not. Debulk effort varies widely with part shape and material condition.
5. For columns 8 through 11, the cost impact @ $100/hr. is calculated at the table bottom in the box – ***Estimated Labor Costs ($'s)***
6. Column 12 presents market value, but not the costs, of the run based on the scale equation [$/lb. = 124.27 X ^-0.1190, where X = sq. inches] and the market value lookup table if the system is special order. Total cost avoidance for this publicly sourced value/ cost is sub-totaled at the bottom with a $10,000 additional savings for 2017 tool reuse for training parts (procurement cost avoidance). While it is slightly different from the official 2017 cost savings value, it illustrates the method and is a credible estimate.

Table 23: 2017 recycling runs cost savings calculation and summary (non-LPMI cost data)

Recycled Composite Materials - 2Q, 2017 (Non-LMPI values)											
1	2	3	4	5	6	7	8	9	10	11	12
Date	Cost/Value Description of Matl	Actual (Lbs.)	Number of Coupons /Panels	Material Value ($/lb.)	Market Value ($/lb.)	Cost Scale Factor (area/lbs effect)	Recycle Fabric. Labor (Hrs)	Standard Labor Estimate - All hours	Layup / Recycle Labor Saved (hrs.)	Total Labor Hours Saved	Market value of Recycled Material ($'s)
Demonstrations											
1/9/2017	Small Proc. Panels	3.8	1		$ 44	1.30	2.1	9.5	-0.6	7.4	$ 216
1/16/2017	Small Proc. Panels	4.8	1		$ 44	1.30	0.66	9.5	1.2	8.8	$ 272
2/28/2017	1 sq. ft. test panels	10.5	7		$ 155	1.00	10.5	8.4	1.6	-2.1	$ 1,625
2/28/2017	1 sq. ft. test panels	10.5	7	L	$ 155	1.00	10.5	8.4	1.6	-2.1	$ 1,625
4/20/2017	1 sq. ft. test panels	10.5	7	M	$ 155	1.00	10.5	8.4	1.6	-2.1	$ 1,625
5/12/2017	Lap shear w/tabs	0.5	21	P	$ 155	1.00	0.5	5.7	1.0	5.2	$ 77
5/12/2017	Lap shear panel & tabs	24.2	4	I	$ 155	1.00	7	7.5	5.1	0.5	$ 3,745
11/10/2017	Shim - commodity	30.0	1		$ 9	0.99	4.5	18.0	4.5	13.5	$ 275
12/14/2017	Raw Matl - Ext. Use	40.0	PP reuse		$ 75					0.0	$ -
ManTech / Training											
3/6/2017	Raw Matl - Ext. Trial	20.0	PP reuse		$ 75	1.00	0.3			-0.3	$ 1,500
3/20/2017	Raw Matl - Internal	20.2	1		$ 75	1.00	0.1			-0.1	$ 1,516
4/12/2017	ManTech Test substrate	20.2	1		$ 174	1.00	5.25	4.7	0.0	-0.5	$ 3,521
5/1/2017	ManTech Test substrate	10.0	1		$ 174	1.00	3.75	4.7	1.0	1.0	$ 1,742
5/18/2017	ManTech Test substrate	9.0	210		$ 174	1.00	4.5	4.7	0.8	0.2	$ 1,567
7/17/2017	ManTech QA substrate	73.0	16		$ 174	1.00	10.5	8.4	7.4	-2.1	$ 12,713
7/25/2017	F35 Training panels	35.0	177	L	$ 53	1.38	8.5	8.4	2.0	-0.1	$ 2,528
9/6/2017	F35 Training coupons	35.0	184	M	$ 53	1.85	5	4.2	5.5	-0.8	$ 3,398
9/8/2017	F35 Training panels	35.0	16	P	$ 53	1.38	6.5	8.4	3.5	1.9	$ 2,528
11/10/2017	F35 Training coupons	35.0	184	I	$ 53	1.85	6.5	4.2	3.5	-2.3	$ 3,398
11/15/2017	F35 Training - Curved	13.5	3		$ 235	1.00	3.5	10.5	3.5	7.0	$ 3,166
11/15/2017	F35 Training - Curved	13.5	3		$ 235	1.00	3	10.5	3.8	7.5	$ 3,166
11/15/2017	F35 Training - Curved	13.5	3		$ 235	1.00	3.75	10.5	3.3	6.7	$ 3,166
12/11/2017	F35 Training - Curved	13.5	3		$ 235	1.00	2.75	10.5	3.8	7.7	$ 3,166
12/11/2017	F35 Training - Curved	13.5	3		$ 235	1.00	4.5	10.5	2.0	6.0	$ 3,166
2017 - 2018	F35 Training - Curved	Values to be captured in 2018									
2017 - 2018	F35 Training - Curved										
Characterization / Composite Testing											
2/14/2017	ManTech substrate	21.9	64	LMPI	$ 174	1.00	4.5	5.4	3.2	0.9	$ 3,814
Program/ Tooling / Misc.											
1/17/2017	High Temp tool plate	16.1	1		$ 235	1.00	8.41	14.8	1.9	6.4	$ 3,776
2/17/2017	Commodity	72.0	2		$ 9	0.87	4.5	24.3	13.1	19.8	$ 579
3/3/2017	ManTech/Training	137.0	36		$ 53	0.87	7.1	24.3	24.3	17.2	$ 6,243
3/15/2017	Training Panels	110.0	48		$ 53	0.87	6.1	24.3	18.6	18.2	$ 5,012
3/23/2017	Commodity	80.0	32	L	$ 16	0.87	4.33	24.3	12.9	20.0	$ 1,111
4/2/2017	Commodity	80.0	34	M	$ 16	0.87	5.5	24.3	14.0	18.8	$ 1,111
11/10/2017	High Temp tool plate	18.2	1	P	$ 235	1.00	5.25	18.0	1.9	12.7	$ 4,269
12/13/2017	High Temp tool plate	14.0	1	I	$ 235	1.00	1.5	18.0	2.0	16.5	$ 3,284
12/13/2017	High Temp tool plate	21.0	1		$ 235	1.00	2	18.0	3.0	16.0	$ 4,926
12/13/2017	High Temp tool plate	14.0	1		$ 235	1.00	1.5	18.0	2.0	16.5	$ 3,284
12/13/2017	High Temp tool plate	21.0	1		$ 235	1.00	2.5	18.0	3.0	15.5	$ 4,926
12/13/2017	High Temp tool plate	35.0	1		$ 235	1.00	2.5	18.0	5.0	15.5	$ 8,209
	Totals	1135	1072	Direct Recycle (dLayup) Hrs.			170	425	161	255	$ 110,246
Piece Sizes: Fines/Sm; Med-lg; BG - Broadgoods; Mix - all sizes			Total Articles	Estimated Labor Costs ($'s)		$100/lb.	$ 17,035	$ 42,491	$ 16,067	$ 25,456	$ 10,000
*Other: Includes fab. labor savings; tooling reuse and fab. matls.											$ 120,246

The recommended cost model for post-2017 recycling vs. internal standard fabrication is based on the differentials of Table 24 and Table 25. Table 23 is the nominal, smoothed, internal fabrication labor requirements of recycling in AFP4's engineering lab. The task hours are summed and divided by weight of the product to yield productivity numbers and costs per pound. Panels less than 1 ft2 are ignored and panels <4 ft2 probably should be supplied from larger panels, but small specific orders may not allow it. Products are 'Made-to-order' in the Engr. Lab. A non-proprieatry $100/hr labor cost value is included to show its effect. A range of market values at various costs/lb. are at the bottom of the table to easily compare the internal vs. external sourcing.

Table 24: Engineering lab cost estimates via labor hours and rate ranges

Panel Area (Sq. Ft.)		0.1	1	4	9	16	48	158
Panel (in2)		12	144	576	1296	2304	6912	22791
Labor	Collection	0.3	0.4	0.5	0.5	0.66	1	2
	Mgmt/Engr	0.4	0.4	0.5	0.5	0.66	1	1.5
	Cutting	2	1.5	1.5	1.75	2.5	6	12
	Layup/Debulk	3.2	3.5	4.25	5	4	10	24
	Tool Prep/Bag	4.5	4.5	4.25	4	3	5.5	10
	Cure	3	3	3	3	3	4	5
	De-bag	1	0.75	0.75	0.75	0.8	1.25	2
	Cutting	2.5	2	2	2	1.5	4	8
	Total Hrs.	**16.9**	**16.05**	**16.75**	**17.5**	**16.12**	**32.75**	**64.5**
Rate	Unit Lbs.	0.200	1.998	7.992	20.0	32.0	95.9	316.2
	Units per run	66	9	3	1.5	1	1	1
	Total Lbs.	**13.19**	**17.98**	**23.98**	**29.97**	**31.97**	**95.90**	**316.22**
	Hrs/lb	1.28	0.89	0.70	0.58	0.50	0.34	0.20
Cost $/lb. vs size		2.54	1.77	1.39	1.16	1.00	0.68	0.40
Cost Equation 'Y'		2.51	1.77	1.39	1.16	1.00	0.68	0.37
Product Cost $/lb. (Material + Labor)								
$50/lb Matl	$100/hr	Use >1 ft2	$ 139	$ 120	$ 108	$ 100	$ 84	$ 70
$75/lb Matl	$100/hr	Use >1 ft2	$ 164	$ 145	$ 133	$ 125	$ 109	$ 95
Commercial Value $/lb. (Non-aerospace requirements)								
Market Value	$50/lb.	$ 126	$ 89	$ 69	$ 58	$ 50	$ 34	$ 19
	$75/lb.	$ 188	$ 133	$ 104	$ 87	$ 75	$ 51	$ 28
	$150/lb.	$ 377	$ 266	$ 208	$ 174	$ 150	$ 102	$ 56

Table 25 has two cost estimate tables with the inputs based on minimum/maximum recycling rates (Left/Right). The minimum rate which is likely economically feasible is about 4 lbs. /hr. making moderate scale panels – 4 ft2 to 9 ft2. Small panels are very expensive, but the added conversion labor load of low rate recycling at 4lbs. /hr. also makes large panels less attractive. Small feedstock sizes significantly reduce rates and complex applications which require layup of smaller pieces fit the 4 lb. /hr. scenario. The maximum rate table uses ~30 lbs. /hr. rate and premises full width broadgoods feedstock. Maximum rate recycling with broadgoods has very rate of return for the effort, but only about 25% of the material is broadgoods. These values will be curve fitted and inserted into a 2018 recycle value calculation table for future assessments.

The impact on cost savings will be highly dependent on the applications pursued, the feedstock materials available and the fabrication strategy used. Table 25 neglects panels <4ft2 for low rate recycling and <16ft2 for high rate recycling due to high total labor per panel made. This implies some cured stock will be inventoried for small orders and orders over 20 lbs. are preferred. This is working as an operational strategy. Again, a non-proprietary $100/lb. labor cost value is included to show its magnitude.

Table 25: Direct Recycling cost estimates based on labor hours and rate ranges: 4lbs. /hr. and maximum rate

Panel Area (Sq. Ft.)		0.1	1	4	9	16	48	158
Panel (in2)		**12**	**144**	**576**	**1296**	**2304**	**6912**	**22791**
Labor	Collection	0.3	0.3	0.3	0.4	0.5	1	2
	Mgmt/Engr	0.3	0.3	0.3	0.4	0.4	0.5	0.75
	Cutting	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Layup/Debulk	4.4	4.5	6.0	7.5	8.0	24.0	79.1
	Tool Prep/Bag	3	3	3	3	3	4	8
	Cure	3	3	3	3	3	4	5
	De-bag	0.5	0.5	0.5	0.5	0.5	0.6	1
	Cutting	1	1	1	1	1.25	3	8
	Total Hrs.	**12.5**	**12.6**	**14.1**	**15.8**	**16.6**	**37.1**	**103.8**
Rate	Lbs.	0.200	1.998	7.992	20.0	32.0	95.9	316.2
	Units per run	66	9	3	1.5	1	1	1
	Total Lbs.	**13.19**	**17.98**	**23.98**	**29.97**	**31.97**	**95.90**	**316.22**
	Hrs/lb	0.95	0.70	0.59	0.53	0.52	0.39	0.33
	Cost vs size	1.82	1.35	1.13	1.01	1.00	0.74	0.63
	Cost Equation 'Y'	2.51	1.77	1.39	1.16	1.00	0.68	0.37
Cost Savings (Avoidance) Estimate								
Market Value	$50/lb.	$ 125.57	$ 88.50	$ 69.27	$ 57.90	$ 50.00	$ 33.86	$ 18.66
	$75/lb.	$ 188.36	$ 132.75	$ 103.91	$ 86.85	$ 75.00	$ 50.79	$ 27.99
Cost	$100/hr	Use 4 ft2 Value		$ 58.78	$ 52.69	$ 52.06	$ 38.66	$ 32.83
Savings $50/lb	@ $100/hr	$ 66.79	$ 29.72	$ 10.49	$ 5.20	$ (2.06)	$ (4.80)	$ (14.17)
$75/lb	@ $100/hr	$ 129.58	$ 73.97	$ 45.12	$ 34.15	$ 22.94	$ 12.13	$ (4.84)

Panel Area (Sq. Ft.)		0.1	1	4	9	16	48	158
Panel (in2)		**12**	**144**	**576**	**1296**	**2304**	**6912**	**22791**
Labor	Collection	0.3	0.3	0.3	0.4	0.5	1	2
	Mgmt/Engr	0.3	0.3	0.3	0.4	0.4	0.5	0.75
	Cutting	0.5	0.6	0.8	0.9	1.0	2.0	3.0
	Layup/Debulk	1.0	1.0	1.0	1.0	1.0	2.5	10.0
	Tool Prep/Bag	2	2	2	2	2	3	6
	Cure	3	3	3	3	3.25	3.5	4
	De-bag	0.5	0.5	0.5	0.5	0.5	0.6	1
	Cutting	1	1	1	1	1.25	3	8
	Labor Hrs.	**8.6**	**8.7**	**8.9**	**9.2**	**9.9**	**16.1**	**34.8**
Rate	Lbs.	0.200	1.998	7.992	20.0	32.0	95.9	316.2
	Units per run	66	9	3	1.5	1	1	1
	Lbs.	**13.19**	**17.98**	**23.98**	**29.97**	**31.97**	**95.90**	**316.22**
	Hrs/lb	0.65	0.48	0.37	0.31	0.31	0.17	0.11
	Cost vs size	2.11	1.56	1.19	0.99	1.00	0.54	0.35
	Cost Scale Factor	2.51	1.77	1.39	1.16	1.00	0.68	0.37
Cost Savings (Avoidance) Estimate								
Value	$50/lb.	$ 125.57	$ 88.50	$ 69.27	$ 57.90	$ 50.00	$ 33.86	$ 18.66
	$75/lb.	$ 188.36	$ 132.75	$ 103.91	$ 86.85	$ 75.00	$ 50.79	$ 27.99
Cost	$100/hr	Use 16 ft2 Mfg.				$ 30.97	$ 16.79	$ 10.99
Savings $50/lb	@ $100/hr	$ 94.60	$ 57.53	$ 38.30	$ 26.93	$ 19.03	$ 17.07	$ 7.67
$75/lb	@ $100/hr	$ 157.39	$ 101.79	$ 72.94	$ 55.88	$ 44.03	$ 34.00	$ 17.00

Full Rate Production (FRP) Impact: F35 FRP will approximately triple the composite prepreg waste. Table 26 is a linear prediction (3X 2016 values) of the various composite fabrication waste streams; the upper section has the raw waste stream numbers. The second box estimates known internal applications demand of 2500 lbs. /yr. for similar applications to 2017 including sustaining training activities, quality assurance articles and miscellaneous needs. This recycle quantity does not fully utilize the waste broadgoods feedstock fraction; permitting the excellent returns ($236K/yr. cost savings) for highly efficient recycling. However, it leaves a large percentage of the waste stream un-utilized and in need of disposal. Two residual waste cases are presented below that: Case 1 – Aggressively pursue one of the original, lower value applications with volume requirements – tooling plate; and Case 2 – Develop an outside application which has unlimited volume, but much lower payback. Case 1could almost double the cost savings, but represents a very large increase in the resources needed for recycling at lower conversion rates. Case 2 could also nearly double cost savings due to its greater reduction of all wastes and would require only modest labor inputs, but requires the development of a bulk material application.

Table 26: Cost savings estimates at Full Rate Production (2022) and estimated application demand

Full Rate Production (FRP)							
Composite Prepreg (2022 lbs.)	**Prepreg Waste(lb) (Hazard)**	**Carrier Weight (lb.)**	**Carrier Paper Waste(lb.)**	**Paper Waste(lb., recycled)**	**Machining Waste (lb.)**	**Total Composite Waste (lb.)**	**Disposal Cost ($)**
79296	15859	48998	23,066.26	(35,683)	11894	99818	
[% of PP #s)	20%	62%	29%		15%	**126%**	
AFP#4 FRP- Full Rate Prod. Estimate	2500	Internal lbs.	Cost Savings Estimate		Material - recycle labor		$ -
					Disposal savings		$ -
					Labor/Tooling Savings		
						Total	$ 236,931
Residual Case 1 = Commodity Tooling Plate with optimize processing							
High $ FRP Residual PP Waste Stream	13359	lbs.	Cost Savings Estimate (10lb./hr & $30/lb value)		Material- Low Commodity		
					Disposal savings		
					Labor/Tooling Savings		
						Total	$ 193,708
Residual Case 2 = Develop Outside Vender Recycle Stream for Long Fiber Use							
LOW $ FRP Secondary Recycle Stream	62357	lbs.	Cost Savings Estimate (All non-optimum matl to bulk reuse - $1.5/lb. sale)		Material- 'Plastic Filler"		
					Disposal savings		
	No release Paper				Labor/Tooling Savings		$ -
						Total	$ 218,250

Case 1, volume production of tooling plate, is a viable option, but the largest internal user, LM Aeronautics – Palmdale has invested heavily to enable large scale in their operation and, thus, reduce costs. Their costs are below the market's lowest values and their manufacturing facility is also configured to large scale effort. Miscellaneous programs in all of the LM business areas can use more standard products, but a ‘marketing’ and ‘business operations’ capability will have to be created to support the effort. A local government/ industry cooperative agreement might provide business and educational opportunities which would utilize these materials and this market to advance general composite capabilities. Some interaction with local community colleges has occurred, but contractual and liability considerations would need to be defined/mitigated. The value of this path is estimated to be $194k; utilizing all of the excess volume at a rate of $12.5/lb. No reduction in other wastes is being credited to this case at this time.

Case 2, developing a commercial application which can utilize most of the entire waste stream. An initial target application would be engineered, recycled wood for decking and other outdoor use. The polyethylene carrier fraction has been co-cured with composites with minimal impact on properties for room temperature applications. These low end polymer-based products usually have low stiffness and have been augmented with fillers or stiffness enhancing cross-sections to mitigate this deficiency. Adding composite prepreg would add stiffness at low loadings and the fabrication could be stratified to form cored sandwich beams with maximum stiffness at minimum composite content. Premium products or cost savings through weight reduction with equivalent performance would drive the product development. A 25% loaded product would be about ten times stiffer, a 10% loaded, stratified product might have 5+ times the stiffness of the present product. These benefits should allow a value of $1.5/lb. or more for the composite and polymer carrier waste streams. Cost savings for avoiding the disposal cost of the total prepreg waste stream would actually be greater than this assumed market value of the uncured prepreg waste stream. Together, this low effort path could achieve savings of $218k/yr.

Case 1 and 2 both require development work, Case 1 is an organizational commitment to a small business enterprise within Lockheed Martin or a local enterprise; Case 2 requires creating a partnership with a recycled wood vender. Both might be possible with the same vender maximizing the yield of the waste stream.

Case 2 also has the possibility of recycling of cured composites with the addition of an effective shredding capability. A swissRTec Delamination Mill (http://www.swissrtec.ch/html/04_03_pcb_low_mid_grade.html) advertises printed circuit board shredding with flaked composites as outputs, Figure 26. This could make the machined, trim waste stream of cured composites into a secondary source of reinforcement. Process development, including coupling agent selection, would be necessary. Comprehensive market development with a dependable, multi-source feedstock stream is expected before a commercial-scale company would invest itself.

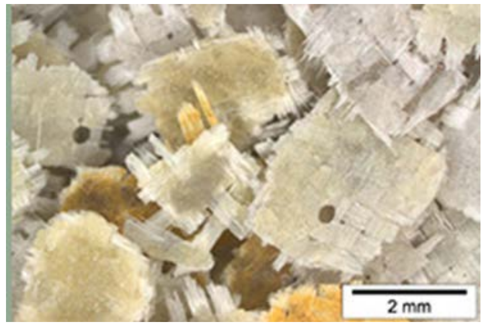


Figure 26: Delamination of cured composites into a possible feedstock for recycled, engineered wood

Note - Risk: All recycling of composite prepregs must clean the feedstock of the silicone coated paper carrier waste which will result in delaminations and serious loss of utility. Higher rate commercial paths will require these papers be removed before delivery or develop their process to remove it.

7.3 Compare to proposal estimates

The ACFJ17PV19 proposal had a range of payback periods from < 5 years as a baseline to 2 – 3 years if higher value added applications were being served. The 2017 results created a more comprehensive cost savings model and utilized the most valuable and productive waste stream feedstocks for a total savings of $108k with an EAC cost of $155K for an ~ 1.5 year payback. 2018 recycling activities should complete payback around mid-year.

Recycling covered a large array of reuse applications, many of them are/will be training support materials. This particular use is considered a ‘sustaining level of effort’ and should continue for many years. Development of another significant application, quality assurance panels is continuing and could support up to half the projected recycle volume (2500 lbs. /yr.).

The cost analysis and internal application volume point to recycling volume limits. Increasing inventory of broadgoods materials shows that increasing out-reach to potential users is needed to increase the potential for reuse and hopefully find matches to a greater fraction of the waste stream. However, at least 10 to 20% of the waste stream does not have a cost effective ‘Direct Recycling” path to reuse. In addition, the known applications volume is tending toward 20 – 30% of the waste stream; thus, we need to continue surveying all available paths to reuse to address the entire waste stream.

The estimate at completion for ACFJ17PV19 is ≤ $155k, ~$31k below the proposal estimate. The reduced expenditure parallels the increased cost savings estimates for the recycling effort. The efficiencies of non-aerospace fabrication methods allow for significant cost reductions for tasks in the 10 – 30 % range. Efficient staging of the various characterization/test cycles also reduced costs of the validation tasks. Projected costs for external testing was also reduced, as the defined test matrices defined provided the data to determine usability for recycling. Some of this cost reduction mitigated extra time spent on the analysis and documentation of recycling methodologies. Overall, the estimate was reasonable. Increased scope items which would have significant impact on P2 objectives did not meet the intent of the project and/or restrictions of the funding agency.

8.0 ACRONYMS AND DEFINITIONS

AFP#4 – Air Force Plant No. 4; Fort Worth, TX
AFLCMC – Air Force Life Cycle Management Center
AFRL – Air Force Research Laboratory
ASTM – American Society for Testing Materials; test methods
BMI – Bismaleimide resin; typically Solvay/Cytec 5250-4 material system
Broadgoods – Full width prepreg feedstocks: fabric, tapes and films
°C – Degrees Celsius

CF-Gl/Ep – Glass and Carbon Fiber/Epoxy composite system
COV – Coefficient of Variation; standard deviation expressed as percentage of value
CRAD – Commercial Research & Development
CT – Computed Tomography; 3D x-ray scan used for non-destructive evaluation
DMA – Dynamic Mechanical Analysis; Visco-elastic behavior instrument
DOD – Department of Defense
Dragonplate – On-line supplier of composites laminates and associated hardware (www.dragonplate.com)
DR – Direct Recycling; patchwork layup of waste prepreg pieces into laminates
DSC – Differential Scanning Calorimeter; reaction heat flux and specific heat instrument
Ep – Epoxy resin; typically Solvay/Cytec 977-3 material system
ESH – Environmental, Safety & Health organization, LM Aero – Fort Worth, TX
°F – Degrees Fahrenheit
Flex – Flexural Strength; 3 pt. bending loading of coupon beam
FM – 300: 3M epoxy film adhesive for bonding composite assemblies
FRP – Full Rate Production; maximum production rate of F35 at AFP#4 ~175 in 2023
Ft. – Feet; Ft2 – Square feet
Gl/ Ep – Glass/Epoxy composite system
Hextool ® - Discontinuous flake sheet molding compound sold for tooling surfaces – (chipboard)
Hillside Composites - On-line supplier of composites laminates (www.hillsidecomposites.com)
hr. – Hours
j/g – Joules per gram; energy change per gram measurement for heat capacity, reactions, changes of state
ksi – Thousand pounds per square inch; force required to fail test specimens
IM – Intermediate Modulus carbon fiber; 40+ msi stiffness
Lbs. – Pounds (weight)
Lbf – Pounds Force; loads in structure or testing

LICA38 – Kenrich Petrochemical Kenreact; Titanium IV 2,2(bis 2-propenolatomethyl)butanolato, tris(dioctyl)pyrophosphato-O in Iso-propyl Alcohol
LM – Lockheed Martin (Aeronautics - Fort Worth, TX)
M&P – Materials and Processing; manufacturing methods to produce product
McMaster-Carr - On-line/Catalog hardware and raw materials supplier (www.mcmaster.com)
msi – Million pounds per square inch (modulus); force measurement to cause strain
NZ 97 - Kenrich Petrochemical Kenreact; Zirconium IV 1,1(bis-2-propenolatomethyl)butanolato, tris(2-amino)phenylato in NMP solvent
Outtime – Specified maximum time at RT allowed for prepreg materials before cure
pli – Pounds force per linear inch; pull-off force for normal tension or peel test
psi – Pounds per square inch; force required to fail test specimens
PPT – Per Ply Thickness; cured thickness (mils) of prepreg materials
Prepreg – Reinforcement fiber/fabric impregnated with matrix resin, usually thermoset resin
QA - Quality Assurance methods; requirements
RT – Room Temperature; standard layup room conditions: ~70-75°F
SM – Standard modulus carbon fiber (30 – 33 msi)
Tee – Perpendicular structural joint configuration – Skin / web joined by shaped bonding element
Tg – Glass Transition Temperature; change from brittle solid to viscoelastic state
Tow – a bundle of filaments
WRAP – AFLCMC project: Wipe Re-Activation of Primer
3D – Three dimensional: textile weave methods for multi-axial reinforcement

9.0 APPENDICES –

A. Cost/Benefit decision – layup planning sheet; Recycle record sheet:
B. M&P Guidelines - Direct Recycling; Prepreg flow test method based on ASTM-D3531
C. Material Handling / Storage recommendations.

Appendix A: Page 1 of 2

Date:	1/5/2018	**Operator:**	DHH	**Specification**			
Disposition of Recycle Material(s)				**Material:**	M 40msi Carb	**Market:**	4_Ind Aero
Reuse 1 :	Training	**Customer:**		**Charge No.:**		**NTE value:**	
Product:							
Length:	12	**Width:**	12	**Thickness:**	0.25	**Quantity:**	24
Intermediate Panel:				**Product size effect:**	1.81	**Est. Value**	$ 50.00
Length:	50	**Width:**	50	**Thickness:**	0.25	**Quantity:**	2
Lbs. Product	47.52	Lbs. Fab.	68.75				
Commodity $/Lb.		*$ 90.33*		Market Value	*$ 174.15*	**Value Est.**	$ 132
Layup	Balanced:	Yes	Symmetric:	Yes	Plies (#, θ's)	31	0/45/90/-45
Ply #/Angle/Time Req'd		Ply #/Angle/Time Req'd		Ply #/Angle/Time Req'd		Ply #/Angle/Time Req'd	
1 | 0 |	min.	| |	min.	| |	min.	| |	min.
| |	min.	| |	min.	| |	min.	| |	min.
| |	min.	| |	min.	| |	min.	| |	min.
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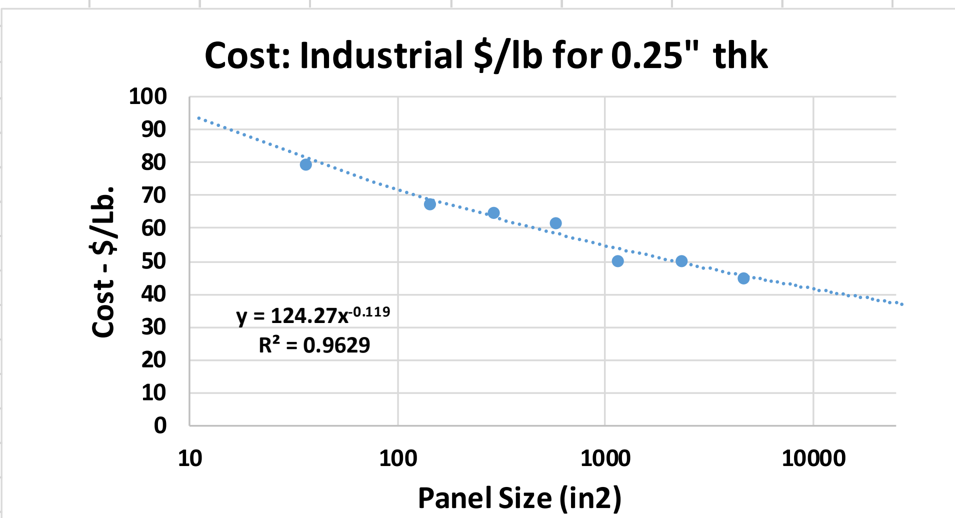
| |	min.	| |	min.	| |	min.	| |	min.
| |	min.	| |	min.	| |	min.	| |	min.
Date:		**Operator:**		**Total Layup (recycle) time:**			**Hr./Min.**
Tool:				**Surface Plies:**			
Special Bagging Req'ts:							
Cure/Schedule; Unit:							
Product:	L:	W:	H:	Qty:	Delivered:		
Repeating order:			Contact No.		**Reuse Value:**		
Comments:							

Appendix A: Page 2 of 2

Lookup tables for Recycle Run Sheet and Cost/Value estimates

E-glass	Ep 977-3	HS fabric	0.002		Partial Rol	300+ hrs	Freezer 1	Virgin	0.039675	
S-glass	BMI-5250-	PW fabric	0.003		Sheets	30+ days	Freezer 2	Good	0.055	
30 msi CF	Ep-	Bias HS	0.004		Med.-Lg.	2 mths	Cart 1	Fair	0.056	
40 msi CF	BMI-	Scrim	0.005		Misc.	4 mths	Cart 2	Poor	0.072137	
Peel Glass	Phenolic	Film Adh.	0.0083		Regular	________	________	________	________	
________	________	OML	0.01	________						
		________	________							
Training				Matl/Market	1_Comme	2_Comm I	3_Industri	4_Ind Aer	5_Aerospace	
ManTech	Yes	0/45/90/-45		1_Glass fiber	4.81	7.04	9.26	15.00	30.00	
Mfg QA	No	0/60/-60		2_GF CF Hybr	12.00	14.00	16.00	20.00	35.00	
M&P	________	0/90		3_Std Mod 33	33.30	38.40	43.50	48.00	52.50	
________		________		4_IM 40msi C	116.10	135.45	154.80	174.15	193.50	
				5_Engrd Com	140.73	164.18	187.64	211.09	234.55	



Recycle summary file - ACFJ17PV19 - P

RECYCLING OF RESIN IMPREGNATED, FIBER REINFORCED COMPOSITE PREPREGS BY THE DIRECT RECYCLING METHOD

PROJECT ACFJ17PV19 - Demonstration and Validation of Uncured, Scrap Composite (Prepreg) Reuse, F-35 Composite Manufacturing

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Approved By:
________/S/_____________
TBD

1 SCOPE
Direct Recycling is a method where uncured, waste prepreg materials are used to layup articles without intermediate processing. Some waste prepreg is still in the broadgoods form and is handled with conventional procedures. The off-cuts of pattern cutting are use in a patchwork manner fitting individual pieces to produce nearly full plies at the orientation specified. After layup, the material is processed like the original composite system, if possible; or with more severe processing if resin advancement no longer responds to the original process parameters.

1.1 PURPOSE
This specification provides guidance for recycling waste and 'expired' composite prepreg materials into value-added articles. The intent is to present methods to evaluate and process materials to reuse the maximum amount of waste and ensure the 'product' has sufficient quality to satisfy new and recurring opportunities.

1.2 INTERPRETATION
Final interpretation of this specification is left to the recycler and the reuse customer; additional local regulations and reuse application requirements may require additions/revisions. The intent is to present methods to process materials while providing flexibility so that the maximum amount of waste is recycled and the 'product' has sufficient quality to encourage recurring application use.

1.3 MATERIAL CLASSIFICATIONS
Composite prepreg waste materials are available from several sources including trim waste from cutting patterns (75%) and expired roll materials (25%) which no longer have sufficient out-time to be processed in accordance with their processing specifications. This specification deals exclusively with fully formulated resin systems; i.e. reactive with a limited storage life, whether refrigerated or at room temperature.

Category	Characteristics			
Form	Fabric	Tape	Non-woven	Other
Resin	Chemistry	Reactivity	Flow	Other
Reinforcement	Chemistry	Modulus	Strength	Physical Prop's
Dimensions	Thickness	Width	(Length)	Container
Condition	Age	Random/Orthogonal	Distortion	(Non-)Pedigreed

1.3.1 FORMS
Composite prepregs are highly controlled mixtures of reinforcing fibers and reactive resins which are categorized by the reinforcement material, textile form, dimensions of the form (width, thickness) and the formulation fraction (Fiber Areal Weight (FAW) and Resin Content (RC)). These prepregs are thin, wide broadgoods of the above constituents, received on rolls. The pattern

cutting waste stream is made up of irregular pieces. All prepregs have at least one carrier film, paper or polymer, used for handling and maintaining prepreg quality.

Tape: A large number of reinforcement tows are uniformly spaced and their filaments spread to produce a unidirectional web of known areal weight impregnated with a pre-determined fraction of resin. Typical tapes are 0.005 to 0.010 inch thick and 3” to 60” wide supported. Tows may not be fully wet-out for robust processing for all processes, which may result in porosity in over-aged material.

Fabric: Tows are woven into various patterns providing robust handling and multi-axis reinforcement, before impregnating with resin. Fabric tows are usually fully wetted during impregnation to the specified resin content. Fabrics range from 0.001" to 0.030” for aerospace materials, but may be heavier for large component fabrication.

Style: Fabrics may be labeled with the weave style; plain or harness satin typically. The style affects the mechanical performance largely dependent on tow crimp.

Non-wovens: A variety of webs produced from (dis-) continuous fibers/tows, usually with random orientation. The textile reinforcement provides handling, thickness control and specialty properties.

Other: Textile prepregs include a wide variety of specifications; this category will vary with site and platform production materials.

These prepreg materials may be restricted for public use. Any recycle use which may end up outside the production facility should be approved for general/public use.

1.3.2 RESINS

Reactive resin systems are the targeted composite systems, but the methods could be used for non-reactive (thermoplastic resins) system if those streams and their processing systems are available. Resins systems commonly recycled are epoxies, bismaleimide, phenolic, cyanate ester, polyester, etc. Resin system processing should be understood in general and its reactivity/interactions with other materials it may contact reviewed before recycling is attempted. The table below lists some of the properties to assist in matching prepreg wastes to applications.

Resin	**Characteristics**				
	Stiffness	**Strength**	**Temperature**	**Reaction**	**Thermal Expansion**
Epoxy	Med-High	High	150 – 350F	Additive	High
Bismaleimide	High	Med–High	350 - 450F	Additive	Med- High
Cyanate ester	Med-High	Med–High	500F	Additive	High
Phenolic	Med-High	Medium	350F	Condensation	Med- High
Polyester	Low - Med	Low - Med	<200F	Additive	Medium

Thermoplastics	Med-High	High	>250F	No	Med- High

Appendix B: Page 4 of 14

1.3.3 REINFORCEMENTS
Fibers are the reinforcement of the materials recycled to date. Carbon and glass fibers are the most common; aramid, nylon, polyester, ceramic and metallic fibers may also be available. Note: Mixing fibers results in the higher modulus (stiffer) fibers carrying most of the load; hybridized reuse applications require extra consideration of final capability.

Fiber	**Characteristics**				
	Modulus	**Strength**	**Temperature limit**	**Conductive**	**Thermal Expansion**
Carbon/Graphite	High (+)	High(+)	2000+F (600F; air)	Yes	Low, ~ 0 ppm/F
Glass	Medium	High	650+F	No	Low
Aramid	Med–High	High	350F	No	Low; negative
Ceramic	High (+)	Med - High	1200 – 3500F	TBD	Low
Metallic	Med–High	Low - Med	250 – 2000F (air)	Yes	Medium
Polymer	Low	Low	<350F	No	Med- High

1.3.4: DIMENSIONS AND CONDITION
Dimensions - Prepreg thicknesses and widths are required to plan reuse fabrication of waste prepreg materials. The condition of the waste stream will impact both the efficiency of fabrication and the mechanical effectiveness in the final application. Cataloging of waste feedstocks includes general dimensions for length for roll goods and piece size for pattern cut trimmings, as well container size/roll diameter. The non-prepreg data is used to estimate the product weight, gross and net, in order to manage inventory effectively.
Condition – The utility of the prepregs is affected by the age and condition of the waste stream. The remaining tack/drape is important for fabricating complex geometry with acceptable quality and rate. Prepreg quality defects; wrinkles, puckers, foreign debris, cuts, missing tows, etc. have been be used, but the highest performance requires these defects to be mitigated – laid up to produce plies with known impacts on performance.

2 APPLICABLE DOCUMENTS

The Materials and Processing (M&P), Environmental, Safety & Health (ESH) specifications and operational procedures of the production facility generating the waste provide a basis for composite recycling. The vendor literature below provides useful, minimum M&P requirements for the effort and guidelines for best performance of the materials.

a. http://www.hexcel.com/user_area/content_media/raw/Prepreg_Technology.pdf
Hexcel® prepreg/ composite brochure: Excellent overview of composite materials and their fabrication methods.
b. https://www.cytec.com/sites/default/files/datasheets/CYCOM_977_3.pdf

Appendix B: Page 5 of 14

Specific recommendations for AFP#4's 977-3 epoxy system.
c. http://www.cytec.com/sites/default/files/datasheets/CYCOM_5250-4_032012.pdf
Specific recommendations for AFP#4's 5250-4 Bismaleimide (BMI) system.
d. https://www.cmh17.org/ Composite Materials Handbook-17 (CMH-17);
e. ASTM D3531-99: Standard Test Method for Resin Flow of Carbon Fiber-Epoxy Prepreg
Appendix: Recycled prepreg evaluation: Flow test – Modified ASTM D3531 method

3 EQUIPMENT

Prepreg recycling can use existing manufacturing equipment, but additional equipment focused on high rate fabrication for lower costs and evaluating processability of out-of-date prepreg improves the out-come.

3.1 RESIN FLOW TEST
A heated and pressure controlled hot press capable of completing ASTM D3531-99 type testing allows the waste feedstock to be quickly tested for processability. A shortened method for this test is presented in 'Recycled prepreg evaluation: Flow test – Modified ASTM D3531 method' using the equipment shown in Figure 27. A Hotronix XRF-TT Table Top Air Fusion 16"x20" (Tee Shirt Press) controls temperature, time, pressure press to test a 0.1m x 0.1m test coupon. The setup pre-heated a lower platen and used a 0.1m x 0.1m Viton pad to control press area. The test schedule was set to maximum cure temperature and pressure for 5 minutes. Laminate resin loss into glass bleeders through porous Teflon cloth was measured after the sample cooled by weight to 0.01 gram for a 4 ply laminate. A simpler criteria uses the same number of similar thickness glass bleeders – if the bleeders saturate, the flow is acceptable. These quick tests complete most of the flow possible and provides direct proof of processability.

Any setup capable of repeatedly conducting the intent of ASTM D3531 is acceptable. If non-repeatable results occur, the reactivity sensitivity of the prepreg should be checked by DSC

(Differential Scanning Calorimetry) for conformance to vendor data and compatibility with the process used.

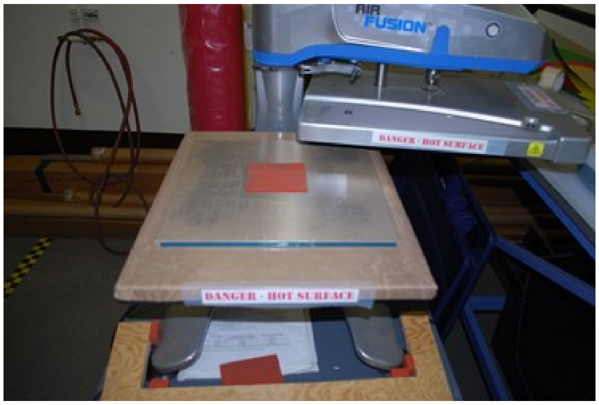

Figure 27 Modified ASTM D3531 Resin Flow test equipment used for quick evaluation of recycle prepreg processability

Appendix B: Page 6 of 14

3.2 RECYCLING - ENHANCED LAYUP RATES

Certified aerospace parts require precision cutting and placement to hold tight tolerances, recycle typically has only one-sided cosmetic requirements at acceptable knockdowns allowing high rate, relaxed tolerance methods to be used. Figure 28 shows a graphic arts cutting table with top loading rollers. The rollers handle many roll diameters and can be aligned with multiple axes. The T-square, Cutting ruler and wooden straight-edge are all low-tech, but extremely flexible and high rate for broadgoods. Their < 1/8” tolerances are sufficient for minimal gaps, but precise enough to support resin-retaining edge dams for net-resin systems. [Higher technology manual sheeting equipment is available if the volume can support capital investment.]

Figure 28 Quick set-up and manual cutting of broadgoods and large pieces allows high layup rates for recycling

3.3 HANDLING AND STORAGE

Poor handling can double or triple labor input and reduce product quality. Waste prepreg should be kept in tensile (on a roll) or laid flat in order to not introduce prepreg misalignment. To maintain initial quality, simple wind/re-wind and large sheet cutters are used to immediately re-instate 'flatness' to the prepreg for uncontrolled feedstock. Prepregs stored flat should be supported and not folded. These rolls or flat stacks then need to be stored securely or refrigerated in sealed bags. Freezer (0F) is preferred, but refrigeration at 30 – 40F is sufficient for long term storage with an estimated tack life of 2 to 4 months in a sealed bag. Frozen prepreg (nom. -10F) has been relatively unchanged for >8 years.

4 WASTE FEEDSTOCK EVALUATION AND SORTING

Waste prepreg material has to be evaluated before storage to determine the status of the resin advancement for appropriate future use.

If outtime information is available, broadgoods material can be quickly sorted into 'in-spec' and 'out-of-spec' with respect to outtime. In-spec broadgoods traceability can be maintained for certified usage and should be stored with in-spec materials. All other materials will follow the flow of Figure 29 to sort the material. When questions arise as to the processing quality of the prepreg, flow testing (Figure 30) will be used to grade the material and match to application need.

Appendix B: Page 7 of 14

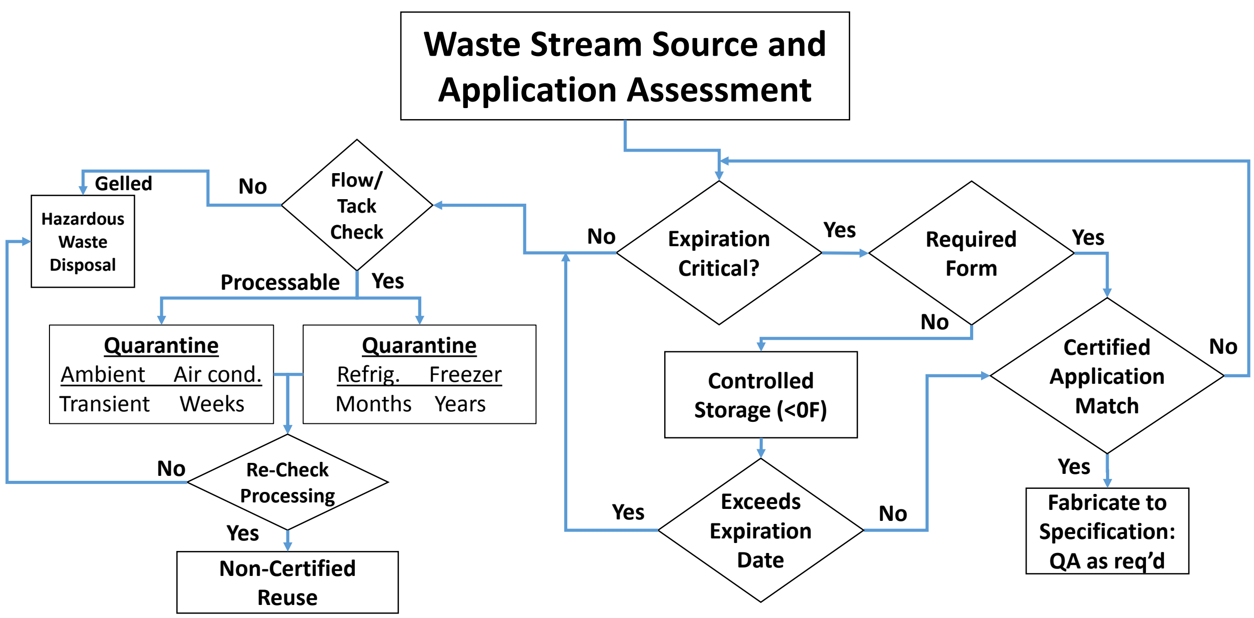

Figure 29 General flowchart for sorting waste prepreg feedstreams for applicable fabrication paths (applications)

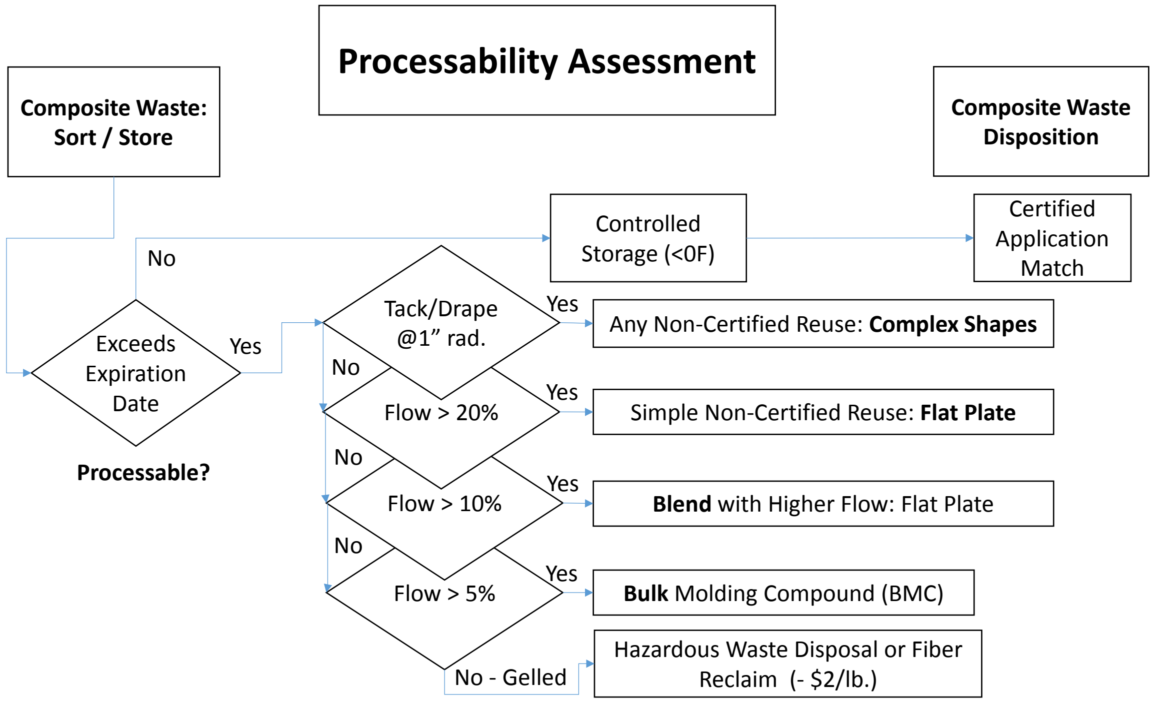

Figure 30 Processability determination flowchart for new waste prepreg materials

Appendix B: Page 8 of 14

5 PROCESSING GUIDANCE

Best practices and lessons learned for direct recycling of uncured waste prepregs:

5.1 PREPREG – Composite prepreg layup is labor intensive; it is much more difficult if the OEM prepreg quality has been degraded. The following items permit higher rates and the best quality:

- Leave the prepreg adhered to the carrier film/paper as long as possible to maintain fiber alignment
- Do not fold the prepreg materials – the extra stress disbonds the carriers allowing misorientation
- Sharp and clean cutting tools cut prepregs cleanly with minimal effort.
  - Open scissors shear through prepreg well if clean, sharp and smooth
    - Serrated blades tend to catch – reducing cut quality and tolerances
  - Knives (razor blades) also need to be sharp and clean
    - Quick change blades are recommended as they dull quickly
  - A cutting frame with a rotating blade against a hard mandrel is expected to perform well – this has not been verified (cost and safety impact)
- Cut orientation and location control speeds the layup process

  - A mechanized cutting frame with < +/- 1/16" accuracy is sufficient
  - 0; +/-45; and 90 angles are sufficient for most applications
  - Roughly layup panels might be trimmed to size after completion – ease of cutting and safety for tough, thick layup is an issue
- Prepreg tapes can have dry filaments in the tow center to provide a vent path, older prepregs may have difficulty wetting these dry filaments; fabrics are typically fully wet out and do not have this issue.

5.2 RESIN – Resin systems provide the tack for the prepreg and must flow during cure to create a high quality laminate. Aging of the resin slowly reduces both of these characteristics.

- Correct 'Tack' (stickiness) is dependent on the part being fabricated.
  - Complex parts will require heating if the tack is too low to hold plies onto the part
  - Large, flat panels layup up best with tack-free, full size plies (0/90 layups)
  - Moderate tack is good for many applications which need to be forcibly adhered to hold the patchwork build-up pattern. Too much tack prevents re-orientation when needed.
- Resin flow requirements are process dependent.
  - Vacuum bag cures need the highest flow – freshest prepregs.
  - Autoclave cures (nom. 90 psi) can cure material with 1 year exposure to room temperature.
  - Press cures, rapid heating and moderate to high pressures, can force resin flow to make parts for highly advanced material
-
- Cure quality appears to be highly dependent on the bagging process – controlled breather paths – porous peel plies appear to be most consistent in net-resin systems to provide temporary off-gassing paths and minimal resin loss

Appendix B: Page 9 of 14

5.3 FIBER – If the waste stream has different fibers, the reuse laminate may not be balanced and warp.

- While carbon and glass fibers are easily distinguished, the various property profiles of standard, intermediate and high modulus of carbon fibers cannot be determined if labels are missing.
- Similarly, differences in fiber volume fraction (resin content) will change the stiffness and thermal expansion impact of lamina causing warping.

If loss of waste stream pedigree is expected, the probability of warping can be minimized by reusing the material in thick panels which mitigate the effects of unbalanced layups.

5.4 LAYUP - Fabrication of articles for 'industrial' uses will require application of generic rules for balanced and symmetric layups to avoid warping panels. But various materials, forms and 'Condition' can be used within the same panel if the product will have positive performance margin for the application.

The reuse application usually determines the ply layup schedule. When the ply layup is undesignated, the ply stack pattern can be written to enhance fabrication efficiency or effectiveness. Maximum layup efficiency comes from a 0/90 ply stack using fabric with the minimum number of cuts if laid up full width. Effectiveness, the highest quality laminate, must minimize detrimental effects of recycling. Duplicate plies of the same orientation when making manual, patchwork layups are hard to track ply completion. In order to reduce missed or duplicate ply sections, quasi-isotropic ply stacks are preferred to more easily control the layup quality, despite the extra effort of additional angles.

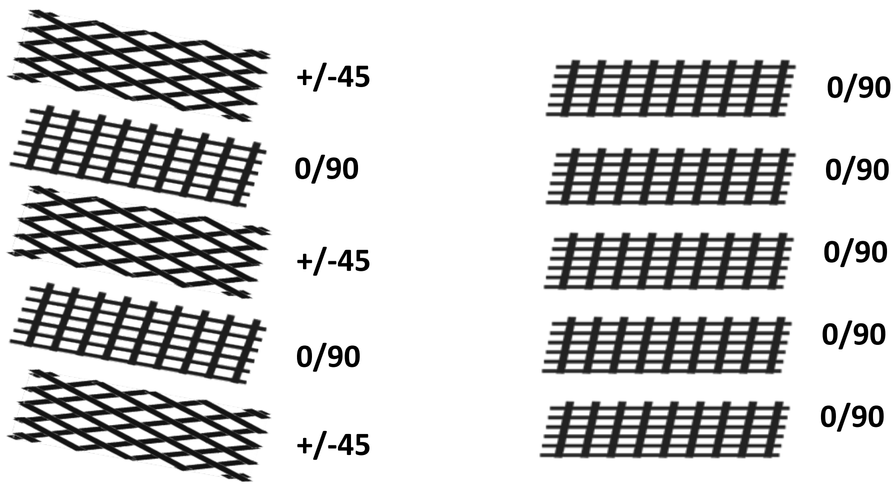

Figure 31 Recommended quasi-isotropic ply sequence for patchwork layups and straight 0/90 for high rate layups

5.5 SOURCE CHARACTERISTICS – The piece sizes of a prepreg waste stream will vary with the products being made and the processes used. A sampling of one waste stream was analyzed; the stream was 75% cut pattern trimmings and 25% broadgoods (short rolls). The trimmings were measured and their relative amounts, including carrier films/papers. A similar analysis should be done for new waste streams to determine economic feasibility and best matches to reuse applications. The average and individual number of pieces/ lb. show that Fines and Small pieces will be expensive to recycle (layup).
Appendix B: Page 10 of 14

Material	Fines < 0.1 ft2	Small <0.5 ft2	Medium 0.5 – 2 ft2	Large 2 – 10 ft2	Totals
Weight (lbs.)	3.04	4.02	7.23	17.06	**31.36**
	Fraction of total				
Paper Carrier	2.9%	2.6%	6.2%	6.2%	**17.9%**
Poly Carrier	2.9%	1.7%	3.5%	3.5%	**11.6%**
Prepreg	3.9%	8.6%	13.5%	41.4%	**67.4%**
% of Prepreg	5.8%	12.8%	20.0%	61.4%	**100.0%**
Sub-Totals	**9.7%**	**12.8%**	**23.1%**	**54.4%**	**100.0%**
Lbs/pc.	0.0032	0.0158	0.0838	0.1891	
Pcs./lb.	317	63	12	5.3	per size
Avg. Pcs./Lb.	30.8	8.1	2.8	2.9	**44.5**

Figure 32 A sample distribution of waste prepreg material sizes for cut pattern trimming; short rolls not included

5.6 MACHINING – Several options are available for machining of recycled articles:

- Waterjet – Abrasive particle waterjet cutting produces acceptable tolerances for many applications and is competitive in costs.
- 2+D Gantry Routers - Programmable machining heads for simple 2D shapes. Specialized composite tools required to minimize laminate damage if using toothed cutters.
- Table saw with grit blades – Simple rectangular shapes are produced easily on wood cutting equipment with grit blades. Diamond, medium grit (40 – 60) blades work well and can be cleaned when clogged with gummy resin systems. Handling for large panels can be difficult and table saws have extra safety issues.
    - Hand held cut off saws with straight edges have been used to cut down extra large panels too awkward to slide smoothly on standard sized tables.
- Complex machining would be expected to use facility or local vendor capabilities – standard practice.
-

Note: most qualified machining methods impart modest interlaminar forces during cutting and can provide indications of sub-standard part quality. This is a real time QA check which is very effective in manual coupon/panel fabrication applications.

6 TEST METHODS

The following tests may be used for prepreg waste stream evaluation:

- Resin Flow Test – Modified ASTM D3531: Determine ability of prepreg to consolidate
    - Modified method attached with test sample setup.

- DSC (Differential Scanning Calorimeter); ASTM – E2160: Determine extent of resin advancement

Appendix B: Page 11 of 14

- Tensile Strength – ASTM – D3039 : Verify mechanical potential
- Flexural Strength – ASTM – D7264M : Verify mechanical potential
- Short Beam Shear Strength – ASTM – D2344: Verify mechanical potential
- Resin Content, Fiber Areal Weight - ASTM D3529 - 16: Determine formulation percentages
- Ultrasonic Inspections – ASTM – E2580: Determine quality of cured panels

After initial validation work, the resin flow test is likely to be only evaluation required until a specific requirement is received which cannot be answered with the database available.

Characterization of medium sized discontinuous trim piece performance appears sufficient to set the lower bound of economically recyclable waste prepregs. Fines, small piece based products need to be characterized for the specific high volume, bulk application that they will be servicing.

7 ENVIRONMENTAL, SAFETY AND HEALTH

Materials supplied and/or parts manufactured to this specification shall comply with all site environmental, safety, and health (ESH) policies and procedures. These requirements may be obtained from a local ESH representative. The following table lists recycling hazards and personal protection equipment; procedures to mitigate hazard.

Items	Hazards	Mitigation
Resins	Reactive formulations Sensitizer	Review the MSDS (SDS) and consult with local ESH representatives for historical hazards. Process in quantities within process capability Protective gloves, etc. to minimize skin contact
Prepreg	Edges during cutting and layup are sharp. Heavy rolls.	Cut-resistant gloves and long sleeves/wrist guards to protect workers. Use lift equipment or ask for assistance.
Heat	Up to 375F (430F max.) Upper platen heated – lower platen may be pre-heated.	Use gloves; minimize material mass; use press platen swing function to remove hazard from work area.
Pressure – Resin press	2200 lbf max.; total force is adjustable through control screens	Do not swing press back until test article is positioned; do not defeat “two-hand” cycle start feature.
Sharp tools	Cutting samples with sharps – blades; scissors; templates - Sharp tools with resin contamination can stick, causing abrupt stick/slick	Cut resistant gloves, Safety training, Cutting aids – Guides with safety features - Clean and sharpen tools periodically.

	movements and increased chance of injury	
Cold storage	Frostbite: large, sub-zero masses	Protective gloves

8 NONCONFORMING MATERIAL

Prepreg determined to be non-processable will be returned to the waste stream and disposed of in an approved manner.

Appendix: Recycled prepreg evaluation: Flow test – Modified ASTM D3531 method

Resin Flow QA Press – Modified ASTM-D3531

Process sequence:

1. Pull samples; thaw to room temperature if needed (until >65F); remove (cut out) of bag.
2. Select schedule required and pre-heat press. Insert bottom, Teflon-coated press plate while pre-heating and close to heat. May take several press cycles to come to temperature.
   a. Epoxy 977-3: 300 seconds/ 75 psi / 350F program
   b. BMI 5250-4: 300 seconds/ 75 psi / 375F program
   c. Other: New programs can be added for additional chemistries; prepreg forms
      i. Note: At 100 psi air pressure, compaction force is 2200 lbs.
      ii. At 16 sq. inches; 65 psi = 90 psi compaction/flow pressure.

   Pre-heat 4" x 4" rubber (Viton or silicone) pad – this pad controls size of area tested.
3. Cut 5" x 5" samples: 4 ply $(0/90; 0/90)_s$ for testing – accuracy not required, but >4.25".
   a. Weigh 4 plies of prepreg/record (W_o).
4. Cut bleed release plies: 2 @ 5" x 5" of TX1040 permeable. 1 each – top/bottom
5. Cut bleeder plies: 4 @ 5" x 5" of 181/7781 glass or equivalent. 2 top/2 bottom
6. Cut/reuse press release plies: 2 @ 8" x 8" Teflon (heavy duty film or glass reinforced) 1 each – top/bottom
7. Stack: 6/5/4/3/4/5 /6 and center on a 4.3" x 4.3" x 0.125" thk. rubber pad (See figure)
8. Swing away hot platen (use foot petal to actuate)
9. Center rubber test stack onto pre-warmed bottom plate
10. Swing hot platen back (foot petal) to press position (keep hands clear)
11. Confirm setup conditions; press Left and Right buttons to actuate air cylinder.
12. Let press cycle run; press will open automatically when done.
13. Use foot petal to swing platen away.
14. Use gloves/ or soft tool to pull sample off press; place on heat safe, flat cooling surface; Cover with plate to cool faster.
15. When cool, remove 4/5/6 materials, measure 4 ply sample weight (grams), record (W_F).
16. Calculate resin flow: XX%
    a. $(W_o – W_F)/ W_o) \times 100\%$
    b. Example: $W_o = 3.2g$; $W_f = 2.5g$
    c. (3.2-2.5)/3.2) x 100% = 21.9% flow

Evaluation Criteria:

Resin Flow %	Low resin content (<35%)	High resin content (>35%)
0 - 5	Fair (blending recommended)*	Fail*

5 – 10	Good	Fair (blend)*
10 – 20	Excellent	Good
>20	Excellent	Excellent

*<5% flow may be usable to high pressure molding operation or when blended with high flow material

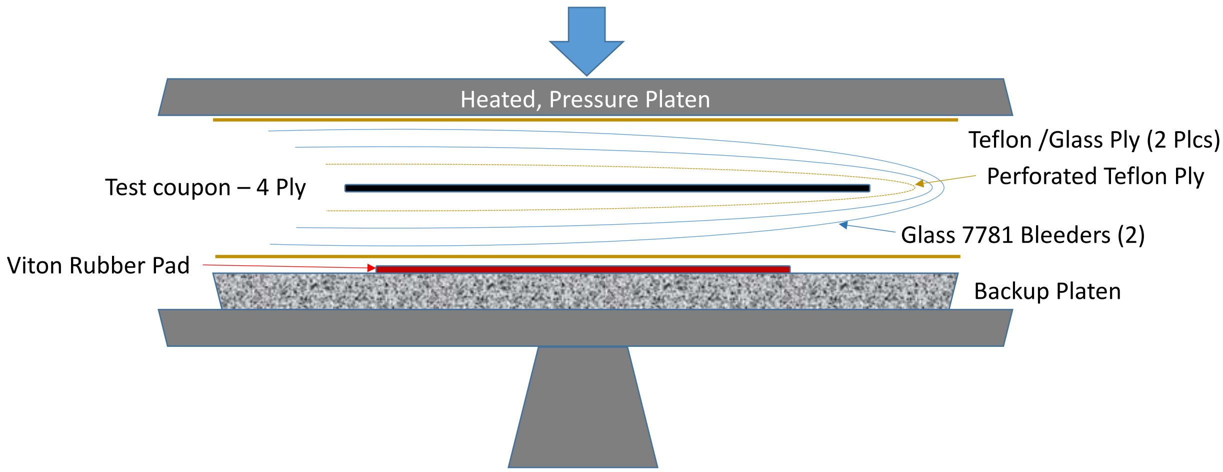

Figure 33 Resin flow test sample and press setup

Appendix C: Page 1 of 1

<u>Material Handling and Storage</u>

Uncured composite prepregs should be removed from the production area soon after they no longer meet the remaining out-time requirements of program Material & Processing specifications. The prepreg material may not have exceeded the maximum out-time, typically 720 hrs. The following procedure will properly handle these material:

Verify that the material has a product label. The label(s) should describe-

- Constituents – Manufacturer's Fiber, Resin, Grade, Form, Type, Width, Material Spec. No.
- Cumulative out-time for the material (hours) if out-time does not exceed spec. limits.

If any of these descriptive datapoints is not available, entries will be marked with a ? to indicate that the information must be verified or treated as an unknown.

Material waste from pattern cutting may not have labels. The cutting table operators may be able to provide waste material identification. Carrier release films/papers along with visual identification may provide material system identification.

Suggested labelling for recycled materials:

Recycle Lot: ______- ____________(Yr- #)

Fiber: ______ Resin:______ Form:______

Net:_____lbs. Gross_____lbs.

Date: ____/_____

Net:___lbs/ Gross___lbs/Location:______

Not for Production– Dan Hecht (x51077)