

INVESTIGATION OF VARTM RESIN FLOW THROUGH 3D NEAR NET-SHAPE AEROSPACE PREFORMS

by

François Proulx

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements for the

MASTER OF APPLIED SCIENCE

degree in Mechanical Engineering

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
University of Ottawa

© François Proulx, Ottawa, Canada, 2016

Abstract

The manufacturing of complex aerospace carbon epoxy components remains dominated by processes involving prepreg cured in autoclaves. This manufacturing route is expensive, not only because prepreg precursor materials have short shelf lives and require refrigerated storage, but also because large autoclaves carry very high operating costs and are in very intensive usage, with limited worldwide availability. Vacuum Assisted Resin Transfer Moulding (VARTM) is an interesting alternative for the manufacturing of near net-shape components as it reduces the costs related to material storage and removes the need for autoclave cure.

The production of parts with complex geometry using VARTM is highly influenced by the kinetics of resin flow into preforms upon infusion, and on optimization of the infusion system for speed, consistency and robustness. In this work, the permeability of carbon fibre textile stacks and of equivalent glass fibre stacks was probed in manufacturing replicate trials, with the aim of bettering the production process. Trials were conducted using a substitute silicon oil infused through glass fibre and carbon preforms to enable capture of the evolving flow fronts on camera. The trials covered the effects of preform geometry, port and vent location, and stitching on resin flow. Tooling necessary for conducting the trials was designed and built. The timing of operations was determined in order to optimise the manufacturing process.

Acknowledgements

I would like to thank my supervisor François Robitaille, CRIAQ, our numerous partners and the COOP and exchange students who helped in the lab; Sebastien Gangné, Khadijah Ahmad and Jaime Ocanã. Also, a special mention goes out to my coffee mates from the machine shop.

Table of Contents

List of Tables	x
List of Figures	xiii
Nomenclature	xxv
1 Introduction	1
1.1 Background	1
1.2 Objectives and Contributions	4
2 Literature Review	7
2.1 Permeability	7
2.1.1 Effects of Preform Compaction	14
2.1.2 Effects of Fibre Volume Fraction and Surface Area	19
2.1.3 Effects of Stitching	22
2.2 Effects Flow Front Velocity on Porosity	24
3 Experimental Setup and Procedures	28
3.1 Textile Reinforcements and Preforms	30

3.1.1	Stitching and Assembly Methods	34
3.1.2	Flat Plate Permeability Preforms - Series T1	38
3.1.3	Translucent Cavity Preforms - Series T2 to T5	39
3.1.4	Full Scale Demonstrator Preforms - Series T6	41
3.2	Common Equipment	44
3.2.1	Silicone Oils and Dyes	44
3.2.2	Vacuum Pump and Catch Pot System	45
3.2.3	Photographic Equipment	46
3.3	Flat Plate Permeability Rig	47
3.3.1	Experimental Setup	47
3.3.2	Procedure	51
3.3.3	Analysis	57
3.4	Translucent Cavity Rig	60
3.4.1	Experimental Setup	60
3.4.2	Procedure	62
3.4.3	Analysis	69
3.5	Full Scale Demonstrator	71
3.5.1	Experimental Setup	71
3.5.2	Procedure	76
3.5.3	Analysis	85
4	Results	87
4.1	Permeability Rig Results	87

4.1.1	Glass Preforms	88
4.1.2	Carbon Preforms	91
4.2	Translucent Cavity Rig Results	100
4.2.1	Plain Weave Glass - Lockstitch T2-G(1-6)	101
4.2.2	Mod Equivalent Quasi Lockstitch T3-MEG(1-8)	108
4.2.3	Interlocking OSS T4-S(1-3)	117
4.2.4	Tufting Through Noodle T4-T(1-3)	121
4.2.5	Carbon Quasi OSS (T5-C1)	125
4.3	Full Scale Demonstrator Rig Results	127
4.3.1	Glass Demonstrator No Stitch T6-BGF(1-2)	127
4.3.2	Glass Demonstrator OSS T6-MEG1	130
5	Conclusions	132
	Bibliography	137
	APPENDICES	144
A	Example of Appendix	145
B	Textile Data Sheets	147
C	Flat Plate Permeability Test Results	152
C.1	T1-B	152
C.1.1	T1-B1	152
C.2	T1-C	153

C.2.1	T1-C1	153
C.2.2	T1-C2	153
C.2.3	T1-C3	154
C.3	T1-EG	154
C.3.1	T1-EG1	154
C.3.2	T1-EG2	155
C.3.3	T1-EG2	155
C.4	T1-W	156
C.4.1	T1-W1	156
C.4.2	T1-W2	156
C.4.3	T1-W3	157
D	Translucent Cavity Rig Drawings	158
E	Translucent Cavity Rig Tests	169
E.1	Series T2	170
E.1.1	Test T2-G1	170
E.1.2	Test T2-G2	171
E.1.3	Test T2-G3	172
E.1.4	Test T2-G4	174
E.1.5	Test T2-G5	176
E.1.6	Test T2-G6	177
E.2	Series T3	178

E.2.1	Test T3-MEG1	178
E.2.2	Test T3-MEG2	180
E.2.3	Test T3-MEG3	182
E.2.4	Test T3-MEG4	184
E.2.5	Test T3-MEG5	186
E.2.6	Test T3-MEG6	188
E.2.7	Test T3-MEG7	190
E.2.8	Test T3-MEG8	192
E.3	Series T4	194
E.3.1	Test T4-S1	194
E.3.2	Test T4-S2	196
E.3.3	Test T4-S3	198
E.3.4	Test T4-T1	200
E.3.5	Test T4-T2	202
E.3.6	Test T4-T3	204
E.4	Series T5	206
E.4.1	Test T5-C1	206
F	Full Scale Demonstrator Cutting Patterns	208
G	Full Scale Demonstrator Rig Drawings	211
H	Needle Valve Flow Rate Tests	223

I	Full Scale Demonstrator Rig Tests	225
I.1	T6-BGF1	226
I.2	T6-BGF2	227
I.3	T6-MEG1	228

List of Tables

1.1	Aerospace Material Comparison	3
2.1	T. Drivas' v_f Compaction Test Results [27]	18
3.1	Trial Series	29
3.2	Detailed Trial Series	29
3.3	COMP-501 Definition of Laminates Considered [60]	30
3.4	Preform Construction	33
3.5	Clear Cavity Test Series Preforms	41
4.1	T1 Trial Test Parameters	88
4.2	Permeability Values for T1-EG1	89
4.3	Permeability Values for T1-EG2	89
4.4	Permeability of Equivalent Glass Preforms	89
4.5	Permeability Values for T1-BGF	90
4.6	Permeability of Plain Weave 2 Glass Preforms	91
4.7	Permeability Values for T1-B1	92
4.8	Permeability of Carbon Quasi Preforms	93

4.9	Permeability Values for T1-C1	94
4.10	Permeability Values for T1-C2	94
4.11	Permeability Values for T1-C3	94
4.12	Permeability of Stitched Carbon Quasi Preforms	95
4.13	T1-W Flow Front Radii and Inlet Pressures	96
4.14	Natural Logarithm of EIS Radius with its Respective X Axis Radius	98
4.15	Permeability Tensor Components	99
4.16	T2-G1 Detailed Report	102
4.17	T3-MEG2 Parameters	103
4.18	T2-G3 Parameters	104
4.19	T2-G4 Parameters	105
4.20	T2-G5 Parameters	106
4.21	T2-G6 Parameters	107
4.22	T3-MEG1 Parameters	109
4.23	T3-MEG2 Parameters	110
4.24	T3-MEG3 Parameters	111
4.25	T3-MEG4 Parameters	112
4.26	T3-MEG5 Parameters	113
4.27	T3-MEG6 Parameters	114
4.28	T3-MEG7 Parameters	115
4.29	T3-MEG8 Parameters	116
4.30	T4-S1 Parameters	118

4.31	T4-S2 Parameters	119
4.32	T4-S3 Parameters	120
4.33	T4-T1 Parameters	122
4.34	T4-T2 Parameters	123
4.35	T4-T3 Parameters	124
4.36	T5-C1 Parameters	125
5.1	Permeability Values for Isotropic Preforms	133
A.1	Constituent Materials and Their Properties	145
H.1	Flow Rate Test Results	224

List of Figures

2.1	Sand Column Permeability Rig [3]	9
2.2	Different Flow Regimes	11
2.3	2D Flow Patterns Quantifiable by Darcy's Law [13]	12
2.4	Flow Scenarios at Inlet [15]	14
2.5	Thickness of Preforms in Relation to Compaction Pressure [26]	16
2.6	Unit-Cell Cross-Section of 2 Layers of Woven Fabric [25]	16
2.7	Pressure as a Function of v_f in Repeated Cycles [21]	17
2.8	T. Drivas' Pressure- v_f Compaction Results [27]	18
2.9	Zones Surrounding a Stitch in NCF [43]	22
2.10	Flow Direction Parallel To OSS [50]	24
2.11	Impregnation Velocity and Void Formation [Ruiz]	25
2.12	Porosity as a Function of Modified Capillary Number [59]	26
3.1	COMP-501 laminate distribution in design envelope [60]	30
3.2	NCS 11 Ply 3D Carbon Weave (701-00037) [61]	31
3.3	Lockstitch Process [62]	34
3.4	Machine One-Sided Stitching [60]	35

3.5	Noodle or gusset filler location and AERO BIB 2005 [63]	36
3.6	Tufting through Noodle in T stringer (Graphic: Lucas West 2014)	37
3.7	OSS line Location on Permeability Preforms (mm)	38
3.8	Translucent Cavity Preform Dimensions and OSS Location (mm)	39
3.9	Translucent Cavity Preform Lockstitch Location (mm)	40
3.10	OSS Through Noodle Placement [64]	41
3.11	Final Demonstrator Dimensions (mm)	42
3.12	Final OSS Location on Stiffeners	43
3.13	Cycom 890 RTM Viscosity as a Function of Temperature Prior to Cure [65]	45
3.14	Catch Pot Assemblies with Vacuum Pump	46
3.15	Permeability rig infusion system [13]	48
3.16	Brass cross with transducers and connectors [13]	49
3.17	Aluminium Base of Permeability Rig [13]	50
3.18	Diagram of Rig and Camera Placement [13]	52
3.19	Permeability Rig, Setting the Spacers (Step 1)	52
3.20	Setting Preform in Permeability Rig (Step 2)	53
3.21	Bracing Permeability Rig (Step 3)	53
3.22	Connecting Cylinder to Instron Testing Frame (Step 5)	54
3.23	Connecting Pressure Gauges to DAQ (Step 6)	54
3.24	Opening Ball Valve (Step 9)	55
3.25	Photographic Equipment Layout (Step 11)	56
3.26	Flow Front Reaching Edge of Preform (Step 12)	56

3.27 Inlet Locations on Translucent Cavity Rig	60
3.28 Inlet Locations on Translucent Cavity Rig	61
3.29 Diagram of Translucent Cavity Rig System	63
3.30 Translucent Cavity Rig Bottom Brace and Base (Step 1)	64
3.31 Translucent Cavity Rig Cover and Mounting Frame (Step 2)	64
3.32 Translucent Cavity Rig Female Mould Section on Base (Step 3)	65
3.33 Translucent Cavity Rig Sail Seal on Female Bottom Mould (Step 4)	65
3.34 Translucent Cavity Rig Sail Section Fitted to Mould Recess (Step 5)	66
3.35 Translucent Cavity Rig Male Bottom Mould Positioned (Step 6)	66
3.36 Translucent Cavity Rig Horizontal Braces Closing Bottom Section (Step 7)	67
3.37 Translucent Cavity Rig Top O-ring Seal (Step 8)	67
3.38 Translucent Cavity Rig Preform Set with O-ring Greased (Step 9)	68
3.39 Sealed Translucent Cavity Rig with Bracing (Step 10)	68
3.40 TC - Example of Flow Progression Graphic	70
3.41 Demonstrator Rig	71
3.42 Demonstrator Rig Bracing	72
3.43 Bracing Assembly DWG, T-frame, Lifter and Braces	73
3.44 Demonstrator Rig Manifolds and Shut-Off Valves	73
3.45 Demonstrator Rig infusion diagrams, Inlets from Top of Sails	74
3.46 Full Scale Demonstrator Rig Infusion System Type #1	75
3.47 Full Scale Demonstrator Rig Infusion System Type #2	75
3.48 Stacking Skin for Full Scale Demonstrator Rig (Step 1)	76

3.49	Cutting to Length Sails for Full Scale Demonstrator (Step 2)	77
3.50	Closing Sail in Brace for Full Scale Demonstrator Rig (Step 3)	77
3.51	Preparing Noodle for Full Scale Demonstrator Rig (Step 4)	78
3.52	Mounting Sails to Full Scale Demonstrator Rig (Step 5)	78
3.53	Mounted Preform on Full Scale Demonstrator Rig (Step 6)	79
3.54	Bagging Preform on Full Scale Demonstrator Rig (Step 7)	79
3.55	Type #1 Infusion Setup (Step 8)	80
3.56	Stacking Skin for Full Scale Demonstrator Rig (Step 9)	80
3.57	Laying Full Scale Demonstrator Preform on Rig (Step 1)	81
3.58	Full Scale Demonstrator Rig Central Outlet Fold (Step 2)	81
3.59	Setting Peel-ply Fold and Central Outlet Tubing (Step 3)	82
3.60	Laying Flow Medium on Sail (Step 4)	82
3.61	Setting Brace Atop Flow Medium (Step 5)	83
3.62	Setting Final Brace of Full Scale Demonstrator Rig (Step 6)	83
3.63	Setting Infusion System for Test (Step 7)	84
3.64	Preparing Bagging Material (Step 8)	84
3.65	FSD - Example of Flow Progression Graphic	86
4.1	Stitched Equivalent Quasi Glass Preforms Inlet Pressure Profiles	88
4.2	Plain Weave 2 (BGF1800) Inlet Preform Pressure Profile	90
4.3	Carbon Baseline Preform Inlet Pressure Profile	92
4.4	Stitched Carbon Preforms Inlet Pressure Profiles	93
4.5	3D Woven Carbon Preforms Inlet Pressure Profiles	95

4.6	Flow Front Position Along Principal Axes	97
4.7	Flow Front Position Along Principle Axes	99
4.8	T2 Series Inlet and Outlet Configurations	101
4.9	T2-G1 Flow Diagram	102
4.10	T2-G2 flow diagram	103
4.11	T2-G3 Flow Diagram	104
4.12	T2-G4 Flow Diagram	105
4.13	T2-G5 Flow Diagram	106
4.14	T2-G6 Flow Diagram	107
4.15	T3 Series Inlet and Outlet Configurations	108
4.16	T3-MEG1 Flow Diagram	109
4.17	T3-MEG2 Flow Diagram	110
4.18	T3-MEG3 Flow Diagram	111
4.19	T3-MEG4 Flow Diagram	112
4.20	T3-MEG5 Flow Diagram	113
4.21	T3-MEG6 Flow Diagram	114
4.22	T3-MEG7 Flow Diagram	115
4.23	T3-MEG8 Flow Diagram	116
4.24	T4-S Series Inlet and Outlet Configurations	117
4.25	T4-S1 Flow Diagram	118
4.26	T4-S2 Flow Diagram	119
4.27	T4-S3 Flow Diagram	120

4.28	T4-T Series Inlet and Outlet Configurations	121
4.29	T4-T1 Flow Diagram	122
4.30	T4-T2 Flow Diagram	123
4.31	T4-T3 Flow Diagram	124
4.32	T5 Series Inlet and Outlet Configurations	125
4.33	T5-C1 Flow Diagram	125
4.34	T2-G1 Flow Diagram	127
4.35	T2-G1 Flow Diagram	129
4.36	T2-G1 Flow Diagram	130
C.1	T1-B1	152
C.2	T1-C1	153
C.3	T1-C2	153
C.4	T1-C3	154
C.5	T1-EG1	154
C.6	T1-EG2	155
C.7	40 sec	155
C.8	T1-W1	156
C.9	T1-W2	156
C.10	T1-W3	157
E.1	T2-G1 [03:00]	170
E.2	T2-G1 [16:00]	170
E.3	T2-G1 [20:00]	170

E.4	T2-G2 [01:00]	171
E.5	T2-G2 [02:00]	171
E.6	T2-G2 [05:00]	171
E.7	T2-G3 [00:20]	172
E.8	T2-G3 [00:40]	172
E.9	T2-G3 [01:00]	172
E.10	T2-G3 [01:20]	173
E.11	T2-G3 [01:40]	173
E.12	T2-G3 [02:00]	173
E.13	T2-G4 [00:30]	174
E.14	T2-G4 [02:00]	174
E.15	T2-G4 [03:30]	174
E.16	T2-G4 [05:00]	175
E.17	T2-G4 [06:30]	175
E.18	T2-G4 [08:00]	175
E.19	T2-G5 [00:20]	176
E.20	T2-G5 [00:45]	176
E.21	T2-G5 [01:10]	176
E.22	T2-G6 [00:05]	177
E.23	T2-G6 [00:35]	177
E.24	T2-G6 [01:15]	177
E.25	T3-MEG1 [00:05]	178

E.26 T3-MEG1 [00:15]	178
E.27 T3-MEG1 [00:30]	178
E.28 T3-MEG1 [01:20]	179
E.29 T3-MEG1 [03:20]	179
E.30 T3-MEG1 [05:20]	179
E.31 T3-MEG2 [00:05]	180
E.32 T3-MEG2 [00:15]	180
E.33 T3-MEG2 [00:30]	180
E.34 T3-MEG2 [01:00]	181
E.35 T3-MEG2 [02:00]	181
E.36 T3-MEG2 [03:00]	181
E.37 T3-MEG3 [Timestamp]	182
E.38 T3-MEG3 [00:30]	182
E.39 T3-MEG3 [02:30]	182
E.40 T3-MEG3 [03:30]	183
E.41 T3-MEG3 [04:30]	183
E.42 T3-MEG3 [05:30]	183
E.43 T3-MEG4 [00:30]	184
E.44 T3-MEG4 [01:30]	184
E.45 T3-MEG4 [02:30]	184
E.46 T3-MEG4 [04:00]	185
E.47 T3-MEG4 [07:00]	185

E.48 T3-MEG4 [10:00]	185
E.49 T3-MEG5 [00:30]	186
E.50 T3-MEG5 [01:30]	186
E.51 T3-MEG5 [02:30]	186
E.52 T3-MEG5 [03:30]	187
E.53 T3-MEG5 [04:30]	187
E.54 T3-MEG5 [05:30]	187
E.55 T3-MEG6 [00:15]	188
E.56 T3-MEG6 [00:45]	188
E.57 T3-MEG6 [01:15]	188
E.58 T3-MEG6 [01:45]	189
E.59 T3-MEG6 [02:15]	189
E.60 T3-MEG6 [02:45]	189
E.61 T3-MEG5 [00:10]	190
E.62 T3-MEG7 [00:30]	190
E.63 T3-MEG7 [00:50]	190
E.64 T3-MEG5 [01:10]	191
E.65 T3-MEG7 [01:30]	191
E.66 T3-MEG7 [01:50]	191
E.67 T3-MEG8 [00:30]	192
E.68 T3-MEG8 [01:00]	192
E.69 T3-MEG8 [01:30]	192

E.70 T3-MEG5 [02:30]	193
E.71 T3-MEG8 [03:30]	193
E.72 T3-MEG8 [04:30]	193
E.73 T4-S1 [00:45]	194
E.74 T4-S1 [02:30]	194
E.75 T4-S1 [04:15]	194
E.76 T4-S1 [06:00]	195
E.77 T4-S1 [07:45]	195
E.78 T4-S1 [09:30]	195
E.79 T4-S2 [00:30]	196
E.80 T4-S2 [01:00]	196
E.81 T4-S2 [02:00]	196
E.82 T4-S2 [03:00]	197
E.83 T4-S2 [04:00]	197
E.84 T4-S2 [05:00]	197
E.85 T4-S3 [00:30]	198
E.86 T4-S3 [01:00]	198
E.87 T4-S3 [01:30]	198
E.88 T4-S3 [02:00]	199
E.89 T4-S3 [02:30]	199
E.90 T4-S3 [3:30]	199
E.91 T4-T1 [00:30]	200

E.92 T4-T1 [01:30]	200
E.93 T4-T1 [02:30]	200
E.94 T4-T1 [04:00]	201
E.95 T4-T1 [05:30]	201
E.96 T4-T1 [07:00]	201
E.97 T4-T2 [00:30]	202
E.98 T4-T2 [01:00]	202
E.99 T4-T2 [01:30]	202
E.100T4-T2 [03:30]	203
E.101T4-T2 [05:30]	203
E.102T4-T2 [07:30]	203
E.103T4-T3 [00:30]	204
E.104T4-T3 [01:30]	204
E.105T4-T3 [02:30]	204
E.106T4-T3 [04:30]	205
E.107T4-T3 [10:30]	205
E.108T4-T3 [18:00]	205
E.109T5-C1 [00:30]	206
E.110T5-C1 [02:30]	206
E.111T5-C1 [06:00]	206
E.112T5-C1 [08:30]	207
E.113T5-C1 [12:30]	207

E.114F5-C1 [18:00]	207
H.1 Flow rate test vaccum tubing setup	223
H.2 Flow rate test graduated cylinder setup	224
I.1 T6-BGF1 Camera #1	226
I.2 T6-BGF1 Camera #2	226
I.3 T6-BGF1 Camera #3	226
I.4 T6-BGF2 Camera #2	227
I.5 T6-BGF2 Camera #2	227
I.6 T6-BGF2 Camera #1	227
I.7 T6-MEG Camera #1	228
I.8 T6-MEG Camera #1	228

Nomenclature

$[K]$ Permeability Tensor

ϵ Preform porosity

$\frac{\partial \rho}{\partial t}$ Partial derivative of fluid density with respect to elapsed time

μ Dynamic viscosity

$\nabla \cdot (\rho \vec{v})$ divergence of the fluid density multiplied to the velocity vector $\vec{v}$

$\vec{v}$ Fluid velocity vector $\vec{v}$

A Cross-sectional area

Ca Capillary number

Ca^* Modified capillary number

g Gravitation acceleration

h_n Pressure head at state n

K Permeability coefficient

k Kozeny constant

k'_{ii} Kozeny constant in transverse flow

K_x	X component of permability tensor
K_y	Y component of permability tensor
L	Length of flow column
m_1	Slope of best fit linear approximation of r_y with respect to r_x
m_2	Slope of inlet pressure with respect to $\ln(r_{ex})$
Q	Volumetric flow rate
q	Flow rate
r_{ex}	Flow front radius in equivalent isotropic system
R_f	Fibre radius
r_f	Flow front radius in isotropic case
r_x	Shorter of the two flow front radius along the principle axes
r_y	Longer of the two flow front radius along the principle axes
s	Standard deviation within data set
S_0	Specific surface
SA	Particle surface area
$SE_{\bar{K}}$	Standard Error of permeability values
V	Volume
v'_a	Fibre volume fraction where flow is cut off
V_M	Macro-void porosity
V_m	Micro-void porosity

z_n	Height of column at state n
r_0	Inlet radius
$v_{f,max}$	Maximal fibre volume fraction for a given arrangement
v_f	Fibre volume fraction
AML	Angle minus longitudinal
DAQ	Data acquisition unit
ID	Internal diameter
LCM	Liquid composite moulding
LM	Liquid moulding
NCF	Non-Crimpted Fabrics
OD	Outer diameter
OSS	One side stitching

Chapter 1

Introduction

1.1 Background

Composite materials are combinations of two or more individual constituent materials that remain identifiable after being combined, as opposed to alloys where constituents form solid solutions. In composites, constituents retain their individual mechanical and chemical properties, yet the composite material offers superior properties that derive from those of the constituent materials. In cases where a composite is made from two constituent materials, these constituents are typically labelled the reinforcement and the matrix; the latter surrounds and encases the former which provides structural load carrying capability.

The structured reinforcements studied in this thesis were made of long dry fibres of either glass or carbon assembled progressively into yarns, textile layers, and near net-shape preforms. Such preforms are typically infused with a liquid epoxy resin which cures into a solid polymer network. The reinforcement is made of high modulus and high strength materials which contribute many sought-after properties towards the final material and product, typically labelled as polymer-matrix composites (PMC).

Fibres are manufactured with the aim of minimizing their diameter, with a lower limit

of 5 to 10 μm ; fibres smaller than this range of diameters constitute a health hazard to workers as they may penetrate deeply into the respiratory tract. Smaller fibre diameters increase the surface of fibres in contact with the matrix for a given mass of fibre material, providing better transfer of loads from the matrix to the fibres. Another advantage offered by small diameter fibres is an increase in fibre flexibility, potentially reducing damage in fibres resulting from fabric handling as allowable bend radii in the elastic range become tighter. This is advantageous in terms of lay-up and draping fabric reinforcements over complex geometries and tight corners.

The matrix encases and provides support for the reinforcement towards maintaining the geometry of the part, as well as preventing buckling of fibres. Any dry fibers subjected to compressive loads would buckle; therefore, it is critical that all interstitial spacings between reinforcement fibres be properly filled with matrix to ensure proper bonding, fibre support and load transfer.

When fibre orientations are optimised, composite materials can provide superior performance to lightweight, high stiffness alloys to be used in structural members of airframes and other aerospace applications. As shown in Table 1, carbon fibre composites can offer high stiffness to weight ratios which are amongst the most sought-after material properties in aerospace applications. This advantage is very noticeable when compared with other structural materials. In addition to high specific stiffnesses, composite panels can be designed for offering known load-bearing capacity after being subjected to excessive loads or impact events. These properties derive from the interaction between the matrix and the reinforcing fibres and shall be discussed in more detail in Chapter 2.

In composite materials, extensive bonding between the matrix and reinforcement is critical to the overall structural properties of the final product. With this in mind porosity, is a foremost concern with composites that must be given thorough and careful consideration in all aspects of manufacturing. The manufacturing process selected for this research work was Vacuum Assisted Resin Transfer Moulding (VARTM), which by its very nature

Table 1.1: Aerospace Material Comparison

Aerospace material	Stiffness [GPa]	Density [g/cc]	Stiffness/Density [GPa/cc/g]
Aluminium 6061-T6 [1]	68.9	2.7	25.52
Titanium Ti-6Al-4V [2]	113.8	4.43	25.69
Unidirectional* carbon fibre composite Vf : 60% Fibre : IM7 12k, Resin : HexFlow RTM6	166.8 (on-axis)	1.52	109.73 (on axis)

*Carbon fibre composite stiffness calculation appears in Appendix A

is prone to induce porosity in composite parts. Therefore, it is imperative to design and adjust the infusion process and parameters to reduce not only the actual creation of voids upon injection, but the potential for their creation, aiming at a manufacturing operation that is robust by design. Another issue that could arise during manufacturing is the partial wetting of the reinforcement at the macroscopic scale, leaving dry spots in the final composite part. As such, the research work conducted in this thesis aimed at exploring resin flow properties within preforms, towards establishing the best possible procedures. Investigations were conducted with test rigs built in-house as described in Chapter 3, and results are presented and tabulated in Chapter 4.

A broadly used method for stiffening structural flat panels is to integrate physical stiffeners in the form of plates extending at 90° from the main panels. Such stiffeners increase the second and polar moments of inertia with little penalty in terms of added mass. With traditional materials and construction methods, these stiffeners are either bolted or welded to the main structure. Such assembly methods are problematic for composite parts as they require additional, delicate and potentially damaging drilling operations along with the use of fasteners featuring different coefficients of thermal expansion to the structure. It

is much preferable to produce composite panels with integrated stiffeners, as single items. The research work presented in this thesis aimed at investigating and understanding resin flow, in cases of increasing complexity, culminating with such panels featuring integrated stiffeners.

1.2 Objectives and Contributions

The research work presented in this thesis was conducted as part of project CRIAQ COMP-501. The industrial partners were Bombardier Inc., Bell Helicopter Textron Canada Inc., Hutchinson SA and Texonic Inc., and the Groupe CTT as contractor for textile reinforcements, stitching and assembly. Academically, the project was led by l'École de Technologie Supérieure (ÉTS) providing the manufacturing facilities and the destructive testing portions of the research, with the University of Ottawa developing manufacturing methods, the analysis of dry preform properties, evaluating preform flow properties and microscopy of produced parts. L'Université Laval was provided non-destructive testing of the completed parts from ÉTS.

COMP-501 aimed at developing manufacturing methods suitable to the production of complex 3D preforms and composite parts using liquid processes, with final properties similar to those of existing pre-preg constructs. The aerospace industry has been using such parts and as a result, they are fully certified for civilian air travel. However, manufacturing using pre-preg routes is inflexible and incurs high costs; chief among these are autoclave curing and the need to keep the pre-preg refrigerated to impede reticulation of the polymer until needed.

Other processes for the manufacturing of composites exist such as Resin Transfer Moulding (RTM) and VARTM, where in both cases dry reinforcements or preforms are infused with a liquid resin. RTM generally uses pressures higher than atmospheric for injecting the resin in a rigid mould while in VARTM, the resin is drawn in the preform resting on a

semi-rigid half mould using a negative pressure difference limited to atmospheric pressure. The VARTM process will be discussed in Chapter 2; however, it should be pointed out now that its primary advantage lies in requiring only 1 rigid half mould, as the preform is contained by flexible bagging, thus reducing costs significantly. As the demonstrator geometry had not been set at the onset of this research work, VARTM was seen as a more flexible option where the geometry of stiffeners could be modified during the course of the work.

VARTM processes generally have been associated with the production of flat plates or simple shell geometries. Therefore, patterns of flow through complex preforms to be expected upon VARTM production of 3D parts are unknown. The central aim of this thesis was to evaluate and improve manufacturing process for stiffened panels made from complex preforms assembled by stitching and tufting, with a focus on resin flow kinematics. The research was planned in 3 different experimental phases determined by individual and sequential goals. Test rigs were designed and built for each phase, and used as described below and in Chapter 3.

The first phase aimed at quantifying the permeability of textile stacks, and at determining the feasibility of replacing carbon preforms with suitable glass fibre equivalents for investigating resin flow kinematics in subsequent phases. The effects of stitching on flow fronts and on permeability were analysed. Furthermore, 3D carbon woven textiles were tested for assessing whether comparable permeability values may be obtained for these potential future replacements of current preforms made using 2D weaving techniques, for parts of complex geometry.

The second phase aimed at testing the effects of part geometry and of inlet and outlet locations on resin flow kinematics. The tests were also used for demonstrating repeatability and to probe further the effects of stitching on resin flow.

The final phase aimed at simulating the high temperature infusion of a full scale demonstrator and at troubleshooting the process developed in collaboration with industrial and academic research partners in CRIAQ COMP-501, on a corresponding metal mould. Effects of stitching the preform on infusion time were noted and compared with times obtained for non-stitched preforms.

Chapter 2

Literature Review

2.1 Permeability

Permeability is a property of porous materials defined with regards to a fluid and its ability to flow through the internal structure of the porous material under an imposed pressure gradient. This engineering property was first investigated in the middle of the 19th century, when experimentation by French engineer Henry Philibert Gaspard Darcy yielded a first analytical solution to flow through porous media. Experiments on flow through sand beds were carried out by Darcy at the end of a prolific career which started after his graduation from *l'École Nationale des Ponts et Chaussées* of Paris in 1826 [3]. Mr. Darcy was assigned to the city of Dijon to assist in test drilling in 1829 for a new well, as the city's water quality was deemed the worst in Europe. These efforts were in vain as the well only provided 500 litres per minute, and therefore could not meet the city's needs. This led him to write a comprehensive proposal which was submitted in 1834 [4] in which he detailed 4 possible methods to supply Dijon, the principal method which he championed being a 12.7 km aqueduct system linked to the Rosoir Spring. One of the alternate solutions was to use steam driven pumps to force the Saint-Michel river water through porous filter material, usually sand. After discussing with English engineers familiar with steam powered pumping

and filtration plants, it became clear that the mechanical reliability of these systems when processing large volumes made them inappropriate to dispensing drinking water to a whole town. This was due to the lack of understanding of flow through such media; a coefficient was simply added to the standard pipe flow equations used at the time. Seeing as this option was to be refused, no further investigation was done at the time but Darcy made multiple connections in England with regards to civil waterworks. The work on the aqueduct began in 1838 and was completed in 535 days, averaging a daily progression of 24 m. From 1845 to 1854, he was put in charge of a hydraulic installation in Chaillot where he started a major experimental program to improve the estimation for the Prony pipe friction coefficient. His findings were acknowledged with a formula co-named after him and Julius Weisbach, the Darcy-Weisbach pipe friction formula [5]. This research into pipe fluid friction led Darcy to the same conclusions about viscosity and velocity stated by Jean Louis Poiseuille in 1841 upon measuring friction losses in capillary tubes [6]. It would later take the research of Osborne Reynolds in 1883 to identify and quantify the differences between laminar and turbulent flow, and to relate these findings [7].

All these efforts culminated in sand column testing under imposed pressure in 1855 with the assistance of Charles Ritter; the findings would be published in *Les Fontaines Publiques de la Ville de Dijon* in 1856 [8]. This sand column was set up with a manometer at the inlet and one at the outlet, the water was fed from the top and trickled down under both gravity and the initial pressure, and the flow rate was determined at the outlet with a cubic meter basin as seen in Figure 2.1. The law derived from this experiment is expressed analytically by the following equation:

$$Q = AK \frac{(h_1 - z_1) - (h_2 - z_2)}{L} \quad (2.1)$$

With regards to modern engineering and more pointedly composites, permeability dictates the flow properties of resin through complex textile reinforcements. The hetero-

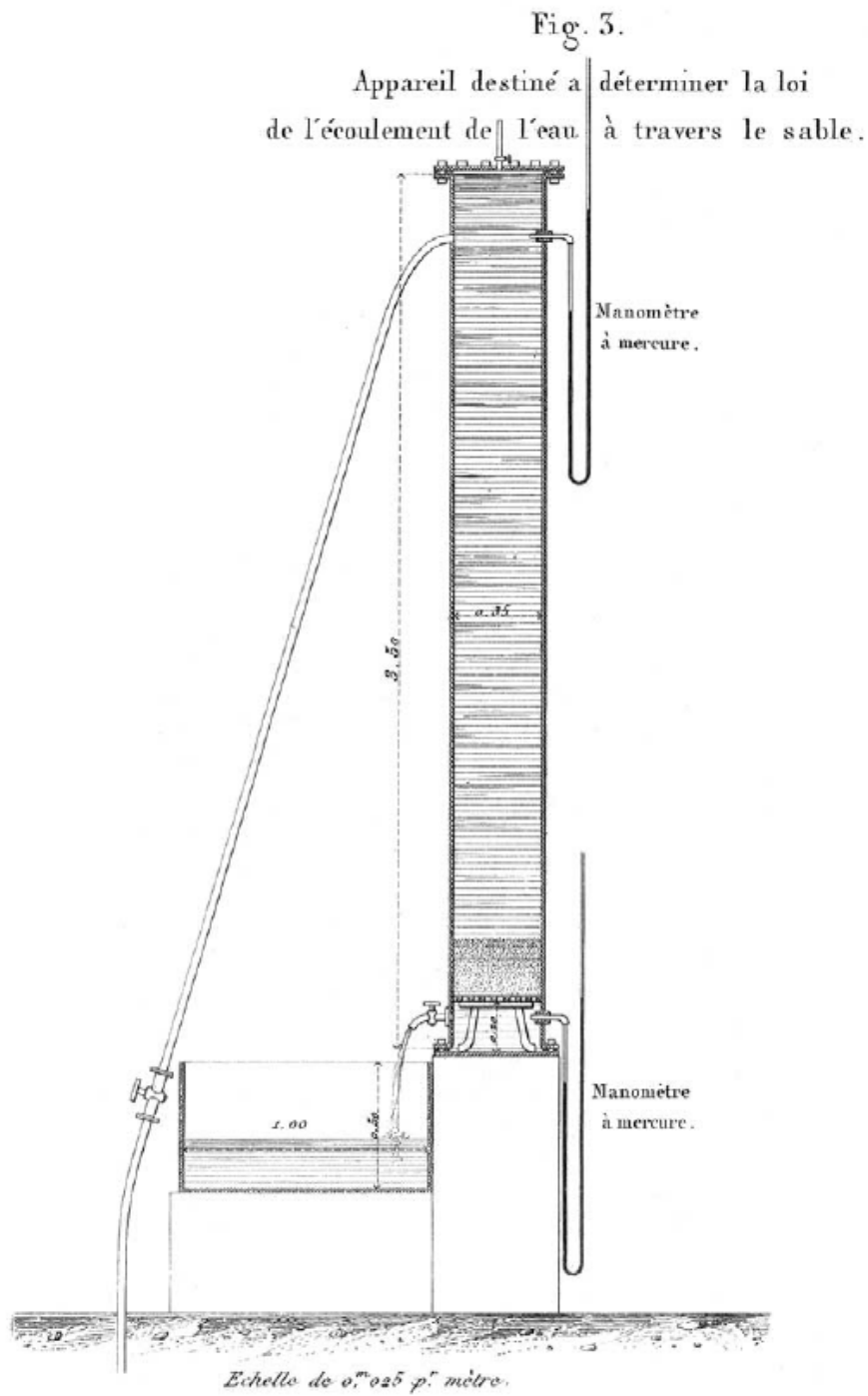


Figure 2.1: Sand Column Permeability Rig [3]

geneous nature of composites will affect the resin differently when the fibres are mostly perpendicular to the flow as compared to a situation where they are parallel. Also, in deformable woven textiles the local permeability will vary from one yarn to the next, though overall for a textile which has a repeatable pattern a macroscopic equivalent permeability value can be experimentally measured. Additional factors affecting permeability at different scales may include manufacturing induced features such as inter-yarn spacing and stitching. By imposing pressure differentials, local permeability will lead to a velocity profile at the flow front which can be defined by the following continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (2.2)$$

Experiments carried out in this thesis used silicon oil as a substitute to commercial resins. Assumed incompressibility of both fluids allow for the simplification of the continuity equation to:

$$\nabla \cdot \vec{v} = 0 \quad (2.3)$$

Darcy's law may be combined with the continuity equation and can be expressed as follows when a pressure gradient is imposed:

$$\vec{v} = \frac{-[K] \cdot \Delta P}{\mu} \quad (2.4)$$

The $\cdot$ used in equation 2.4 is the only instance of a dot product in this thesis, all other occurrences of $\cdot$ are only used for distinguishing constants and variables in a clear fashion. This form of Darcy's law has been derived theoretically assuming a fully saturated Newtonian flow through a semi-infinite, uniformly porous medium [9]. When considering permeability there are two different flow regimes by which a fluid can propagate through a medium. As seen in Figure 2.2, the first flow regime is fully saturated, whereby there

are no voids left behind the initial flow front. By contrast, an unsaturated flow regime has voids or bubbles of a different fluid such as air present behind the main flow front. Due to heterogeneties and the presence of distinct yarns in the reinforcement's constitution, in LM (liquid moulding) processes the flow tends to be unsaturated in nature. As such, permeability measurements are based on this assumption [10]. Another characteristic of unsaturated flow regimes is their variability with flow rate [11] and as such, a thorough understanding of the experimental process at hand must be had. Nevertheless, the derivation of Darcy's equation under the assumption of uniformly porous media remains applicable in most LM applications, including VARTM [12].

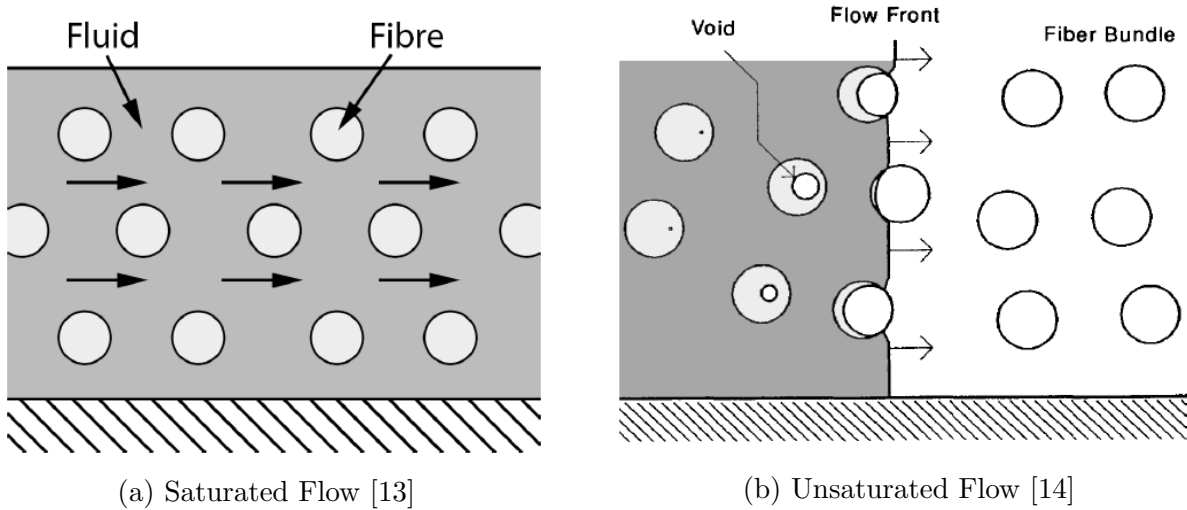


Figure 2.2: Different Flow Regimes

By defining the permeability tensor $[K]$ from Equation 2.4 for a specific material and applying Darcy's law, the relationship between the flow velocity and pressure can be determined. The experimental simulations of part production in this thesis all occurred under vacuum and therefore under a constant pressure difference nearing 1 atm, but permeability trials were done under imposed flow rates with measured inlet pressure as detailed in Section 3.1.2. In a standard RTM setting a balance must be struck between maximum pressure which leads to mould deflection, and velocity which is limited by the resin's gel time. In VARTM, however, with pressure difference being constant, the primary concern

is minimizing porosity caused by the unsaturated nature of the flow.

The RTM processes for manufacturing thin-shelled composite parts is an example of in-plane ‘pseudo’ two dimensional flow also commonly referred to as plug flow. In such cases, the uniformity of the flow front across any cross-section normal to the mould faces is assumed. In this case, the permeability tensor takes the following form, also known as the general in-plane orthotropic case: [13]

$$[K] = \begin{pmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{pmatrix} \quad (2.5)$$

The through-thickness permeability K_{zz} is generally lower than any in-plane permeability term by a measured factor of 6 to 8 times [10, 15].

When observing a flow front propagating from a center point infusion into a 2D preform the flow front can evolve following one of the scenarios outlined in Figure 2.3.

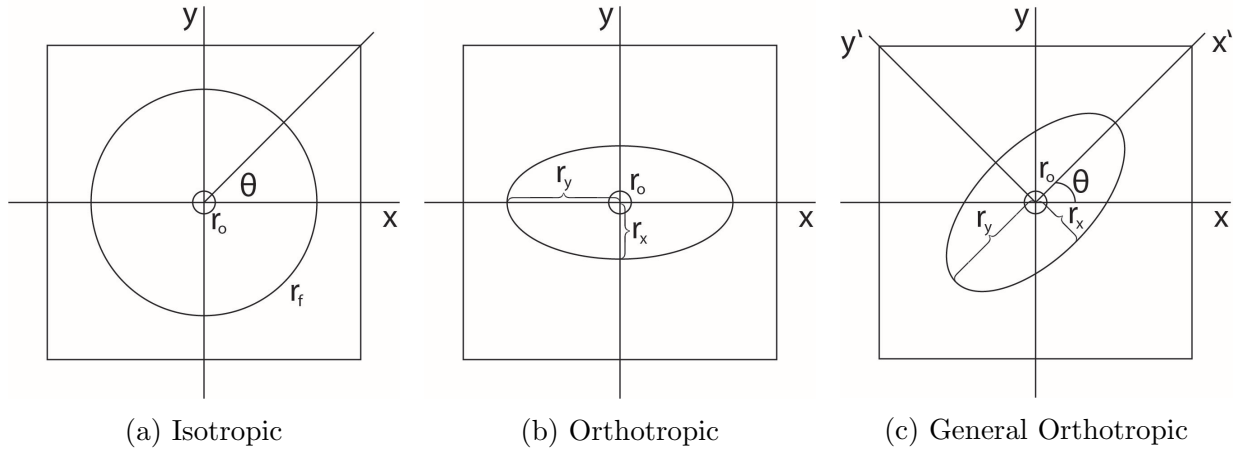


Figure 2.3: 2D Flow Patterns Quantifiable by Darcy's Law [13]

The simplest observable case is a 2D in-plane isotropic flow which arises when the flow front progression from the central inlet is independent of orientation and thus resin propagates as an expanding circle, seen in Figure 2.3a. In this instance the permeability tensor can be simplified to:

$$[K] = \begin{pmatrix} K & 0 \\ 0 & K \end{pmatrix} \quad (2.6)$$

When the flow front progression varies according to orientation, tensor theory states that it forms an ellipsis whose primary axes are orthogonal to each other, though in a testing scenario the flow front may only approximate as an ellipsis. When the primary axes of the ellipse correspond to the axes of the preform, as in Figure 2.3b, the flow pattern is termed orthotropic and is quantified by the following permeability tensor:

$$[K] = \begin{pmatrix} K_x & 0 \\ 0 & K_y \end{pmatrix} \quad (2.7)$$

When the principal axes of the flow front do not coincide with the reference axes as in Figure 2.3c, the flow pattern can be quantified with the general orthotropic permeability tensor presented in Equation 2.5. A general orthotropic case can be simplified to an orthotropic case through a coordinate change.

In all cases, the terms of the permeability tensors are constant respective to both time and position, though values in each direction will vary relative to the principal axes which correspond to the directions of largest and smallest resistance to flow. Though more accurate models could use microscopic analysis to account for the fibre bundle's geometry variation, the aforementioned Darcy's law is highly effective in modelling industrial applications [10], hence it is used for quantifying preform permeability in this thesis. Permeability values can be obtained experimentally, as seen in the work of Chan, *et al.* [16, 17] and Adams, *et al.* [18]. Methodology will be covered in the Analysis Section 3.3.3.

Certain sources of error must be taken into account to ensure the accuracy of permeability values obtained from the above method. As previously mentioned, mould deflection will be induced by fluid pressures [10]. This can be mitigated through proper mould de-

sign and bracing where necessary. This issue is mostly relevant in High Pressure Resin Transfer Moulding (HP-RTM) processes where pressures can reach 120 bar in the mould, but even Low Pressure Resin Transfer Moulding (LP-RTM) can involve pressures of up to 20 bar [19]. Without proper bracing, permeability values can have up to 50% error [10]. The second major issue which can arise when evaluating the permeability of a textile is flow-induced matcompression, which can be harder to correct. This effect is generated by the pressure of a viscous fluid causing a local compression at the inlet, where the pressure differential is highest. As seen in Figure 2.4, the flow is directed around the preform pushing it out of the way, rather than passing through it. To prevent this type of flow, the mould must be designed to apply a closing pressure within the exponential range of compaction pressure, covered in Section 2.1.1.

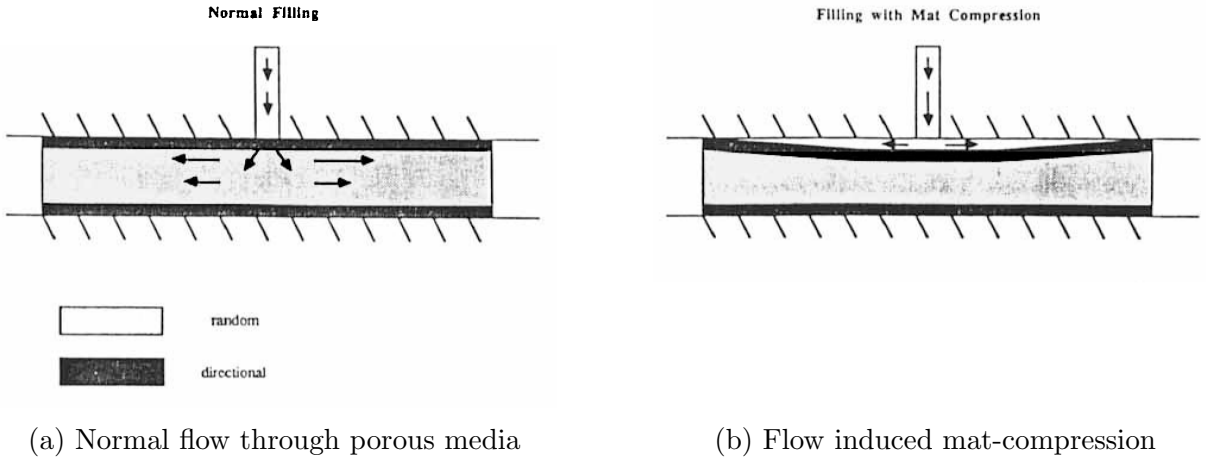


Figure 2.4: Flow Scenarios at Inlet [15]

2.1.1 Effects of Preform Compaction

In addition to preventing undesirable flow conditions in the preforms, compression is necessary to achieve the high fibre volume fractions (50%-70%) expected in aerospace composites [20, 21]. This in itself warrants compaction but in the context of this thesis, the fibre volume fraction has an effect on permeability which is covered in Section 2.1.2.

The study of the compaction behaviour of fibres dates back to the textile industry and the research of *C. M. van Wyk* published in 1946 on the pressure required to compact wool to a desired volume [22]. As such, this compaction model allowed the selection of a volumetric fibre fraction for the fibrous material. This early model only took into consideration the bending of fibres as though they were rods between points of contacts with no other fibres. This model assumed a random orientation of uniformly packed fibres without friction or slippage. From there, multiple investigations into the behaviour of fibrous materials under compaction have been published, regarding both single and multilayered fabrics [13].

Due to the variation within a single preform, mathematical models of compaction need to be supplemented by experimental data to provide an accurate representation of the effects of the compressive force exerted on the fibre reinforcement on the volumetric fibre fraction. The behaviour of a preform under compaction can be observed with a standard load cell and a platen of known surface area [23]. This recorded data can be used to present 2 main comparisons, the first being the relationship between pressure and the fibre layer thickness and the second being the pressure necessary to achieve a desired volumetric fibre fraction. In analysing this compaction behaviour for a single layer or stack, the curve displays non-linear properties which may be divided into 3 different stages, Figure 2.5. The first stage displays a linear profile where intra-yarn voids are easily reduced. The second stage shows a progressive increase in the amount of pressure necessary to achieve an equivalent displacement. This is attributed to the on-going reduction of gaps in the fabric. In the third stage, the gaps in the fabric are greatly reduced making fibre reorganisation increasingly difficult; this leads to an asymptotic behaviour towards a theoretical minimum thickness [24] beginning at point $(2h_y, p_0)$ [25].

When considering a stack as opposed to a single layer, the equipment and testing methods are identical, but due to nesting, the behaviour is similar though not as consistent as for the individual layer. Nesting occurs when yarns move horizontally to settle into a

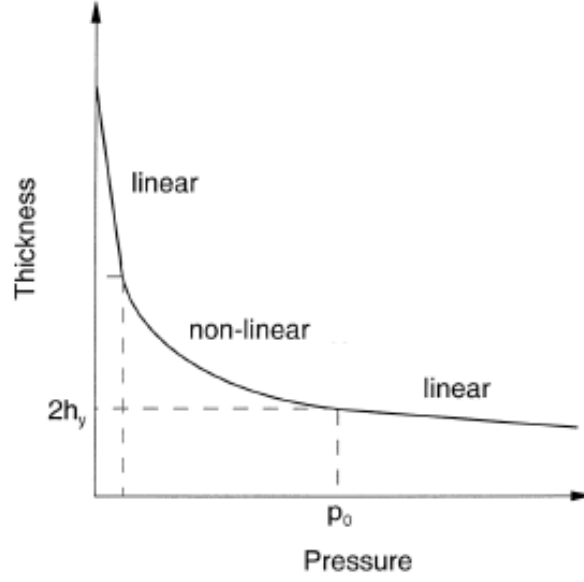


Figure 2.5: Thickness of Preforms in Relation to Compaction Pressure [26]

trough between two parallel yarns on the layer directly below, Figure 2.6.

Multiple cycles of compaction will further reduce the void content of a textile preform though each successive cycle will have a diminishing rate of return, Figure 2.7. As the number of cycles increases and the preform approaches asymptotically a theoretical maximum, a stable hysteresis loop is obtained [24].

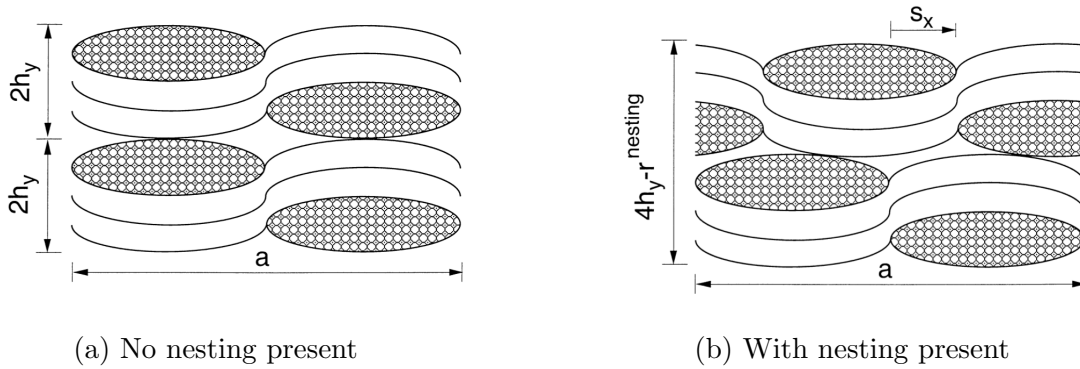


Figure 2.6: Unit-Cell Cross-Section of 2 Layers of Woven Fabric [25]

Testing performed by Thanos Drivas in the context of CRIAQ COMP-501 on the carbon fibre Quasi preforms will be used in this thesis to establish the volumetric fraction of the

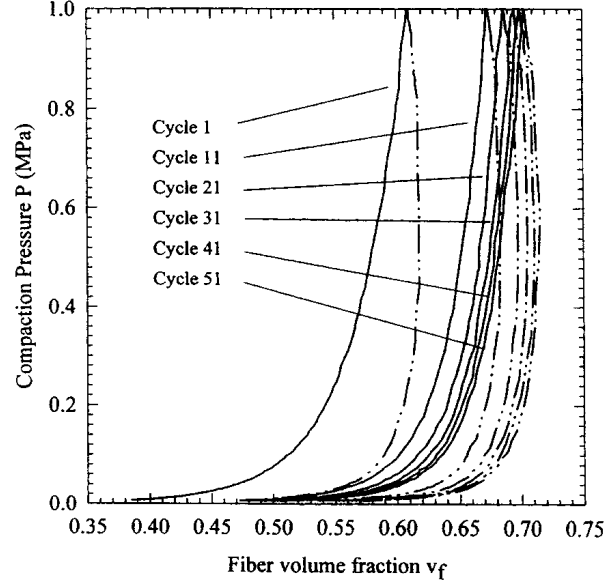


Figure 2.7: Pressure as a Function of v_f in Repeated Cycles [21]

preforms under 1 atmosphere. These results feature multiple compaction cycles. However infusion and permeability trials were all conducted without prior compaction and therefore the first cycle v_f results will be used in calculations [27]. Table 2.1 shows v_f values obtained for various preforms with differing stitch patterns; Sans-stitch was the bare preforms, Single refers to a single line of stitching while the Super designation refers to superimposed perpendicular stitching lines. Pitch is expressed in millimetres where applicable. Important to this thesis are the results of the first compaction cycle of the 4 mm Single, 8 mm Single and the Sans Stitch tests. Permeability tests were conducted on preforms with the 4 mm Single stitch line and no stitching at all, while further flow tests in rigs had 8 mm Single stitch lines. The nature of the stitching and the preforms is covered in Section 3.1. Figure 2.8 shows the final compression cycle results in the series of tests performed on the COMP-501 preforms.

Table 2.1: T. Drivas' v_f Compaction Test Results [27]

Sample	v_f at cycle [%]				
	1	2	3	4	5
4mm Super	50.73	51.83	52.08	52.39	52.64
4mm Single	52.85	53.71	54.22	54.61	54.88
8mm Single	53.11	53.99	54.53	54.9	55.22
8mm Super	51.44	52.27	52.79	53.18	53.83
Sans Stitch	55.5	56.29	56.81	57.22	57.5

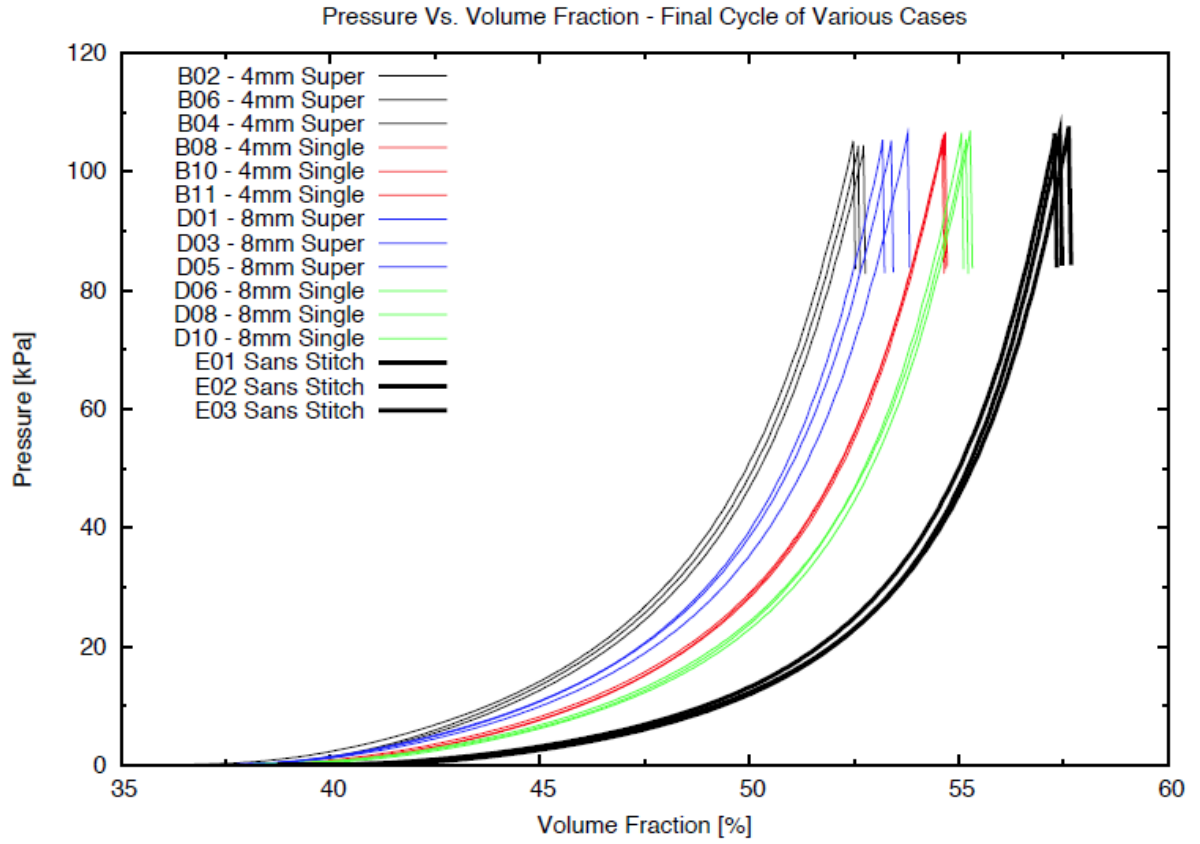


Figure 2.8: T. Drivas' Pressure- v_f Compaction Results [27]

2.1.2 Effects of Fibre Volume Fraction and Surface Area

Barring the variability incurred from mould and preform design deficiencies, taking into account the microstructure of the preform itself is vital in defining the flow field and permeability [10, 12, 28, 29]. In an ideal case where identical fibres are uniformly distributed, the surface density of the textile can be used directly to determine the fibre volume fraction v_f in the preform, although the level of variation within even a single roll of fabric can make measurements taken at an arbitrary point less than ideal when attempting to predict the permeability of a preform. Other factors such as assembly, stitching and fibre orientation will influence permeability measurements within preforms, even those made of the same textile, in 1D and 2D settings [10, 30]. Past trials also revealed that permeability is strongly impacted by fibre orientation in high v_f preforms.

Permeability prediction equations for aligned fibres are based on prior work done on packed beds of rigid particles. The model known as the Kozeny-Carman Equation 2.8, uses spherical particles of uniform diameter and defines an isotropic flow field [31].

$$K = \frac{g}{k \cdot S_0^2} \cdot \frac{\epsilon^3}{(1 - \epsilon)^2} \quad (2.8)$$

where k is the Kozeny constant of 5.0 and S_0 is the specific surface:

$$S_0 = \frac{SA}{V} \quad (2.9)$$

This packed bed spherical particles model was adapted to aligned fibre beds by Gutowski *et al.*, leading to Equation 2.10, predicting permeability in transverse flow [32, 33]. For unidirectional fibres oriented in the x-direction in this notation, $K_{yy} = K_{zz}$ [34]. While rearranging Equation 2.8 leads to an expression for flow progressing in a direction parallel to the fibres, Equation 2.11.

$$K_{ii} = \frac{R_f^2}{4 \cdot k'_{ii}} \frac{\left(\sqrt{\frac{v'_a}{v_f}} - 1\right)^3}{\left(\frac{v'_a}{v_f} - 1\right)} \quad (2.10)$$

$$K_{||} = \frac{R_f^2}{4 \cdot k_{||}} \frac{(1 - v_f)^3}{v_f^2} \quad (2.11)$$

In this notation, v'_a stands for the fibre volume fraction where the flow cuts off, approximated to 0.76. The variation observed in the trials to determine the Kozeny constants in the case of fibres, 0.7 and 0.2 for parallel flow and transverse flow respectively, was $\pm 35\%$ which has lead Skartsis *et al.* to posit that the Kozeny-Carman equation was not suitable to predicting permeability in fibre stacks [35, 36].

In response to this criticism, Gebart derived a relation between the geometric shape of the fibres and the Kozeny constant for flow parallel to the fibres, Equation 2.12. This relation holds true for Newtonian creeping flows with a very small Reynolds number [37].

$$k_{||} = \frac{c}{32} \quad (2.12)$$

The value of c is dependent on shape of the flow channels between fibres; these values are tabulated and may be used for determining an equivalent Kozeny constant. For quadratic fibre packing the equivalent Kozeny constant is 1.78 while for hexagonal fibre packing the equivalent Kozeny constants is 1.66.

The perpendicular permeability was also derived by Gebart and is expressed by Equation 2.13.

$$K_{\perp} = C_1 \left(\sqrt{\frac{v_{f,max}}{v_f}} - 1 \right)^{5/2} R_f^2 \quad (2.13)$$

where C_1 is a constant representative of the fibre packing arrangement, equal to $\frac{16}{9\pi\sqrt{2}}$ for quadratic packing and $\frac{16}{9\pi\sqrt{6}}$ for hexagonal packing. The maximum fibre volume fraction

$v_{f,max}$ is a function of the geometry of the packing arrangement of cylindrical fibres, $\frac{\pi}{4}$ for a square formation and $\frac{\sqrt{3}\cdot\pi}{6}$ for a hexagonal one [35].

The above permeability value prediction equations are only valid for a single layer of unidirectional fibres; however, composite parts are rarely constructed in such fashion. A first and simple approximation applicable to multi-layer stacks could be to use a weighted average of individual in-plane permeability values adjusted for their specific height, Equation 2.14.

$$\bar{K}_{uv} = \frac{1}{h} \sum_{j=1}^n h^{(j)} K_{uv}^{(j)} \quad (2.14)$$

This method does not take into account the transverse flow between layers, but to do so effectively the arithmetic average length of the flow front from each individual layer must be taken into account, Equation 2.15 [29, 38].

$$\bar{K}_{TF} = \frac{1}{h} \sum_{j=1}^n w_j K_j h_j \quad (2.15)$$

where

$$\bar{r}_f = \frac{1}{h} \sum_{j=1}^n \frac{r_{f,j} h_j}{N_j} \quad w_j = \frac{\bar{r}_f}{r_{f,j}}$$

For preforms made of more than two layers, a numerical solution is necessary to determine $r_{f,j}$ and $\bar{r}_f$ [39], effectively increasing the complexity of the calculations and the susceptibility of the results to larger errors when considering multi-layered industrial preforms. This is a major reason for the continued permeability testing of preforms used in composite part manufacturing. Furthermore, these predictive models do not fully encapsulate other parameters important to manufacturers, such as reproducibility and uniformity of flow fronts.

2.1.3 Effects of Stitching

Research into the effects of stitching dry stacks of reinforcements on the production of composites led to significant increases in interlaminar fracture toughness and in resistance to low speed impact damage, while also reducing free edge delamination [40, 41, 42]. Though for all these added benefits, the primary reasons to stitch a preform are to ease its handling during the manufacturing process and to reduce the variation in layer orientation caused by handling.

Stitching also comes with certain drawbacks. Research on non-crimpted fabrics (NCF) has shown that as the binding filament penetrates the fibre stack and displaces the fibres therein. These disruptions can lead to resin rich zones while a high stitch tension can compact fibres locally, whereby a 50% nominal v_f preform increases to 70% [43, 44]. Perturbations around the stitching zone have been described by Wei *et al.* as the I) undistorted zone, II) fibre distorted region, III) resin rich pocket, and IV) the through-thickness reinforcement region [43].

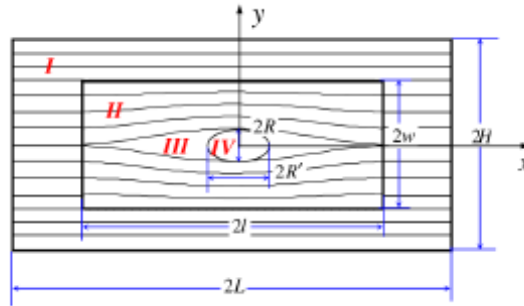


Figure 2.9: Zones Surrounding a Stitch in NCF [43]

Fibre misalignment in region II can reach up to 20% from the original axis, though typical variations between 4.0 to 5.5% are more common [43, 45]. Such deviations from the intended fibre direction can have noticeable effects on the composite's strength. Another concern with stitching is fibre damage due to the needle penetrating the stack, but such effects are generally controlled for dry preforms to less than 0.5% of fibres damaged [46].

As for effects on the flow pattern through the preform and its permeability, in NFCs a two-to three-fold increase of the in-plane permeability in the direction of the stitch line has been recorded when compared to the direction perpendicular to the stitch line, though variability remained high [29, 46]. In NCFs there is even the possibility to create channels within the preform, leading to preferential flow into the voids rather than into the fibre bundles. This effect is very much reduced in woven fabrics as there are transverse yarns preventing the complete separation of two bundles through friction. In certain cases stitching lines have created a draining effect which has improved the impregnation process [47].

Research by Chiu and Cheng determined that a line of stitching perpendicular to the flow direction acts as an obstacle while not affecting the permeability when said line was parallel to the flow direction [48, 49]. Work on the effects of One Side Stitching (OSS) on permeability conducted by Song concluded that permeability on the macroscopic scale was not affected significantly, but that permeability gradients were present within the preform in the stitching zone [50]. Regions featuring loops facilitate the flow front's advance while the perpendicular ladder seems to have permeability comparable to that of non-stitched zones, Figure 2.10.

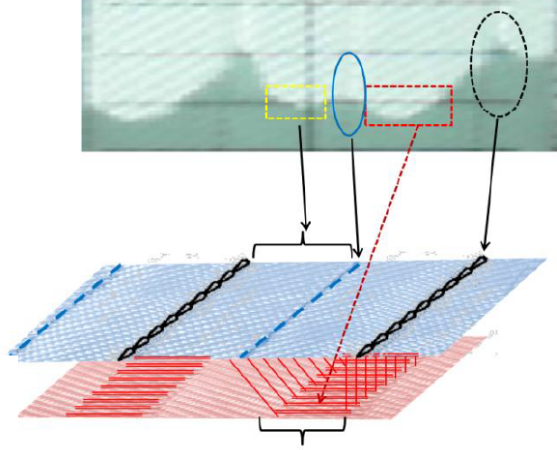


Figure 2.10: Flow Direction Parallel To OSS [50]

2.2 Effects Flow Front Velocity on Porosity

During the infusion of a preform, the flow front can be saturated or unsaturated, as mentioned in Section 2.1. This is due to the dual-scale porosity of the medium, with fibre tows defined at the macroscopic level while individual filaments within the tows themselves defined at the microscopic level [51, 52].

Research has shown that velocity impacts the formation and location of both macro and micro porosity within LCM parts [52, 53, 54, 55]. Experimental observations by Bréard *et al.* [51, 56, 57] have demonstrated how two competing forces, viscosity and capillarity, affect void formation. When viscous forces are dominant, the fluid flows preferentially between the tows leaving behind micro-porosity within the tows themselves. When, on the other hand, capillary forces are dominant, the fluid progresses more rapidly through the tows leaving behind macro-porosity in the channels between the tows. This duality is illustrated in Figure 2.11.

Experiments have demonstrated that the level of both micro and macro porosity can be plotted as a logarithmic function of flow field velocity [53, 54, 55]. In addition, the slopes of these functions indicate the existence of an optimal infusion velocity [52]. The relation

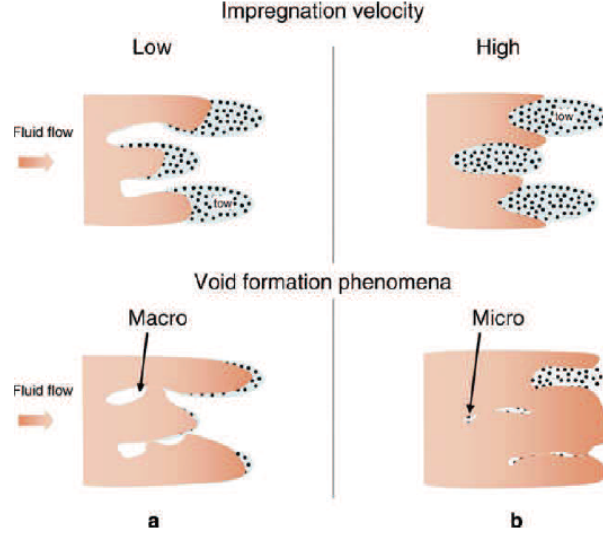


Figure 2.11: Impregnation Velocity and Void Formation [Ruiz]

of macro-voids (V_M) and micro-voids (V_m) to flow velocity is expressed by Equation 2.16 and 2.17, respectively.

$$V_M = -C_1 - C_2 \log(v) \quad (2.16)$$

$$V_m = C_3 + C_4 \log(v) \quad (2.17)$$

Flow front speed is related to the capillary force by the dimensionless capillary number, Equation 2.18 [58]. Patel and Lee modified this parameter to take into account the contact angle between liquid and fibre, Equation 2.19 [52, 55].

$$Ca = \frac{\mu v}{\gamma} \quad (2.18)$$

$$Ca^* = \frac{\mu v}{\gamma \cos(\theta)} \quad (2.19)$$

As the capillary number is a function of the flow velocity, Equations 2.16 and 2.17 can be rewritten as:

$$V_M = -C_1 - C_2 \log \left(\frac{Ca^* \gamma \cos(\theta)}{\mu} \right) \quad (2.20)$$

$$V_m = C_3 + C_4 \log \left(\frac{Ca^* \gamma \cos(\theta)}{\mu} \right) \quad (2.21)$$

This way, both the micro and macro porosity levels can be plotted as functions of the dimensionless capillary number. Such graphs demonstrate a clear optimum capillary number which reduces overall porosity in LCM parts, Figure 2.12 [59].

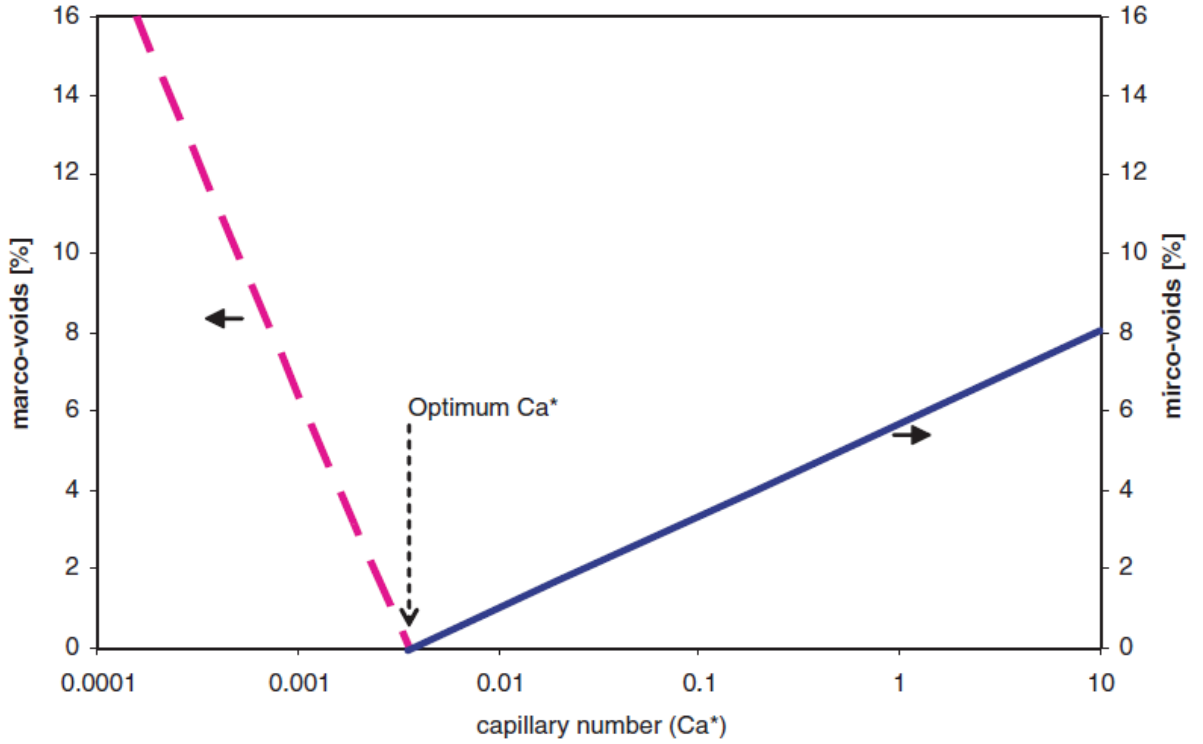


Figure 2.12: Porosity as a Function of Modified Capillary Number [59]

When testing for permeability with resin substitutes, viscosity is used in the selection of the oil but this is independant of capillary effects within the tows. As such, the information derived simply from these tests does not enable full predictive capabilities for porosity levels expected within the completed part. Other than incomplete wetting of the preform or noticeable voids it is not possible to know the porosity levels from an oil infusion alone, which is why trials with resin must be performed to determine porosity. In the context of this thesis, tests performed by partners with resin infusion informed the flow velocity requirements to reduce porosity.

Chapter 3

Experimental Setup and Procedures

In the interest of quantifying textile reinforcement permeability and resin flow through assembled preforms for stiffened panels, three flow testing rigs were used with reinforcements and preforms. Two of these rigs were designed and built by the author. This chapter opens with a presentation of the various textile reinforcements and net-shape 3D preforms tested. Then, common equipment used with all rigs such as fluids, pumps, cameras and ancillaries is detailed. Finally, the three testing rigs are described along with procedures and analysis associated with specific trials.

Rig #1 enables permeability trials to be conducted on flat stacks of reinforcements and preforms leading to a quantitative evaluation of permeability. This first rig is referred to as the permeability rig hereafter. Rig #2 was designed for viewing resin flow fronts in a smaller section (200 mm x 200 mm) of a single T-stringer and for evaluating the effects of different inlet and outlet positions. The second rig is referred to as the translucent cavity rig hereafter. Rig #3 is effectively a translucent mould which replicated the injection of full scale demonstrators (1.2 m x 0.6 m) featuring two integrated stiffeners, corresponding exactly to actual composite demonstrator parts produced by the COMP-501 research team.

This third rig is referred to as the demonstrator rig hereafter. Trials performed with all testing rigs were separated into 6 trial series labeled as T1 through T6, presented in Table 3.1.

Table 3.1: Trial Series

Trial Series	Rig	Intent
T1	Permeability	Permeability of Preforms
T2	Translucent Cavity	Testing Mould and Manifold
T3	Translucent Cavity	Effects of Inlet Locations
T4	Translucent Cavity	Effects of Preform Assembly
T5	Translucent Cavity	Validation of Demonstrator Geometry
T6	Demonstrator	Full Scale Demonstrator

Each trial series subdivides into further sub-series of tests executed on the various preforms, as detailed in Table 3.2. The sub-series are given a numerical identifier in the form T1-C# where T1 represents the primary trial series and C is the material or other defining characteristic, followed by an exclusive digit. Further information about the preforms used in the sub-series appears in Section 3.1 and the tests themselves are discussed in Sections 3.3, 3.4 and 3.5.

Table 3.2: Detailed Trial Series

Rig	Trial Series	Tests	Repeats
Permeability	T1	Baseline Carbon Quasi (T1-B#)	1
		Stitched Carbon Quasi 4mm pitch (T1-C#)	3
		Stitched Equivalent Quasi 4mm pitch (T1-EG#)	2
		3D Woven Carbon (T1-W#)	3
Translucent Cavity	T2	Plain Weave Glass - Lockstitch (T2-G#)	6
	T3	Mod Equivalent Quasi - Lockstitch (T3-MEG#)	8
	T4	Interlocking – OSS (T4-S#)	3
		Tufting Through Noodle (T4-T#)	3
	T5	Carbon Quasi OSS 4mm Pitch (T5-C#)	1
Demonstrator	T6	Glass Demonstrator No Stitch (T6-BGF#)	2
		Glass Demonstrator OSS (T6-MEG#)	1
Total			33

3.1 Textile Reinforcements and Preforms

Preform stacking sequences were defined by the COMP-501 industrial partners to meet stiffness requirements along the 0° axis as shown in Figure 3.1. Three types of stacking sequences were identified, Table 3.3. All stacking sequences featured $0/90^\circ$ and $\pm 45^\circ$ plies of twill fabric. Once flat plate sample tests were conducted by *C. Leduc* [60] early on in the COMP-501 project, the need to focus on a single stacking sequence was recognised. Selecting 1 type of preform and stacking sequence negated the need for generating multiple baselines for analysis. The Quasi stacking sequence was selected as the more isotropic preform with regards to the effects of stacking sequence on flow, as well as for its midrange material properties in the final composite part.

Table 3.3: COMP-501 Definition of Laminates Considered [60]

Laminate	Stacking sequence	AML
Soft	$[((\pm 45)_2/(0 - 90)/(\pm 45)_2)_2]_S$	70
Quasi	$[((\pm 45)/(0 - 90))_5]_S$	25
Hard	$[((0 - 90)_2/(\pm 45)/(0 - 90)_2)_2]_S$	-20

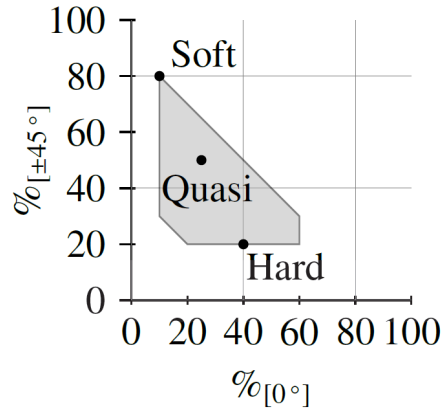


Figure 3.1: COMP-501 laminate distribution in design envelope [60]

Preforms were to be stitched and/or tufted; both techniques were considered for potentially increasing resistance during tear-out tests on composite parts where stiffeners are concerned, and for easing the handling of dry preforms. Another textile was proposed by CTT group in the form of a 3D woven reinforcement produced as a single part that would match the x and y yarn densities of the Quasi preforms, Figure 3.2.

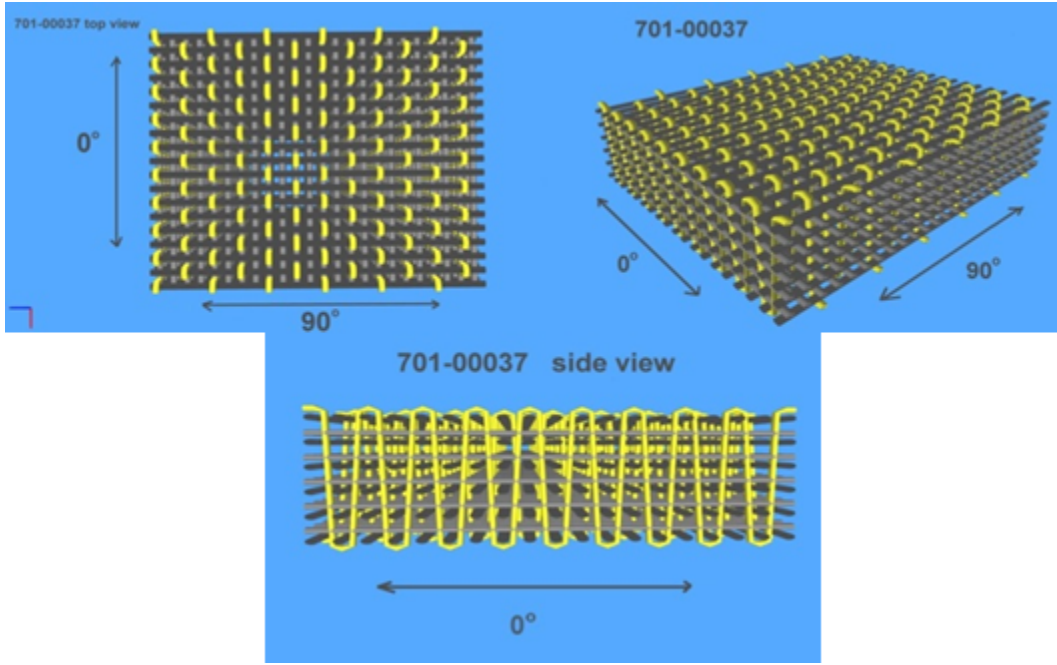


Figure 3.2: NCS 11 Ply 3D Carbon Weave (701-00037) [61]

As stitching or any form of through-thickness reinforcement would be mostly perpendicular to the flow front, it was deemed important to quantify the effects that such structures may have on overall infusion patterns. Therefore, in addition to quantifying the permeability of the textiles used in their actual stacking sequences, one aim of this thesis work was to evaluate the effects of through-thickness reinforcements on the flow properties in the context of the COMP-501 project.

Preforms of various types were manufactured from fabrics provided by Texonic for developing demonstrators. The primary carbon fabric used in this work was TC-06-T, a 2x2 twill woven made of Toho Tenax HTS40 E13 3K 200 tex yarns with total surface

density of 205 g/m² (6.0 oz/yd²). In Table 3.2, test sub-series labelled C feature this fabric in a Quasi stack.

To help visualising flow in the rigs and to reduce cost, glass fabrics were used in performing many injections reported in this thesis. In replacing carbon with glass, the architecture and fibre volume fraction were maintained as these are the principal parameters controlling impediment to resin flow in a VARTM infusion. Since volume is the important parameter, once weave pattern and yarn sizes are matched as closely as possible, neither the density of the fibre material, nor the surface density of the fabric should affect the flow and observations.

The main glass fabric used as replacement to its equivalent carbon counterpart was Texonic TG-09-T, a 2x2 twill woven made of AGY E-glass 245 tex yarns with total surface density of 315 g/m²(9.3 oz/yd²). Secondary glass fibre fabric BGF 1800 purchased through Composites Canada and used for producing the larger demonstrator preforms, was a plain weave of ECK 18 1/0 yarns with total surface density of 326 g/m²(9.6 oz/yd²). Trials conducted with this material are labeled BGF. Material properties for all textile reinforcements as supplied by the manufacturers appear in Appendix B. In addition to these materials, some readily available glass plain weave and randomly orientated mat were used for testing the equipment upon commissioning. The plain woven material had a surface density of 363 g/m²(10.7 oz/yd²), labeled simply G (Glass), while the randomly orientated mat had a surface density of 475 g/m² (14oz/yd²).

Out of the various preform stacking sequences architectures considered in project COMP-501, the Quasi sequence and 3D woven fabrics were selected for testing and proving the concept in this thesis. As availability allowed, testing was performed on carbon Quasi and glass Equivalent Quasi stacks, but when transferring to glass preforms, it was noticed that the weave pattern did not compress to the desired thicknesses within the tooling. As such a glass Modified Equivalent Quasi preform stacking sequence was developed to solve this issue, with the removal of the top and bottom 45° layers. When stacked according to

the Quasi sequence, the tests were labeled EG (Equivalent Glass), and when the modified Quasi sequence was used the tests were labeled MEG (Modified Equivalent Glass).

Another important design criterion that evolved over the course of this thesis was the final desired plate thickness. The aim was to recreate current industrial parts towards providing viable comparisons, and as such the goal was set for a 4.2 mm plate thickness. Through VARTM infusions performed by the research team, it was discovered that the final thickness of plates could not be reduced beyond 4.3 mm. Volumetric fraction of fibres in preforms is affected by thickness and therefore, v_f is reported for both 4.2 and 4.3 mm thicknesses in Table 3.4. In the case of the randomly oriented mats, reported v_f is at 3 mm as these preforms were used in preparatory tests on the permeability rig; thickness was controlled through the use of shims. These very early tests were performed before the establishment of 4.2 mm as the initial target thickness.

Table 3.4: Preform Construction

Preform Type	Fabric	Stacking Sequence	Nominal v_f % @ 4.2 mm	Nominal v_f % @ 4.3 mm
Random Mat 1	Uniflo (Glass)	4 ply	24.4 (v_f % @ 3 mm)	
Random Mat 2	Uniflo (Glass)	6 ply	36.5 (v_f % @ 3mm)	
Plain Weave 1	Available (Glass)	$[(0/90)_8]_S$	53.2	51.9
Plain Weave 2 - Mod. Equivalent Quasi	BGF 1800 (Glass)	$[(0/90)/((\pm 45)/(0/90))_4]_S$	47.6	46.5
Quasi	TC-06-T (Carbon)	$[((\pm 45)/(0/90))_5]_S$	55.2	53.9
Equivalent Quasi	TG-09-T (Glass)	$[((\pm 45)/(0/90))_5]_S$	57.7	56.4
Modified Equivalent Quasi	TG-09-T (Glass)	$[(0/90)/((\pm 45)/(0/90))_4]_S$	51.9	50.7
Carbon 3D Weave	3K yarn	45% X, 45% Y, 10% Z	55	54

3.1.1 Stitching and Assembly Methods

The effects on resin flow of two methods for the physical assembly of preforms, namely stitching and tufting, were evaluated. In this work, preforms assembled in-house using lockstitch and preforms assembled at CTT using One-Sided Stitching (OSS) were tested.

To ease the production of samples and help handling, traditional lockstitch assembly was used for binding the translucent cavity preforms (Trial series T2 and T3) using a Kevlar thread (Protek 100% Kevlar 30/2 lb 35 tex) with an average pitch of 5 mm. Figure 3.3 displays the working of a lockstitch sewing head and the lockstitch pattern it creates; to prevent unraveling, knots must be tied at either end of the stitch line. Two parallel stitch lines were sewn 12.5 mm (0.5 in) apart in an attempt to mimic the OSS produced by CTT.

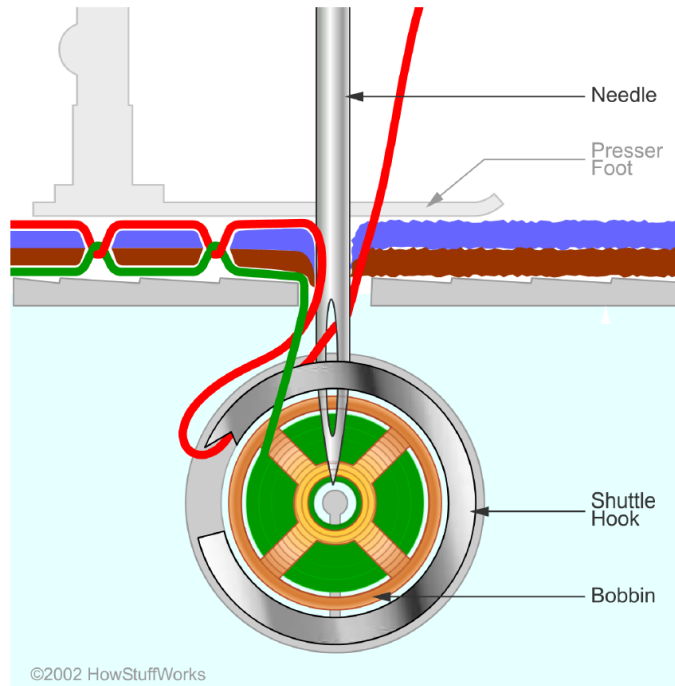


Figure 3.3: Lockstitch Process [62]

As mentioned above the CTT provided preforms assembled using OSS, a technique developed by Keilmann Sondermaschinenbau GmbH (Lorsch, Germany) which uses of a single multi-axis robotic stitching head and removes the need for the underside mechanism

usually associated with stitching machines. Figure 3.4(a) shows the thread pattern as seen from the stitching head side; the preform is not shown for clarity. Figure 3.4(b) illustrates the needle arrangement. In all preforms provided by the CTT the catcher needle was oriented at 45° from the vertical and the stitching line was 25 mm (1 in) wide. In permeability trials (T1) the pitch was 4 mm while on all remaining OSS preforms it was 8 mm. The thread used for all OSS was 67 x 2 tex (linear mass of 0.14 g/m) TENAX® carbon fiber yarn.

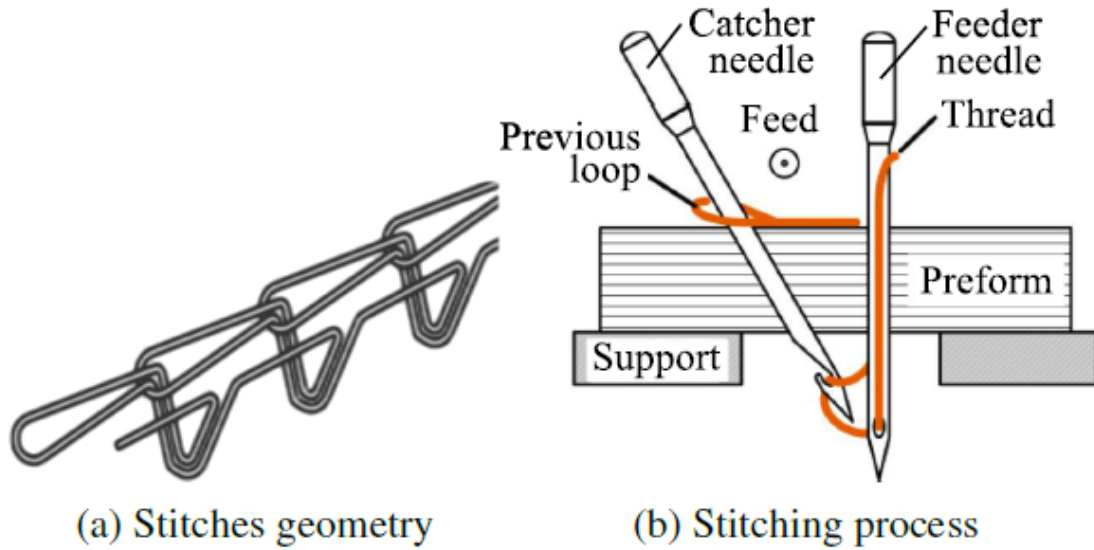


Figure 3.4: Machine One-Sided Stitching [60]

During the construction of preforms including stiffeners, certain stacks are bent to form a new plane perpendicular to the first. In doing so, the stack will bend to a radius and thus leave a zone devoid of reinforcements at the intersection. Such zones must be filled with reinforcement fibres to prevent a dramatic reduction in v_f of the stacks themselves through their inevitable sagging into the void, and also to prevent the formation of a large resin rich section in the preform. Fibers used for filling such zones are called noodles. Three different types of fibre assemblies were used as noodles in this thesis. Noodle type

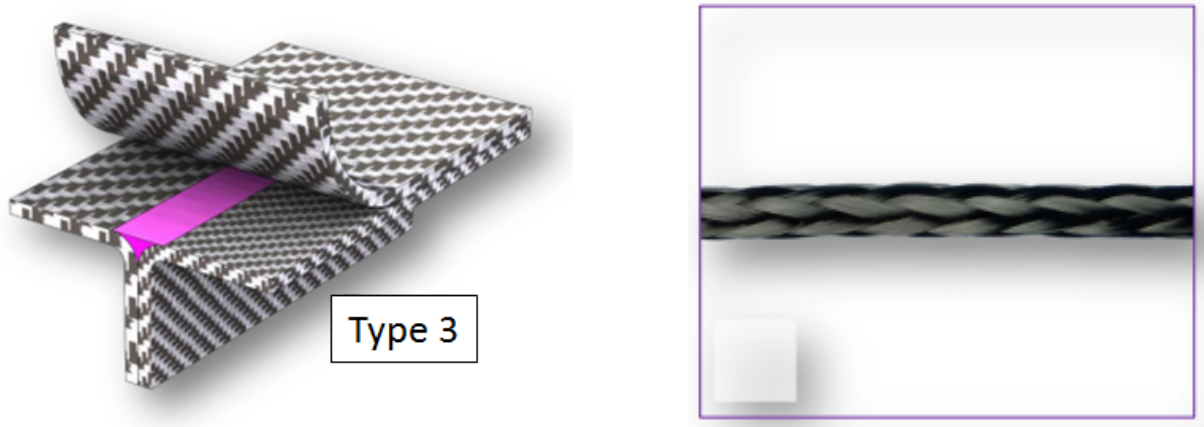


Figure 3.5: Noodle or gusset filler location and AERO BIB 2005 [63]

#1 featured 6 strands of E-glass yarn, each with a linear density of 4.5 g/m twisted 1 full rotation over the length of the preform, providing a nominal v_f of 61%. Noodle type #2 featured 22 strands of Tenax-J HTS40 E13 12k 800 tex carbon yarn twisted 1 full rotation over the length of the preform, providing a v_f of 55%. Noodle type #3 was the AERO BIB 2005 ± 45 braided Tenax-J HTA40 E13 carbon strand purchased from Eurocarbon B.V. providing a v_f of 53%, Figure 3.5.

Tufting through the noodle was considered as a method to increase the volumetric fraction of fibres running in the z direction, in this case, the plane of the sail with respect to the skin. This was also thought to potentially reduce delamination. The tufting process consists of inserting a hooked needle which, when pulling out of a textile stack, leaves a loop of material embedded in it. Tufting relies on friction to maintain the loops in position as there is no attaching thread on either side. Tufting patterns considered initially in COMP-501 are detailed in Figure 3.6; in the end only the alternating double line tufting pattern, on the right, was tested. The thread used for these trials was identical to the thread used in OSS.

3.1.2 Flat Plate Permeability Preforms - Series T1

The flat plate permeability rig requires square preforms measuring 300 mm (12 in) in length and width. The rig was tested initially using stacks of Random Mat 1 and 2 at a thickness of 3 mm. Once calibration procedures were completed, testing was conducted on CTT preforms. Cavity thickness was adjusted to 4.2 mm through the use of shims for tests conducted on Quasi, Equivalent Quasi and 3D Weave preforms. The stitched preforms featured a single centrally located OSS line with a 4 mm needle pitch and a standard 25 mm width as seen in Figure 3.7.

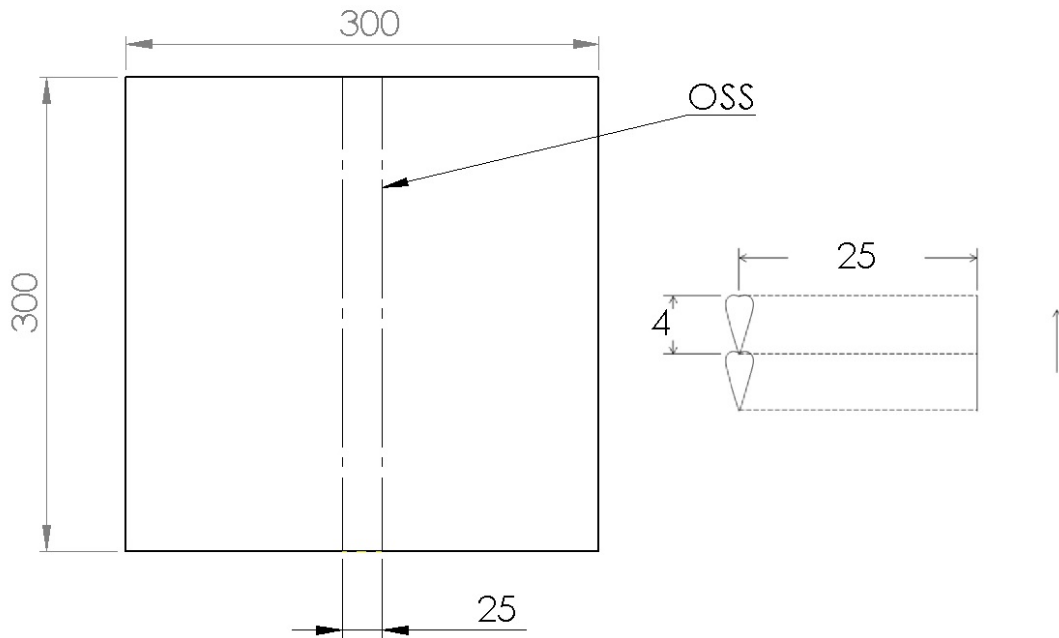


Figure 3.7: OSS line Location on Permeability Preforms (mm)

3.1.3 Translucent Cavity Preforms - Series T2 to T5

Preforms for these test series had the same final dimensions dictated by the rigid nature of the Translucent Cavity, although their construction and assembly differed. The preforms consisted of a skin and a perpendicular sail, Figure 3.8. The skin of the stiffened panel was a square with sides measuring 203.2 mm (8 in) and 4.2 mm in thickness. The sail material was split down its centerline and bent to form the foot which was in contact with the skin. The foot extended by 50.8 mm (2 in) either side of the sail centerline, while the sail extended by 46.6 mm from the skin's contact surface to the tip. The inner radii formed by this bend measured 4.2 mm, equal to the initial target thickness of a Quasi preform.

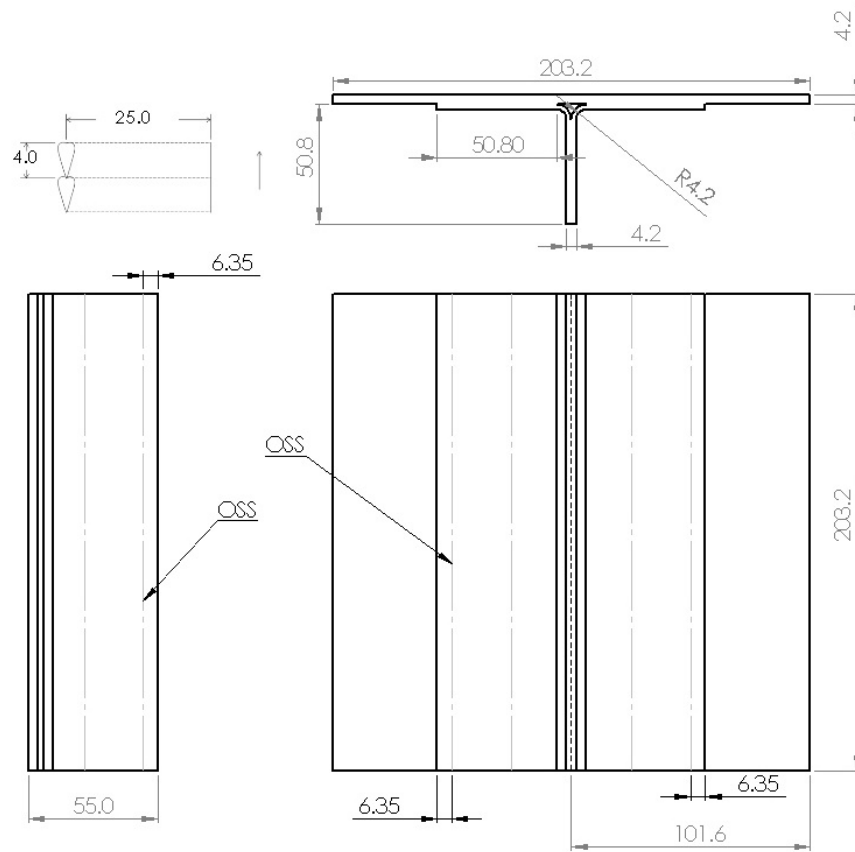


Figure 3.8: Translucent Cavity Preform Dimensions and OSS Location (mm)

The assembly method of this 3 dimensional preform leaves a void in the center of the sail where it contacts the skin. As mentioned in Section 3.1.1, if left devoid of fibres, such

a large space would create a resin rich zone and greatly reduce the overall v_f in a critical region of the structure. A linear assembly of yarns, typically called a noodle in industry, was used for maintaining v_f and prevent the sail plies from collapsing into the cavity. Different noodles were used in different preforms. The type of noodle used for each specific test is detailed in Appendix E.

Constructions of preforms used in test series T2 to T5 using the Translucent Cavity Rig are detailed in Table 3.5. It must be noted that in the interest of reducing the lead time on preform production, an in-house sewing machine was used for stitching some of these preforms. Tests performed in series T2 and T3 involved sewing in a lockstitch pattern as shown in Figure 3.9. Tests performed in series T4 and T5 used OSS preforms provided by the CTT and stitched as indicated in Figure 3.8, with the exception of series T4.

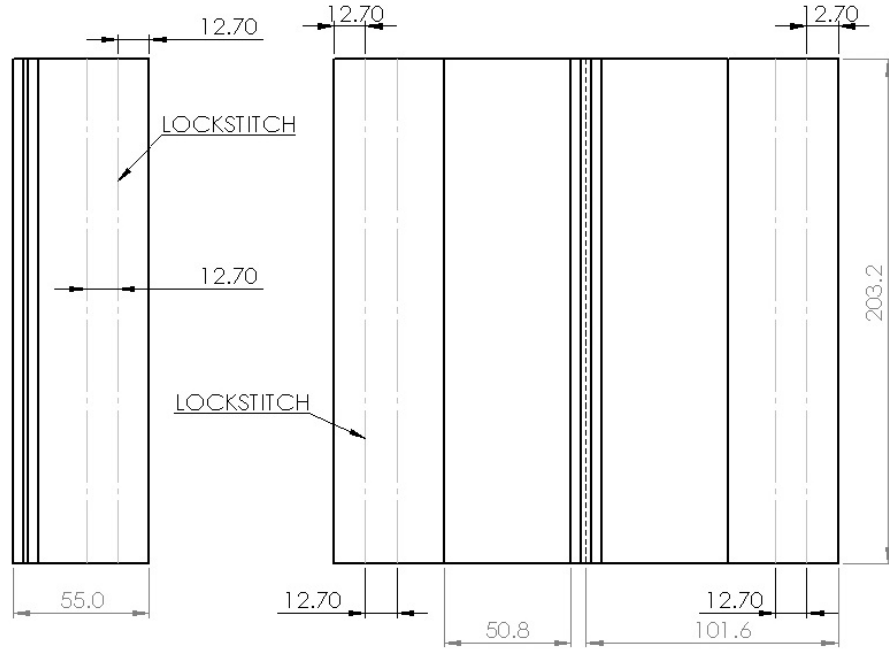


Figure 3.9: Translucent Cavity Preform Lockstitch Location (mm)

Test series T4 aimed at determining the effects of stitching and tufting in the immediate area of the noodle, and at investigating whether noodle v_f and construction affected macroscopic flow through the preforms. As illustrated in Figure 3.10, the CTT OSS per-

Table 3.5: Clear Cavity Test Series Preforms

Trial Series	Preform Type	Associated Tests
T2	Plain Weave 1G - Lockstitch	6
T3	Equivalent Quasi - Lockstitch	8
T4	Modified Equivalent Quasi: -OSS through Noodle	3
	-Tufting Through Noodle	3
T5	Carbon Quasi - Ladder Stitch	1

forated the noodle or displaced material on its fringe while tufting directly penetrated the noodle and in some cases the sail, Figure 3.6.

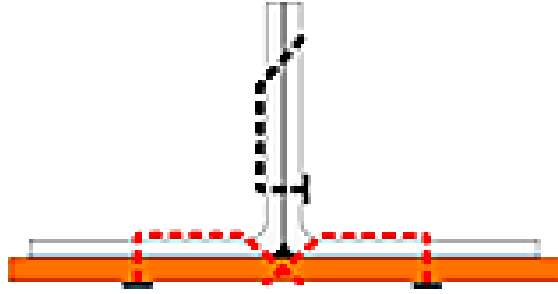


Figure 3.10: OSS Through Noodle Placement [64]

3.1.4 Full Scale Demonstrator Preforms - Series T6

Building on lessons learned from previous Translucent Cavity tests and sample parts produced by research partners at ÉTS and CTT, a full scale demonstrator was designed to showcase technological capabilities to industrial partners. The sail dimensions were modified to better accommodate the robotic stitching done at CTT. Whereas the 50.8 mm (2 in) dimension was measured from the top surface of the foot initially, it was now measured from the point where the radius became tangent with the sail, adding 2.15 mm to its length. Also, since the minimal thickness of laminates produced by VARTM was 4.3 mm rather than the 4.2 mm previously used, all radii and thicknesses were changed to reflect this, Figure 3.11.

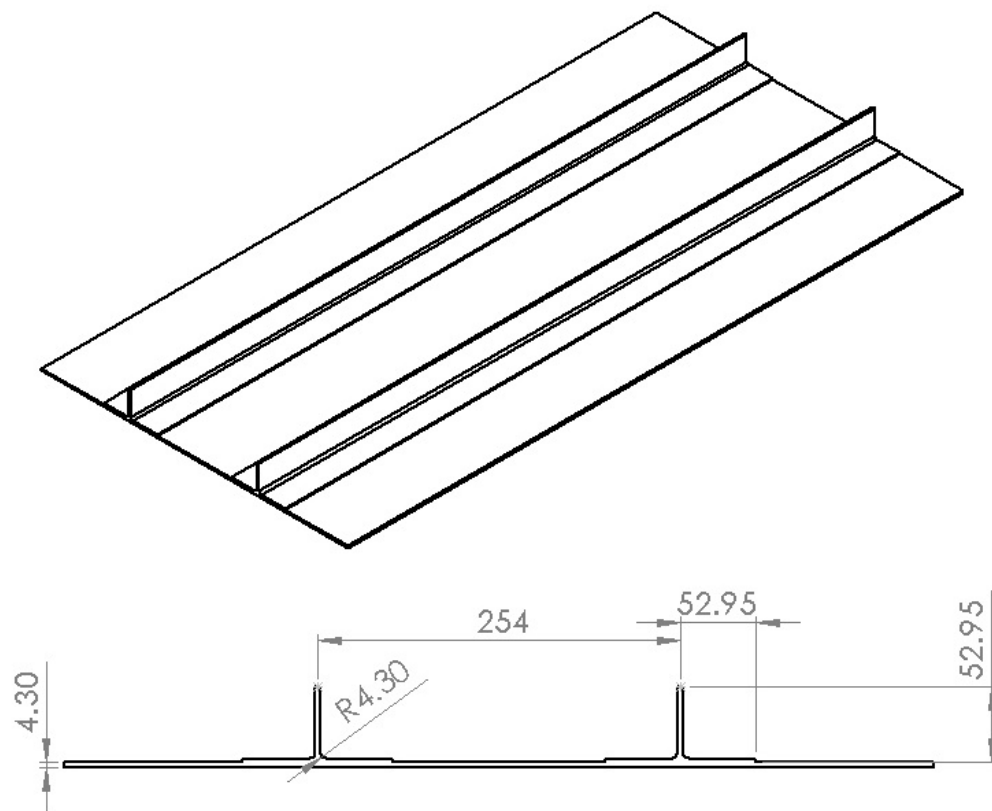


Figure 3.11: Final Demonstrator Dimensions (mm)

Full scale demonstrators measured 1.219 m by 0.610 m (4 ft by 2 ft) with two T stiffeners running along the length. These T stiffeners were positioned 254 mm (10 in) apart at their centerlines in a symmetric fashion about the part's centerline. Two different constructions were tested as part of trial series T6. Two preforms were assembled in-house without any stitching using the Plain Weave 2 material and the Modified Equivalent Quasi stacking sequence. A third preform was stitched and assembled at CTT using project selected twill fabric TG-09-T in Modified Equivalent Quasi stacking sequence. Appendix F details the cutting patterns used for both 1270 mm (50 in) and 1524 mm (60 in) fabric rolls to minimise both the loss of material and the amount of mating lines in each ply within the preform.

Final stitching configuration for the demonstrator was based on the distance between the centerlines of the sails as well as the height from the skin, Figure 3.12. The needle penetrating at 45° through the foot is oriented towards the sail, while on the sail itself, it is oriented towards the edge of the preform. This arrangement provided the best performance in composite parts tested by partners, while also easing the production of the stiffened panels as a whole.

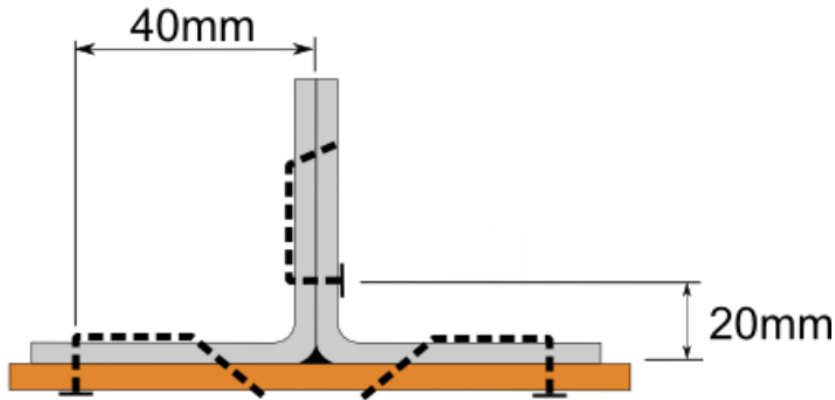


Figure 3.12: Final OSS Location on Stiffeners

3.2 Common Equipment

Given the nature of flow experiments performed towards this thesis, some pieces of equipment and ancillaries were used with multiple rigs. The testing fluid used as a replacement for epoxy resin was pure silicone oil (polydimethylsiloxane) in all trials; two grades of silicone oil were employed as described below. The vacuum pump and catch pot system were also used with all testing rigs, in various configurations. The common equipment is described in this section along with the photographic equipment used for documenting all tests.

3.2.1 Silicone Oils and Dyes

Silicone oils obtained from Clearco Products were used as replacement fluids for reactive epoxy resin in all infusion trials, allowing translucent moulds to be made from polymethyl methacrylate whilst avoiding softening and dissolution issues. To be an adequate substitute in flow experiments and permeability trials, a fluid must have the same viscosity as the resin to be used in making the actual composite parts. The resin used for making these parts is Cycom 890 RTM and its viscosity is a function of infusion temperature as shown in Figure 3.13. Initially, infusion temperature for composite part manufacturing was set at 80°C by industrial partners, but it was later changed to 120°C. Initial permeability tests (T1-B, T1-C, T1-EG) were conducted using 500 cSt silicone oil. All following tests were conducted using 50 cSt silicone oil. The change in viscosity is of no consequence in permeability measurement tests as viscosity is factored in Darcy's law, and the permeability K is independent of viscosity. However, it is important to use a fluid of appropriate viscosity when aiming to replicate manufacturing operations, as was the case for the latter series of tests conducted towards the end of this thesis. One difference between silicone oil and the epoxy resin that it replaces lies in values of surface tension which could affect capillary flow.

However, under the pressure gradients imposed in the reported work, any effects are expected to be minimal.

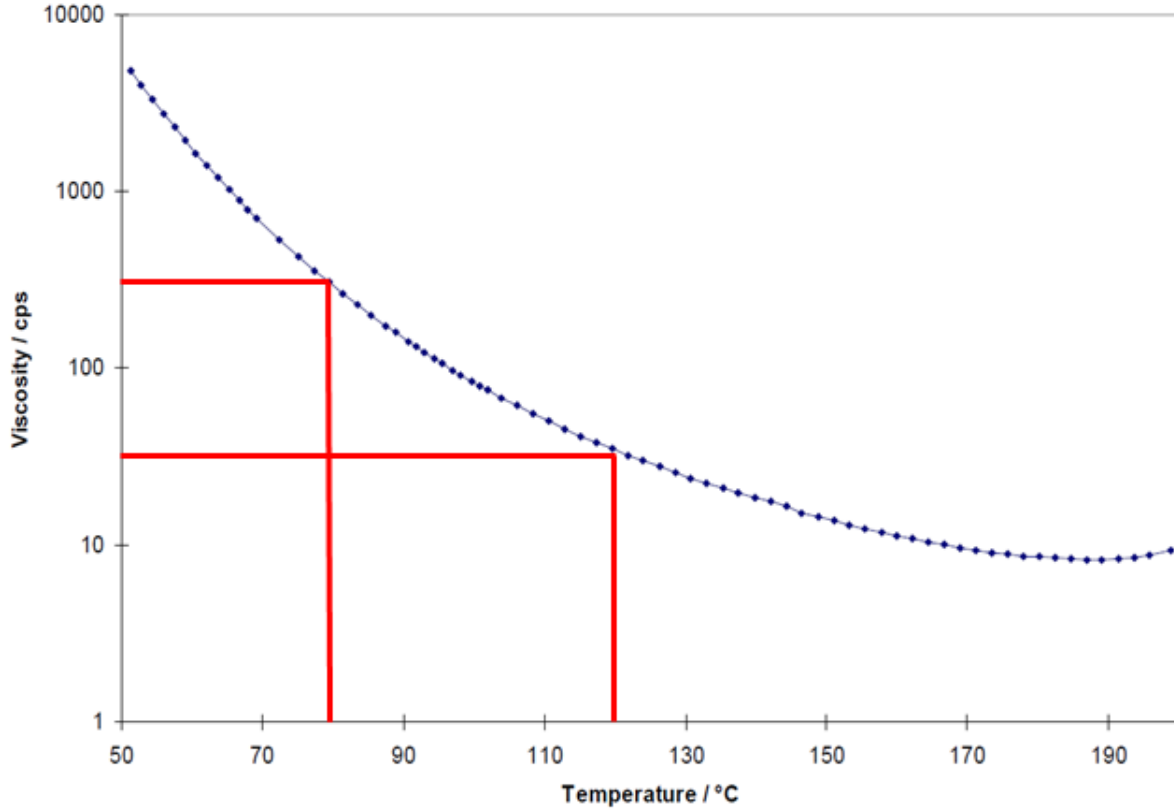


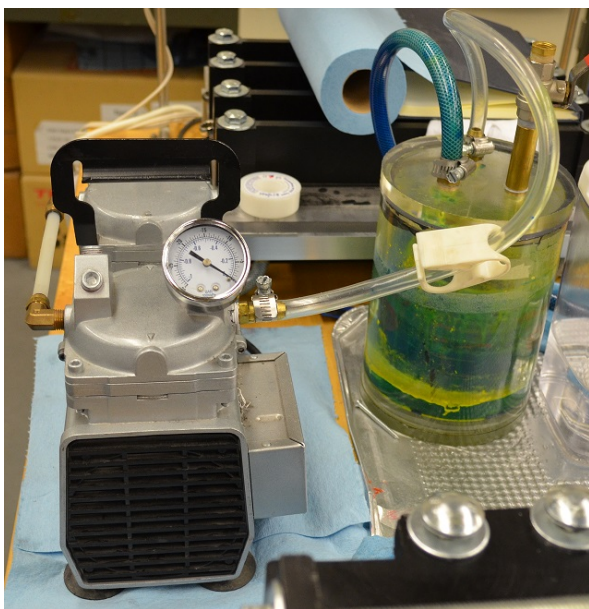
Figure 3.13: Cycom 890 RTM Viscosity as a Function of Temperature Prior to Cure [65]

Dyes were used with the silicone oil to increase contrast of the flow front. Dye 1 was LX 6258 Pylakrome Bright Blue from Pylam Products, mixed at 0.5% by mass. This deep blue dye was ideal for use with fiberglass preforms. Dye 2 was Struers EpoDye which is fluorescent under UV illumination, mixed at 5 grams per litre of silicone oil. Both dyes were mixed with the oil at room temperature using a stirring rod and a hand drill.

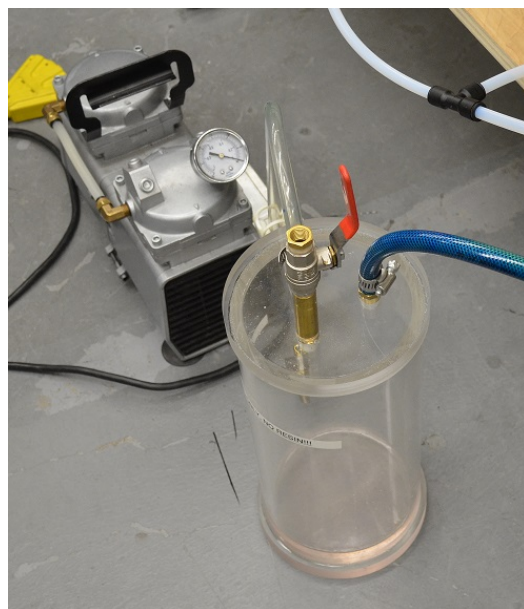
3.2.2 Vacuum Pump and Catch Pot System

The vacuum pump used in all trial series was a GAST DAA-V715A-EB 1/4hp unit capable of drawing a maximum vacuum of 0.97 atm (29.0" Hg) on a continuous duty cycle.

Two different catch pots were used ahead of the vacuum pump for preventing resin entry over the course of this work. The first catch pot, Figure 3.14a, had a gasket-seal lid and used a removable plastic cup for resin collection. A larger catch pot was designed and built by the author from 152.4 mm (6") OD PMMA pipe and 25.4 mm (1") PMMA plates. This catch pot was sealed at both ends as it was to be used with silicone oil only. The oil could be drained through the braided PVC tube, Figure 3.14b.



(a) Silicone oil catch pot 1



(b) Silicon oil catch pot 2

Figure 3.14: Catch Pot Assemblies with Vacuum Pump

3.2.3 Photographic Equipment

Main image capture was accomplished using a Nikon D5100 digital single lens reflex (DSLR) (camera 1) allowing high resolution imaging, in conjunction with an arm-equipped tripod. Additional image capture from different perspectives was done using a Sony Cyber-shot DSC-W310 digital camera (camera 2) and a Sony Cyber-shot DSC-WX200 digital camera (camera 3), both mounted on tripods. Camera positioning is illustrated in Sections 3.3, 3.4 and 3.5.

3.3 Flat Plate Permeability Rig

3.3.1 Experimental Setup

Evaluating permeability through Darcy’s law requires quantifying of time t , inlet gauge pressure P_o , flow rate q and flow front position relative to the inlet $r_f(x, y)$. Test-specific data such as the fibre volume fraction v_f and thickness h are also needed along with dynamic viscosity μ of the permeating fluid.

The flat plate permeability rig consisted of a covered cavity containing the preform, connected to a hydraulic cylinder used for driving the permeating fluid into the preform at a constant flow rate. The cylinder was actuated by a 4482 screw-driven Instron universal testing frame, which can provide a constant displacement rate and by extension a constant flow rate while recording loads through a 100 kN calibrated load cell. For all tests the Bluehill 2 software was used for running the Instron frame. Inlet pressures were recorded by a data acquisition system (DAQ) for correlating with the flow front position. Figure 3.15 shows a diagram of the infusion setup. The following paragraphs detail the operation of the flat plate permeability rig and provide an overview of the equipment used; a more detailed description of the rig’s components is available in the work of *A. Stewart* [13].

A container (termed resin pot in Figure 3.15) was placed on the floor and connected to the lowest point of the hydraulic cylinder by 9.5 mm (3/8”) internal diameter (ID), 3.2 mm (1/8”) wall thickness braided wire high pressure PVC flexible tubing rated for 1.9 MPa (275 psi). The same flexible tubing was used for all connections in the flat plate permeability rig. The end of the tube was submerged in the silicone oil in the container and the flow could be interrupted by closing a ball valve. Male and female quick connect fittings were used for coupling all tubing and rig components. Worm drive hose clamps were used for securing female fittings to the tubing by tightening the screws over the barbed extension designed for 3/8” ID tubes. The male fittings had 1/4” NPT thread which was wrapped

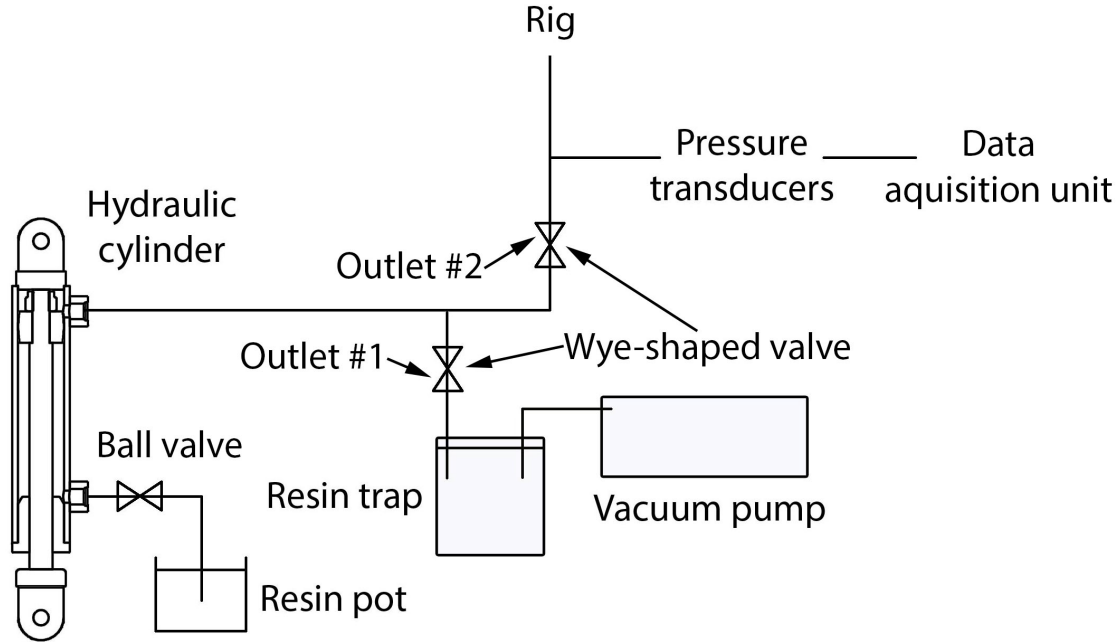


Figure 3.15: Permeability rig infusion system [13]

in teflon pipe thread sealant tape before being screwed manually into the adjoining rig element. Tape thickness was 0.071 mm (0.0028"); an appropriate seal was provided by wrapping the threads 3 times.

The hydraulic cylinder used was a Kinecor 30AGU08-ASAE with maximum stroke of 203.2 mm (8.0") and 76.2 mm (3.0") ID. The maximum safe operating pressure of 17.2 MPa (2500 psi) was well in excess of pressure levels expected or encountered during testing [66]. This piston featured 3 1/2" NPT female ports; the two ports connecting to the piston chamber were fitted with brass reducers compatible with the connectors used elsewhere on the rig, while the other port on the opposite side was open to ambient conditions. The first of the ports leading to the piston chamber was connected to the aforementioned container (resin pot) while the second led to a wye-shaped 3-port brass ball valve. This valve had a safety exhaust so that when closed the outlet would be open to ambient conditions.

Outlet #1 seen in Figure 3.15 was connected to catch pot 1 (resin trap) which is connected to the vacuum pump also represented.

Outlet #2 was connected to a high pressure brass cross (rated 20.7 MPa - 3000 psi) seen in Figure 3.16, which connects to 2 pressure transducers exposed to inlet pressure. The remaining tube ran to the test rig inlet.

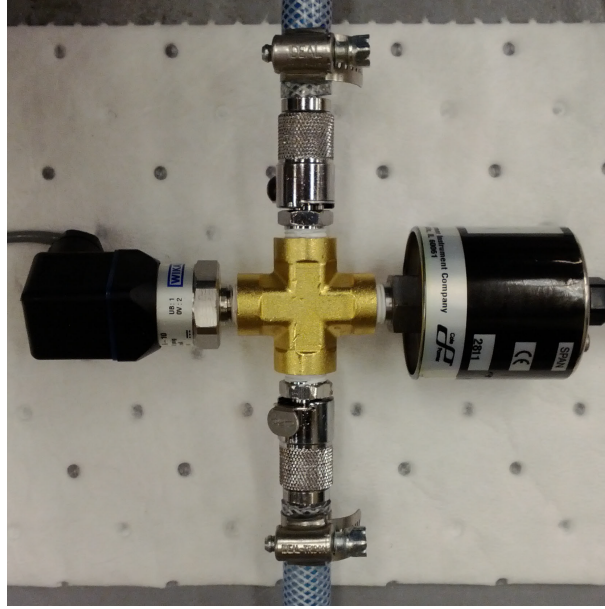


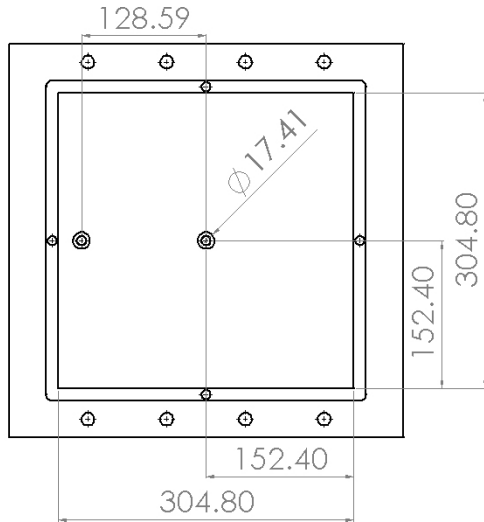
Figure 3.16: Brass cross with transducers and connectors [13]

Pressure transducer 1 was a Setra Systems Model DPT 209, right side on Figure 3.16, accurate from 0 kPag to 689kPag (0 psig to 100 psig). Pressure transducer 2 was a Wika Tronic Industrial pressure transducer, left side on Figure 3.16, accurate from 0 MPag to 2.07 MPag (0 psig to 300 psig). Both transducers were 12V 2-wire units with output current (1-20 mA) linearly correlated to pressure over their respective ranges. The use of 2 transducers ensured high accuracy over the 0-689 kPag range while allowing data collection in the event of pressure exceeding 689 kPag. Error is $\pm 0.13\%$ full scale and $\pm 0.5\%$ full scale for transducers 1 and 2 respectively, amounting to 1.79 kPa (0.26 psi) and 20.7 kPa (3.0 psi) respectively.

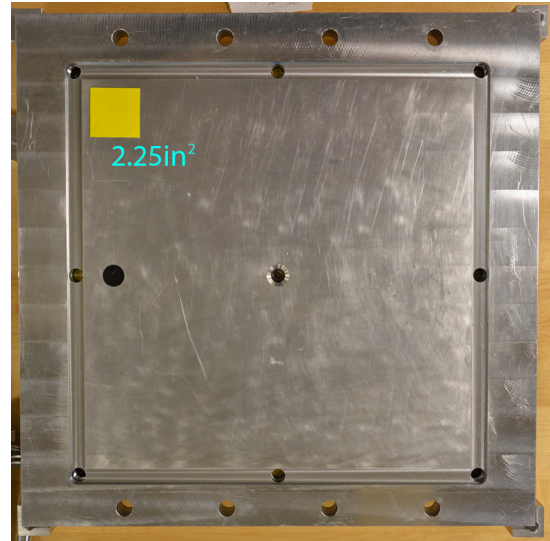
The pressure transducers were connected to a computer running LabView versions 8.2 then 9.0 via a National Instruments unshielded 68-pin I/O block (NI CB-68LPR) which served as data acquisition unit (DAQ). A 100 ohm resistor was placed between the positive

and negative leads of the load monitor to complete the circuit.

The cavity of the flat plate permeability rig consisted of an aluminium base, a translucent polycarbonate cover, spacers and steel braces. The base was an aluminium square plate measuring 406.4 mm to a side and 25.4 mm in thickness, with a central inlet port. Inlet hole was 11.1 mm ID with a 45° chamfer and inlet diameter of 17.4 mm at preform level. The underside was fitted with a male quick connect fitting allowing the coupling of the injection system to the rig. A groove, 3.3 mm deep and 12.7 mm wide, was milled in the periphery of the surface. This created a 304.8 mm by 304.8 mm usable surface upon which preforms were laid, thus allowing excess oil to drain. To this end, four 9.5 mm holes were centered along this perimeter groove while four more identically sized holes were set in each corner. Two rows of four holes 13.3 mm ID, 81.3 mm spacing center to center were drilled 19.1 mm from two opposing sides of the plate to accomodated grade 5 12.7 mm (1/2") steel bolts used for securing 4 steel braces holding the square polycarbonate cover, which featured similar holes. A drawing and picture of the plate appear in Figure 3.17. The cover and braces are described below.



(a) Plate Drawing (mm)



(b) Top View with 2.25 in^2 Paper Marker

Figure 3.17: Aluminium Base of Permeability Rig [13]

Spacers 38.1 mm wide and 4.2 mm thick ran the full width of the base. They fea-

tured corresponding holes for the bolts and were used for matching the preform’s expected thickness. Along each of the boltless sides of the plate, a 254 mm long by 38.1 mm wide strip of compressible rubber was used for spreading the bracing load and minimizing stress concentration at the edge of the spacers.

The cover was a 12.7 mm thick sheet of polycarbonate with outer dimensions identical to those of the aluminium base, and corresponding bolt holes.

The 4 steel braces measuring 12.7 mm wide, 50.8 mm tall and 406.4 mm long had undergone a black oxide coating for protection. A strip of rubber 12.7 mm wide, 3.2 mm thick and 330.2 mm long was used under each brace to protect the cover’s surface.

3.3.2 Procedure

All tests followed the same experimental procedure. A notable difference was the oil viscosity of 500 cSt oil used for tests T1-B, T1-C, T1-EG and 50 cSt used for preforms of test subseries T1-W. The use of dyes is mentioned for each test in Section 4.1. Appendix C contains images extracted from the raw video data as used for analysis.

The flow front was captured with camera 2 for test subseries T1-B, T1-C and T1-EQ, while camera 1 was used for the test subseries T1-W. Certain test series were performed under UV illumination provided by two 15 watt Stanpro BLB compact fluorescent light bulbs emitting wavelengths in the 300-400 nm range. These will be pointed out accordingly. The camera was set on a tripod to shoot downwards, Figure 3.18.

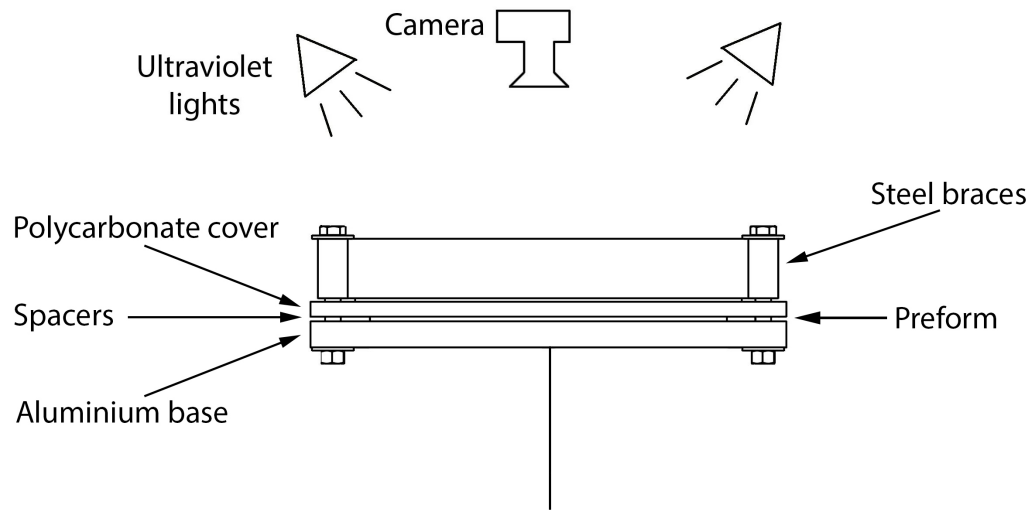


Figure 3.18: Diagram of Rig and Camera Placement [13]

Following are the steps and procedures required for operating and conducting a test with the Flat Plate Permeability Rig.

- Step 1: Select and set spacers for appropriate height and place rubber strips along the edge of the rig, Figure 3.19.

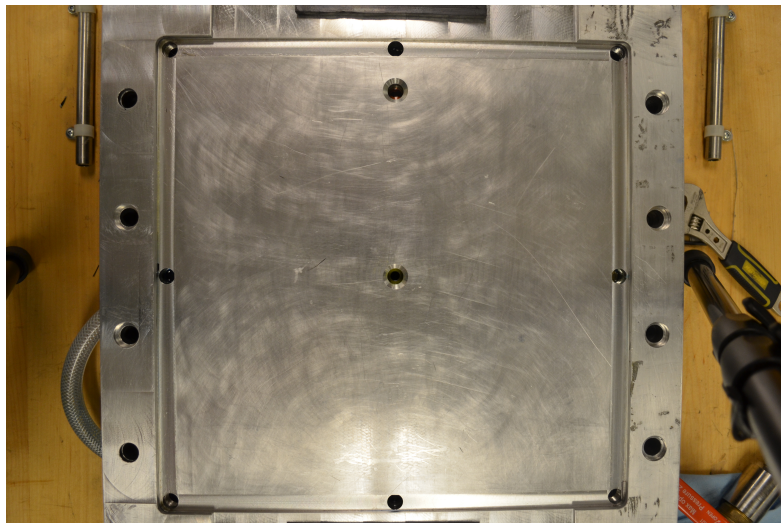


Figure 3.19: Permeability Rig, Setting the Spacers (Step 1)

Step 2: Place preform on center platform of permeability rig, Figure 3.20.

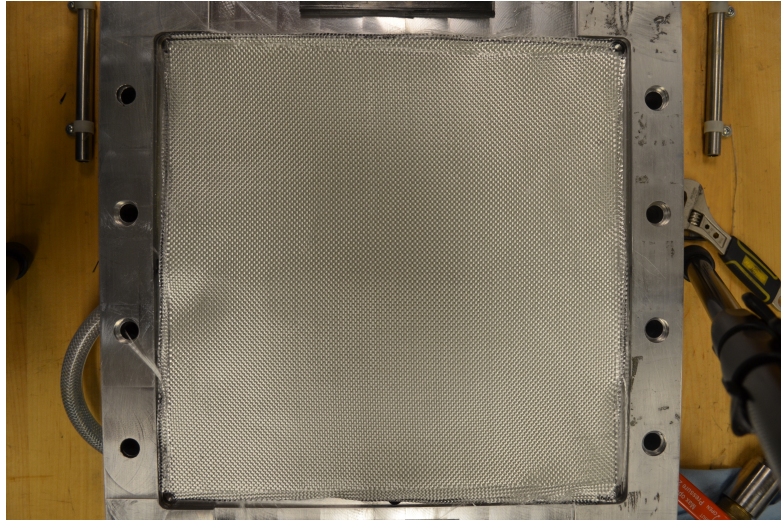


Figure 3.20: Setting Preform in Permeability Rig (Step 2)

Step 3: Close polycarbonate cover, set rubber strips under steel braces, tighten bolts until preform is compressed to desired height, Figure 3.21.

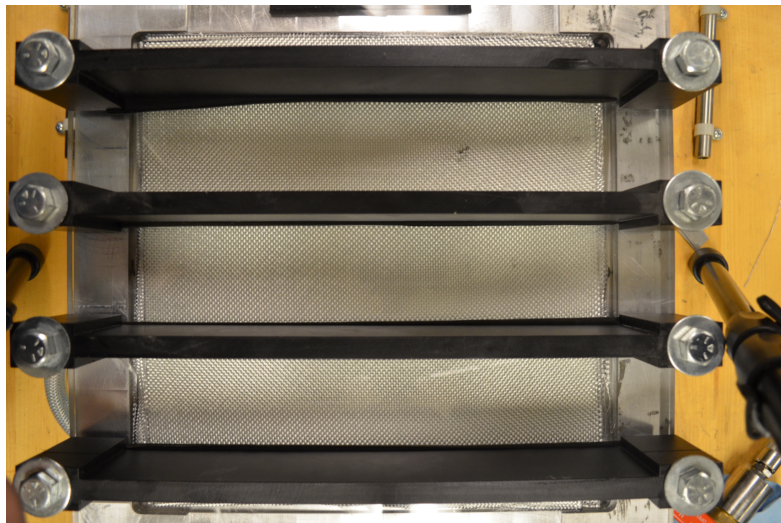


Figure 3.21: Bracing Permeability Rig (Step 3)

Step 4: Connect all tubing as per system diagram, Figure 3.15.

Step 5: Install cylinder in Instron testing frame and extend fully with all valves open, Figure 3.22.

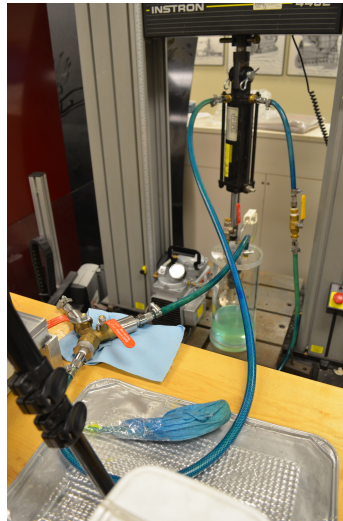


Figure 3.22: Connecting Cylinder to Instron Testing Frame (Step 5)

Step 6: Connect pressure gauges to LabView DAQ, Figure 3.23.

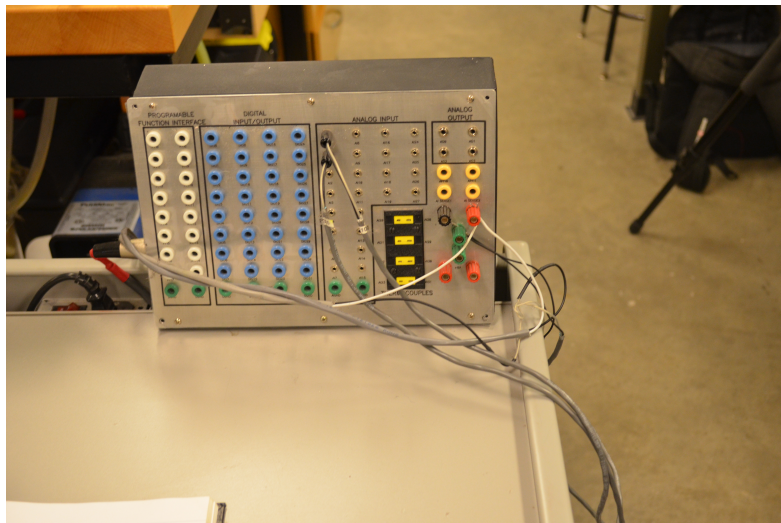


Figure 3.23: Connecting Pressure Gauges to DAQ (Step 6)

- Step 7: Close exhaust valve of catch pot, ball valve and outlet #2, keep outlet #1 open. Turn vacuum pump on, let vacuum reach a steady state of 0.97 atm or more.
- Step 8: Turn off vacuum pump to pressure test fittings; if pressure stays low over a few minutes, turn vacuum pump back on.
- Step 9: Open ball valve to let fluid fill all tubing, Figure 3.24.

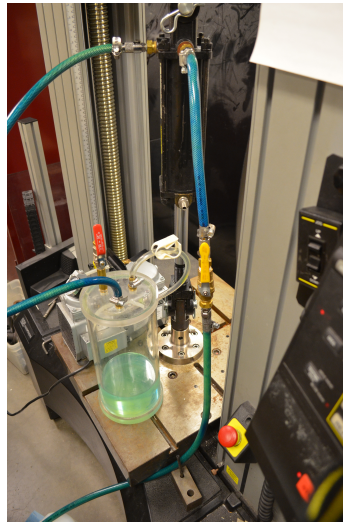


Figure 3.24: Opening Ball Valve (Step 9)

- Step 10: Close ball valve once fluid is flowing into catch pot and close outlet #1. Open catch pot exhaust valve to return that tubing section to atmospheric pressure. Vacuum pump can be turned off permanently.

Step 11: Start video recording with camera on 90° tripod, Figure 3.25. Start LabView recording, open outlet #2, start Bluehill 2 software to run compression routine.



Figure 3.25: Photographic Equipment Layout (Step 11)

Step 12: When flow reaches edges of preform, Figure 3.26, stop all instruments in reverse order as presented in step 11.

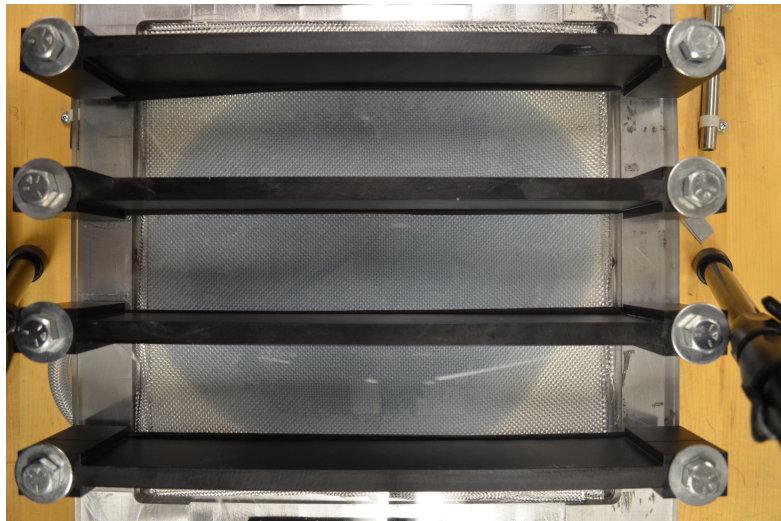


Figure 3.26: Flow Front Reaching Edge of Preform (Step 12)

3.3.3 Analysis

From experimental data and imposed conditions, it is possible to calculate the permeability tensor to Darcy's law, Equation 2.4. The first quantity necessary is the flow rate of the fluid at the inlet. This is proportional to the piston's displacement rate, hence it can be obtained as follows.

$$V_{cyl} = \frac{\pi}{4} \cdot D_{cyl}^2 \cdot (H_{cyl} - h_{cyl}) \quad (3.1)$$

$$E = \frac{dh_{cyl}}{dt} \quad (3.2)$$

$$q = \frac{dV_{cyl}}{dt} = \frac{dV_{cyl}}{dh_{cyl}} \cdot \frac{dh_{cyl}}{dt} \quad (3.3)$$

$$q = \frac{\pi}{4} \cdot D_{cyl}^2 \cdot E \quad (3.4)$$

With an imposed piston displacement rate of 1 cm/min used in all permeability tests, the flow rate at the inlet of the preform can be determined:

$$q = \frac{\pi}{4} \cdot (76.2mm)^2 \cdot 10.0 \frac{mm}{min} = 45603.67 \frac{mm^3}{min} = 0.76 \frac{cm^3}{s}$$

The second step in the analysis consists in determining the pressure at the inlet. To do so, the average pressure reading was taken from both gauges and tracked with respect to time.

Isotropic Case

For all permeability tests demonstrating isotropic flow, the radius of the expanding circular flow front is mathematically derived, Equation 3.6. With these parameters and the method developed by *Chan et al.* [16] for constant flow rates into porous media, permeability can be calculated.

From the conservation of mass:

$$t = \frac{\pi(r_f^2 - r_0^2) \cdot h \cdot \epsilon}{q} \quad (3.5)$$

In an isotropic case permeability is calculated as follows:

$$r_f = \sqrt{\frac{q \cdot t}{\pi \cdot h \cdot \epsilon} + r_0^2} \quad (3.6)$$

$$K(P_{0,t}) = \frac{q \cdot \mu}{2\pi \cdot h \cdot P_0} \cdot \ln \frac{r_f}{r_0} \quad (3.7)$$

Since permeability values were averaged over a series, calculations were performed for standard deviation and error of the mean using Equations 3.8 and 3.9 respectively:

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (K_i - \bar{K})^2} \quad (3.8)$$

$$SE_{\bar{K}} = \frac{s}{\sqrt{N}} \quad (3.9)$$

Orthotropic Case

In the case of orthotropic flow, the time-stamped videographic data was analysed with the method described by *A. Stewart* [13] and an image processing software (ImageJ), both

radius along the principle axes of the flow front can be identified and correlated with pressure. To properly compare the radius to the inlet pressure, the two principle axes radii need to be expressed as a radius in an equivalent isotropic system (EIS), r_{ex} . This is accomplished by first plotting r_y with respect to r_x and finding the slope (m_1) of the best fitting linear approximation of these values and then applying Equation 3.10.

$$r_{ex} = \sqrt{m_1} \cdot r_x \quad (3.10)$$

The inlet pressure can now be plotted with respect to the natural logarithm of this equivalent radius and a new best fitting linear approximation of the data set can be used to find a second slope, m_2 . This slope can now be used to find the equivalent permeability value K_e , Equation 3.11.

$$K_e = \frac{q \cdot \mu}{2\pi \cdot h \cdot m_2} \quad (3.11)$$

Using this equivalent permeability value in conjunction with the previously calculated m_1 the components of the permeability tensor can be calculated, Equation 3.12.

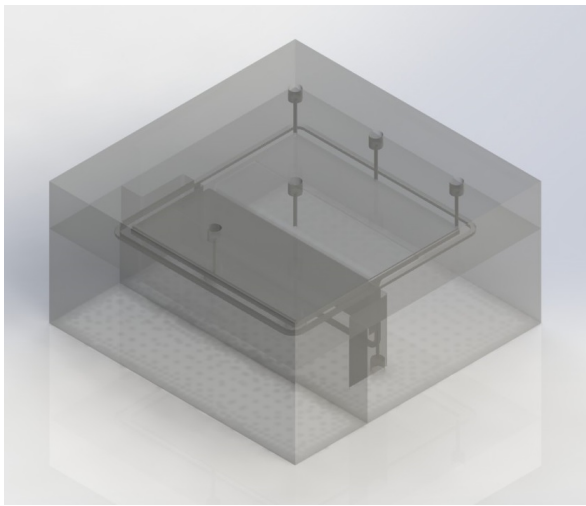
$$K_x = \frac{K_e}{m_1}, \quad K_y = K_e \cdot m_1 \quad (3.12)$$

$$[K] = \begin{pmatrix} K_x & 0 \\ 0 & K_y \end{pmatrix} \cdot m^2 \quad (3.13)$$

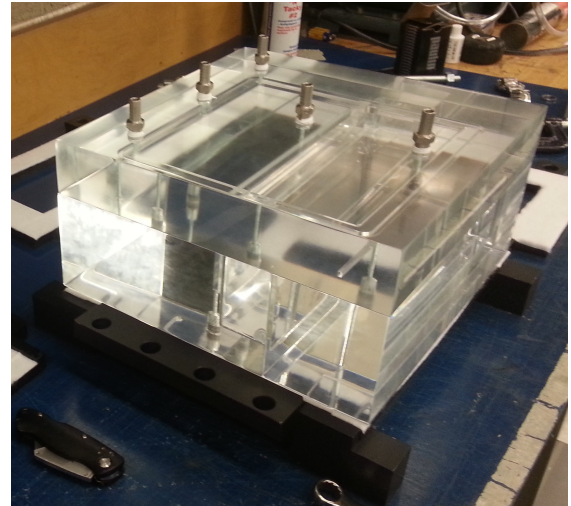
3.4 Translucent Cavity Rig

3.4.1 Experimental Setup

A 300 mm x 300 mm x 200 mm, 3 part translucent PMMA cavity with interchangeable inlet and outlet ports was designed and built for exploring the effects of multiple inlets and outlet port locations on resin impregnation and flow. The cavity can be seen in Figure 3.27.



(a) Initial Render of Translucent Cavity



(b) Inlets on Translucent Cavity

Figure 3.27: Inlet Locations on Translucent Cavity Rig

The two-part cavity was milled out of two 300 mm x 300 mm, 102 mm thick translucent PMMA blocks sourced from McMaster-Carr (PN 8560K925) using a Haas CNC mill. The cover was machined out of a 300 mm x 300mm, 50.8 mm thick block of the same material (PN 8560K914). The two larger parts formed an interlocking mould cavity, between which the sail was held as well the cavity into which the skin was dropped, while the cover was flat and only featured injection ports. All parts were polished to maintain sealable surfaces. Two soft silicone 1/8th in o-ring cord stocks were used for sealing the cavity in conjunction with Lucas Oil Products Red N Tacky #2 EP general purpose grease. The injection ports were two-staged: in each case a 3.18 mm hole served as the main port while a 19.1 mm deep

hole was tapped for 1/4" NPT fittings. There were 8 such ports allowing for 5 different filling scenarios. The possibility of injecting under positive pressure was considered early in the design phase and as such, single point ports would be compared with line or slot injection ports.

As shown in Figure 3.28, the configuration on the top plate features three ports (P1, P2, P3) lined to one side, one port at the midpoint of the skin (C), and one port connected to a 3 mm (1/8 in) line milled 2 mm deep on the opposite side (L). The 3 final ports are located at the tip of the sail, at the corners and center (SP1, SP2, SP3). Corresponding locations on the preform appear in the engineering drawings of the Translucent Cavity and frame, Appendix D.

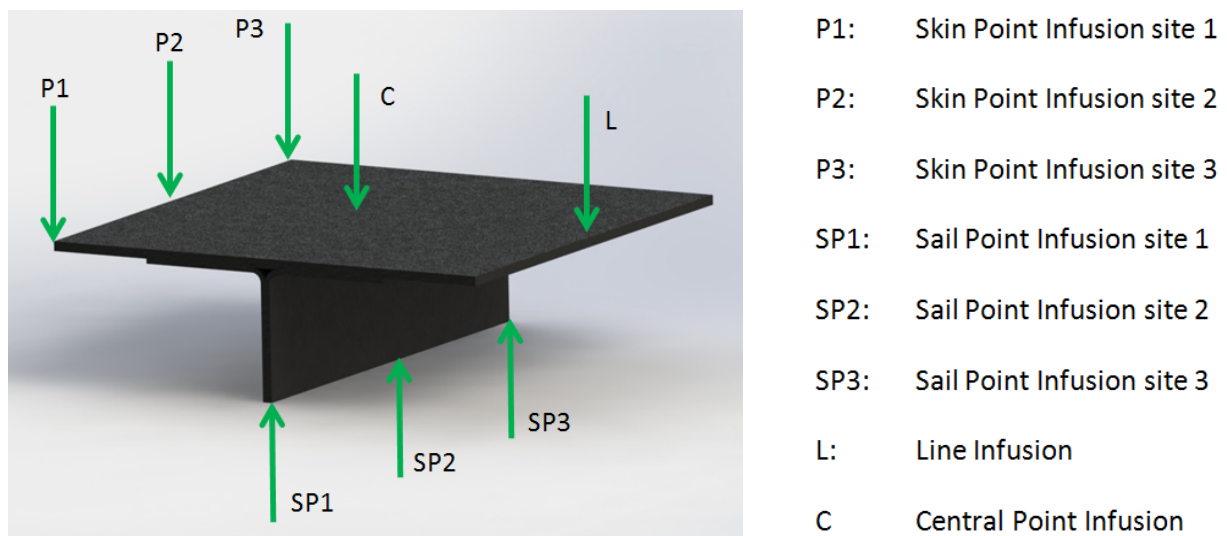


Figure 3.28: Inlet Locations on Translucent Cavity Rig

Complementing the acrylic cavity, a steel frame was built for bracing the mould toward conventional RTM injections under positive pressure, and for pressing the preform into shape for the case of VARTM infusion under vacuum. These braces were cut by the author using a CNC acetylene torch, from 12.7 mm (0.5 in) hot rolled steel plates with 19.05 mm (0.75 in) holes drilled for carriage bolts. There were 8 vertical (12.7 mm) 0.5 in UNC carriage bolts used, 4 either side putting sealing pressure on the O-ring of the top cover.

Four threaded (12.7 mm) 0.5 in UNC rods were used for clamping the faces corresponding to the male and female lower mould cavities and this pressure would seal the sail portion of the mould. The whole assembly sat on steel mounts to support the combined mass and allow for the injection tubes to pass underneath the cavity.

Braided PVC vacuum- and pressure-rated tubes (McMaster-Carr PN 5238K748) with 15.9 mm (0.625 in) OD and 9.5 mm (0.375 in) ID were connected to the cavity via 12.7 mm (0.5 in) NPT fittings with 9.5 mm (0.375 in) barbed male ends. The tubes were connected to a manifold, reducing 8 entries/exits to 2, one vacuum lead and one inlet tube. The tubes could be blocked using C-clamps, allowing control of vacuum applied within the cavity. The manifold was milled by the author from a 25.4 mm (1 in) thick block of aluminium measuring 100 mm x 100 mm (4 x 4 in). The manifold featured 3 lines of 3 holes threaded to accept 1/2 in NPT fittings on its upper surface, and three drilled holes from the side connecting an entire line; these were also threaded with 1/2 in NPT. As seen in Figure 3.29, connecting 2 of the lines together reduces the 7 outputs to a single lead which is connected to the vacuum pump and acts as the vacuum outlet through the catch pot, preventing oil from reaching and damaging the pump.

Camera 1 was setup to capture the infusion from the top of the Translucent Cavity, filming the skin of the preform, while camera 2 and camera 3 were on either sides of the mold for capturing flow evolution through the sail.

3.4.2 Procedure

The Translucent Cavity was used in three separate test series T2 through T4, each using different preforms to test either the equipment and general functionality, or specific features of the preforms and their effects on flow. As mentioned in Section 3.1.1, there were significant differences in preform construction and laydown between lockstitch preforms made in-house and preforms provided by CTT featuring ladder stitching of T-stringers.

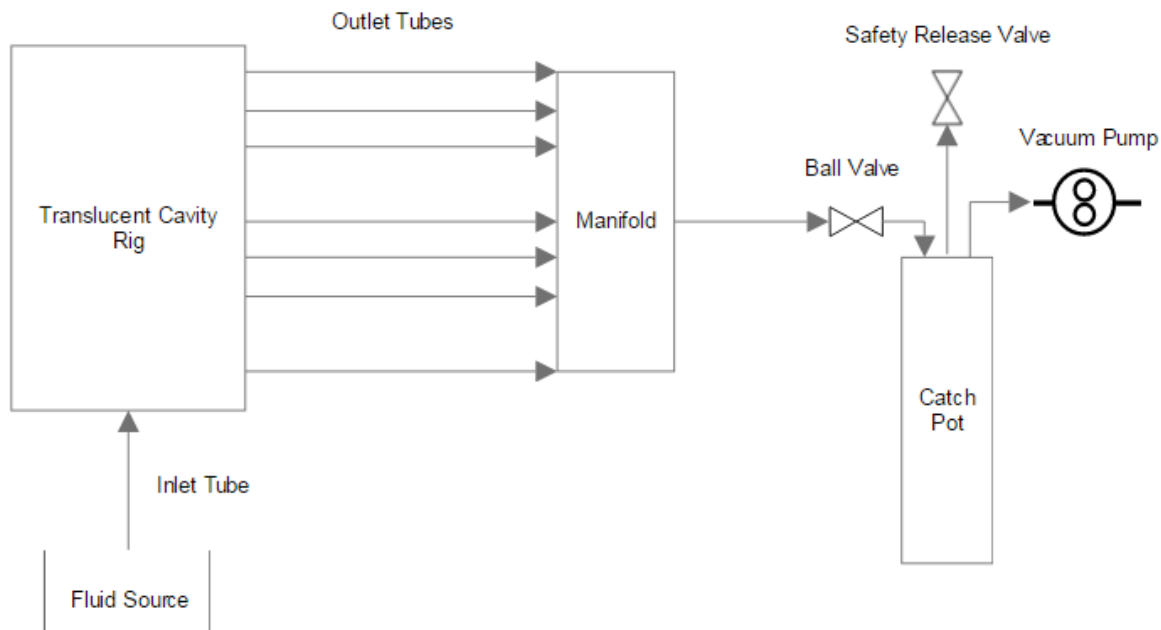


Figure 3.29: Diagram of Translucent Cavity Rig System

Most notably, the sail and noodle had to be assembled within the mould for the former whilst they were stitched directly to the skin for the latter. Therefore, the procedure to close and brace the cavity differed slightly with both types of preforms, as noted where applicable.

Closing and Bracing the Translucent Cavity Rig:

- Step 1: Once the PMMA components have been cleaned thoroughly, the cavity's bottom brace is laid out in the desired orientation onto 2" by 6" wood offcuts, allowing the tubing connected to the underside of the cavity to extend without being bent shut, Figure 3.30.

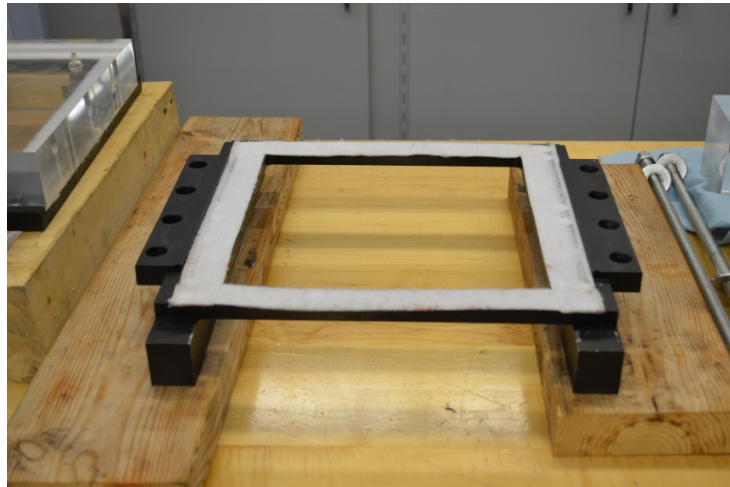


Figure 3.30: Translucent Cavity Rig Bottom Brace and Base (Step 1)

- Step 2: Cover is laid onto separate frame to preserve tubes, also making cleaning and general maintenance easier, Figure 3.31.

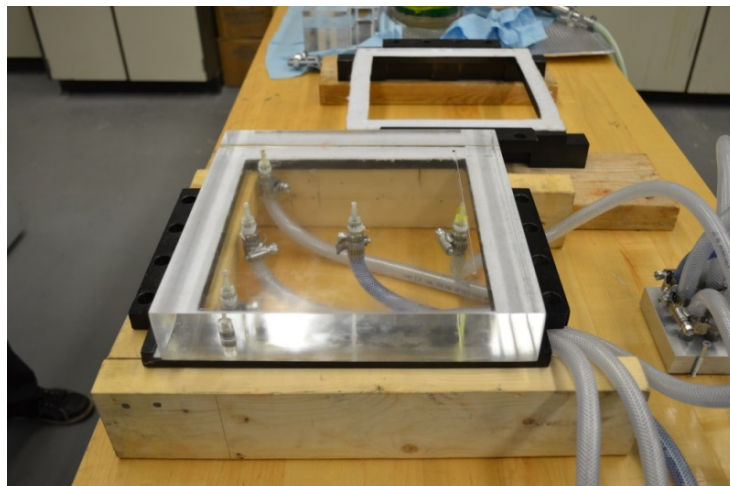


Figure 3.31: Translucent Cavity Rig Cover and Mounting Frame (Step 2)

Step 3: Lower female part of mould is set on base with sail perpendicular to the row of bolts on either side of base. Tubes are pulled out and under bottom brace, out towards male section, Figure 3.32.

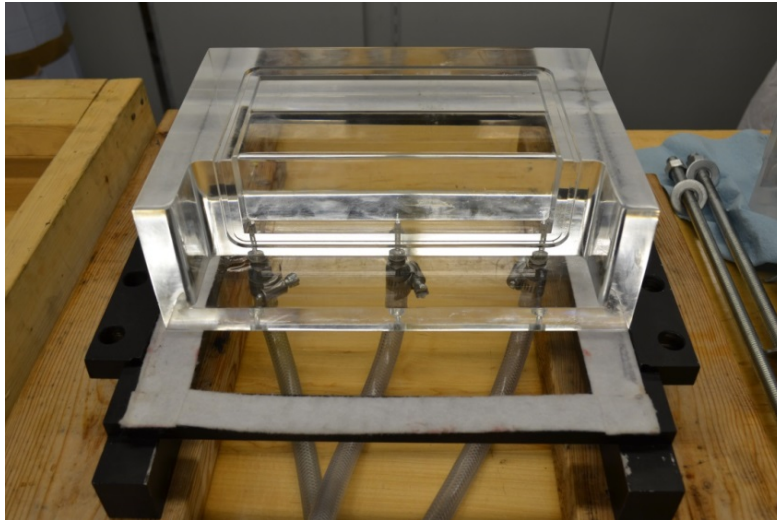


Figure 3.32: Translucent Cavity Rig Female Mould Section on Base (Step 3)

Step 4: Lower O-ring and grease are inserted in bottom seal of lower female mould. Grease is applied gingerly to avoid spilling onto mating faces marked with green arrow, Figure 3.33.

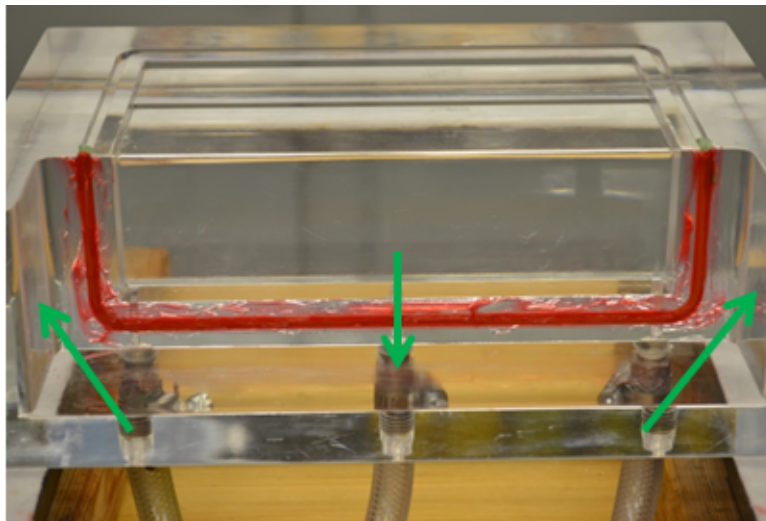


Figure 3.33: Translucent Cavity Rig Sail Seal on Female Bottom Mould (Step 4)

- Step 5: In the case of in-house preforms, the sail is set in its appropriate recess, Figure 3.34; this is necessary for preventing race tracking along the edges during the injection. In the case of CTT preforms, the skin must be supported while the sail is fitted in its recess.

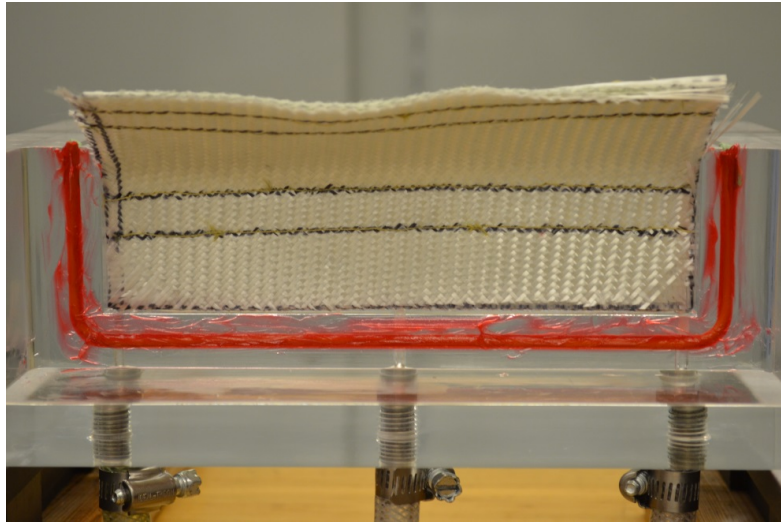


Figure 3.34: Translucent Cavity Rig Sail Section Fitted to Mould Recess (Step 5)

- Step 6: The male bottom section of the mould is inserted while ensuring that the protruding end plate fits into the sail cavity. This may be done with a slight downward twist.

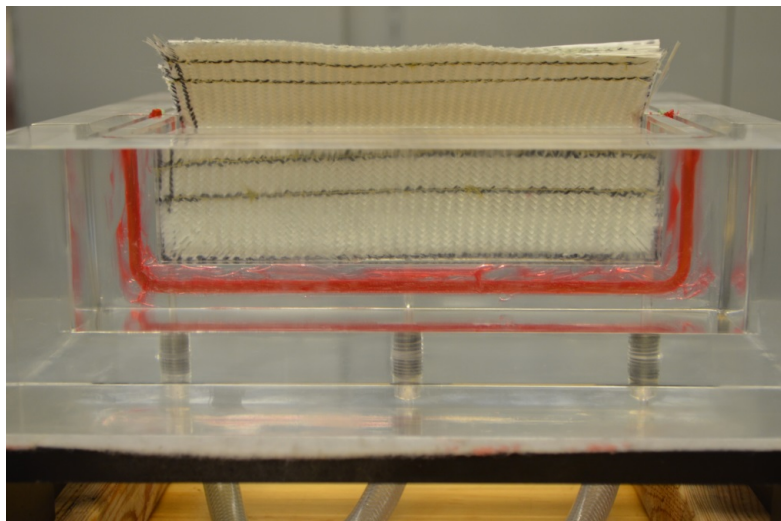


Figure 3.35: Translucent Cavity Rig Male Bottom Mould Positioned (Step 6)

Step 7: The horizontal braces are mounted onto the male and female bottom section to ensure a tight fit, all the while keeping mounting pressure even to prevent the mould from opening up from the top as the male section is only encased into its female counterpart along the bottom and sides at this point, Figure 3.36.

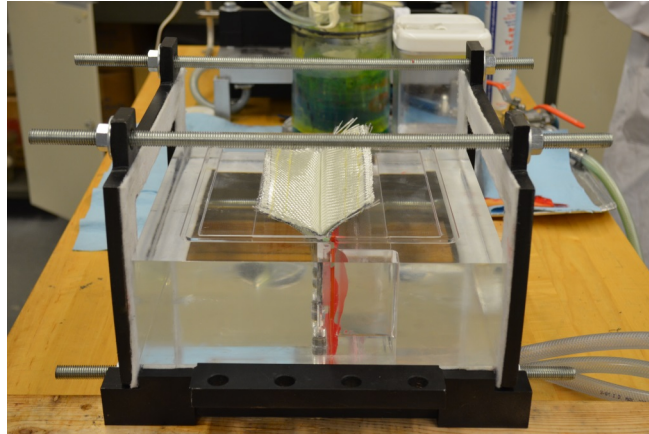


Figure 3.36: Translucent Cavity Rig Horizontal Braces Closing Bottom Section (Step 7)

Step 8: The mounting pressure applied using the horizontal braces is relieved and the 2 superior threaded rods are removed, allowing access to the skin cavity from the top. The upper o-ring is inserted in the seal groove and held in place with tacky tape, Figure 3.37.

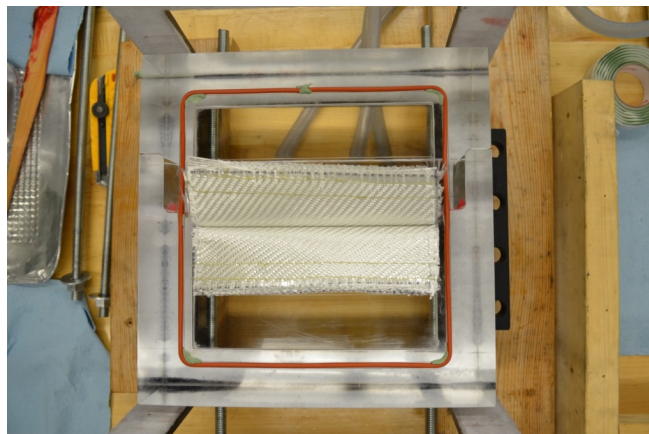


Figure 3.37: Translucent Cavity Rig Top O-ring Seal (Step 8)

Step 9: In the case of in-house lockstitch preforms the noodle and skin are positioned into the allotted slot. In the case of CTT preforms, they already come integrated with the preform. Grease is then applied to the o-ring seal groove, Figure 3.38.

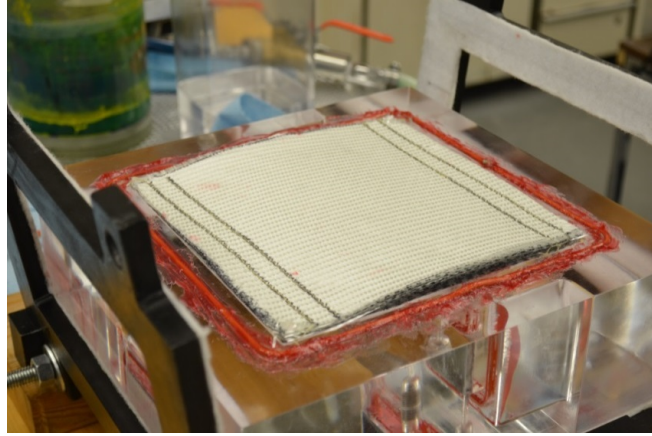


Figure 3.38: Translucent Cavity Rig Preform Set with O-ring Greased (Step 9)

Step 10: The top mould is brought into position over the lower mould sections, and the horizontal and vertical bracing is mounted to seal the cavity. Bolts attached at the bottom of the threaded rods must be tightened significantly by applying pressure to the steel frame; they should be tightened progressively, ensuring that pressure is applied equally over the entire skin of the preform, Figure 3.39.

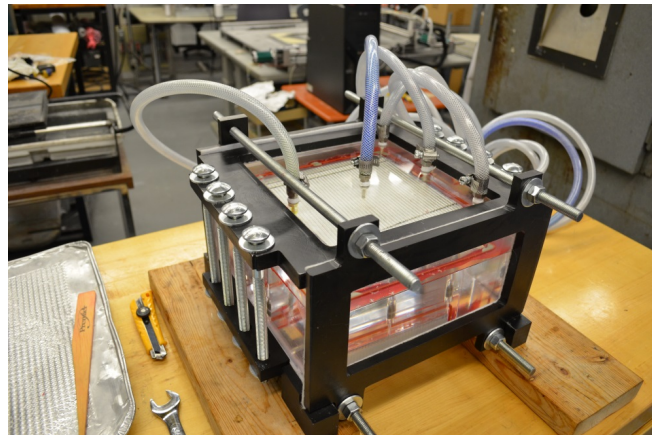


Figure 3.39: Sealed Translucent Cavity Rig with Bracing (Step 10)

Infusion Procedure:

- Step 1: Mix dye to oil if necessary, ensure tube is secure in oil container.
- Step 2: Arrange tripods, focus cameras and start recording.
- Step 3: Start vacuum pump with ball valve (Figure 3.29) closed.
- Step 4: When pressure reaches -0.97 bar, open ball valve to start infusion.
- Step 5: As oil reaches outlet tubes, clamp tubing with 3" C-clamps to prevent preferential flow.
- Step 6: When infusion is complete, turn off recording and vacuum pump. Open safety valve to return system to ambient pressure.

3.4.3 Analysis

Video files of the Translucent Cavity rig trials are first matched with the start of the infusion so that all movies made from different angles have the same timestamp. Within trial series, any repeats of a specific infusion protocol were compared with each other to assess consistency, while separate infusion protocols were also compared to determine preferability of the protocol.

The principal quantitative result which was used for comparison is the completion time of an infusion. This completion time may be either to the complete impregnation of the preform or to the stoppage of the trial by the author. The full impregnation or, in the opposite case, the existence of voids and dry locations following completion of a test was also noted and compared. General flow kinematics and occurrence of major events were also detailed in a log adjoining each test and in a flow progression graphic. Figure 3.40 is an example of such a flow progression graphic. Lessons learned from a single test and from specific test series are detailed in Section 4.2.

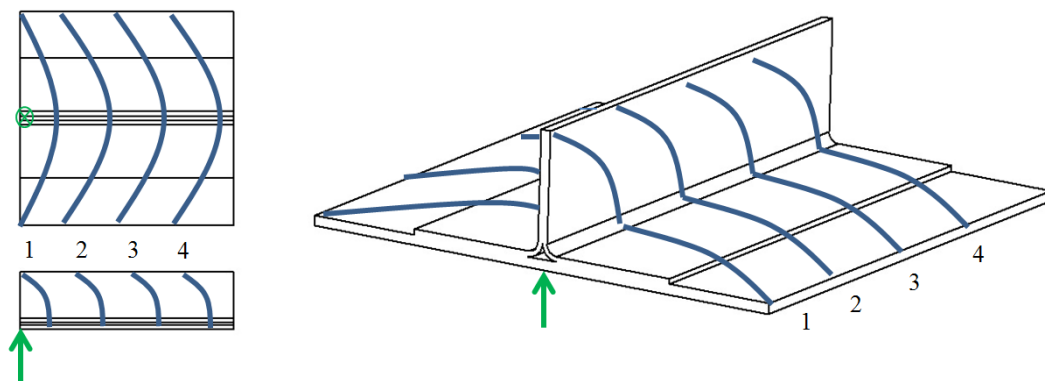


Figure 3.40: TC - Example of Flow Progression Graphic

3.5 Full Scale Demonstrator

3.5.1 Experimental Setup

The primary component of the Full Scale Demonstrator Rig is a 25 mm thick base PMMA plate measuring 1524 by 813 mm (60 x 32 in) onto which the main panel of the dry preform is laid down, allowing visualizing and capturing of simulated resin flow through this base plate, as well as 2 sets of 2 PMMA triangular cross-section braces measuring 1321 mm in length (52 in). The PMMA base rests on a steel frame set on coasters, and the braces are attached to the base. Figure 3.41 shows a CAD rendering and the final rig.



(a) Initial render of Demonstrator Rig



(b) Demonstrator Rig with Shelving

Figure 3.41: Demonstrator Rig

The braces replicate aluminium tooling used by COMP-501 partners for moulding carbon fibre preforms at high temperatures. As such, additional steel stiffeners were mounted in the PMMA braces for increasing their bending stiffness. The braces were made from three layers of 25 mm thick PMMA plates 75mm x 1525 mm glued with #16 weld-on acrylic glue using a wooden press made by the author, Figure 3.42. The original rectangular beams were cut at 45° using a band saw to create 2 triangular beams, which were milled by University technicians into their final shape and polished with a rotary hand

tool leading to the final profile, surface finish and optical transparency. Also shown are the black painted steel stiffeners made of 12.5 mm by 3 mm bar stock cut to length and glued to the PMMA braces using epoxy. Full dimensions of Bracing Assembly and Demonstrator Rig appear in Appendix G.

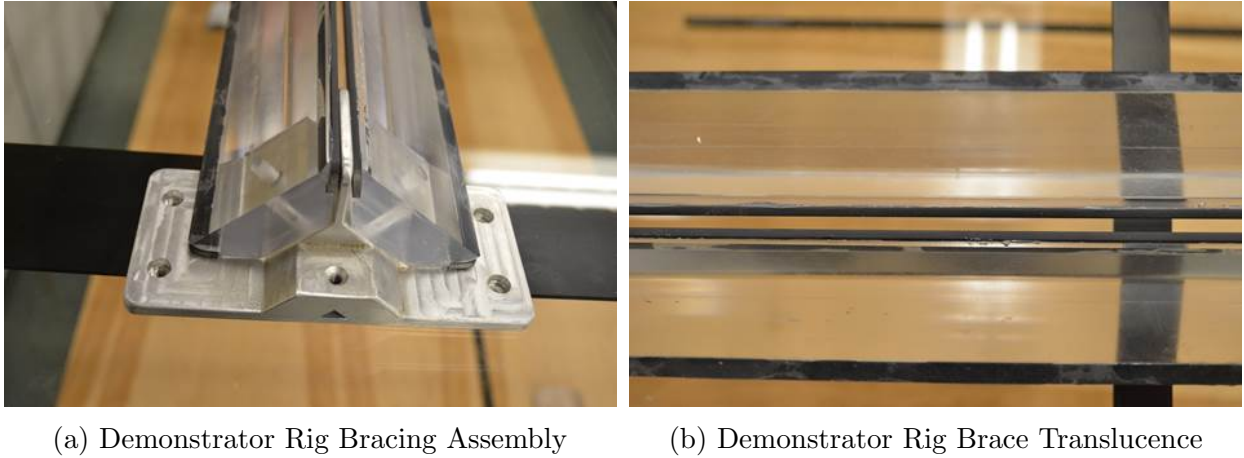


Figure 3.42: Demonstrator Rig Bracing

Holes drilled at both ends of the braces allowed them to be affixed to aluminium T-frames maintaining a 4.3 mm gap between them for housing the preforms sails. The profile of the PMMA braces matches the desired preforms dimensions. The aluminium T-frame is set on a corresponding aluminium lifter which allows clamping of the noodle to maintain tension. A hole tapped for 8-36 UNF thread is located on a flat section on the back of the T-frames, for set screws to pinch the noodle to the lifter plates at both ends. The whole assembly was fixed to the bottom plate via threaded aluminium inserts, 12.5 mm OD and 12.5 mm long, which were epoxied into holes drilled in said plate. 10-32 UNF screws were used for fixing the T-frames in the appropriate location, while 2 more 10-32 UNF bolts were used for attaching the braces to each T-frame. A bracing assembly drawing appears in Figure 3.43.

Two manifolds machined by the author were used for controlling outlets during infusions. They were milled out of aluminium bars to allow up to 5 different outlet lines to culminate into a single tube. Overall dimensions are shown in Appendix G. Holes were

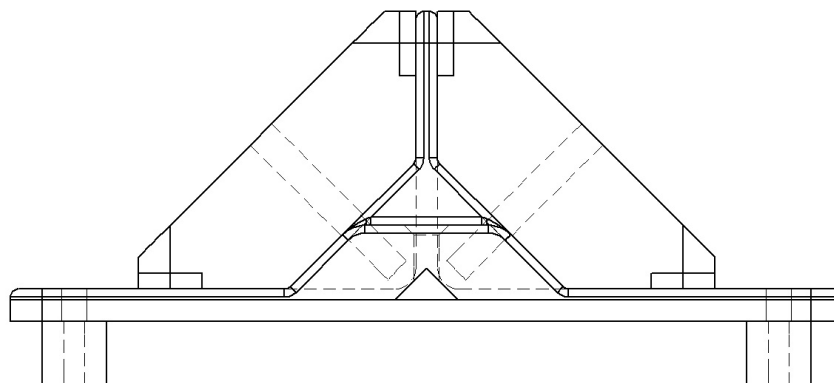


Figure 3.43: Bracing Assembly DWG, T-frame, Lifter and Braces

tapped to 3/8 in NPT standard thread to accept male to male connectors (McMaster Carr PN 5485k23) leading to 5 needle valves (McMaster Carr PN 7824k13) culminating to 3/8 in OD push-to-connect fittings (McMaster Carr PN 5779k117). A 90° elbow push-to-connect fitting (McMaster Carr PN 5779k221) was screwed into the final hole which lead to a tee connector (McMaster Carr PN 5779k36) gathering all outlets towards the vacuum pump, Figure 3.44. Two adjustable easy-set needle valves (McMaster Carr PN 4982k73) were used for controlling the inlet flow rate; flow rate tests of these valves are detailed in Appendix H. Tubing used was extreme temperature Teflon PTFE with 5/16 in ID and 3/8 in OD (McMaster Carr PN 5239k14) alongside Teflon spiral tubing (McMaster Carr PN 7432k114) which matched those used by the high temperature infusion setup of partners.



Figure 3.44: Demonstrator Rig Manifolds and Shut-Off Valves

The manifolds allowed the Full Scale Demonstrator Rig to infuse preforms from a variety of directions; only two of these were used in this work, Figure 3.45. Type #1 infusion features inlets from a single side through the whole length of the sails with vacuum drawn from spiral tubing on either side, center of the preform and at the point of contact between the sail and the skin through the noodle. Figure 3.46 shows the corresponding system diagram. Type #2 infusion features the same inlet setup but line outlets only on the sides and center of the preform. Figure 3.47 shows the corresponding system diagram.

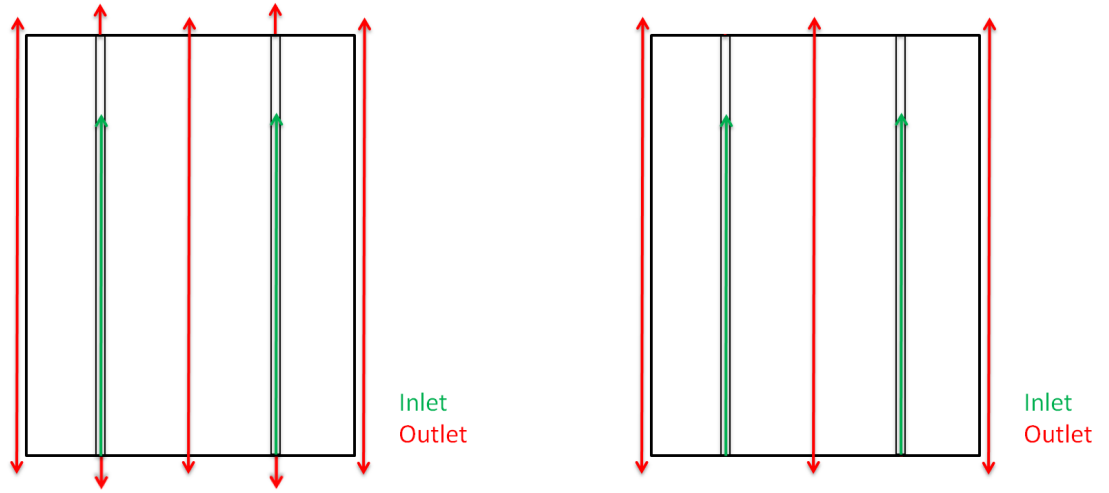
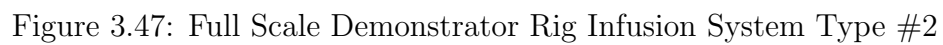
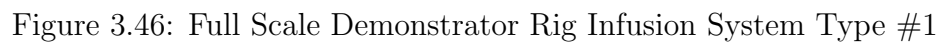


Figure 3.45: Demonstrator Rig infusion diagrams, Inlets from Top of Sails

Camera 1 was used on a tripod for filming the infusion from above, while camera 2 was used for filming from underneath from the shelf. Camera 3 located on a tripod from the side was used for capturing the flow evolution in the vertical sails.



3.5.2 Procedure

Three different trials were performed using the Full Scale Demonstrator Rig. The first two trials were conducted on preforms assembled in-house by the author and as such the process was generally similar in both cases. Minor differences are pointed out where applicable in the Non-Stitched Preform sub-section below. The third trial was performed on a preform stitched at CTT; the procedure is detailed in the CTT Stitched Preform sub-section that follows.

Non-Stitched Preforms:

- Step 1: Layers of woven fabric BFG 1800 are cut following pattern presented in Appendix F, trimmed to length of 600 mm (48 in) instead of the 49 in prescribed by l'ÉTS to fit the rig, Figure 3.48. The stacking sequence used for the first and second trials were Equivalent Quasi (20 plies) and Mod-Equivalent Quasi (18 plies), respectively.

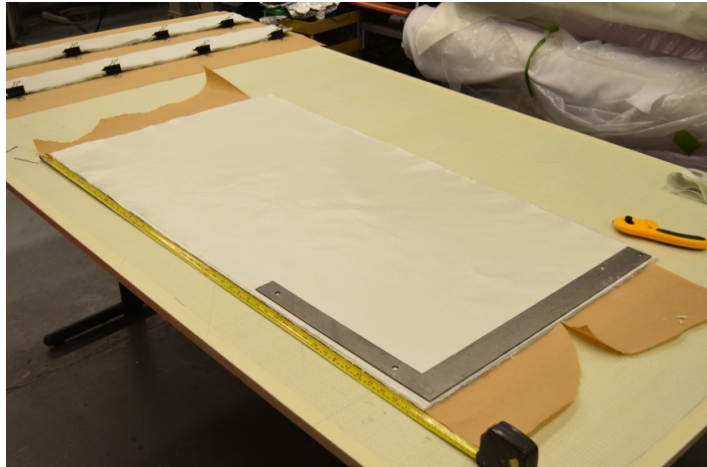


Figure 3.48: Stacking Skin for Full Scale Demonstrator Rig (Step 1)

Step 2: Sails are secured with binder clamps every 10 - 15 in for preventing material from shearing and for maintaining fibre orientation, Figure 3.49. They are stacked in same way as skin, Equivalent Quasi for the first trial and Mod-Equivalent Quasi for the second.

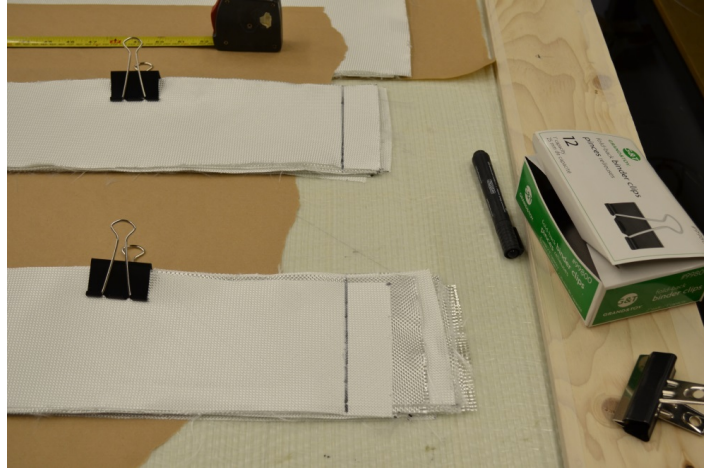


Figure 3.49: Cutting to Length Sails for Full Scale Demonstrator (Step 2)

Step 3: Sail stacks are split down center line and pressed in-between support braces to form sail and its foot. Support braces are bolted to aluminum anchor point so that preform material extends beyond braces edge both at top and at foot, Figure 3.50.

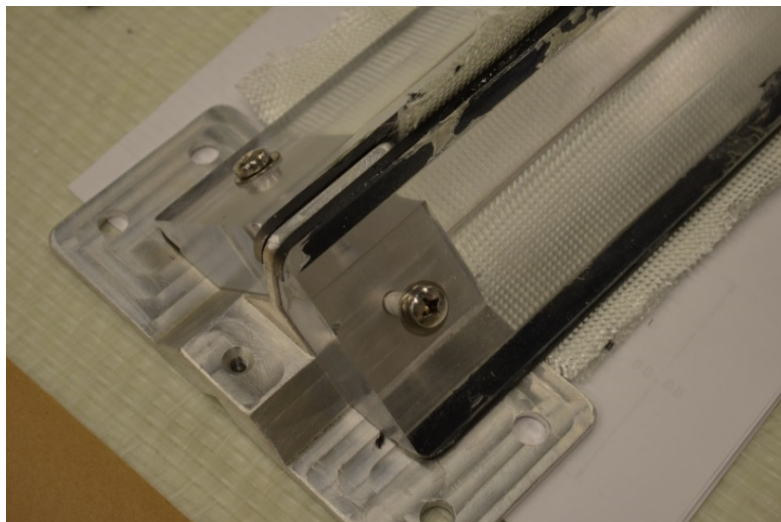


Figure 3.50: Closing Sail in Brace for Full Scale Demonstrator Rig (Step 3)

Step 4: Noodle material is cut to exceed length of preforms (50 in) and held in tension by aluminum anchor, Figure 3.51.



Figure 3.51: Preparing Noodle for Full Scale Demonstrator Rig (Step 4)

Step 5: Skin fabric stack is placed on base plate and centered using measuring tape; noodles are extended along skin and support braces are lowered on top of noodle, which is tensioned, Figure 3.52.

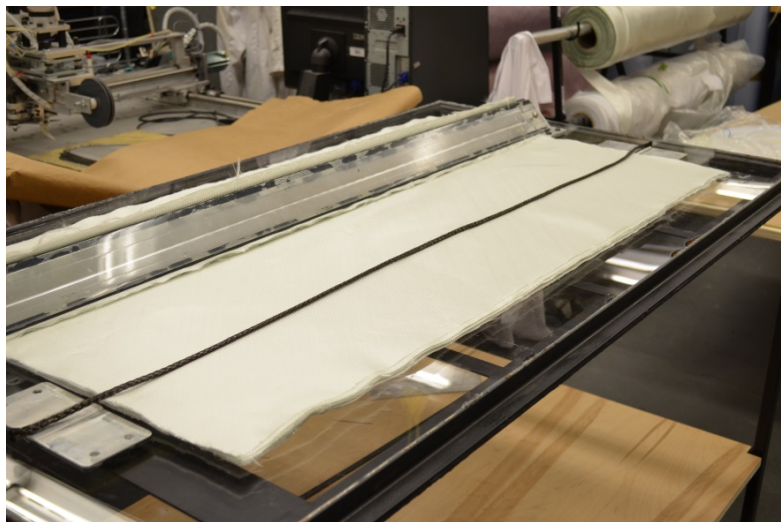


Figure 3.52: Mounting Sails to Full Scale Demonstrator Rig (Step 5)

Step 6: Aluminum anchors are secured to base plate using screws. Preform is trimmed using scissors before bagging, Figure 3.53.



Figure 3.53: Mounted Preform on Full Scale Demonstrator Rig (Step 6)

Step 7: Layer of peel ply is wrapped around spiral tubing and taped to rig's clear surface. Using tacky tape, preform is bagged with bunny ears at tube inlets and outlets as well as location of support beams.

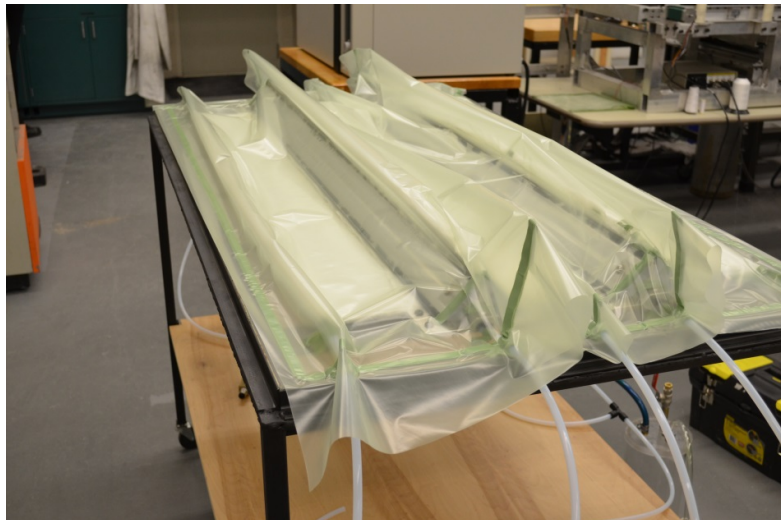


Figure 3.54: Bagging Preform on Full Scale Demonstrator Rig (Step 7)

Step 8: Manifolds are hooked to catch pot and vacuum pump, Figure 3.55.

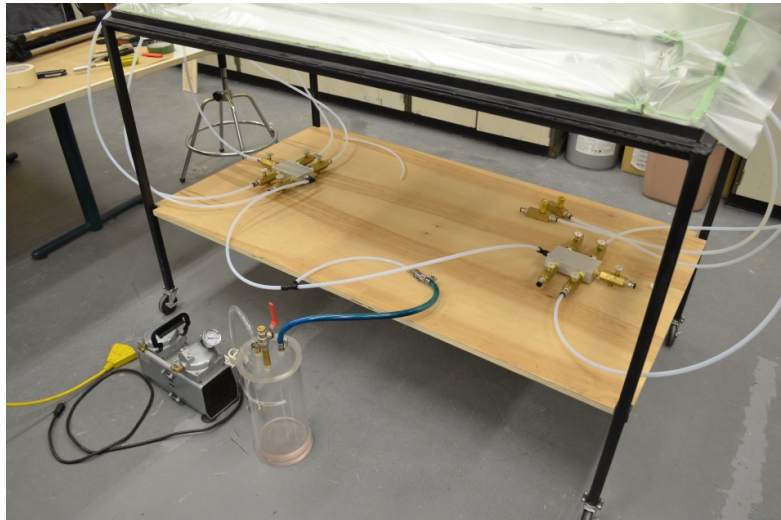


Figure 3.55: Type #1 Infusion Setup (Step 8)

Step 9: Vacuum is pulled to -0.9 bar and bag is inspected for leaks, Figure 3.56.

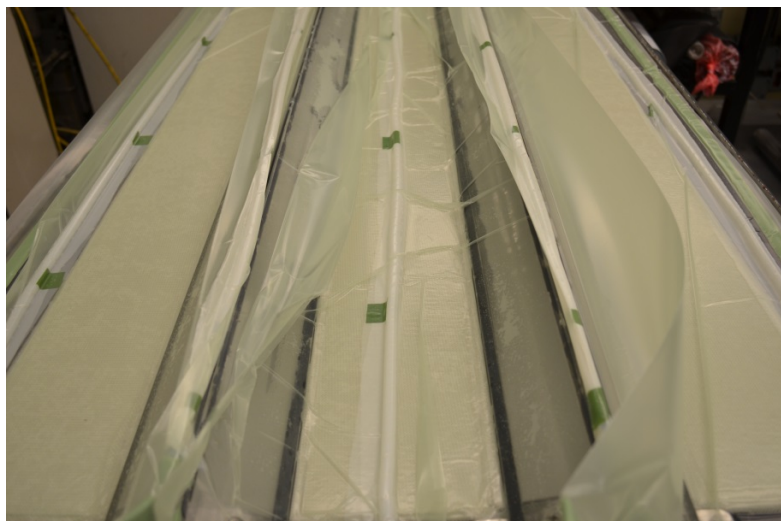


Figure 3.56: Stacking Skin for Full Scale Demonstrator Rig (Step 9)

Stitched Preform:

- Step 1: Lay stitched preform on bottom plate. Figure 3.57 has the left-hand side completed but procedure for either sides is nearly identical.

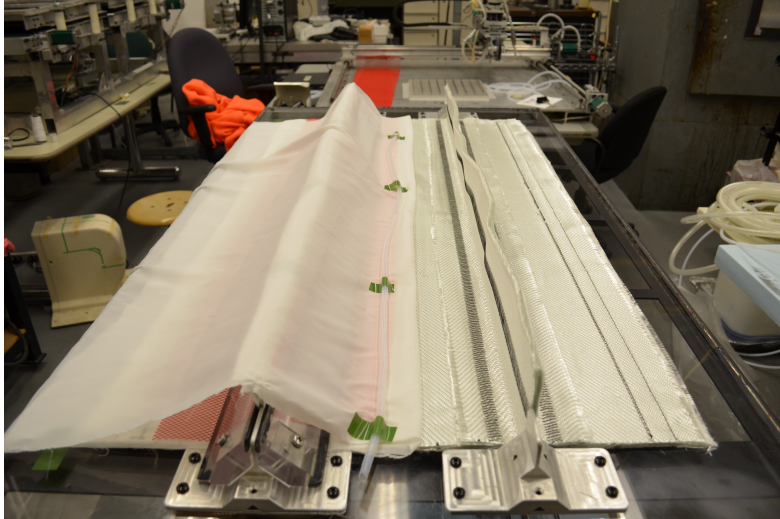


Figure 3.57: Laying Full Scale Demonstrator Preform on Rig (Step 1)

- Step 2: Notable difference between first and second sail is need to create an elevated fold for central outlet tube. This is achieved by taping tubing to peel-ply, Figure 3.58.

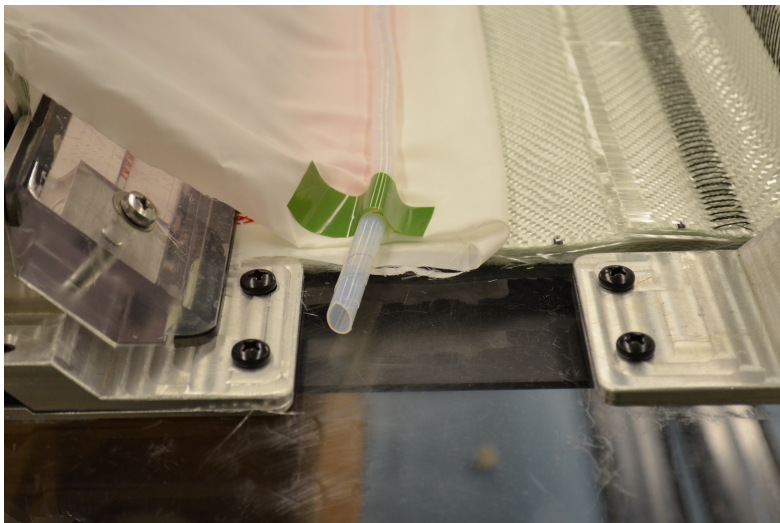


Figure 3.58: Full Scale Demonstrator Rig Central Outlet Fold (Step 2)

Step 3: Peel-ply is draped over sail and spiral tubing used for inlet is taped into place atop sail, Figure 3.59.

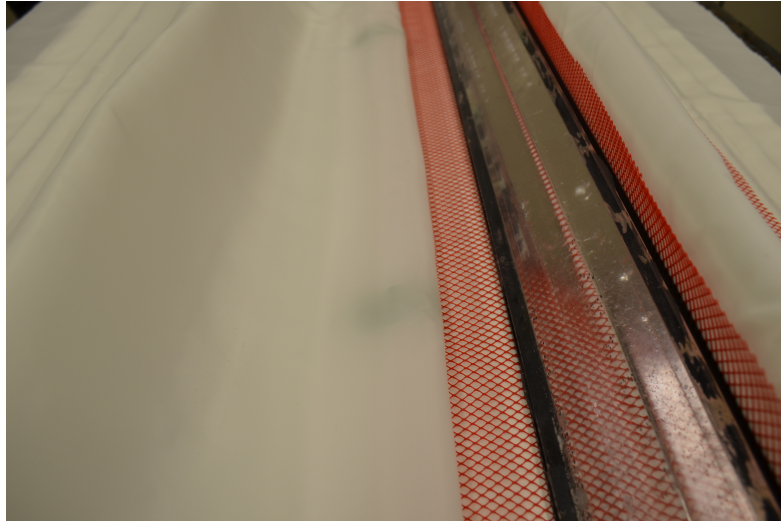


Figure 3.59: Setting Peel-ply Fold and Central Outlet Tubing (Step 3)

Step 4: Flow medium is cut to size and placed on a single side of preform's sail, Figure 3.60.

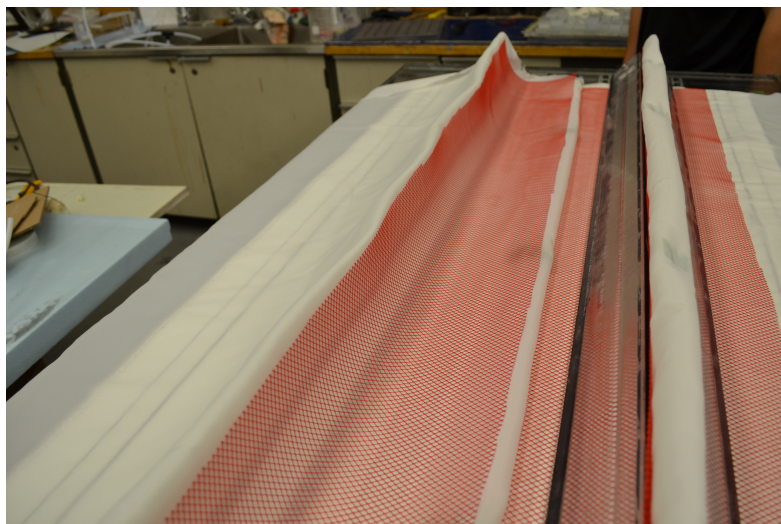


Figure 3.60: Laying Flow Medium on Sail (Step 4)

Step 5: Brace is laid on top of flow medium and secured with screws; note fold for central outlet, Figure 3.61

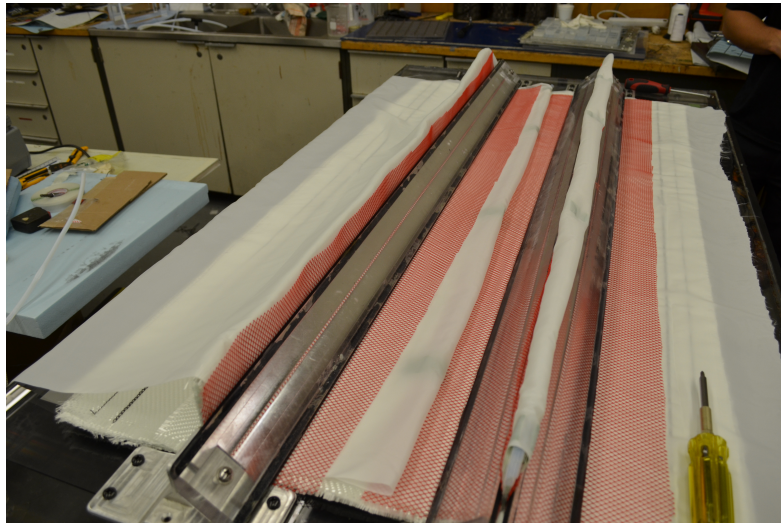


Figure 3.61: Setting Brace Atop Flow Medium (Step 5)

Step 6: Repeat Steps 4 and 5 on opposite side of sail. Use tape to secure side outlets to bottom plate and envelop it in peel-ply, Figure 3.62.

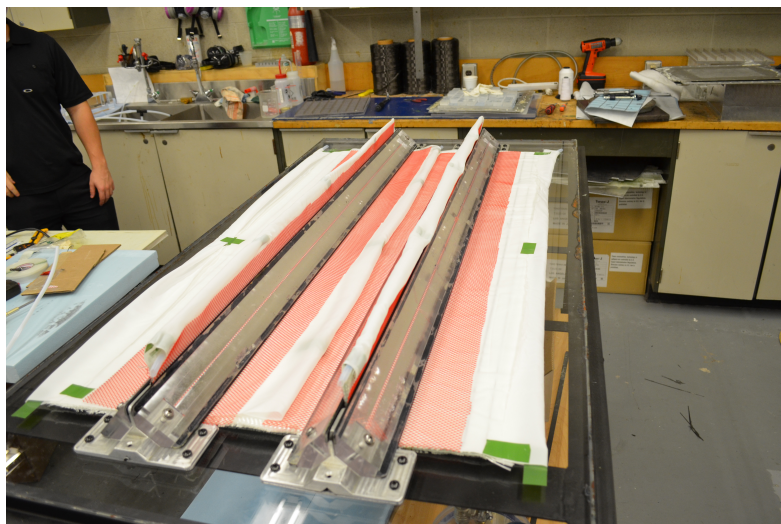


Figure 3.62: Setting Final Brace of Full Scale Demonstrator Rig (Step 6)

Step 7: Setup infusion system tubing as per system diagram, Figure 3.47.

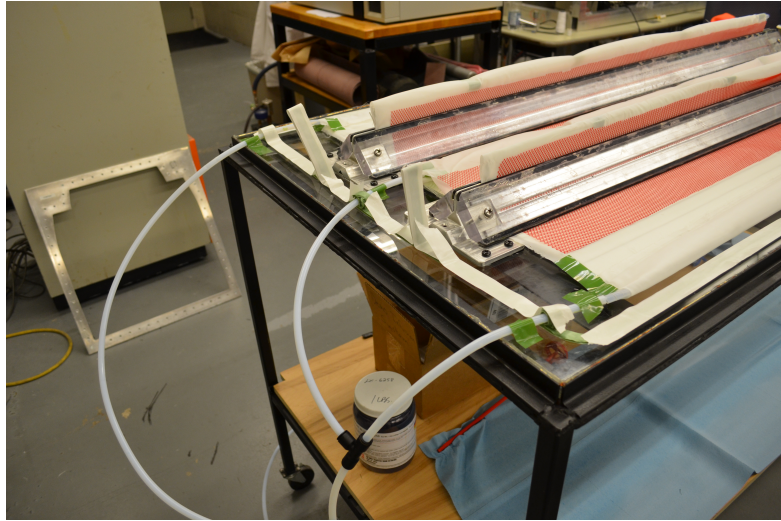


Figure 3.63: Setting Infusion System for Test (Step 7)

Step 8: Cut out appropriate length of vacuum bagging and bag preform as previously shown, Figure 3.64. Pull vacuum to -0.9 bar with inlets plugged, and search for leaks in bagging.

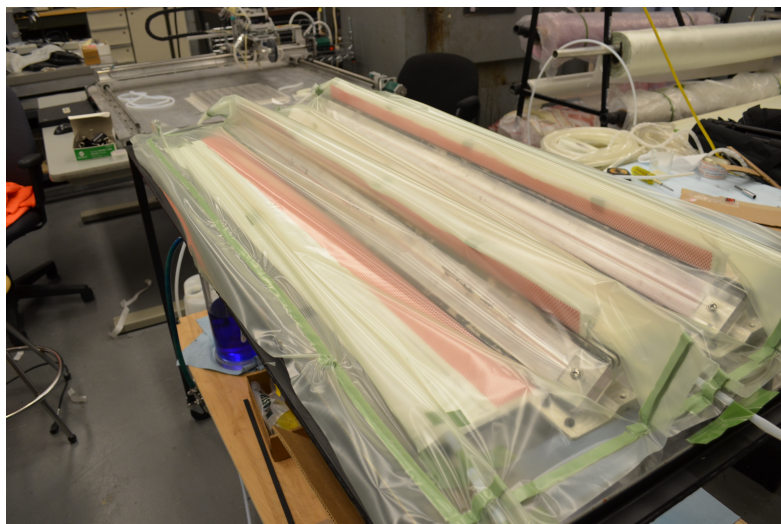


Figure 3.64: Preparing Bagging Material (Step 8)

Infusion Procedure:

- Step 1: Mix dye to oil if necessary, ensure tube is secure in oil container.
- Step 2: Arrange tripods, focus cameras and start recording.
- Step 3: For type #1 infusions set needle valve, Figure 3.46, to a point between red 3 and 4, Appendix H. For type # 2 infusion the clamps holding the tube closed are released and set at the appropriate height to restrict flow, Figure 3.47.
- Step 4: When flow front reaches edge of camera frame, move tripod 1/3rd of the way down preform, repeat as needed.
- Step 5: As oil reaches outlet tubes, close corresponding ball valves in a type #1 infusion and clamp tubing with 3" C-clamps in a type #2 infusion to prevent preferential flow.
- Step 6: When infusion is complete, turn off recording and vacuum pump. Open safety valve to return system to ambient pressure.

For filming purposes, due to the limitation on frame size, only 1 third of the preform appears in shot. As the infusion progresses the camera is moved with the flow front to capture all of its evolution.

3.5.3 Analysis

Video files of the Full Scale Demonstrator rig tests are first matched with the start of infusion and notes taken of camera movement, to ensure that all video captured from different angles can be presented chronologically. Within this trial series, repeats of a infusion protocol type #2 were compared with each other to assess consistency and also compared to infusion protocol type #1 to determine protocol preferability.

The principal quantitative result which was used for comparison is the completion time of an infusion. This completion time may be either to the complete impregnation of the preform or to the stoppage of the trial by the author. The full impregnation or in the

opposite case, the existence of voids and dry locations following completion of a test was also noted and compared. General flow kinematics and occurrence of major events were also detailed in a log adjoining each test and in a flow progression graphic. Figure 3.65 is an example of such a flow progression graphic. Lessons learned from a single test and from specific tests are detailed in Section 4.3.

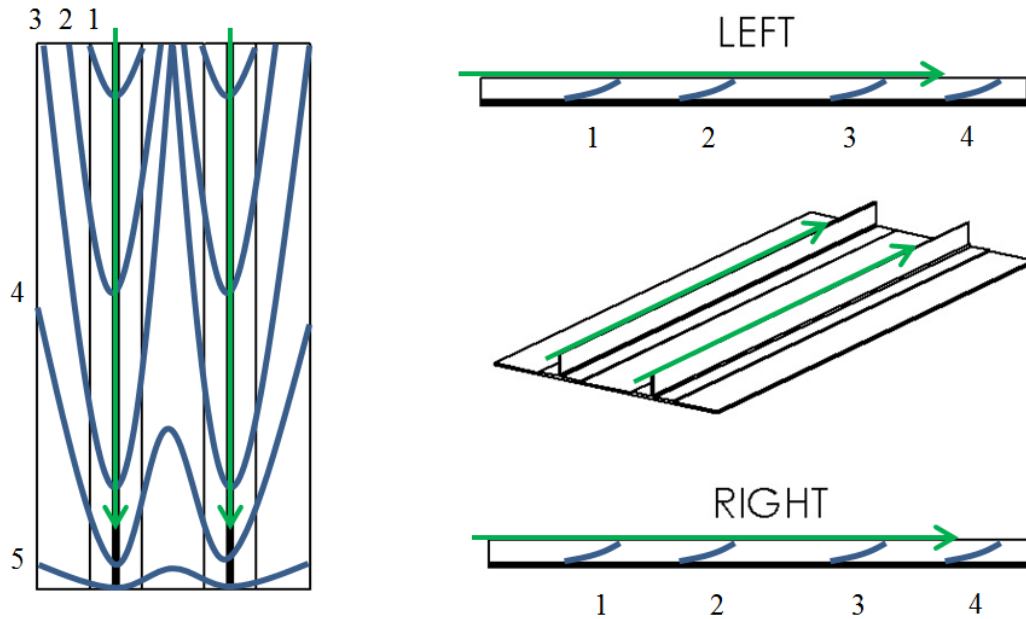


Figure 3.65: FSD - Example of Flow Progression Graphic

Chapter 4

Results

4.1 Permeability Rig Results

For all cases of isotropic flow (T1-B, T1-C, T1-EG and T1-BGF), video evidence was not necessary to calculate the permeability values of the preforms. Instead it was used to ascertain that the flow front was indeed isotropic. In these cases, the DAQ data set was taken and analysed as per the method highlighted in Section 3.3.3 to calculate an average permeability value for each preform type. Of these, 6 points correlating to frames taken from the video data, Appendix C, were tabulated for each trial in this section.

In the case where orthotropic flow was observed (T1-W), the video data was used to ascertain the 2 primary radii of the ellipsis. The orthotropic analysis, also described in Section 3.3.3, was used for analysis. As with the isotropic case, 6 points were used from the test to calculate an average permeability tensor value. Frames taken from videos presented in Appendix C.

Individual test parameters, such as dyes used and the viscosity of the infusion oil, appear in Table 4.1.

Table 4.1: T1 Trial Test Parameters

Test	Viscosity μ (cSt)	Dye Used
T1-EG1	500	EpoDye
T1-EG2	500	EpoDye
T1-BGF	50	Pylakrome Blue
T1-B1	500	EpoDye
T1-C1	500	EpoDye
T1-C2	500	EpoDye
T1-C3	500	EpoDye
T1-W1	50	Pylakrome Blue
T1-W2	50	Pylakrome Blue
T1-W3	50	Pylakrome Blue

4.1.1 Glass Preforms

Stitched Equivalent Quasi Preforms - T1-EG(1-2)

Pressure profiles obtained when testing the stitched glass preforms used as an equivalent to the carbon preforms, Figure 4.1.

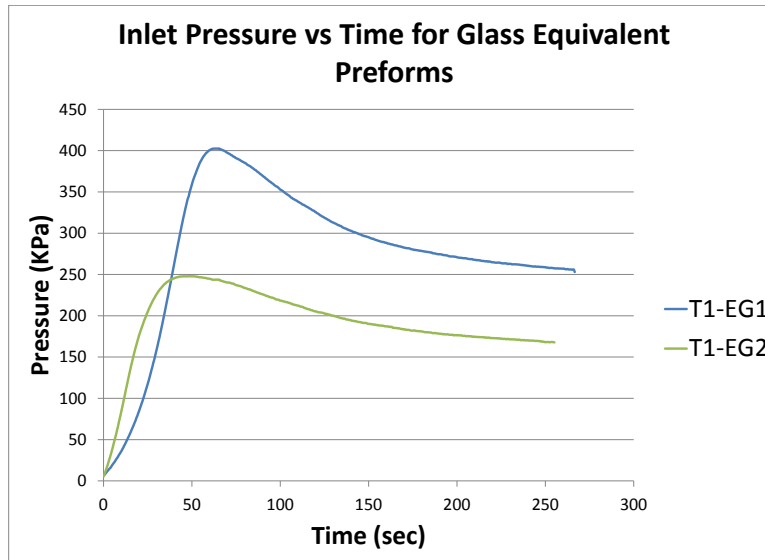


Figure 4.1: Stitched Equivalent Quasi Glass Preforms Inlet Pressure Profiles

Tables 4.2 and 4.3 show 6 points from each pressure curve, the calculated radius and associated permeability value.

Table 4.2: Permeability Values for T1-EG1

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
40	2.65E+05	7.58E-02	8.01E-08
80	3.85E+05	1.06E-01	6.75E-08
120	3.26E+05	1.29E-01	8.86E-08
160	2.88E+05	1.49E-01	1.07E-07
200	2.71E+05	1.66E-01	1.20E-07
240	2.61E+05	1.82E-01	1.30E-07

Table 4.3: Permeability Values for T1-EG2

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
40	2.45E+05	7.58E-02	8.63E-08
80	2.31E+05	1.06E-01	1.12E-07
120	2.04E+05	1.29E-01	1.42E-07
160	1.85E+05	1.49E-01	1.67E-07
200	1.76E+05	1.66E-01	1.85E-07
240	1.69E+05	1.82E-01	1.99E-07

Table 4.4, details the overall average permeability for the Glass Equivalent preforms, the standard deviation and error observed, as well as the sample size. As can be seen, the standard error from these results is two orders of magnitude smaller than the calculated permeability value.

Table 4.4: Permeability of Equivalent Glass Preforms

Average Permeability $\bar{K}$ (m^2)	1.31E-07
Standard Deviation s (m^2)	5.64E-08
Standard Error SE_k (m^2)	1.76E-09
Sample Size N_k	1027

Plain Weave 2 Quasi Preform - T1-BGF1

Pressure profile of Plain Weave 2 preform used in the full scale demonstrator, Figure 4.2.

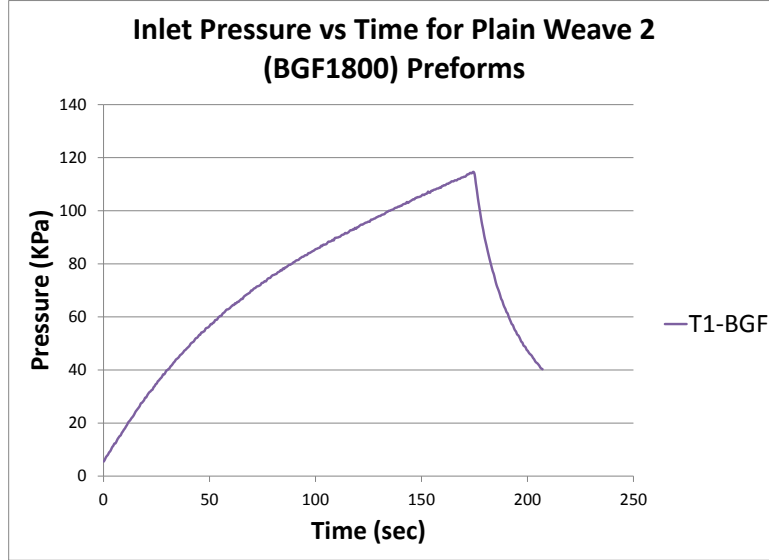


Figure 4.2: Plain Weave 2 (BGF1800) Inlet Preform Pressure Profile

Table 4.5 shows 6 point taken from the pressure curve, the calculated radius and associated permeability value.

Table 4.5: Permeability Values for T1-BGF

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
30	4.00E+04	6.00E-02	4.46E-08
60	6.38E+04	8.31E-02	3.53E-08
90	8.07E+04	1.01E-01	3.14E-08
120	9.38E+04	1.16E-01	2.91E-08
150	1.06E+05	1.30E-01	2.73E-08
180	8.87E+04	1.42E-01	3.40E-08

Table 4.6, details the overall average permeability for the Glass Equivalent preforms, the standard deviation and error observed, as well as the sample size. The standard error for this test exceeds the calculated permeability value, which could be attributed to a lower sample size, but may also be attributed to a potential air pocket in the piston and tubes during infusion, altering the expected pressure profile.

Table 4.6: Permeability of Plain Weave 2 Glass Preforms

Average Permeability $\bar{K}$ (m^2)	3.97E-08
Standard Deviation s (m^2)	1.99E-04
Standard Error SE_k (m^2)	9.79E-06
Sample Size N_k	415

4.1.2 Carbon Preforms

The carbon preforms proved too tightly woven and the dyes would be filtered out of the oil. As such, usage of the dyes is not apparent in the videos taken.

Carbon Quasi Preform Baseline - T1-B1

Pressure profile of the Baselin Carbon preform, Figure 4.3.

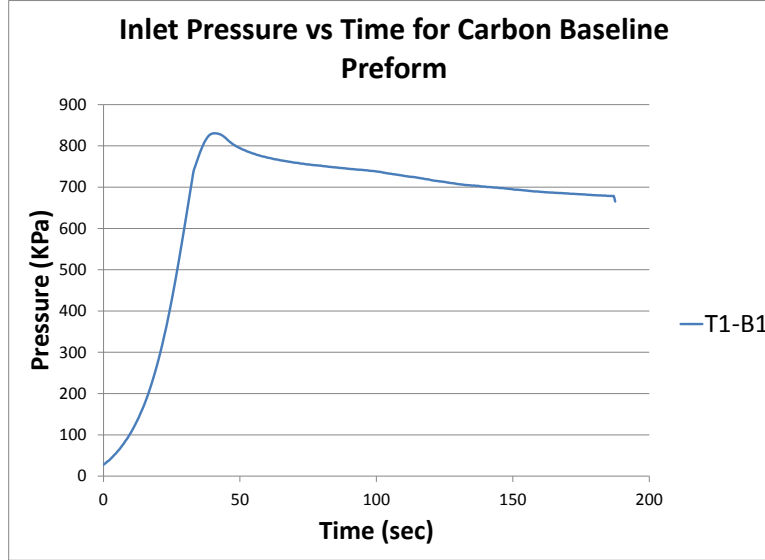


Figure 4.3: Carbon Baseline Preform Inlet Pressure Profile

Table 4.7 shows 6 point taken from the pressure curve, the calculated radius and associated permeability value.

Table 4.7: Permeability Values for T1-B1

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
30	6.17E+05	6.45E-02	3.06E-08
60	7.72E+05	8.95E-02	3.06E-08
90	7.44E+05	1.09E-01	3.55E-08
120	7.17E+05	1.25E-01	3.97E-08
150	6.95E+05	1.40E-01	4.32E-08
180	6.81E+05	1.53E-01	4.60E-08

Table 4.8, details the overall average permeability for the Glass Equivalent preforms, the standard deviation and error observed, as well as the sample size. The smaller sample size could affect the precision of this result.

Table 4.8: Permeability of Carbon Quasi Preforms

Average Permeability $\bar{K}$ (m^2)	4.43E-08
Standard Deviation s (m^2)	8.99E-08
Standard Error SE_k (m^2)	4.64E-09
Sample Size N_k	376

Stitched Carbon Quasi Preforms - T1-C(1-3)

Pressure profile of the Stitched Carbon preforms, as seen in Figure 4.4 the pressure profile for T1-C1 varied noticeably from the other two, though the calculated permeability were similar.

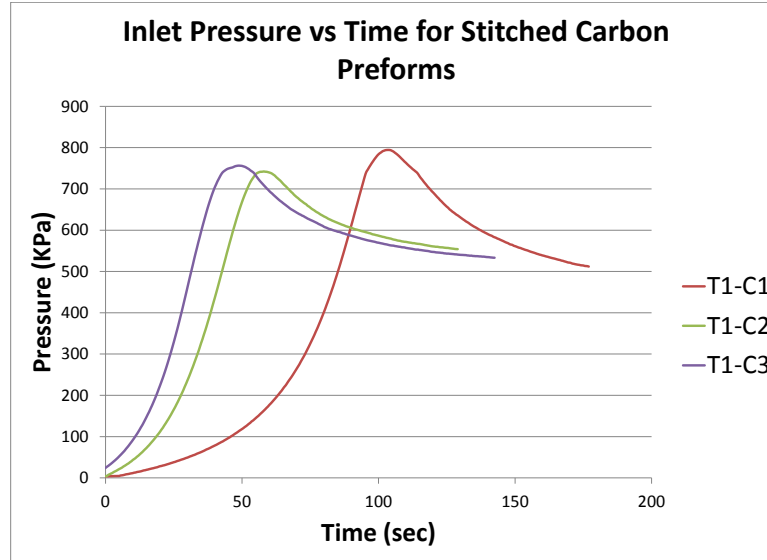


Figure 4.4: Stitched Carbon Preforms Inlet Pressure Profiles

Tables 4.9, 4.10 and 4.11 show 6 point taken from the pressure curve, the calculated radius and associated permeability value.

Table 4.9: Permeability Values for T1-C1

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
30	4.92E+04	6.45E-02	3.83E-07
60	1.77E+05	8.95E-02	1.33E-07
90	6.11E+05	1.09E-01	4.32E-08
120	6.91E+05	1.25E-01	4.11E-08
150	5.61E+05	1.40E-01	5.35E-08
177	5.12E+05	1.52E-01	6.09E-08

Table 4.10: Permeability Values for T1-C2

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
20	1.12E+05	5.36E-02	1.44E-07
40	4.35E+05	7.38E-02	4.78E-08
60	7.40E+05	8.95E-02	3.19E-08
80	6.33E+05	1.03E-01	4.04E-08
100	5.87E+05	1.15E-01	4.63E-08
120	5.61E+05	1.25E-01	5.07E-08

Table 4.11: Permeability Values for T1-C3

Time (sec)	Inlet Pressure (Pa)	Radius r_f (m)	Permeability Value $K(P_{0,t})$ (m^2)
25	3.29E+05	5.93E-02	5.37E-08
50	7.56E+05	8.20E-02	2.95E-08
75	6.25E+05	9.97E-02	4.02E-08
100	5.70E+05	1.15E-01	4.77E-08
125	5.43E+05	1.28E-01	5.29E-08
142	5.33E+05	1.36E-01	5.56E-08

Table 4.12 details the overall average permeability for the Stitched Carbon preforms, the standard deviation and error observed, as well as the sample size. The standard error is two orders of magnitudes smaller than the permeability value.

Table 4.12: Permeability of Stitched Carbon Quasi Preforms

Average Permeability $\bar{K}$ (m^2)	1.26E-07
Standard Deviation s (m^2)	2.19E-07
Standard Error SE_k (m^2)	7.30E-09
Sample Size N_k	900

3D Woven Carbon T1-W(1-3)

Pressure profile of the Stitched Carbon preforms, as seen in Figure 4.5 the pressure profile for T1-W1 varied noticeably from the other two, this may have been caused by air in the tubing or piston during the infusion.

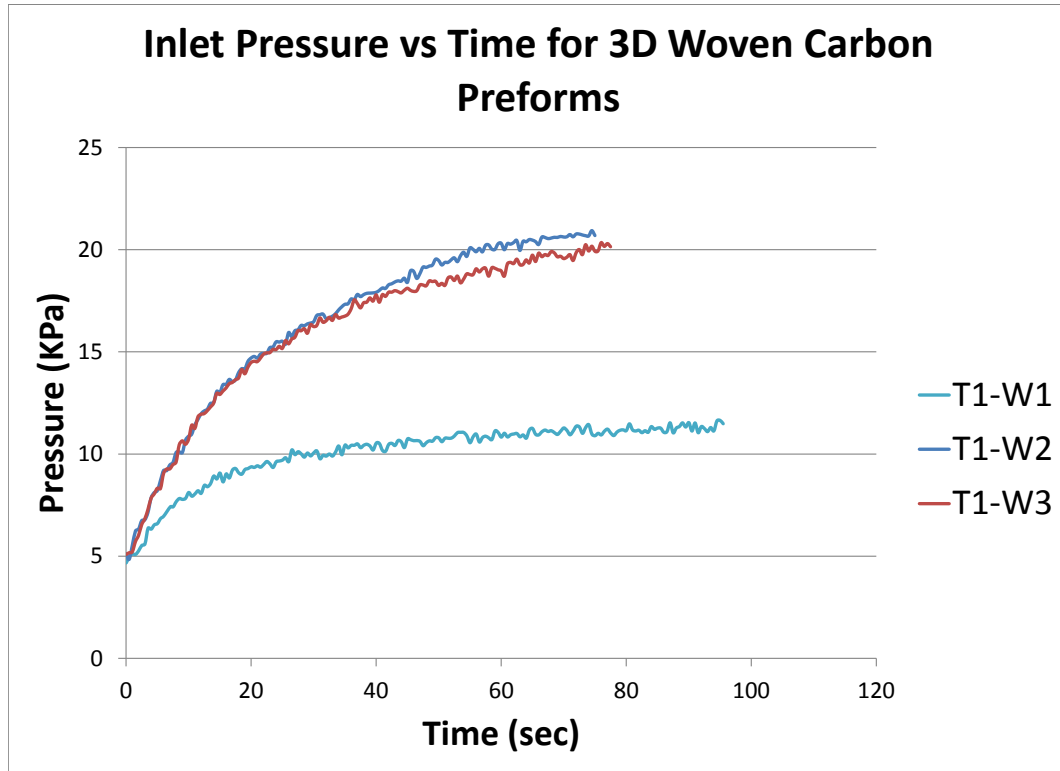


Figure 4.5: 3D Woven Carbon Preforms Inlet Pressure Profiles

Table 4.13 shows the 6 points taken from each pressure curve and the associated radii measured from the video data.

Table 4.13: T1-W Flow Front Radii and Inlet Pressures

T1-W1			
Time (sec)	r_x (m)	r_y (m)	Inlet Pressure (Pa)
15	0.04453	0.11415	9.07E+03
30	0.07015	0.17483	1.01E+04
45	0.08659	0.21013	1.07E+04
60	0.09352	0.23785	1.08E+04
75	0.10696	0.26685	1.09E+04
90	0.11618	0.29101	1.15E+04
T1-W2			
Time (sec)	r_x (m)	r_y (m)	Inlet Pressure (Pa)
12	0.04717	0.08743	1.20E+04
24	0.07361	0.16792	1.55E+04
36	0.08857	0.20589	1.76E+04
48	0.09970	0.23719	1.91E+04
60	0.12306	0.25649	2.03E+04
72	0.12883	0.27950	2.08E+04
T1-W3			
Time (sec)	r_x (m)	r_y (m)	Inlet Pressure (Pa)
12	0.04255	0.08743	1.19E+04
24	0.07247	0.16563	1.51E+04
36	0.08857	0.20477	1.71E+04
48	0.10582	0.23810	1.82E+04
60	0.12192	0.25763	1.90E+04
72	0.13345	0.27960	1.99E+04

From the method explained in Section 3.3.3, the slope of the best-fit line of r_y with respect to r_x is found on Figure 4.6.

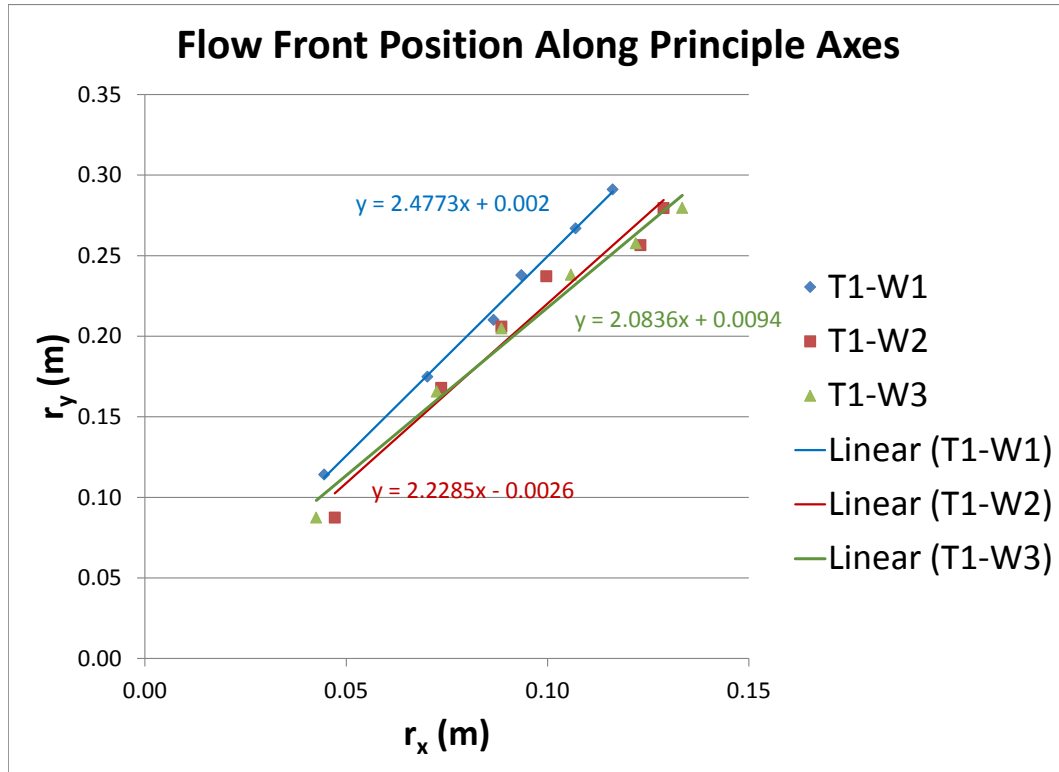


Figure 4.6: Flow Front Position Along Principal Axes

Table 4.14 relates the natural logarithm of the equivalent isotropic system radius to the inlet pressure for the 6 selected points.

Table 4.14: Natural Logarithm of EIS Radius with its Respective X Axis Radius

T1-W1			
Time (sec)	r_x (m)	$\ln(r_{ex})$ (m)	Inlet Pressure (Pa)
15	0.04453	-2.65809	9.07E+03
30	0.07015	-2.20347	1.01E+04
45	0.08659	-1.99300	1.07E+04
60	0.09352	-1.91597	1.08E+04
75	0.10696	-1.78172	1.09E+04
90	0.11618	-1.69903	1.15E+04
T1-W2			
Time (sec)	r_x (m)	$\ln(r_{ex})$ (m)	Inlet Pressure (Pa)
12	0.04717	-2.65331	1.20E+04
24	0.07361	-2.20825	1.55E+04
36	0.08857	-2.02323	1.76E+04
48	0.09970	-1.90491	1.91E+04
60	0.12306	-1.69433	2.03E+04
72	0.12883	-1.64854	2.08E+04
T1-W3			
Time (sec)	r_x (m)	$\ln(r_{ex})$ (m)	Inlet Pressure (Pa)
12	0.04255	-2.79014	1.19E+04
24	0.07247	-2.25759	1.51E+04
36	0.08857	-2.05692	1.71E+04
48	0.10582	-1.87900	1.82E+04
60	0.12192	-1.73734	1.90E+04
72	0.13345	-1.64697	1.99E+04

Following the orthotropic analysis method, the slope of the inlet pressure plotted with respect to the natural logarithm of the EIS radius is determined, Figure 4.7.

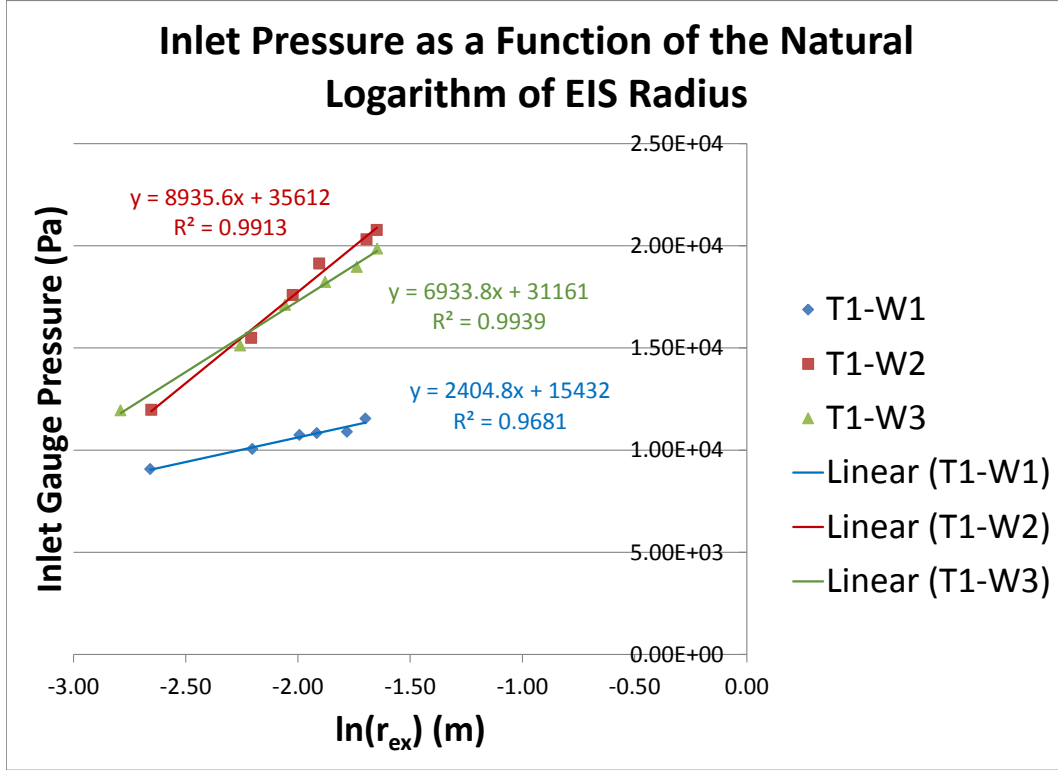


Figure 4.7: Flow Front Position Along Principle Axes

With both slopes and the equivalent permeability, the tensor components forming the permeability tensor are calculated, Table 4.15.

Table 4.15: Permeability Tensor Components

Preforms	m_1	m_2	K_e	K_x	K_y
T1-W1	2.4773	2404.8	5.99E-07	2.42E-07	1.48E-06
T1-W2	2.2288	8935.6	1.61E-07	7.23E-08	3.59E-07
T1-W3	2.0836	6933.8	2.08E-07	9.97E-08	4.33E-07

The individual permeability tensors for each preform are:

T1-W1:

$$[K] = \begin{pmatrix} 2.42 & 0 \\ 0 & 14.8 \end{pmatrix} \cdot 10^{-7} m^2 \quad (4.1)$$

T1-W2:

$$[K] = \begin{pmatrix} 7.23 & 0 \\ 0 & 35.9 \end{pmatrix} \cdot 10^{-8} m^2 \quad (4.2)$$

T1-W3:

$$[K] = \begin{pmatrix} 9.97 & 0 \\ 0 & 43.3 \end{pmatrix} \cdot 10^{-8} m^2 \quad (4.3)$$

Results for T1-W1 may not be representative of preform permeability, air in the piston and tubing may have caused a drop in inlet pressure.

4.2 Translucent Cavity Rig Results

Within each trial series, tests are grouped by configurations of inlets and outlets used during infusion. Each test was analysed independently and then compared directly with repeat tests of the same configuration. When differing inlet and outlet configurations are present within a series, the various infusion protocols are compared with each other. Lessons learned from a series are then gathered and presented, with the follow up objectives for the next test series.

4.2.1 Plain Weave Glass - Lockstitch T2-G(1-6)

Inlet and outlet configurations tested in series T2-G are detailed in Figure 4.8.

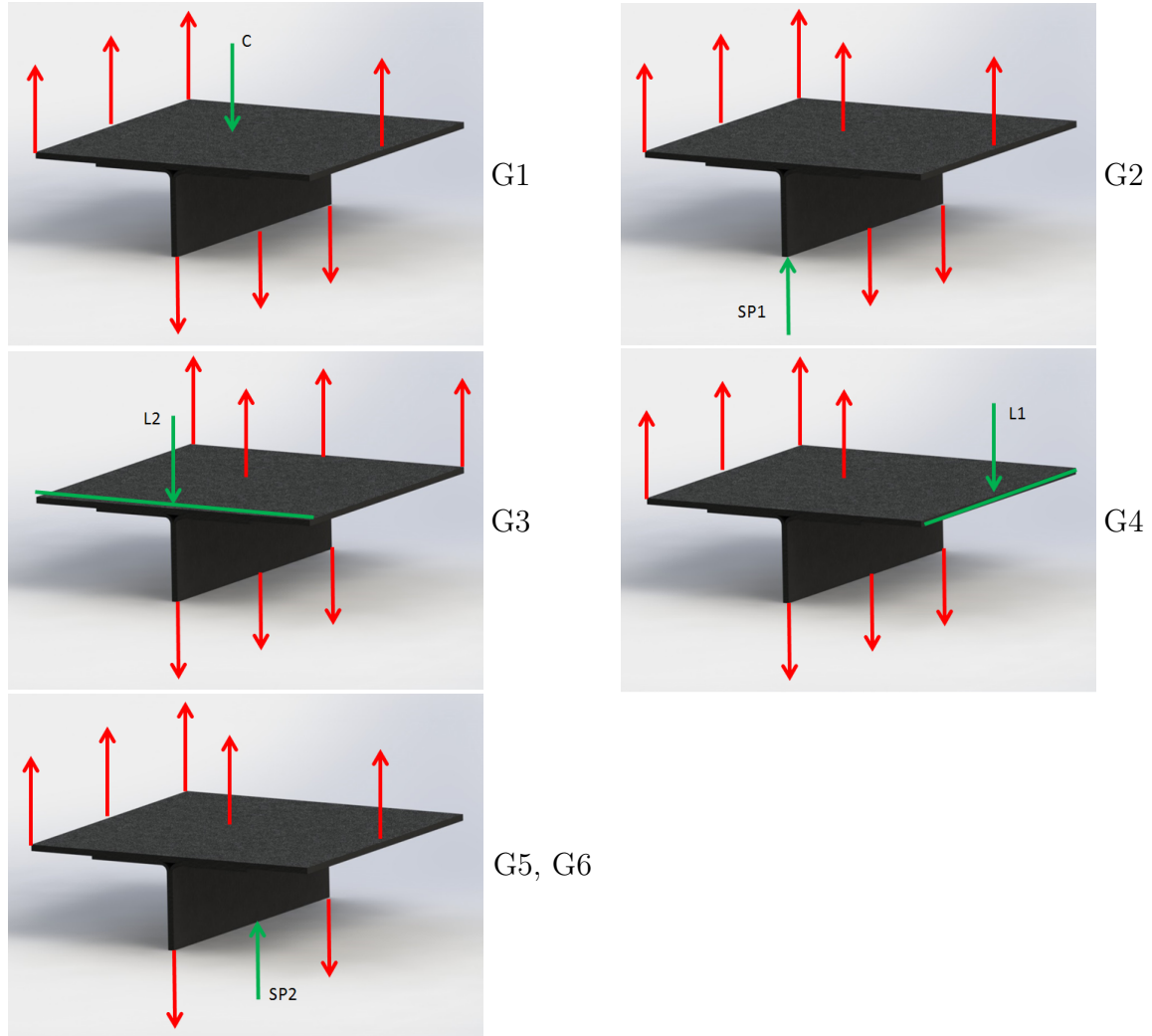


Figure 4.8: T2 Series Inlet and Outlet Configurations

Central Inlet Configuration (C)

Table 4.16: T2-G1 Detailed Report

Material:	Plain Weave 1	Oil Viscosity:	50 cSt
Complete Infusion:	no	Elapsed Time:	20:00

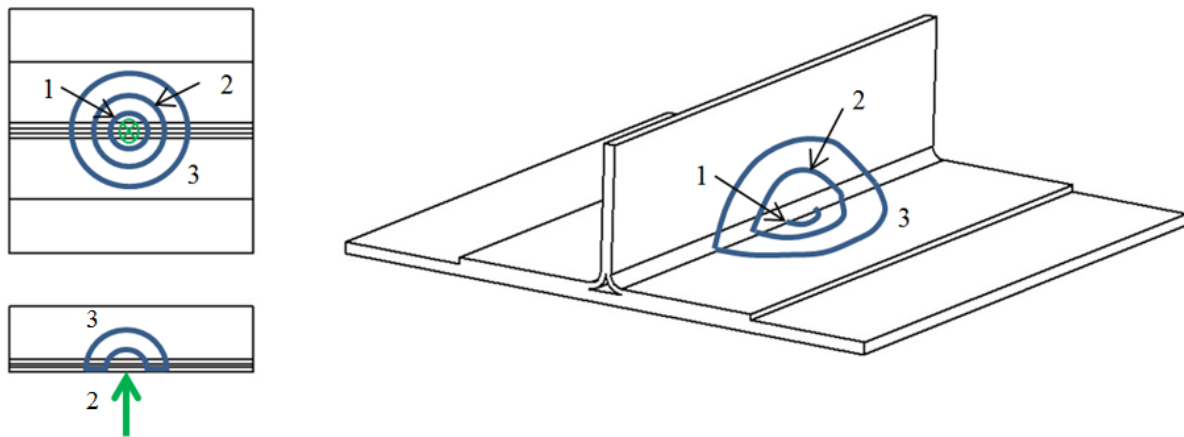


Figure 4.9: T2-G1 Flow Diagram

Kinematic-Defining events:

1. 03:00 Fluid spreads in circular fashion from center point inlet; no visible shooting of fluid along the noodle.
2. 16:00 Front spreads circularly into sail as well.
3. 20:00 Final position of flow front.

Notes:

Test stopped at 20:00 min. Infusion incomplete, single port infusion under vacuum does not create sufficient pressure gradient to move fluid throughout preform.

Sail Corner Inlet Configuration (SP1)

Table 4.17: T3-MEG2 Parameters

Material:	Plain Weave 1	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	05:32

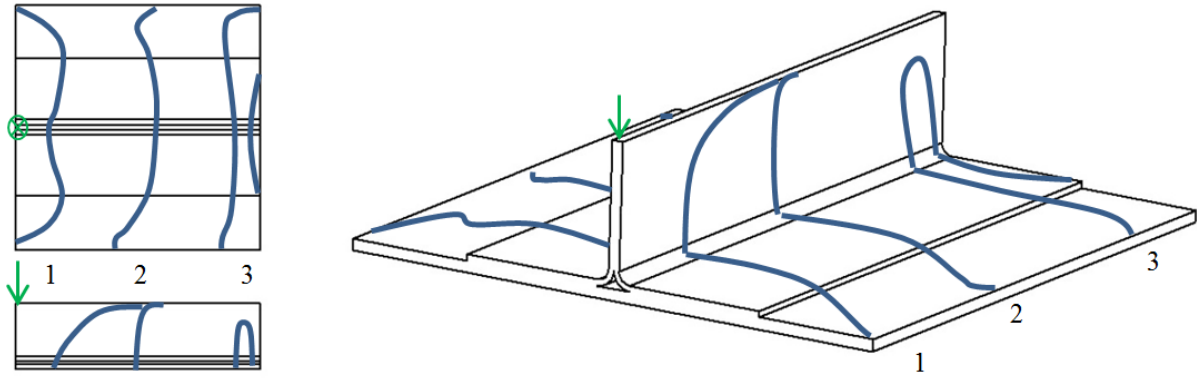


Figure 4.10: T2-G2 flow diagram

Kinematic-Defining events:

1. 01:00 Fluid flows faster along sail's edge than preform.
2. 02:00 Flow along the edge slows down as fluid is drawn in SP2.
3. 05:00 Past SP2 outlet racetracking resumes and creates a pocket on sail and skin.

Notes:

Completed in 5:32. Racetracking along the tip of the sail and then down to the skin creates a pocket between 2 fronts though the preform was fully wetted.

Line Inlet Configuration Along Sail (L2)

Table 4.18: T2-G3 Parameters

Material:	Plain Weave 1	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	02:13

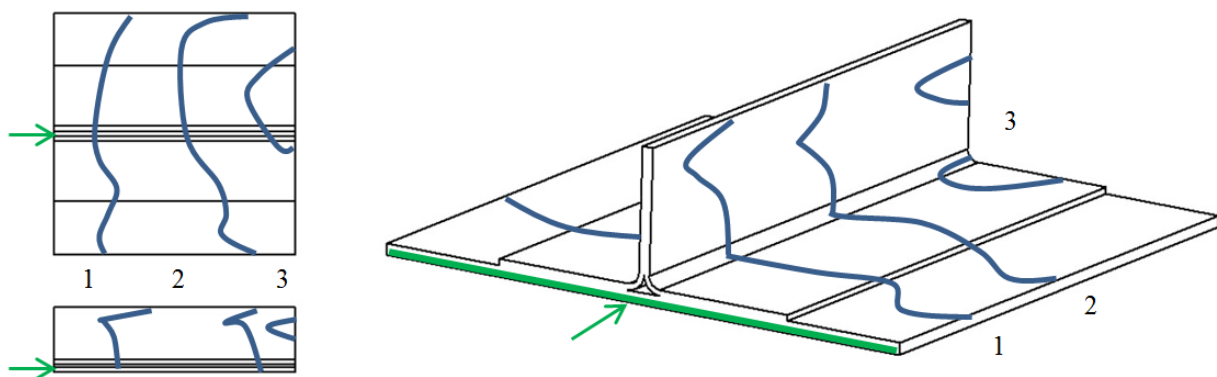


Figure 4.11: T2-G3 Flow Diagram

Kinematic-Defining events:

1. 00:20 Fluid racetracks along edge of sail and skin keeping the front in both parts equal.
2. 00:40 Slight racetracking at all edges, constant front.
3. 01:40 Separate pockets form on sail and skin.

Notes:

Completed in 2:13. Rapid infusion compared to prior tests. Shooting through the noodle and racetracking along the sail's edge created pockets which were fully infused by end of test on the opposite edge of the preform from the infusion line.

Line Inlet Configuration Parallel to Sail (L1)

Table 4.19: T2-G4 Parameters

Material:	Plain Weave 1	Oil Viscosity:	500 cSt
Complete Infusion:	yes	Elapsed Time:	09:04

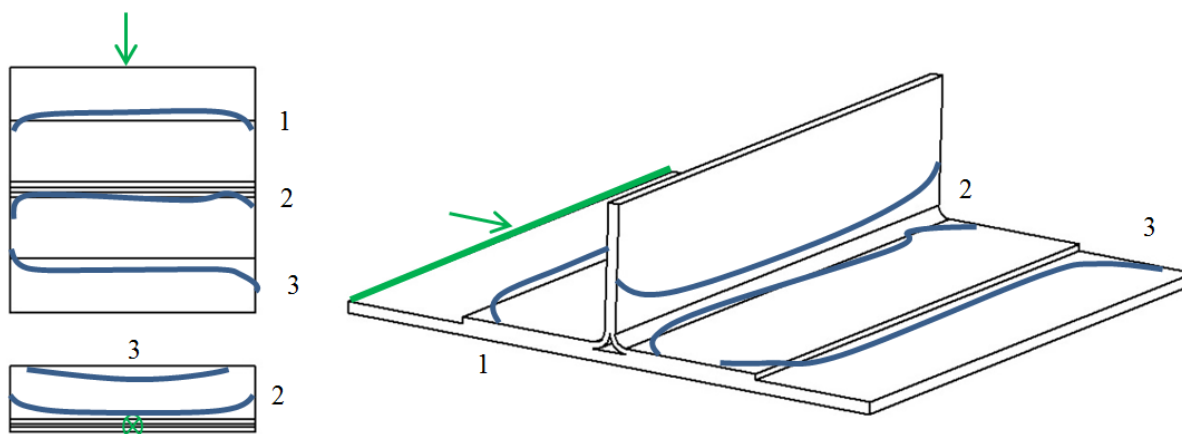


Figure 4.12: T2-G4 Flow Diagram

Kinematic-Defining events:

1. 00:30 Even flow front through skin.
2. 02:00 Separation of fronts down the sail and continuing in skin.
3. 05:00 Slight racetracking along right edge of skin.

Notes:

Completed in 9:04. Sail completed at 5:45. Oil used was 500 cSt. Slight racetracking along one edge of the preform, consistent and uniform infusion otherwise.

Center Sail Inlet Configuration (SP2)

Table 4.20: T2-G5 Parameters

Material:	Plain Weave 1	Oil Viscosity:	50 cSt
Complete Infusion:	no	Elapsed Time:	01:10

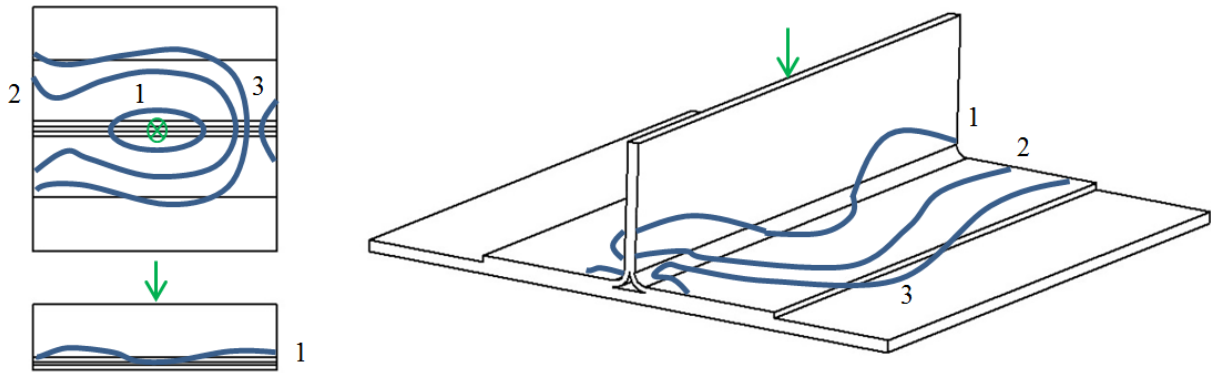


Figure 4.13: T2-G5 Flow Diagram

Kinematic-Defining events:

1. 00:20 Flow front is hemispherical from SP2 but racetracking along either edges out paces central front.
2. 00:45 Flow front expands through the skin radially from the sail.
3. 01:10 Flow front continues progression until loss of vacuum.

Notes:

Test stopped at 1:10, tube frayed and burst. Peel ply was used to cover the preform as it would in the moulding process of the composite parts.

Table 4.21: T2-G6 Parameters

Material:	Plain Weave 1	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	01:25

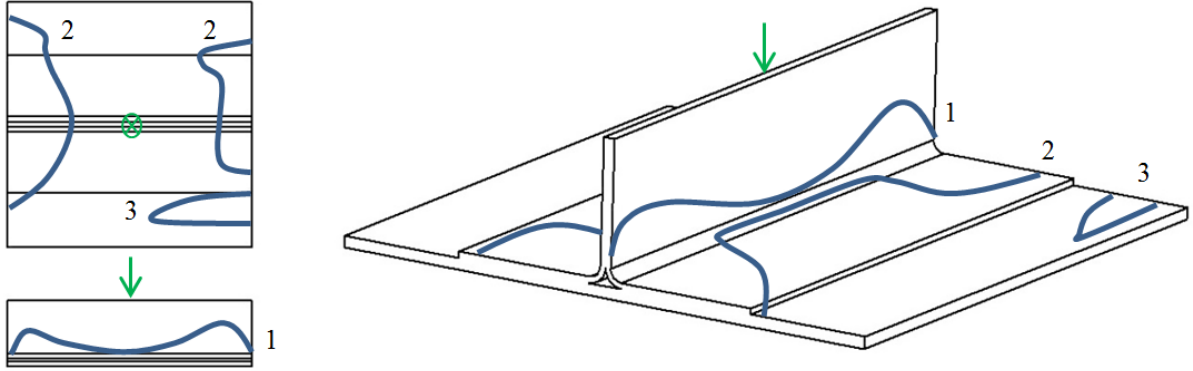


Figure 4.14: T2-G6 Flow Diagram

Kinematic-Defining events:

1. 00:05 Flow front is hemispherical from SP2 but racetracking along either edges out paces central front.
2. 00:35 Flow front pierces through to the skin from either sides but not through the center initially.
3. 01:15 Flow front continues unabated on the far side of preform but race-tracking creates a pocket on the skin on the closer side.

Notes:

Completed in 1:25. Noodle had 22 strands of carbon, for a lower density, this could explain why at event time 2, the flow front if the fluid was shooting through the noodle and bypassing the skin of the preform.

Lessons Learned

Central port like infusions in VARTM do not perform well because the small pressure difference does not impart enough velocity to the fluid in the small inlet. Line inlet infusions provide the most consistent flow fronts. Infusing from the sail's edge is akin to using a line inlet due to the racetracking along the edges. A lower density noodle acts as a pathway for fluid impeding flow front progression through the center of the preform and should be avoided.

4.2.2 Mod Equivalent Quasi Lockstitch T3-MEG(1-8)

Inlet and outlet configurations tested in series T3-MEG are detailed in Figure 4.15.

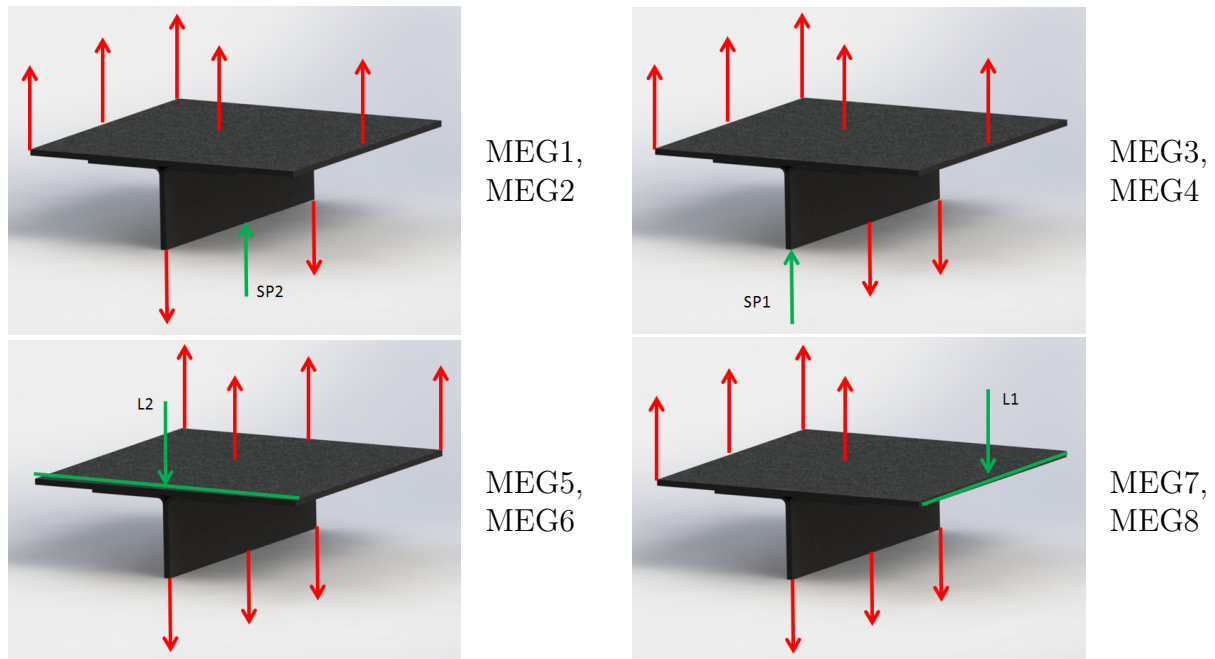


Figure 4.15: T3 Series Inlet and Outlet Configurations

Sail Center Inlet Configuration (SP2)

Table 4.22: T3-MEG1 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	no	Elapsed Time:	05:26

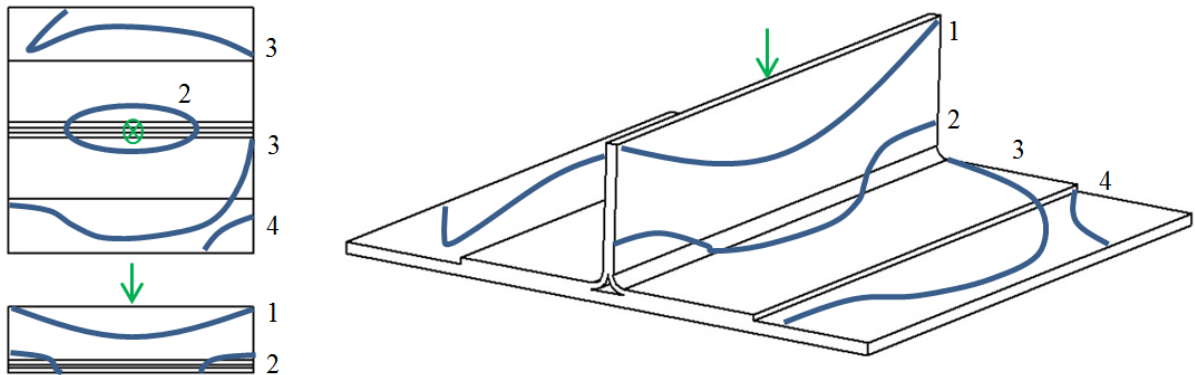


Figure 4.16: T3-MEG1 Flow Diagram

Kinematic-Defining events:

1. 00:05 Flow front is hemispherical from SP2.
2. 01:20 Flow front pierces through to the skin in the center, as viewed from under the preform.
3. 03:20 Flow front continues with slight racetracking on the far side.
4. 05:20 Flow front come to a halt due to grease blocking the line outlet.

Notes:

Test stopped at 5:26. Upper right corner of skin left unwetted due to grease in the lined outlet port and small leak in corner. The use of grease from this point onward was reduced in an attempt to avoid a similar result.

Table 4.23: T3-MEG2 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	03:21

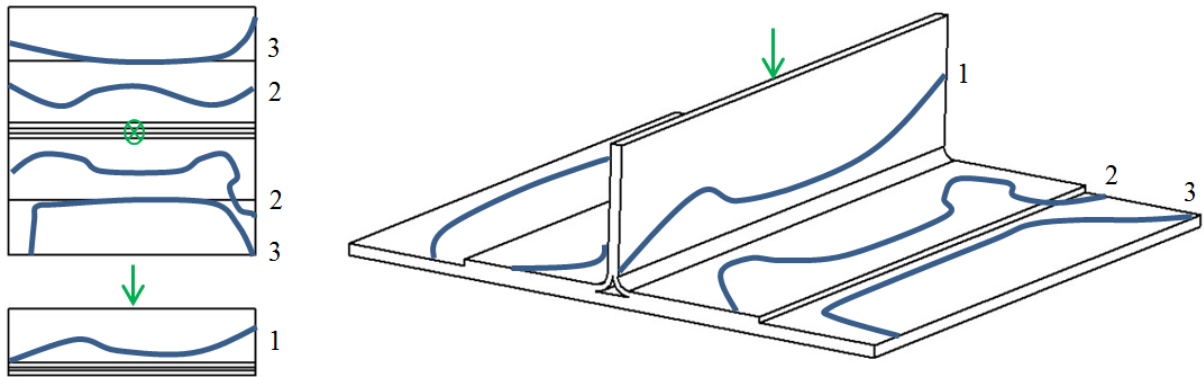


Figure 4.17: T3-MEG2 Flow Diagram

Kinematic-Defining events:

1. 00:05 Flow front is steady though slight racetracking on left side.
2. 00:30 Flow front pierces through to the skin from the center and separates uniformly.
3. 01:00 Flow front is uniform with racetracking along the edges.

Notes:

Completed in 3:21. Formation of pockets on left side of skin which were effectively wetted by end of test.

Sail Corner Inlet Configuration (SP1)

Table 4.24: T3-MEG3 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	06:00

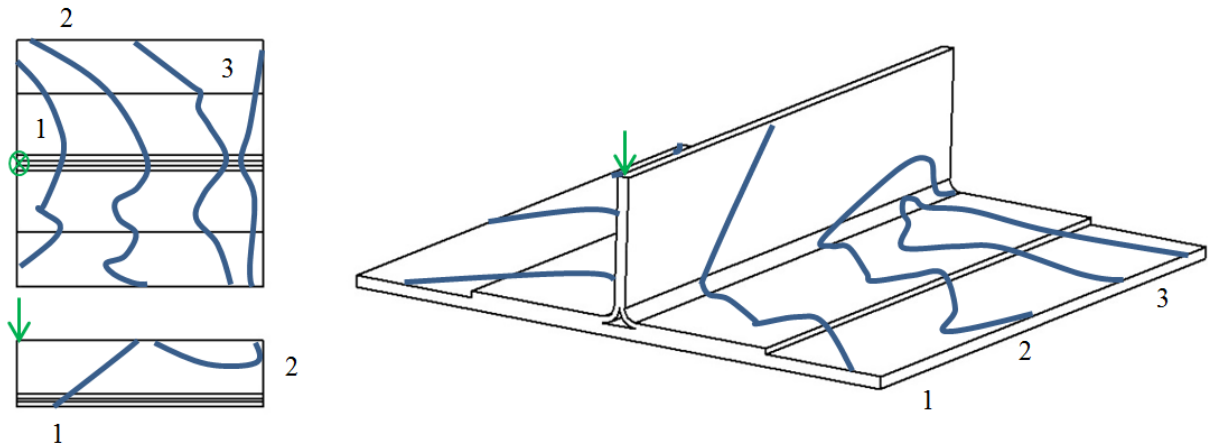


Figure 4.18: T3-MEG3 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front progresses through sail and onto the skin.
2. 02:30 Racetracking along the sail's edge creates a pocket.
3. 04:30 Flow front advances from either side to close the pocket.

Notes:

Completed in 6:00. Outlets along the sail (SP2,SP3) and the central port (C) greatly impeded flow progression. Race track on the opposite end of sail created pocketing in skin and sail. Pockets were eventually wetted by end of test.

Table 4.25: T3-MEG4 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	no	Elapsed Time:	10:25

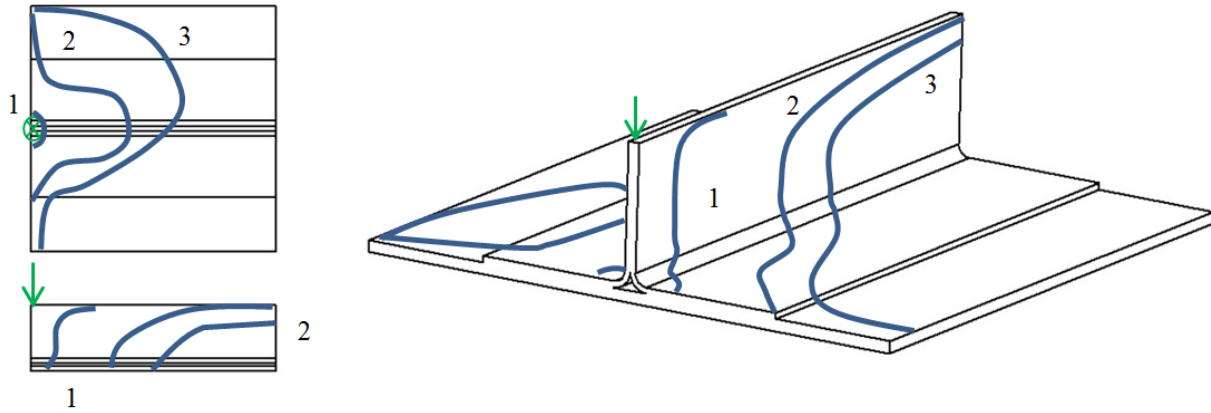


Figure 4.19: T3-MEG4 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front progresses through sail and onto the skin.
2. 04:00 Racetracking along the sail's edge is pronounced.
3. 10:00 Flow front barely advances, preferential flow along the edge of the sail goes directly to the outlets.

Notes:

Stopped at 10:25. Some tubes were gummed by grease and the preform was too small for the cavity, which led to racetracking and preferential flow along the edges.

Line Inlet Configuration Along Sail (L2)

Table 4.26: T3-MEG5 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	06:00

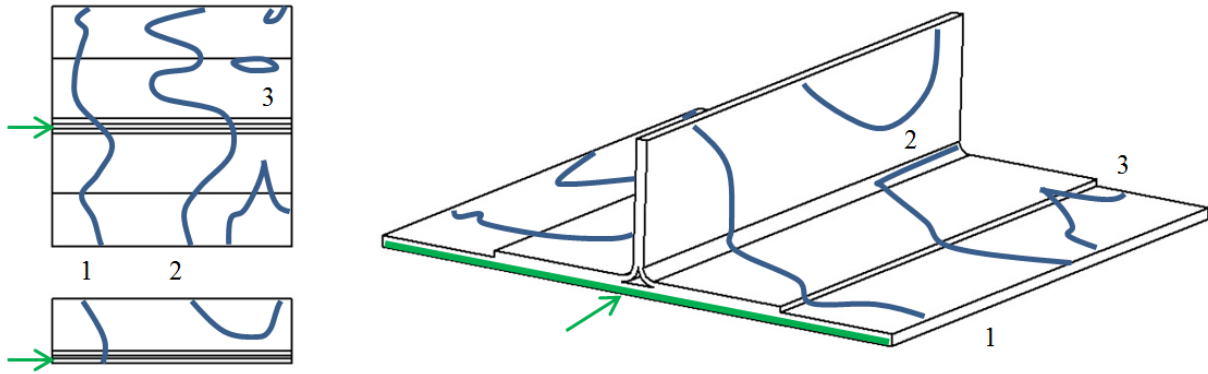


Figure 4.20: T3-MEG5 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front progresses through skin and sail at the same pace.
2. 01:30 Flow front progresses rapidly through center of sail, leaving a pocket along its edge.
3. 02:30 Multiple pockets are created in the skin by non-uniform flow front.

Notes:

Completed in 6:00. Sail fully wetted at 2:32. Right closest corner pocket took nearly 3 minutes to fully wet. Shooting from the sail occurred once again when infusing from the edge L2.

Table 4.27: T3-MEG6 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	02:56

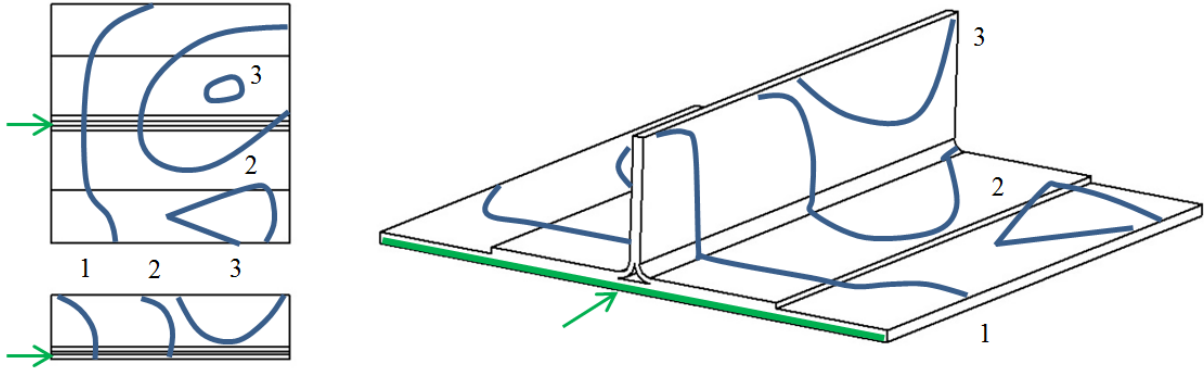


Figure 4.21: T3-MEG6 Flow Diagram

Kinematic-Defining events:

1. 00:15 Flow front progresses through skin and sail at the same pace.
2. 00:45 Flow front progresses rapidly through center of sail, leaving a pocket along its edge and one on the skin.
3. 01:45 Small pocket on the skin is left.

Notes:

Completed in 2:56. Two pockets on skin and one at the tip of the sail were formed but were wetted by the end of test.

Line Inlet Configuration Parallel to Sail (L1)

Table 4.28: T3-MEG7 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	01:56

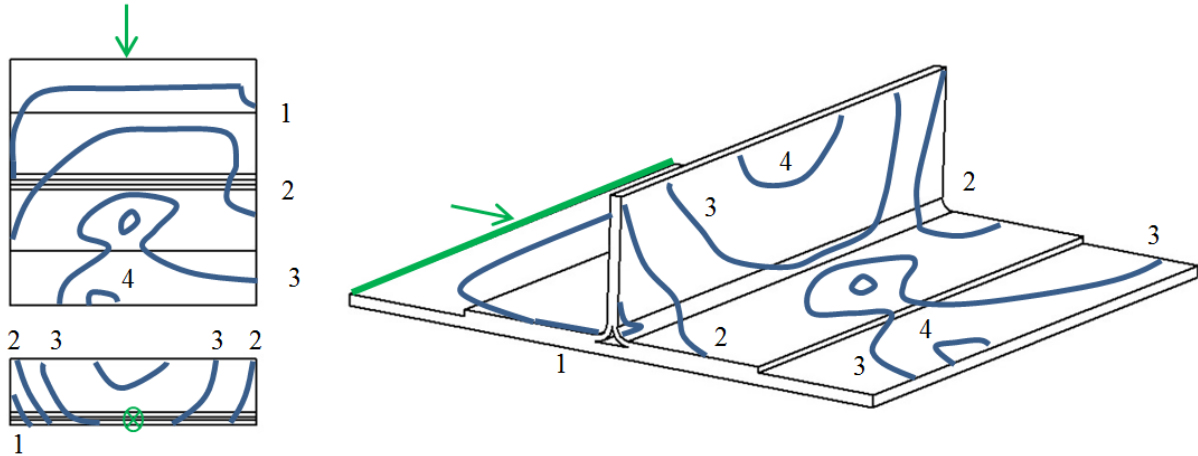


Figure 4.22: T3-MEG7 Flow Diagram

Kinematic-Defining events:

1. 00:10 Flow front progresses through skin with racetracking along the edge.
2. 00:30 Flow front progresses down sail from the edges first.
3. 01:10 Large pocket created from racetracking on the contact zone between the skin and the foot of the sail.
4. 01:30 Small pockets on the skin are left.

Notes:

Completed in 1:56. Racetracking at the edges outstrips the central front. Once front reaches central port, it seems to slow down the front completely and create pockets behind it. Preform fully wetted. The complex flow front seen at event times 3 and 4 were caused by racetracking along the edge of the step between the foot of the skin and the sail.

Table 4.29: T3-MEG8 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	05:12

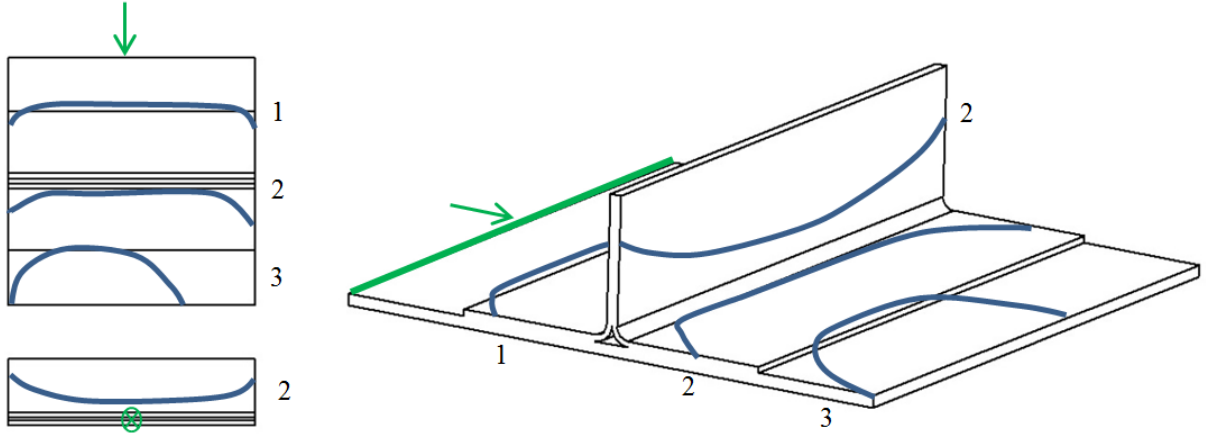


Figure 4.23: T3-MEG8 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front progresses through skin with slight racetracking along the edge.
2. 01:30 Flow front progresses down sail from the edges first.
3. 03:30 Small crescent is closing on the opposite edge.

Notes:

Completed in 5:12. Less racetracking and less loss of flow front velocity from central port as it was clamped as soon as front reached it. No pocketing.

Lessons Learned

In a rigid cavity with a high v_f preform, the edge effect becomes a primary concern to accomplish a full infusion. Line infusions from either sides of the skin were taken off the

table in future testing due to the geometry of the full scale demonstrator having 2 sails. In addition, tests from SP2 seemed to exhibit less racetracking and edge effects prompting future tests to be conducted with this methodology.

4.2.3 Interlocking OSS T4-S(1-3)

Inlet and outlet configuration tested in series T4-S is detailed in Figure 4.24.

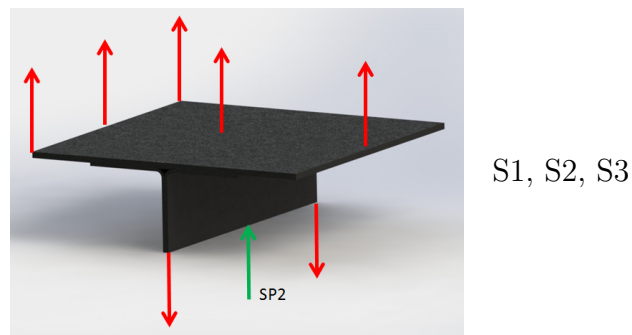


Figure 4.24: T4-S Series Inlet and Outlet Configurations

Table 4.30: T4-S1 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	12:34

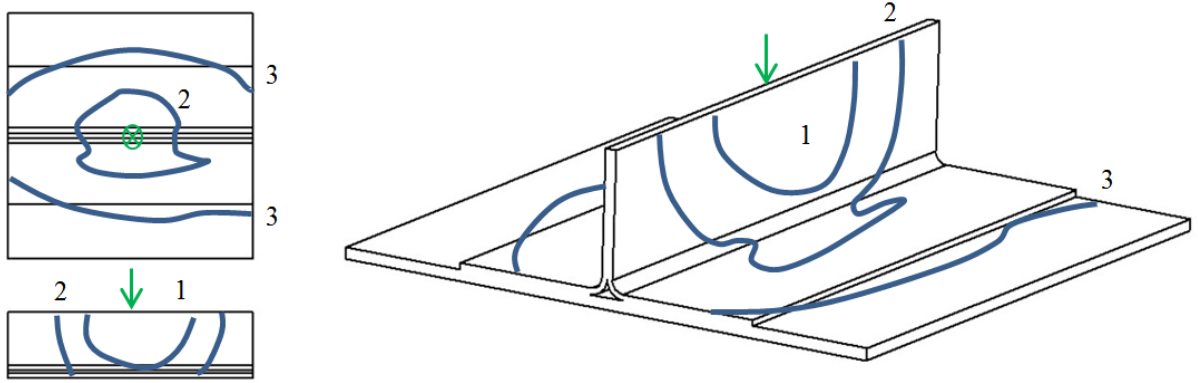


Figure 4.25: T4-S1 Flow Diagram

Kinematic-Defining events:

1. 00:45 Flow front is hemispherical until passing through first stitch line, where it accelerates towards the skin.
2. 02:30 Flow front pierces through the stitchlines unevenly at the base of the sail.
3. 06:00 Flow front returns to uniform state past the stitching lines.

Notes:

Completed in 12:34. Pierce through skin was asymmetric and followed the stitch lines, returns to isotropic flow past stitching.

Table 4.31: T4-S2 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	05:32

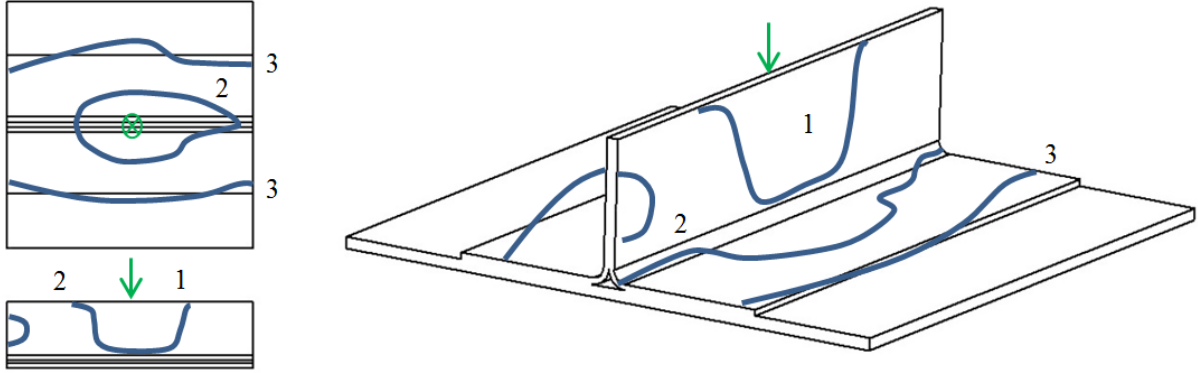


Figure 4.26: T4-S2 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front is hemispherical until passing through first stitch line, where it accelerates towards the skin. Slight racetracking along the edge.
2. 01:00 Flow front pierces through the stitchlines unevenly at the base of the sail. Small pocket formed on the sail in the stitching region.
3. 03:00 Flow front returns to uniform state past the stitching lines.

Notes:

Completed in 5:32. Pierce through skin was asymmetric and followed the stitch lines, returns to isotropic flow past stitching.

Table 4.32: T4-S3 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	03:55

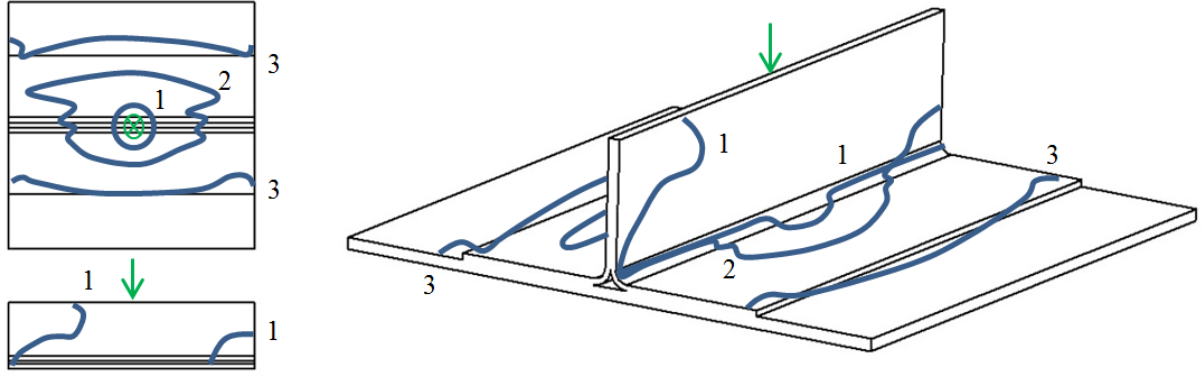


Figure 4.27: T4-S3 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front is uneven and a pocket is created along the edge while one corner is slower to reach the foot of the sail. Flow pierces through the center of the preform.
2. 01:00 Flow front pierces through the stitchlines unevenly at the base of the sail.
3. 03:00 Flow front returns to uniform state past the stitching lines.

Notes:

Completed in 3:55. Pierce through skin was asymmetric and followed the stitch lines, returns to isotropic flow past stitching.

Lessons Learned

Stitching close the T-section geometry location of the preform leads to uneven flow fronts. Relating with composite parts produced by partners leads the team to conclude that such uneven flow front causes micro porosity in the noodle.

4.2.4 Tufting Through Noodle T4-T(1-3)

Inlet and outlet configuration tested in series T4-T is detailed in Figure 4.28.

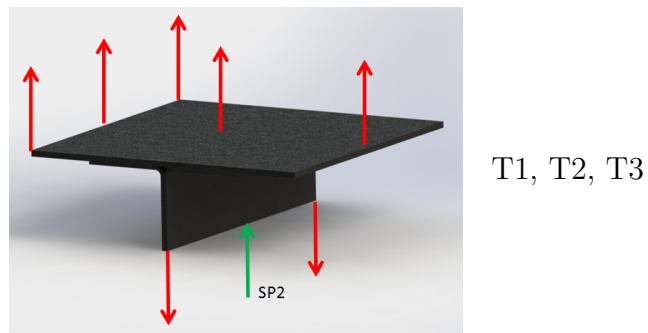


Figure 4.28: T4-T Series Inlet and Outlet Configurations

Table 4.33: T4-T1 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	08:13

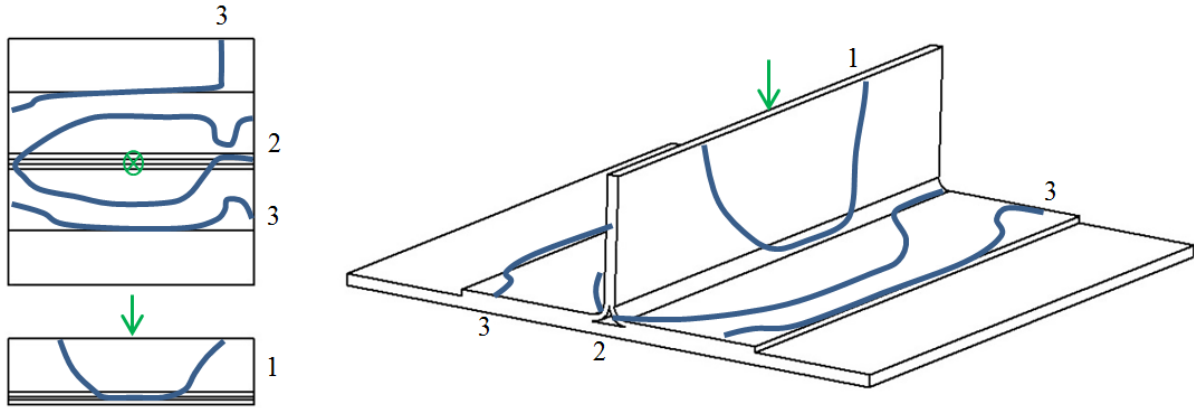


Figure 4.29: T4-T1 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front is hemispherical until passing through first stitch line, where it accelerates towards the skin.
2. 02:30 Flow front pierces through the tufting lines unevenly at the base of the sail, with flow impeded on one side entirely.
3. 05:30 Flow front returns to uniform state past the stitching lines.

Notes:

Completed in 8:13. Pierce through skin was asymmetric and followed the tufting line, returns to isotropic flow past stitching.

Table 4.34: T4-T2 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	14:21

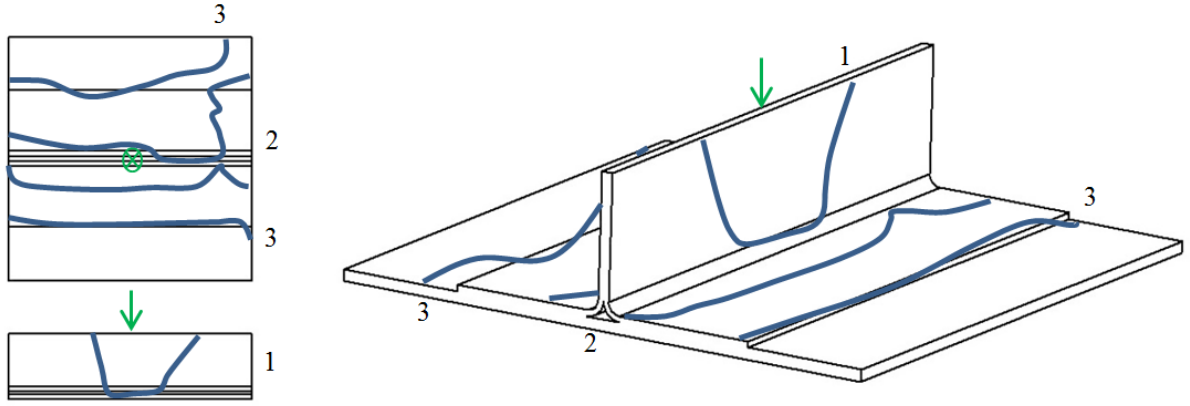


Figure 4.30: T4-T2 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front is hemispherical until passing through first stitch line, where it accelerates towards the skin.
2. 03:30 Flow front pierces through the tufting lines unevenly at the base of the sail, with flow severely impeded on one side.
3. 07:30 Flow front returns to uniform state past the stitching lines.

Notes:

Completed in 14:21. Pierce through skin was asymmetric and followed the tufting line, returns to isotropic flow past stitching. Grease in tubes possibly hampering flow.

Table 4.35: T4-T3 Parameters

Material:	Mod Equivalent Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	18:17

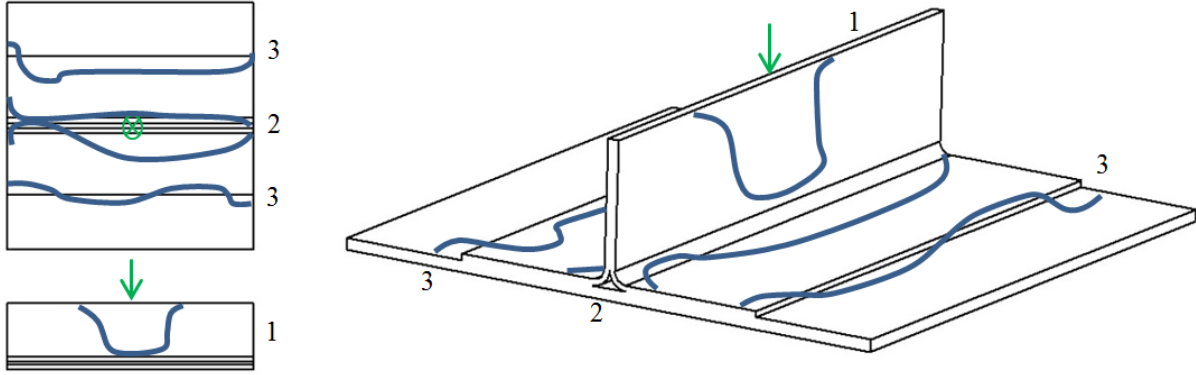


Figure 4.31: T4-T3 Flow Diagram

Kinematic-Defining events:

1. 01:30 Flow front is hemispherical until passing through first stitch line, where it accelerates towards the skin.
2. 10:30 Flow front pierces through the tufting lines with the flow front completely impeded on one side.
3. 18:00 Flow front returns to uniform state past the stitching lines.

Notes:

Test stopped at 18:17. Pierce through skin was asymmetric and followed the tufting line, returns to isotropic flow past stitching. Grease in tubes hampered and prevented flow.

Lessons Learned

Tufting through the noodle directs the flow preferentially to one side or the other as the front pierces through the skin. Such perturbations have also lead to microporosity in composite parts produced by partners.

4.2.5 Carbon Quasi OSS (T5-C1)

Inlet and outlet configurations tested in series T5 are detailed in Figure 4.32.

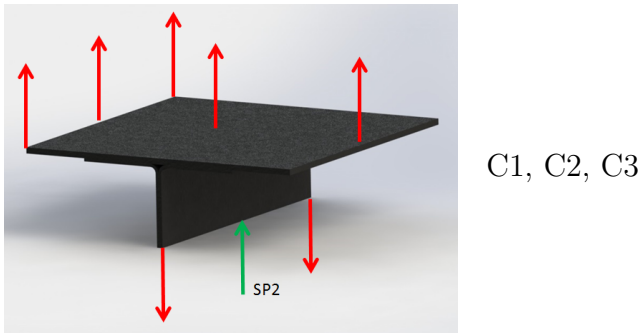


Figure 4.32: T5 Series Inlet and Outlet Configurations

Table 4.36: T5-C1 Parameters

Material:	Carbon Quasi	Oil Viscosity:	50 cSt
Complete Infusion:	yes	Elapsed Time:	19:13

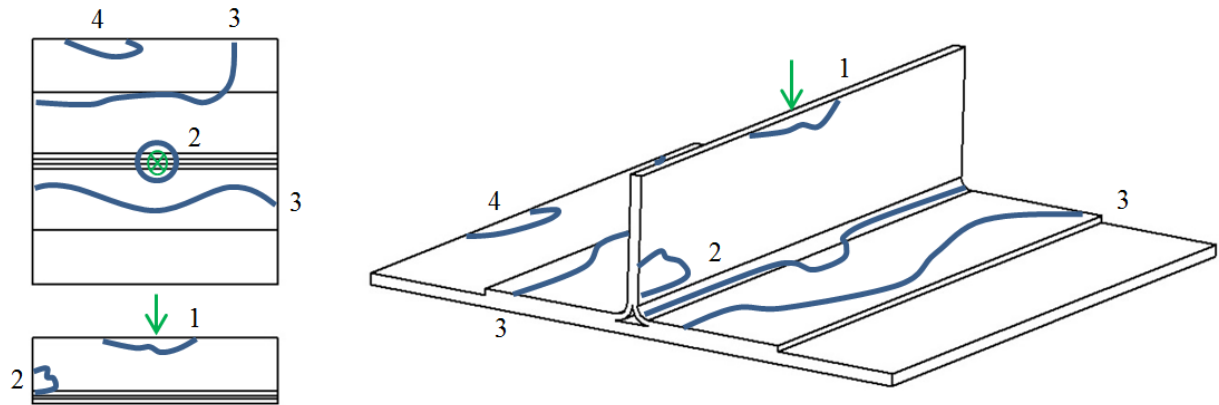


Figure 4.33: T5-C1 Flow Diagram

Kinematic-Defining events:

1. 00:30 Flow front is uniform though spread out due to racetracking from the top edge.
2. 02:30 Flow front pierces through the center of the preform.
3. 08:30 Flow front is uniform except for racetracking along on edge of the skin.
4. 12:30 Small pocket left on the far side of the skin.

Notes:

Completed in 19:13. Slow infusion, race tracking at the edges of the sail outstripped the main flow front, with some shooting through the noodle. Once the flow front moved into the skin racetracking was only an issue on one side of the preform. Due to the pocket shown in event time 4 being located near the single outlet ports rather than against the line outlet the full wetting took longer due to preferential flow.

Lessons Learned

The final stitching configuration does not hamper flow through the varying geometry at the sail/skin interface.

4.3 Full Scale Demonstrator Rig Results

4.3.1 Glass Demonstrator No Stitch T6-BGF(1-2)

Frames taken from the video of tests in this series are found in Appendix I. Silicon oil viscosity for all tests was 50 cSt.

T6-BGF1

This test used the type #1 infusion configuration, Figure 3.45a. No dyes were added to the oil.

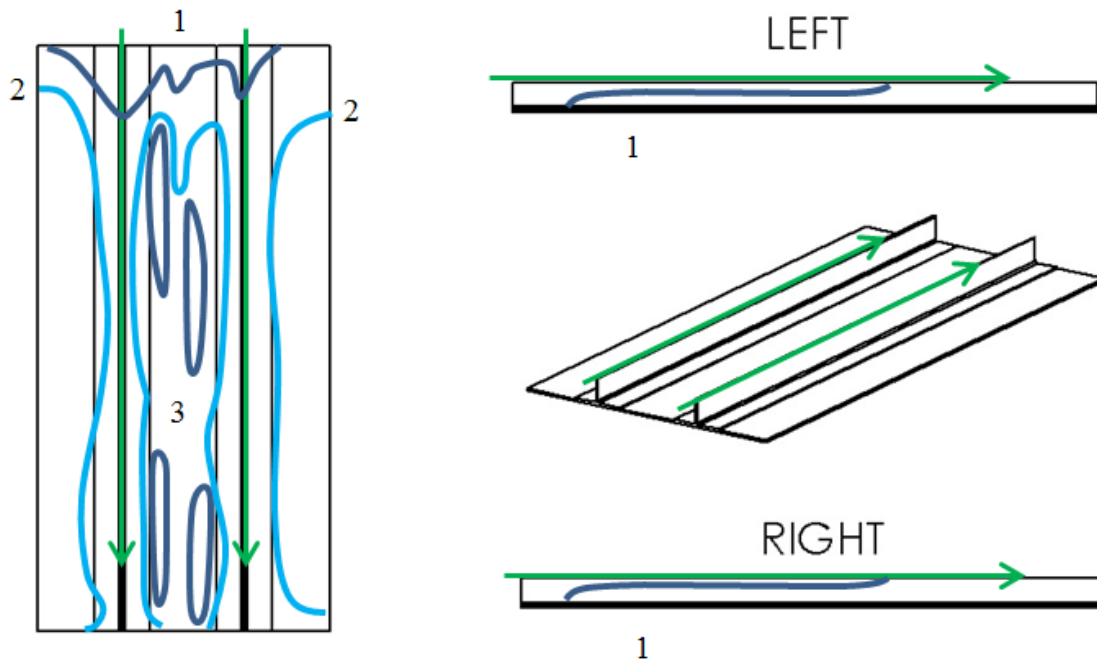


Figure 4.34: T2-G1 Flow Diagram

Kinematic-Defining events:

1. 10:00 Oil is racetracking into the T-Frame support via the outlets located at their base, Flow progresses principally along the spiral tubing through the top of

the sail.

2. 30:00 Flow fronts separate and progress fairly symmetrically on either side of both sails.
3. 50:00 Small pockets are left near the central inlet, by clamping the outlets on either side they start closing.

Notes:

Completed in 57:00, all pockets and voids have been infused. The needle valves seemed to be leaking; bubbles would appear in the tube following it. These could also be void bubbles created by the changing geometry, but in both cases these can lead to micro porosity in the final composite parts. The additional outlets at the base of the T-section in line with the noodle may be inducing preferential flow directing fluid away from the preform. Closing the outlets which the flow front has reached will reduce waste of oil or resin and help direct the flow to the dry regions of the preform.

T6-BGF2

This test used the type #2 infusion configuration, Figure 3.45b. Pylakrome Blue was added to the oil. Clamps were used instead of the manifold to control the inlets and outlets.

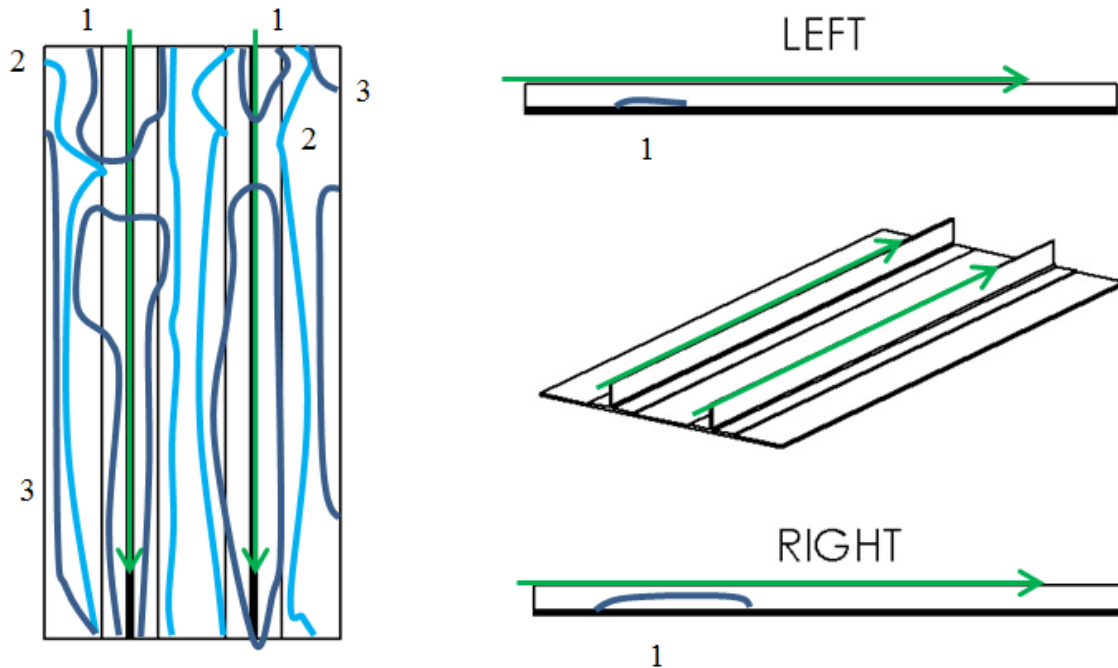


Figure 4.35: T2-G1 Flow Diagram

Kinematic-Defining events:

1. 12:30 Little to no racetracking on the edges of the skin, but longer spiral tubing reaching the other edge of the preform leads the flow front to primarily descend into the sail from either end rather than uniformly through the preform.
2. 16:30 Flow fronts return to near symmetrical progression on either sides of the sails.
3. 23:00 Central port was closed and flow fronts progress towards the outside edges.

Notes:

Completed in 41:00. Clamps were used to restrict flow at the inlet, but the rigid tubing would collapse and kink also creating what would appear to be bubbles in the inlet tube. These again may be void pockets rather than air ingress seeing no noticeable leak was detected on the inlet tube. From 35:00 onward, only the top right corner of the preform was left to wet, at 38:00 a leak was detected in that area and sealed, leading to a quickening of the infusion front and completing the process.

4.3.2 Glass Demonstrator OSS T6-MEG1

This test used the type #2 infusion configuration, Figure 3.45b. Pylakrome Blue was added to the oil. Clamps were used instead of the manifold to control the inlets and outlets.

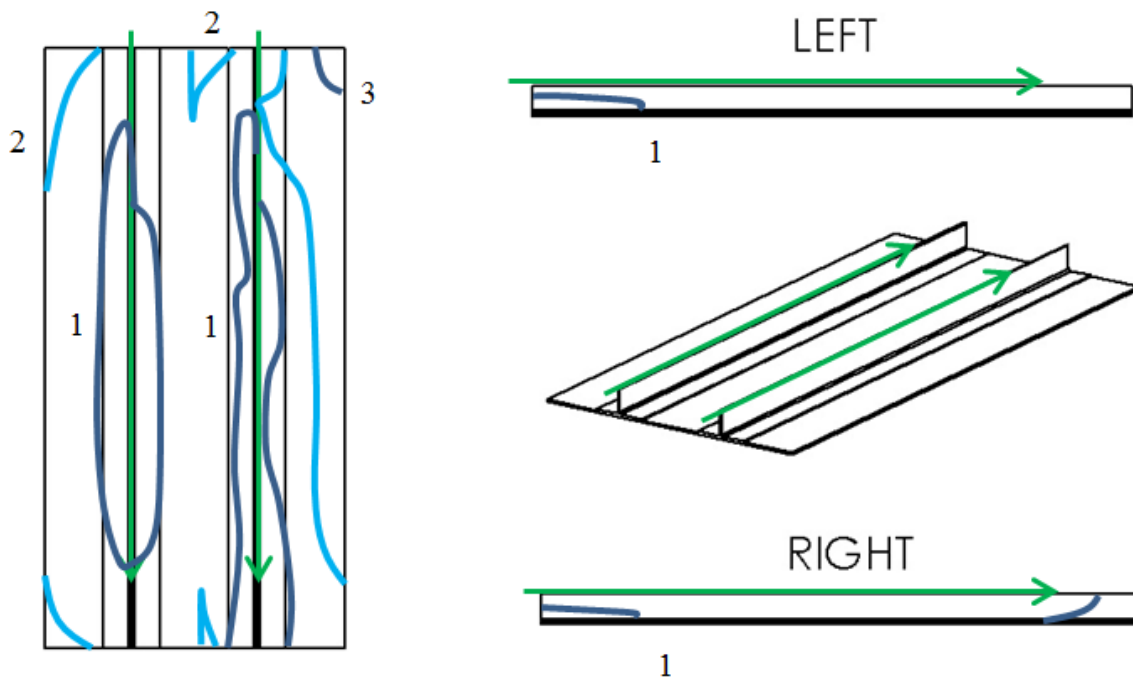


Figure 4.36: T2-G1 Flow Diagram

Kinematic-Defining events:

1. 02:00 Flow front progresses faster through the center of the sail than along its edges, piercing through the skin. Flow front from the sail into the skin was not symmetric about the centerline.
2. 04:00 Flow fronts meeting at the central outlet while propagating rapidly towards either sides.
3. 11:00 Upper right corner left dry, tear in the bag detected and attempts to patch it begin.

Notes:

Stopped at 12:50. Infusion was too fast and such speeds would incur high levels of porosity in a composite part. In an effort to avoid kinking of the inlet tube to prevent void creation, the inlet clamp came undone and the flow was unrestricted into the preform. A tear in the bag was detected in the upper right corner. The outlet spiral tubing was too short and once the flow front reached it, preferential flow and the presence of a tear prevented the preform from being fully wetted.

Chapter 5

Conclusions

The objectives of this research were threefold: firstly, to determine the permeability of preforms used in this thesis; secondly, to determine the best approach to infusing a T-section demonstrator; and thirdly, to develop the infusion procedure for the full scale demonstrator composite part.

The preforms tested with the Permeability Rig in trial series T1 were mainly isotropic. Permeability values are presented in Table 5.1. From these values, we can see that the permeability of stitched carbon preforms and selected glass equivalents are extremely close, and thus the latter provided an adequate substitute. The permeability of the baseline carbon preform is off from that of the stitched preforms by a factor of 2.83 which could mean that stitching increases the permeability accordingly. Else, that a larger sample size could reduce this deviation since variability on permeability values is notoriously high.

The evaluation of various stitching arrangements tested over the course of this thesis seems to confirm the findings of Song [50], in which the effects of stitching on overall permeability were localised around the immediate stitching region with flow fronts returning to isotropic once the obstacle is cleared, in the case of 2D preforms. There were noted disturbances to the flow regime when the stitching was in a location of varying geometry, such as the interface between the sail and skin.

Table 5.1: Permeability Values for Isotropic Preforms

Preform	Permeability $K(m^2)$	Standard Deviation $s(m^2)$	Standard Error SE_K	Sample Size N_K
Carbon Quasi Baseline (T1-B)	4.43E-08	8.99E-08	4.64E-09	376
Carbon Stitched Quasi (T1-C)	1.26E-07	2.19E-07	7.30E-09	900
Equivalent Glass Quasi (T1-EG)	1.31E-07	5.64E-08	1.76E-09	1027
Plain Weave 2 Mod Equivalent Quasi (T1-BGF)	3.97E-08	1.99E-04	9.79E-06	415

The permeability of the Plain Weave 2 preform is smaller by a factor of 3.16 to that of the Stitched Carbon preforms, but the standard deviation and error indicate that more tests may help in determining the permeability more accurately for this preform. It is important to note, however, that flow through the preform was isotropic and as such the flow front behaviours observed in later tests would be indicative of the behaviour of the front in the final composite part.

The 3D woven preforms provided by the CTT group proved to have an orthotropic flow pattern, and as such their permeability was presented in a tensor format. Test T1-W1 proved to be have a permeability tensor which deviated from the set norm of tests T1-W2 and T1-W3 and hence two different average permeability tensors are presented. The standard deviation and error for the orthotropic analysis method are hard to quantify because of the visual nature of the video analysis, therefore these values were not calculated in this work.

3D Woven Preform Overall Average Permeability tensor:

$$[K] = \begin{pmatrix} 1.38 & 0 \\ 0 & 7.58 \end{pmatrix} \cdot 10^{-7} m^2 \quad (5.1)$$

3D Woven Preform Average Permeability Tensor Excluding T1-W1:

$$[K] = \begin{pmatrix} 8.60 & 0 \\ 0 & 39.6 \end{pmatrix} \cdot 10^{-8} m^2 \quad (5.2)$$

Trial series T2 through T5 conducted in the Translucent Cavity Rig, allowed for the exploration of multiple inlet and outlet configurations which yielded important information regarding flow behaviour in a complex 3D form. Trial T2 showed that central infusion ports were not effective in VARTM as the relatively small pressure gradient could not induce enough force into the fluid column to infuse the preform properly. Edge effects were also noted as being a primary concern with this specific configuration. In trial series T3, the comparison was made between line infusion either along or perpendicular to the sail, and infusing from the sail's corner or center. These trials identified once again racetracking as primary concern, but also led to concluding that infusing from the corner of the sail and in a line along the sail's edge had similar effects on the infusion pattern and pocket creation, which is a concern for porosity in the composite part. This information combined with the geometry of the full scale demonstrator prompted the decision to infuse from the center of the sail for future tests in the Translucent Cavity Rig.

Trials T4-S and T4-T investigated the effects of z axis reinforcements in the region of the noodle, primarily OSS and tufting. These methods of reinforcement proved to have detrimental effects on the flow properties in the zone of the interface between the sail and skin. The flow front could be directed entirely to one side rather than both upon piercing through the skin. In addition to these findings, microscopy performed by Lucas West on

manufactured parts using these same reinforcement methods showed severe porosity in the noodle region.

Trial series T5 confirmed that flow behaviour observed in prior tests on equivalent or substitute materials was indeed representative of the flow behaviour with the final stitched configuration of carbon preforms. In addition to identifying the best approach to manufacturing, these tests provided valuable experience relating to the management of inlets and outlets, and to the effects that closing or modulating them could have on an infusion.

The third principal task of this work covered the procedures surrounding the infusion of a full scale demonstrator with the goal of producing composite parts and to demonstrate the technology to industrial partners. To this effect, test series T6 infused 3 full scale glass fibre demonstrators and tested various inlet and outlet configurations as well as their layout about the preform. The use of needle valves proved to be unsatisfactory and led to the formation of visible voids in both the first test (T6-BGF1) and an equivalent infusion on a composite part by partners at ÉTS. The second test (T6-BGF2) demonstrated the need to have access to the infusion equipment and for continuous surveillance of the process as once the leak was detected and rectified, the infusion was completed successfully. The use of clamps was deemed preferable to that of needle valves in both controlling inlet flow as well as closing outlets which have seen their effective preform region fully infused. The final test (T6-MFG) showed the possible downside to using clamps to modulate inlet flow, and that the outlet spiral tubing should reach the whole extent of the preform to reduce the effects of preferential flow.

Difficulties encountered provided an opportunity to improve the methods currently used in the production of composite parts necessitating slower flow fronts. Current vacuum rated adjustable valves are too expensive to qualify as consumables, and most of their inner workings are too complex to protect them from curing resin, rendering them single-use items. Their replacement could be an interesting avenue of research, to improve overall

control of the flow regime in preforms. Another important lesson was that rigid tubing could easily kink, preventing it from returning to its prior shape and affecting the flow rate at the inlet.

In the context of the CRIAQ COMP 501 project, the work presented in this thesis successfully helped to develop the infusion methods necessary to produce multiple carbon and glass fibre composite parts as demonstrators of the technology.

Bibliography

- [1] ASM Aluminium 6061-T6. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6>. Accessed: 2015-12-10.
- [2] ASM Titanium Ti-6Al-4V. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MTP641>. Accessed: 2015-12-10.
- [3] G. O. Brown. Henry Darcy and the making of a law. *Water Resources Research*, 38(7), 2002.
- [4] Henry Darcy. *Rapport à le Maire et au Conseil Municipal, de Dijon, sur les Moyens de Fournir l'Eau Nécessaire à cette Ville*. Douillier, Dijon, France, 1834.
- [5] H. Rouse and S. Ince. *History of Hydrolics*. Iowa Inst. of Hydrolics, University of Iowa, Iowa City, 1957.
- [6] Poiseuille J.L. *Recherches expérimentales sur le mouvement des liquides dans les tubes de très-petits diamètres, comptes rendus*,. Acad. des Sci., Paris, France, 1841.
- [7] Reynolds O. An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and of the law of resistance in parallel channel. *Philos. Trans. R. Soc.*, 174:935–982, 1883.
- [8] Henry Darcy. *Les Fontaines Publiques de la Ville de Dijon*. Dalmont, Paris, France, 1856.

- [9] P.M. Adler. *Porous Media: Geometry and transports*. Butterworth/Heinemann, Boston, Massachusetts, 1992.
- [10] K.M. Flynn R.S. Parnas and M.E. Dal-Favero. A permeability database for composite manufacturing. *Polymer Composites*, 18(5):623–633, 1997.
- [11] T. Luce R. Parnas, J. Howard and S. Advani. Permeability characterization. part 1: A proposed standard reference fabric for permeability. *Polymer Composites*, 16(6):429–445, 1995.
- [12] A. Kerachni R. Gauvin and B. Fisa. Variation of mat surface density and its effects on permeability evaluation for rtm modelling. *Journal of Reinforced Plastics and Composites*, 13:371–383, Apr. 1994.
- [13] A.L. Stewart. *Measurement and analysis of flow in 3D preforms for aerospace composites*. University of Ottawa, Canada, 2012.
- [14] S.G. Advani T.A.K. Sadiq and R.S. Parnas. Experimental investigation of transverse flow through aligned cylinders. *International Journal of Multiphase Flow*, 21(5):755–774, 1995.
- [15] M.J. Liou L. Trevino, W.B. Young and L.J. Lee. Analysis of resin injection molding in molds with preplaced fiber mats. i permeability and compressibility measurements. *Polymer Composites*, 12(1):20–29, 1991.
- [16] D.E. Larive A.W. Chan and R.J. Morgan. Anisotropic permeability of fiber preforms: Constant flow rate measurment. *Journal of Composites Materials*, 27(10):996–1008, 1993.
- [17] A.W. Chan and S.-T Hwang. Anisotropic in-plane permeability of fabric media. *Polymer Engineering & Science*, 31(16):1233–1239, 1991.

- [18] W.B. Russel K.L. Adams and L. Rebenfeld. Radial penetration of a viscous liquid into a planar anisotropic porous medium. *International Journal of Multiphase Flow*, 14(2):203–215, 1988.
- [19] HP-RTM on the Rise. <http://www.compositesworld.com/articles/hp-rtm-on-the-rise>. Accessed: 2016-04-16.
- [20] Editor Elsevier. Technology update: prepregs. *Reinforced Plastics*, 47(6):20–21, June 2003.
- [21] F. Robitaille and R. Gauvin. Compaction of textile reinforcements for composites manufacturing. iii: Reorganization of the fiber network. *Polymer Composites*, 20(1):48–61, Feb. 1999.
- [22] C.M. van Wyk. 20-note on the compressibility of wool. *Journal of the Textile Institute Transactions*, 37(12):T285–T292, 1946.
- [23] C. Lekakou R.A. Saunders and M.G. Bader. Compression and microstructure of fibre plain woven cloths in the processing of polymer composites. *Composites Part A: Applied Science and Manufacturing*, 29(4):443–454, Jan. 1998.
- [24] P. Boisse. *Composite Reinforcements for Optimum Performance*. Woodhead Publishing Series in Composites Science and Engineering, Elsevier Science, 2011.
- [25] B. Chen. Compaction of woven-fabric preforms: nesting and multi-layer deformation. *Composites Science and Technology*, 60(12-13):2223–2231, Sep. 2000.
- [26] A.H.-D Cheng B. Chen and T.-W Chou. A nonlinear compaction model for fibrous preforms. *Composites Part A: Applied Science and Manufacturing*, 32(5):701–707, Sep. 2000.
- [27] T. Drivas. *Manufacturing Three-dimensional Carbon-fibre Preforms for Aerospace Composites*. University of Ottawa, Canada, 2014.

- [28] C. Zhang R. Pan, Z. Liang and B. Wang. Statistical characterization of fiber permeability for composite manufacturing. *Polymer Composites*, 21(6):996–1006, 2000.
- [29] T. Lundström. The permeability of non-crimp stitched fabrics. *Composites Part A: Applied Science and Manufacturing*, 31(12):1345–1353, 2000.
- [30] R. Arbter, J. Beraud, C. Binetruy, L. Bizet, J. Bréard, S. Comas-Cardona, C. Demaria, A. Endruweit, P. Ermanni, F. Gommer, S. Hasanovic, P. Henrat, F. Klunker, B. Laine, S. Lavanchy, S. Lomov, A. Long, V. Michaud, G. Morren, E. Ruiz, H. Sol, F. Trochu, B. Verleye, M. Wietgreffe, W. Wu and G. Ziegmann. Experimental determination of the permeability of textiles: a benchmark exercise. *Composites Part A: Applied Science and Manufacturing*, 42:1157–1168, Sept 2011.
- [31] P.C. Carman. Permeability of saturated sands, soils and clay. *The Journal of Agricultural Science*, 29:262–273, 1939.
- [32] S. Bauer D. Boucher J. Kingery T.G. Gutowski, Z. Cai and S. Wineman. Consolidation experiments for laminate composites. *Journal of Composites Materials*, 21(7):650–669, 1987.
- [33] T. Morigaki T.G. Gutowski and Z. Cai. The consolidation of laminate composites. *Journal of Composites Materials*, 21(2):172–188, 1987.
- [34] S. Wineman T.G. Gutowski and Z. Cai. Application of the resin flow/fibre deformation model. *31st International SAMPE Symposium and Exhibition*, Apr. 1986.
- [35] J. Kardos L. Skartsis and B. Khomami. Resin flow through fiber beds during composite manufacturing processes. part i: Review of newtonian flow through fiber beds. *Polymer Engineering & Science*, 32(4):221–230, 1992.
- [36] J. Kardos L. Skartsis and B. Khomami. Resin flow through fiber beds during composite manufacturing processes. part ii: Numerical and experimental studies of newtonian

- flow through ideal and actual fiber beds. *Polymer Engineering & Science*, 32(4):230–239, 1992.
- [37] B. Gebart. Permeability of unidirectional reinforcements for rtm. *Journal of Composite Materials*, 26(8):1100–1133, 1992.
- [38] Y. Song K. Shin and J. Youn. Radial flow advancement in multi-layered preform for resin transfer molding. *Korea-Australia Rheology Journal*, 18(4):217–224, 2006.
- [39] V.M. Calado and S.G. Advani. Effective average permeability of multi-layer preforms in resin transfer molding. *Composite Science and Technology*, 56(5):519–531, 1996.
- [40] C. Baillie K. Dransfield and Mai Y. Improving the delamination resistance of cfrp by stitching - a review. *Composites Science and Technology*, 50(3):305–317, 1994.
- [41] U. Beier, F. Fischer, J.K.W. Sandler, V. Altstädt, C. Weimer and W. Buchs. Mechanical performance of carbon fibre-reinforced composites based on stitched preforms. *Composites: Part A*, 38:1655–1663, 2007.
- [42] P. Mitschang and A. Ogale. Quality aspects of and thread selection for stitched preforms. ICCM.
- [43] Y. Wei and J. Zhang. Characterization of microstructure in stitched unidirectional composite laminates. *Composites Part A: Applied Science and Manufacturing*, 39(5):815–824, 2008.
- [44] V. Yavari and M. Kadivar. Fiber volume fraction around stitch in ncf composites. *Procedia Engineering*, 14:3191–3198, 2011.
- [45] S. Lomov I. Verpoest V. Witzel V. Koissin, A. Ruopp and K. Drechsler. On-surface fiber-free zones and irregularity of piercing pattern in structurally stitched ncf preforms. *Advanced composites letters*, 15(3):81–88, 2006.

- [46] H. Talvensaari, E. Ladstätter and W. Billinger. Permeability of stitched preform packages. *Composites Structures*, 71(3-4):371–377, 2005.
- [47] J. Schlimbach F. Weyrauch P. Mitschang, A. Ogale and C. Weimer. Prefomr technology: a necessary requirement for quality controlled lcm-processes. *Polymer Composites*, 11(8):605–622, 2003.
- [48] C.H. Chiu and C.C. Cheng. In-plane permeability of stitched mmwk laminates in rtm. *Reinforced plastics and composites*, 21:391–408, 2002.
- [49] R. Rieber and P. Mitschang. 2d permeability changes due to stitching seams. *Composites: Part A*, 41:2–7, 2010.
- [50] Z. Abour Y. Song, K. Khellil and A. Ouahsine. Influence of one side stitching on the permeability of composite reinforced by transverse sewing. *ECCM16*, 2014.
- [51] J. Bréard, Y. Henzel, F. Tronchu and R. Gauvin. Analysis of dynamic flows through porous media. part i: Comparison between saturated and unsaturated flows in fibrous reinforcements. *Polymer Composites*, 24(3):391–408, 2003.
- [52] N. Patel and L.J. Lee. Effects of fibre mat architecture on void formation and removal in liquid composite molding. *Polymer Composites*, 16(5):386–399, 1995.
- [53] L. Labat, J. Bréard, S. Pillut-Lesavre and G. Bouquet. Void formation prevision in lcm parts. *European Physics Journal*, 16:157–164, 2001.
- [54] N. Patel and L.J. Lee. Modeling of void formation in liquid composite molding. part ii: Model development and impregnation. *Polymer Composites*, 17(1):104–114, 1996.
- [55] N. Patel and L.J. Lee. Modeling of void formation in liquid composite molding. part i: Wettability analysis. *Polymer Composites*, 17(1):96–103, 1996.
- [56] M. Spaid and F. Phelan. Modeling void formation dynamics in fibrous porous media with lattice boltzmann method. *Composites: Part A*, 29(A):749–755, 1998.

- [57] B. Hilaire C. Benetruy and J. Pabiot. Tow impregnation model and void formation mechanism during rtm. *Journal of Composites Materials*, 32(3):223–245, 1998.
- [58] J.-S. Leclerc and E. Ruiz. Porosity reduction using optimized flow velocity in resin transfer molding. *Composites: Part A*, 39:1859–1868, 2008.
- [59] E. Ruiz, V. Achim, S. Soukane, F. Tronchu and J. Bréard. Optimization of injection flow rate to minimize micro/macro-voids formation in resin transfer molded composites. *Composites Science and Technology*, 66:475–486, 2006.
- [60] S. Joncas C. Leduc and J.-S. Leclerc. Effect of one-sided stitching on the mechanical properties of vacuum-infused carbon-epoxy laminates. *16th European Conference on Composite Materials*, June 2014.
- [61] M. Beauregard. personal communication. Oct. 14, 2014.
- [62] How Sewing Machines Work. <http://home.howstuffworks.com/sewing-machine1.htm>. Accessed: 2016-03-21.
- [63] Eurocarbon standard program product catalog. <http://www.eurocarbon.com/pdf/Standard%20Program%202016.pdf>. Accessed: 2016-06-02.
- [64] S. Morin. Project presentation. Dec. 15, 2014.
- [65] Cycom®890 RTM. Datasheet. Sept. 2, 2002.
- [66] Hy-spec hydraulik. Hy-spec Hydraulik catalogue. Jan. 2008.
- [67] HexTow IM7. <http://www.hexcel.com/Resources/DataSheets/Carbon-Fiber-Data-Sheets/IM7>. Accessed: 2015-12-10.
- [68] Hexflow RTM6. http://www.hexcel.com/Resources/DataSheets/RTM-Data-Sheets/RTM6_global.pdf. Accessed: 2015-12-10.

APPENDICES

Appendix A

Example of Appendix

Table A.1: Constituent Materials and Their Properties

IM7-12K Carbon Fibre [67]		
Density (ρ_f)	1.78	g/cc
Elastic Modulus (E_X)	276	Gpa
HexFlow RTM6 Resin [68]		
Density (ρ_R)	1.14	g/cc
Elastic Modulus (E_R)	2.89	Gpa

Assuming a 60% volume fraction of fibres,

Longitudinal modulus:

$$E_{long} = E_X * vf + E_R * (1 - vf) \quad (\text{A.1})$$

$$E_{long} = 276GPa * 0.6 + 2.89GPa * 0.4 \quad (\text{A.2})$$

$$E_{long} = 166.76GPa \quad (\text{A.3})$$

Density:

$$\rho = \rho_f * vf + \rho_R * (1 - vf) \quad (\text{A.4})$$

$$\rho = 1.78g/cc * 0.6 + 1.14g/cc * 0.4 \quad (\text{A.5})$$

$$\rho = 1.524g/cc \quad (\text{A.6})$$

Appendix B

Textile Data Sheets

Fabric Availability*/Specification

FABRIC DESCRIPTION

 <i>ib martin</i>		Resain Compatibility		Warp				Fill				Int Style	
Style	Length Yards	Weave	Thickness mm in.	Nominal g/m ² oz/yd ²	Prim. Fiber	Sec. Fiber	Counts ends/cm	Theoretical g/m ² oz/yd ²	Prim. Fiber	Sec. Fiber	Counts ends/cm	Theoretical g/m ² oz/yd ²	Replace

E Glass 0790°

TG-04-P	165	A	PW	0.15	0.006	122	3.6	E-Glass	68	n/a	n/a	8.7	61	1.8	E-Glass	68	n/a	n/a	8.7	61	1.8	1522
TG-06-P	190	A	PW	0.20	0.008	207	6.1	E-Glass	134	n/a	n/a	7.5	104	3.0	E-Glass	134	n/a	n/a	7.5	104	3.1	
TG-09-P	110	A	PW	0.33	0.013	306	9.0	E-Glass	275	n/a	n/a	5.5	154	4.5	E-Glass	275	n/a	n/a	5.5	152	4.5	
TG-09-T	110	A	2X2 T	0.41	0.016	315	9.3	E-Glass	275	n/a	n/a	5.5	154	4.5	E-Glass	275	n/a	n/a	5.5	161	4.8	
TG-09-N	110	A	NCS	0.60	0.024	325	9.6	E-Glass	275	Polyester	16.66	5.5	163	4.9	E-Glass	275	Polyester	16.66	5.1	162	4.7	
TG-12-N	110	A	NCS	0.61	0.024	380	11.2	E-Glass	330	Polyester	16.66	5.5	195	5.7	E-Glass	330	Polyester	16.66	5.5	185	5.5	
TG-15-N	80	A	NCS	0.76	0.030	518	15.3	E-Glass	735	Polyester	16.66	3.1	224	6.6	E-Glass	275	E-Glass	275	7.0	402	11.8	
TG-22-N	55	A	NCS	0.95	0.037	744	21.9	E-Glass	1100	Polyester	16.66	3.1	342	10.1	E-Glass	275	E-Glass	275	7.0	402	11.8	
TG-33-N	55	A	NCS	1.42	0.056	1125	33.2	E-Glass	2200	Polyester	16.66	2.1	516	15.3	E-Glass	735	E-Glass	735	4.2	809	17.9	
TG-54-N	38	A	NCS	2.05	0.081	1830	54.0	E-Glass	1100	E-Glass	68	2.7	952	28.1	E-Glass	735	E-Glass	735	5.7	876	25.9	
TG-75-N	33	A	NCS	2.80	0.110	2542	75.0	E-Glass	1100	E-Glass	275	3.8	1325	39.0	E-Glass	1100	E-Glass	735	6.4	1217	36.0	
TG-96-N	27	A	NCS	3.10	0.122	3250	95.9	E-Glass	1100	E-Glass	275	2.3	1723	50.8	E-Glass	1100	E-Glass	1100	6.8	1528	45.1	

E Glass Uni

TG-09-U	110	A	Uni Warp	0.50	0.020	303	8.9	E-Glass	735	n/a	n/a	3.8	286	8.4	Hot melt	60	E-Glass	134	1.6	17	0.5	
TG-13-U	110	A	Uni Warp	0.55	0.022	443	13.1	E-Glass	1100	n/a	n/a	3.8	434	12.8	Hot melt	60	E-Glass	68	1.6	9	0.3	
TG-18-U	80	A	Uni Warp	1.00	0.039	805	17.8	E-Glass	1100	n/a	n/a	5.5	594	17.5	Hot melt	60	E-Glass	134	1.0	11	0.3	
TG-27-U	80	A	Uni Warp	1.10	0.043	925	27.3	E-Glass	1100	n/a	n/a	4.0	916	27.0	Hot melt	60	E-Glass	68	1.6	9	0.3	

Carbon 0790°

TC-06-P	110	B	PW	0.30	0.012	197	5.8	Carbon 3K	200	n/a	n/a	4.7	99	2.9	Carbon 3K	200	n/a	n/a	4.7	99	2.9	282
TC-06-T	110	B	2X2 T	0.30	0.012	197	5.8	Carbon 3K	200	n/a	n/a	5.0	99	2.9	Carbon 3K	200	n/a	n/a	5.0	99	2.9	
TC-06-P	110	B	PW	0.42	0.017	205	6.0	Carbon 12K	800	n/a	n/a	1.2	103	3.0	Carbon 12K	800	n/a	n/a	1.2	103	3.0	
TC-07-N	110	B	NCS	0.66	0.026	252	7.4	Carbon 12K	800	Polyester	16.66	1.8	155	4.6	Carbon 3K	200	Polyester	14	4.5	97	2.9	
TC-12-T	110	B	2X2 T	0.76	0.030	405	11.9	Carbon 6K	400	n/a	n/a	5.0	200	5.9	Carbon 6K	400	n/a	n/a	5.0	205	6.0	
TC-12-P	110	B	PW	0.76	0.030	412	12.2	Carbon 12K	800	n/a	n/a	2.6	206	6.1	Carbon 12K	800	n/a	n/a	2.5	206	6.1	
TC-18-N	80	B	NCS	1.09	0.043	610	18.0	Carbon 12K	800	Polyester	16.66	3.8	311	9.2	Carbon 12K	800	Polyester	16.66	3.6	299	8.8	

Carbon Uni

TC-09-U	110	B	Uni Warp	0.75	0.030	315	9.3	Carbon 12K	800	n/a	n/a	3.8	298	8.8	Hot melt	60	E-Glass	68	1.6	17	0.5	
TC-14-U	80	B	Uni Warp			470	13.9	Carbon 12K	800	n/a	n/a		481	14.2	Hot melt	60	E-Glass	68	1.6	17	0.5	
TK-09-U	110	B	Uni Warp	0.84	0.033	305	9.0	Carbon 48K	3300	n/a	n/a	0.8	288	8.5	Hot melt	60	n/a	n/a	n/a	17	0.5	

Aramid 0790°

Fabric Availability*/Specification

FABRIC DESCRIPTION



 <i>jb martin</i>		Warp				Fill											
Style	Length Yards	Resin Compatibility	Thickness		Nominal g/m² oz/yd²	Fiber		Sec. Fiber	Counts ends/cm	Theoretical		Fiber g/m² oz/yd²	Fiber g/m² oz/yd²	Int Style			
			Weave	mm in.		Prim.	Tex			Prim.	Tex				Sec. Fiber	Counts ends/cm	
TA-05-P	165	B	PW	0.33 0.013	165 4.9	Aramid	158	n/a	n/a	5.1	83	2.4	Aramid	158	n/a	83 2.4	500
TA-09-S	110	B	3X2 T	0.66 0.026	305 9.0	Aramid	240	n/a	n/a	6.3	156	4.6	Aramid	240	n/a	149 4.4	

Hybrids and other 0790°

TN-05-P	110	B	PW	0.31 0.012	184 5.4	Aramid	158	n/a	n/a	5.0	80	2.4	Carbon 3K	200	n/a
TN-07-T	110	B	2X2 T	0.43 0.017	238 7.0	Aramid	158	Carbon 3K	200	6.4	119	3.5	Aramid	158	Carbon 3K
TH-09-N	110	B	NCS	0.61 0.024	288 8.5	E-Glass	275	Polyester	16.66	5.5	166	4.9	Aramid	158	Polyester
TP-04-P	110	A	PW	0.30 0.012	150 4.4	Color P.	110	n/a	n/a	6.7	67	2.0	Color P.	110	n/a
TP-05-P	110	A	PW	0.30 0.012	176 5.2	Polyester	110	n/a	n/a	8.0	88	2.6	Polyester	110	n/a
TR-08-P	110	A	2X1 T	0.36 0.014	270 8.0	Polyester	111	n/a	n/a	9.2	103	3.1	E-Glass	330	n/a
TR-16-N	80	A	NCS	0.84 0.033	523 15.4	E-Glass	735	Polyester	16.66	3.1	224	6.6	E-Glass	330	Color P.
TT-04-P	110	B	PW	0.28 0.011	145 4.3	Polyester	110	n/a	n/a	4.5	40	1.2	Carbon 3K	200	n/a
TT-05-P	110	B	PW	0.43 0.017	195 5.8	Polyester	110	n/a	n/a	8.9	77	2.3	Carbon 3K	200	n/a
TH-12-R	110	B	3X1 T	0.76 0.030	390 11.5	Aramid	316	E-Glass	275	4.4	193	5.7	Aramid	316	E-Glass
TH-20-E	110	B	3X2 T	1.40 0.055	675 19.9	Aramid	316	E-Glass	275	7.6	337	9.9	Aramid	316	E-Glass
TH-38-E	55	B	Double 3X2 T	2.20 0.087	1288 38.0	Aramid	316	E-Glass	1100	7.1	640	18.9	Aramid	632	E-Glass

Resin compatibility: A Polyester, Vinylester, Epoxy Weaves: NCS No Chimp Structure
B Vinylester, Epoxy PW Plain Weave

Notes: All values may vary by ± 10%

2X1 T 2X1 Twill
2X2 T 2X2 Twill
3X1 T 3X1 Twill
3X2 T 3X2 Twill

Jun-06



3802 Robert Porcher Way
Greensboro, NC 27410
336-545-0011
800-476-4845
Fax: 336-545-0233
Email: info@bgf.com
Website: www.bgf.com

Data Sheet - Product Information	
Style	1800
Finish	Untreated
Weave Pattern	Plain
Fiber Type	Glass
Yarn Description	
Warp	ECK 18 1/0
Fill	ECK 18 1/0
Count: Ends x Picks in	16.0 x 14.0
Weight	9.60 oz/yd ²
Breaking Strength	
Warp	450 lb / in
Fill	350 lb / in
Thickness	0.0121 in

Values shown are based on typical greige fabric data and should be used only as a guide, not a specification.

[Print Window](#)

[Close Window](#)



HexForce™ 282

Carbon Fabric

Product Data

STYLE 282

US System

Type of Yarns	Warp Yarn:	3K Carbon, 33MSI	
	Fill Yarn:	3K Carbon, 33MSI	
Fabric Weight, Dry		5.80 oz/yd ²	197 g/m ²
Weave Style	Plain		

CONSTRUCTION

Nominal Construction	Warp Count:	12/in	
	Fill Count:	12/in	
Fabric Thickness		10.10 mil	0.26 mm

IMPORTANT

All information is believed to be accurate but is given without acceptance of liability. All values have been generated from limited data. The values listed for weight, thickness and breaking strengths are typical greige values, unless otherwise noted. Users should make their own assessment of the suitability of any product for the purpose required. All sales are made subject to our standard terms of sales which include limitations on liability and other important terms. The fabric style listed may not be available from inventory and minimum order quantities may apply.

FOR FURTHER INFORMATION, PLEASE CONTACT US



1913 North King Street
Seguin, Texas 78155
Phone: 830-379-1580
Fax: 830-379-9544
Customer Service Toll Free: 1-866-601-5430

For European sales office numbers and a full address list, please go to:
<http://www.hexcel.com/contact/salesoffices>

Appendix C

Flat Plate Permeability Test Results

C.1 T1-B

C.1.1 T1-B1

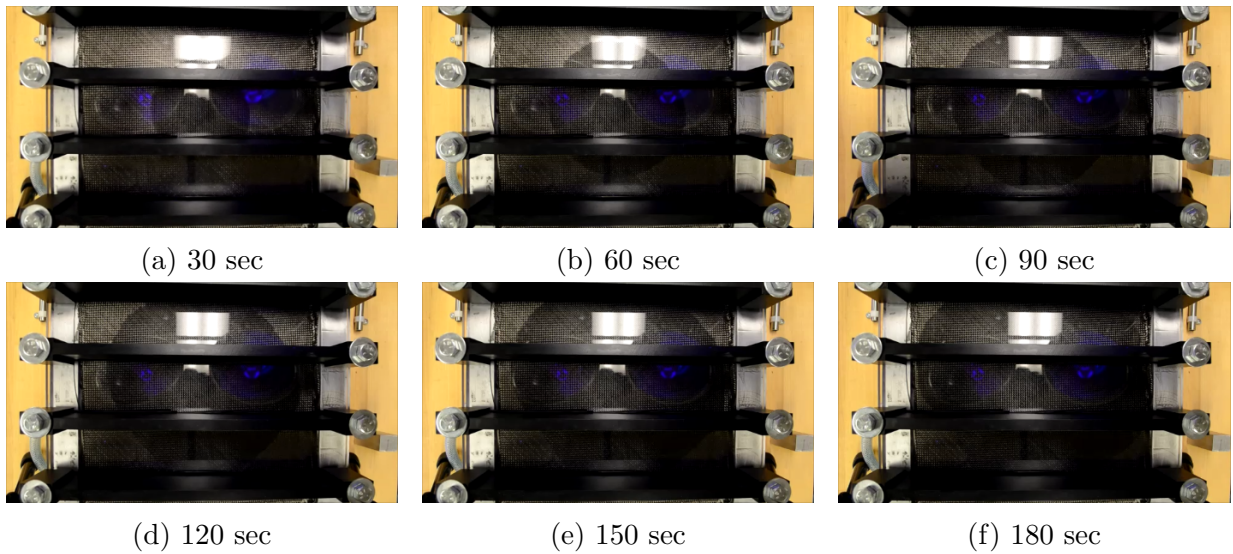


Figure C.1: T1-B1

C.2 T1-C

C.2.1 T1-C1

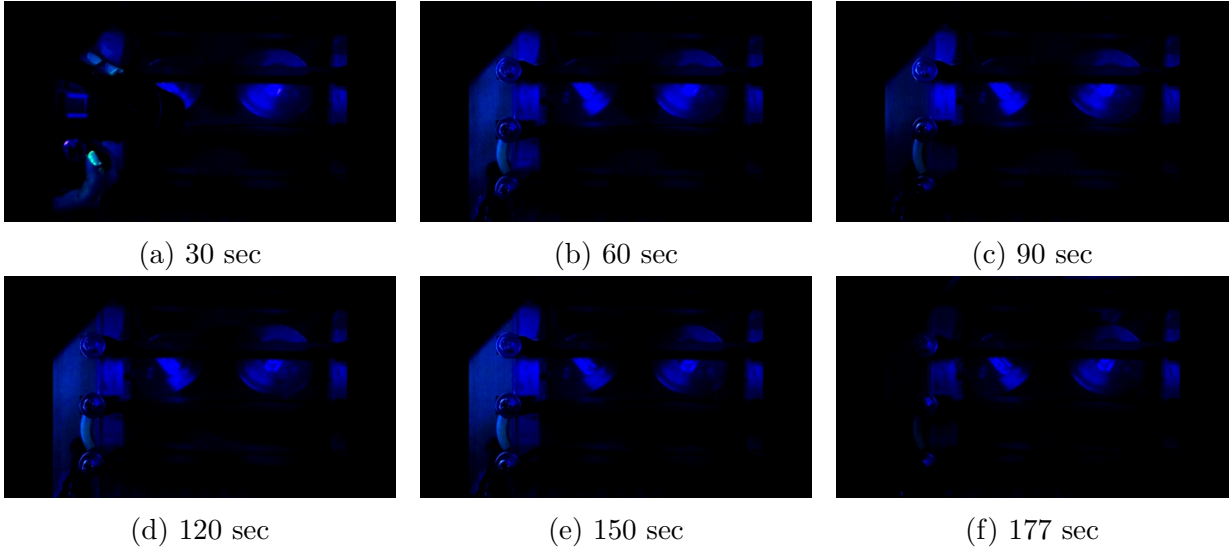


Figure C.2: T1-C1

C.2.2 T1-C2

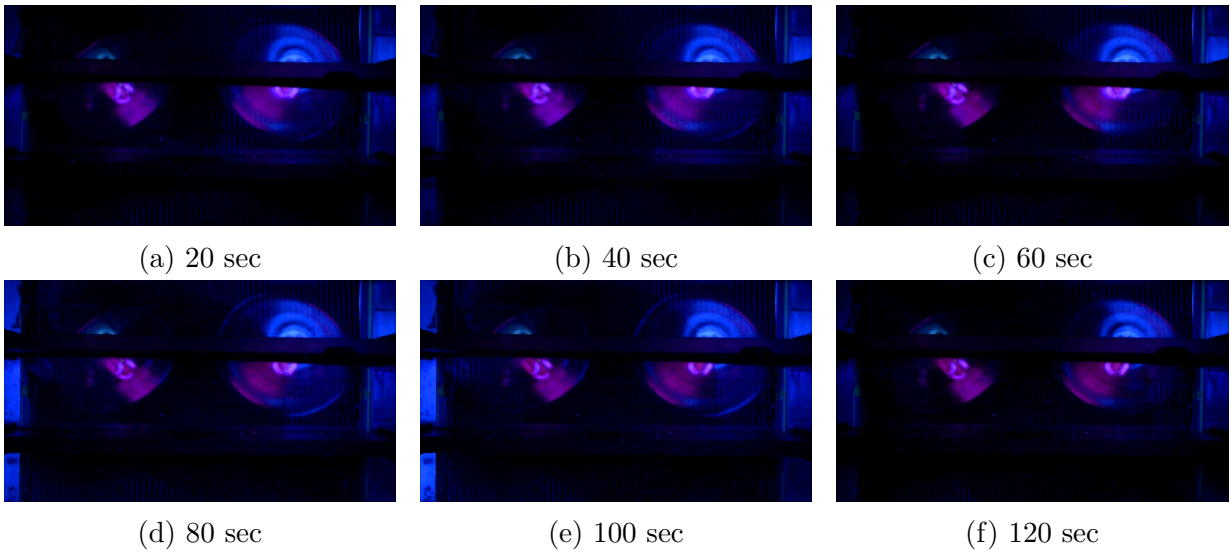
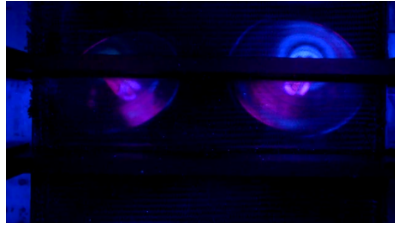


Figure C.3: T1-C2

C.2.3 T1-C3



(a) 25 sec



(b) 50 sec



(c) 75 sec



(d) 100 sec



(e) 125 sec

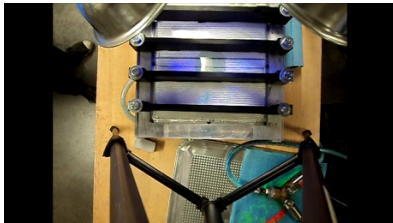


(f) 142 sec

Figure C.4: T1-C3

C.3 T1-EG

C.3.1 T1-EG1



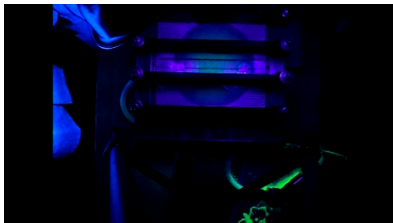
(a) 40 sec



(b) 80 sec



(c) 120 sec



(d) 160 sec



(e) 200 sec



(f) 240 sec

Figure C.5: T1-EG1

C.3.2 T1-EG2

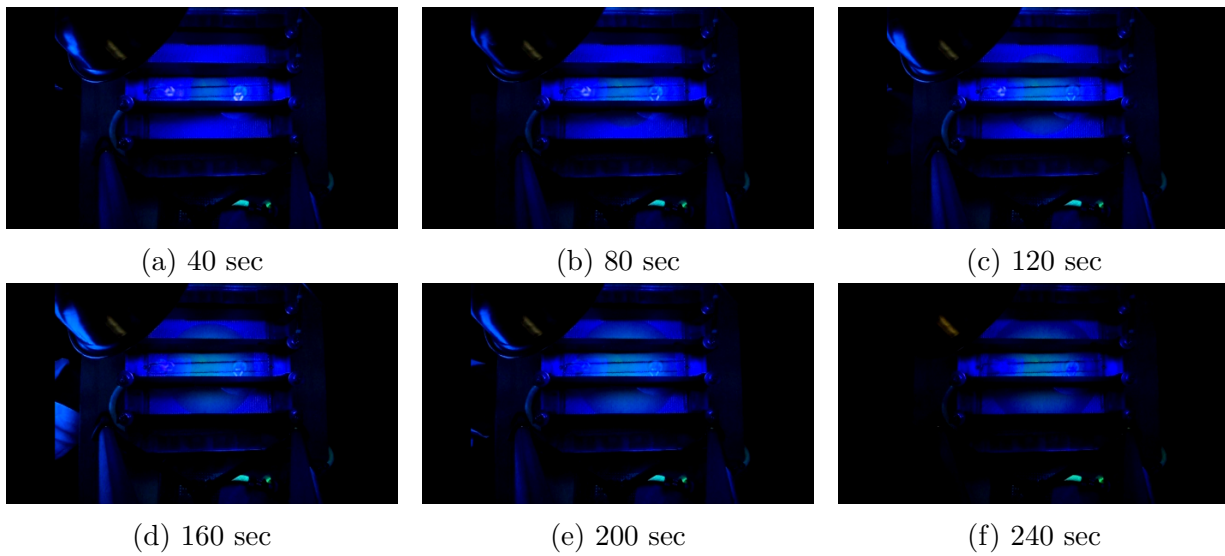


Figure C.6: T1-EG2

C.3.3 T1-EG2

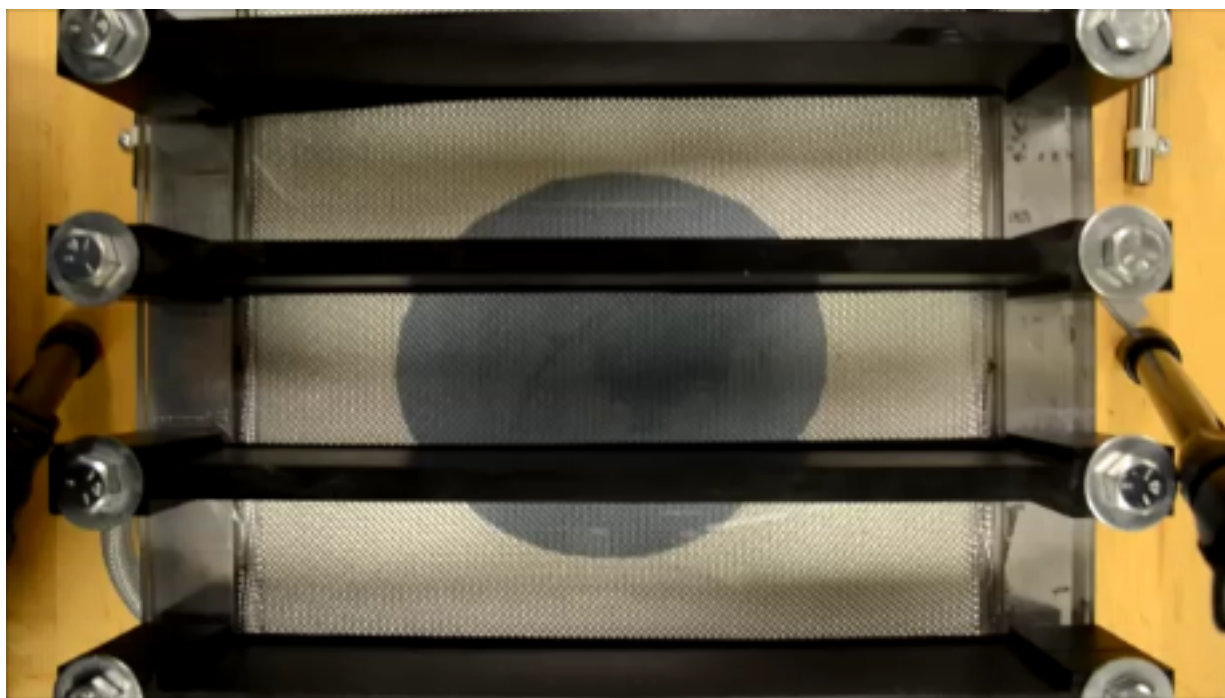


Figure C.7: 40 sec

C.4 T1-W

C.4.1 T1-W1

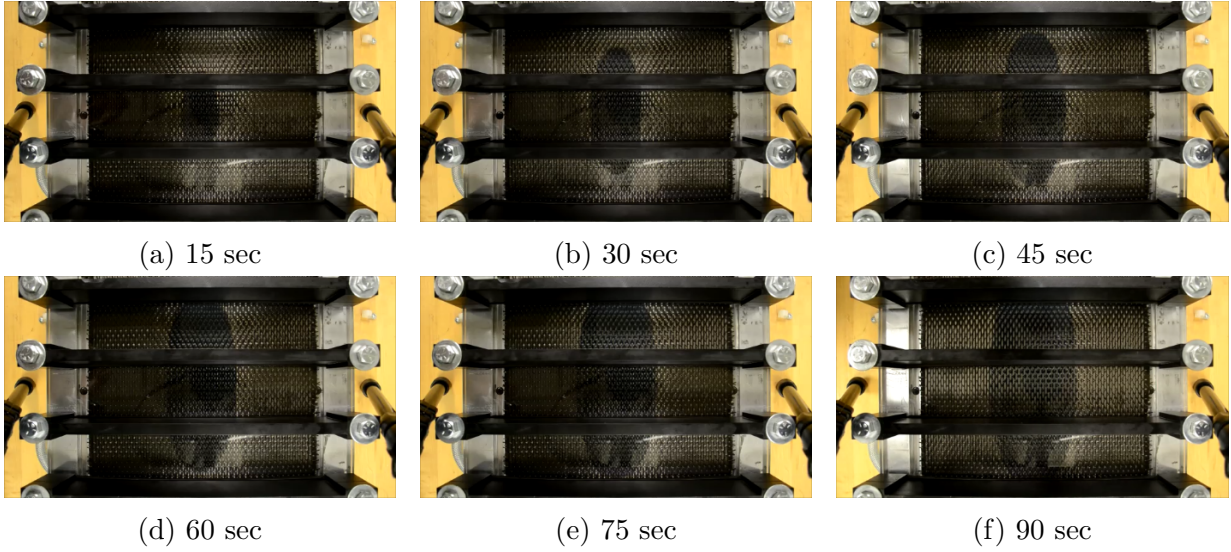


Figure C.8: T1-W1

C.4.2 T1-W2

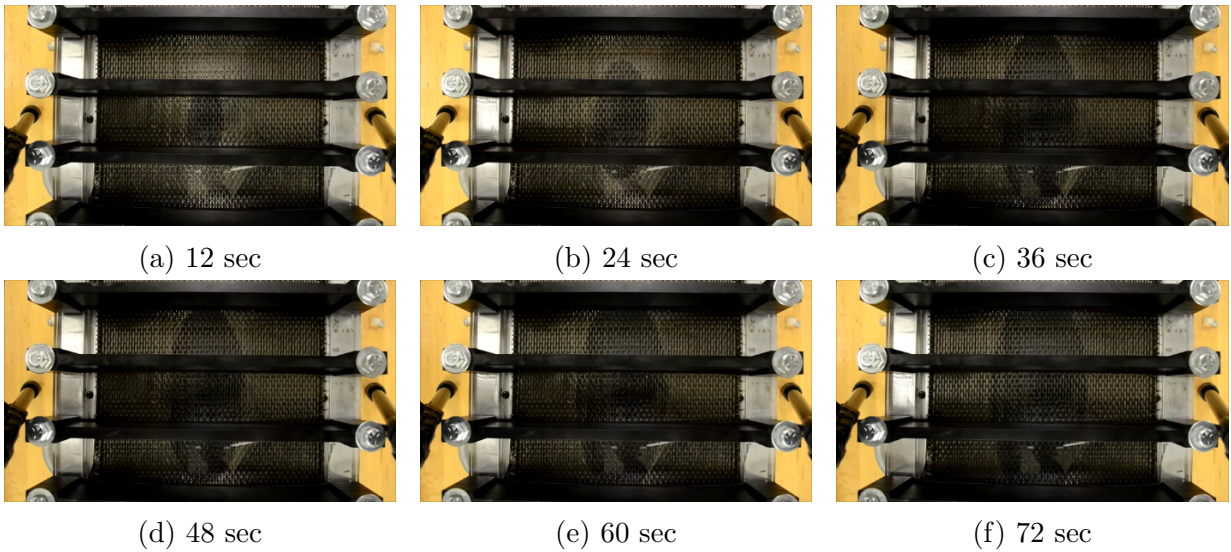
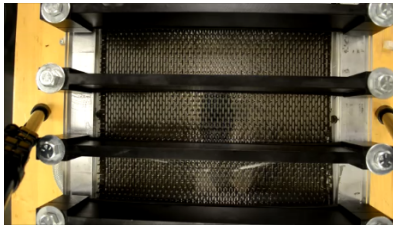
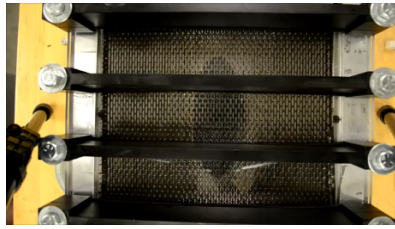


Figure C.9: T1-W2

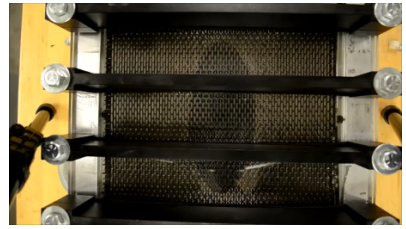
C.4.3 T1-W3



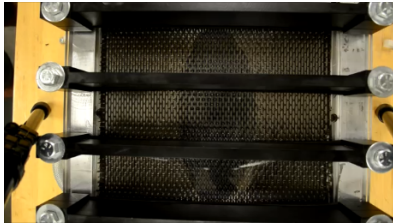
(a) 12 sec



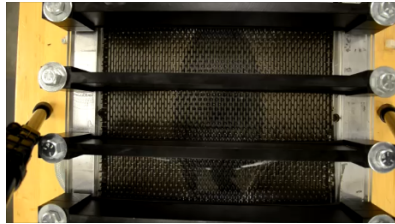
(b) 24 sec



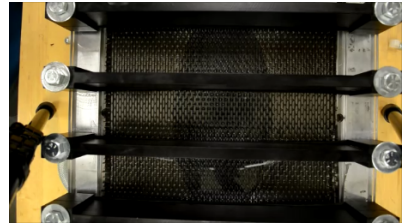
(c) 36 sec



(d) 48 sec



(e) 60 sec

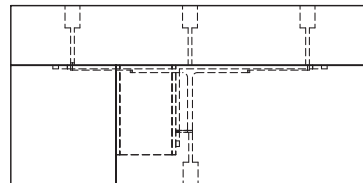
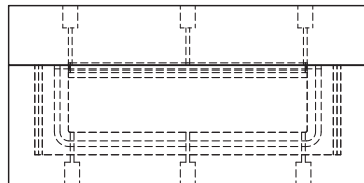
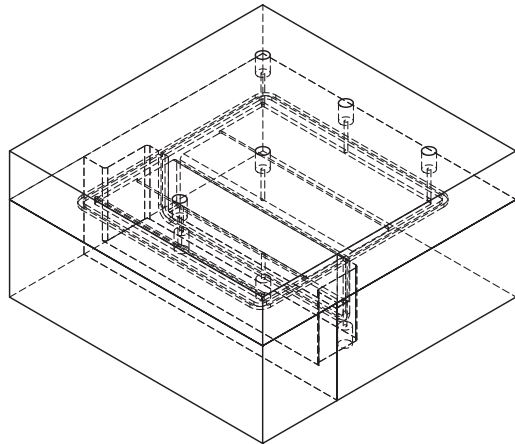
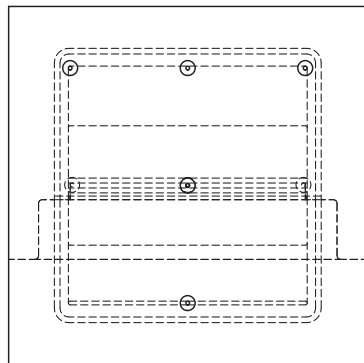


(f) 72 sec

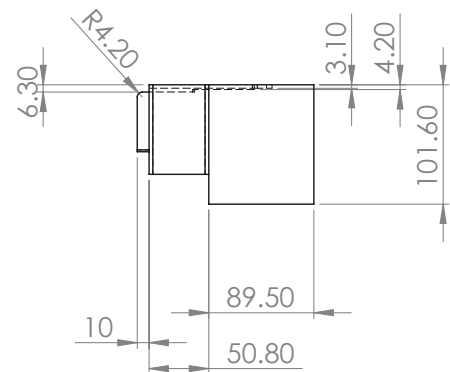
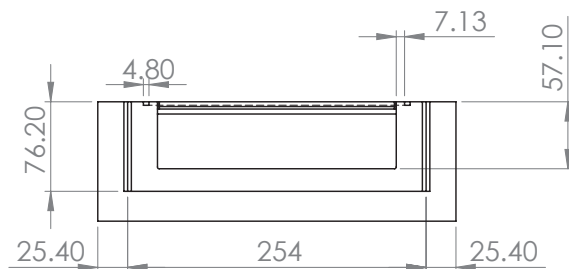
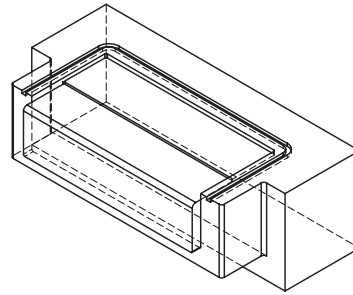
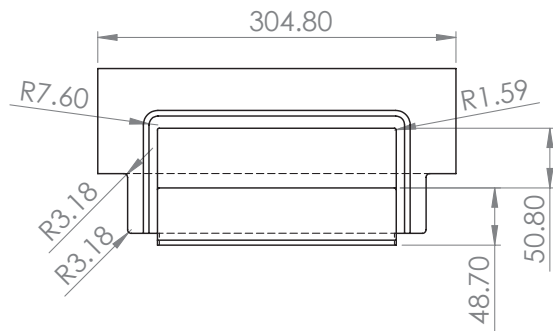
Figure C.10: T1-W3

Appendix D

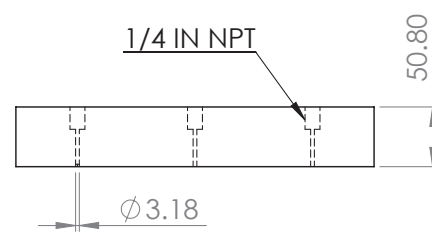
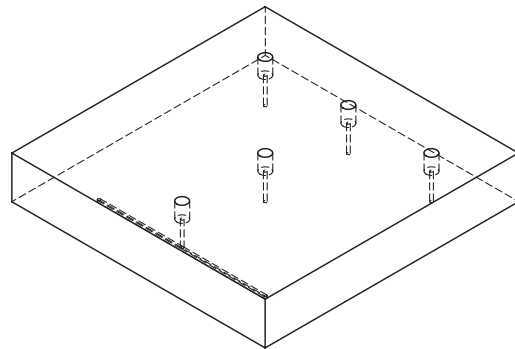
Translucent Cavity Rig Drawings

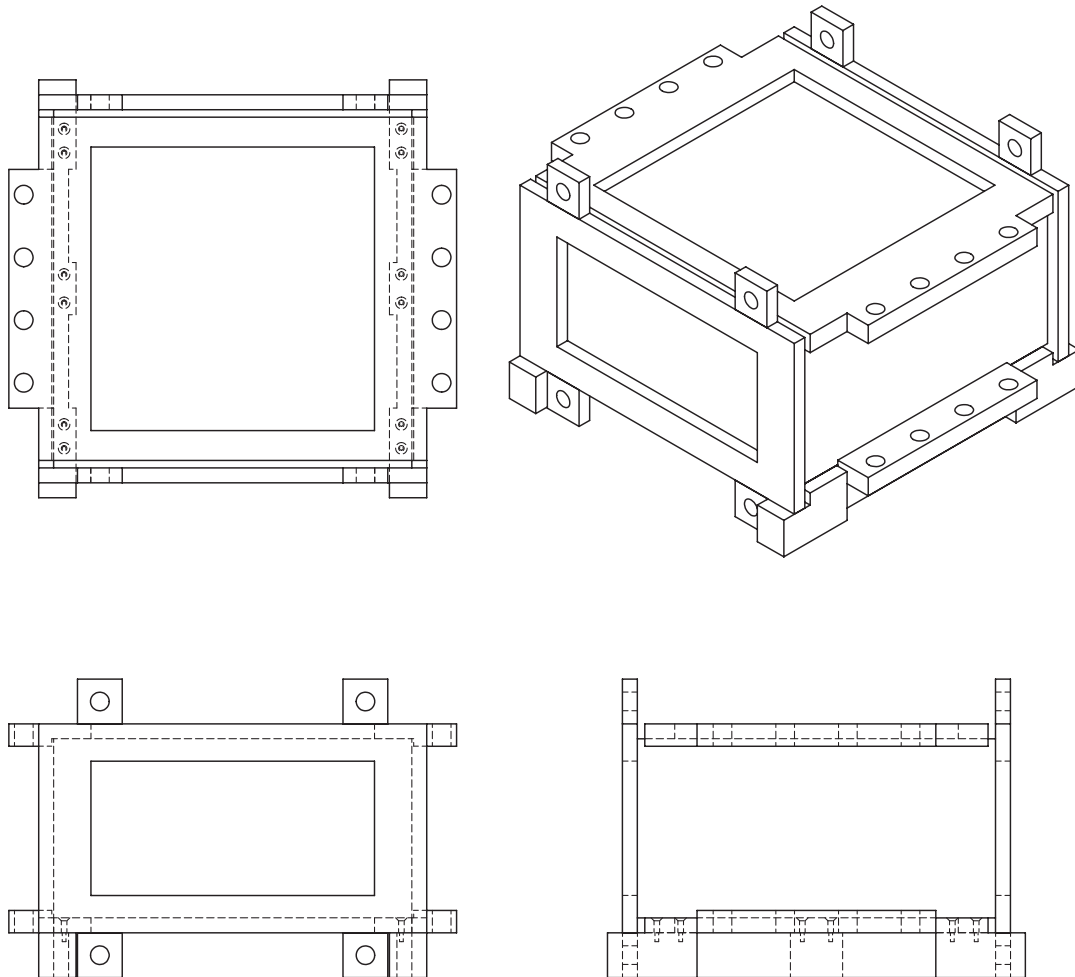


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE:			
FRANCOIS PROULX		18/05/13					
FINISH:		TC-ASSEMBLY					
OPTICAL TRANSPARENCY							
MATERIAL:		DWG NO.		TC-ASSEM-1		8.5/11	
PMMA							
WEIGHT: 16.628 kg		SCALE:1:5			SHEET 1 OF 4		

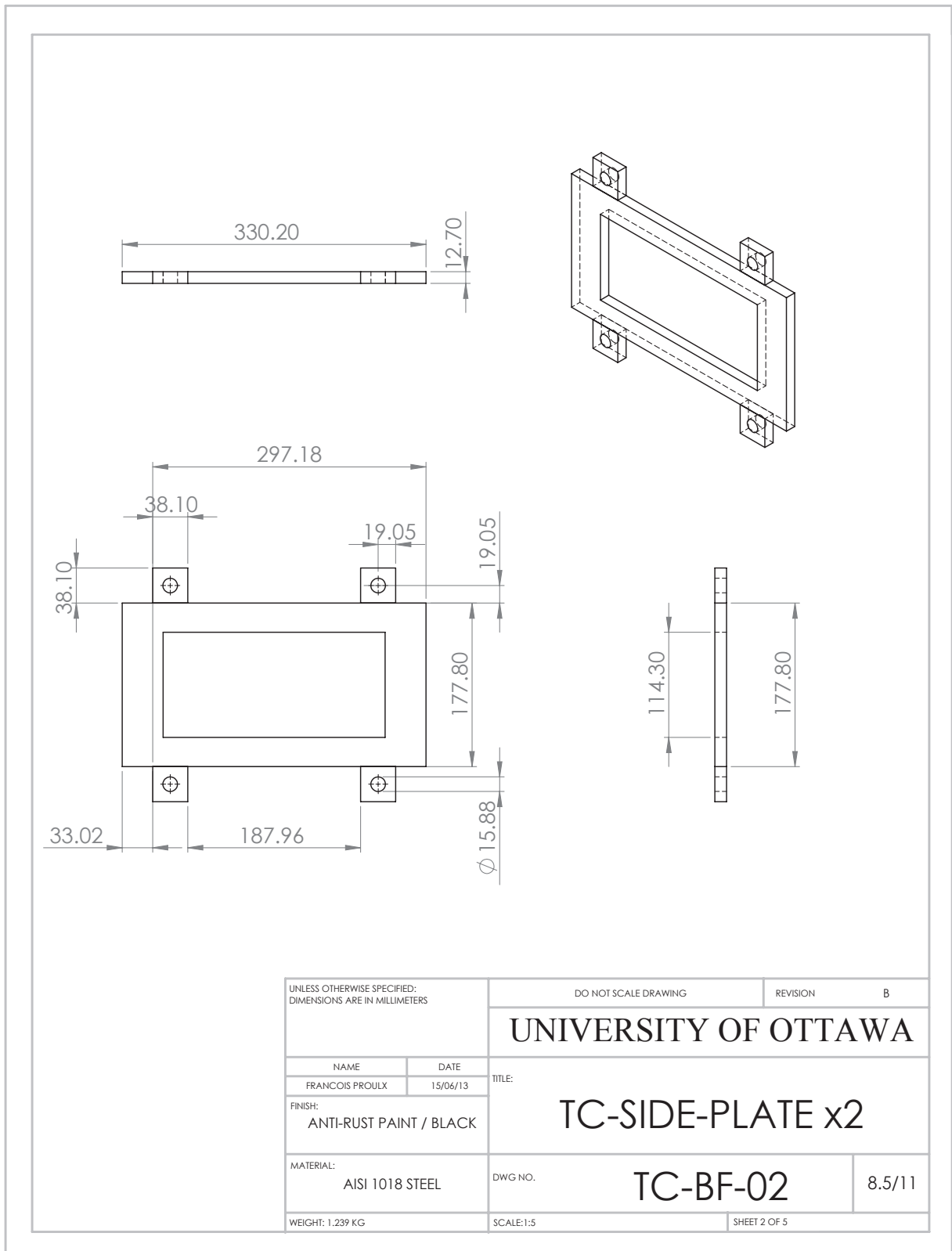


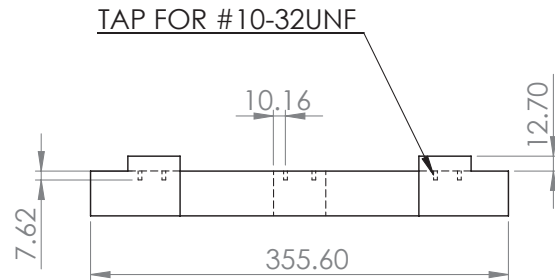
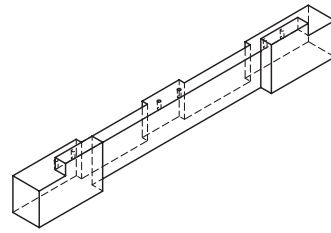
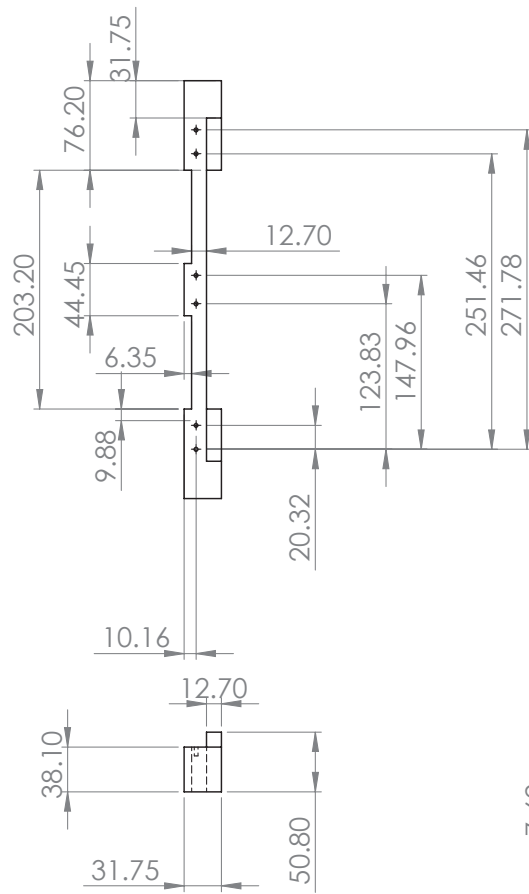
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION	C
		UNIVERSITY OF OTTAWA			
NAME	DATE	TITLE: TC-BASE-MALE			
FRANCOIS PROULX	18/05/13				
FINISH: OPTICAL TRANSPARENCY		DWG NO. TC-ASSEM-3 8.5/11			
MATERIAL: PMMA					
WEIGHT: 4.510 kg		SCALE:1:5		SHEET 3 OF 4	





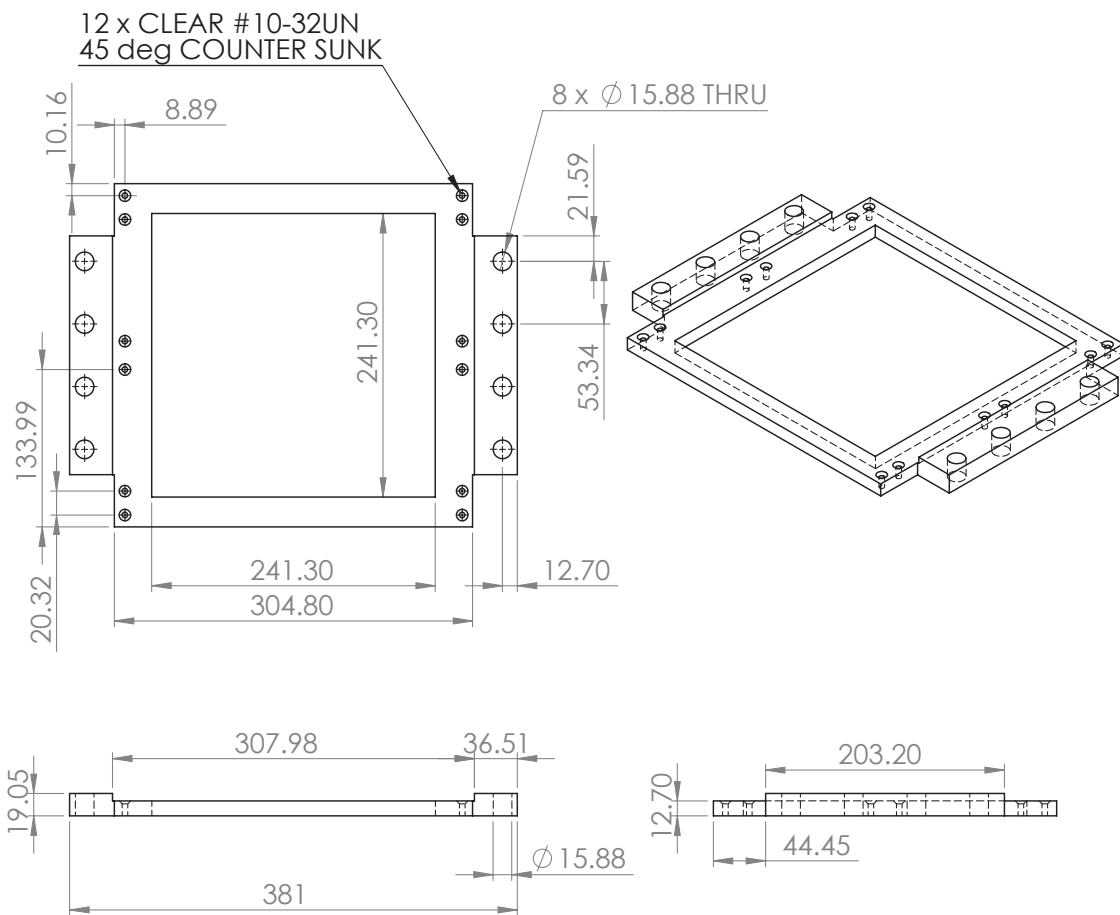
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE:			
FRANCOIS PROULX		15/06/13					
FINISH: ANTI-RUST PAINT / BLACK				TC-BRACING-FRAME			
MATERIAL: AISI 1018 STEEL							
DWG NO.				TC-BF-01		8.5/11	
WEIGHT: 24.389 kg				SCALE:1:5		SHEET 1 OF 5	



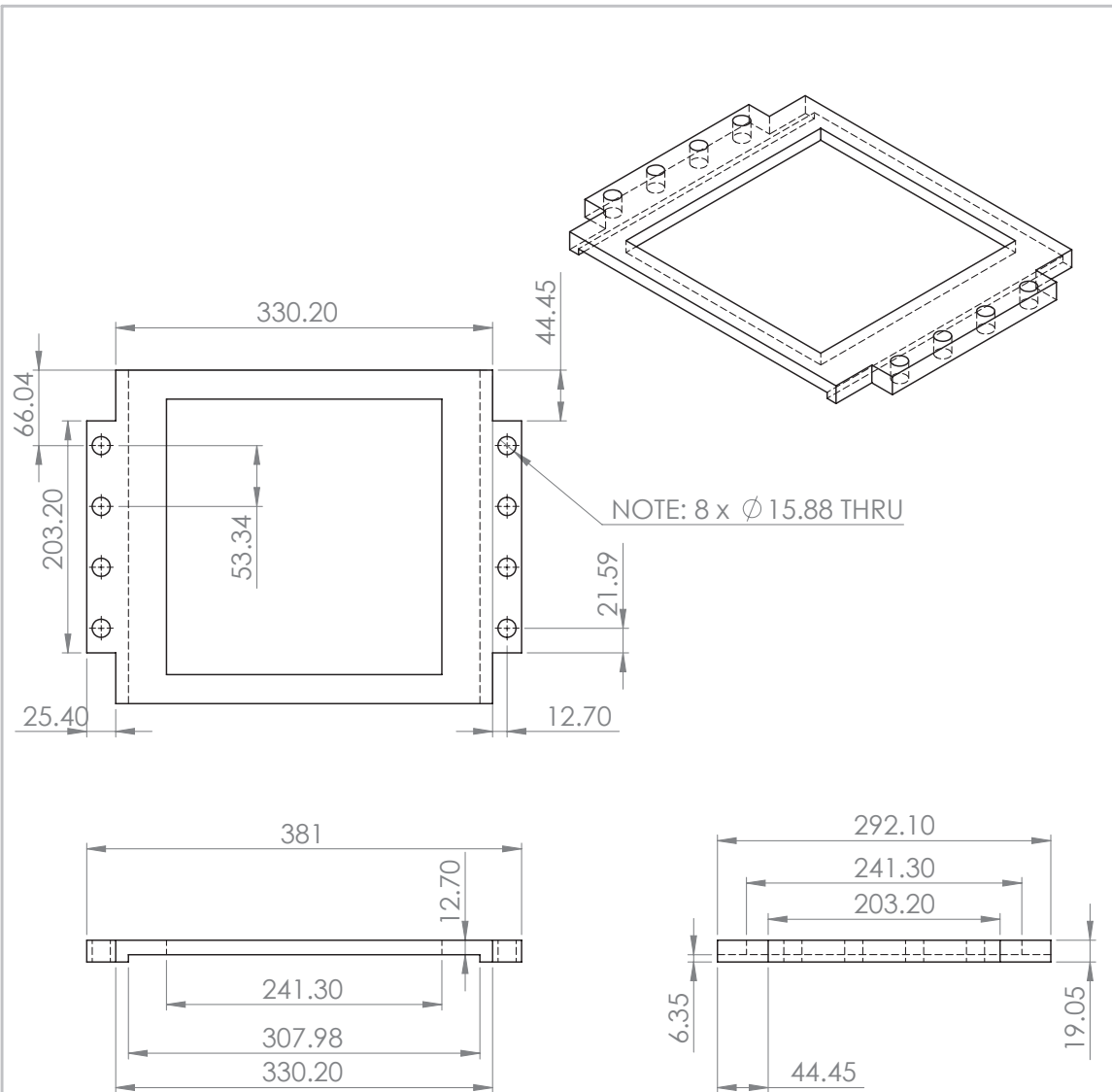


TAP FOR #10-32UNF

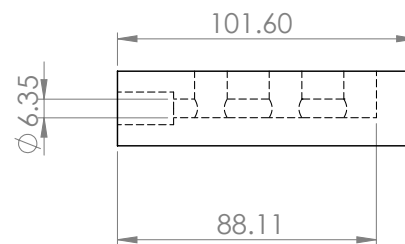
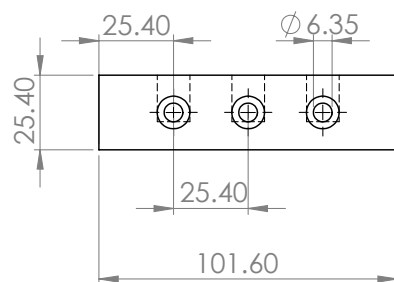
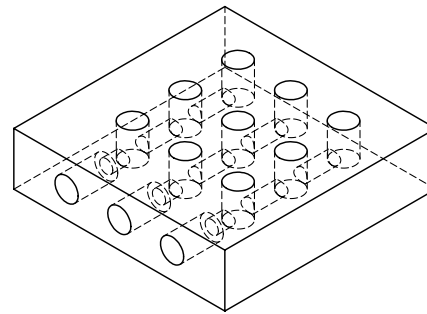
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		C		
		UNIVERSITY OF OTTAWA						
NAME		DATE		TITLE:				
FRANCOIS PROULX		15/06/13						
FINISH: ANTI-RUST PAINT / BLACK		TC-BASE-SUPPORT x2						
MATERIAL: AISI 1018 STEEL		DWG NO.				TC-BF-03		8.5/11
WEIGHT: 0.830 kg		SCALE:1:5				SHEET 3 OF 5		



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		C	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE:			
FRANCOIS PROULX		15/06/13					
FINISH:		TC-BOTTOM-PLATE					
ANTI-RUST PAINT / BLACK							
MATERIAL:		DWG NO.		TC-BF-04		8.5/11	
AISI 1018 STEEL							
WEIGHT: 1.751 kg		SCALE:1:5			SHEET 4 OF 5		



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		B	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE:			
FRANCOIS PROULX		15/06/13					
FINISH:		TC-TOP-PLATE					
ANTI-RUST PAINT / BLACK							
MATERIAL:		DWG NO.				8.5/11	
AISI 1018 STEEL		TC-BF-05					
WEIGHT: 1.872 kg		SCALE:1:5			SHEET 5 OF 5		



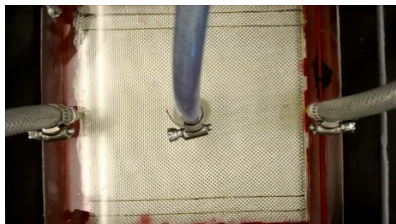
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE:			
FRANCOIS PROULX		28/06/13					
FINISH:				TC-MANIFOLD			
DRAW FILED AND DEBURRED							
MATERIAL:				DWG NO.		8.5/11	
ALUMINIUM 6061				TC-M-01			
WEIGHT: 0.646 kg				SCALE:1:2		SHEET 1 OF 1	

Appendix E

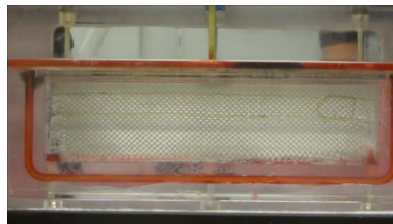
Translucent Cavity Rig Tests

E.1 Series T2

E.1.1 Test T2-G1

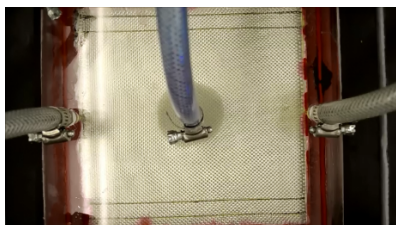


(a) Camera #1

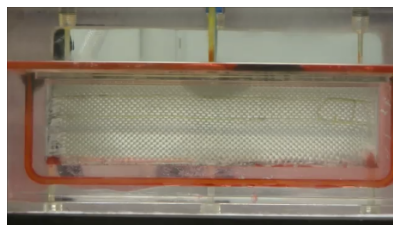


(b) Camera #2

Figure E.1: T2-G1 [03:00]

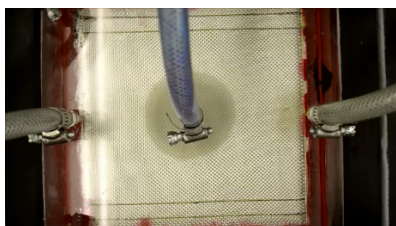


(a) Camera #1

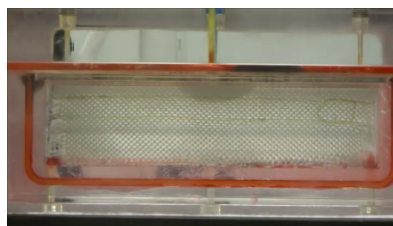


(b) Camera #2

Figure E.2: T2-G1 [16:00]



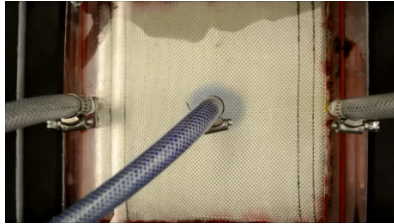
(a) Camera #1



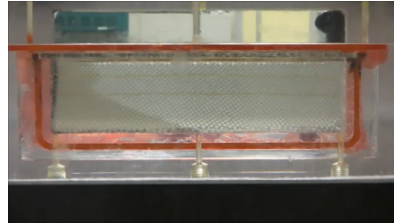
(b) Camera #2

Figure E.3: T2-G1 [20:00]

E.1.2 Test T2-G2



(a) Camera #1

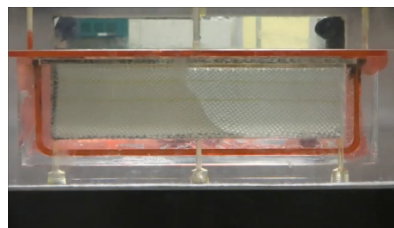


(b) Camera #2

Figure E.4: T2-G2 [01:00]



(a) Camera #1

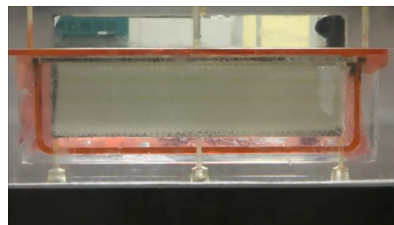


(b) Camera #2

Figure E.5: T2-G2 [02:00]



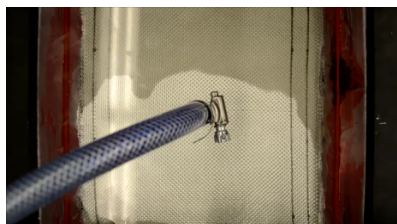
(a) Camera #1



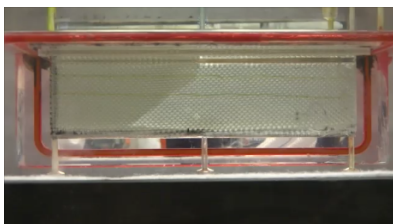
(b) Camera #2

Figure E.6: T2-G2 [05:00]

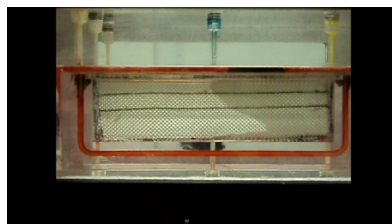
E.1.3 Test T2-G3



(a) Camera #1

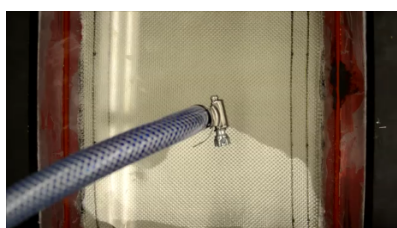


(b) Camera #2

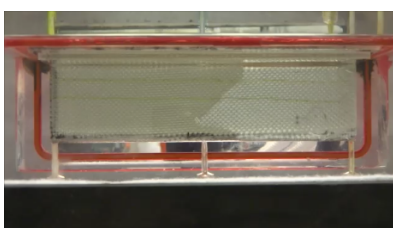


(c) Camera #3

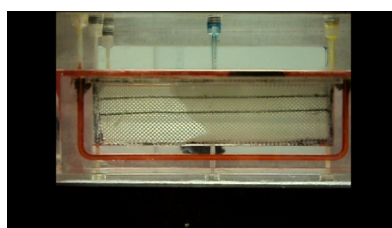
Figure E.7: T2-G3 [00:20]



(a) Camera #1



(b) Camera #2

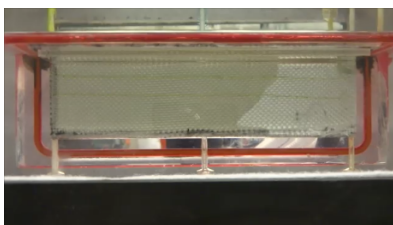


(c) Camera #3

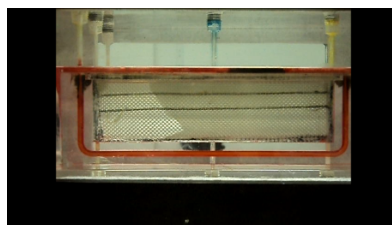
Figure E.8: T2-G3 [00:40]



(a) Camera #1

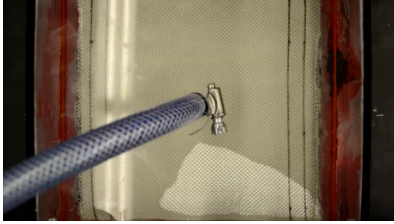


(b) Camera #2

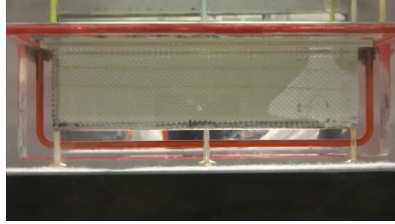


(c) Camera #3

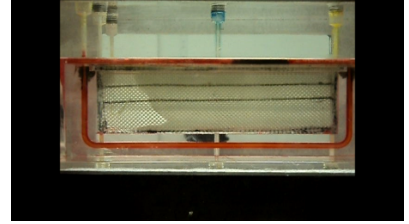
Figure E.9: T2-G3 [01:00]



(a) Camera #1

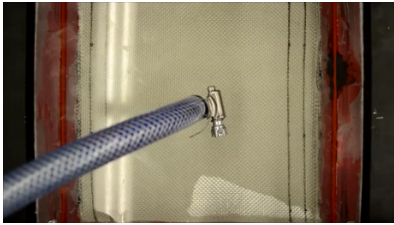


(b) Camera #2

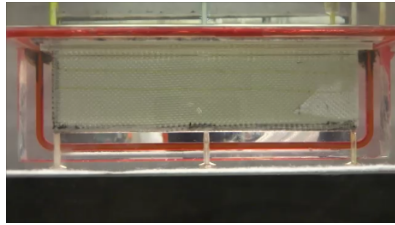


(c) Camera #3

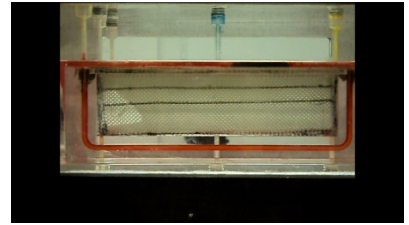
Figure E.10: T2-G3 [01:20]



(a) Camera #1

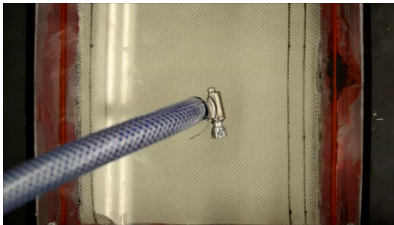


(b) Camera #2

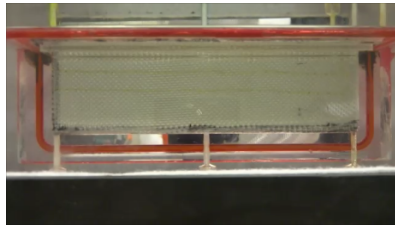


(c) Camera #3

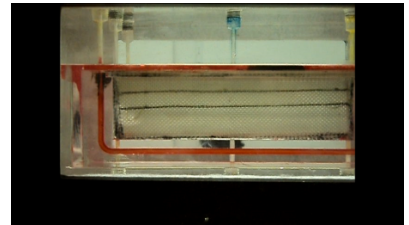
Figure E.11: T2-G3 [01:40]



(a) Camera #1



(b) Camera #2



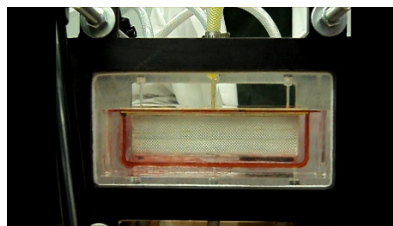
(c) Camera #3

Figure E.12: T2-G3 [02:00]

E.1.4 Test T2-G4

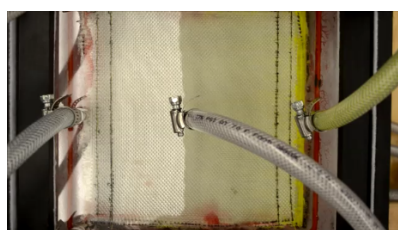


(a) Camera #1

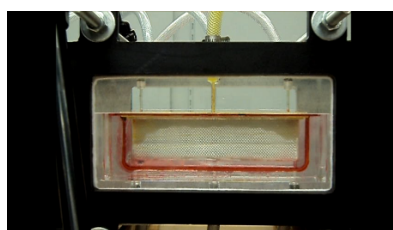


(b) Camera #2

Figure E.13: T2-G4 [00:30]

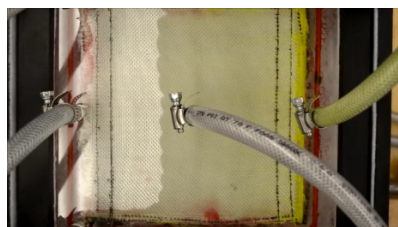


(a) Camera #1

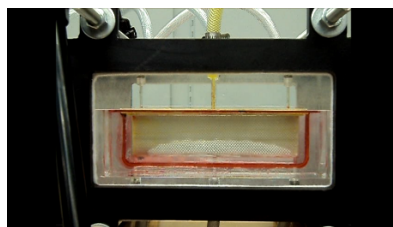


(b) Camera #2

Figure E.14: T2-G4 [02:00]

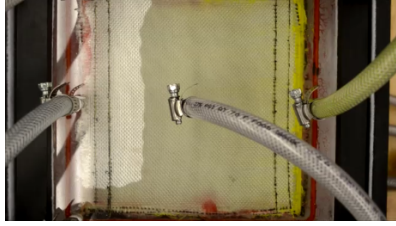


(a) Camera #1

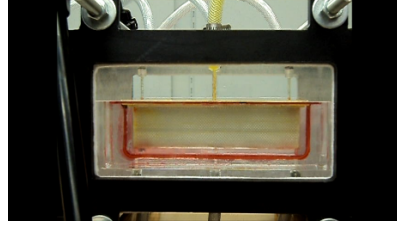


(b) Camera #2

Figure E.15: T2-G4 [03:30]



(a) Camera #1

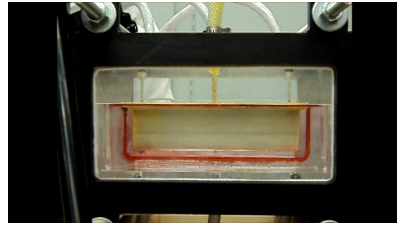


(b) Camera #2

Figure E.16: T2-G4 [05:00]

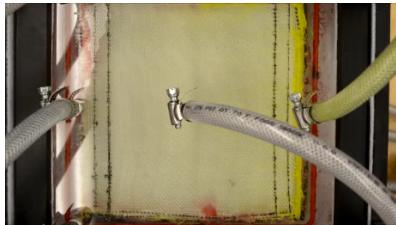


(a) Camera #1

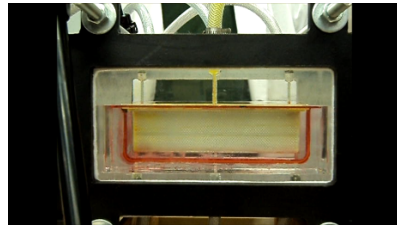


(b) Camera #2

Figure E.17: T2-G4 [06:30]



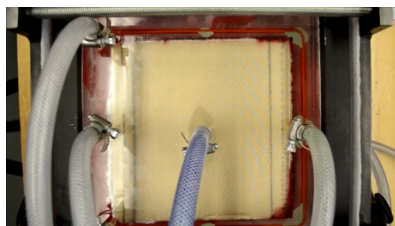
(a) Camera #1



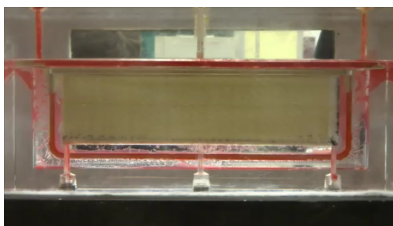
(b) Camera #2

Figure E.18: T2-G4 [08:00]

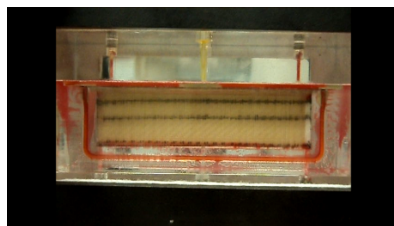
E.1.5 Test T2-G5



(a) Camera #1

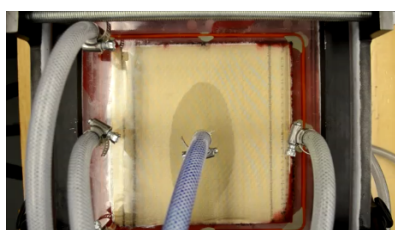


(b) Camera #2

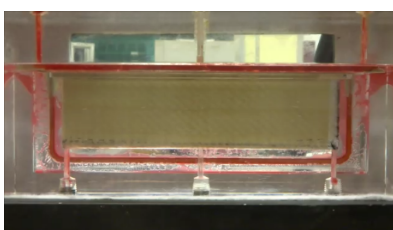


(c) Camera #3

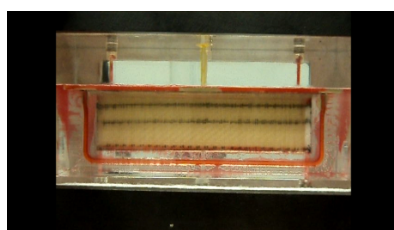
Figure E.19: T2-G5 [00:20]



(a) Camera #1

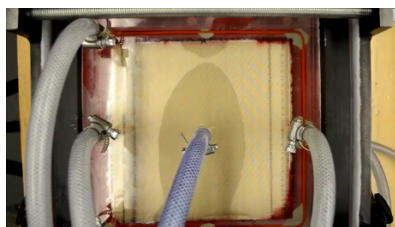


(b) Camera #2

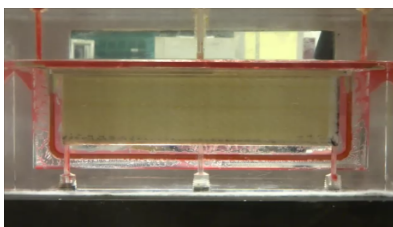


(c) Camera #3

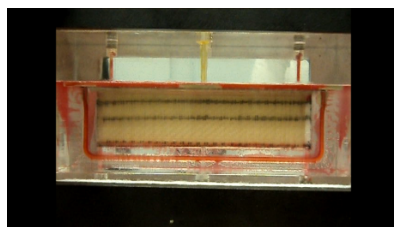
Figure E.20: T2-G5 [00:45]



(a) Camera #1



(b) Camera #2



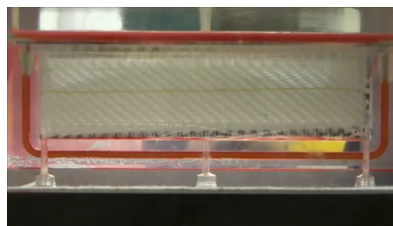
(c) Camera #3

Figure E.21: T2-G5 [01:10]

E.1.6 Test T2-G6



(a) Camera #1

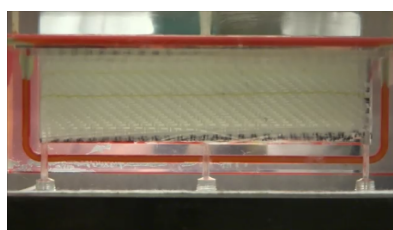


(b) Camera #2

Figure E.22: T2-G6 [00:05]

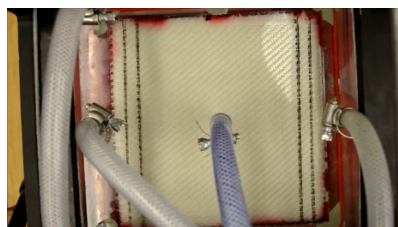


(a) Camera #1

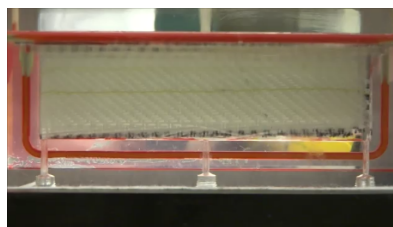


(b) Camera #2

Figure E.23: T2-G6 [00:35]



(a) Camera #1

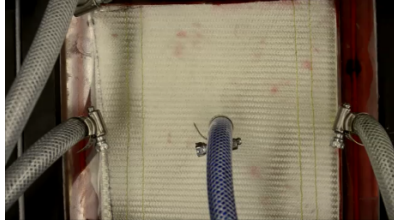


(b) Camera #2

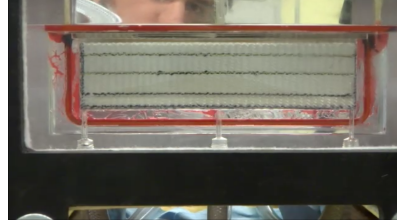
Figure E.24: T2-G6 [01:15]

E.2 Series T3

E.2.1 Test T3-MEG1

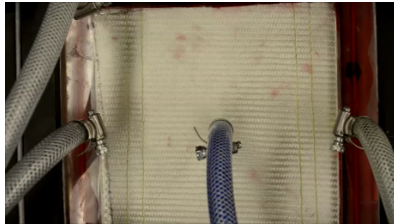


(a) Camera #1

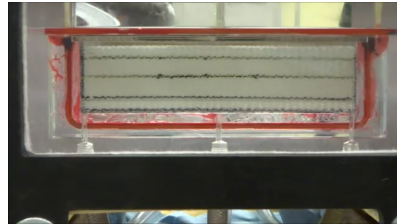


(b) Camera #2

Figure E.25: T3-MEG1 [00:05]

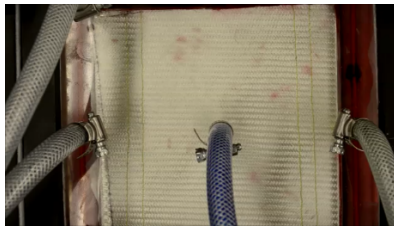


(a) Camera #1

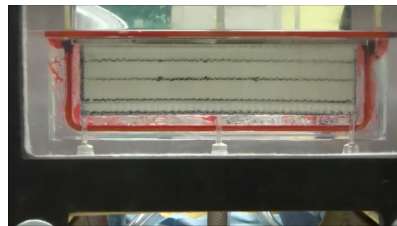


(b) Camera #2

Figure E.26: T3-MEG1 [00:15]

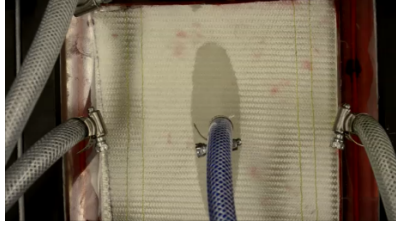


(a) Camera #1

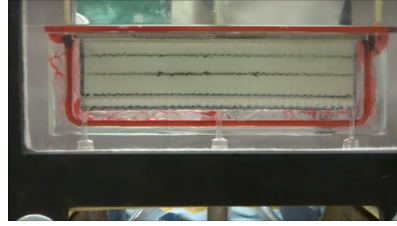


(b) Camera #2

Figure E.27: T3-MEG1 [00:30]

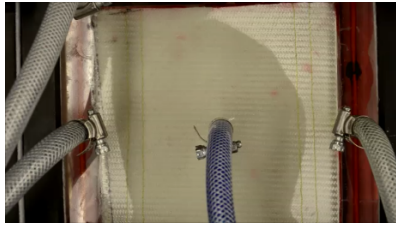


(a) Camera #1

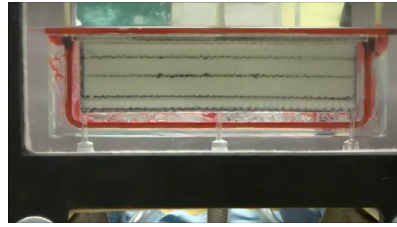


(b) Camera #2

Figure E.28: T3-MEG1 [01:20]

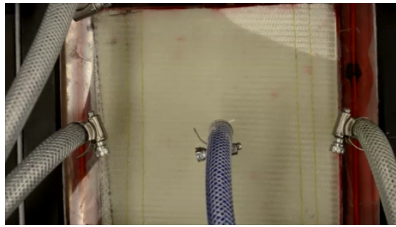


(a) Camera #1

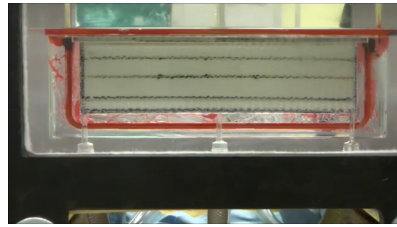


(b) Camera #2

Figure E.29: T3-MEG1 [03:20]



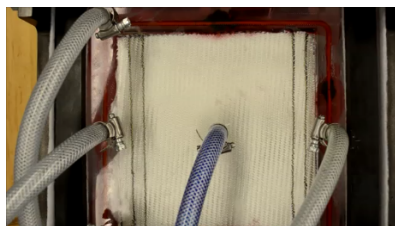
(a) Camera #1



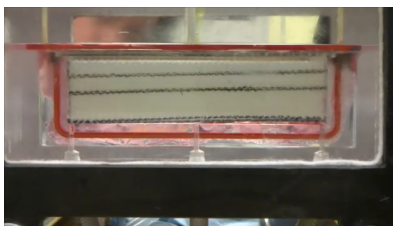
(b) Camera #2

Figure E.30: T3-MEG1 [05:20]

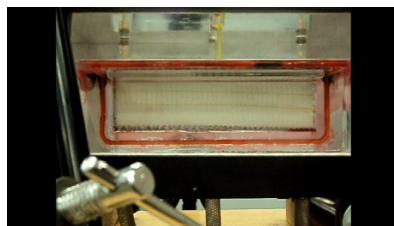
E.2.2 Test T3-MEG2



(a) Camera #1



(b) Camera #2

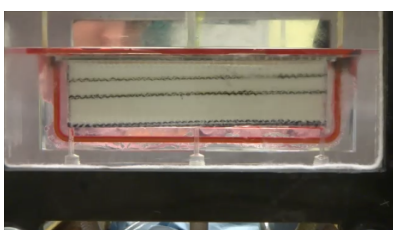


(c) Camera #3

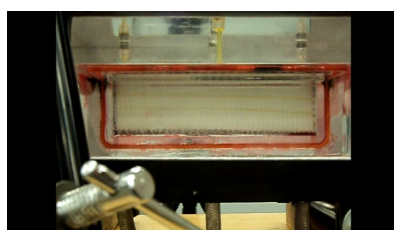
Figure E.31: T3-MEG2 [00:05]



(a) Camera #1



(b) Camera #2

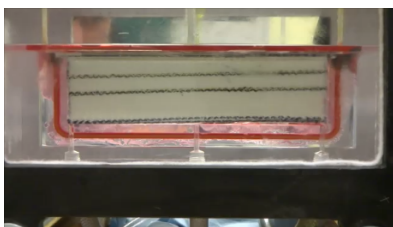


(c) Camera #3

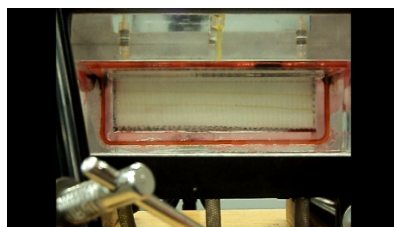
Figure E.32: T3-MEG2 [00:15]



(a) Camera #1

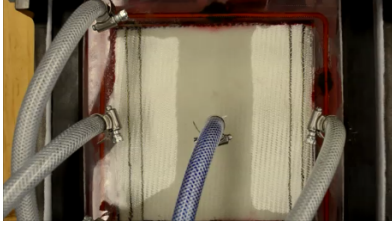


(b) Camera #2

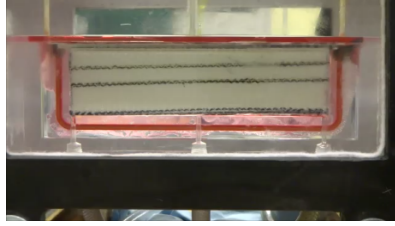


(c) Camera #3

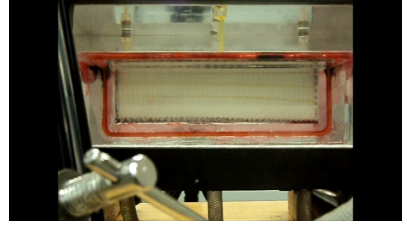
Figure E.33: T3-MEG2 [00:30]



(a) Camera #1

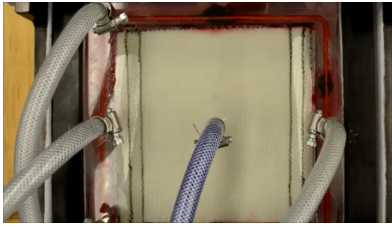


(b) Camera #2

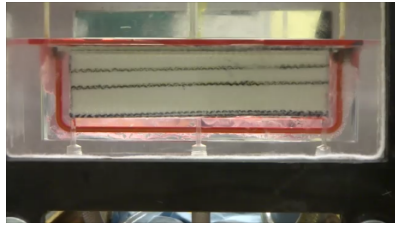


(c) Camera #3

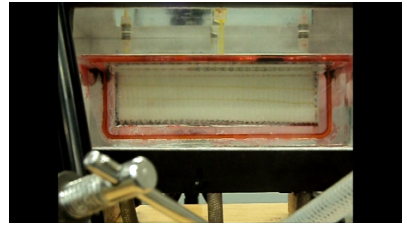
Figure E.34: T3-MEG2 [01:00]



(a) Camera #1

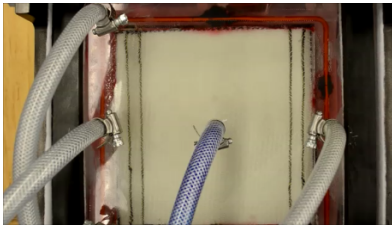


(b) Camera #2

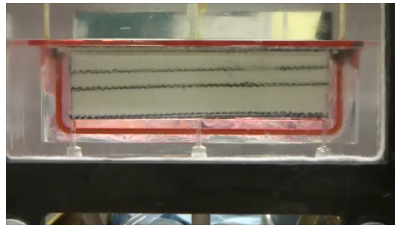


(c) Camera #3

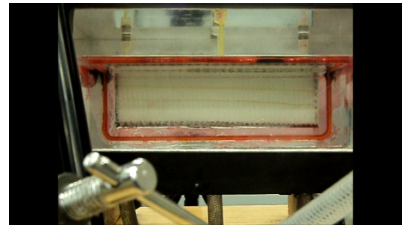
Figure E.35: T3-MEG2 [02:00]



(a) Camera #1



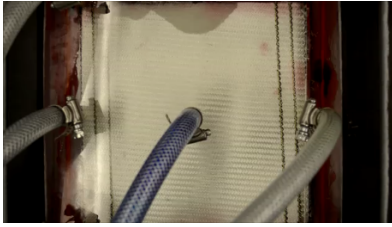
(b) Camera #2



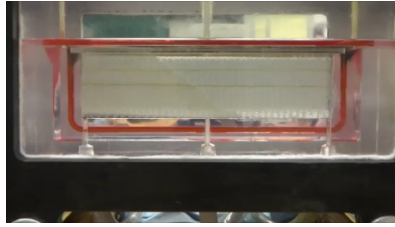
(c) Camera #3

Figure E.36: T3-MEG2 [03:00]

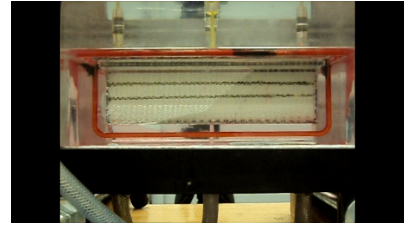
E.2.3 Test T3-MEG3



(a) Camera #1

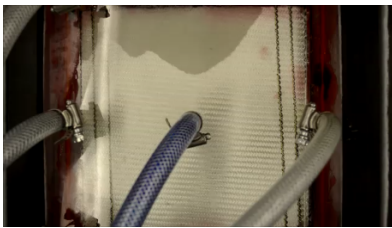


(b) Camera #2

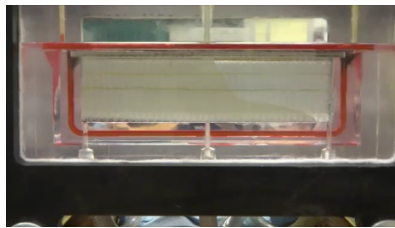


(c) Camera #3

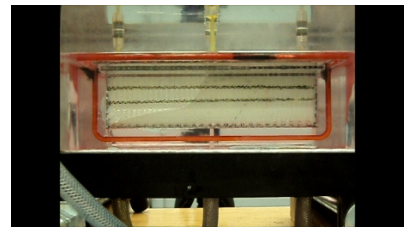
Figure E.37: T3-MEG3 [Timestamp]



(a) Camera #1



(b) Camera #2

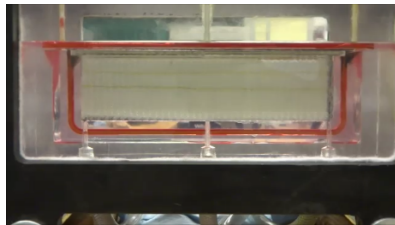


(c) Camera #3

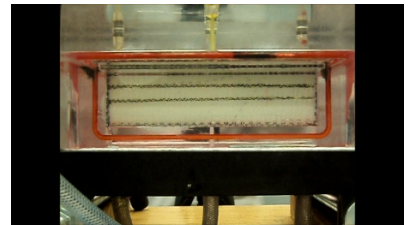
Figure E.38: T3-MEG3 [00:30]



(a) Camera #1

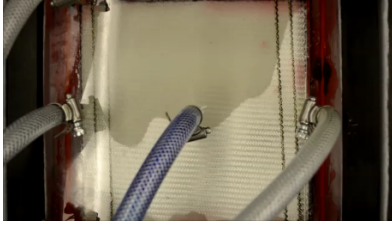


(b) Camera #2

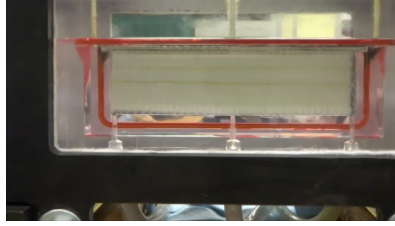


(c) Camera #3

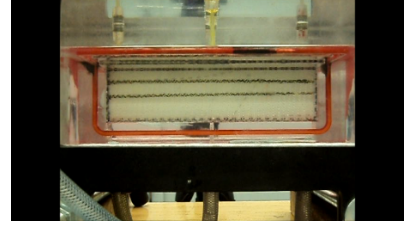
Figure E.39: T3-MEG3 [02:30]



(a) Camera #1

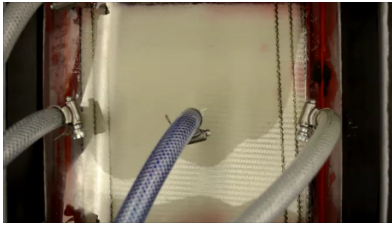


(b) Camera #2

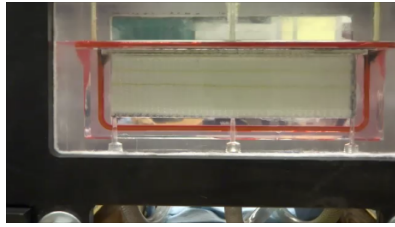


(c) Camera #3

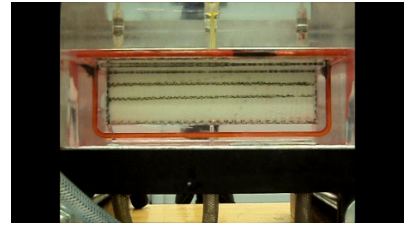
Figure E.40: T3-MEG3 [03:30]



(a) Camera #1

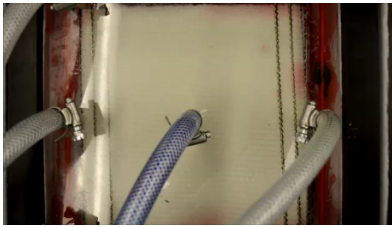


(b) Camera #2

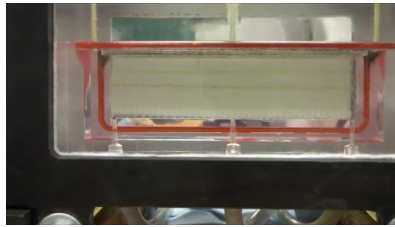


(c) Camera #3

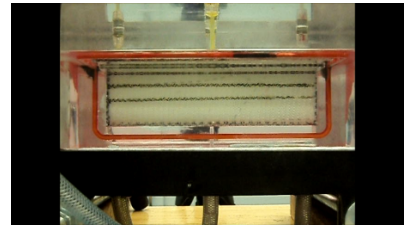
Figure E.41: T3-MEG3 [04:30]



(a) Camera #1



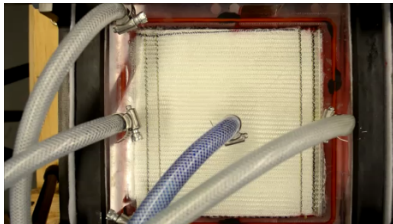
(b) Camera #2



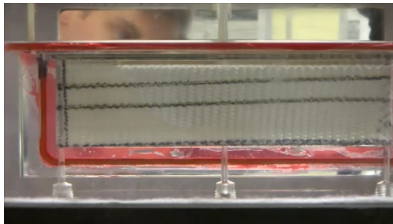
(c) Camera #3

Figure E.42: T3-MEG3 [05:30]

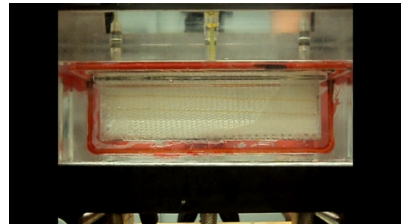
E.2.4 Test T3-MEG4



(a) Camera #1

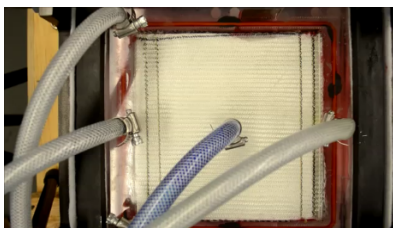


(b) Camera #2

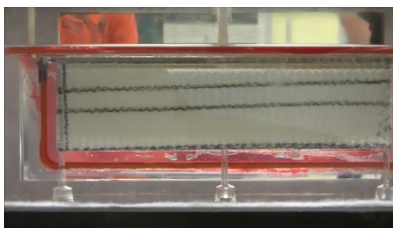


(c) Camera #3

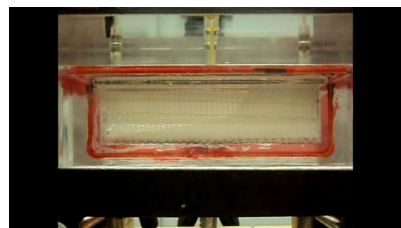
Figure E.43: T3-MEG4 [00:30]



(a) Camera #1

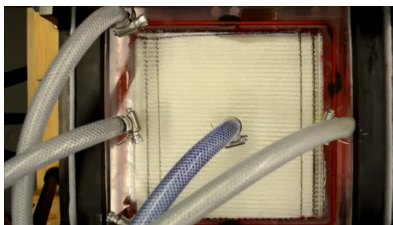


(b) Camera #2

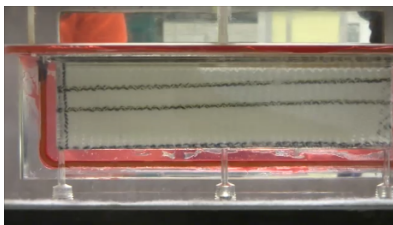


(c) Camera #3

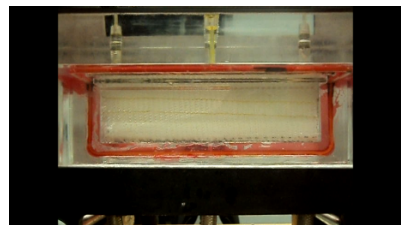
Figure E.44: T3-MEG4 [01:30]



(a) Camera #1

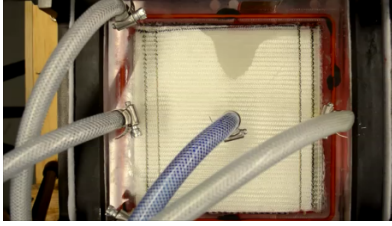


(b) Camera #2

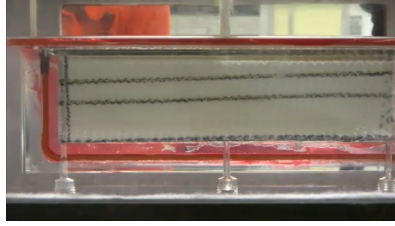


(c) Camera #3

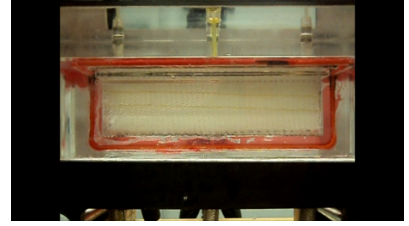
Figure E.45: T3-MEG4 [02:30]



(a) Camera #1

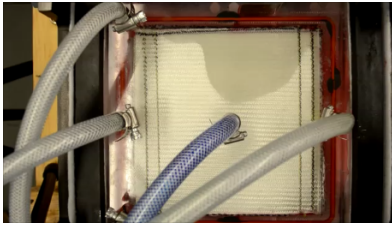


(b) Camera #2

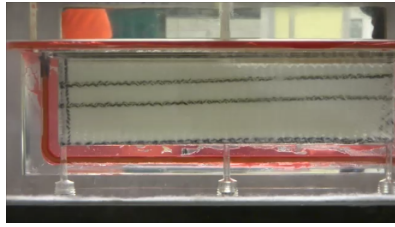


(c) Camera #3

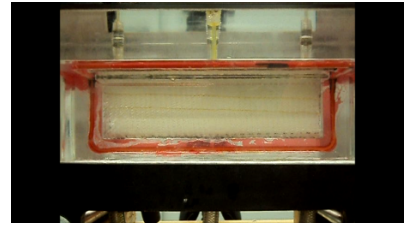
Figure E.46: T3-MEG4 [04:00]



(a) Camera #1

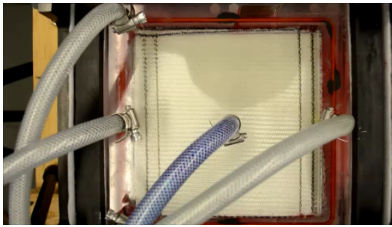


(b) Camera #2

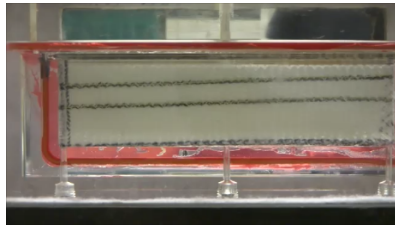


(c) Camera #3

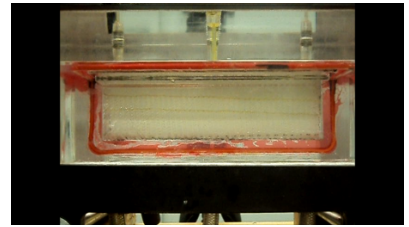
Figure E.47: T3-MEG4 [07:00]



(a) Camera #1



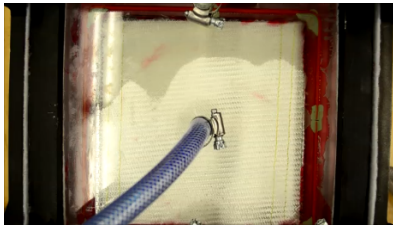
(b) Camera #2



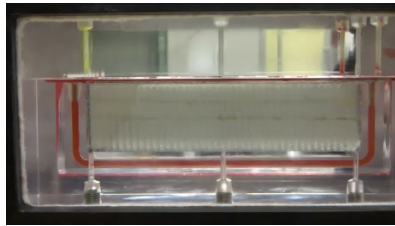
(c) Camera #3

Figure E.48: T3-MEG4 [10:00]

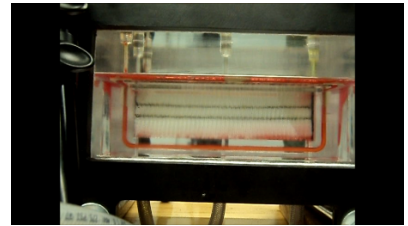
E.2.5 Test T3-MEG5



(a) Camera #1

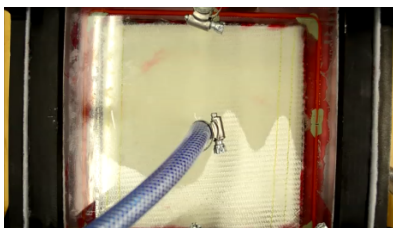


(b) Camera #2

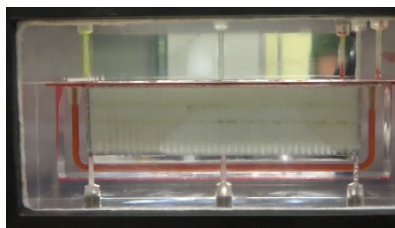


(c) Camera #3

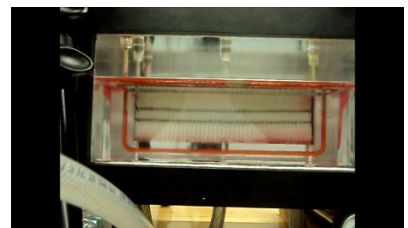
Figure E.49: T3-MEG5 [00:30]



(a) Camera #1



(b) Camera #2

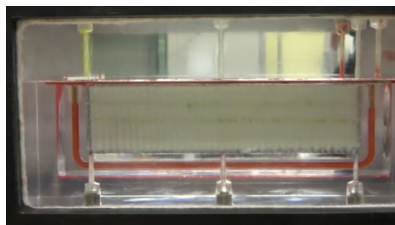


(c) Camera #3

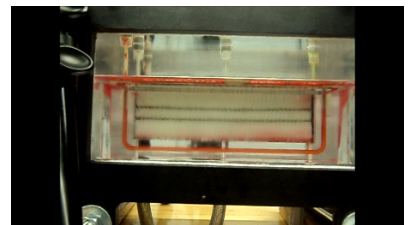
Figure E.50: T3-MEG5 [01:30]



(a) Camera #1

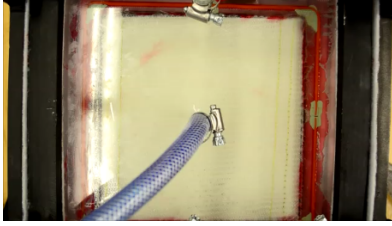


(b) Camera #2

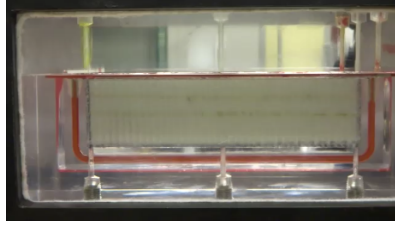


(c) Camera #3

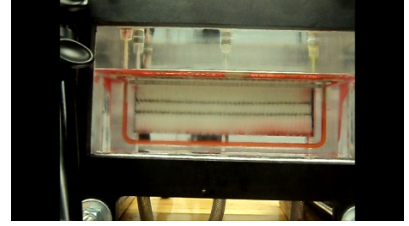
Figure E.51: T3-MEG5 [02:30]



(a) Camera #1

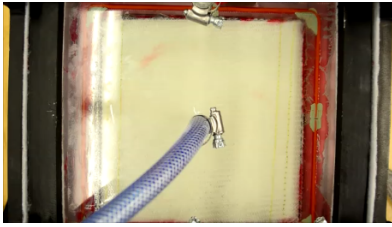


(b) Camera #2

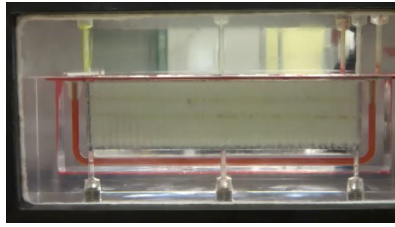


(c) Camera #3

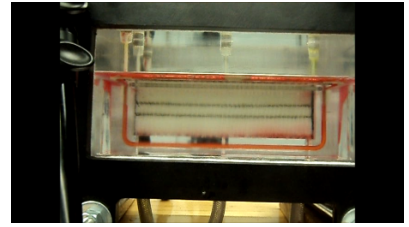
Figure E.52: T3-MEG5 [03:30]



(a) Camera #1

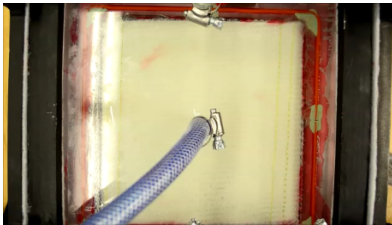


(b) Camera #2

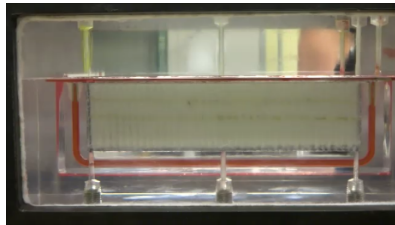


(c) Camera #3

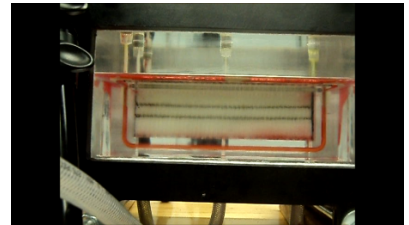
Figure E.53: T3-MEG5 [04:30]



(a) Camera #1



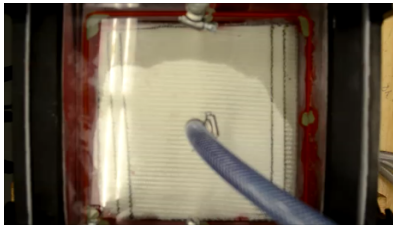
(b) Camera #2



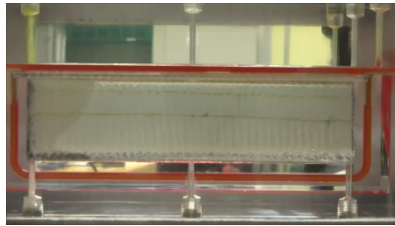
(c) Camera #3

Figure E.54: T3-MEG5 [05:30]

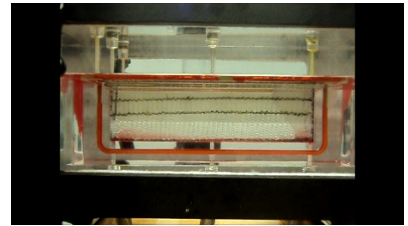
E.2.6 Test T3-MEG6



(a) Camera #1



(b) Camera #2

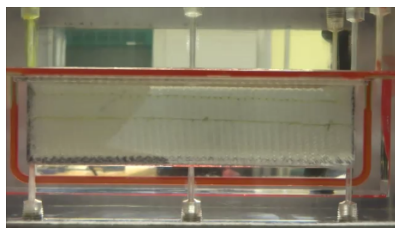


(c) Camera #3

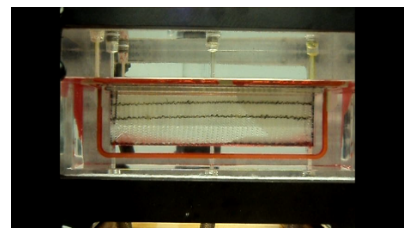
Figure E.55: T3-MEG6 [00:15]



(a) Camera #1



(b) Camera #2

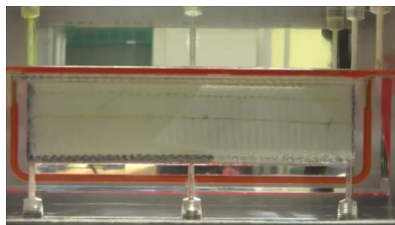


(c) Camera #3

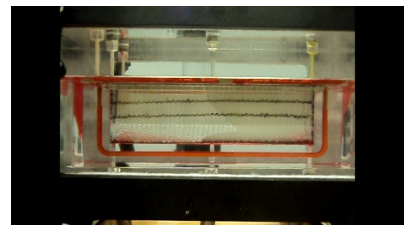
Figure E.56: T3-MEG6 [00:45]



(a) Camera #1

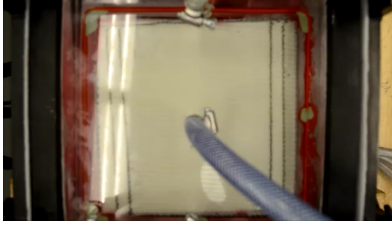


(b) Camera #2

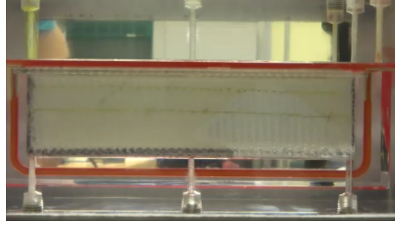


(c) Camera #3

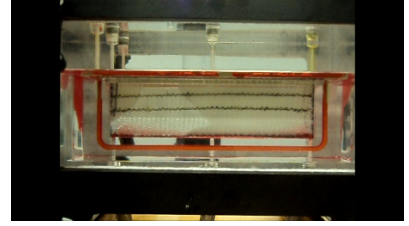
Figure E.57: T3-MEG6 [01:15]



(a) Camera #1

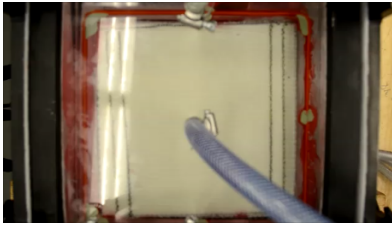


(b) Camera #2

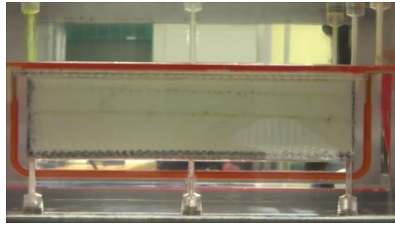


(c) Camera #3

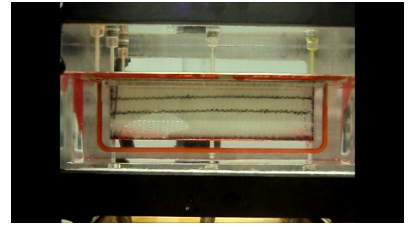
Figure E.58: T3-MEG6 [01:45]



(a) Camera #1

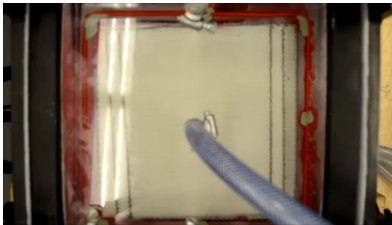


(b) Camera #2

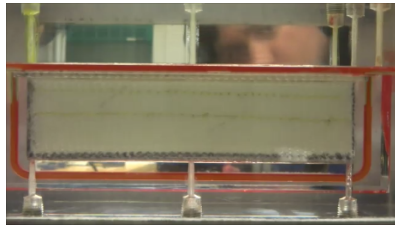


(c) Camera #3

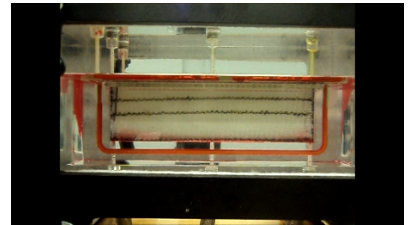
Figure E.59: T3-MEG6 [02:15]



(a) Camera #1



(b) Camera #2



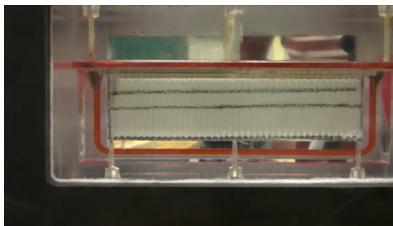
(c) Camera #3

Figure E.60: T3-MEG6 [02:45]

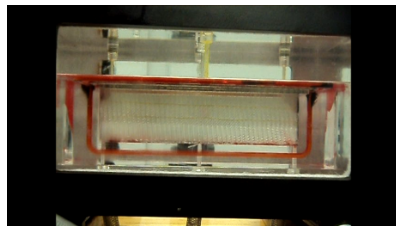
E.2.7 Test T3-MEG7



(a) Camera #1



(b) Camera #2

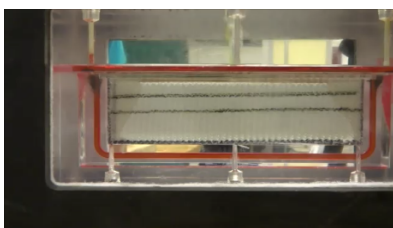


(c) Camera #3

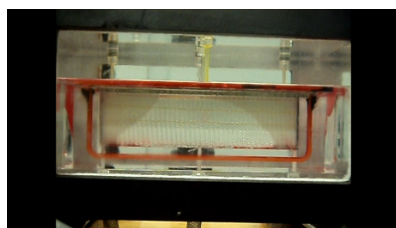
Figure E.61: T3-MEG5 [00:10]



(a) Camera #1



(b) Camera #2

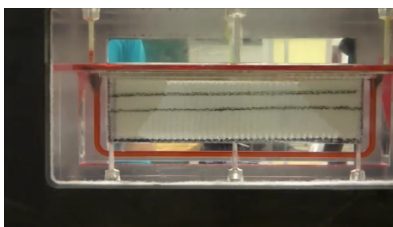


(c) Camera #3

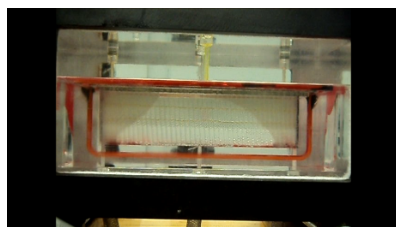
Figure E.62: T3-MEG7 [00:30]



(a) Camera #1

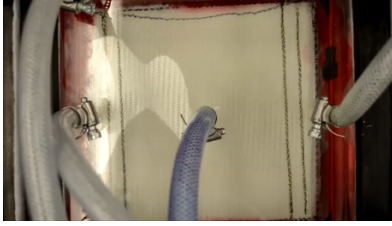


(b) Camera #2

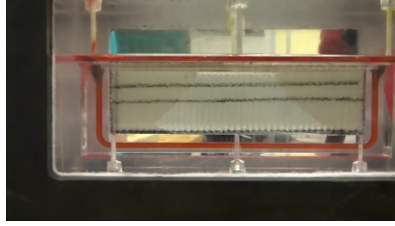


(c) Camera #3

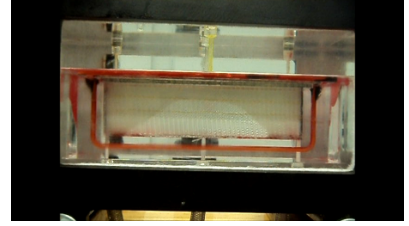
Figure E.63: T3-MEG7 [00:50]



(a) Camera #1

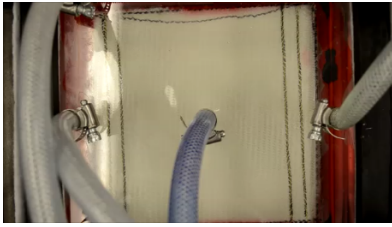


(b) Camera #2

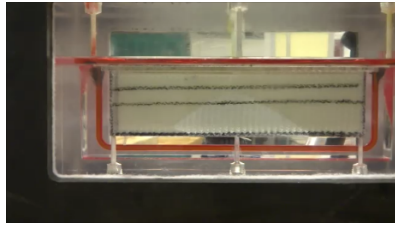


(c) Camera #3

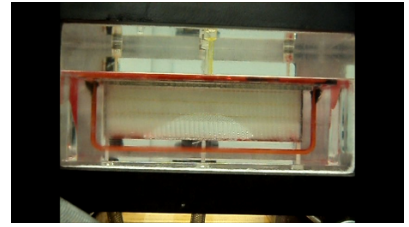
Figure E.64: T3-MEG5 [01:10]



(a) Camera #1

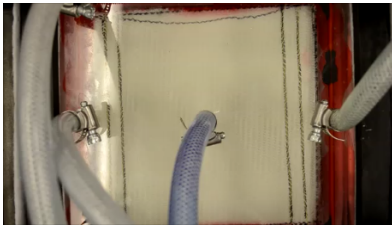


(b) Camera #2

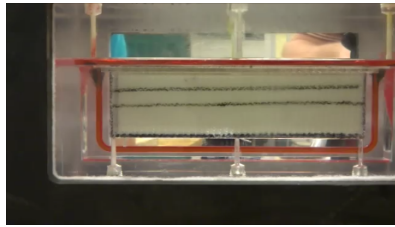


(c) Camera #3

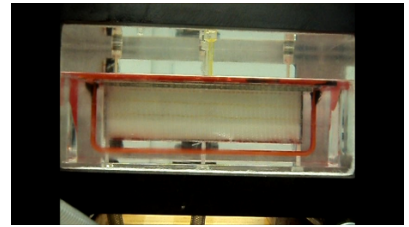
Figure E.65: T3-MEG7 [01:30]



(a) Camera #1



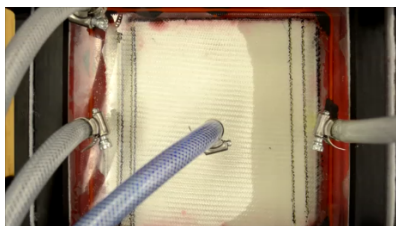
(b) Camera #2



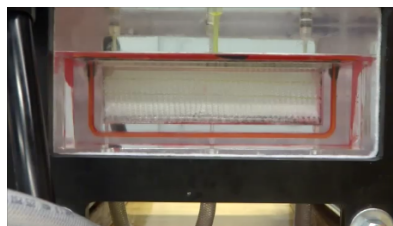
(c) Camera #3

Figure E.66: T3-MEG7 [01:50]

E.2.8 Test T3-MEG8

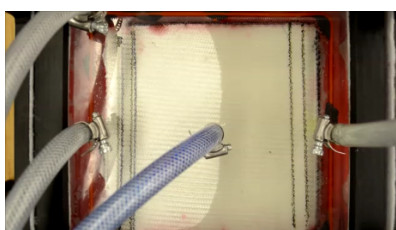


(a) Camera #1

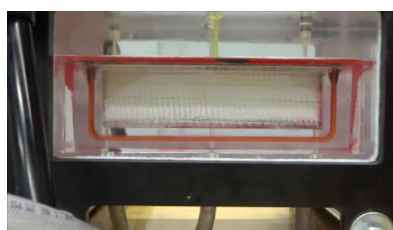


(b) Camera #2

Figure E.67: T3-MEG8 [00:30]



(a) Camera #1

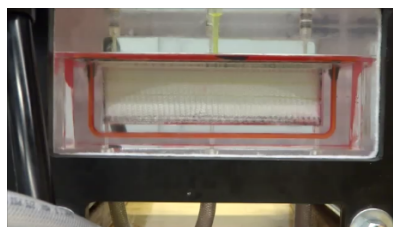


(b) Camera #2

Figure E.68: T3-MEG8 [01:00]

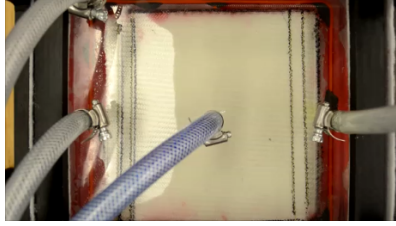


(a) Camera #1

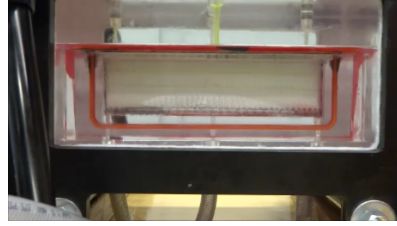


(b) Camera #2

Figure E.69: T3-MEG8 [01:30]

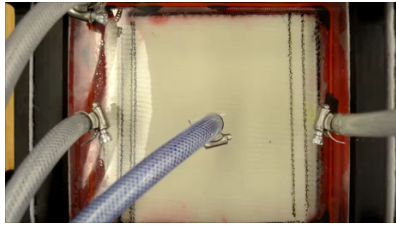


(a) Camera #1

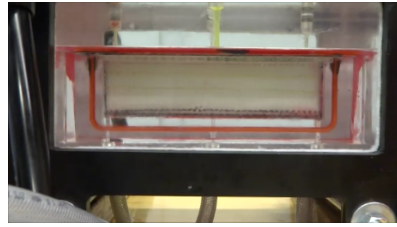


(b) Camera #2

Figure E.70: T3-MEG5 [02:30]

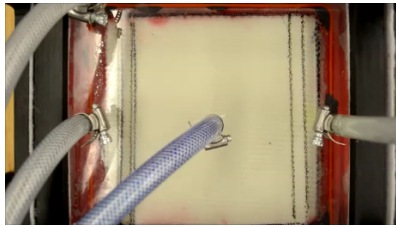


(a) Camera #1

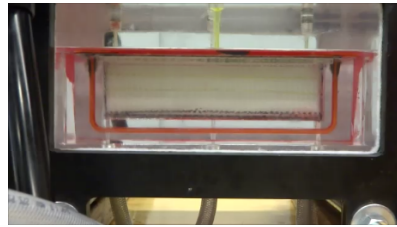


(b) Camera #2

Figure E.71: T3-MEG8 [03:30]



(a) Camera #1

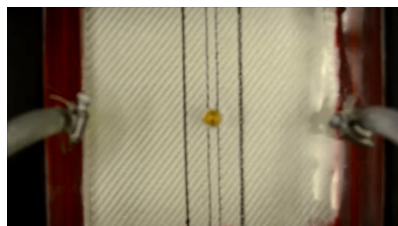


(b) Camera #2

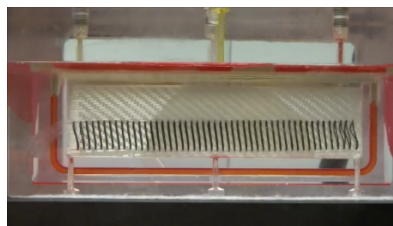
Figure E.72: T3-MEG8 [04:30]

E.3 Series T4

E.3.1 Test T4-S1

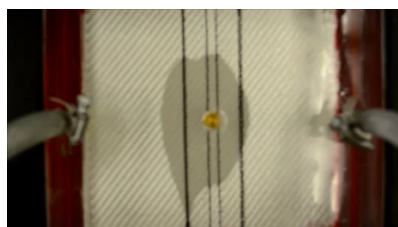


(a) Camera #1

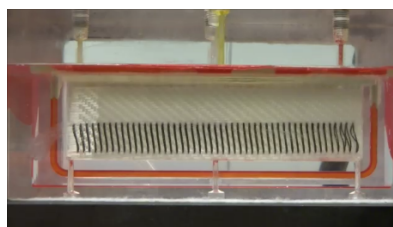


(b) Camera #2

Figure E.73: T4-S1 [00:45]

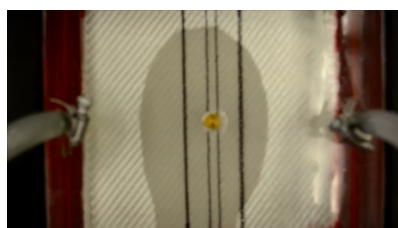


(a) Camera #1

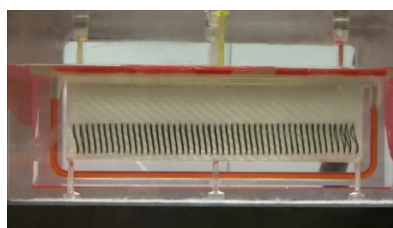


(b) Camera #2

Figure E.74: T4-S1 [02:30]

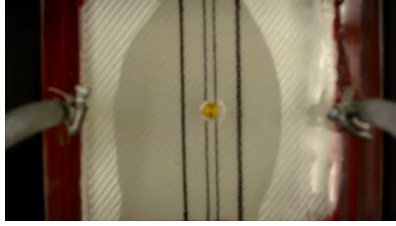


(a) Camera #1

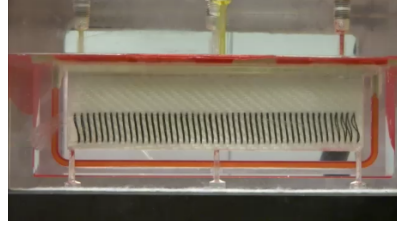


(b) Camera #2

Figure E.75: T4-S1 [04:15]

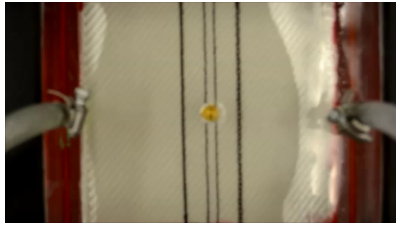


(a) Camera #1

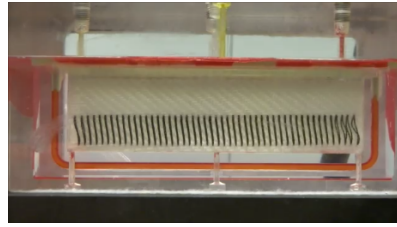


(b) Camera #2

Figure E.76: T4-S1 [06:00]

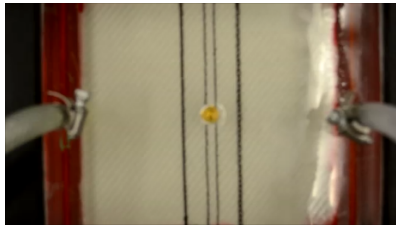


(a) Camera #1

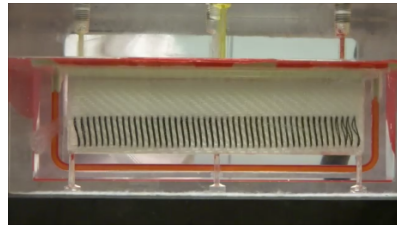


(b) Camera #2

Figure E.77: T4-S1 [07:45]



(a) Camera #1



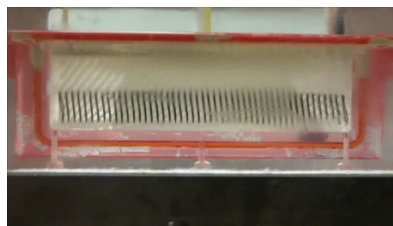
(b) Camera #2

Figure E.78: T4-S1 [09:30]

E.3.2 Test T4-S2

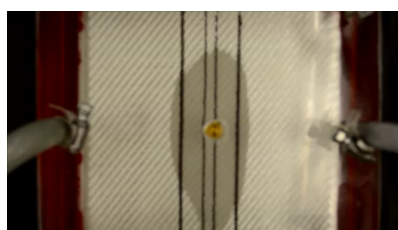


(a) Camera #1

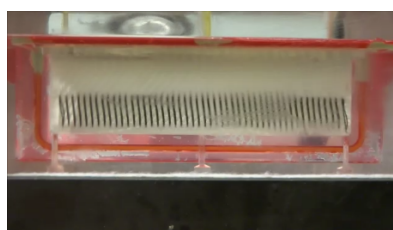


(b) Camera #2

Figure E.79: T4-S2 [00:30]



(a) Camera #1

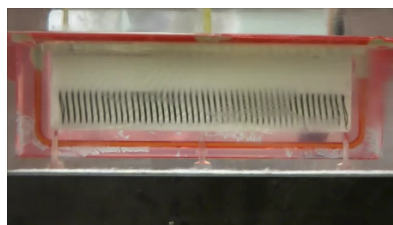


(b) Camera #2

Figure E.80: T4-S2 [01:00]

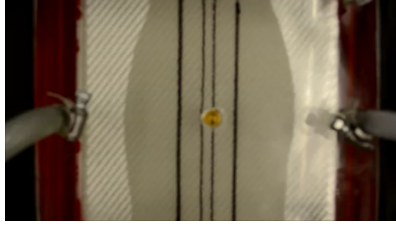


(a) Camera #1

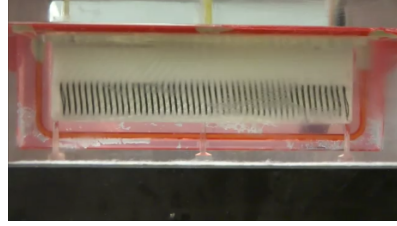


(b) Camera #2

Figure E.81: T4-S2 [02:00]

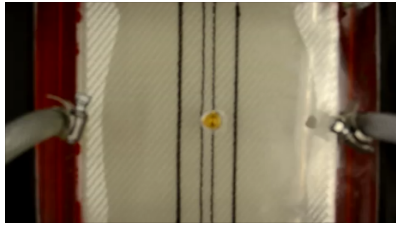


(a) Camera #1

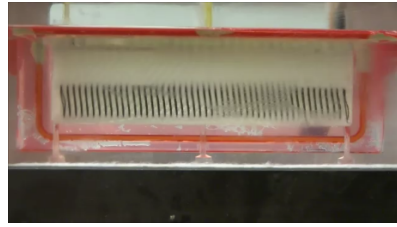


(b) Camera #2

Figure E.82: T4-S2 [03:00]

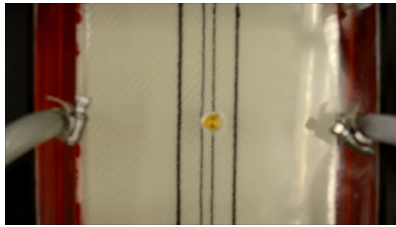


(a) Camera #1

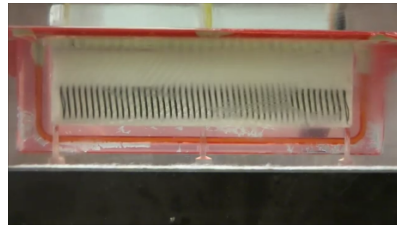


(b) Camera #2

Figure E.83: T4-S2 [04:00]



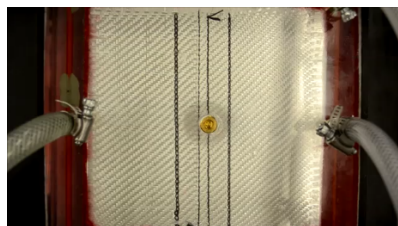
(a) Camera #1



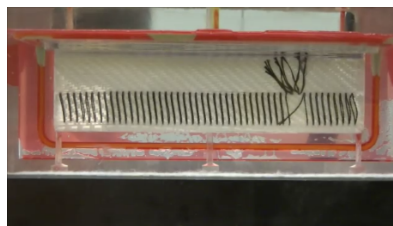
(b) Camera #2

Figure E.84: T4-S2 [05:00]

E.3.3 Test T4-S3

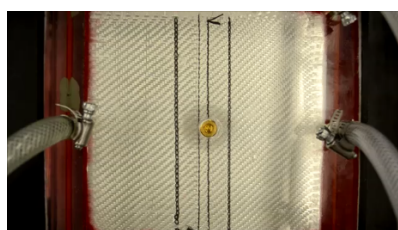


(a) Camera #1

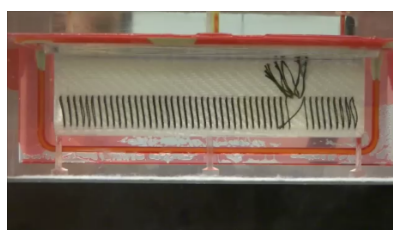


(b) Camera #2

Figure E.85: T4-S3 [00:30]

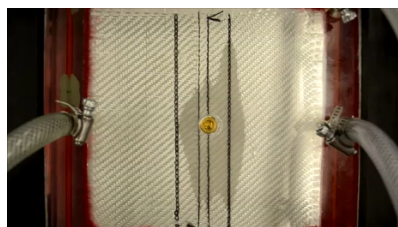


(a) Camera #1

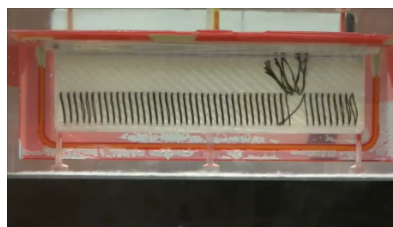


(b) Camera #2

Figure E.86: T4-S3 [01:00]

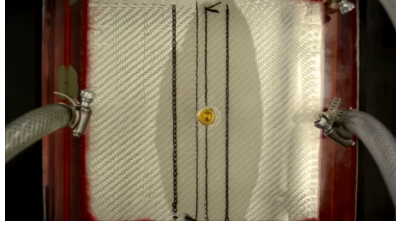


(a) Camera #1

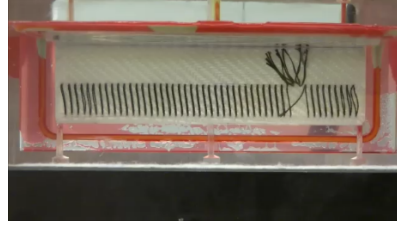


(b) Camera #2

Figure E.87: T4-S3 [01:30]

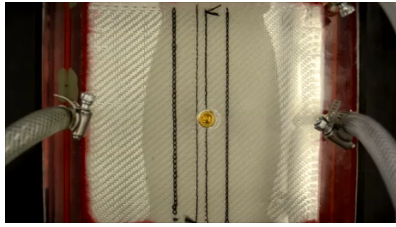


(a) Camera #1

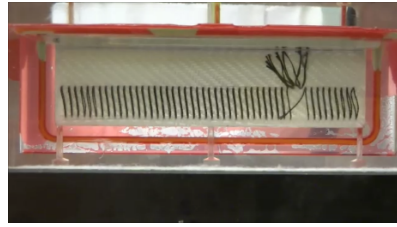


(b) Camera #2

Figure E.88: T4-S3 [02:00]

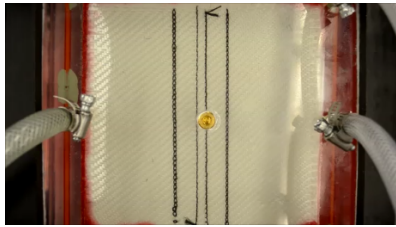


(a) Camera #1

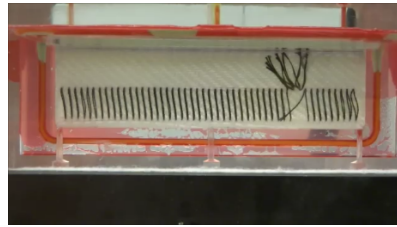


(b) Camera #2

Figure E.89: T4-S3 [02:30]



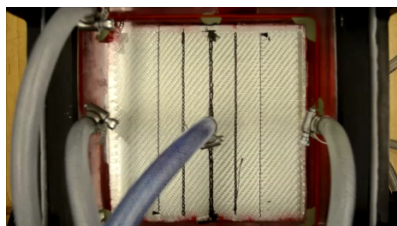
(a) Camera #1



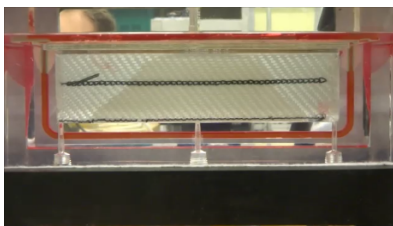
(b) Camera #2

Figure E.90: T4-S3 [3:30]

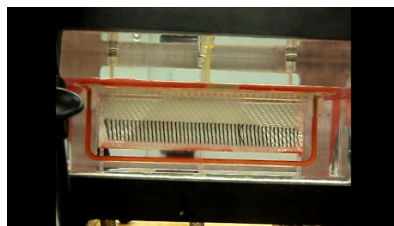
E.3.4 Test T4-T1



(a) Camera #1

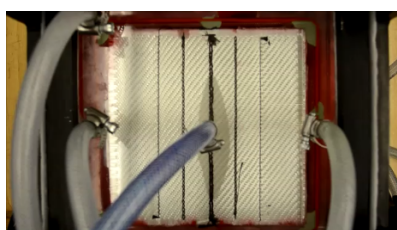


(b) Camera #2

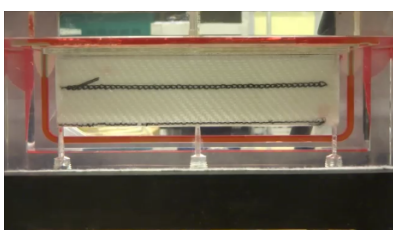


(c) Camera #3

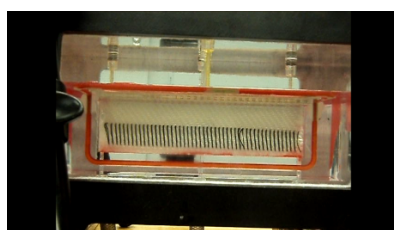
Figure E.91: T4-T1 [00:30]



(a) Camera #1

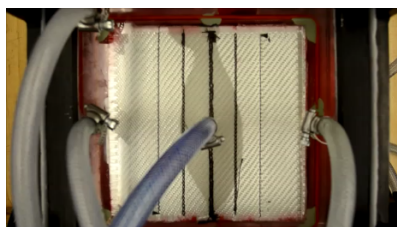


(b) Camera #2

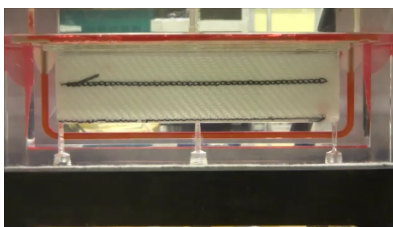


(c) Camera #3

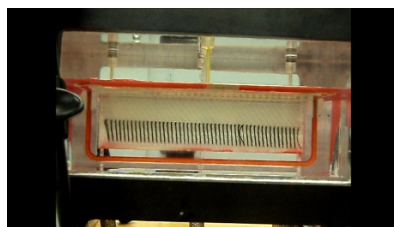
Figure E.92: T4-T1 [01:30]



(a) Camera #1

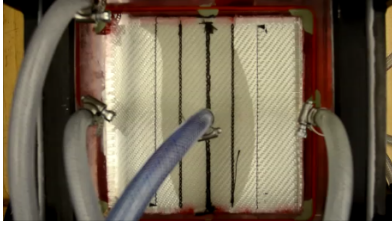


(b) Camera #2

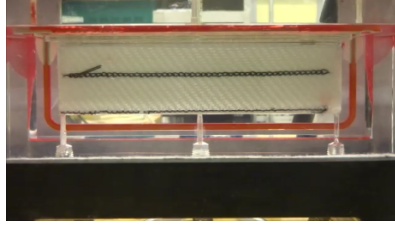


(c) Camera #3

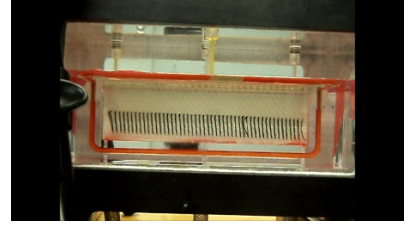
Figure E.93: T4-T1 [02:30]



(a) Camera #1

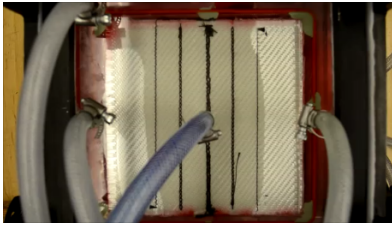


(b) Camera #2

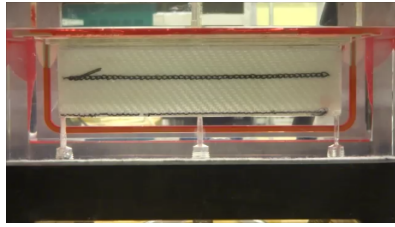


(c) Camera #3

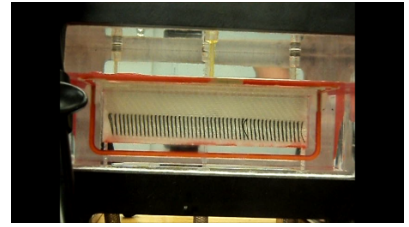
Figure E.94: T4-T1 [04:00]



(a) Camera #1

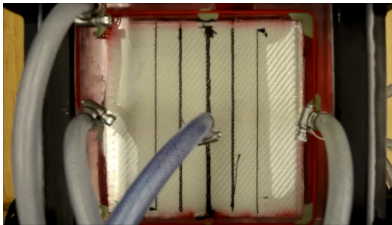


(b) Camera #2

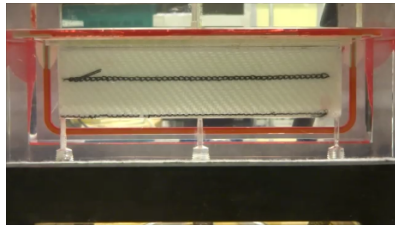


(c) Camera #3

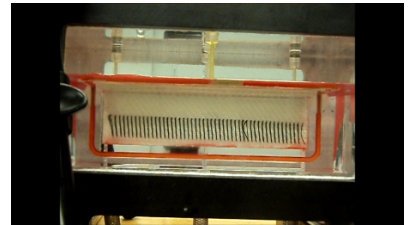
Figure E.95: T4-T1 [05:30]



(a) Camera #1



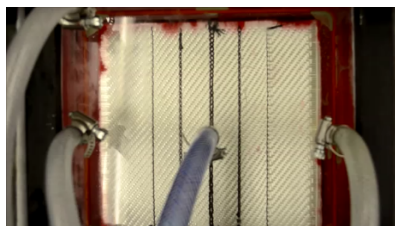
(b) Camera #2



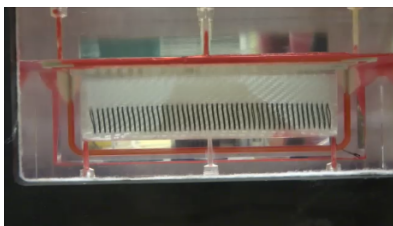
(c) Camera #3

Figure E.96: T4-T1 [07:00]

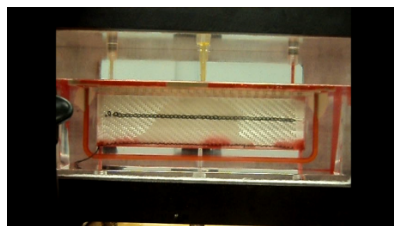
E.3.5 Test T4-T2



(a) Camera #1

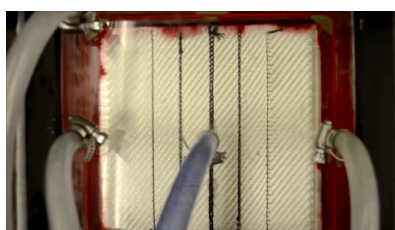


(b) Camera #2

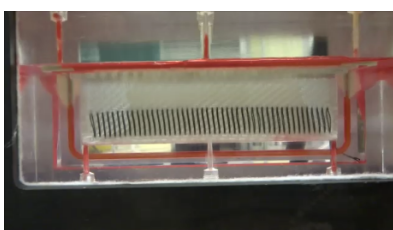


(c) Camera #3

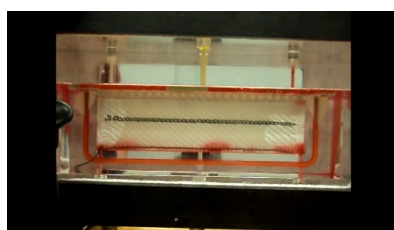
Figure E.97: T4-T2 [00:30]



(a) Camera #1

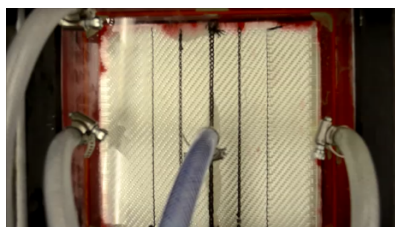


(b) Camera #2

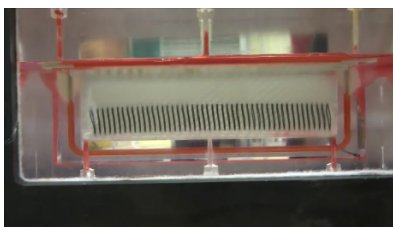


(c) Camera #3

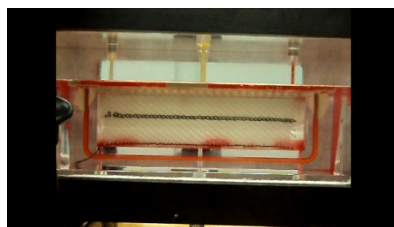
Figure E.98: T4-T2 [01:00]



(a) Camera #1

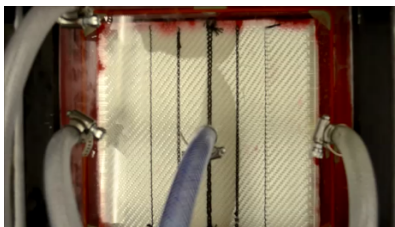


(b) Camera #2

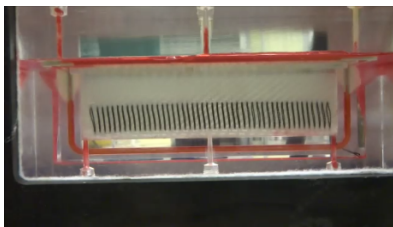


(c) Camera #3

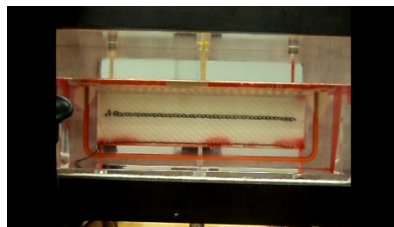
Figure E.99: T4-T2 [01:30]



(a) Camera #1

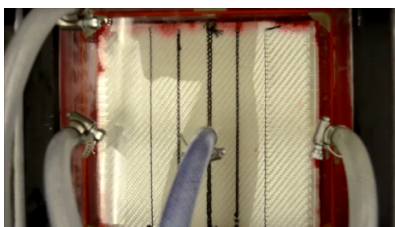


(b) Camera #2

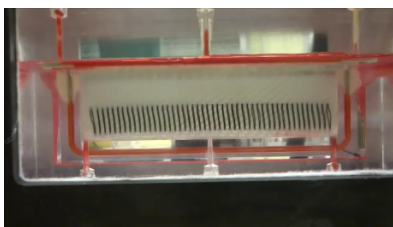


(c) Camera #3

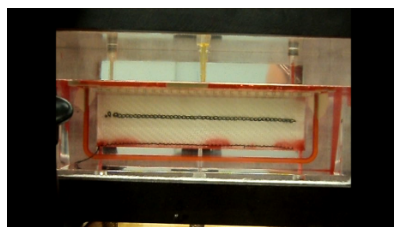
Figure E.100: T4-T2 [03:30]



(a) Camera #1

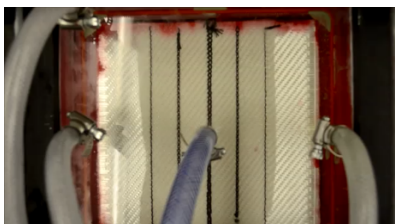


(b) Camera #2

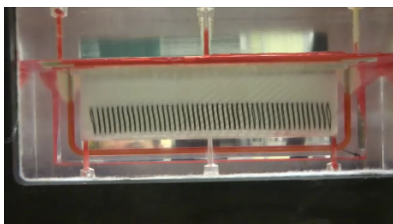


(c) Camera #3

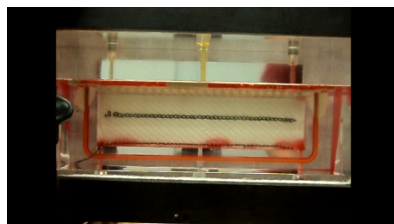
Figure E.101: T4-T2 [05:30]



(a) Camera #1



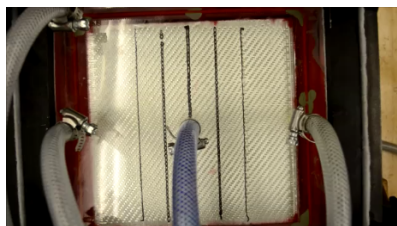
(b) Camera #2



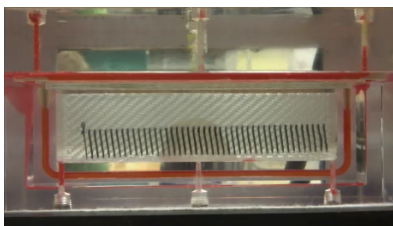
(c) Camera #3

Figure E.102: T4-T2 [07:30]

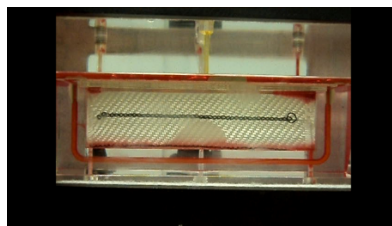
E.3.6 Test T4-T3



(a) Camera #1



(b) Camera #2

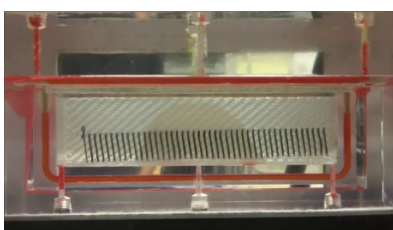


(c) Camera #3

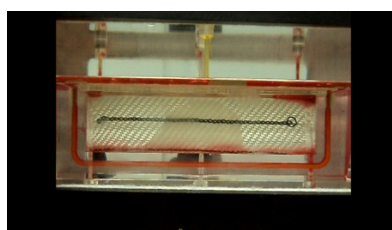
Figure E.103: T4-T3 [00:30]



(a) Camera #1

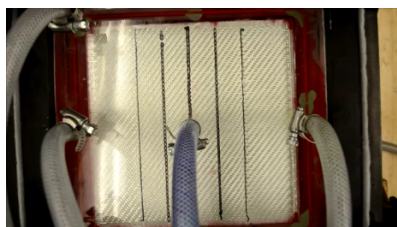


(b) Camera #2

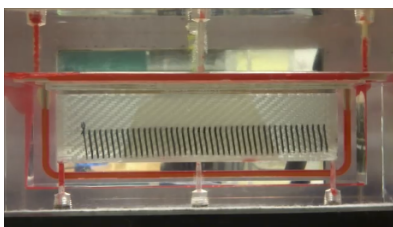


(c) Camera #3

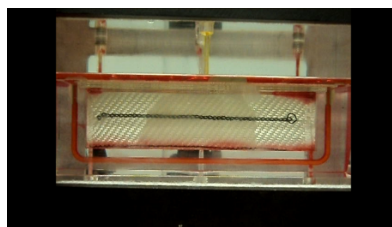
Figure E.104: T4-T3 [01:30]



(a) Camera #1

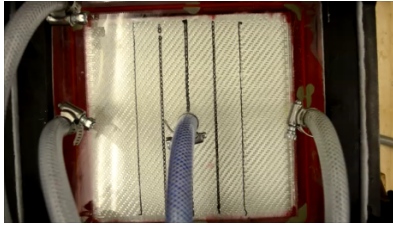


(b) Camera #2

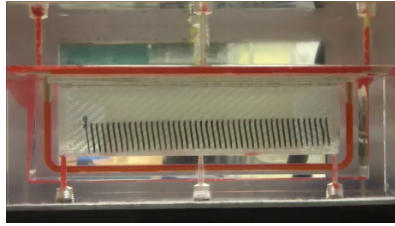


(c) Camera #3

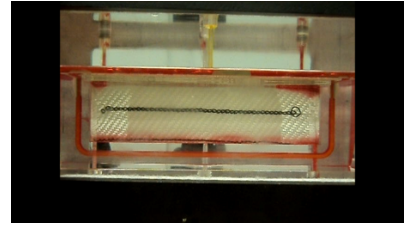
Figure E.105: T4-T3 [02:30]



(a) Camera #1



(b) Camera #2

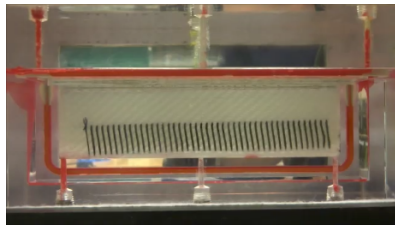


(c) Camera #3

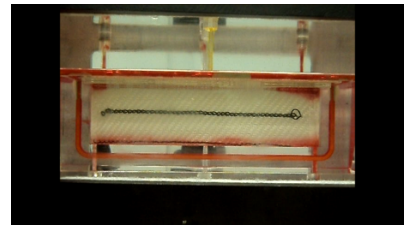
Figure E.106: T4-T3 [04:30]



(a) Camera #1

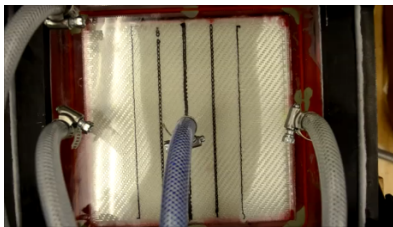


(b) Camera #2

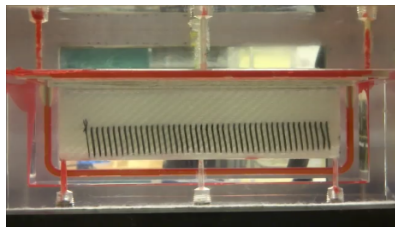


(c) Camera #3

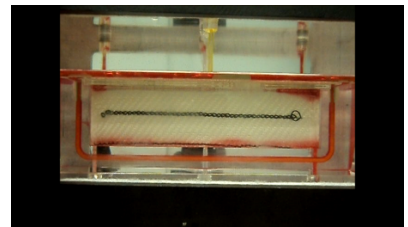
Figure E.107: T4-T3 [10:30]



(a) Camera #1



(b) Camera #2

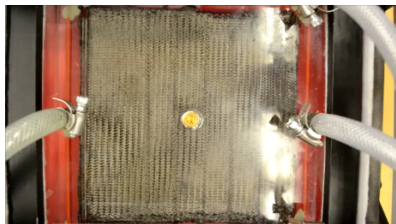


(c) Camera #3

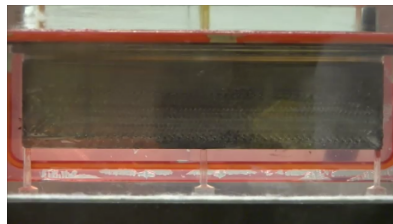
Figure E.108: T4-T3 [18:00]

E.4 Series T5

E.4.1 Test T5-C1

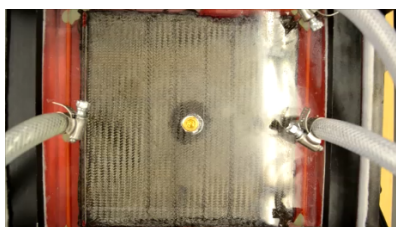


(a) Camera #1

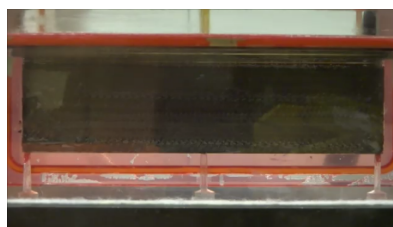


(b) Camera #2

Figure E.109: T5-C1 [00:30]

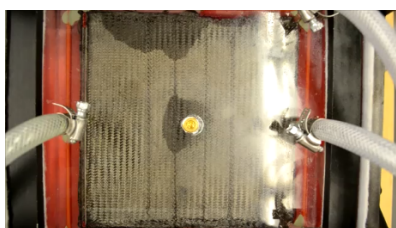


(a) Camera #1

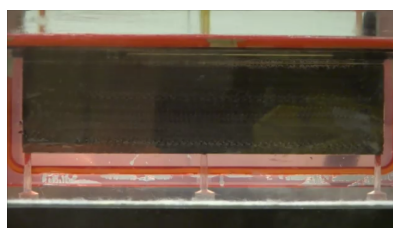


(b) Camera #2

Figure E.110: T5-C1 [02:30]

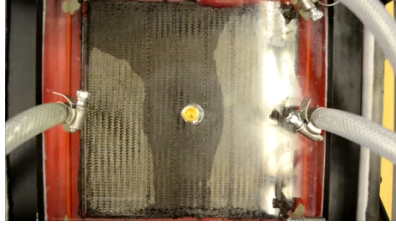


(a) Camera #1

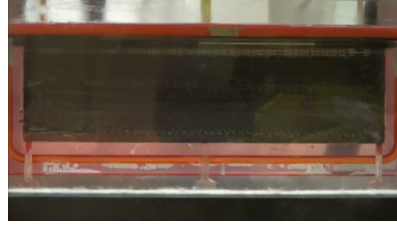


(b) Camera #2

Figure E.111: T5-C1 [06:00]

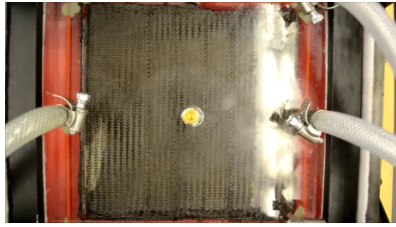


(a) Camera #1

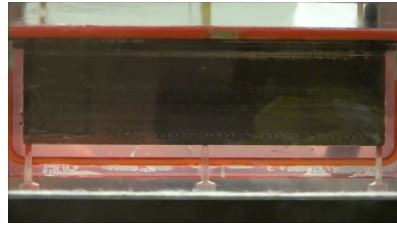


(b) Camera #2

Figure E.112: T5-C1 [08:30]

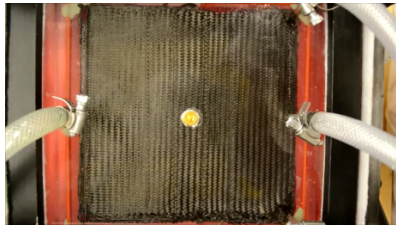


(a) Camera #1

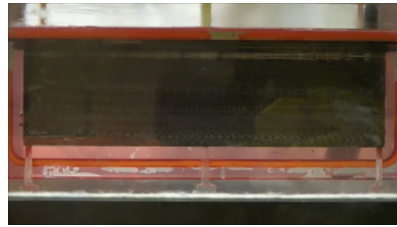


(b) Camera #2

Figure E.113: T5-C1 [12:30]



(a) Camera #1



(b) Camera #2

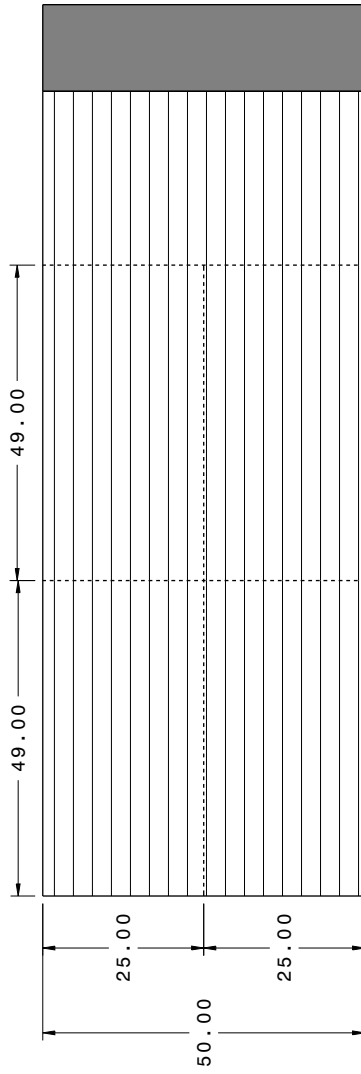
Figure E.114: T5-C1 [18:00]

Appendix F

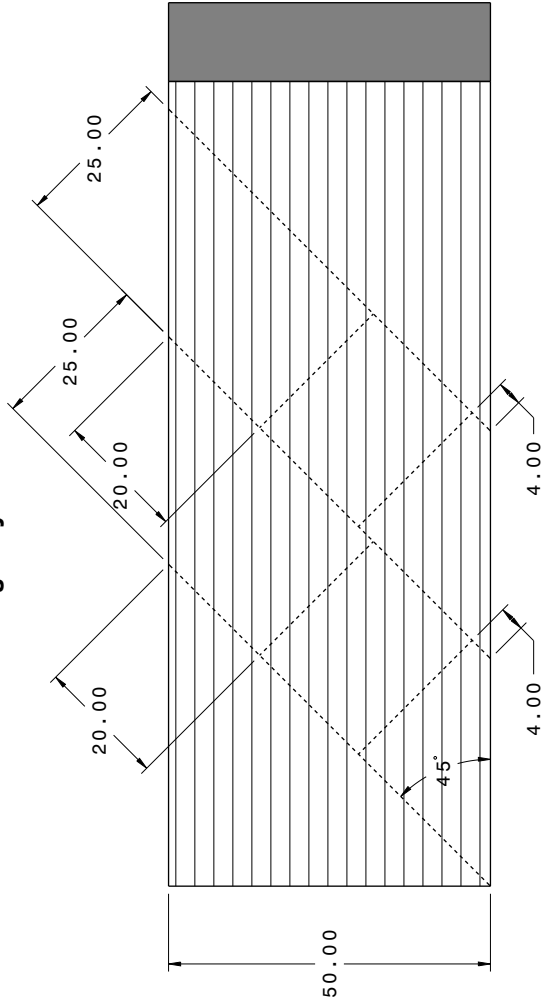
Full Scale Demonstrator Cutting Patterns

Ply Cut Patern for: 50 in wide roll

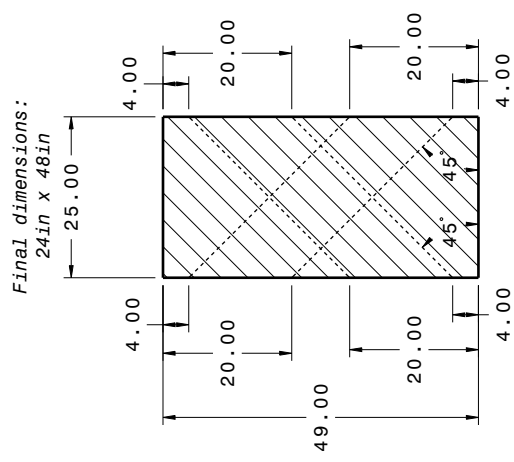
0-90 deg Ply Cut for 50 in wide roll



±45 deg Ply Cut for 50 in wide roll

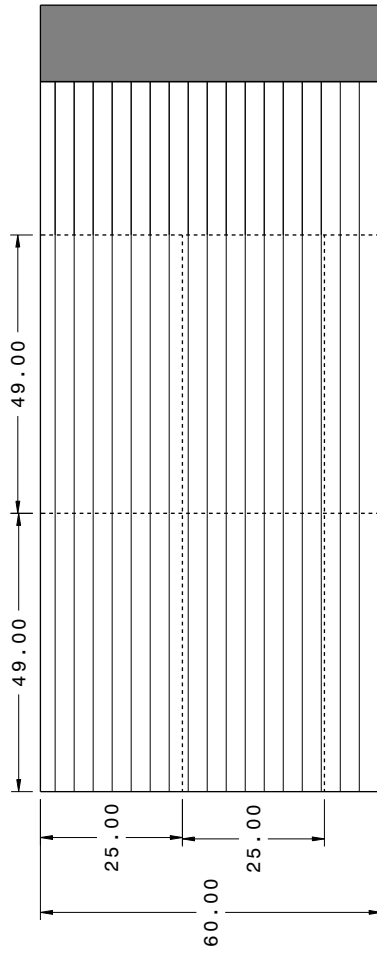


45 deg Stacking Setup

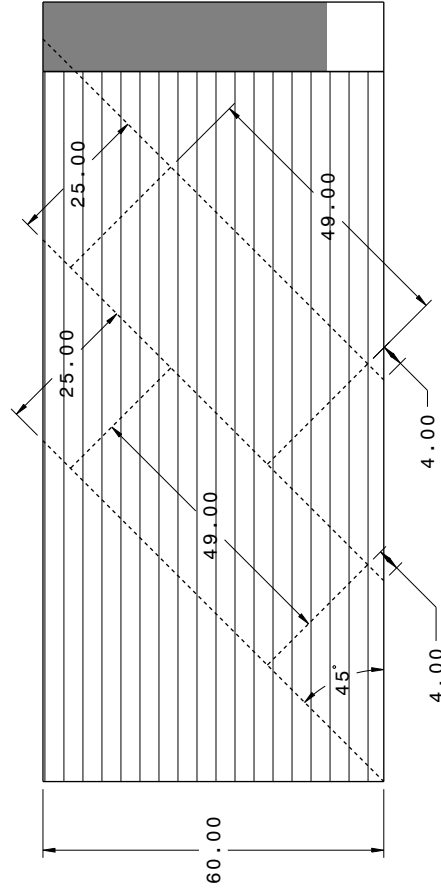


Ply Cut Patern for: 60 in wide roll

0-90 deg Ply Cut for 60 in wide roll

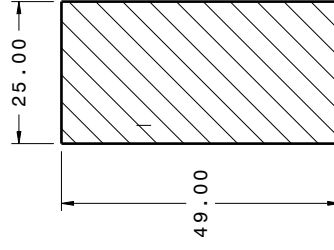


±45 deg Ply Cut for 60 in wide roll



45 deg Stacking Setup

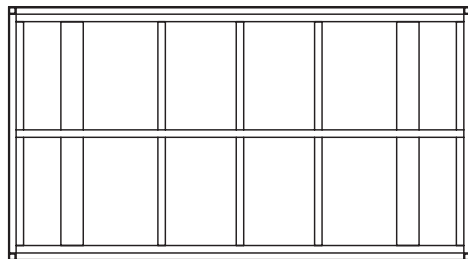
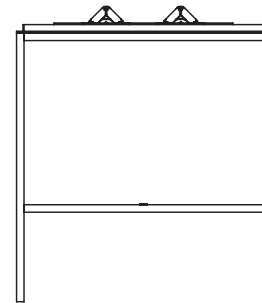
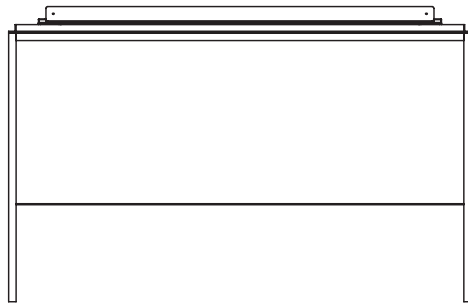
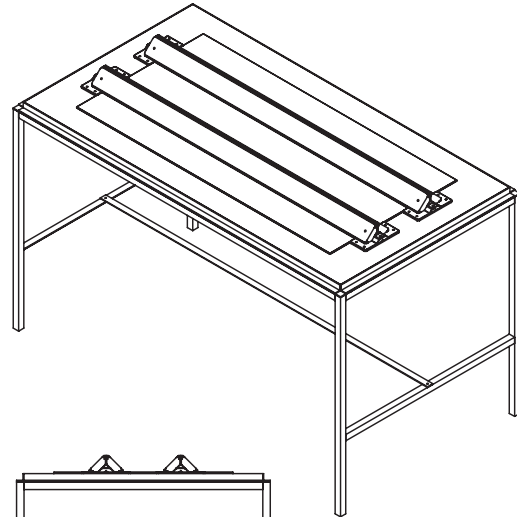
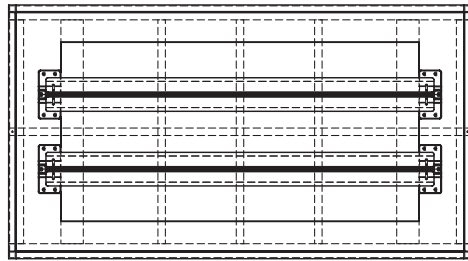
*Final dimensions:
24in x 48in*



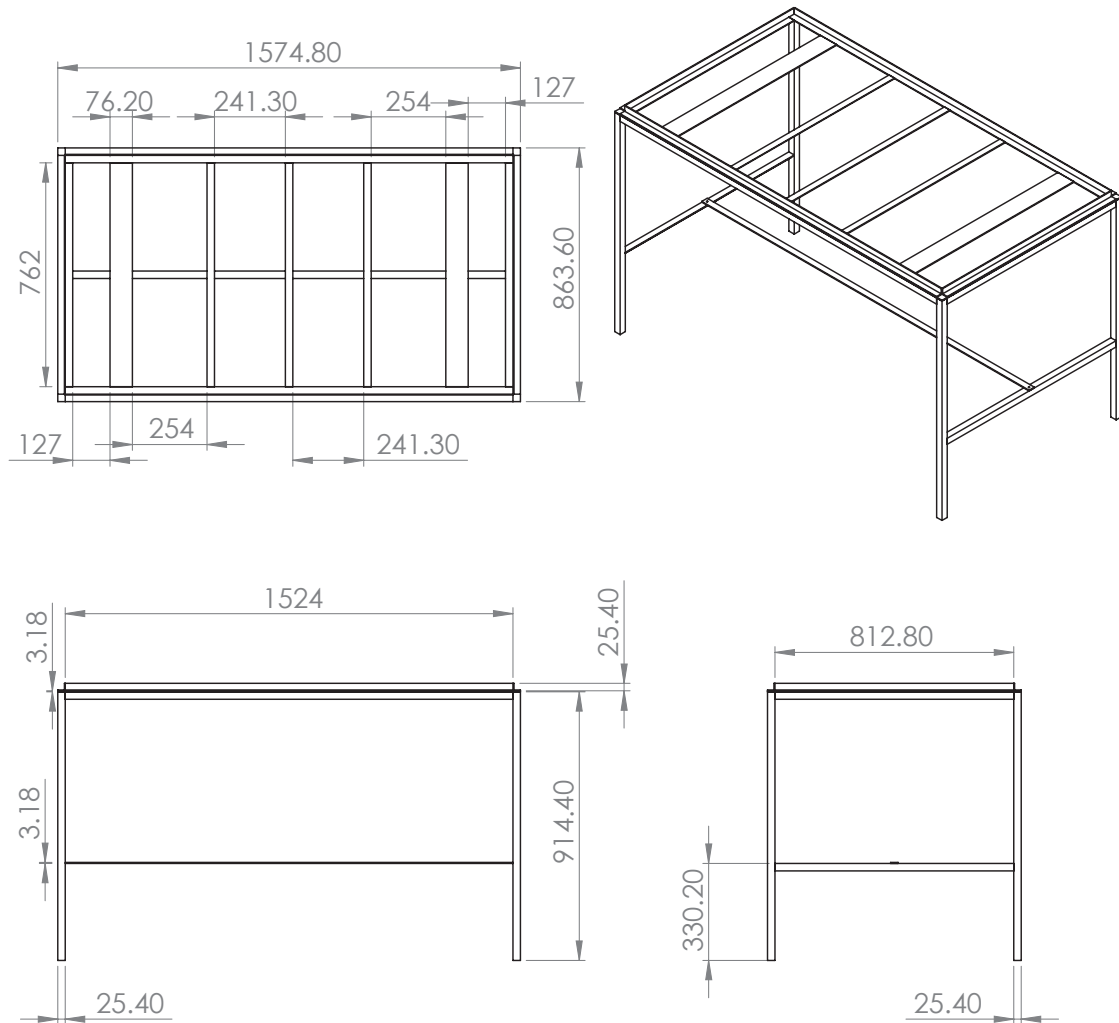
Appendix G

Full Scale Demonstrator Rig

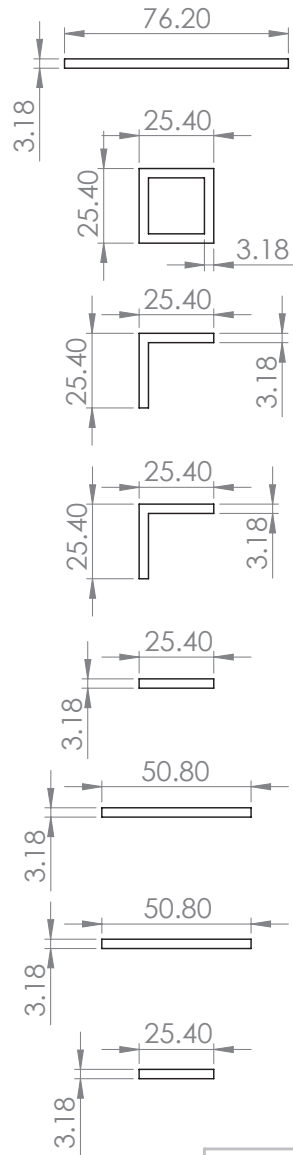
Drawings



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		B	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE: FULL-SCALE-DEMO			
FRANCOIS PROULX		15/05/14					
FINISH: PAINT AND POLISH				DWG NO. FSD-001 8.5/11			
MATERIAL: VARIOUS							
WEIGHT: 87.451 kg				SCALE:1:20		SHEET 1 OF 11	



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A			
		UNIVERSITY OF OTTAWA							
NAME		DATE		TITLE:					
FRANCOIS PROULX		10/05/14							
FINISH: ANTI-RUST PAINT / BLACK				TABLE-FRAME					
MATERIAL: AISI 1018 STEEL				DWG NO.		FSD-02		8.5/11	
WEIGHT: 32.591 kg				SCALE:1:10			SHEET 2 OF 11		



30in COLD ROLLED BAR STOCK x2

36in WELDED SQUARE TUBE x4

60in HOT ROLLED L-BAR x4

32in HOT ROLLED L-BAR x6

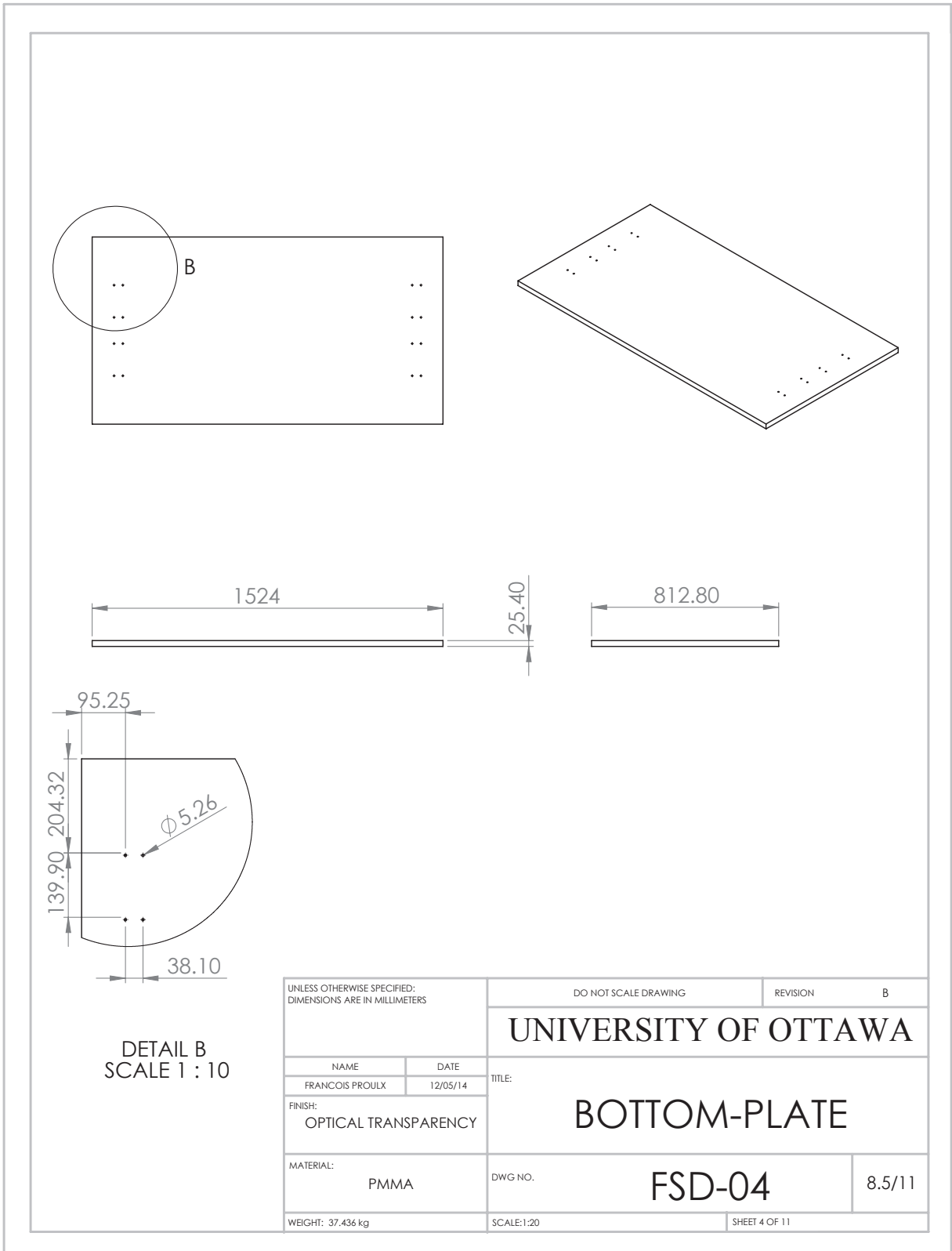
62in HOT ROLLED BAR STOCK x1

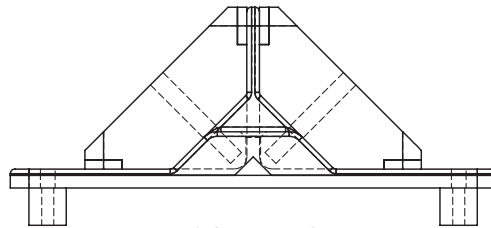
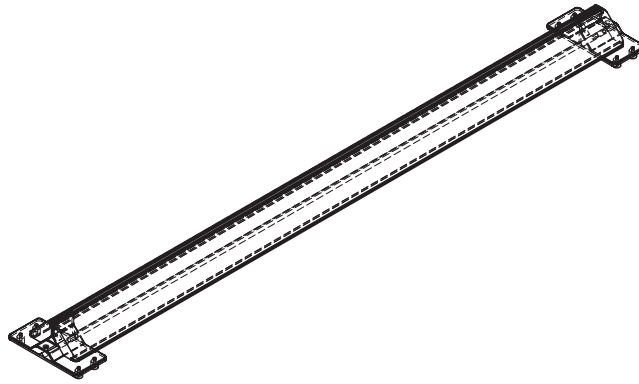
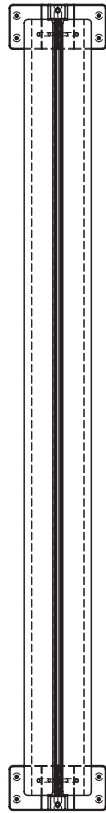
62in COLD ROLLED BAR STOCK x2

30in COLD ROLLED BAR STOCK x2

30in COLD ROLLED BAR STOCK x3

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A			
		UNIVERSITY OF OTTAWA							
NAME		DATE		TITLE: TABLE-PARTS					
FRANCOIS PROULX		10/05/14							
FINISH:									
WELD TO ASSEMBLE									
MATERIAL:		AISI 1018 STEEL		DWG NO.		FSD-03		8.5/11	
WEIGHT: 32.591 kg		SCALE:1:2			SHEET 3 OF 11				

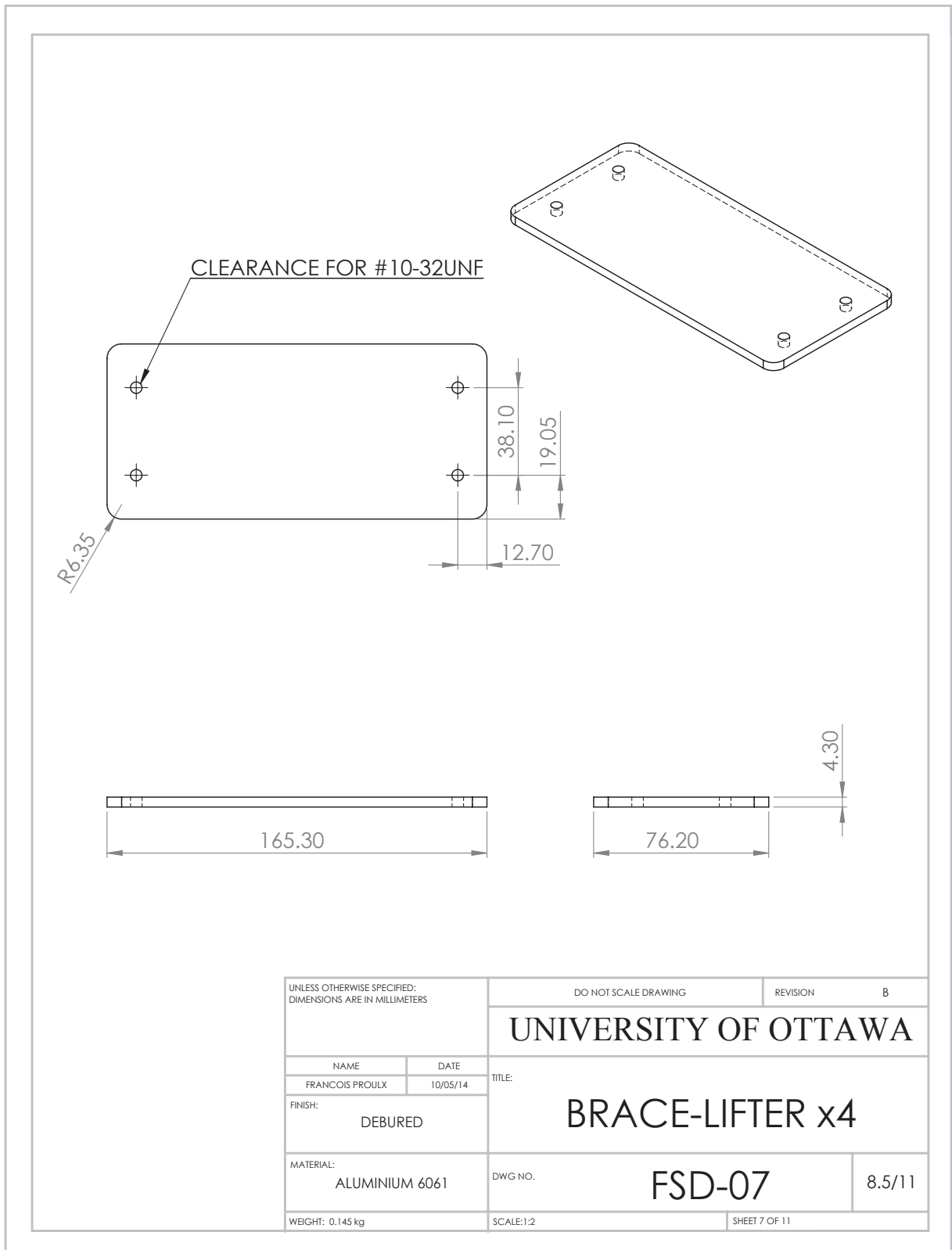


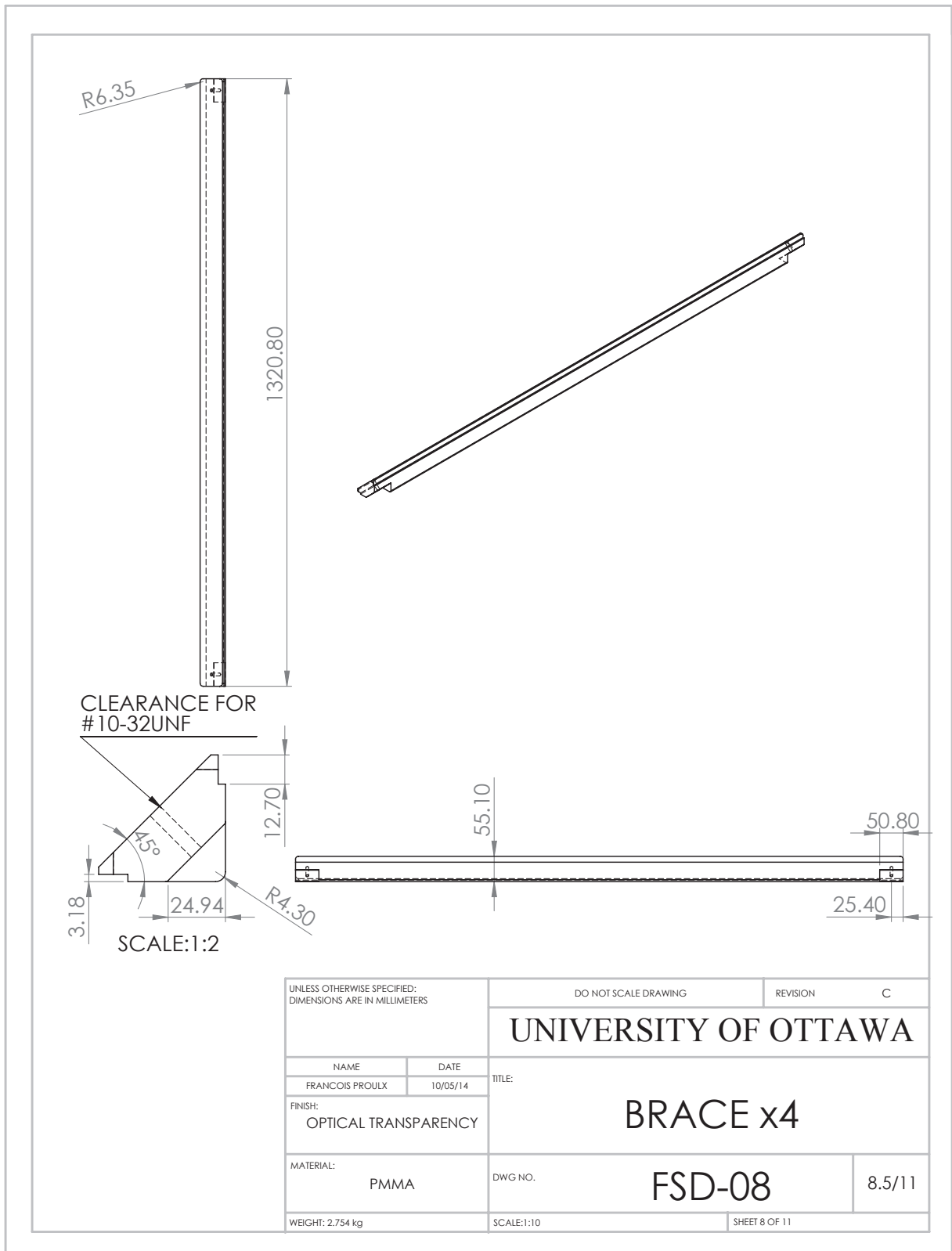


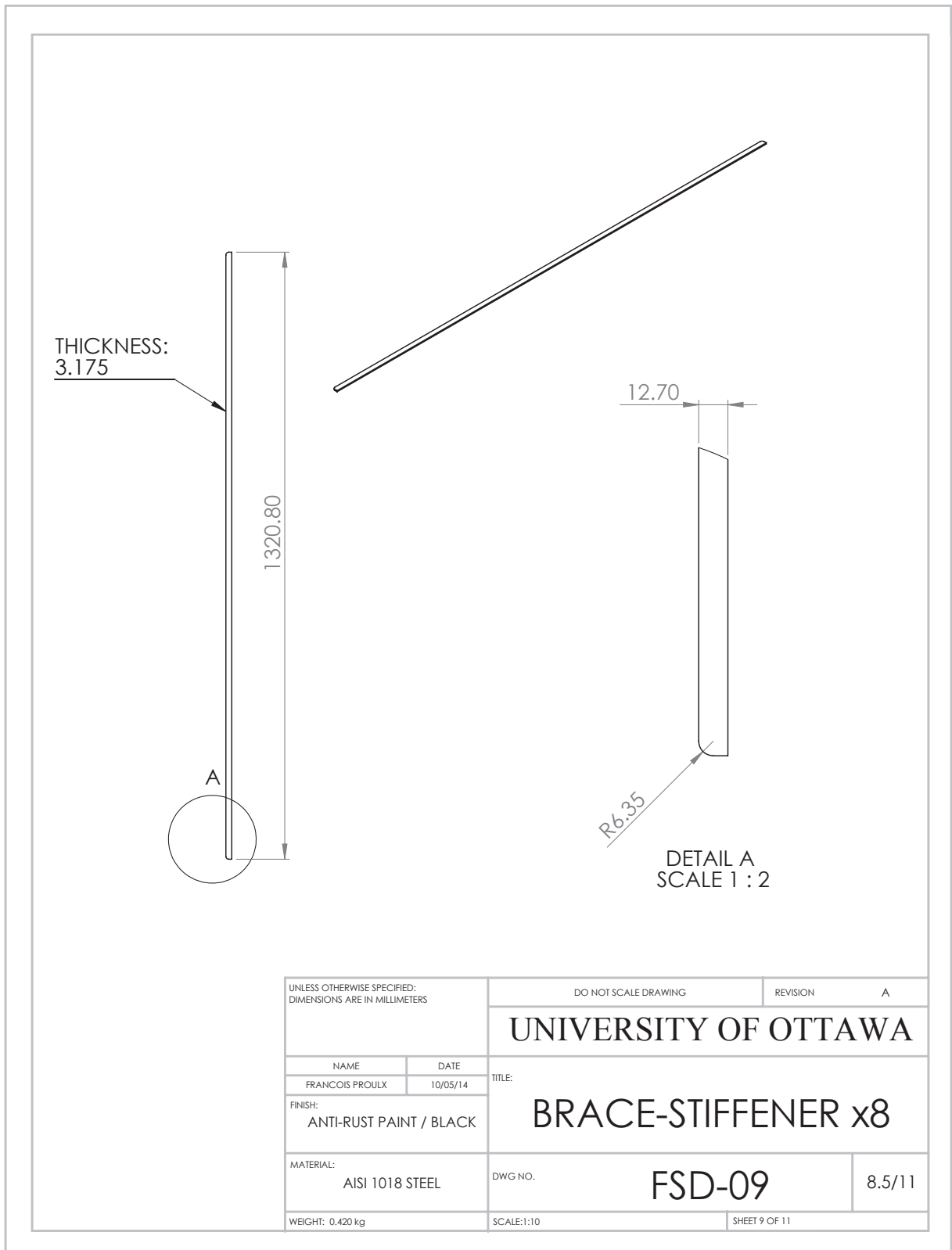
SCALE:1:2

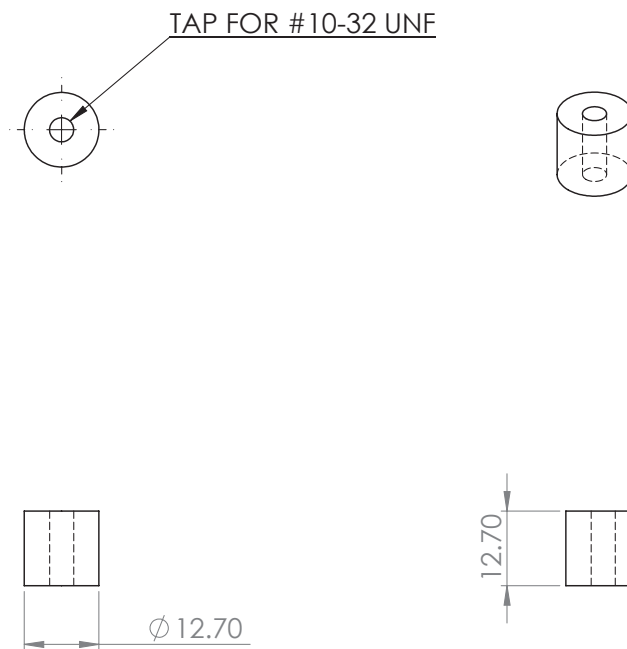


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING	REVISION	C
NAME		UNIVERSITY OF OTTAWA		
DATE		TITLE:		
FRANCOIS PROULX		BRACING-ASSEMBLY x2		
FINISH:		DWG NO.		
VARIOUS		FSD-05		8.5/11
MATERIAL:		SCALE:1:10		
VARIOUS		SHEET 5 OF 11		
WEIGHT: 7.948 kg				

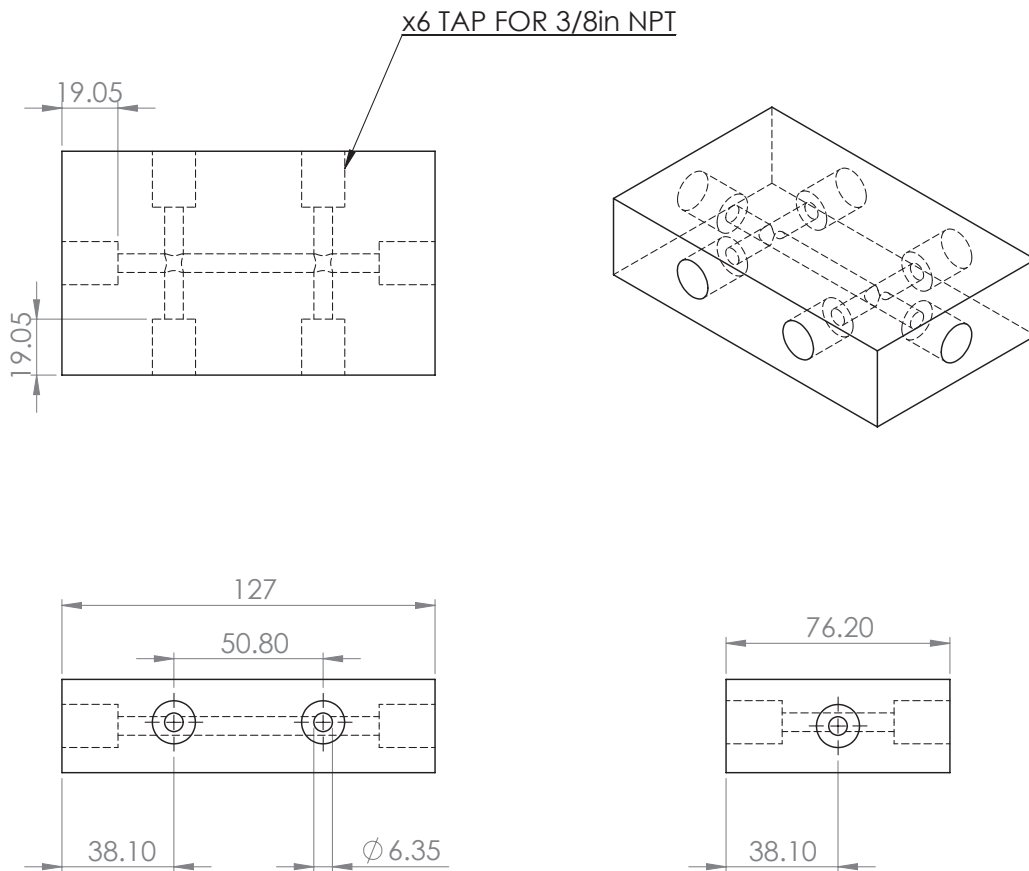








UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A			
		UNIVERSITY OF OTTAWA							
NAME		DATE		TITLE: BRACE-ANCHORS x16					
FRANCOIS PROULX		12/05/14							
FINISH: DEBURED AND TAPED				DWG NO. FSD-10				8.5/11	
MATERIAL: ALUMINIUM 6061									
WEIGHT: 0.004 kg				SCALE: 1:1			SHEET 10 OF 11		



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS		DO NOT SCALE DRAWING		REVISION		A	
		UNIVERSITY OF OTTAWA					
NAME		DATE		TITLE: FSD-MANIFOLD x2			
FRANCOIS PROULX		24/05/14					
FINISH: DEBURED AND TAPED				FSD-11			
MATERIAL: ALUMINIUM 6061							
WEIGHT: 0.764 kg				SCALE:1:2		SHEET 11 OF 11	

Appendix H

Needle Valve Flow Rate Tests

Settings for the adjustable needle valves needed to be quantified in terms of flow rate to allow greater control of resin or oil flow at the inlet during infusions. To this effect, a single line of tubing with an adjustable needle valve, catch pot and vacuum pump was setup to draw 50 cSt silicone oil from a graduated cylinder.

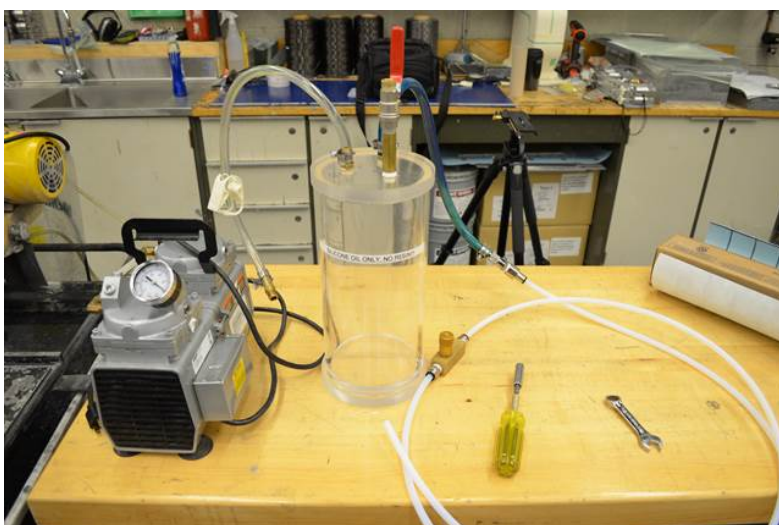


Figure H.1: Flow rate test vacuum tubing setup

Partners provided the ideal flow rate (18.4 ml/min) which was thought to limit micro-porosity through the needle. When the tube is inserted into 9 ml of silicone oil the

graduated cylinder indicates 10 ml, when the vacuum was drawn the time necessary for 10 indicated ml was measured with a chronometer. 10 seconds were given after the application of the vacuum to insure a steady state was achieved. The target time was 29.4 sec/ 9 ml.

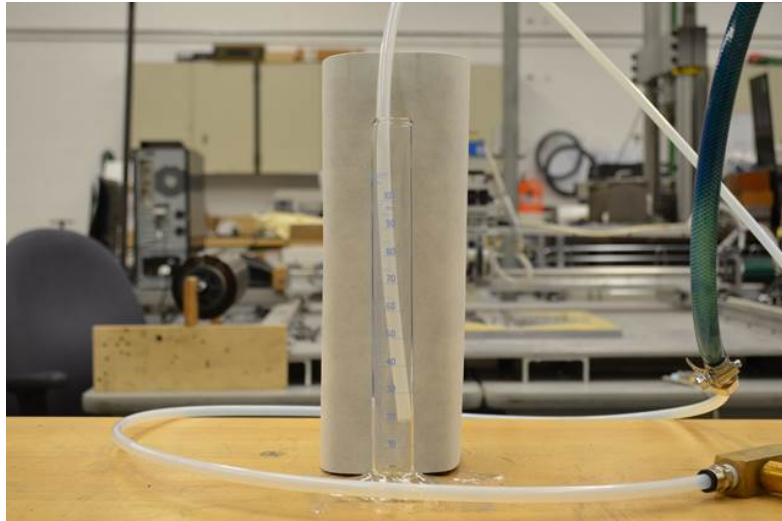


Figure H.2: Flow rate test graduated cylinder setup

The adjustable needle valve had multiple setting, starting with colour rings and positions of the handle numbered from 0 to 9 which allowed for a precise setting to be tested. Table H.1 details the results obtain from testing the first coloured ring, red, at 6 positions. Red 4 was selected as the most appropriate setting for the inlet valves.

Table H.1: Flow Rate Test Results

Test	Times	Flow Rate
Red 1	49.8 sec	10.9 ml/min
Red 2	36.9 sec	14.6 ml/min
Red 3	24.5 sec	22.0 ml/min
Red 4	17.0 sec	31.8 ml/min
Red 5	12.5 sec	43.2 ml/min
Red 6	10.7 sec	50.5 ml/min

Appendix I

Full Scale Demonstrator Rig Tests

I.1 T6-BGF1

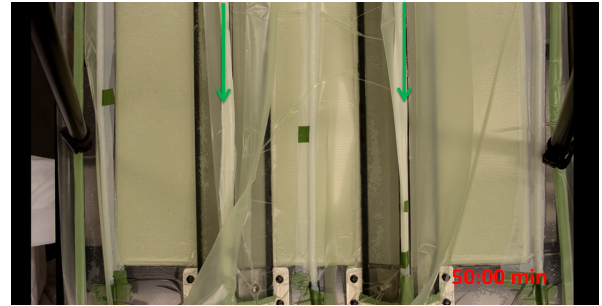
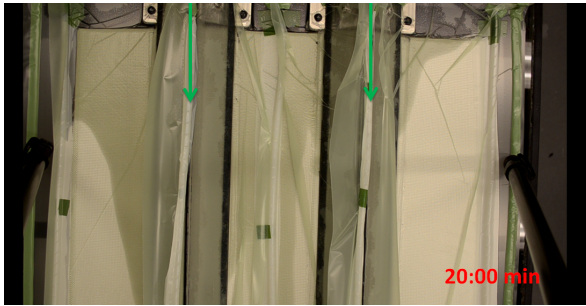


Figure I.1: T6-BGF1 Camera #1

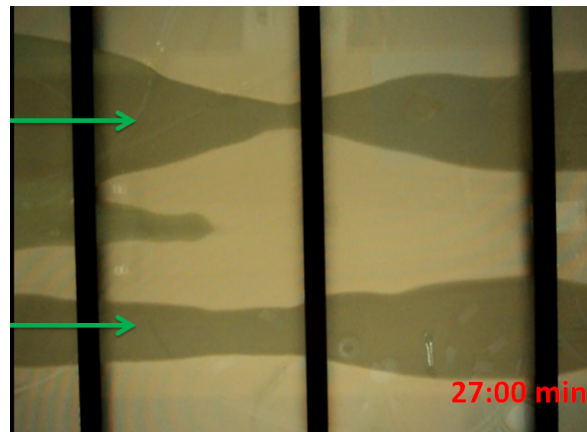


Figure I.2: T6-BGF1 Camera #2



Figure I.3: T6-BGF1 Camera #3

I.2 T6-BGF2

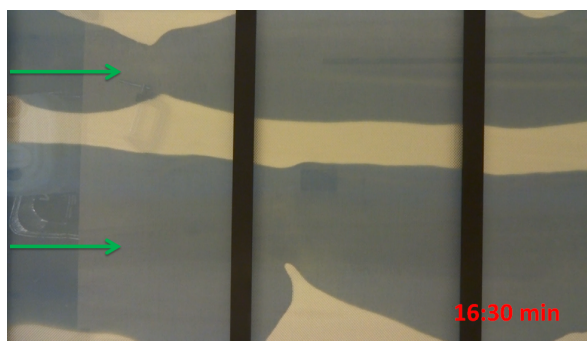


Figure I.4: T6-BGF2 Camera #2



Figure I.5: T6-BGF2 Camera #2

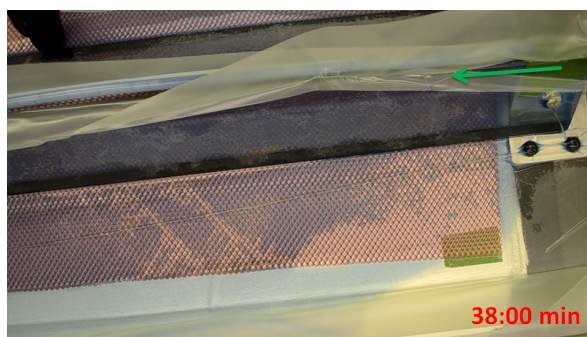
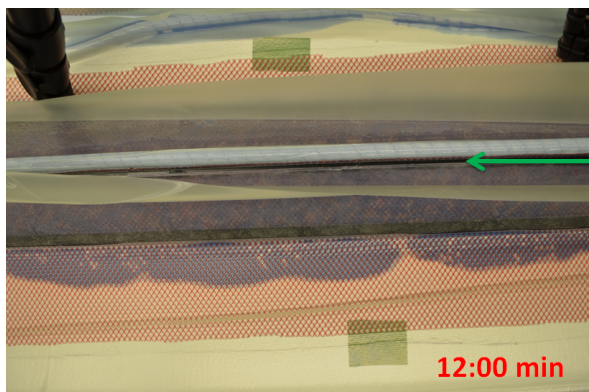


Figure I.6: T6-BGF2 Camera #1

I.3 T6-MEG1



Figure I.7: T6-MEG Camera #1

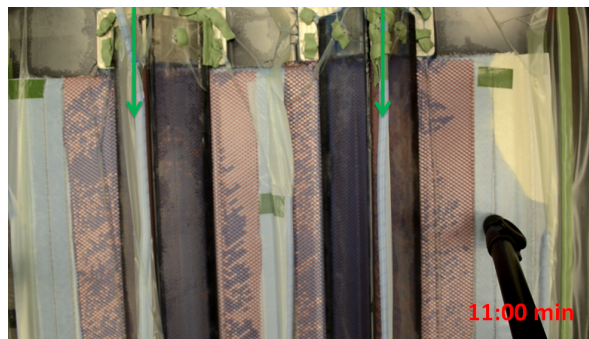


Figure I.8: T6-MEG Camera #1