Test Summary: Tensile Properties Test with Accelerated UV Aging
A Demonstration of NOAA DeOrbit Guideline Compliance in an 'Edge Case' Scenario

Summary

Spire is committed to demonstrating compliance to the NOAA guideline for Low Earth Orbit satellites to deorbit within 25 years. This is typically done by completing the Orbital Debris and Reentry (ODAR) report that is required to secure a NOAA Commercial Remote Sensing license. The completed ODAR assessment for LEMUR-2 shows compliance to the guideline in all launch and deployment scenarios except one. For the highest altitude orbital plane (650km), if the LEMUR is completely non-functional upon deployment from the launch vehicle, such that there is no attitude control and a total failure to deploy antennae and solar arrays, then the spacecraft could have an orbital lifetime of up to 40 years.

This document summarizes the analysis and testing that was done to demonstrate that LEMUR is designed to ensure that solar arrays will deploy even on a completely non-functional satellite, thus providing sufficient surface area and drag to comply with the 25 year deorbit guideline.

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Overview of ODAR Assessment

Following its deployment from the launch vehicle, the satellite's orbit will naturally decay until it reenters the atmosphere. The time to reenter depends on the effective area exposed to drag. Nominally, the spacecraft deploys solar panels and antennae, and uses an on-board Attitude and Control Determination System (ADCS) to maintain the +Z direction pointing nadir. Figure 1 shows a nominal, fully deployed LEMUR-2 satellite.

Figure 1. LEMUR-2 in Fully Deployed Configuration

Several configurations of LEMUR-2 were included in the ODAR assessment to account for a case in which any deployables fail to deploy (decreasing effective surface area) or the ADCS fails to operate (eliminating pointing control and leaving the satellite tumbling randomly). Table 1 summarizes the orbital lifetime results in all scenarios. The highlighted case is the subject of this analysis.

Table 1. Orbital Lifetime of LEMUR in Worst Case Orbit

Description	Satellite Configuration	Effective Area-to-Mass (m2/kg)
Satellite Nonfunctional	• Antennas **do not** deploy • Solar panels **do not** deploy • Satellite tumbles randomly	0.0074
Solar panels failure	• Antennas deploy • Solar panels **do not** deploy • Satellite maintains +Z axis nadir • Positioning around Z axis as needed	0.0130
ADCS Nonfunctional	• Antennas deploy • Solar Arrays deploy • Satellite tumbles randomly	0.0169
Operational, Nominal	• Antennas deploy • Solar panels deploy • Satellite maintains +Z axis nadir • Positioning around Z axis as needed	0.0208

In any given orientation, the solar panels (if deployed) provide enough of a drag profile to reduce the orbital lifetime to below 25 years. If solar panels fail to deploy, and the ADCS fails to operate, this results in the case where orbital lifetime could potentially exceeds 25 years, if the orbital altitude is high enough. To ensure decay in any scenario even at high orbital altitudes, Spire wanted to test materials for decay in space for entirely passive deployment.

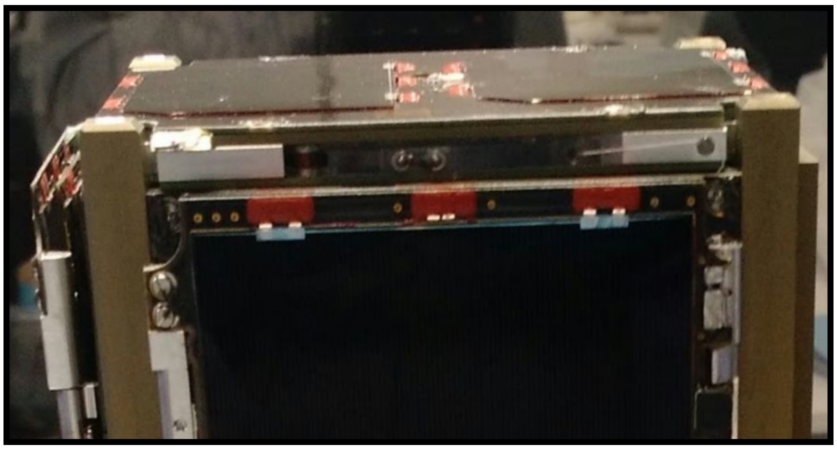
Solar Panel Deployment

When the satellite is in the stowed launch configuration, the solar panels are physically restrained (attached to satellite body) only by a thin burn wire. The burn wire is a 0.22mm diameter mono-filament nylon material string (fishing wire, essentially), with two tie-down locations on each of the two (2) solar panel faces.

Nominal solar array deployment is in the built-in post-deployment sequence programmed ont on-board software before launch. The timing depends on the launch profile and requirements, but is nominally between 15-30 minutes post deployment from the cubesat dispenser.

The first backup method for solar array deployment is sending a command through the UHF radio from the ground.

If those two methods are unsuccessful, then the solar arrays will be deployed once the burn wire's material strength degrades over time as it is exposed to the space environment. The burn wire is selected to have a material that will degrade over time in the space environment, therefore providing a redundant mechanism (i.e., mechanical failure) for the deployment of the solar arrays.



Material Strength Test - Burn Wire

To demonstrate the decreased material strength properties over time in a space environment, Spire contracted an outside test facility to conduct accelerated UV aging testing for 1200 hours on two (2) types of materials that could be used for the burn wire. To assess the degradation in material properties, samples were subject to tensile strength testing at t=0, 200 hours, 400 hours, 600 hours, 800 hours and 1200 hours.

The wires were exposed to aggressive non-standard dry UV test at the Materials Technology Ltd. facility, in 5 Rushington Court, Rushington Business Park, Chapel Lane, Southampton SO40 9NA, UK. The UV testing was performed using a QUV tester manufactured by Q Lab, to the non-standard parameters detailed in the table below, using UVB313 bulbs, which have a peak wavelength of 313nm.

Bulb Type	Irradiance	Black Panel Temperature	Test Duration
UVB 313nm	$1W/m^2$ @ 313 nm	60°C	1200hrs

Two different materials were tested, namely the Nanofil 6lbs ClearMist[1] and the Vantage Pro Fishing Line[2].

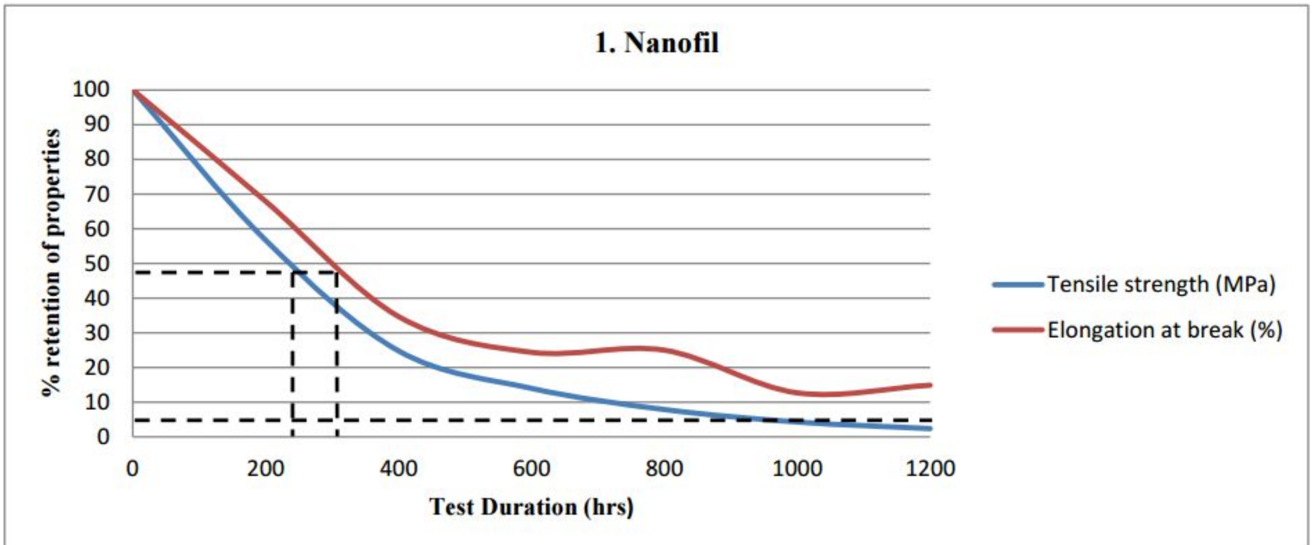
[1] e,g, http://www.amazon.com/Berkley-NanoFil-Uni-Filament-Fishing-Line/dp/B0053X8ACE
[2] e.g http://www.amazon.co.uk/Fladen-13-353-06-Vantage-Fishing-2410M/dp/B006LERNA4

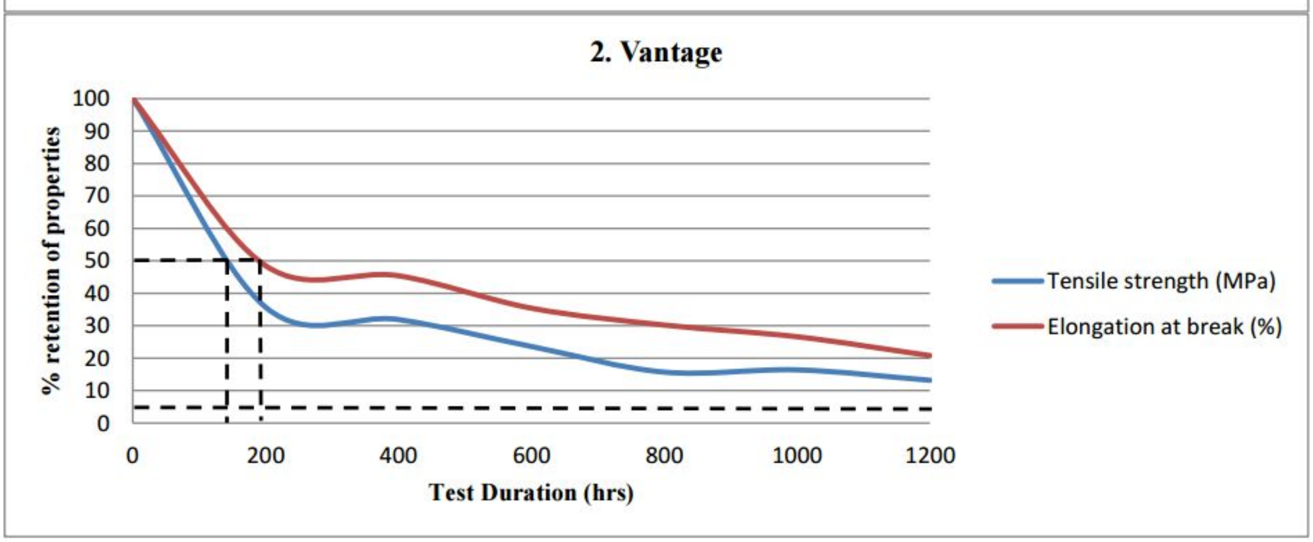
Results

The testing showed a marked decrease in material properties after exposure to UV. The Nanofil sample degraded to less than 15% of original tensile strength at the 1200 hours of testing.

The tensile strength test clearly demonstrates the degradation of material strength of the burn wire over time.

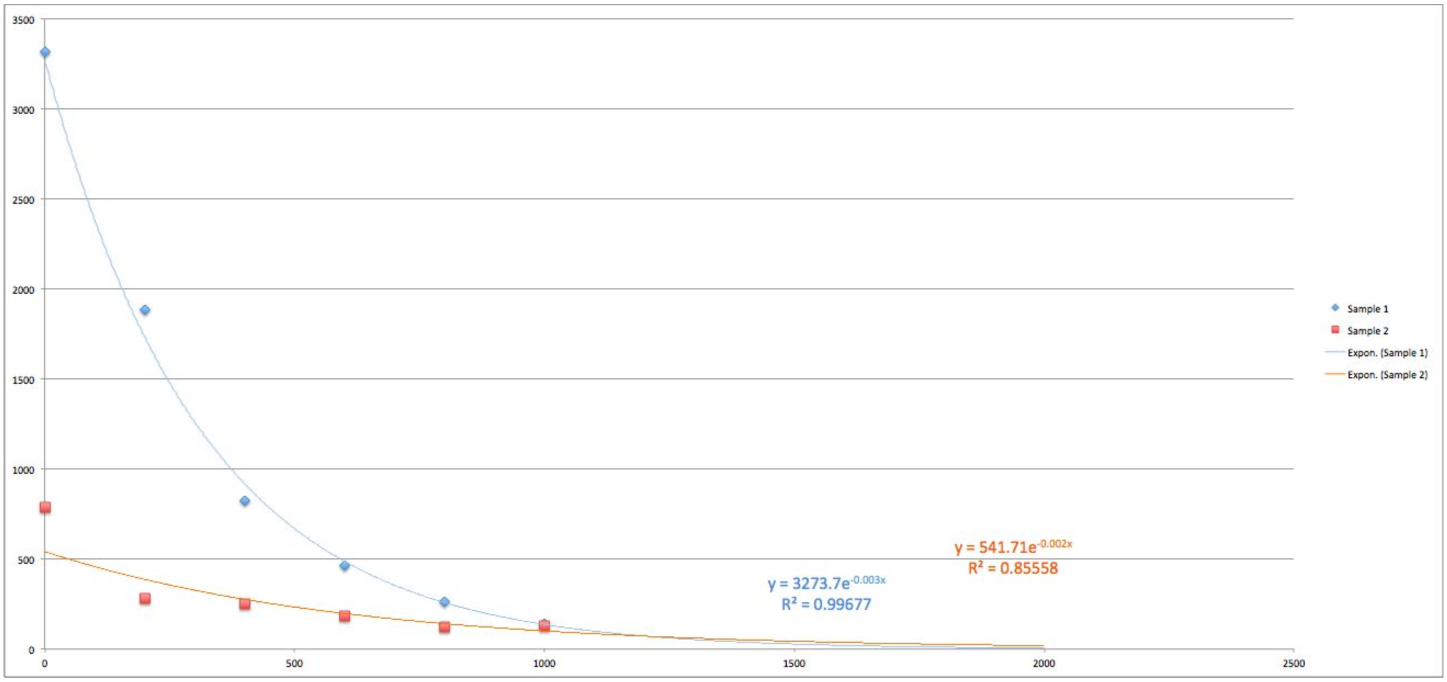
		Test Duration (hrs)						
	Sample	0	200	400	600	800	1000	1200
Tensile strength (MPa)	1. Nanofil	3320.8	1882.7	825	464.03	263.7	141.5	79.2
	% retention	100	56.7	24.8	14	7.9	4.3	2.4
	2. Vantage	784.6	280.4	250	185.36	123.57	128.77	103.4
	% retention	100	35.7	31.9	23.6	15.7	16.4	13.2
Elongation at break (%)	1. Nanofil	12.38	8.4	4.3	3.02	3.095	1.57	1.84
	% retention	100	67.9	34.7	24.4	25	12.7	14.9
	2. Vantage	69.64	33.79	31.64	24.62	21.05	18.55	14.46
	% retention	100	48.5	45.4	35.4	30.2	26.6	20.8





Breaking Point Calculation

When fitting the test data to calculate a certain breaking point, one can see that after about 3600 hours or less than 2 month, tensile strength has decayed to basically 0 (see chart below).



Conclusion

Results of this testing demonstrate that the material selected for the burn wire will steadily degrade with exposure to sunlight while on orbit and lose almost the entirety of it's tensile strength capability after about 3600 hours of UV exposure. It can therefore be stated that the burn wire will eventually experience mechanical failure and the solar arrays will deploy.

Once the solar arrays are deployed, even if the rest of the satellite (including the ADCS) is entirely non-operational, the satellite will decay within less than 25 years due to the atmospheric drag created by the solar panels.

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UV Weathering & Tensile Tests on Nanofil & Vantage Lines

Client:	**Date:** 27th July 2015	**Mat Tech Job No:** F5144
Mr. P. Platzer & G. Grantham Spire Global UK Ltd. Unit 5B, Sky Park 5 45 Finnieston Street Glasgow, G3 8JU		

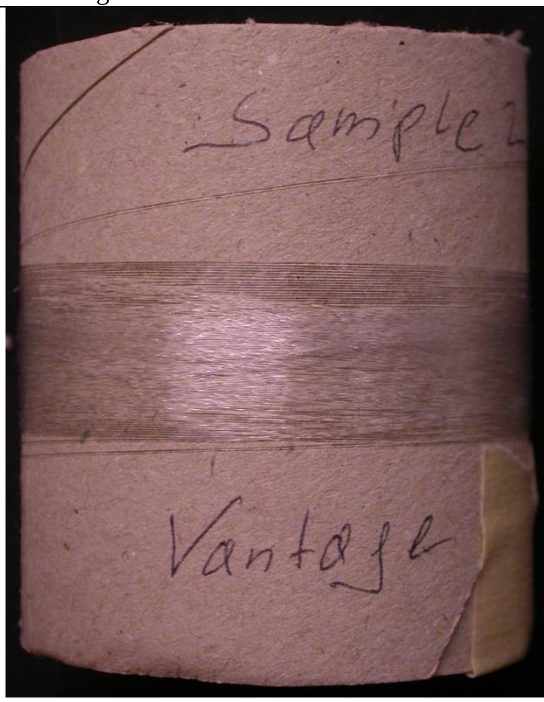
Request Details:
Perform a UV weathering test on Nanofil & Vantage lines to assist in understanding how their tensile properties decay for a satellite application.

The lines were exposed to an aggressive non-standard dry UV test (parameters detailed below). To assess degradation levels tensile tests were performed at the following exposure intervals: 0, 200, 400, 600, 800, 1000 & 1200 hrs.

Sample List:
The samples supplied are detailed in the table below:

1. Nanofil

2. Vantage



Test parameters:
UV weathering testing was performed using a QUV tester manufactured by Q Lab, to the non-standard parameters detailed below. Testing was performed using UVB313 bulbs, these have a peak wavelength of 313nm, which is below that which would normally be experienced on earth and are therefore more aggressive than a standard bulb. In addition the test was performed with a high irradiance level, as an example a standard UVB bulb test in accordance with ISO 4892 part 3 would operate at an irradiance level of 0.48W/m^2 at 313nm, this test was run at 1W/m^2 at 313nm. The test was also run with no moisture cycle, normally UV weathering tests would include a moisture cycle, however this was omitted in this instance as there would be no moisture experienced in a satellite application.

Bulb Type	Irradiance	Black Panel Temperature	Test Duration
UVB 313nm	1W/m^2 @ 313 nm	60°C	1200hrs

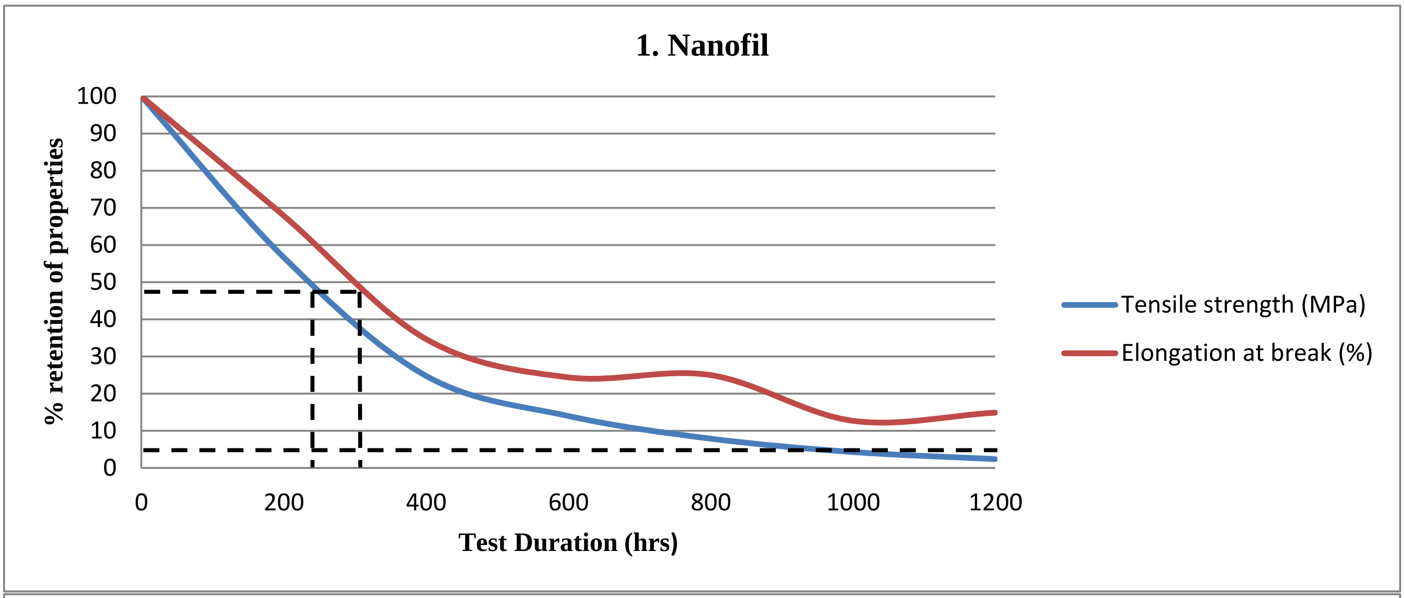
At 200hr intervals tensile tests were performed on the samples in accordance with ISO 2062.

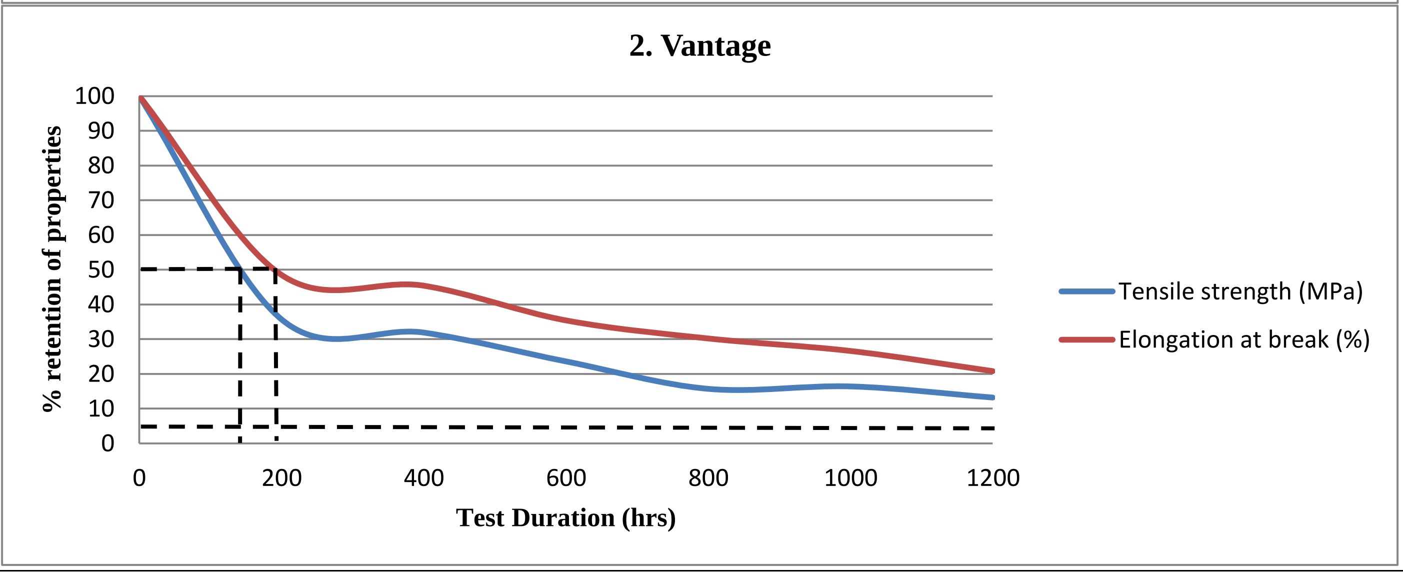
Results:
Results are shown in the table & graphically below:

	Sample	Test Duration (hrs) 0	200	400	600	800	1000	1200
Tensile strength (MPa)	1. Nanofil	3320.8	1882.7	825	464.03	263.7	141.5	79.2
	% retention	100	56.7	24.8	14	7.9	4.3	2.4
	2. Vantage	784.6	280.4	250	185.36	123.57	128.77	103.4
	% retention	100	35.7	31.9	23.6	15.7	16.4	13.2
Elongation at break (%)	1. Nanofil	12.38	8.4	4.3	3.02	3.095	1.57	1.84
	% retention	100	67.9	34.7	24.4	25	12.7	14.9
	2. Vantage	69.64	33.79	31.64	24.62	21.05	18.55	14.46
	% retention	100	48.5	45.4	35.4	30.2	26.6	20.8

It was requested that the test times at which the properties had dropped to 50% & 5% of original were highlighted. These are indicated by the dotted lines on the graphs and tabulated below:

		Tensile strength (MPa)	Elongation at break (%)
1. Nanofil	50% retention	243hrs	320hrs
	5% retention	943hrs	-
2. Vantage	50% retention	146hrs	197hrs
	5% retention	-	-





Discussion:
Following 1200hrs of UV weathering performed on Nanofil & Vantage monofilaments the following comments are made:

The Nanofil had a significantly higher tensile strength than the Vantage at the test start (3320.8 & 784.6MPa respectively) however by the test completion it had retained only 2.4% of its tensile strength and had a lower tensile strength than the Vantage.

The Vantage had a higher elongation at break than the Nanofil (69.64% & 12.38% respectively). The Vantage retained a greater percentage of its elongation at break over the test duration than the Nanofil.

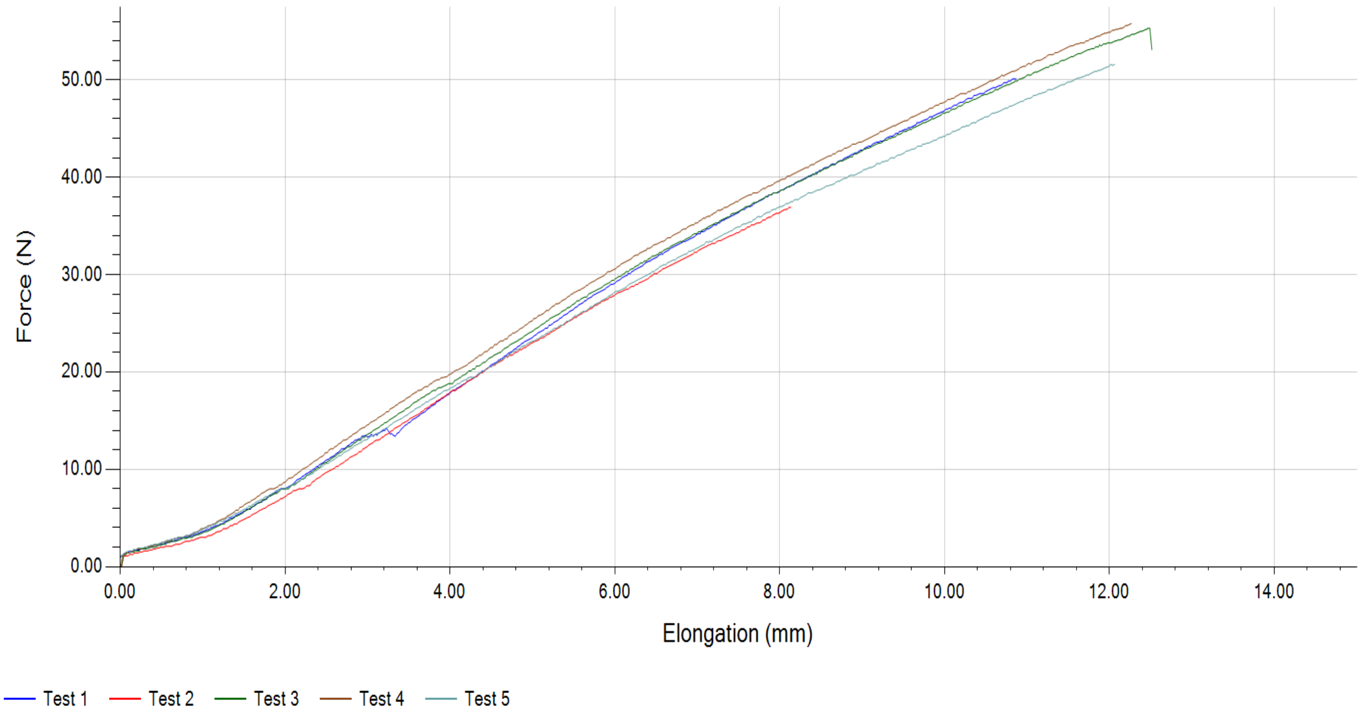
Full traces are appended to the report.

J. Bates (Director)

Client : Spire	Test Name : ISO 2062
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 04/06/2015 13:39
Age : Virgin	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

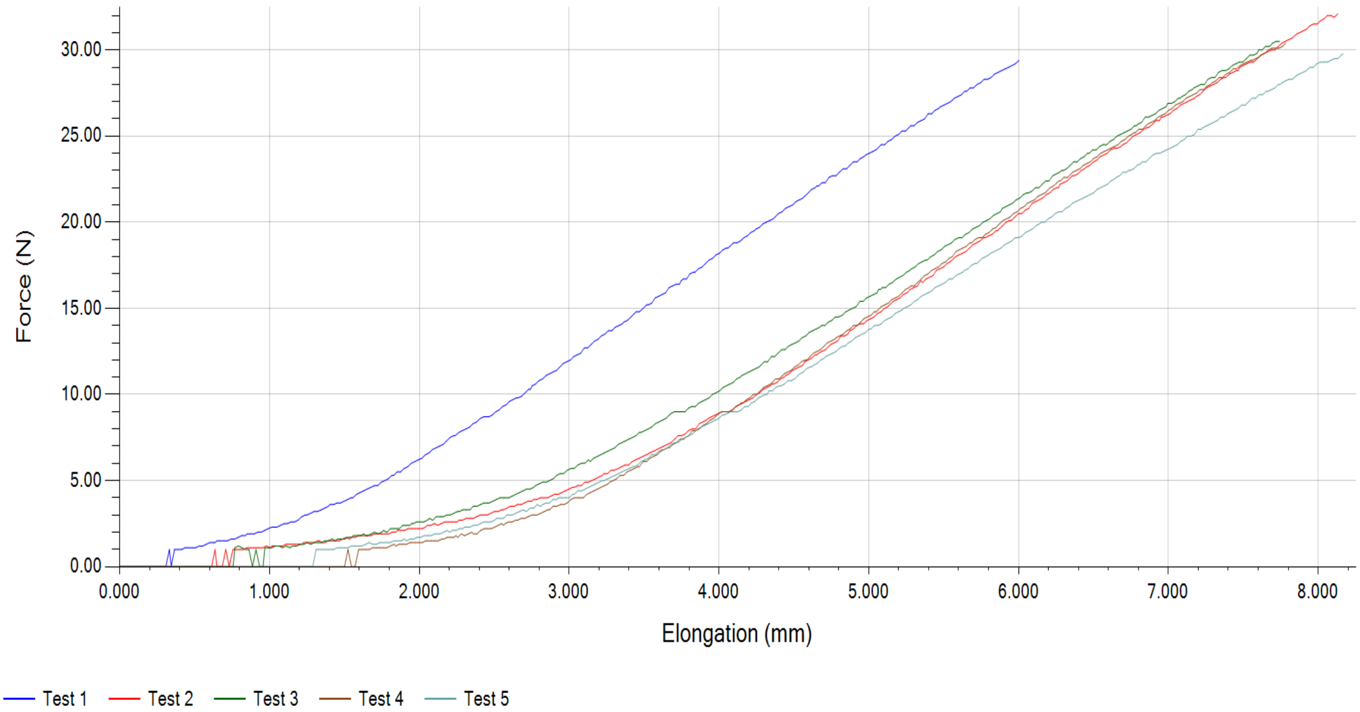
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm^2)
1	50.100	10.825	12.028	0.140	3254.556
2	36.900	8.114	9.016	0.130	2780.032
3	55.300	12.467	13.852	0.140	3592.354
4	55.800	12.269	13.632	0.140	3624.835
5	51.600	12.019	13.354	0.140	3351.998
Mean	49.940	11.139	12.376	0.138	3320.755
S.D.	7.679	1.807	2.008	0.004	340.577



Client : Spire	Test Name : ISO 2062
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 08/06/2015 08:56
Age : 200 hrs	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

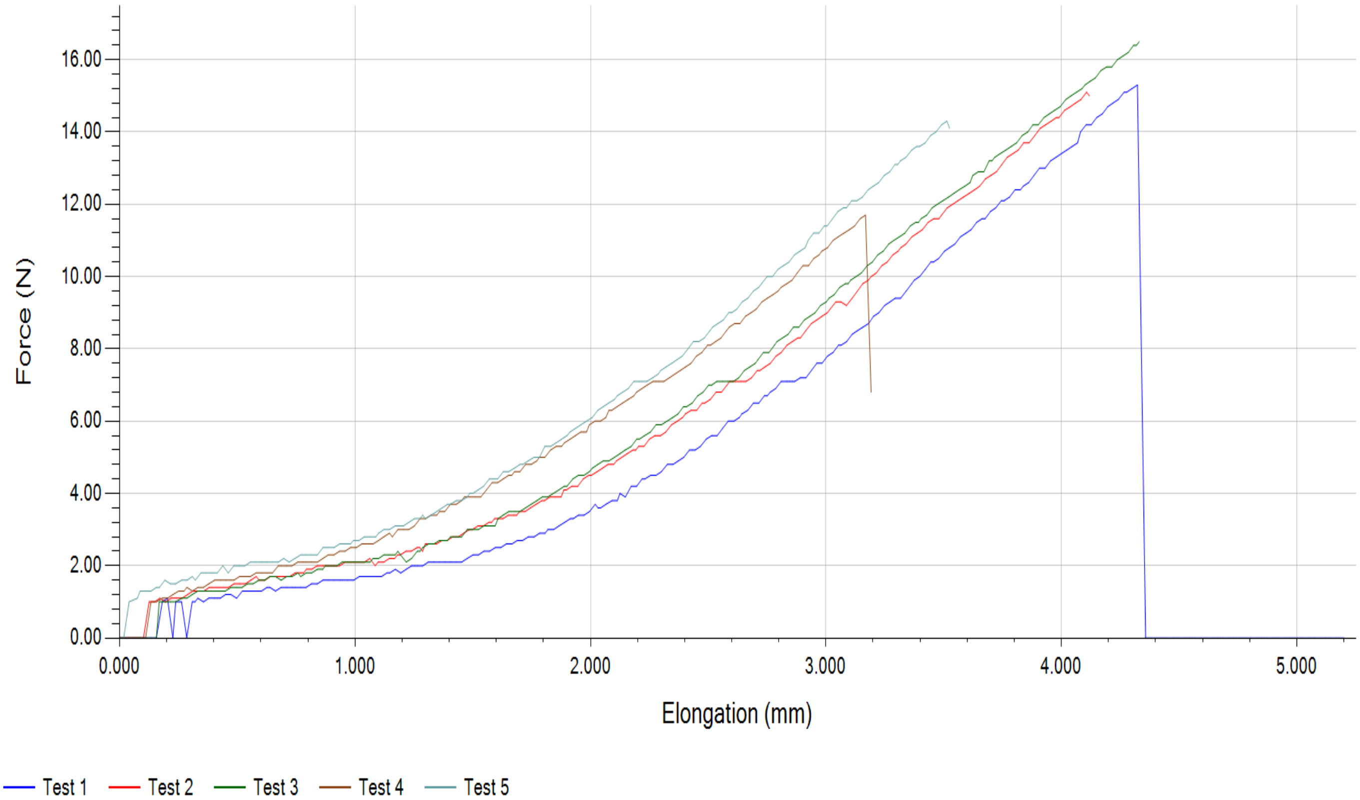
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	29.400	6.004	6.671	0.130	2214.985
2	32.100	8.131	9.034	0.150	1816.488
3	30.500	7.719	8.577	0.150	1725.947
4	30.400	7.784	8.649	0.150	1720.288
5	29.800	8.166	9.073	0.140	1935.844
Mean	30.440	7.561	8.401	0.144	1882.710
S.D.	1.031	0.893	0.992	0.009	205.287



Client : Spire	Test Name : ISO 2062 Line
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 17/06/2015 10:39
Age : 400 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

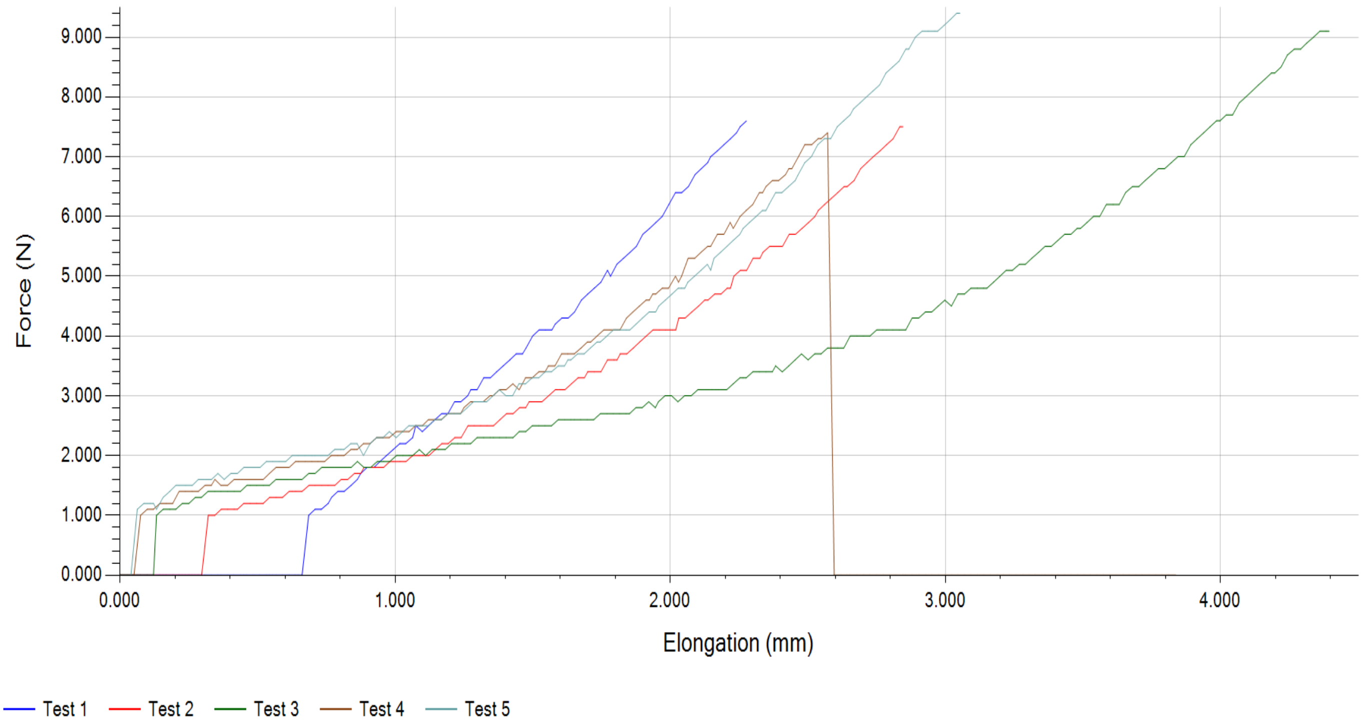
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	15.300	4.323	4.803	0.150	865.803
2	15.100	4.107	4.563	0.150	854.485
3	16.500	4.331	4.812	0.150	933.709
4	11.700	3.168	3.520	0.150	662.085
5	14.300	3.514	3.904	0.150	809.214
Mean	14.580	3.889	4.321	0.150	825.059
S.D.	1.792	0.522	0.580		101.418



Client : Spire	Test Name : ISO 2062
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 26/06/2015 09:16
Age : 600 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

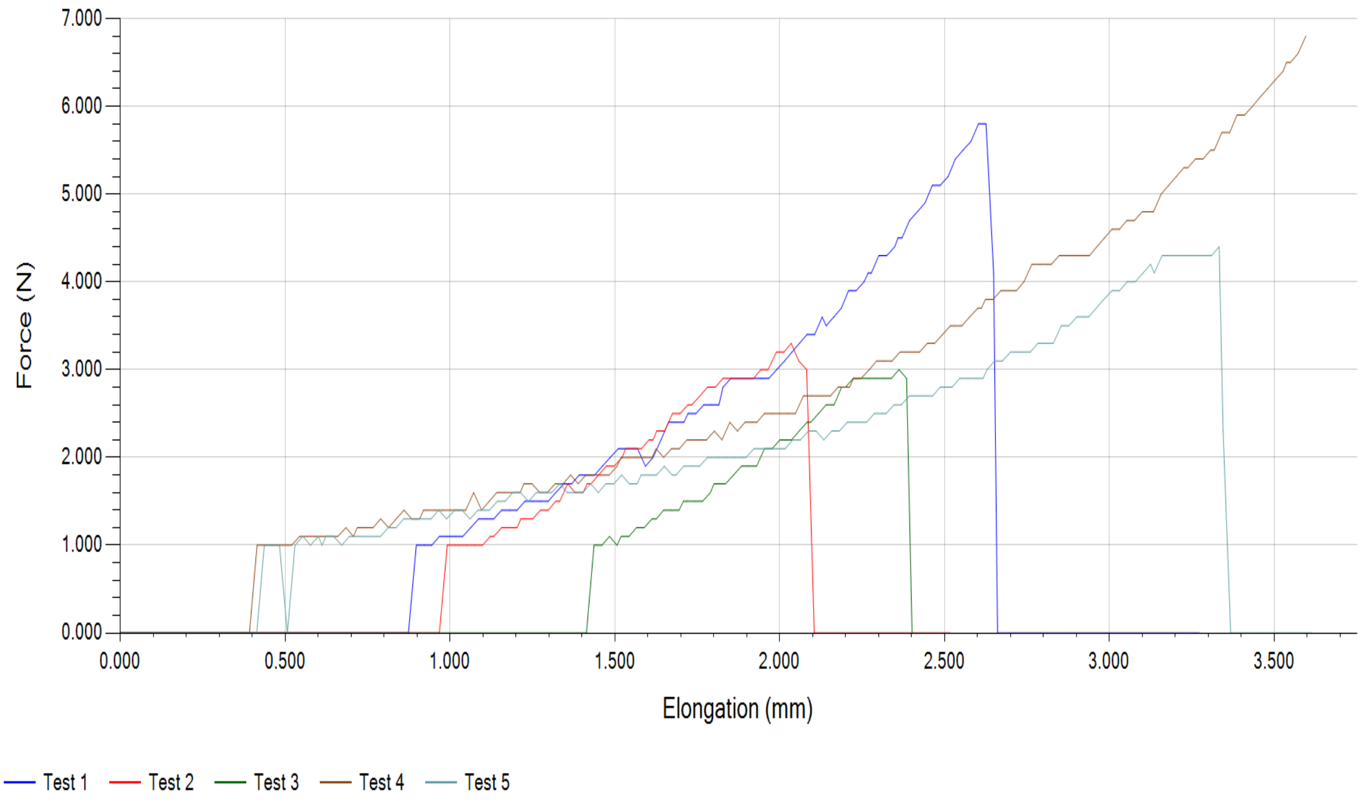
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	7.600	2.277	2.530	0.150	430.072
2	7.500	2.834	3.149	0.150	424.413
3	9.100	4.361	4.846	0.150	514.955
4	7.400	2.572	2.858	0.150	418.754
5	9.400	3.041	3.379	0.150	531.931
Mean	8.200	3.017	3.352	0.150	464.025
S.D.	0.967	0.804	0.893		54.718



Client : Spire	Test Name : ISO 2062 Fibre
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 06/07/2015 11:34
Age : 800 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

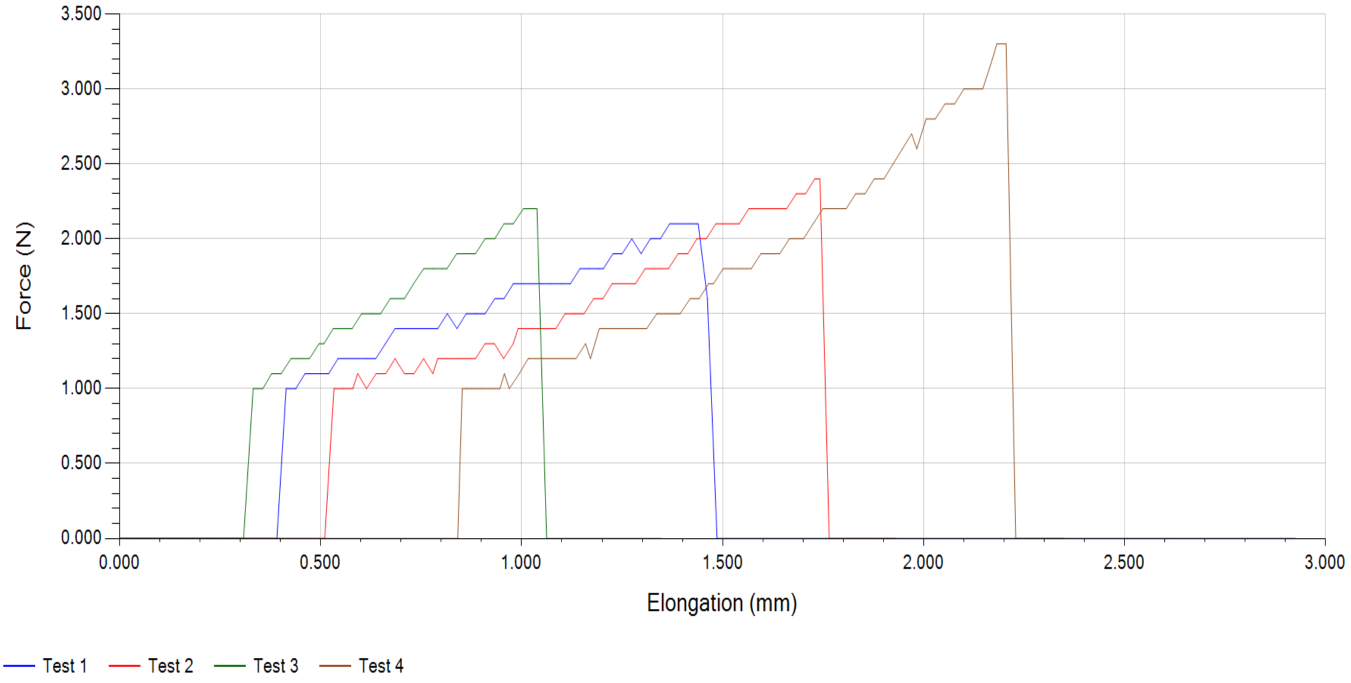
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	5.800	2.603	2.892	0.150	328.213
2	3.300	2.035	2.261	0.150	186.742
3	3.000	2.362	2.624	0.150	169.765
4	6.800	3.596	3.996	0.150	384.801
5	4.400	3.333	3.703	0.150	248.989
Mean	4.660	2.786	3.095	0.150	263.702
S.D.	1.624	0.658	0.731		91.910



Client : Spire	Test Name : ISO 2062 Line
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 21/07/2015 14:30
Age : 1000 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	2.100	1.368	1.520	0.150	118.836
2	2.400	1.729	1.921	0.150	135.812
3	2.200	1.004	1.116	0.150	124.495
4	3.300	2.182	2.424	0.150	186.742
Mean	2.500	1.571	1.745	0.150	141.471

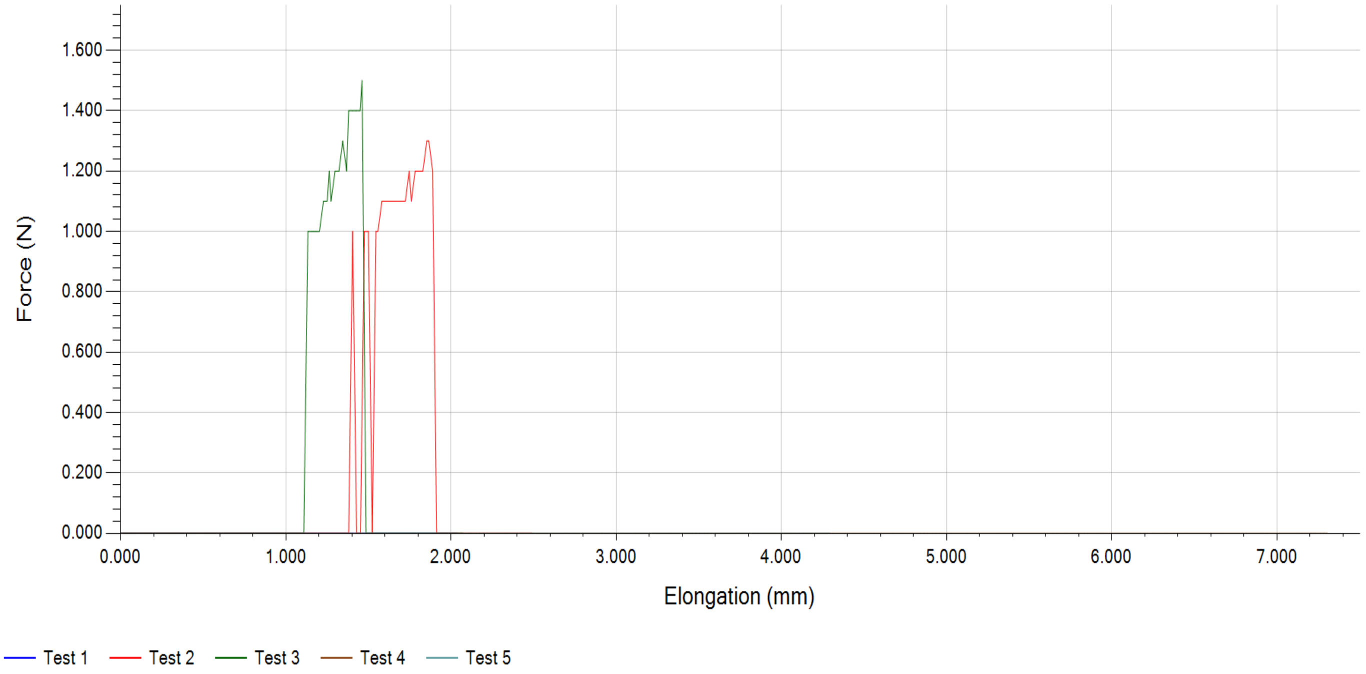


Client : Spire	Test Name : ISO 2062 Line
Job Number : F5144-1	Test Type : Tensile
Material : 1	Test Date : 27/07/2015 13:46
Age : 1200 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

Note tensile strength significantly reduced such that no braeak was detected on samples 1, 4 & 5.

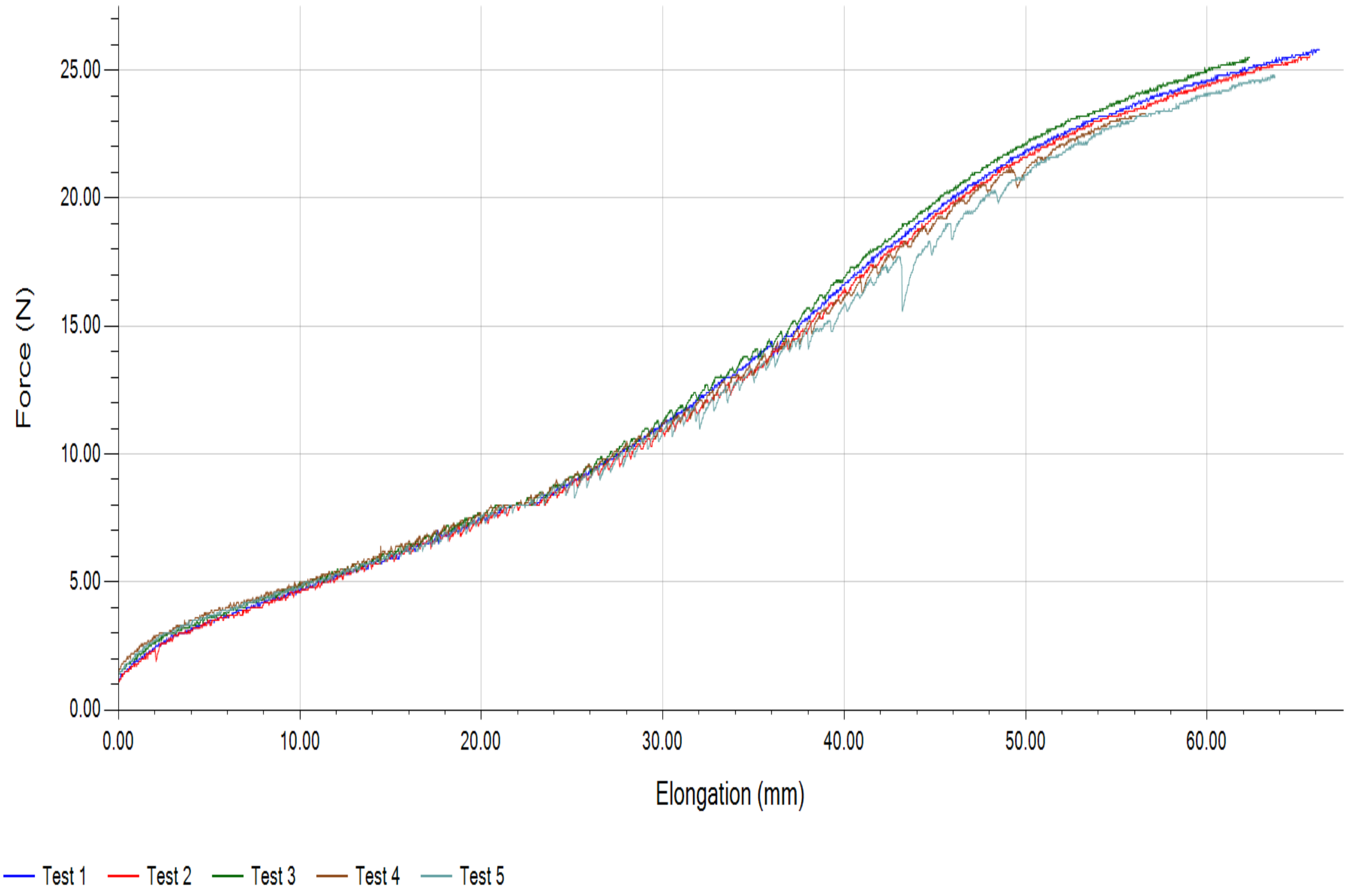
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1				0.150	
2	1.300	1.854	2.060	0.150	73.565
3	1.500	1.462	1.624	0.150	84.883
4				0.150	
5				0.150	
Mean	1.400	1.658	1.842	0.150	79.224



Client : Spire	**Test Name : ISO 2062**
Job Number : F5144-1	**Test Type : Tensile**
Material : 2	**Test Date : 04/06/2015 13:58**
Age : Virgin	**Test Speed : 25.000 mm/min**
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

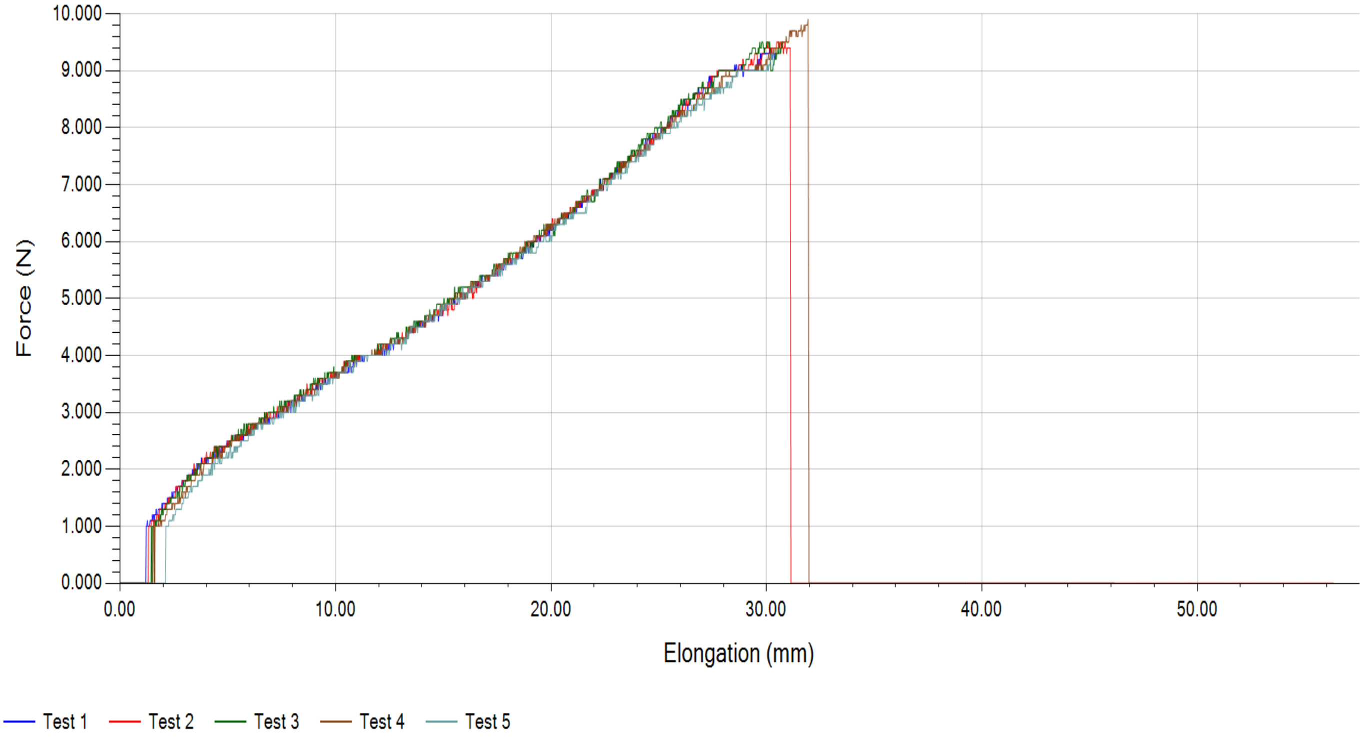
Test No	**Force @ Peak (N)**	**Elong. @ Peak (mm)**	**Strain @ Peak (%)**	**Diameter (mm)**	**Stress @ Peak (N/mm^2)**
1	25.800	65.762	73.069	0.190	909.961
2	25.600	65.682	72.980	0.210	739.114
3	25.500	62.107	69.008	0.200	811.690
4	23.300	56.295	62.550	0.210	672.709
5	24.800	63.512	70.569	0.200	789.408
Mean	25.000	62.672	69.635	0.202	784.577
S.D.	1.022	3.883	4.314	0.008	88.120



Client : Spire	Test Name : ISO 2062
Job Number : F5144-1	Test Type : Tensile
Material : 2	Test Date : 08/06/2015 09:34
Age : 200 hrs	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

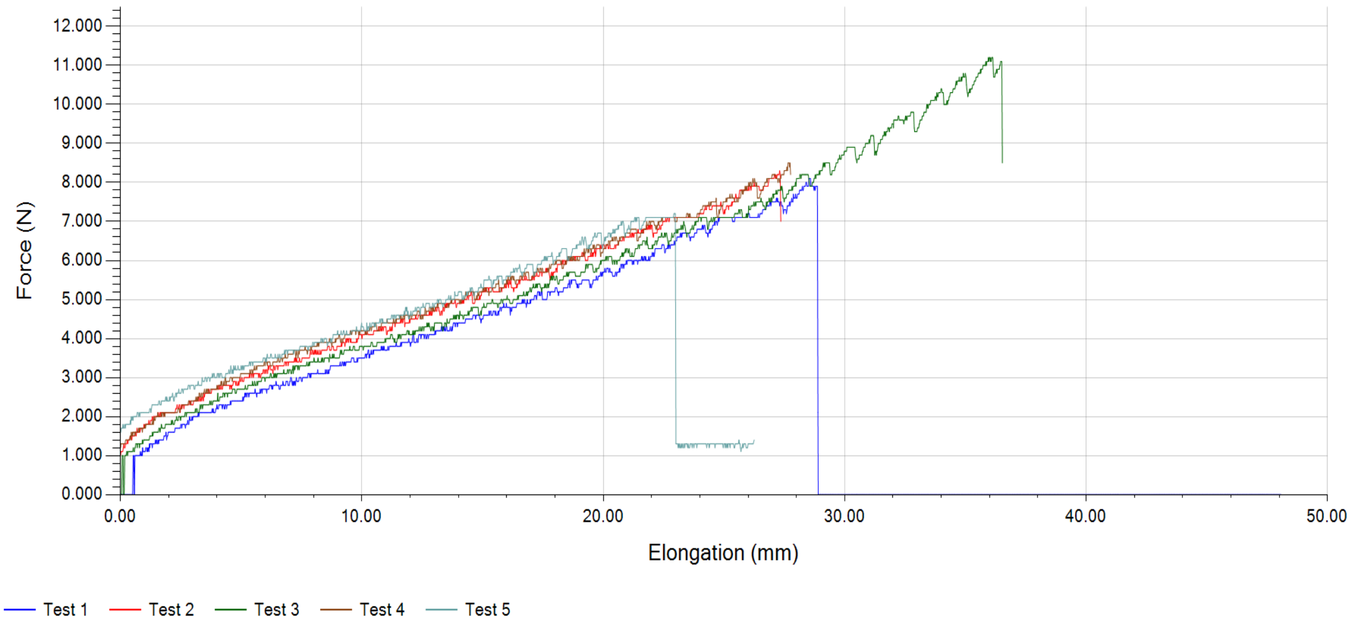
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	9.400	30.146	33.496	0.200	299.211
2	9.500	30.038	33.376	0.210	274.281
3	9.500	29.691	32.990	0.210	274.281
4	9.900	31.929	35.477	0.210	285.829
5	9.300	30.249	33.610	0.210	268.506
Mean	9.520	30.411	33.790	0.208	280.422
S.D.	0.228	0.874	0.972	0.004	12.244



Client : Spire	**Test Name : ISO 2062 Line**
Job Number : F5144-1	**Test Type : Tensile**
Material : 2	**Test Date : 17/06/2015 10:59**
Age : 400 Hours	**Test Speed : 25.000 mm/min**
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

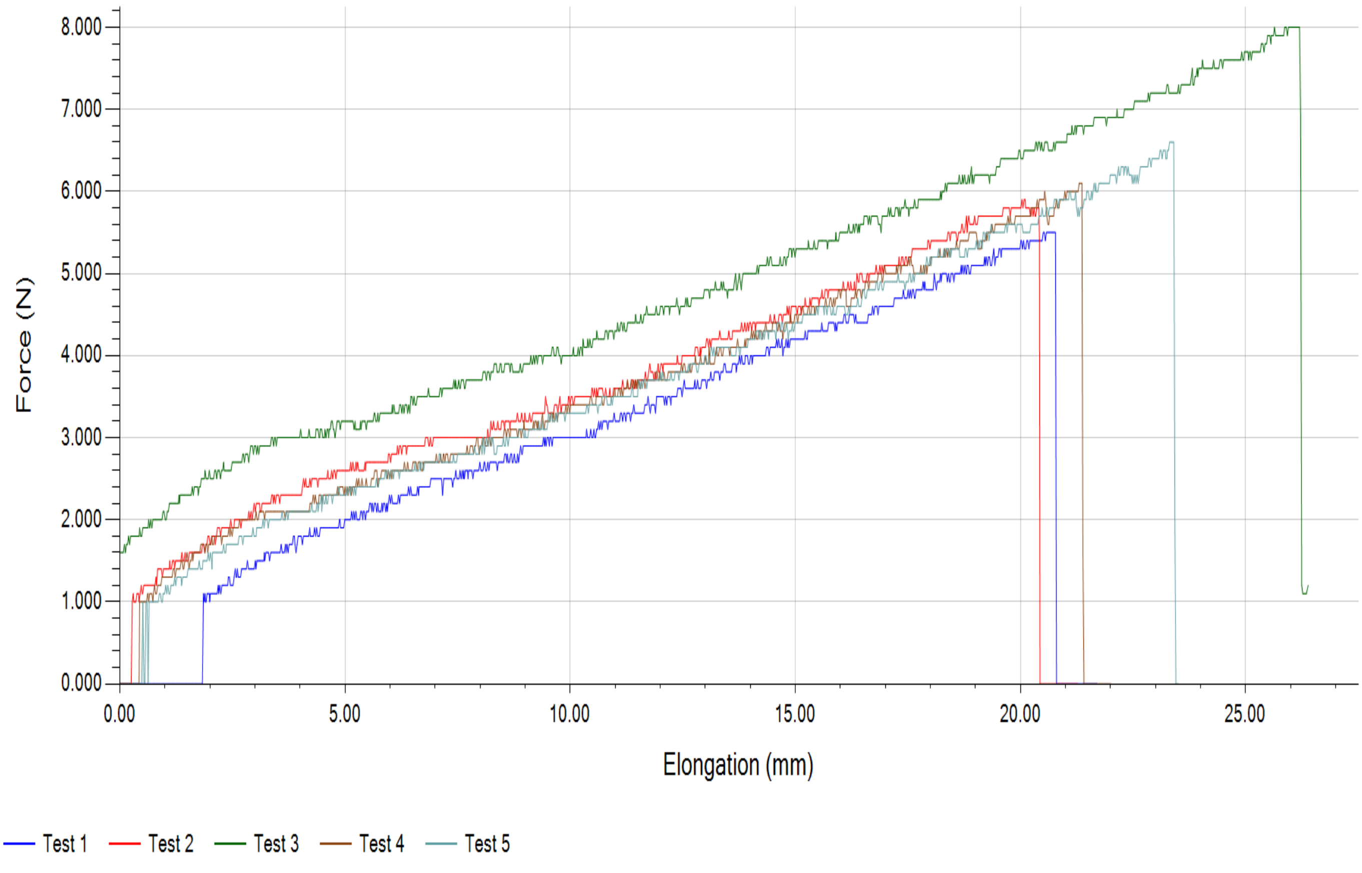
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	8.100	28.523	31.692	0.210	233.860
2	8.300	27.305	30.339	0.210	239.635
3	11.200	35.949	39.943	0.210	323.362
4	8.500	27.653	30.726	0.210	245.409
5	7.200	22.928	25.476	0.210	207.876
Mean	8.660	28.472	31.635	0.210	250.028
S.D.	1.504	4.708	5.232	0.000	43.432



Client : Spire	**Test Name : ISO 2062**
Job Number : F5144-1	**Test Type : Tensile**
Material : 2	**Test Date : 26/06/2015 09:42**
Age : 600 Hours	**Test Speed : 25.000 mm/min**
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

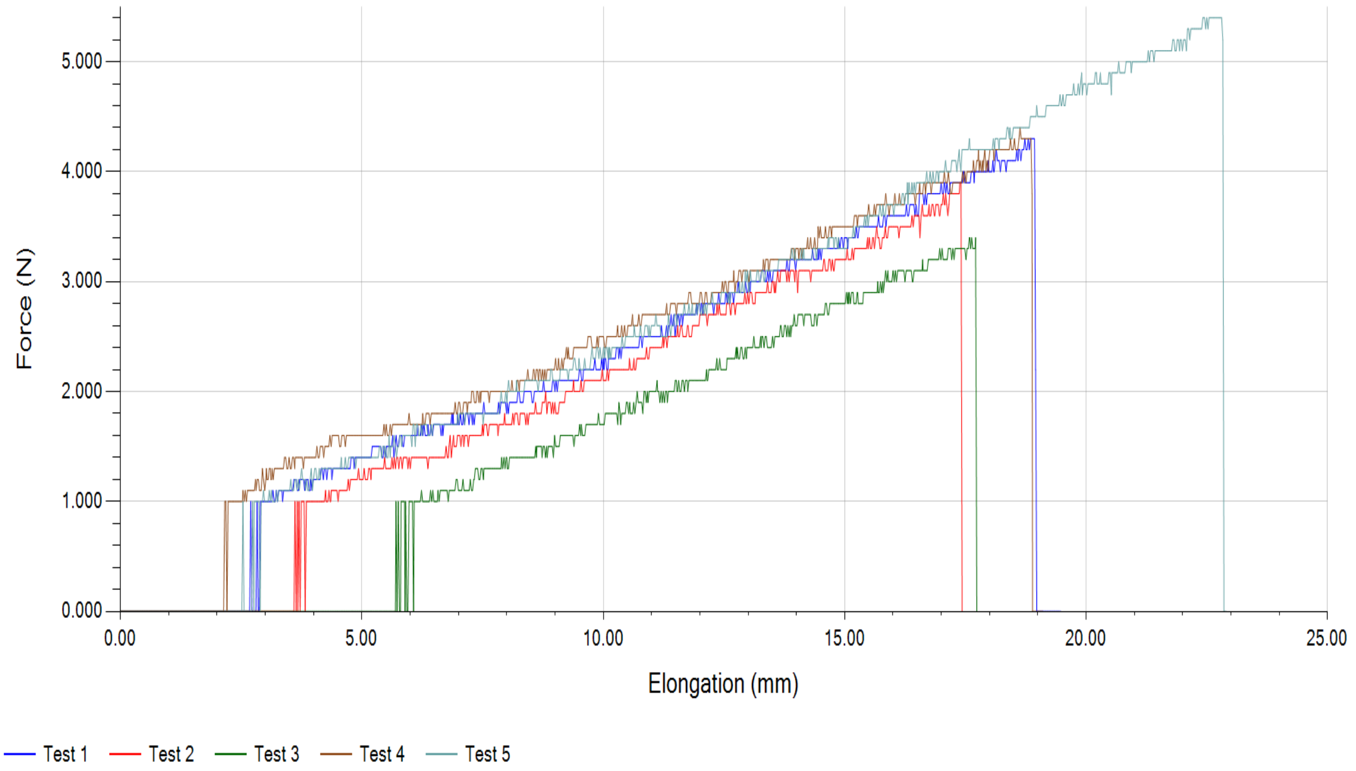
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm^2)
1	5.500	20.507	22.786	0.210	158.794
2	5.900	20.034	22.260	0.210	170.343
3	8.000	25.644	28.493	0.210	230.973
4	6.100	21.305	23.672	0.210	176.117
5	6.600	23.312	25.902	0.210	190.553
Mean	6.420	22.160	24.623	0.210	185.356
S.D.	0.968	2.316	2.573	0.000	27.947



Client : Spire	Test Name : ISO 2062 Fibre
Job Number : F5144-1	Test Type : Tensile
Material : 2	Test Date : 06/07/2015 11:40
Age : 800 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

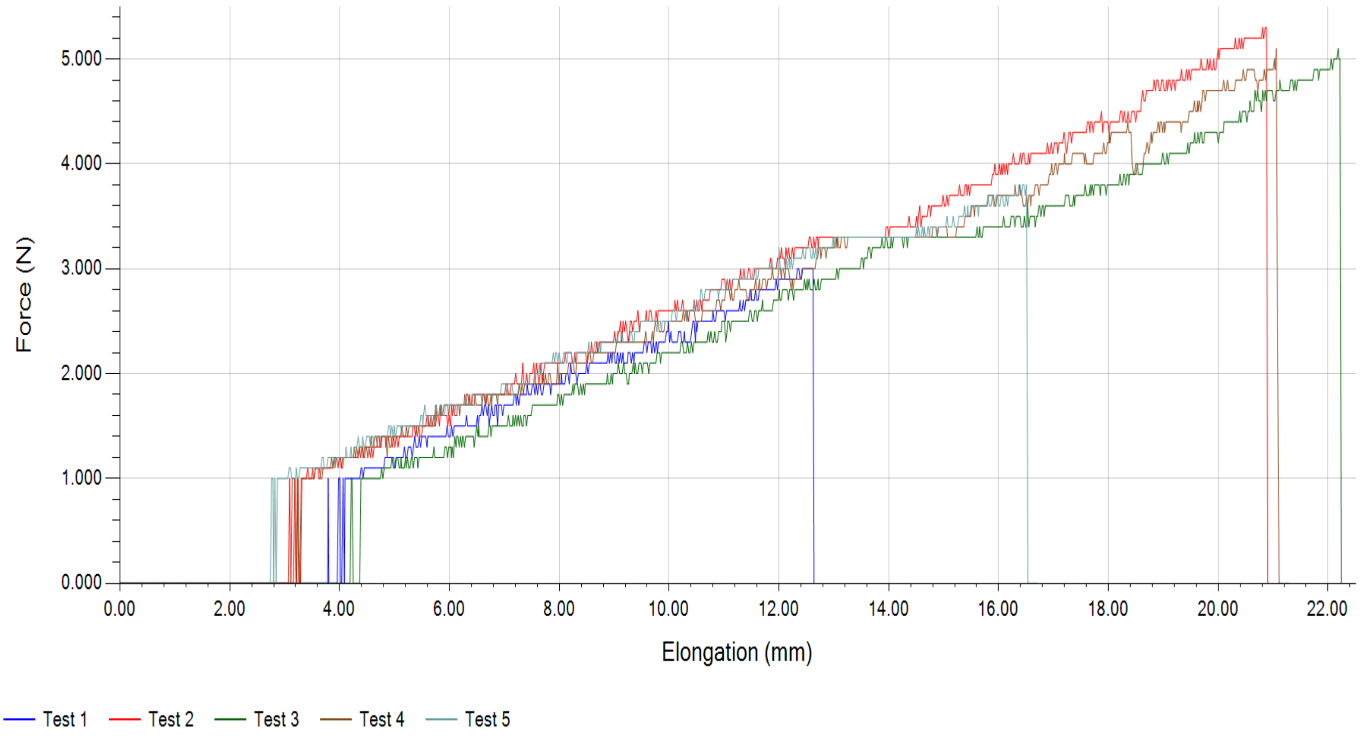
Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	4.300	18.730	20.811	0.210	124.148
2	3.900	17.384	19.316	0.210	112.599
3	3.400	17.582	19.536	0.210	98.164
4	4.400	18.631	20.701	0.210	127.035
5	5.400	22.417	24.908	0.210	155.907
Mean	4.280	18.949	21.054	0.210	123.571
S.D.	0.740	2.031	2.256	0.000	21.353



Client : Spire	Test Name : ISO 2062 Line
Job Number : F5144-1	Test Type : Tensile
Material : 2	Test Date : 21/07/2015 14:38
Age : 1000 Hours	Test Speed : 25.000 mm/min
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	3.000	12.337	13.708	0.210	86.615
2	5.300	20.808	23.120	0.210	153.020
3	5.100	22.184	24.649	0.210	147.245
4	5.100	21.058	23.398	0.210	147.245
5	3.800	16.370	18.189	0.210	109.712
Mean	4.460	18.551	20.613	0.210	128.768



Client : Spire	**Test Name : ISO 2062 Line**
Job Number : F5144-1	**Test Type : Tensile**
Material : 2	**Test Date : 27/07/2015 13:55**
Age : 1200 Hours	**Test Speed : 25.000 mm/min**
	Pretension : Off
	Diameter : 0.150 mm
	Sample Length : 90.000 mm

Comments :

Test No	Force @ Peak (N)	Elong. @ Peak (mm)	Strain @ Peak (%)	Diameter (mm)	Stress @ Peak (N/mm²)
1	3.800	16.435	18.261	0.210	109.712
2	4.000	13.701	15.223	0.210	115.487
3	3.200	11.195	12.439	0.210	92.389
4	3.300	12.182	13.536	0.210	95.276
5	3.600	11.568	12.853	0.210	103.938
Mean	3.580	13.016	14.462	0.210	103.360