Analysis of the impregnation process

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outline

- Key parameters of the analysis
- Analysis criteria
- Results for 11T dipole
- Results for MQXF
- Spare slides with additional information

Key parameters

- Curing temperature: **μ** +/- **σ** , and max-min.
- Post-curing temperature: **μ** +/- **σ**, and max-min.
- Curing time.
- Post-curing time.
- Time from start of mixing to start of curing.
- Coil degassing time.
- Soaking time duration.
- Temperature during mixing:**μ** .
- Level of vacuum pressure in the mixer during mixing time.
- Level of vacuum pressure in the big tank during injection.
- Total time duration of the VPI process and duration of the individual sub-processes.

Impossible to retrieve from the data

Standard thermal cycle

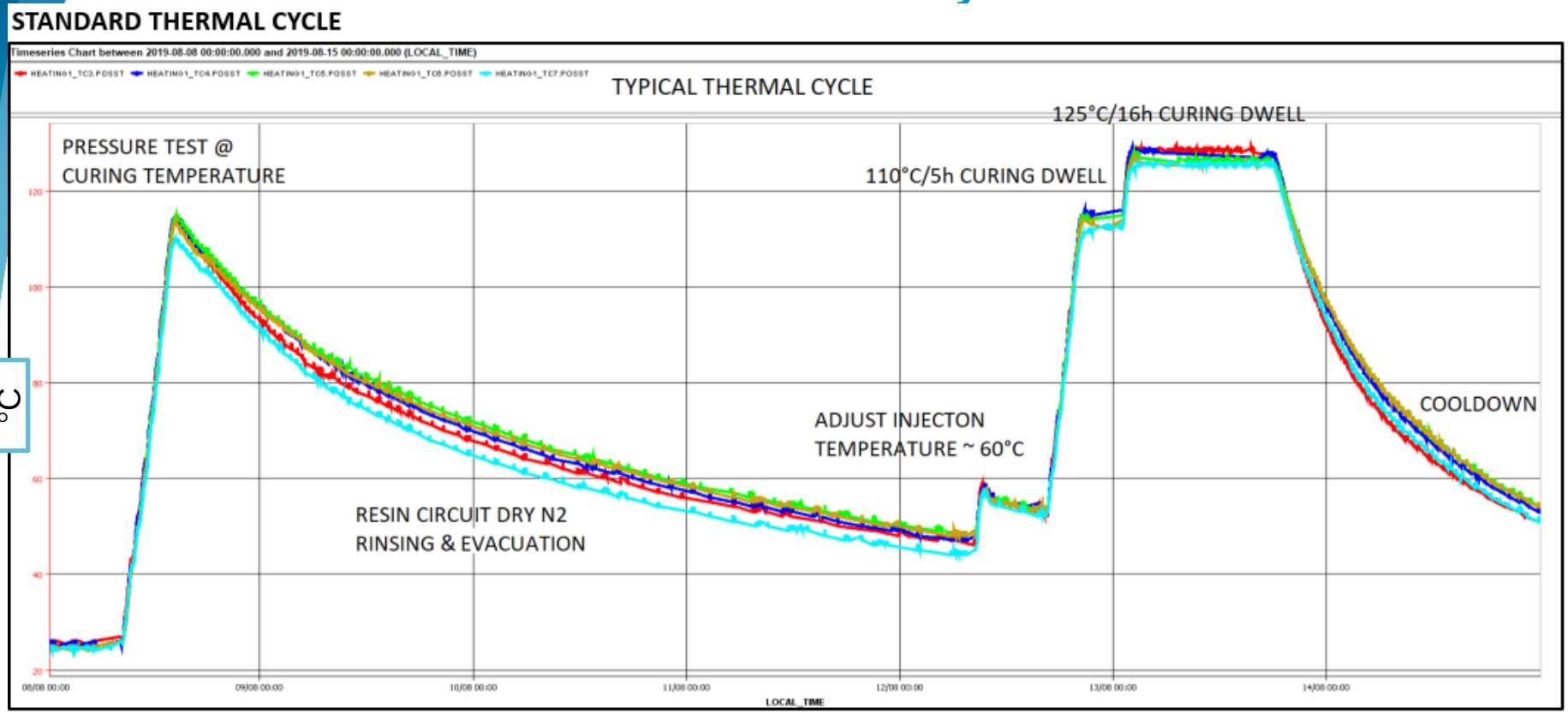
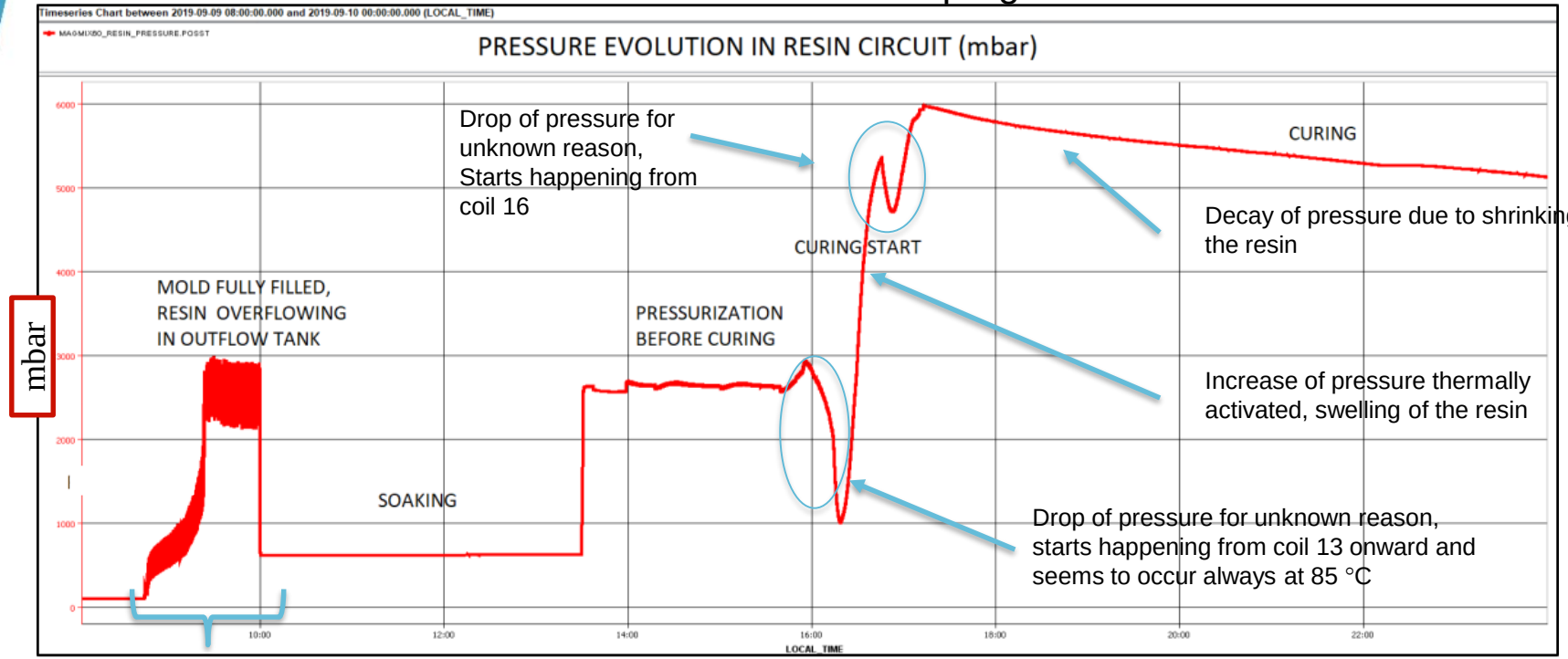


Image taken from poster at MT 26 international conference on magnet technology; J.Axensalva et al.

Resin pressure from impregnation to end of curing

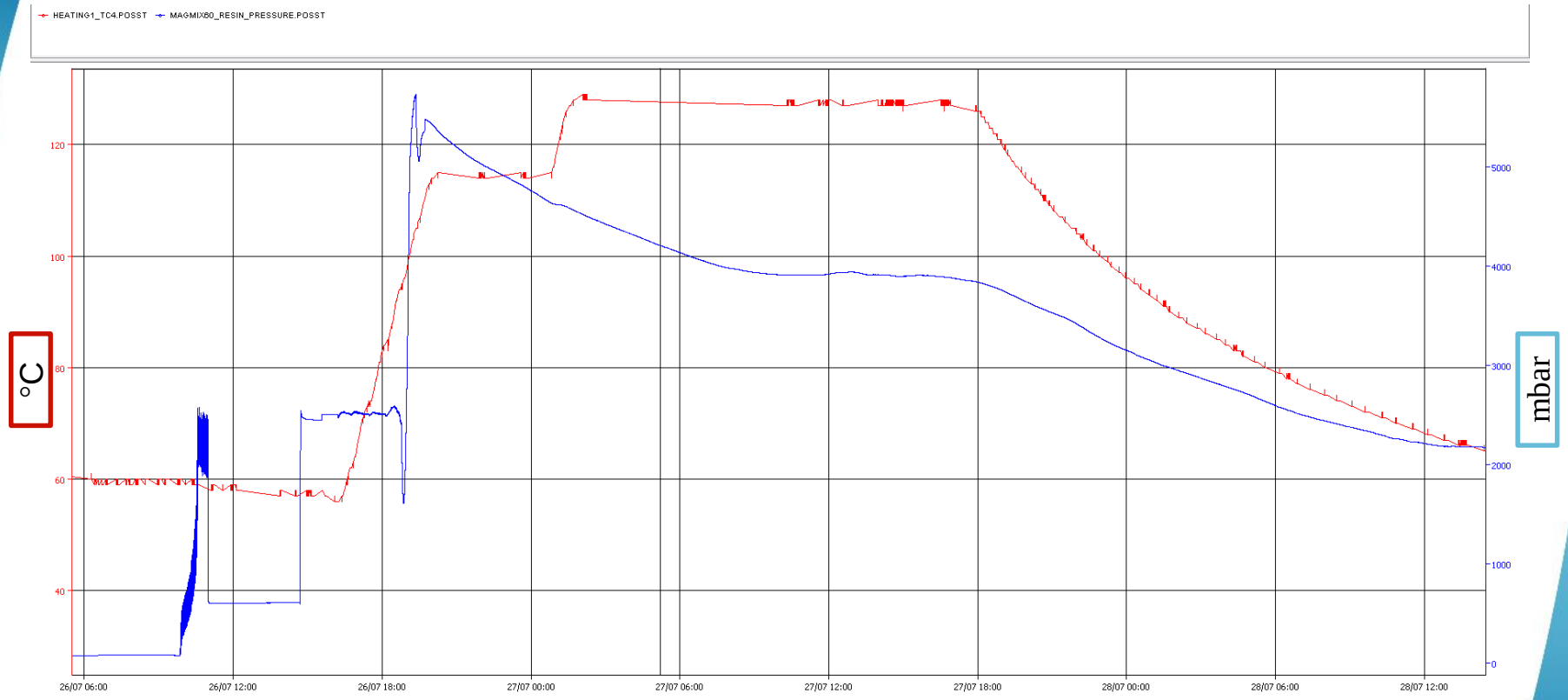
RESIN PRESSURE DURING INJECTION AND CURING Taken from the impregnation of coil 19



Resin filling

Image taken from poster at MT 26 international conference on magnet technology; J.Axensalva et al.

Behavior of temperature and pressure for coil 16



Example of a good impregnation cycle

Variable of the analysis

The position of the thermocouple is the one used for the 11T

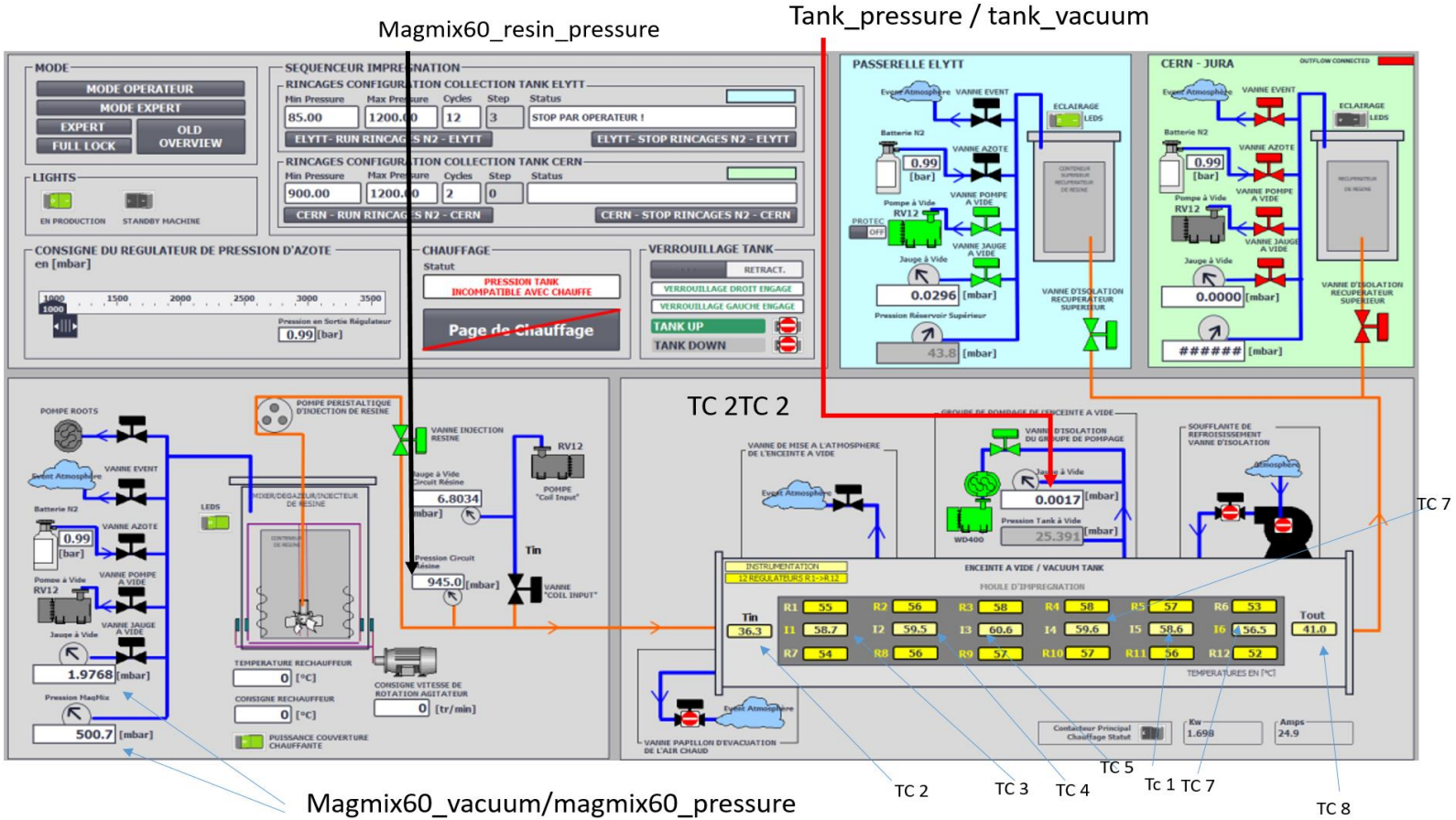


Image taken from poster at MT 26 international conference on magnet technology; J.Axensalva et al.

Analysis criteria

Mixing and degassing impossible to retrieve from the data ,so their duration and beginning are supposed:

- Mixing start 3h before injection and last 1h
- Degassing start 2h before injection and last 2h

Starts and ends of curing and post-curing are determined by temperature :

- Starts , all of the thermocouples reached the set point temperature (110 °C for curing 125 °C for post curing)
- Ends, all of the thermocouples reach 120 °C for curing and for post curing when all of them are below 125 °C.

[this values are indicative ,for lots of coils the values of the set points were changed]

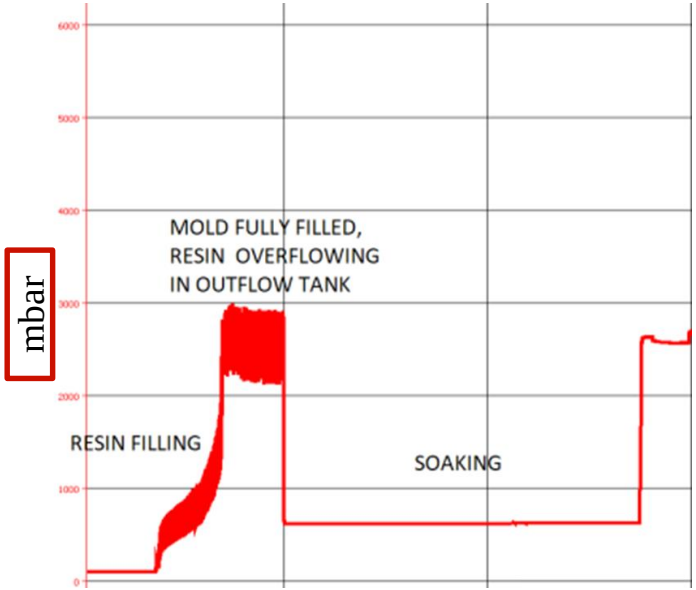
Analysis criteria

Injection :

- Start when pressure of the resin (variable magmix60_resin pressure in timber) goes over 200 mbar and the temperature of all of the thermocouples (excluded the ones in the inlet and the outlet) is between 55 and 65 °C (indicative values)
- End when the pressure drop down to a value near to 650 mbar ,which means the start of the soaking.

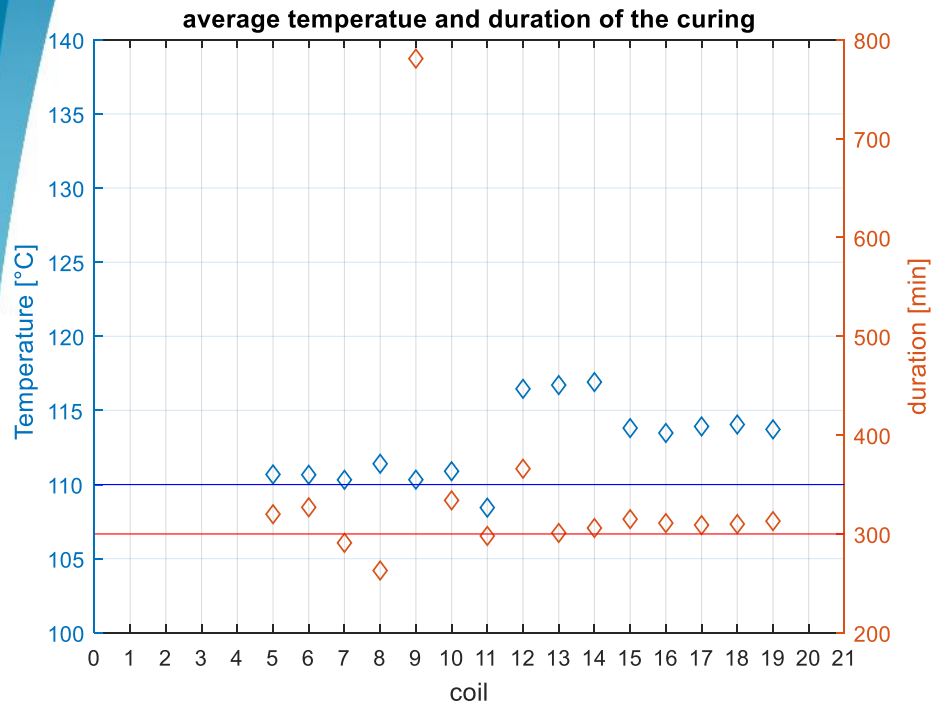
Soaking :

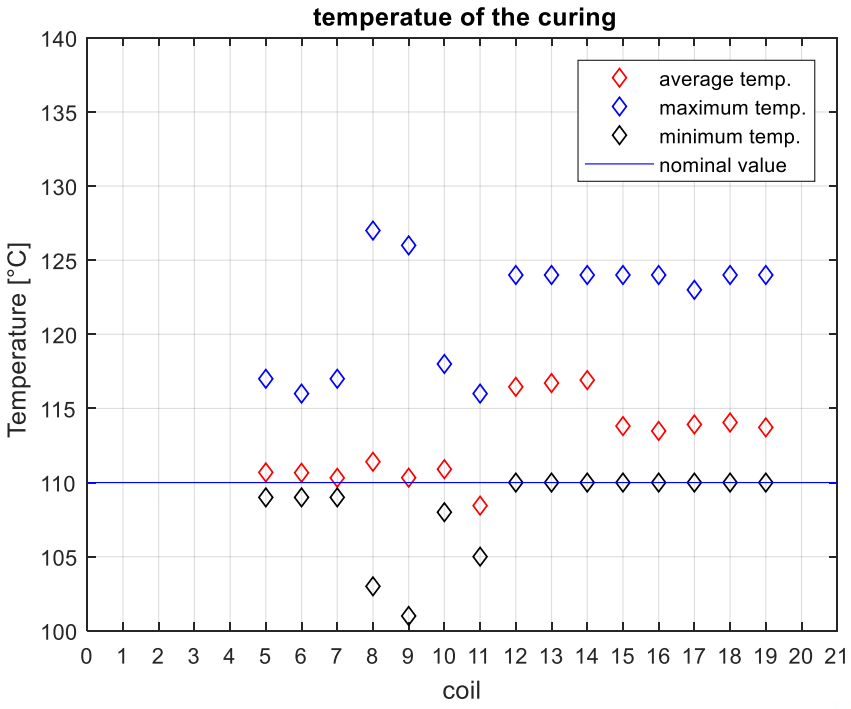
- Start when the pressure of the resin goes down from the ~2 bar of the injection plateau to 650 mbar (indicative value)
- During the soaking the pressure is constant
- End when the pressure start changing and became higher than 650 mbar (indicative value).



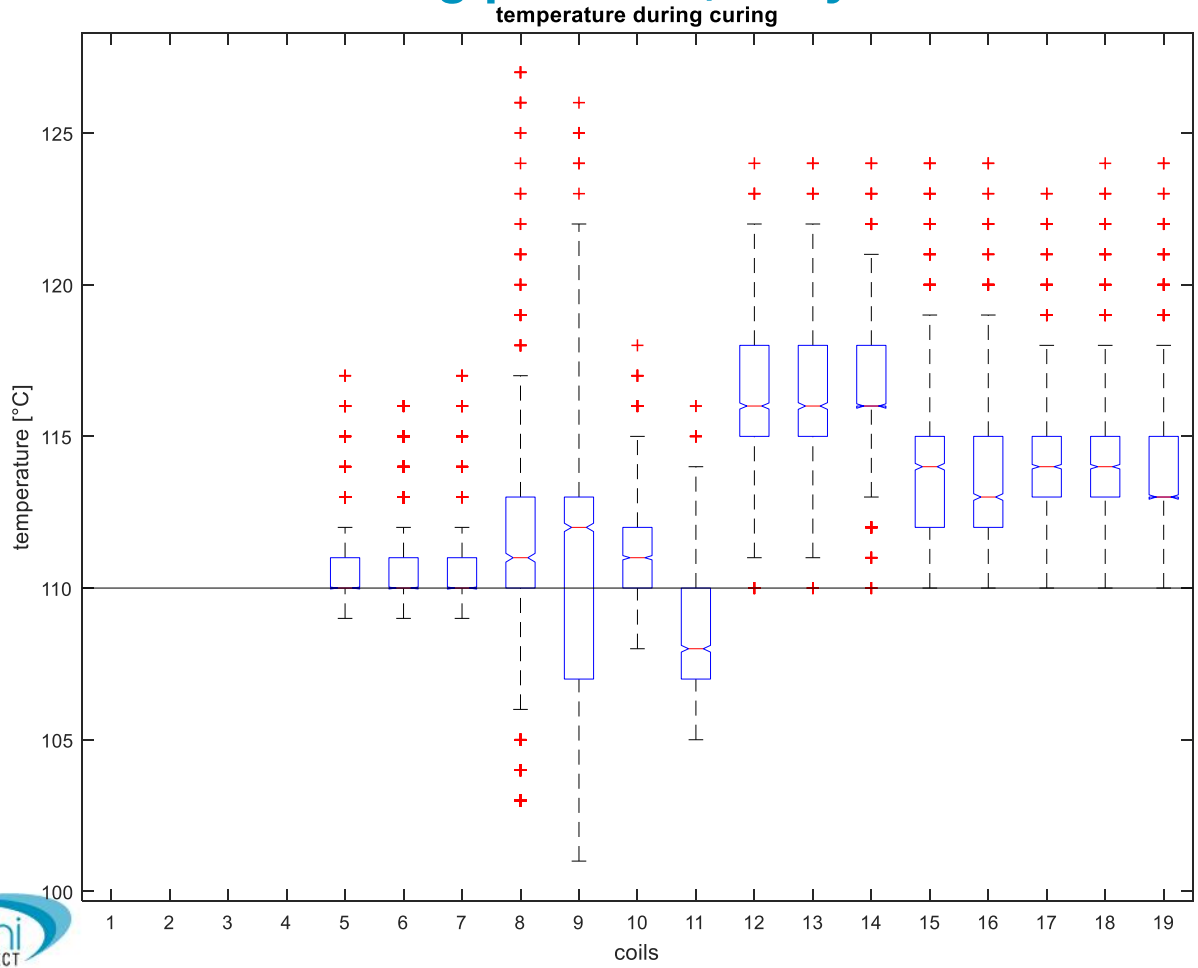
Resin pressure during injection and soaking

Curing process ,analysis results 11T





Curing process ,analysis results 11T



The box represent the interquartile range (50% of the observation are in this range of temperature), the red line is the median value,
The extreme of the box are the first and third quartile
the upper limit has value equal at the third quartile +1.5the interquartile range;
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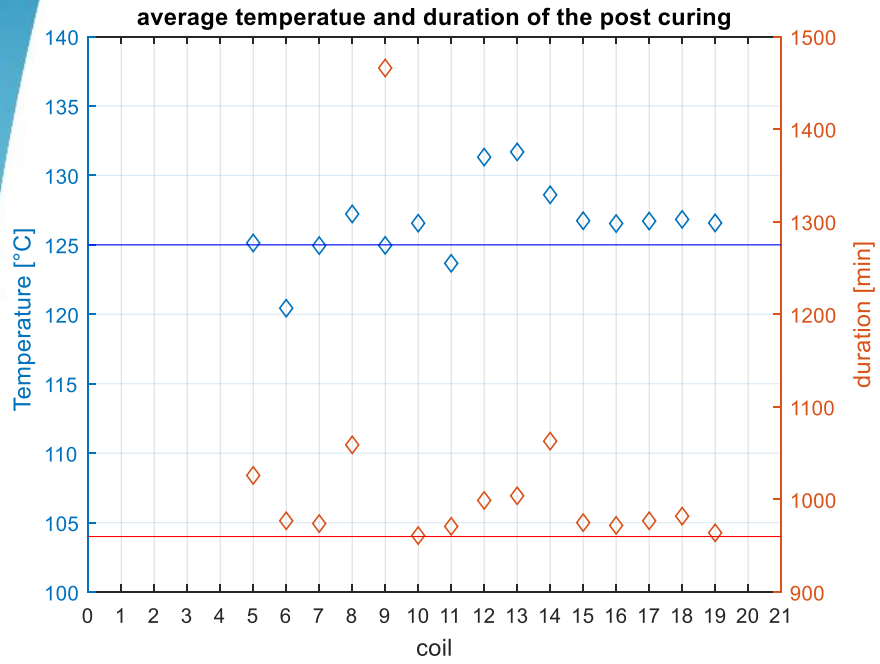
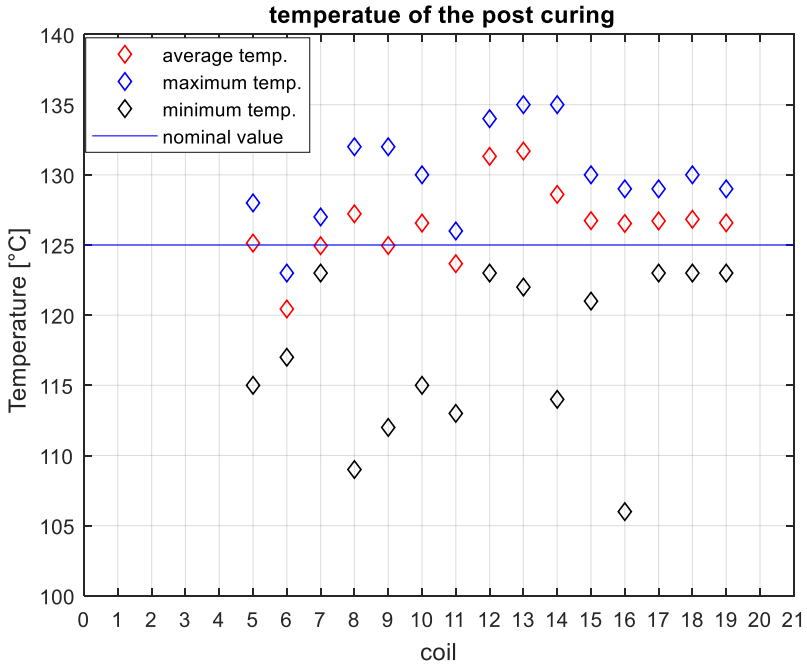
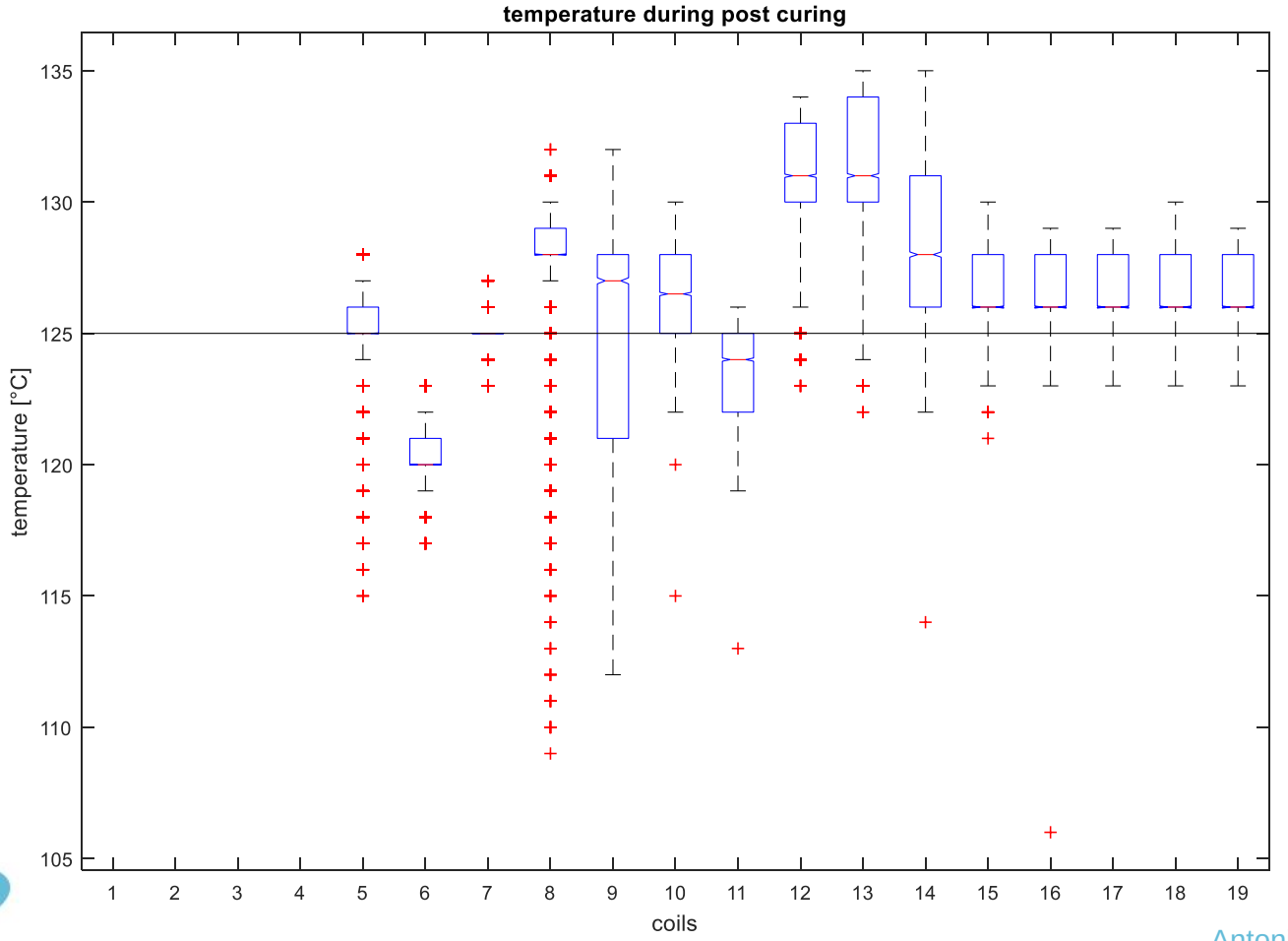
99.3% of the observation are in the range between the two limits
The outliers (red point) represent the remaining observation

Post curing process ,analysis results 11T





Post curing process ,analysis results 11T



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MQXF analysis

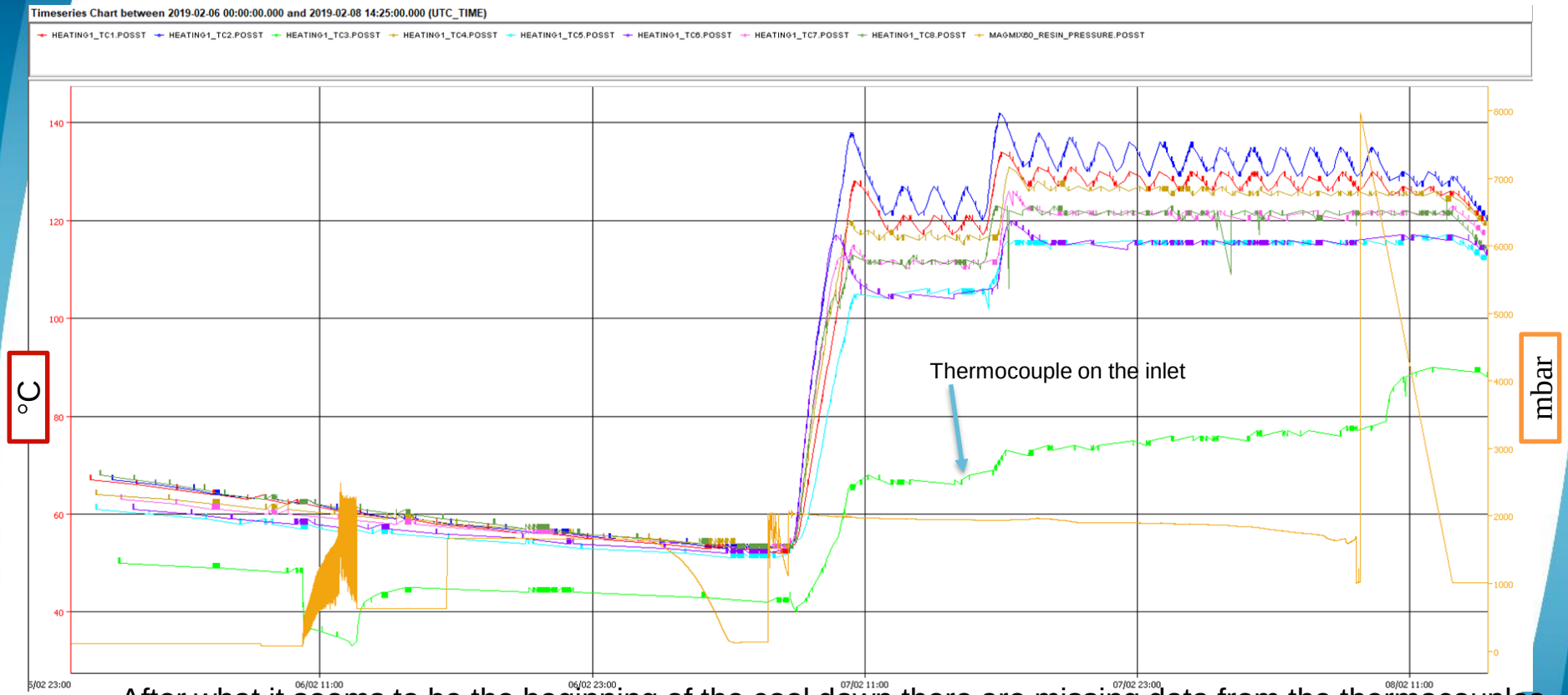
Coil analyzed,
Data retrieved from timber :

- 204 = good data, analysis performed
- 203 = bad data (temperature never goes over 85 °C)
- 202 = analysis performed, wide span between thermocouples values during curing and post curing
- 201 = good data, analysis performed
- 111 = good data, analysis performed
- 110 = good data, analysis performed
- 109 = good data, analysis performed

Data retrieved from MTF :

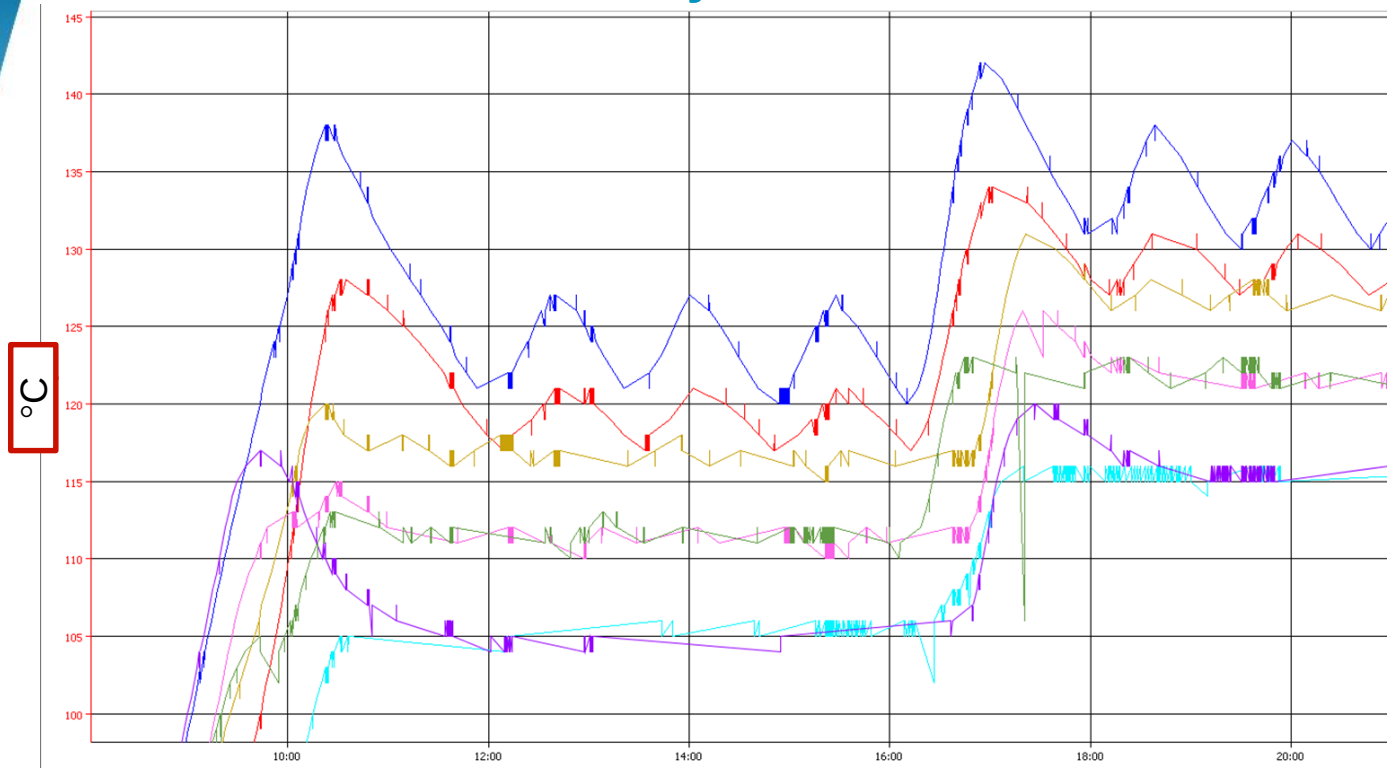
- 104 = missing data, no info about pressure, no info before start curing, analysis performed
- 105 = missing data, no info about pressure, no info before start curing, analysis performed
- 107 = missing data, no info about pressure, no info before start curing, analysis performed
- 108 = missing data, no info about pressure, no info before start curing, analysis performed

Cycle of coil 202



After what it seems to be the beginning of the cool down there are missing data from the thermocouples.
Strange behavior of the resin pressure after soaking and start curing

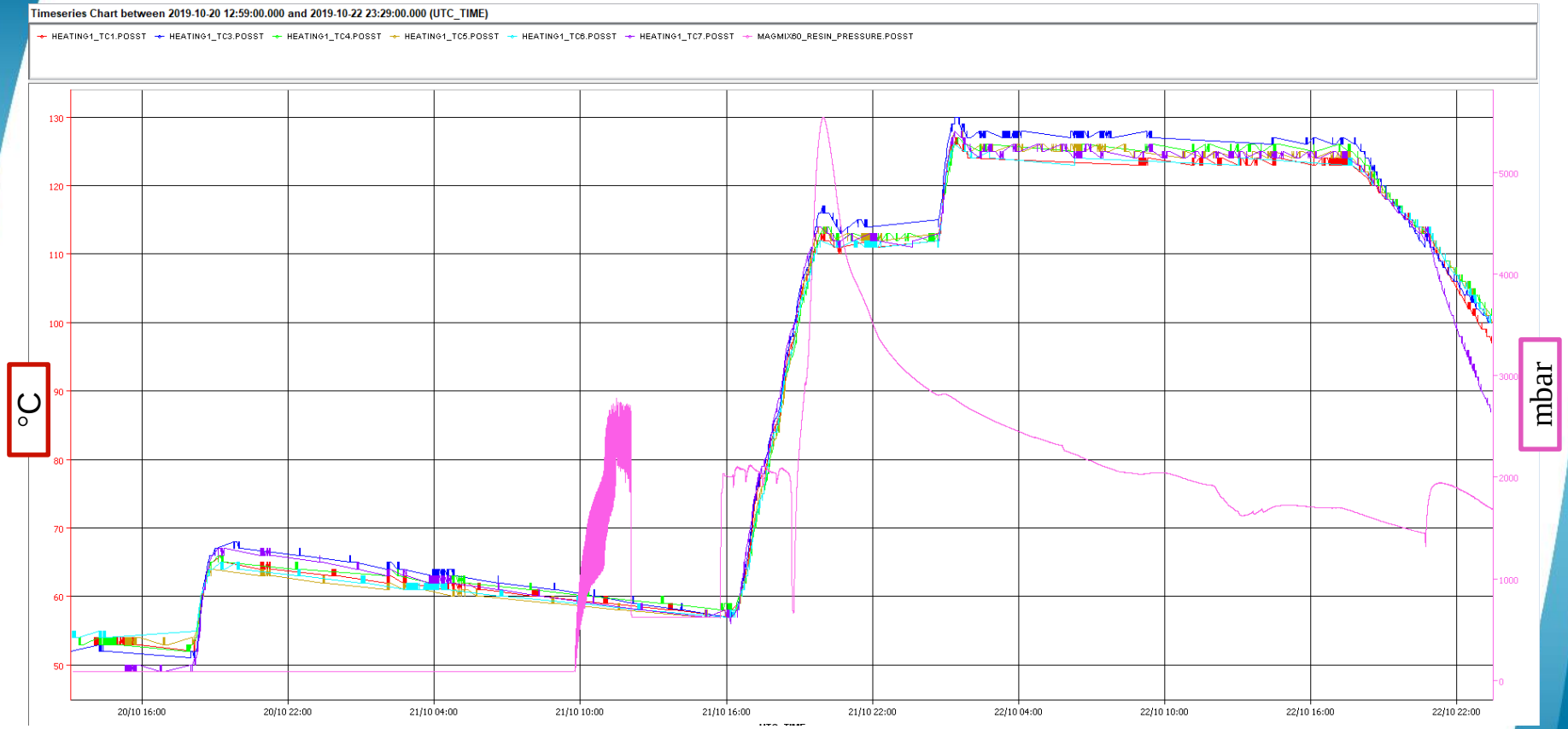
Cycle of coil 202



The hottest thermocouple (TC2) has a temperature of 20 °C higher than the two coldest (TC5 & TC6)
The cause of the ripple is the tuning of the PID. This ripple is also present in the cycle of coil 8 and 9 of the 11T and coil 201;but here the span between thermocouples id the biggest one

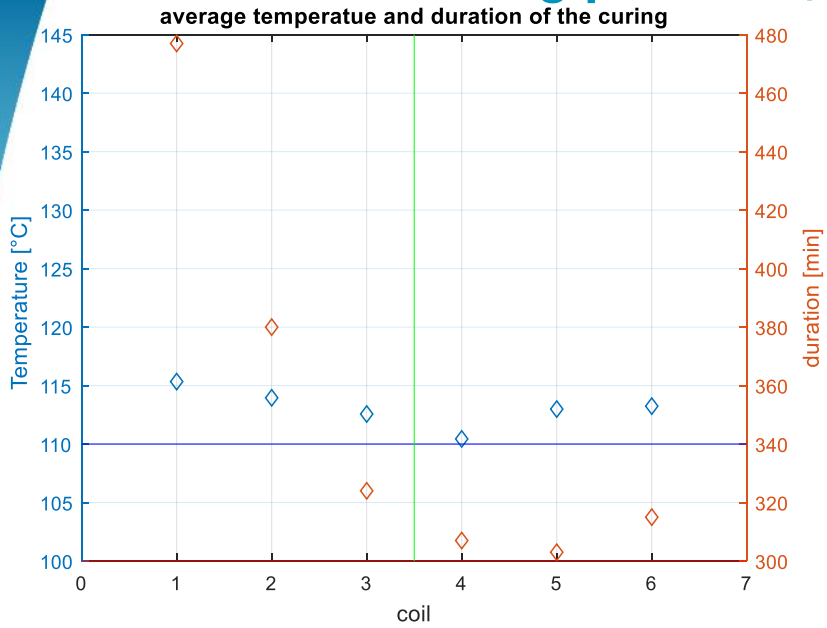
This data doesn't seem very reliable, the changes in the temperature are to large and happens in so few time that it seems not being physically possible and also the difference between the thermocouples are to large considering their position

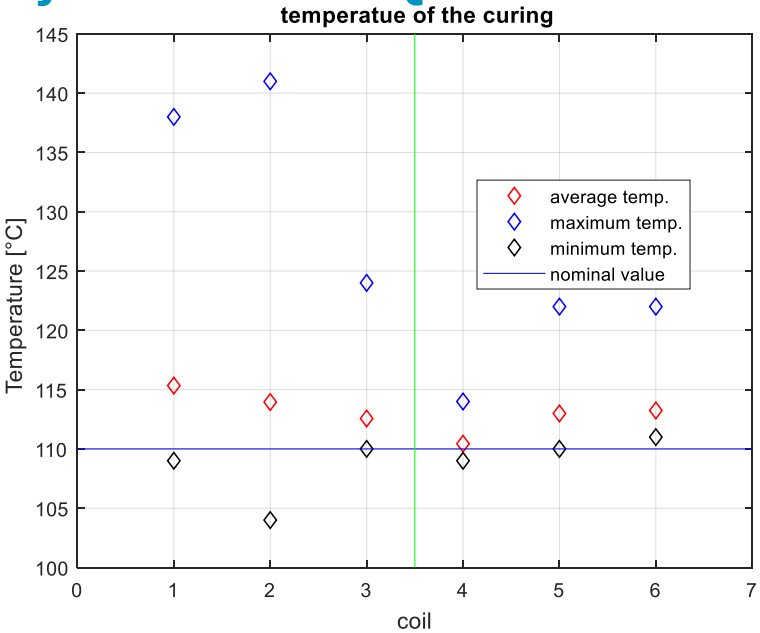
Cycle of coil 204



Example of a good impregnation process

Curing process ,analysis results MQXF

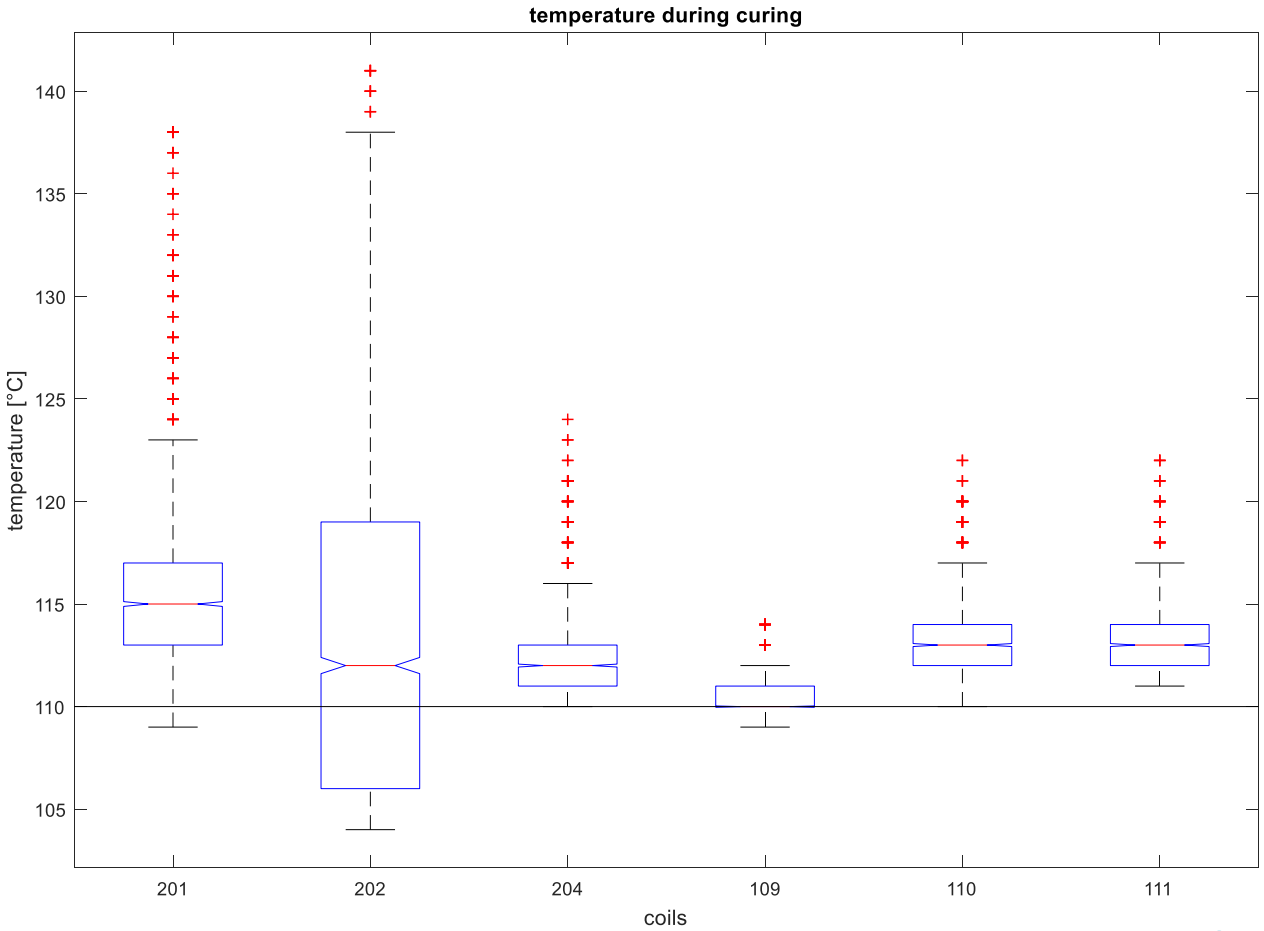




The green line divide the coil series with PIT conductor from the one with RRP conductor.

- 1 = coil 201
- 2 = coil 202
- 3 = coil 204
- 4 = coil 109
- 5 = coil 110
- 6 = coil 111

Curing process ,analysis results MQXF



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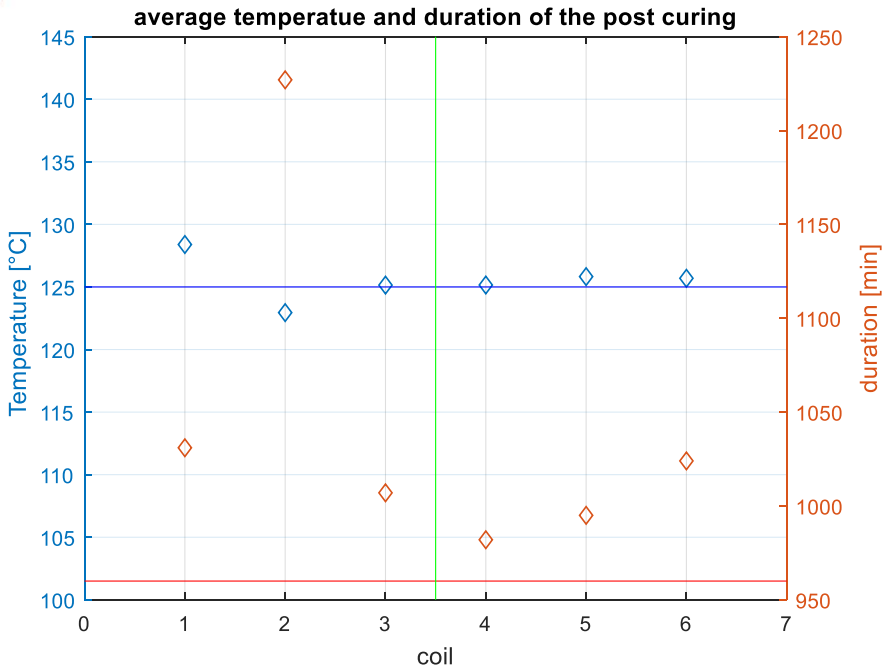
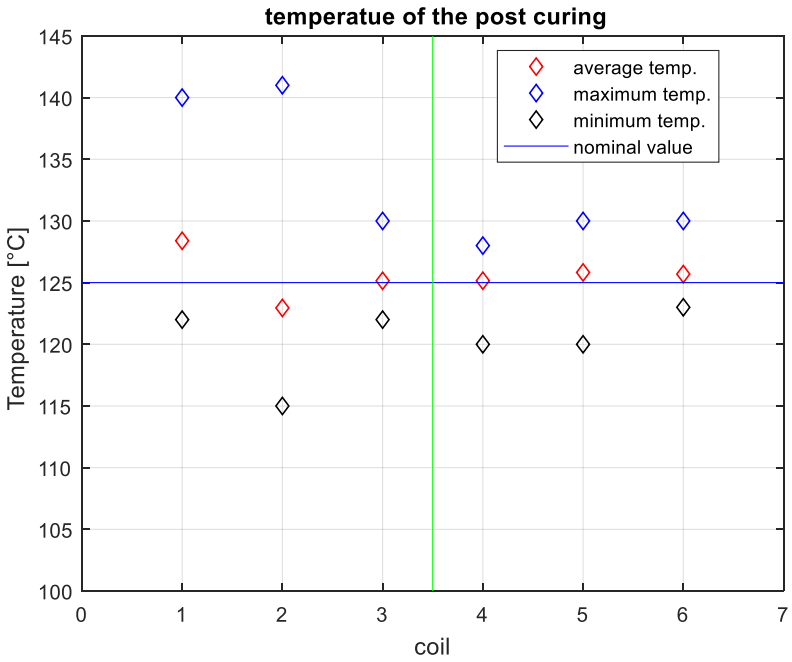
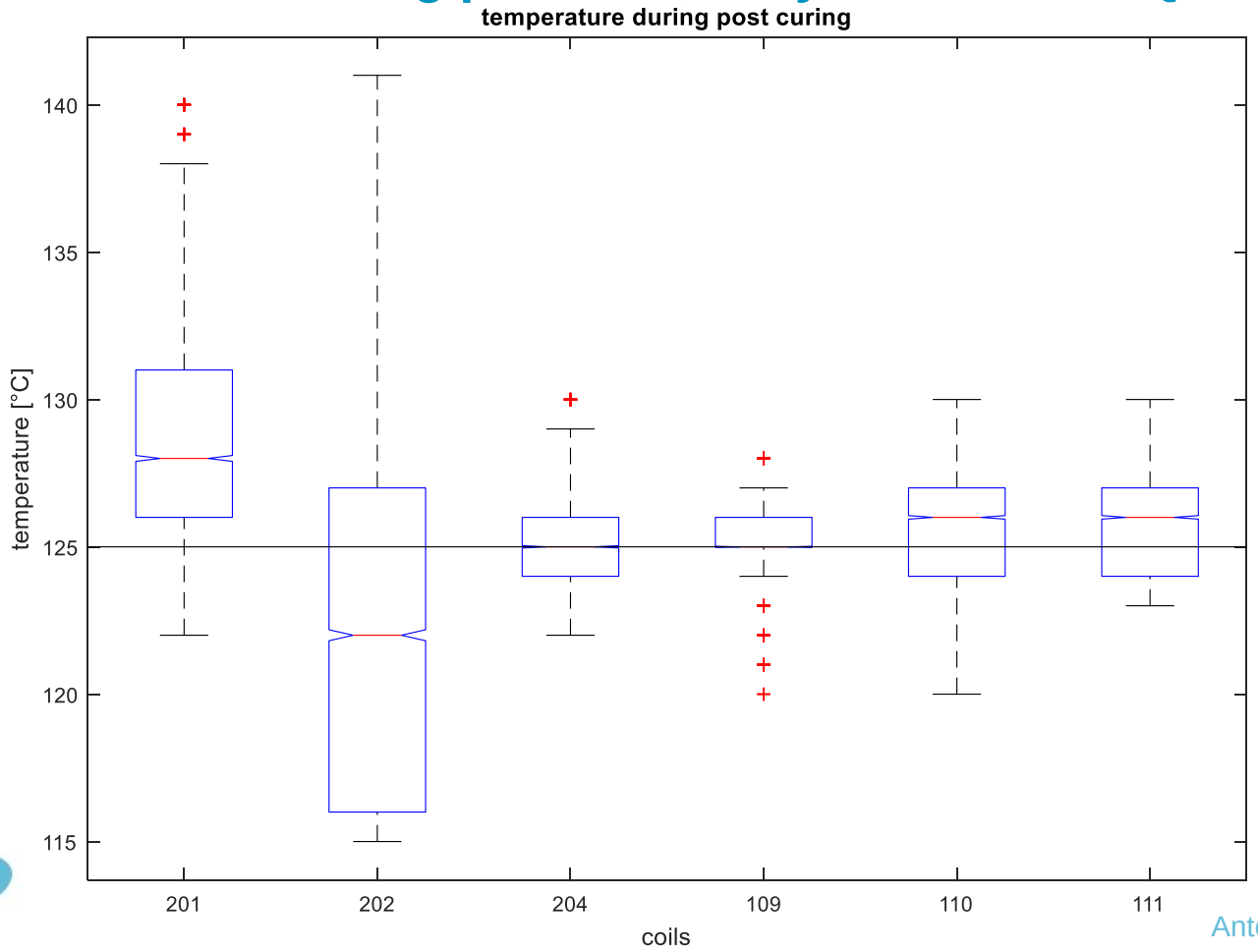
Post curing process ,analysis results MQXF





Post curing process ,analysis results MQXF



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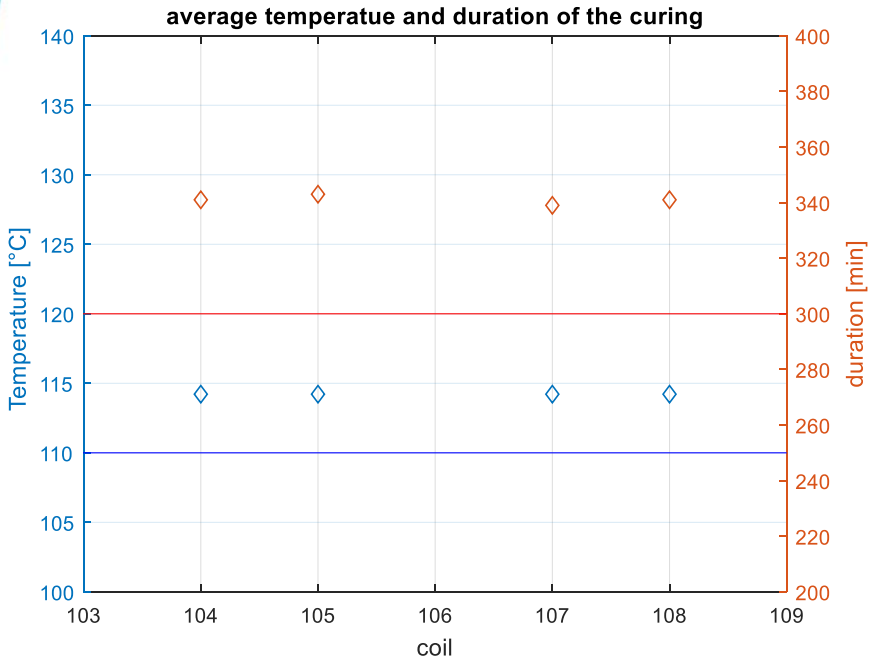
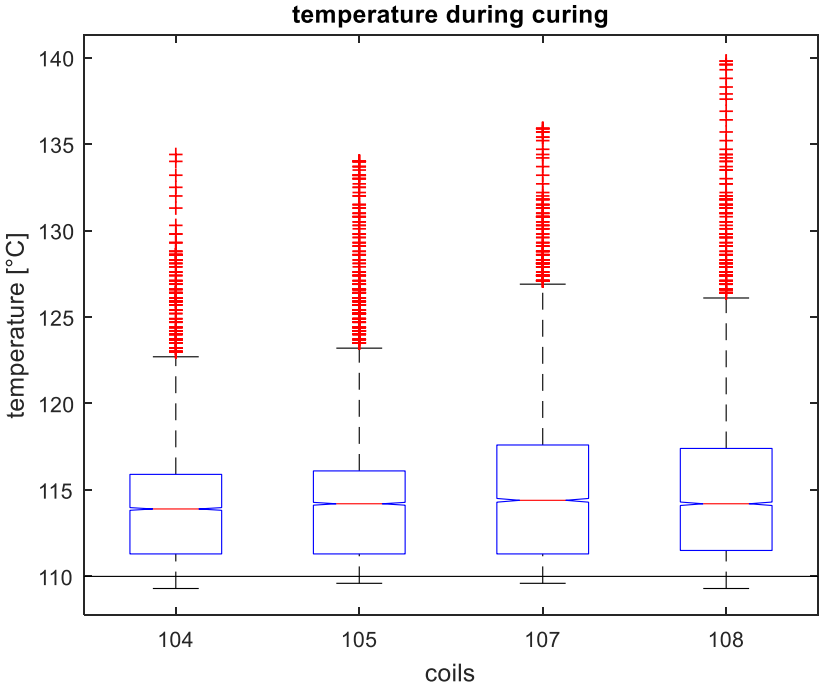
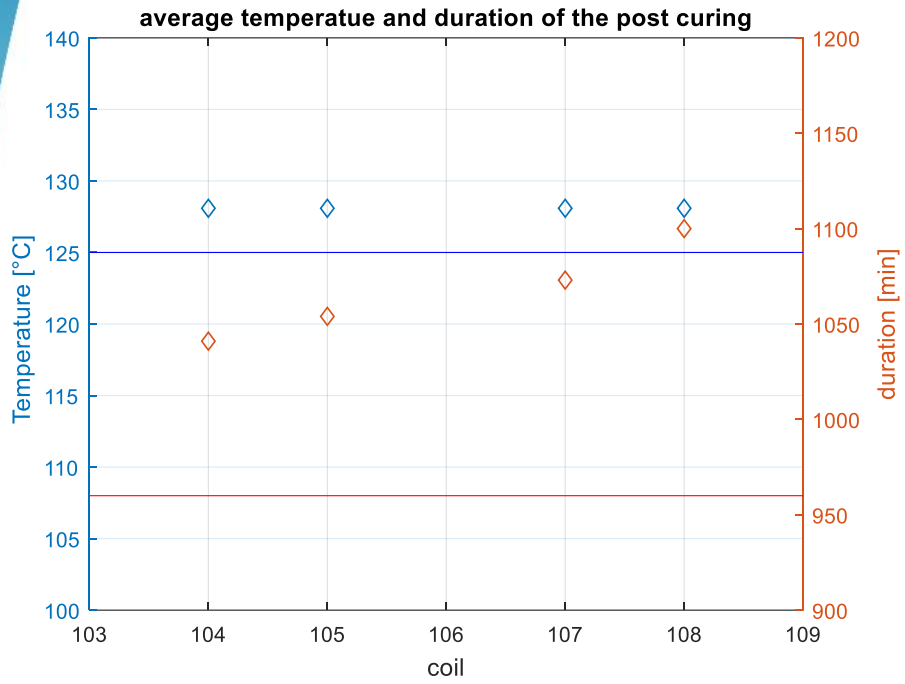
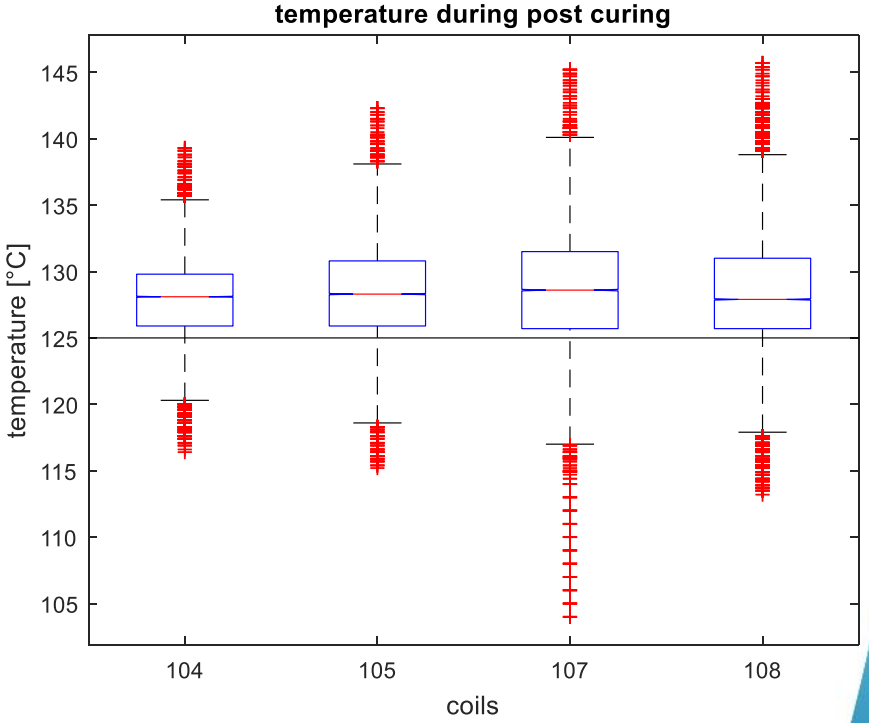
Curing process ,analysis results MQXF, coils from first prototype





Post curing process ,analysis results MQXF, coils from first prototype





Thank you for the attention

Spare slides

Notable information about 11T coils

- Coil 5 was cured when the injection machine was still the ELYTT one, from coil 6 the impregnation machine starts to be the CERN one.
- From coil 8 onwards start of the soaking practice
- Coil 8 is the first one cured after the change of the heating system from ELYTT to CERN; also there is a strange drop in the resin pressure after the start of the curing.
- Coil 8 & 9 due to the tuning of the PID have a strange ripple in the measurements of the thermocouples, <u>maybe there is an issue about the reliability of this data.</u>
- The duration of the curing and post curing phase of coil 9 is due to an error in the software.
- Coil 10 has a peculiar behavior of the resin pressure during the post curing phase, there is a fierce drop then the pressure is increasing instead of subsiding.

Notable information about 11T coils

- Coil 13 is the first coil for which we see a drop of pressure at the end of the soaking time(this will be present for each coil after 13),also the ramp to reach the curing plateau is composed of 2 sub-plateau necessary to slow down the heating (there was a changing in the software)
- Coil 15 has an additional plateau at 105 °C for unknown reason, also has a strange behavior of the resin pressure after the start of the curing with an abrupt decay (similar to coil 204 of MQXF)
- From coil 16 onward there is a small drop in pressure (resin pressure) after the start of the curing followed by an increase of the pressure.
- Coil 17 does not show the drop of pressure after the soaking or the start of the curing also the pressure never exceed 2.6 bar. It’s behavior is dissimilar from all of the other coils and probably is the ones that respect more the expectation.

Notable information about 11T coils

After having checked all of the procedure used during the impregnation of all of the coils studied in this work, seems not to be there any relevant changes that can explain the difference in the behavior of the values of the resin pressure, especially the occurrence of the two additional drop of pressure after the start of the heating ramp and at the start of the curing.

Results 11T

coil	Duration injection [min]	Duration curing [min]	Average temperature curing [°C]	Standard deviation curing [°C]	Max temperature curing [°C]	Min temperature curing [°C]	Duration post curing [min]	Average temperature post curing [°C]	Standard deviation post curing [°C]
5	154	320	110.68	1.3	117	109	1026	125.1	1.4
6	113	327	110.66	1.34	116	109	977	120.44	1.07
7	108	291	110.32	1.13	117	109	974	124.95	0.63
8	104	263	111.4	3.7	127	103	1059	127.22	3.65
9	126	781	110.33	4.32	126	101	1466	124.96	4.51
10	73	334	110.9	1.41	118	108	961	126.56	1.88
11	93	298	108.44	1.64	116	105	971	123.67	1.79
12	60	366	116.46	1.59	124	110	999	131.32	1.88
13	83	301	116.71	1.82	124	110	1004	131.69	2.12
14	86	306	116.91	1.71	124	110	1063	128.6	3
15	128	315	113.81	1.98	124	110	975	126.73	1.54
16	67	311	113.48	1.76	124	110	972	126.53	1.36

Results 11T

coil	Duration injection [min]	Duration curing [min]	Average temperature curing [°C]	Standard deviation curing [°C]	Max temperature curing [°C]	Min temperature curing [°C]	Duration post curing [min]	Average temperature post curing [°C]	Standard deviation post curing [°C]
17	72	309	113.92	1.65	123	110	977	126.71	1.24
18	75	310	114.05	1.7	124	110	982	126.83	1.32
19	70	313	113.72	1.7	124	110	964	126.58	1.33

coil	Max temperature post curing[°C]	Min temperature post curing[°C]	Duration soaking [min]	Average vacuum level tank injection [mbar]	Standard deviation injection [mbar]	Max vacuum level tank injection [mbar]	Min vacuum level tank injection [mbar]
5	128	115	1	1.84E-3	2.1E-4	2.21E-3	1.62E-3
6	123	117	1	3.72E-3	2.2E-3	7.8E-3	1.6E-3
7	127	123	0	2.17E-3	1.15E-05	2.2E-3	2.15E-3
8	132	109	227	2.27E-3	4.7E-05	2.4E-3	2.21E-3
9	132	112	187	1.74E-3	1.35E-05	1.77E-3	1.71E-3
10	130	115	225	2.59E-3	2.8E-4	3.39E-3	2.37E-3
11	126	113	182	1.79E-3	1.30E-05	1.8E-3	1.77E-3

Results 11T

coil	Max temperature post curing[°C]	Min temperature post curing[°C]	Duration soaking [min]	Average vacuum level tank injection [mbar]	Standard deviation injection [mbar]	Max vacuum level tank injection [mbar]	Min vacuum level tank injection [mbar]
12	134	123	187	2.75E-3	4.07E-05	2.85E-3	2.72E-3
13	135	122	211	2.15E-3	1.14E-05	2.17E-3	2.13E-3
14	135	114	210	2.62E-3	4.3E-4	3.68E-3	2.29E-3
15	130	121	211	1.9E-3	2.9E-05	1.96E-3	1.84E-3
16	129	106	221	1.7E-3	5E-06	1.71E-3	1.69E-3
17	129	123	218	10.5E-3	1.9E-3	1.45E-2	8.05E-3
18	130	123	210	1.7E-3	1.3E-05	1.73E-3	1.67E-3
19	129	123	179	1.9E-3	1.33E-05	1.97E-3	1.93E-3

Notable information about MQXF coils

- Coil 201 as stated before, along coil 202,8,9, has an issue due to the tuning of the PID, also there is a large time lap between the start of the pressurization and the heating of the mold. This time was used to do test on the resin; during the heating ramp due to a system bug the process was slowed down.
- Coil 202 as previously discussed has severe problem with the measurements of the thermocouples , the long time in which the tank is pressurized is <u>probably</u> due to tests on the resin, the abnormal drop in pressure before the heating ramp, has still unknown origin.
- Coil 203 was not analyzed because was cured with another thermal cycle with plateau at 80 °C and 85 °C

Notable information about MQXF coils

- Coil 204 shown a fierce decay in the value of the resin pressure that seems typical of the MQXF impregnation and differs from the one of the 11T. First with pressure drop after pressurization (this coil was impregnated after coil 13)
- Coil 109 does not have a soak and the drop of pressure after the pressurization , also the measurement of pressure are not reliable after the start of the curing (we are constantly at full-scale)
- Coil 111 has an abruptly drop of pressure after start of the curing and a sudden recovery.

Results MQXF

coil	Duration injection [min]	Duration soaking [min]	Duration curing [min]	Average temperature curing [°C]	Standard deviation curing [°C]	Max temperature curing [°C]	Min temperature curing [°C]	Duration post curing [min]	Average temperature post curing[°C]
201	170	158	477	115.3	3.5	138	109	1031	128.4
202	142	239	380	113.9	7.4	141	104	1227	122.9
204	138	220	324	112.5	1.7	124	110	1007	125.1
109	128	3	307	110.4	0.88	114	109	982	125.6
110	126	1	303	113	1.71	122	110	995	125.8
111	130	154	315	113.2	1.71	122	111	1024	125.7

Results MQXF

coil	Standard deviation post curing[°C]	Max temperature post curing[°C]	Min temperature post curing[°C]	Average vacuum level tank injection [mbar]	Standard deviation injection [mbar]	Max vacuum level tank injection [mbar]	Min vacuum level tank injection [mbar]
201	3.1	140	122	1.62E-03	3.58E-06	1.63E-03	1.61E-03
202	5.9	141	115	2.99E-03	9.16E-05	3.18E-03	2.82E-03
204	1.3	130	122	2.96E-03	8.16E-06	2.98E-03	2.94E-03
109	0.95	128	124	1.96E-03	2.15E-04	2.42E-03	1.81E-03
110	1.51	130	120	2.37E-3	3.79E-06	2.42E-03	2.4E-3
111	1.44	130	123	2.5E-3	1.83E-05	2.6E-3	2.5E-3

Results MQXF, first prototype

coil	Curing temperature [°C]	Post curing temperature [°C]	Curing duration [min]	Post curing duration [min]
104	114.2	128.08	341	1041
105	114.45	128.5	343	1054
107	114.97	128.85	339	1073
108	114.89	128.47	341	1100