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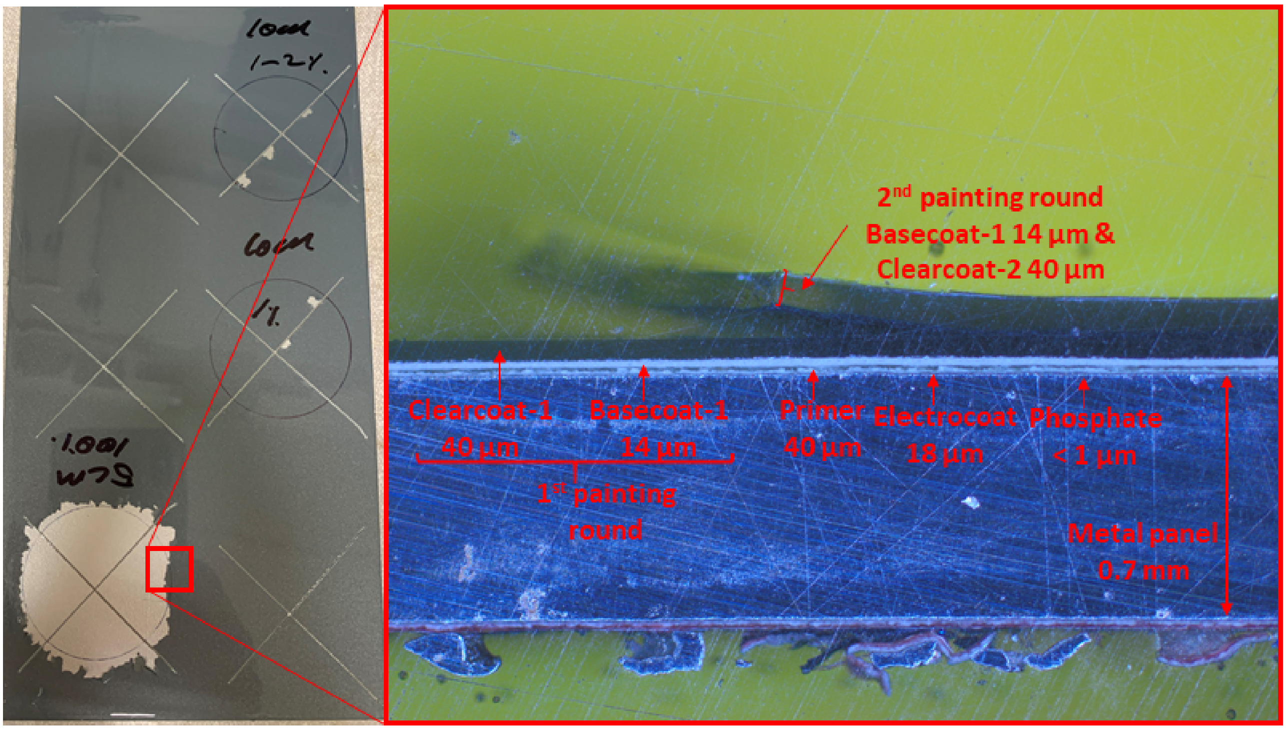

Evaluation of Factors Affecting Repaint Adhesion of Automotive Coating Systems

Master's Thesis in Materials Chemistry

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Department of Chemistry and Chemical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Conducted at Volvo Cars, Gothenburg, Sweden

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Cover image: An image of a test panel after a high pressure car wash jet test next to a microscope photography, of the crossection from the marked area, where the adhesion loss can be seen as delamination. The thickness of the different coatings are marked. Image made by the author of this document.

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Abstract

As it is today, when for some reason a car body needs to be repainted in the factory, either because of defects, or because an additional colour is to be applied, the body must go through a step called sanding. Sanding is a process where the top layer of the car body coating is being grinded. This is required in order to prepare a surface on which a required adhesion can be achieved. However, with sanding comes consequences. The process of sanding takes time and additional place on the conveyor belt, which in turn costs a lot of money and reduces the productivity. An additional negative side effect is that the sanding causes pollutant particles in the air in the factory, which leads to other car body coatings to get defects, which in turn leads to additional car bodies requiring repainting and sanding. Thus, a vicious circle is created. It is therefore desired to skip sanding. It is suspected that different factors and processes from the painting process have different influence on the repaint adhesion. In this work, the goal was to evaluate some of these factors influence on the repaint adhesion. This was done by applying coatings to test panels in a procedure simulating the steps in the factory. The repaint adhesion was evaluated by exposing the panels to a high pressure car wash jet. Examples from the factors evaluated are, curing time and temperature. Also, different coating materials and properties of the repainted surface, such as surface energy and hardness were among the factors evaluated. This work resulted in the findings that, among the factors evaluated, the most significant was those concerning the curing of the clear coat, namely, curing time and temperature. Also, indications, that suggest that the amount of rest-isocyanate on the repainted surface could have an influence on the repaint adhesion, was observed.

Keywords: Adhesion, repaint, automotive coating systems, car wash jet

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Firat Koca, Gothenburg, December 2020

Contents

List of Figures

List of Tables

1 Introduction

As it is today, when for some reason a car body needs to be repainted in the factory, either because of defects, or because an additional different colour is to be applied, the body must go through a process called sanding and repainting. This is the case for cars that for example has a roof in contrasting colour to the rest of the car body. In this process the top layer of the car body coating, the clear coat (CC), is being sanded. This is required in order to prepare a surface on which a required repaint adhesion can be achieved between the layer that is to be applied, the base coat (BC), and the CC. However, with sanding comes consequences, the sanding causes pollutant particles in the air in the factory which leads to other car body coatings to get defects. After the sanding, the car body has to run through the CC application process once more, which in turn costs a lot of money and reduces the productivity.

Because of the negative side effects of sanding, it is desirable to skip that step. However, that often means that the adhesion between the applied coating and the un-sanded car body can become too poor. A circumstance where the coating is put under severe conditions is when washed with a high pressure car wash. Therefore a standardised high pressure car wash jet test has been designed to test if the adhesion reaches the criteria, a test that acts a benchmark throughout the industry. The test procedure and details has been specified by Volvo Cars internal test standards VCS 1029,54719 [1].

In internal pre-studies conducted at Volvo Cars, it has been seen that for some combinations of clear coats and base coats, that has been applied without sanding, the adhesion has reached the adhesion criteria, as specified by Volvo Cars internal test standard VCS 1029,54719. However why those combinations reach that level, what the important factors affecting the adhesion is, and what other possible combinations of coatings that reaches an accepted level of adhesion is unknown and needs to be understood better. There are potentially several other factors that can influence the adhesion, such as the curing of the coatings with respect to temperature and time inside the oven and the properties of the surface with respect to surface energy and chemical composition. These, are among the factors whose influence on adhesion needs to be understood better and which this project will evaluate.

1.1 Purpose and Objective

The purpose of this work is to evaluate the factors influencing the repaint adhesion. This is desired to be able to in the future know what factors to manipulate to achieve a required repaint adhesion. And, to ideally, achieve such a high adhesion that sanding can be skipped.
The objective is to evaluate what factors in the process of coating application, at Volvo Cars, that has an influence, and to what extent, for achieving a desired adhesion for repainted surfaces. Furthermore, the objective is also to investigate if there exist any easily measurable property, that could tell if sanding could be skipped.

1.2 Limitations

Practically, the focus will initially be on finding out what process-factors that are a part of the Volvo Cars surface treatment process, that are the most significant for achieving a desired adhesion. Since there are several different coatings, and potentially several factors that could affect the adhesion, a lot of samples will be prepared, tested and analysed which is a time-consuming process. Therefore only a small selection of the coatings available at Volvo Cars will be analysed, due to the project is time limited, which also is the biggest limitation of the project.

2
Methods & Theory

Under this section, the relevant theory for the work together with the associated methods deployed are presented and described, respectively.

2.1 Litterature Studies

Throughout the whole project, litterature studies regarding usage of instruments and chemical compounds used were made continuously. *Google Scholar* was the most frequently used search engine but also *Scopus* was used.

2.2 General Procedure of Experimental work

The experimental procedure of the work can generally be described as, painting the test panels for the first round followed by a specified waiting time (TBR) after which measurements on the surface are conducted before finally repainting the panels in the second painting round. After a specified second waiting time, the panels are then subject to the car wash for adhesion evaluation. Note that no sanding is made prior to repainting. The overall procedure is visualised in the Figure 2.1 below.

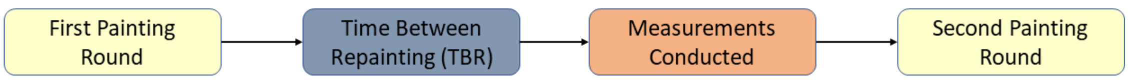

Figure 2.1: Simplified overview of experimental procedure

The first round, implies the application of the first base coat (BC-1), followed by an intermediate dryer oven (IDO-1) and then the first clear coat application (CC-1) followed by a curing oven (CO-1). The second round is a repetition of the first round, with the steps of BC-2 application followed by IDO-2 and then CC-2 application followed by CO-2. In this work, the influence of these processes on the repaint adhesion will be evaluated. In Figure 2.2 below an overview of the first painting round is presented.

Figure 2.2: Overview of a painting round

The panels used, are cold rolled steel, which are pre-treated on the factory line prior to the first painting round. The panels have been treated by applying the following, phosphate at a thickness of about 1 µm, electro coat with a thickness of 18 µm and primer at thickness of 40 µm. The phosphate and electro coat, are for protection against corrosion, while the primers main function is protection against stone chip.

After the second round of painting, the cross section of the panel can be illustrated as in Figure 2.3. This work specifically does not focus on the primer and layers below. For the whole work, those parts remained the same to be able to exclude any possible influence of those layers on the repaint adhesion.

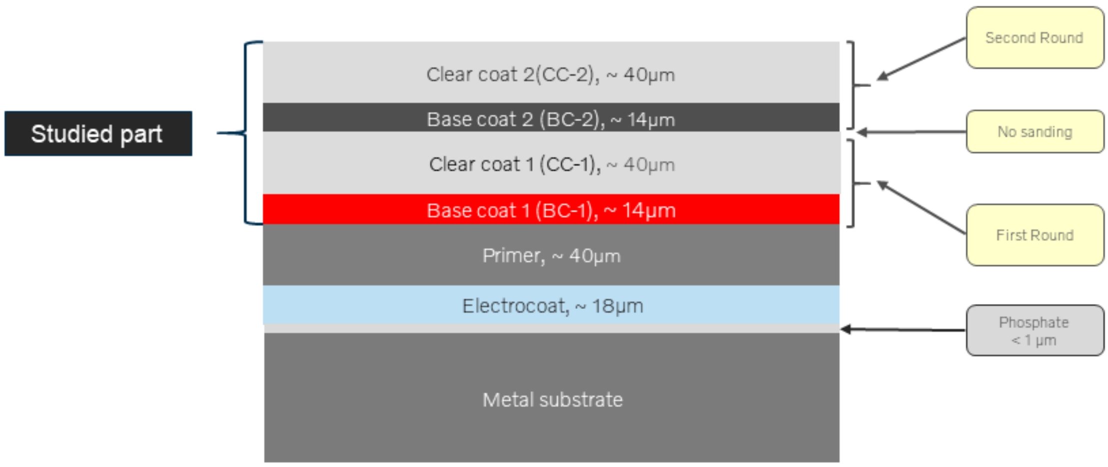

Figure 2.3: An illustration of the cross section of the panel after the second round of painting. The part studied in this work is the upper part, consisting of the first and second painting rounds.

The measurements were, as mentioned, conducted after the TBR i.e. just before re-painting in the second painting round. Firstly, the ATR-FTIR spectra of the panels were analysed. Secondly, the hardness of the surface was measured with the König Pendulum. Finally, the surface energy was measured.

This specific order of conducting the measurements was selected to make sure that the diiodomethane used for the surface energy measurements would not react with the surface and influence the chemical composition of the surface. Therefore, caution was taken not to spread the droplets over the surface when wiping them. Instead, they were removed by using the capillary force of the liquid by using the edge of a paper towel. How these methods were deployed are described in more detail below together with the associated theory.

2.3 Design of Experiments

For this work, it is the processes in Figure 2.1 and Figure 2.2, that are of interest. Because these are the processes that the manufacturer can manipulate in the paint shop, if it was to be found that a setting, different from today, is more favourable for the repaint adhesion. More specifically, the processes evaluated were curing holding-time (CO-1 time), curing object temperature (CO-1 temp.), intermediate dryer holding time (IDO-1 time), time between repainting (TBR). Comparative panels were also constructed to be able to compare the modified properties. These were Control panels where only standard settings were used, panels with a higher surface energy called Higher S.E. panels, and finally, panels that were sanded. Also non-process factors i.e. the materials were evaluated, these were two different clear coats from two different suppliers for the CC-1 layer, CCM-A and CCM-B. And two different base coats from two different suppliers for the BC-2 layer, BCM-A and BCM-B, see Table 2.1.

Table 2.1: Table over over the materials used

Material Factors
Base Coat Material-A (BCM-A)
Clear Coat Material-A (CCM-A)
Base Coat Material-B (BCM-B)
Clear Coat Material-B (CCM-B)

To evaluate the impact each factor had on the repaint adhesion, different settings of the factors had to be evaluated, therefore it was decided that two settings of each factor should be evaluated. For example, for the case of curing object temperature, the temperatures of 140°C and 160°C were evaluated. The selected settings of each factor were selected based on previous findings and what the original setting was at Volvo Cars paint shop process. For example the original setting for the object temperature for curing was 140°C. The selected settings were also selected with the desire that they should result in a clearly distinguishable adhesion result, in order to clearly see its influence on the repaint adhesion. The evaluated settings for each factor are presented in Table 2.2.

In order to isolate each factor's influence on the repaint adhesion, the factors were evaluated one by one, therefore standardised settings for each factor had to be selected, which would remain unchanged when not evaluated, for the example of object temperature of curing, the standard setting was set to be 150°C. All the standard settings for each factor are presented in the table below.

Another limitation of the experimental work was made by always keeping the material for BC-1 the same for all factors, mainly because of the assumption that the influence of BC-1 has on the repaint adhesion is probably not as significant.This was also because of the limited time, as varying that factor too would mean more experimental work. Meaning that the two different base coats were evaluated in BC-2.

Table 2.2: This table shows the standard settings together with the evaluated settings for each factor. Higher S.E. panels are panels that are modifired to have higher surface energy. For the factors Higher S.E, control, and sanding the standard settings were used for the process parameters.

Factors	**Standard Setting**	**Two Tested Settings**
TBR	24h	24h and 1h
CO-1 temp.	150°C	140°C and 160°C
CO-1 time	20 min	10 min and 30 min
ID-1 time.	1 min	1 min and 10 min
Comparative Factors		
Higher S.E. panels	standard settings used	
Sanded Panels	standard settings used	
Control Panels	standard settings used	

2.4 Construction of Tests

The tests were constructed so that one factor was evaluated at a time. For each combination of a factor, a doublet was prepared, resulting in a total of 16 panels per factor. A flow chart representing the procedure is presented below for one factor, the flow charts for the remaining factors can be found in the Appendix A.

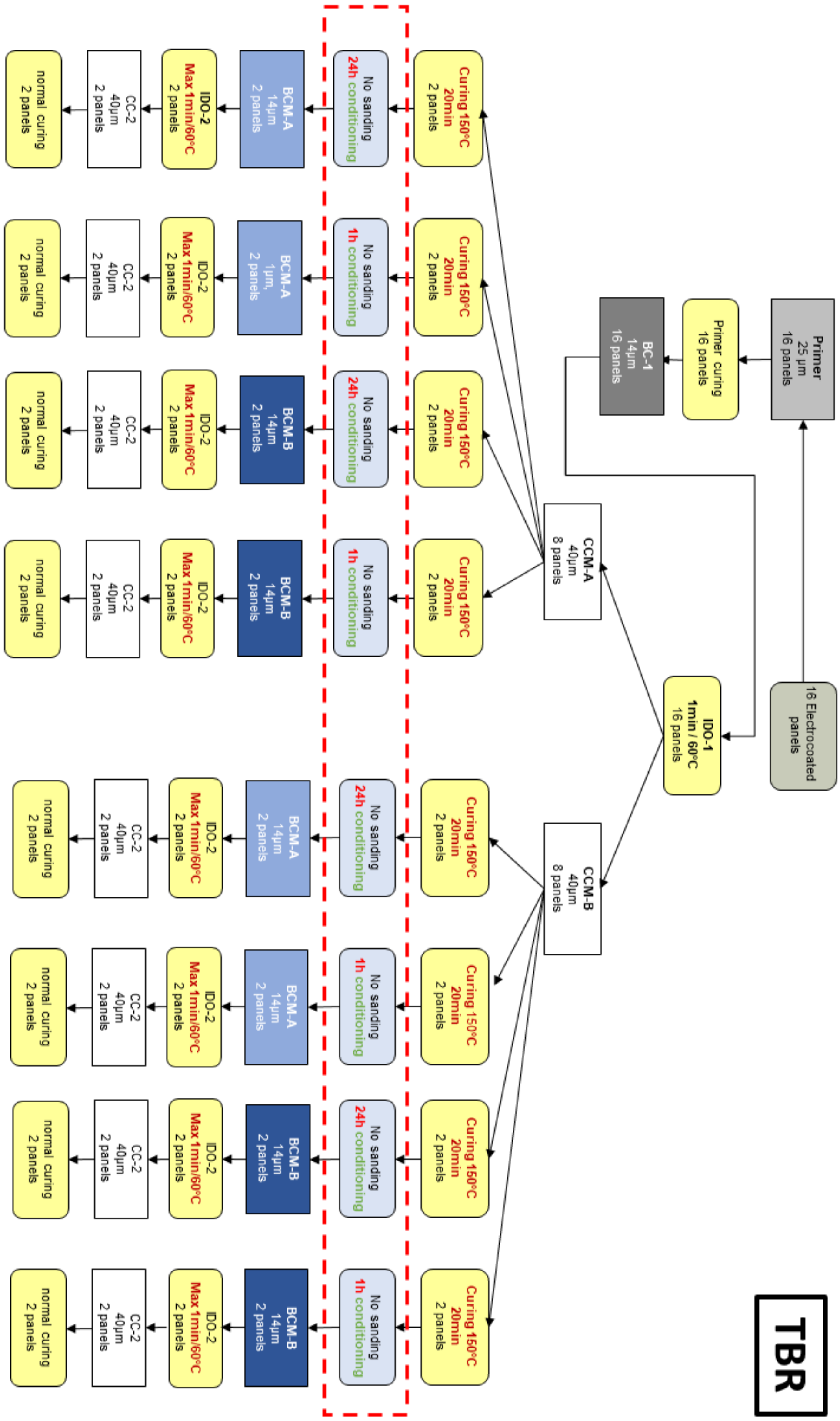

Figure 2.4: Flow chart for the preparation of 16 panels for the factor TBR. The factor-specific treatment occurs within the dotted red line, there, 8 of the panels will be conditioned for 1h while the remaining 8 panels are conditioned for 24h

2.5 Fundamental Polymer Coatings Kinetics

The clear coats used in this work forms polyurethane cross linked polymer networks when cured. In Figure 2.5 below, is the basic reaction of a polyurethane synthesis with an isocyanate and a polyol presented [2]. The factors evaluated in this work, especially curing time and curing temperature, could have an impact on how much this reaction will proceed. Depending on how much the reaction proceeds, there will be more or less of the reactants and the products, which in turn is expected to have an influence on the repaint adhesion [3]. The reactants and products of interest in this case are, the -NCO and -NHCO groups, respectively.

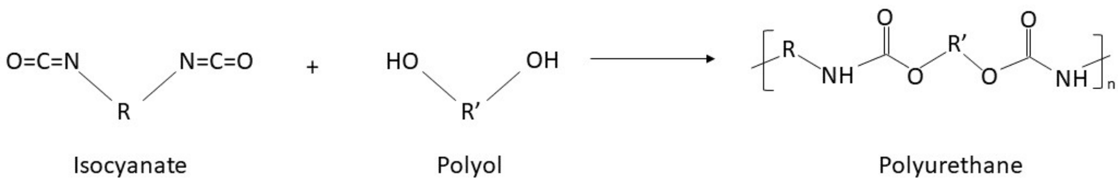

Figure 2.5: The reaction formula for the synthesis of polyurethane by isocyanate and polyol.

2.5.1 Polymer Adhesion

A polymer surface operates mainly through van der Waals and electrostatic interactions. Hydrogen intermolecular bonds may be generated within the polymer interface. A hydrogen bond is formed at very short distances between polymer molecules containing the functional groups -OH, -COOH, -NHCO, and other groups where the hydrogen atom is linked to the electronegative one [4].

2.5.2 Experimental

In this work, polyurethane based spray coating were used as clear coat, CC, and water borne coatings as base coat, BC. The preparation process of the CC included mixing of a clear coat base (CC-base) and a hardener. The mixing ratio was 1-part hardener and 3-parts CC-base, or 1:3. For each factor, a total of 200 g of clear coat was prepared by weighing 150 g CC-base to which 50 g of hardener was added. The mixing was stirred thoroughly, an effort was paid to not let it take more than 10 min from the mixing of the CC to its application, as the reaction starts as the hardener gets in contact with the CC-base. The BC required no preparation, since it was a one component product.

2.5.3 Clear Coat With Higher Surface Energy

Another factor that also was evaluated was to investigate the influence of surface energy on the repaint adhesion. This was done by modifying the clear coat by adding a silicon-based additive that increased the surface energy of the measured CC-1 surface. For this experiment, an amount of the additive, corresponding to 0.5 w.t.% of the CC-base was added to the clear coat mixture. The curing and application steps that followed was not changed.

2.5.4 Coating Application

Several factors of the coating application step may influence the result of the applied coating, such as the air pressure of the spraying gun, the distance between the nozzle of the gun and the coated panel, air-to-liquid mass flow ratio and the temperature and humidity of the environment where the coating takes place. The longer the distance is, the wider will the spread of particles be, i.e. the concentration of coating particles per unit area decreases with increasing distance, the longer time the liquid particles travels through air the more will the carrying solution evaporate into the air, and the concentration of the paint inside the liquid particles will increase.

2.5.5 Testing Method

The coatings applied to the test panels were applied by two conventional methods. Both involved pneumatic painting guns. One being a robotized application, with a higher accuracy and repeatability, and one manual method where the paint gun was controlled by hand. All the factors tested, except the Control factor, were applied by robot, due to practical limitations at the time. The equipment was carefully and thoroughly cleaned each time a different material was to be applied in order to prevent contamination. After a clear coat had been applied the equipment was cleaned by paint thinner. After the application of base coat, the instrument were cleaned with water. The coatings were applied at a distance of 20 cm between the nozzle and the panels, the objected thickness of the applied base coats was 14 µm and 40 µm for the clear coat, see Figure 2.3. The application of coatings took place in room temperature. Caution was taken to make the complete process of coatings application as similar as possible for all factors. It is worth mentioning that nowadays so called rotational bell painting is used in the paint shop in the factory.

2.6 Curing - Experimental

A thermometer was attached to the panels that had been applied with BC-1 and subsequently placed inside the intermediate dryer oven. The temperature of the oven was set at a temperature that was always 3°C above the factor specified object temperature. This was done to make sure that the panels reached the object temperature. The panels were kept in the oven until they had reached that temperature and then continued to be kept at that temperature for the factor specified time, called the holding time. They were then taken out to cool in room temperature. The temperature was logged once every minute while in the oven. See Figure 2.6

below showing the panels placed inside the IDO.

Figure 2.6: Figure a) to the left shows the panels placed inside the intermediate dryer oven and a thermometer attached to one of the top panels. Figure b) shows the same oven now closed together with a timer.

An almost identical process was carried out for the curing of the clear coat. After the application of clear coat, a thermometer was attached to one of the panels and subsequently placed inside the curing oven. For the same reason as for the previous oven, also this oven, was set at a temperature that was always 3°C above the factor specified object temperature. The panels were kept in the oven until they had reached that temperature and then continued to be kept at that temperature for the factor specified holding time. They were then taken out to cool in room temperature. The temperature was logged once every two minutes while in the oven. After cooling, they were placed in a panel holder and rested for either 1h or 24h, depending on the time between repainting specific for the tested factor. See Figure 2.7 below showing the panels placed inside the CO.

Figure 2.7: Figure a) to the left shows the panels placed inside the curing oven and a thermometer attached to one of the top panel. Figure b) shows the same oven now closed together with a timer.

The same process was repeated for when the panels were repainted. In Table 2.3, the object temperatures and holding-times used for each factor in each oven is presented.

The sanded factor are panels that were sanded to compare their result with the remaining factors. The control factor are panels that were prepared with standard settings only. After both painting rounds, the panels were kept in a constant room, where temperature and relative humidity were kept at 23°C ± 2°C and 50% ± 5%, respectively.

Table 2.3: In this table the object temperatures and holding-times for each factor is presented. The temperature T, is given in °C and the time t, is given in minutes.

Factors	IDO-1		CO-1		IDO-2		CC-2	
	t	T	t	T	t	T	t	T
1h vs. 24h	1	60	20	150	1	60	20	150
140°C vs. 160°C	1	60	20	140/160	1	60	20	150
10 min vs. 30 min	1	60	10/30	150	1	60	20	150
1 min vs. 10 min	1/10	60	20	150	1	60	20	150
Higher S.E.	1	60	20	150	1	60	20	150
Sanded	1	60	20	150	1	60	20	150
Control	1	60	20	150	1	60	20	150

2.7 Attenuated Total Reflectance - Fourier Transform Infrared Spectroscopy, ATR-FTIR

Fourier Transform Infrared Spectroscopy in combination with Attenuated Total Reflectance, is a technique that allows for the chemical composition of the analysed surface to be determined without further sample preparation. This is done by projecting a multiple frequency infra-red light and monitor how much of the light is absorbed. The absorbed light depends on the vibrations of the chemical bonds which in turn depends on their bonding energies which are different for each bonding. By knowing what frequencies are being absorbed, it is possible to tell what, and how much of a chemical compound there exists on the analysed surface. The absorption bands at 2270 cm^{-1} and at 1720 cm^{-1} are assigned to be -NCO and -NHCO groups [5, 6, 7].

2.7.1 Testing Method

The CC-1 layer of all panels was examined by FTIR. The equipment used was Perkin Elmer, Paragon 1000 (PerkinElmer, Inc., Waltham, MA, USA). Each panel was tested once. For consistency the area tested was chosen so that it was as close to the centre of the panel as possible as long as it was a spot that was free from, any by the eye, visible defect and/or dirt. The measurements were performed in room temperature in the spectral range of 450 - 4000 cm^{-1} with a resolution of 4 cm^{-1}. Before each factor was run, or at least once every hour, background was measured, and the instrument calibrated.

Figure 2.8: In this figure the ATR-FTIR instrument can be seen with a panel fastened and being measured

2.8 Surface Hardness

Surface hardness can be measured by a König Pendulum that embodies the principle that the oscillation amplitude of a pendulum that is in contact with a surface, through a bearing ball, decreases more rapidly the softer the surface. This because the bearings sinks more in a softer surface and thus increases the area on which the friction acts on. The result from this measurements is obtained in seconds and is a measure of the time that the amplitude of the oscillation falls from 6° to 3°.

2.8.1 Testing Method

The surface hardness was measured by BYK-Gardner - Pendulum Hardness Test König (BYK-Gardner GmbH, Wesel Germany). The panels were placed under the pendulum in such a position that the area of the panel that was in contact with the pendulum did not have any defects, damage or unevenness, in order to avoid them affecting the pendulums movement, and thereby the hardness result. The result was received in seconds. Each panel was measured once. An effort was made to conduct the measurement as close to the centre of the panel as possible for all panels to achieve maximum repeatability. The tests were performed according to ISO 1522.

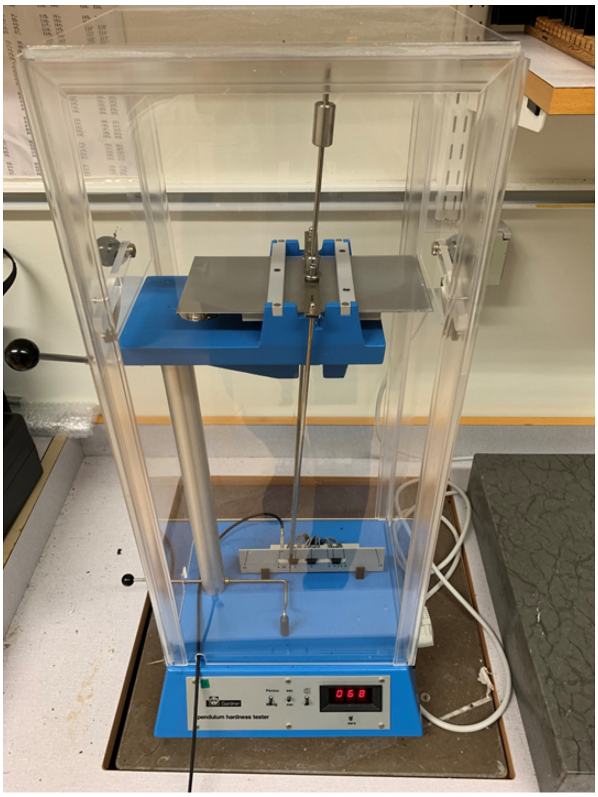

Figure 2.9: An image of the König Pendulum where the panel can be seen placed at the top. The panels is in contact with the bearings while the pendulum is oscillating.

2.9 Surface Energy

On a liquid droplet, placed on a solid surface, there are mainly three forces that act on the droplet, determining the wetting characteristics. These are the solid surface energy of the surface, γ_{SV} , the liquid surface energy, γ_{LV} and the solid/liquid interfacial energy, γ_{SL}. These forces are most common expressed in the unit mN/m. The relation between the forces is given by the Young's equation, see equation 2.1 below. Where, θ is the angle between solid and liquid droplet edge. Depending on the surface energy of a surface, that surface will have a certain wetting characteristic. The higher the surface energy the higher the wetting [8].

$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} cos\theta \tag{2.1}$$

A schematic representation of the forces acting on a liquid droplet placed on a surface can be seen in Figure 2.10 below.

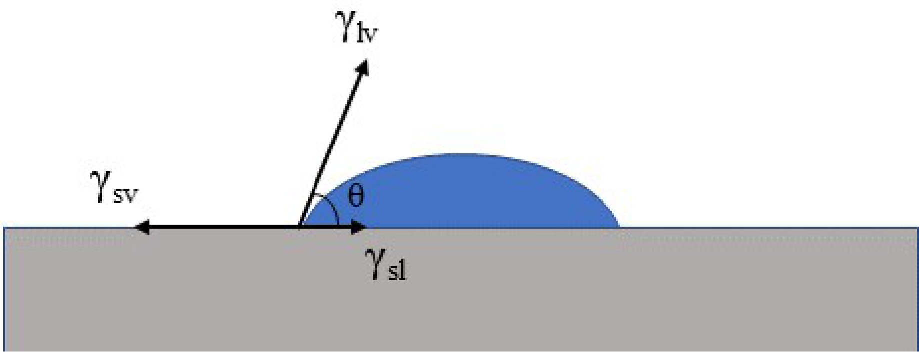

Figure 2.10: A schematic representation of the forces acting on a liquid droplet placed on a surface.

2.9.1 Testing Method

Surface energy of each panel was measured by Krüss- Mobile Surface Analyzer (KRÜSS GmbH, Germany). All the measurements was carried out with the "Double Sessile Drop" function of the instrument, meaning that the measurements were made using two liquids, water and diiodomethane. For each panel, three measurements were conducted. The measurements were made at the top, middle and bottom of the panel. An average from the results of these three measurements were obtained from the instrument as a representative surface energy value of the CC-1. Caution was taken not to include any extreme outlier, if this happened which was rare, that measurement was cancelled and another measurement was done close to the same area on the panel.

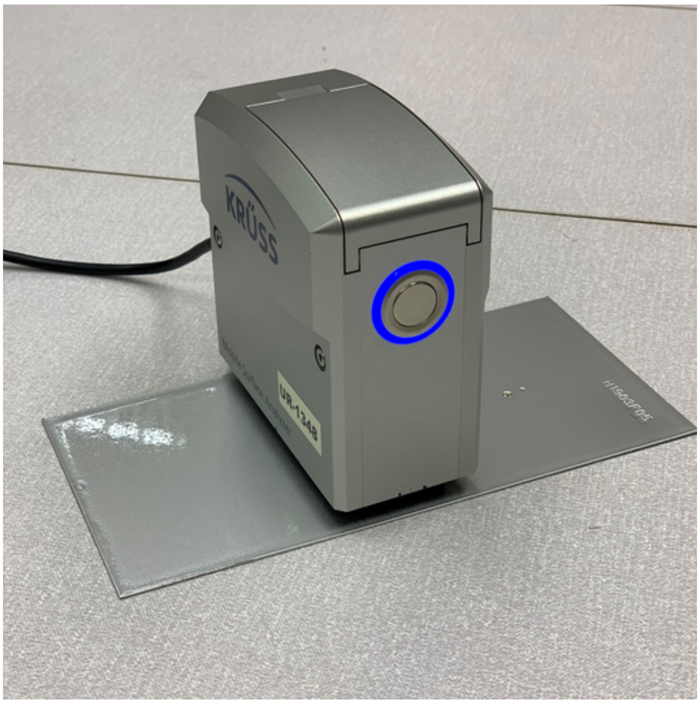

Figure 2.11: In this figure, the surface energy measurement being conducted can be seen, where the first of three measurements just has been made (see the two drops behind the MSA) and the second measurement is being carried out

In Figure 2.12 below, is a screenshot from the surface energy measurement from the computer program of the MSA where the two droplets can be seen.

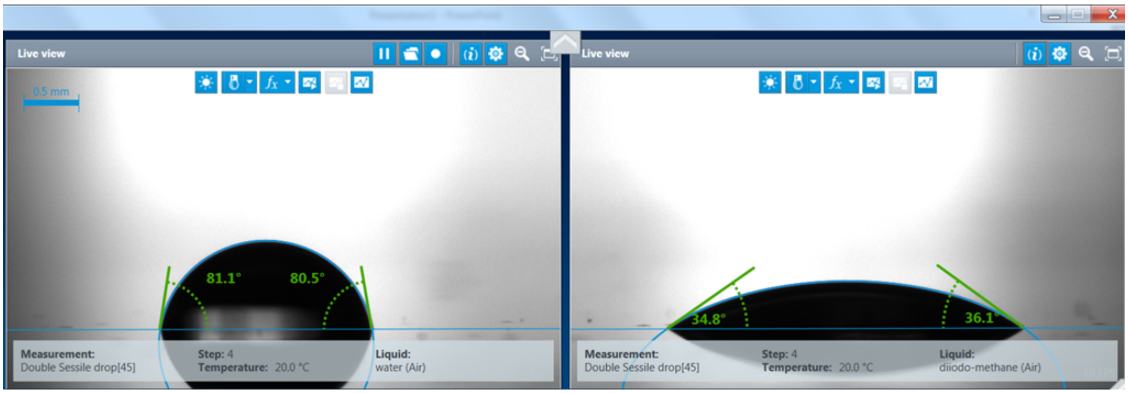

Figure 2.12: In this figure a screenshot from the surface energy measurement from the computer program of the MSA is presented where the two droplets

2.10 High Pressure Car Wash Jet

The high pressure car wash jet, HPCWJ, is a standard benchmark test throughout the industry to evaluate coating adhesion. The test simulates a car with a scratch being washed with a high pressure car wash jet. Depending on how much the adhesion loss is, it is considered as a pass or fail by the manufacturer.

2.10.1 Testing Method

The test was conducted according to the Volvo Cars standard VCS 1029,54719. Before the panels could be tested with the HPCWJ, the panels were prepared by etching six crosses on them. The crosses were made by a knife tool which had a knife width of 0.5 mm. The force applied was such that the knife would reach the base metal plate. Since a total of four crosses was used, there were always two extra left in case of tests had to be re-run.

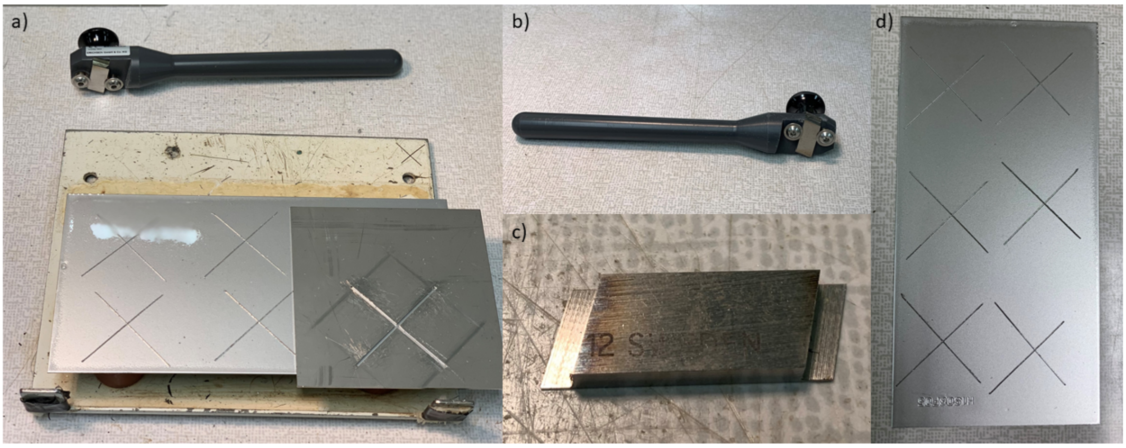

Figure 2.13: This is a summarising figure where an overview of the etching process can be seen in image a). The etching tool is showed in image b). The 0.5 mm wide cutting knife is seen in image c). The panel with the 6 crosses etched is showed in image d).

The panels were evaluated in a high pressure car wash jet test rig developed by NIFAB. The test panels were fastened in a pocket-like holder that only exposes one crossed area to the water jet. The standard parameters that always were kept the same for all panels, and which are the minimum setting values that Volvo Cars requires for a test to be considered as a pass, were; that the water jet was sweeping the test area for 30 seconds, at a rate of 1 sweep per second with a water temperature of 50°C, water pressure of 120 bar. The test was performed at two different distances between the nozzle and the test panel, 5 cm and 10 cm. Visual details of the HPCWJ is presented in the two Figures 2.14 and 2.15 below.

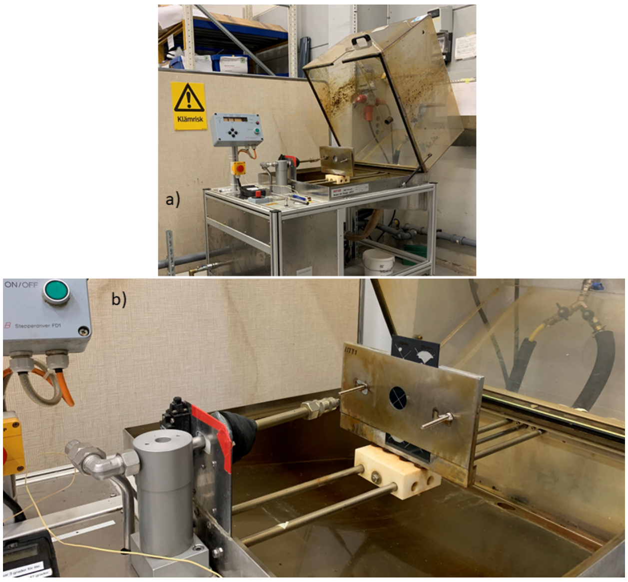

Figure 2.14: In fiugre a) an overview of the car wash instrument is presented. In figure b) the panel can be seen fastened in the pocket-like holder prior to the start of the test.

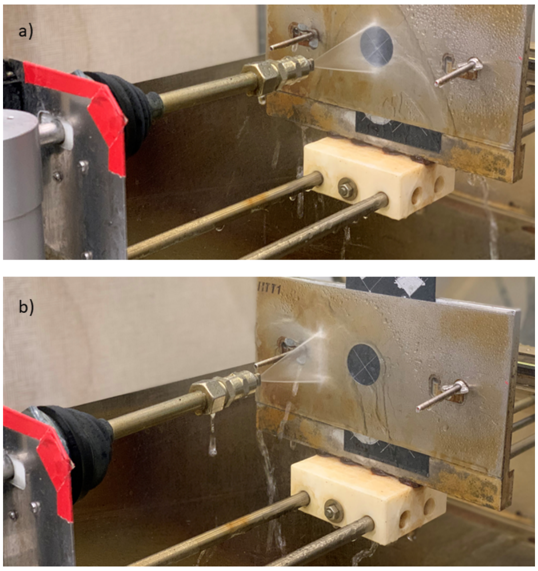

Figure 2.15: In this figure the test is ongoing. The picture in figure a) was taken when the nozzle was precisely on the test area. The picture in figure b) was taken when the nozzle is just outside the test area.

The resulting adhesion loss from the test was estimated by eye with an accuracy of two percent units. Because each panel was tested at least two times per distance, resulting in a panel being tested four times for two different distances, this meant that for each factor tested there were 16 panels x 4 crosses i.e. 64 data points collected. Below is an image of a panel after the car wash test presented.

Figure 2.16: A panel after the car was test. The adhesion loss can clearly be seen on two of the crosses, which were tested at 5 cm while there are barely any adhesion loss for the crosses marked with a circle, tested at 10 cm.

2.11 Data Handling Statistical Analysis

Data was collected and logged from the following parts of the experiments, temperatures in oven over time, ATR-FTIR spectra, hardness, surface energy and percentage of coating loss from the car wash. The graphs were constructed in Excel. An average value was calculated for the doublet pair panels for surface energy, hardness and coating loss.

To be able to tell whether the obtained data is significant, statistical methods are used. Statistical methods provides means that show if there exist a significant variance between the analysed factors and combinations. All data is assumed to have a Gaussian distribution and that the variance between the samples is similar.

The mean plus the standard deviation can be used to investigate if any significant difference exist between two data sets [9]. Which is also the main statistical method used in this work. The mean and standard deviation was calculated by the two following equations:
Mean:

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{2.2}$$

Standard deviation:

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{2.3}$$

where N represents the sample size.

3
Results

Under this section, the results from the ATR-FTIR-, hardness-, surface energy measurements, and HPCWJ tests are presented an commented, separately. To avoid unnecessary repetition, graphs and raw data will be inserted in appendix. The Flow Charts of the preparation of the panels for each factor can be found in Appendix A. The raw data of which the graphs under this section are constructed from can be found in Appendix B. The ATR-FTIR spectra can be found in Appendix C.

3.1 ATR-FTIR

Under this section, the results from the ATR-FTIR measurements are presented and commented. While all results are commented, only one spectrum from one factor, CO-1 time, will be presented here as an illustrating example, to avoid repetition, remaining spectra can be found in Appendix C.

Evaluating the spectra of factor CO-1 time, for the clear coat material B (CCM-B), at the absorption bands 2270 cm-1 and at 1720 cm-1 which corresponds to the -NCO and -NHCO groups respectively, a trend can be observed. For the panels that were cured for 10 min in the curing oven CO-1, it can be observed that the absorbance at the 2270 cm-1 band is higher than the absorbance for the 30 min panels, this is true for all panels except one, panel 7, see Figure 3.1. In Figure 3.1 below, is the complete scanned spectrum presented.

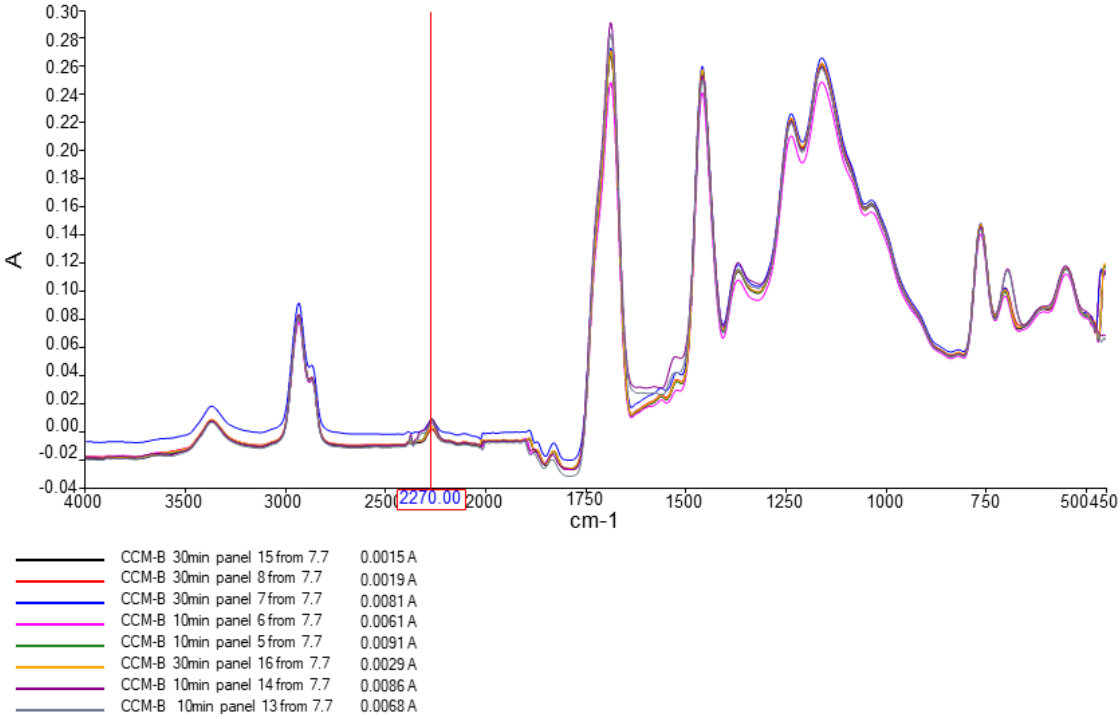

Figure 3.1: Complete ATR-FTIR spectra for 8 panels of the CO-1 time factor for the clear coat material B (CCM-B). Four 10 minute-panels and four 30 minute-panels. The red-line cursor is placed at the 2270 cm-1 band.

In Figure 3.2 below, is a zoomed in/cut section of the above spectrum around the 2270 cm-1 band presented, where the differences in absorbance between the 10 min and 30 min panels can be seen.

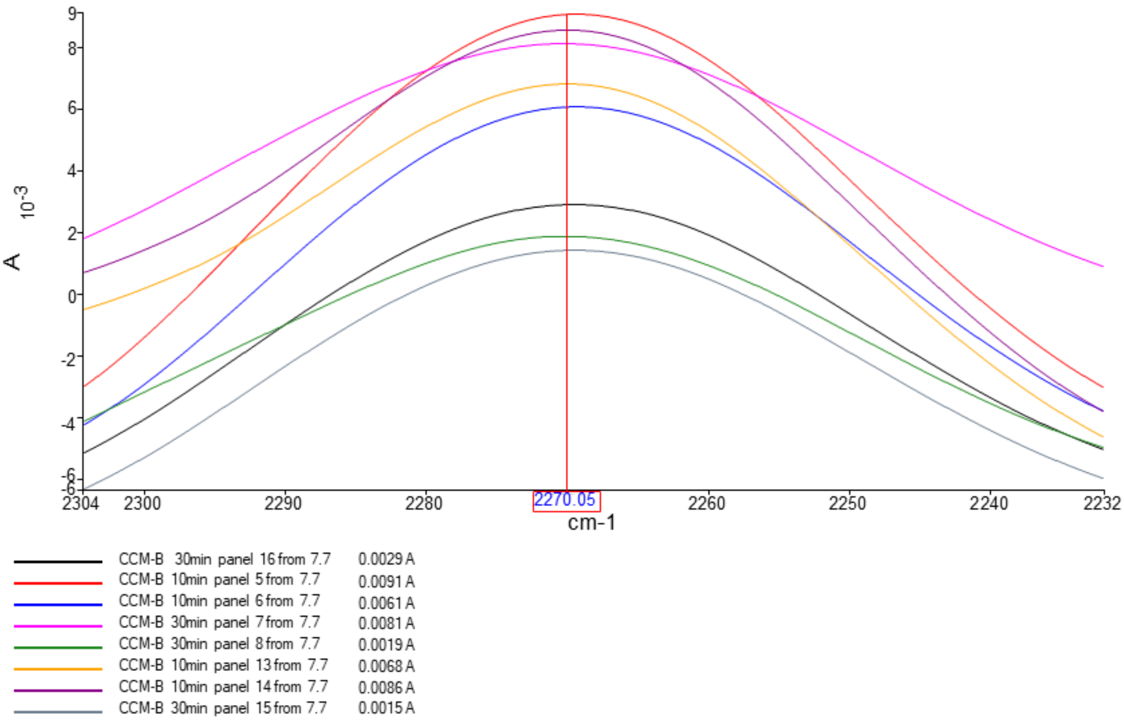

Figure 3.2: Zoomed in/cut out ATR-FTIR spectrum for 8 panels of the CO-1 time factor for the clear coat material B (CCM-B). Four 10 min-panels and four 30 min-panels. The red-line cursor is placed at the 2270 cm-1 band.

For the factor CO-1 temperature, where the curing temperature was evaluated with the two temperature settings of 140°C and 160°C, a trend similar to above was observed. The panels that were cured at a higher temperature had a higher absorbance at the 1720 cm-1 band. The difference is not as obvious at the 2270 cm-1 band. See spectrum attached in Appendix C.

For the panels that had a modified clear coat to obtain a higher surface energy, no significant difference could be observed in the evaluated bands at 1720 cm-1 and 2270 cm-1, see attached spectra in appendix.

The control panels that were processed with standard settings showed no significant difference in the spectra, all of the panels had a similar spectrum, see attached spectrum in appendix.

The panels that were sanded prior to repainting were also processed with standard settings, and neither did they show any significant difference in the spectrum, all of the panels had a similar spectrum, see attached spectrum in appendix.

3.2 Surface Energy

Under this section, the surface energy results from the surface energy measurement, sorted for each factor and each combination of each factor, is presented and analysed, respectively. Results from only one factor, CC-1 time, is presented, the data for the remaining factors can be found in Appendix B. Observations from all surface energy results for all factors and combinations are commented, however.

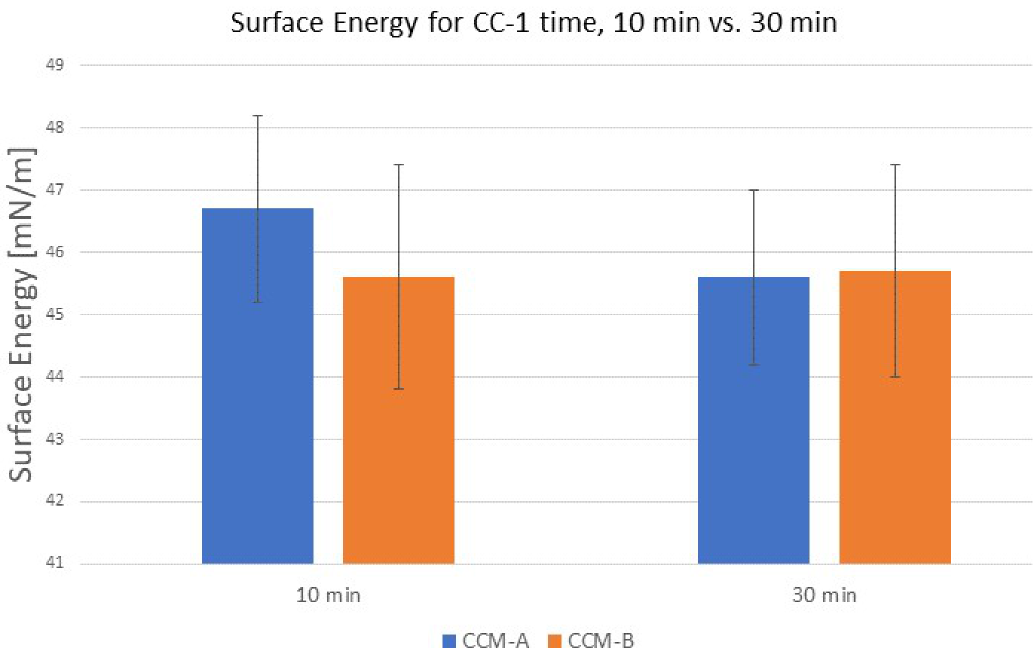

Figure 3.3: Surface Energy results for the factor CC-1 time. The result is presented as the average together with the standard deviation.

For all factors except CC-1 time, CCM-B resulted in significantly higher surface energy. When evaluating the different settings within the factors for the same clear coat material, only two significant differences are observed. One where 1 min holding-time for the factor IDO-1 time resulted in higher surface energy for the CC-1 material, CCM-A. And another where the significant difference was observed for factor TBR, where 1h between repainting resulted in higher surface energy for the CC-1 material CCM-A.

The panels with a modified clear coat had reached a surface energy that in average was 7 % higher than the surface energy of the control panels.

The sanded panels, resulted in a surface energy that in average was 10 % lower than surface energy of the control panels.

3.3 Hardness

Under this section, the hardness measurement results obtained from the König Pendulum measurements of the CC-1, sorted for factor and combination within each factor, is presented and analysed, respectively.

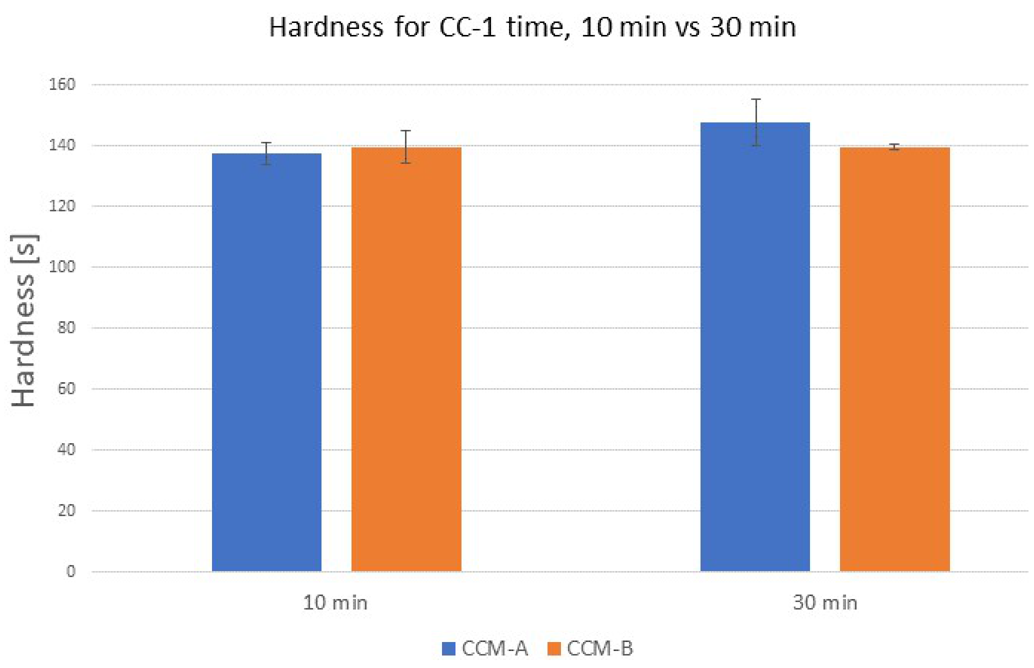

Figure 3.4: Hardness measurement results for the factor CC-1 time.

Observations made for the measurement of hardness for all factors can be summarized as, although significant differences in hardness could be observed, no trend of the differences could be observed between the factors, combinations or settings, i.e. the differences were random.

3.4 High Pressure Car Wash Jet Test

Under this section, the adhesion loss results from the HPCWJ test, sorted for each factor and each combination of the different materials, is presented and commented, respectively. The results are presented in a bar chart, where the percentage of adhesion loss, of the area subject to the HPCWJ, is shown as the average value of the 4 data points for the specific combination together with the respective standard deviation.

3.4.1 Curing Oven Time, CO-1 time

The results of the impact the factor CO-1 had on repaint adhesion is presented in the Figure 3.5 below. Evaluating the results, it is possible to observe that the curing time of 10 minutes resulted in better repaint adhesion for all combinations.

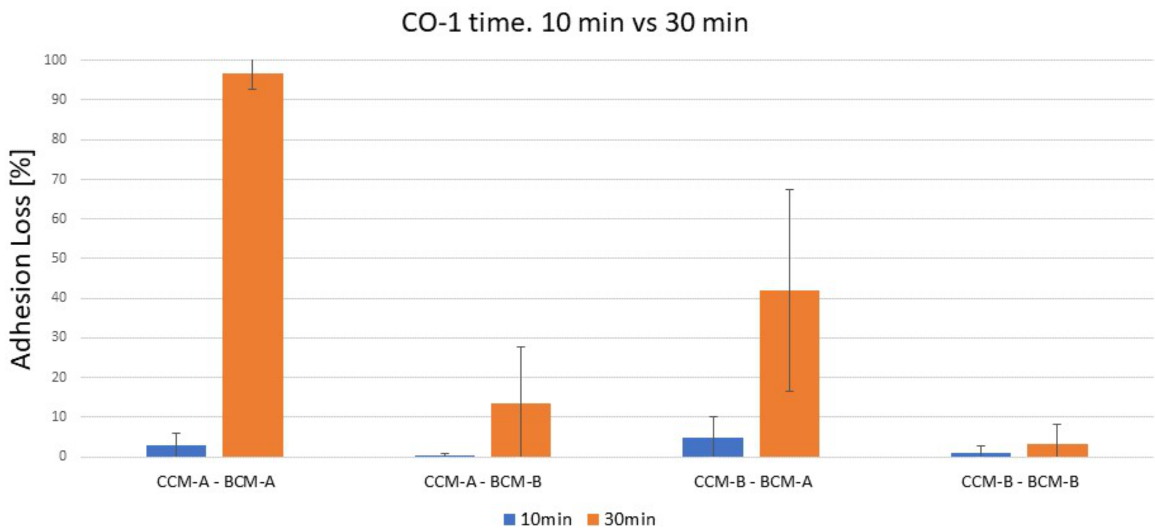

Figure 3.5: Adhesion loss results for the factor CO-1 time for all combinations are given as the average and standard deviation. In this figure, only the tests conducted at 10 cm in the HPCWJ are shown.

3.4.2 Curing Oven Temperature, CO-1 temperature

The evaluated curing holding temperatures of 140°C and 160°C for the CO-1 resulted in a significantly different repaint adhesion for all combinations. The curing temperature of 140°C yielded in better repaint adhesion for all combinations.

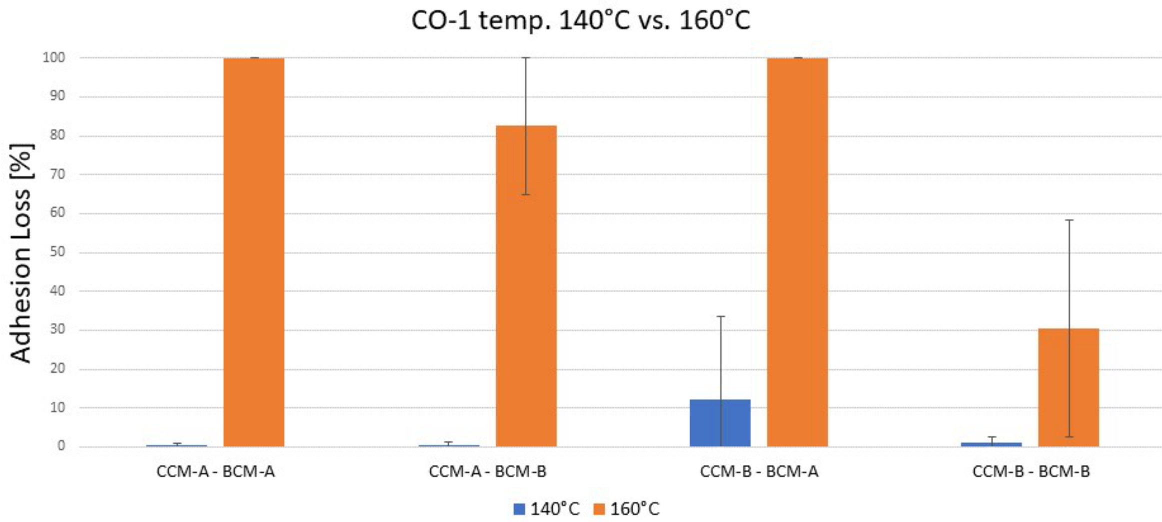

Figure 3.6: Adhesion loss results for the factor CO-1 temperature for all combinations are given as the average and standard deviation. In this figure, only the tests conducted at 10 cm in the HPCWJ are shown.

3.4.3 Time Between Repainting, TBR

When examining the adhesion loss results of the factor Time Between Repainting, no significantly clear trend can be observed for all combinations. However, for the combination CCM-A - BCM-B, it can be observed that, 24 h time between repainting results in better repaint adhesion than 1 h.

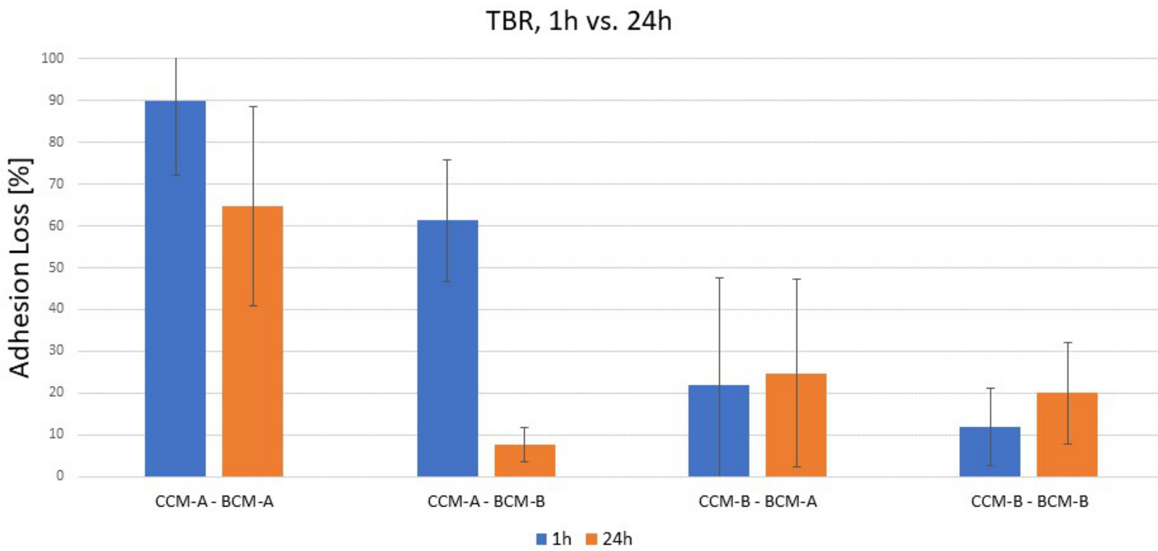

Figure 3.7: Adhesion loss results for the factor TBR for all combinations are given as the average and standard deviation. In this figure, only the tests conducted at 10 cm in the HPCWJ are shown.

3.4.4 Intermediate Dryer Time, IDO-1 time

For the factor Intermediate Dryer Time, where the holding-time of 1 min and 10 min inside the IDO-1 were tested, no significant difference can be observed for all the combinations. Thus, it is not possible to say that the tested holding times have a significant role in the repaint adhesion for all cases. The combinations where the factor IDO-1 time resulted in a significantly different repaint adhesion were CCM-A-BCM-B at 10 cm, CCM-B-BCM-A at 5 cm and CCM-B-BCM-B at 5 cm. For these combinations, the 1 min holding-time yielded in better repaint adhesion.

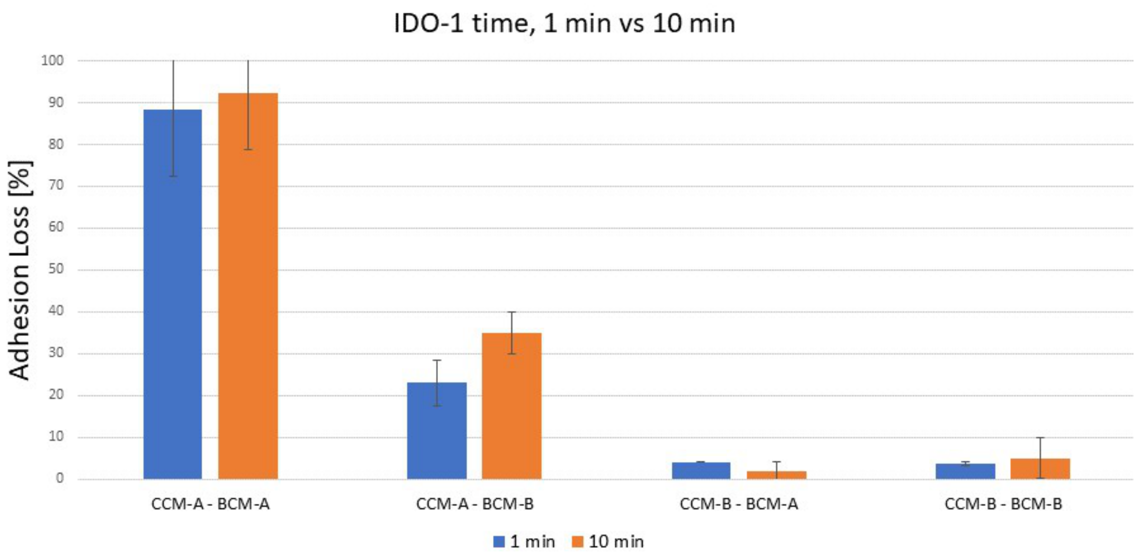

Figure 3.8: Adhesion loss results for the factor IDO-1 time for all combinations are given as the average and standard deviation. In this figure, only the tests conducted at 10 cm in the HPCWJ are shown.

3.4.5 Clear Coat Material A vs. B as Clear Coat Layer 1

The observations made under this section is based on the results presented in tables in Appendix B.

No unambiguous difference in repaint adhesion can be observed between the two evaluated clear coat materials that are true for all or majority of the factors, settings and combinations. However, when evaluating the results combination for combination significant differences in the repaint adhesion can be observed.

For the factor 10 min CC-1 time, CCM-A resulted in better repaint adhesion for the combinations 5CM-BCM-A and 10CM-BCM-B, for 30 min CC-1 time the CCM-B, gave better repaint adhesion for 10CM-BCM-A and also 10CM-BCM-B, for the remaining combinations within this factor it was not possible to observe any significant differences.

For the factor CC-1 temperature, CCM-A was found to be more favorable than CCM-B for the combinations 5CM-BCM-A and 10CM-BCM-A, while CCM-B was more favorable for the combination 5CM-BCM-B for 140°C CC-1 temperature. Within the same factor, CCM-B was more favorable for the combination 10cm-BCM-B at 160C, the remaining combinations showed no significant difference.

For the factor TBR, CCM-B resulted in more favorable adhesion for the combinations 10cm-BCM-A and 10cm-BCM-B for 1 h between repainting. For 24 h between repainting, no significant difference in repaint adhesion could be observed, remaining combinations of this factor showed no significant difference between the panels.

Finally for the factor IDO-1 time, CCM-B resulted in better repaint adhesion than CCM-A for all combinations for 1 min holding time. The same could not be observed for the holding time 10 min where CCM-B only resulted in better repaint adhesion for the combinations 10cm-BCM-A and 10cm-BCM-B.

3.4.6 Base Coat Material A vs. B as Base Coat Layer 2

The observations made under this section is based on the results presented in tables in Appendix B.

Examining the repaint adhesion results sorted after BC-1, no general trend could be observed that is true for all factors, settings and combinations within the factors. When examining the results as in the case with the factor CC-1 significant differences can be observed.

For the factor CC-1 time, BCM-B was found to be more favorable for repaint adhesion for the combination 5cm-CCM-B for 10 min curing time. For 30 min curing time, BCM-B was found to be more favorable for both combinations 10cm-CCM-A and 10cm-CCM-B, remaining combinations showed no significant difference within the factor.

For the factor CC-1 temperature, BCM-B resulted in better repaint adhesion for the combination 5cm-CCM-B at 140°C curing temperature. BCM-B also shows better adhesion result for 10cm-CCM-B for 160C. Remaining combinations showed no significant difference within the factor.

For the factor TBR, the only significant result in repaint adhesion was observed for BCM-B for the combination 10cm-CCM-A for 24 h between repainting. Remaining combinations showed no significant difference within the factor.

For the factor IDO-1 time BCM-B resulted in better repaint adhesion for 10cm-CCM-A for 1min holding-time. Evaluating the results of 10 min holding-time it was observed that BCM-B performed better for 10cm-CCM-A. Remaining combinations showed no significant difference within the factor.

4 Discussion

Below follows a summarizing discussion of the results, possible sources of errors, an analysis of social and ethical aspects and also future outlooks of possible studies.

4.1 Analysis of Results

The purpose of this work was to evaluate the influence of the factors on the repaint adhesion, which is what this discussion will focus on. More specifically, the analysis of the result focuses on the correlation of the measured properties and the results from the high pressure car wash jet test.

The factor that had the biggest impact on the repaint adhesion was the CO-1 temperature factor, as seen when comparing Figures 3.5, 3.6, 3.7 and 3.8. The panels that were cured at 160°C had a inferior repaint adhesion compared to the panels cured at 140°C. This could be because of, at such a high curing temperature, the degree of polymerization reaches such a level making the surface inert, hindering it to interact or bond to the applied BC-2 layer. More specifically, it could be because of not enough electrostatic interactions are allowed to be formed.

The influence the curing time in the CO-1 oven, i.e. factor CO-1 time, had on the repaint adhesion, is similar to the influence of CO-1 temperature. Although, the difference was not as big between the settings 10 min and 30 min, as between 140°C and 160°C. In this case, the lower curing time of 10 min performed better, by resulting in a stronger repaint adhesion. This further strengthens the reasoning previously made, that the surface can become inert, preventing it from proper interaction with the applied BC-2 layer.

For both the factors CO-1 time and CO-1 temperature, the panels that were cured for a shorter time or lower temperature, were found to have more isocyanate on the first clear coat layer, through the ATR-FTIR measurements. This also, could be an explanation to why those panels had better repaint adhesion. The isocyanate could react and cross link with the on top applied base coat 2 layer, BC-2. Thus creating a stronger connection to the next layer and therefore a better repaint adhesion.

When looking at the influence the -NHCO group had on the repaint adhesion, the panels of the factors CO-1 time and CO-1 temperature did not show any trend, both had similar amount of -NHCO. This means that -NHCO could not be related to the repaint adhesion. To be able to say if this is the case or not, further studies are required.

Time between repainting, TBR, resulted in no significant influence on the repaint adhesion. However, it does not necessarily translate into that it has no significance on the repaint adhesion at all. After curing, the compounds in the clear coat surface are much less mobile, therefore any interaction between them will be extremely slow, especially compared to when in the oven for example. Therefore, a significant influence might be observed if a longer time was evaluated.

For the factor intermediate dryer time, IDO-1 time, no significant influence of the evaluated settings on the repaint adhesion was observed. Considering that this layer, BC-1, is two layers below the surface that is exposed to the water jet from the car wash test, it is not especially surprising. Because the adhesion that actually is evaluated by the HPCWJ test, is the adhesion between the layers CC-1 and BC-2. This means that, in order for BC-1 to influence the repaint adhesion, it must first influence the properties of the layer above, CC-1, which is much thicker and made up of strong covalent bonds, which in turn must influence the repaint adhesion between CC-1 and BC-2. Therefore, BC-1 has a relatively small impact. Another explanation could also be that the influence the IDO-1 curing has on the BC-1 is relatively small. The influence of the IDO time, would probably be greater if evaluated on the BC-2 layer, as it is directly involved in the evaluated repaint adhesion.

To evaluate if surface energy had an impact on the repaint adhesion, an additive was added to the clear coat to increase the surface energy, and then compare it to the original clear coat with no additive. The reason this method had to be deployed was because the alternative would be to use a clear coat that happens to have a higher surface energy. The problem with that would be that there would be too many unknown variables between the different CC's and no conclusion could be made regarding the surface energy's influence on repaint adhesion.

As the BC-2 is waterborne, a higher surface energy of the CC-1 was expected to result in higher wetting and thereby higher repaint adhesion. As the higher wetting would increase the contact between the two layers. Especially considering that it is the adhesion between those layers that is tested in the car wash test. However, comparing the results from the car wash test, of the panels with higher surface energy and the control panel with "normal" surface energy, no significant difference in the repaint adhesion was observed. This could mean that the wetting characteristics of the CC-1 layer might not be amongst the significant factors for repaint adhesion, contrary to the hypothesis. However, too little data exists to be able to make such a conclusion. If the surface energy was increased more than the average 7 % a different result could have been obtained. This must therefore be studied further.

The hardness results followed no pattern and could not be correlated to the repaint adhesion results. It was thought of as a possibility that a clear coat with higher degree of curing would have both a harder surface and a worse repaint adhesion. Which is why this was thought as a possible way to characterize the clear coat surface.

No clear significant difference between the evaluated coating materials were observed that were true for all factors, settings, or combinations. However clear coat material B, generally performed better that clear coat material A, for most of the factors and combinations. The significant differences between the materials that were observed between the combinations, must therefore be studied further.

4.2 Evaluation of Error Sources

The main error sources are believed to lie in the experimental part of the work, which includes several manual steps. One of these steps could be the preparing of the two component clear coat. Even though it was aimed to not let it take more than 10 minutes from mixing the clear coat to its application on the panels, occasionally this happened anyways. Therefore, this could be a potential source of experimental error.Since, as the mixing starts, the reaction starts, which also means that the hardening starts.

Analysing the results, several factors or combinations were observed to have a significant influence on the repaint adhesion or any of the other measured properties. However, some of these did not follow a trend and did not reoccur for a different material combination for example. Therefore, these are considered to be a coincidence, that would probably not be observed again if the tests were rerun or a larger test sample was used.

As previously mentioned, the coatings of the control factor was applied manually, however this seem not to have resulted in any significantly different results. This can be see when comparing with the panels of the factor Higher S.E. with normal surface energy, which had exactly the same settings during painting.

For the sanded panels, a surface energy lower than the Control panels was observed. This was rather unexpected because an increased wetting is expected as the surface is made rougher. This is phenomenon that can not be explained at this stage. Therefore it is believed to be an error that could be due to an experimental reason. However the sanded panels were not the focal point of this work, they were merely used for comparison.

4.3 Social and Ethical Aspects

One of the areas that the repainting process without sanding will affect, is the environment. By skipping sanding the air will be less polluted and microplastics will not be released into the nature. In the factory this will lead to fewer car bodies getting defects due to particles in the air, which will in turn decrease the repainting it self. Better air quality will also result in a better working environment for the workers as the air will be cleaner. Finally, there is a great economic potential in skipping sanding. Because, the repainting is now done quicker by removing a step that requires man power. The workers would also skip the non ergonomic process of sanding.

4.4 Future Outlook

As further work, more factors could be studied, as the thickness of the coatings. However, I think that most of the focus should be on the factors originating from the curing and especially curing oven 1. Also, the hypothesis regarding the possible influence of isocyante resins on the repaint adhesion should be studied. Furthermore, the sample size of the tests could be better designed to be able to use stronger statistical methods.

5

Conclusion

The conclusion of this work is that the most significant parameters influencing the repaint adhesion are the curing-process factors of an automotive paint system application process. The curing oven temperature and and curing oven time of the first clear coat layer is found to be the most significant processes. No relation was observed between repaint adhesion and surface energy or hardness measurements, therefore the decision to skip sanding cannot be made based on these properties. No significant influence of the coating materials on the repaint adhesion could be observed.

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A

Appendix A

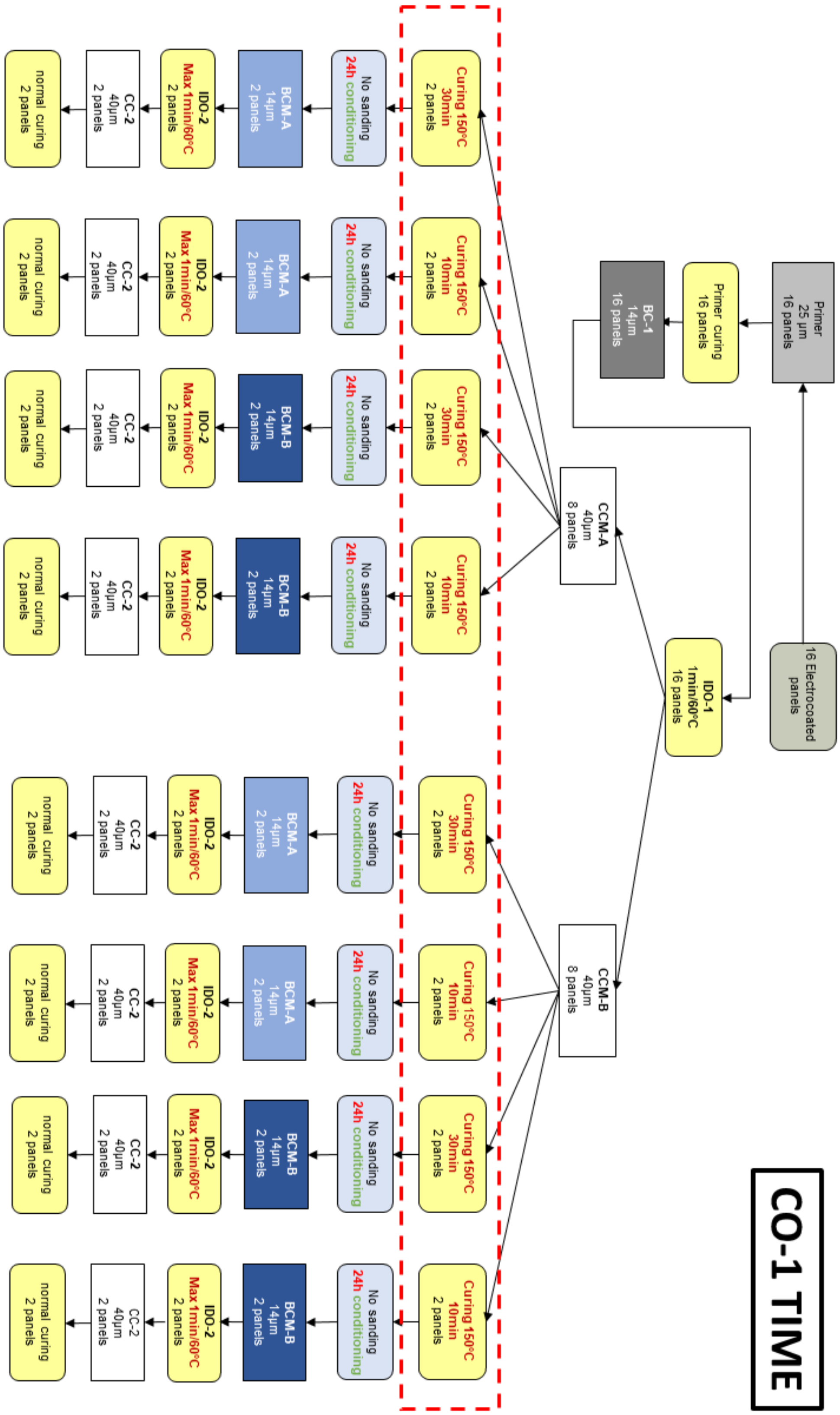


Figure A.1: Flow chart for the preparation of 16 panels for the factor TBR. The factor-specific treatment occurs within the dotted red line, there, 8 of the panels will be conditioned for 1h while the remaining 8 panels are conditioned for 24h

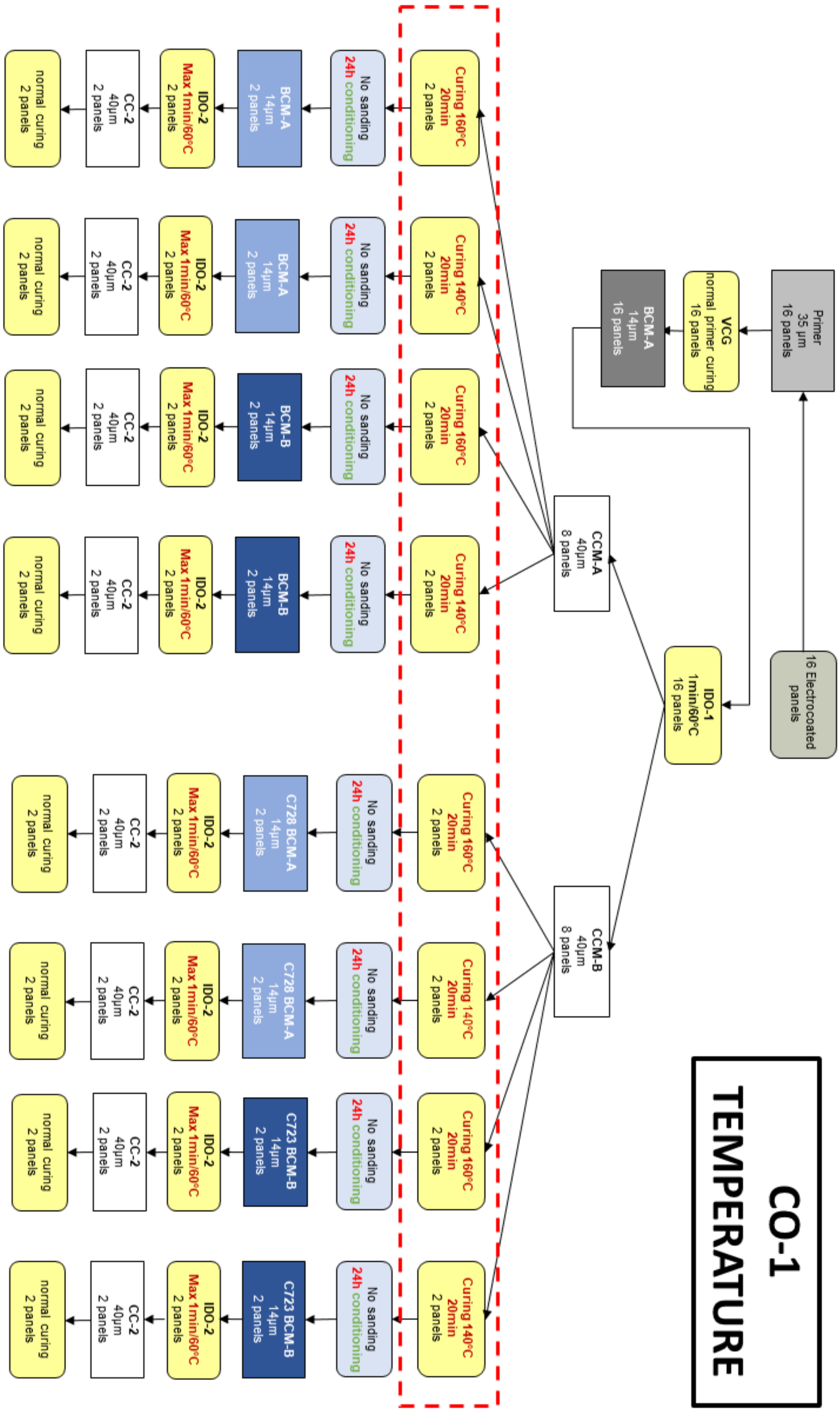


Figure A.2: Flow chart for the preparation of 16 panels for the factor TBR. The factor-specific treatment occurs within the dotted red line, there, 8 of the panels will be conditioned for 1h while the remaining 8 panels are conditioned for 24h

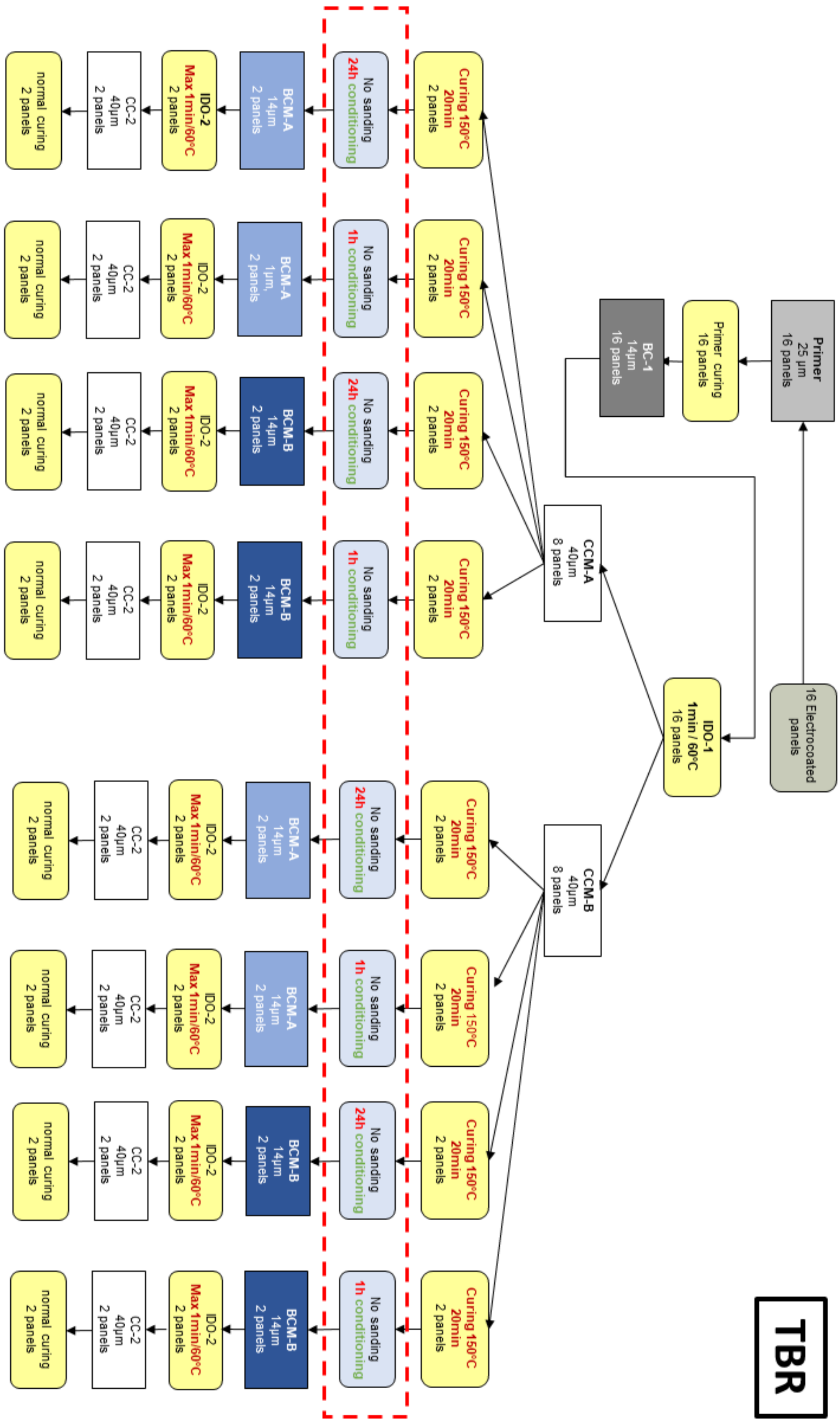


Figure A.3: Flow chart for the preparation of 16 panels for the factor TBR. The factor-specific treatment occurs within the dotted red line, there, 8 of the panels will be conditioned for 1h while the remaining 8 panels are conditioned for 24h

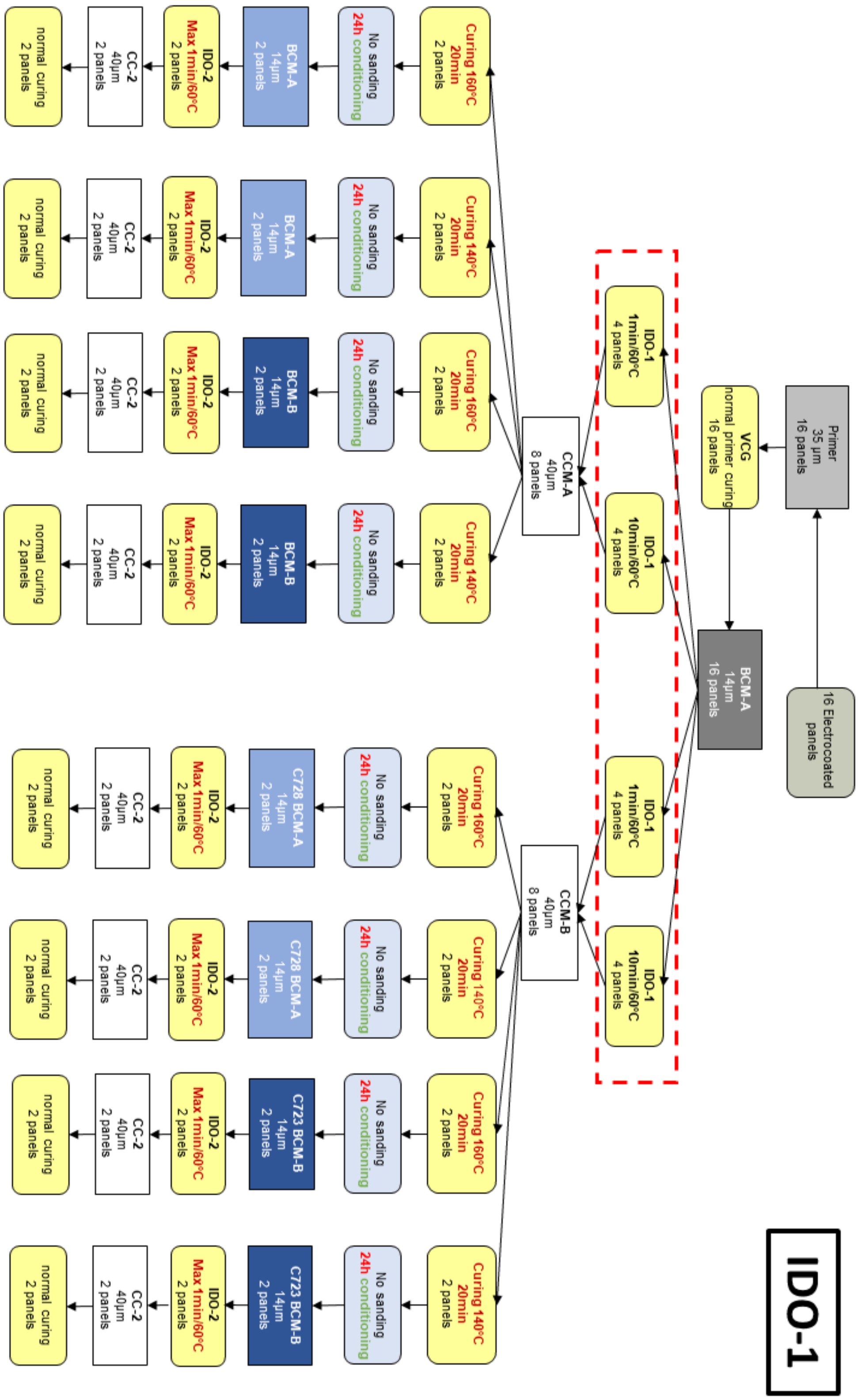


Figure A.4: Flow chart for the preparation of 16 panels for the factor TBR. The factor-specific treatment occurs within the dotted red line, there, 8 of the panels will be conditioned for 1h while the remaining 8 panels are conditioned for 24h

B

Appendix B

CO-1 Time height																
BC-2	723								728							
CC-1	AX				HR				AX				HR			
CO-1 time	10		30		10		30		10		30		10		30	
Panel nr.	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Hardness [s]	140	134	154	140	127	144	140	138	142	134	151	146	140	147	140	140
SE [mN/m]	44.1	47.83	47.32	47.5	44.89	48	47.37	47.43	47.26	47.57	43.74	43.87	44.4	45.02	44.28	43.74
Loss @ 5 cm [%]	90	54-56	88-89	100	41-43	100	100	100	56-58	88-90	100	100	72-74	72-74	100	97-98
Loss @ 10 cm [%]	3-4	2-3	6-7	27	0	6-7	100	10-12	0	3-4	95-96 3-4	2-3	0	98-99	23-25	

Table B.1: Surface energy results for both CC-1 materials for each factor.

Combinations	CC-1 time		CC-1 temp.		TBR		IDO-1 time	
	10 min	30 min	140°C	160°C	1 h	24 h	1 min	10 min
SE-CCM-A [mN/m]	46,7 ± 1,5	45,6 ± 1,8	46,7 ± 0,8	45,5 ± 1,3	45,4 ± 0,3	43,5 ± 0,3	45,2 ± 0,3	43,7 ± 0,5
SE-CCM-B [mN/m]	45,6 ± 1,4	45,7 ± 1,7	49,1 ± 1,2	47,3 ± 0,9	47,8 ± 0,8	47,1 ± 0,3	47,8 ± 0,1	46,7 ± 1,0

Table B.2: Hardness result for both CC-1 materials for each factor.

	CC-1 time		CC-1 temp.		TBR		IDO-1 time	
Combinations	10 min	30 min	140°C	160°C	1 h	24 h	1 min	10 min
CCM-A [s]	137,5 ± 3,6	147,8 ± 5,3	117 ± 3,9	131 ± 3,8	142,75 ± 7,2	129 ± 4,3	100,0 ± 4,9	92,8 ± 9,8
CCM-B [s]	139,5 ± 7,6	139,5 ± 0,9	126,25 ± 8,6	137,75 ± 2,5	152,25 ± 11,9	146,75 ± 3,6	77,3 ± 1,2	112,5 ± 6,8

Table B.3: Hardness, Surface energy and adhesion loss data for factor the CC-1 time

CO-1 Temperature																
	BCM-A															
CCM	CCM-A								CCM-B							
Temp.[°C]	140				160				140				160			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	148		132		130		147		141		132		140		135	
S.E. [mN/m]	47.9		47.1		45.8		43.9		48.1		47.8		45.9		48.3	
A.L. (5cm) [%]	4-6	13-15	93-95	19-21	100	100	100	100	76-78	68-70	74-76	100	100	100	100	100
A.L. (10cm) [%]	0	0	0	0	100	100	100	100	0	0	0	48-50	100	100	100	100

Table B.4: Hardness, Surface energy and adhesion loss data for factor the CC-1 time

CC-1 Temperature																
	BCM-B															
CCM	CCM-A								CCM-B							
Temp.[°C]	140				160				140				160			
Panler nr.	9		10		11		12		13		14		15		16	
Hardness [s]	146		139		120		139		117		141		140		127	
S.E. [mN/m]	45.8		46.1		44.9		47.5		49.9		50.6		47.9		47.1	
A.L. (5cm) [%]	4-6	13-15	93-95	19-21	100	100	100	100	76-78	68-70	74-76	100	100	100	100	100
A.L. (10cm) [%]	0	0	0	0	100	100	100	100	0	0	0	48-50	100	100	100	100

Table B.5: Hardness, Surface energy and adhesion loss data for factor the CC-1 time

IDO-1 Time																
CCM			CCM-A				BCM-A				CCM-B					
Temp.[°C]	140				160				140				160			
Panler nr.	1		2		5		6		3		8		7		16	
Hardness [s]	114		123		116		120		127		117		137		140	
S.E. [mN/m]	44.4		44.5		42.9		43.6		47.7		47.7		46.5		45.13	
A.L. (5cm) [%]	100	100	100	100	100	100	100	100	8-10	8-10	5-7	6-8	100	100	NA	NA
A.L. (10cm) [%]	96-97	95-97	60-62	100	68-70	100	100	100	NA	NA	3-5	3-5	3-4	36-38	NA	NA

Table B.6: Hardness, Surface energy and adhesion loss data for factor the CC-1 time

IDO-1 Time	BCM-B															
CCM	CCM-A								CCM-B							
Temp. [°C]	140				160				140				160			
Panler nr.	9		13		14		11		12		10		16		15	
Hardness [s]	100		NA		79		90		77		NA		114		117	
S.E. [mN/m]	43.9		NA		44.1		44.2		47.9		NA		47.1		47.8	
A.L. (5cm) [%]	100	100	NA	NA	100	100	100	100	7-8	7-8	7-9	7-9	100	100	100	100
A.L. (10cm) [%]	20-22	6 14-16	NA	NA	19-21	39-41	27-29	27-29	3-4	3-4	3-4	2-3	1-2	4-5	0	12-14

Table B.7: Hardness, Surface energy and adhesion loss data for factor the TBR

TBR	BCM-A															
CCM	CCM-A								CCM-B							
Temp. [h]	1				24				1				24			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	147		150		123		127		143		164		141		151	
S.E. [mN/m]	45.7		45.1		43.3		43.3		48.3		47.8		46.7		47.0	
A.L. (5cm) [%]	100	100	NA	NA	100	100	100	100	7-8	100	100	100	100	100	100	100
A.L. (10cm) [%]	100	100	57-59	100	100	29-31	44-46	83-85	0	0	24-26	63-66	3-4	3-4	59-62	28-31

Table B.8: Hardness, Surface energy and adhesion loss data for factor the TBR

TBR																
	BCM-B															
CCM	CCM-A								CCM-B							
Temp. [h]	1				24				1				24			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	147		150		123		127		143		164		141		151	
S.E. [mN/m]	45.2		45.7		44.1		43.5		46.4		48.5		47.6		47.0	
A.L. (5cm) [%]	100	100	NA	NA	100	100	100	100	7-8	100	100	100	100	100	100	100
A.L. (10cm) [%]	48-51	42-45	71-73	78-80	11-13	18-20	1-3	7-9	3-4	4-6	6-7	4-5	42-45	48-51	33-36	27-30

Table B.9: Hardness, Surface energy and adhesion loss data for factor the CO-1 time

CO-1 Time	BCM-A															
CCM	CCM-A								CCM-B							
Temp.[°C]	10				30				10				30			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	140		134		154		140		127		144		140		138	
S.E. [mN/m]	44.1		44.4		43.7		44.3		48.0		47.6		47.5		47.4	
A.L. (5cm) [%]	100	80	80-82	63-65	100	100	100	100	100	100	88-90	88-90	100	100	100	100
A.L. (10cm) [%]	0	6-8	0	4-6	100	89-91	96-98	100	12-14	0	0	5-7	50	3-4	50-52	3-5

Table B.10: Hardness, Surface energy and adhesion loss data for factor the CO-1 time

CO-1 Time								
	BCM-B							
CCM	CCM-A				CCM-B			
Temp.[°C]	10		30		10		30	
Panler nr.	9	10	11	12	13	14	15	16
Hardness [s]	142	134	151	146	140	147	140	140
S.E. [mN/m]	45.0	44.9	43.7	43.9	47.8	47.3	47.4	47.3
A.L. (5cm) [%]	78-80 63-65	48-51 33-35	100 93-95	100 100	40-42 68-70	64-66 48-50	100 97-99	75-77 100
A.L. (10cm) [%]	0 0	0 0	10-12 36-38	0 5-7	0 3-5	0 0	12-14 7-9	1-3 11-13

Table B.11: Hardness, Surface energy and adhesion loss data for factor the Higher S.E.

Higher S.E.	BCM-A															
CCM	CCM-A								CCM-B							
Temp.[°C]	140				160				140				160			
Panler nr.	1		2		5		6		3		4		7		8	
Hardness [s]	114		123		116		120		127		117		137		140	
S.E. [mN/m]	45.2		46.2		47.6		47.0		47.3		46.7		47.3		47.9	
A.L. (5cm) [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
A.L. (10cm) [%]	0-1	2-3	1-3	1-3	0-1	2-3	0	1-2	0	8-10	0	4-5	0	1-3	0	1-3

Table B.12: Hardness, Surface energy and adhesion loss data for factor the Higher S.E.

Higher S.E.	BCM-B															
CCM	CCM-A								CCM-B							
Temp.[°C]	140				160				140				160			
Panler nr.	9		10		13		14		11		12		15		16	
Hardness [s]	114		123		116		120		127		117		137		140	
S.E. [mN/m]	46.1		46.6		47.9		46.9		47.2		47.3		47.6		47.3	
A.L. (5cm) [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
A.L. (10cm) [%]	NA	NA	23-25	15-17	0	7-9	0	0	0	4-6	6-8	4-6	0	22-24	0	19-21

Table B.13: Hardness, Surface energy and adhesion loss data for factor the SANDED

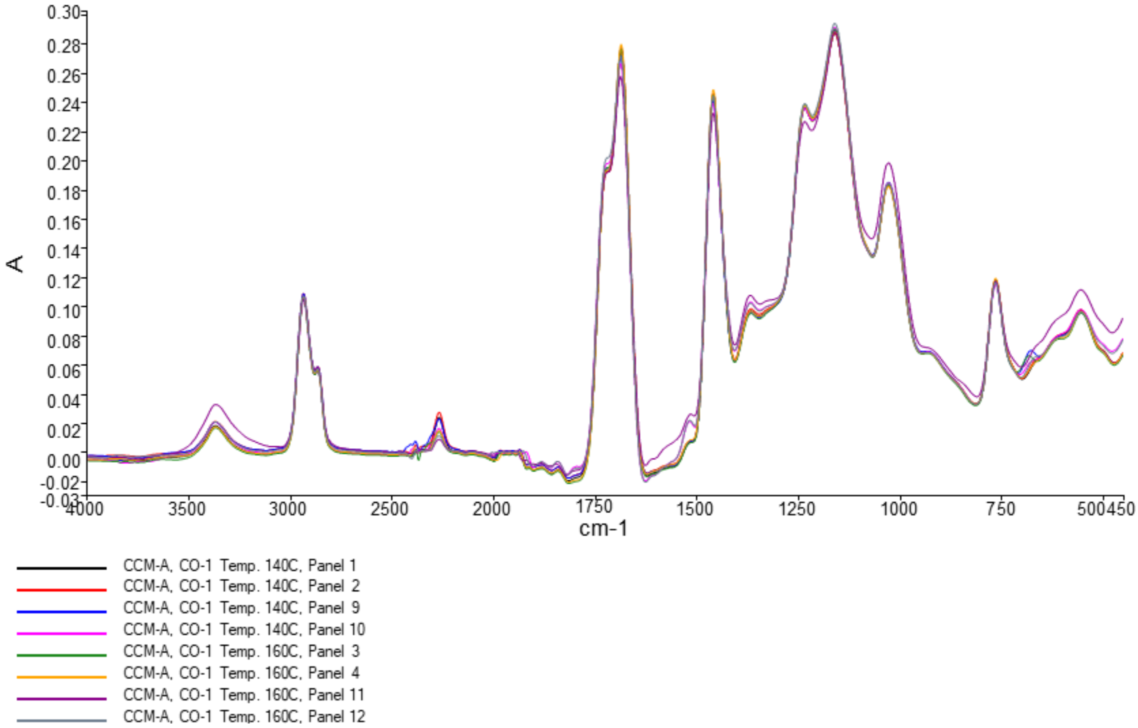
SANDED	BCM-A								BCM-B							
CCM	CCM-A				CCM-B				CCM-A				CCM-B			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	106		77		73		90		100		104		74		74	
S.E. [mN/m]	43.4		42.3		47.5		47.4		44.5		43.6		47.1		NA	
A.L. (5cm) [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
A.L. (10cm) [%]	33-35	26-28	28-30	55-57	1-2	13-15	0	3-4	8-10	9-11	7-9	6-8	13-15	27-30	2-4	0

Table B.14: Hardness, Surface energy and adhesion loss data for factor the CONTROL

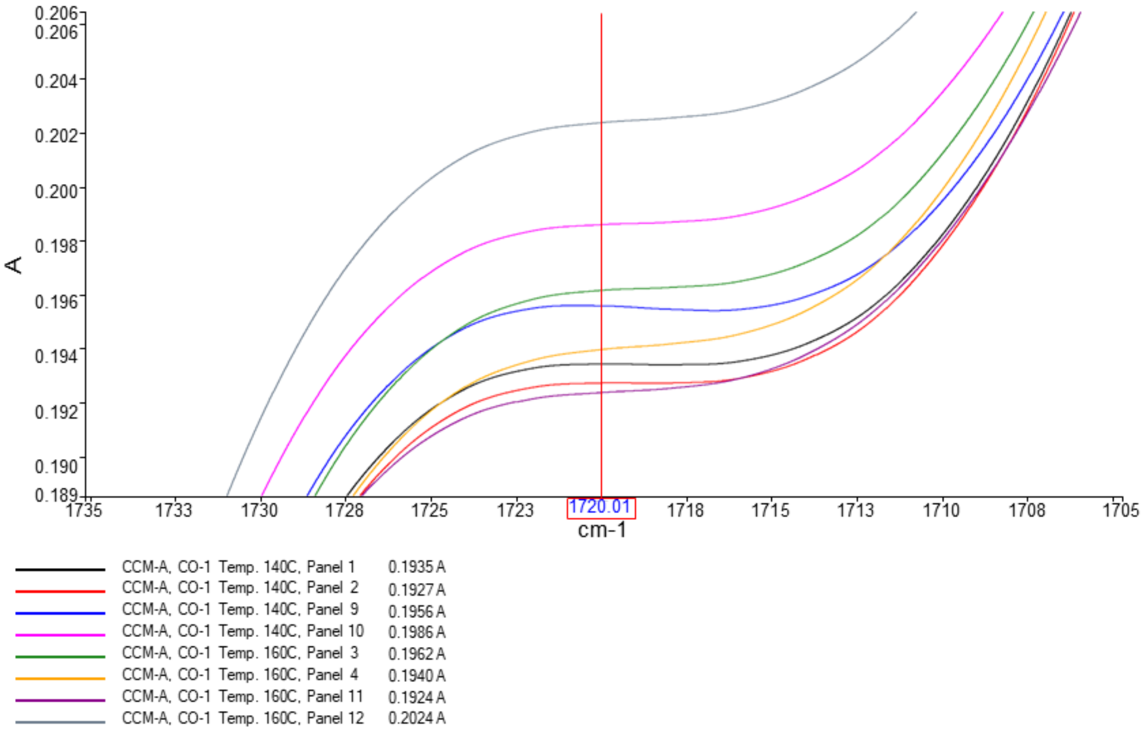
CONTROL	BCM-A								BCM-B							
CCM	CCM-A				CCM-B				CCM-A				CCM-B			
Panler nr.	1		2		3		4		5		6		7		8	
Hardness [s]	123		127		145		120		142		146		136		131	
S.E. [mN/m]	43.4		42.3		45.3		46.8		43.7		41.8		47.0		44.8	
A.L. (5cm) [%]	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
A.L. (10cm) [%]	33-35	26-28	28-30	55-57	1-2	13-15	0	3-4	8-10	9-11	7-9	6-8	13-15	27-30	2-4	0

C
Appendix C

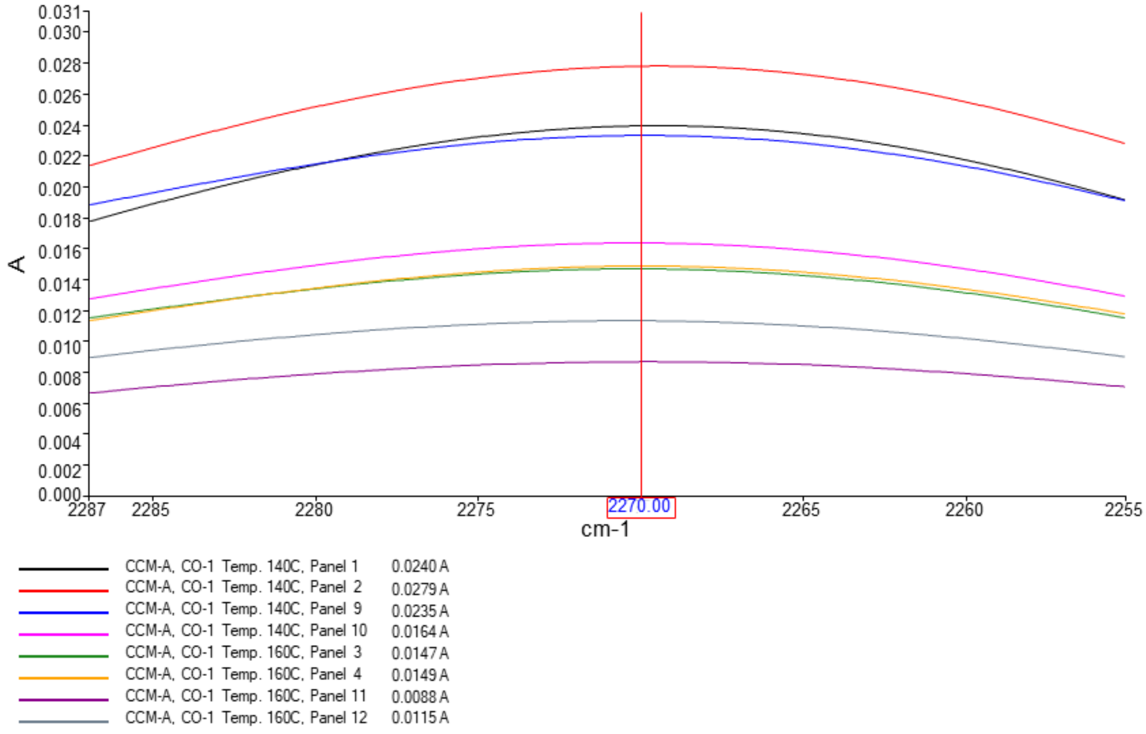
CO-1 temperature
CCM-A



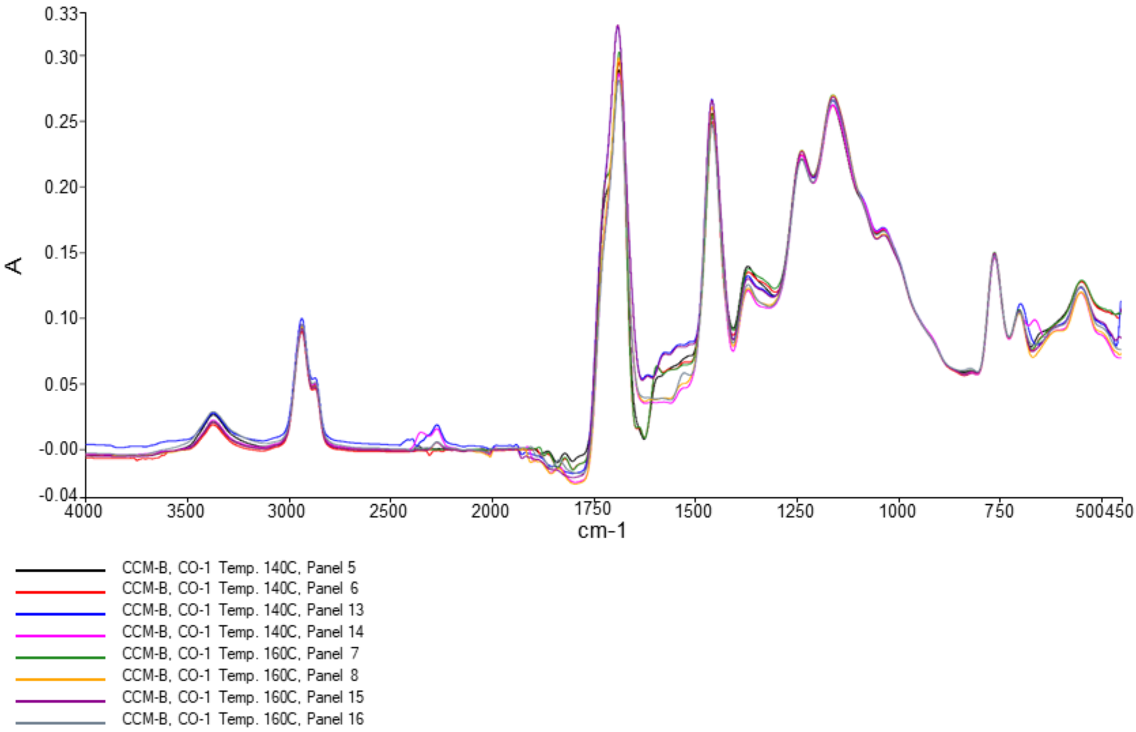
CO-1 temperature
CCM-A - 1720 cm^{-1}



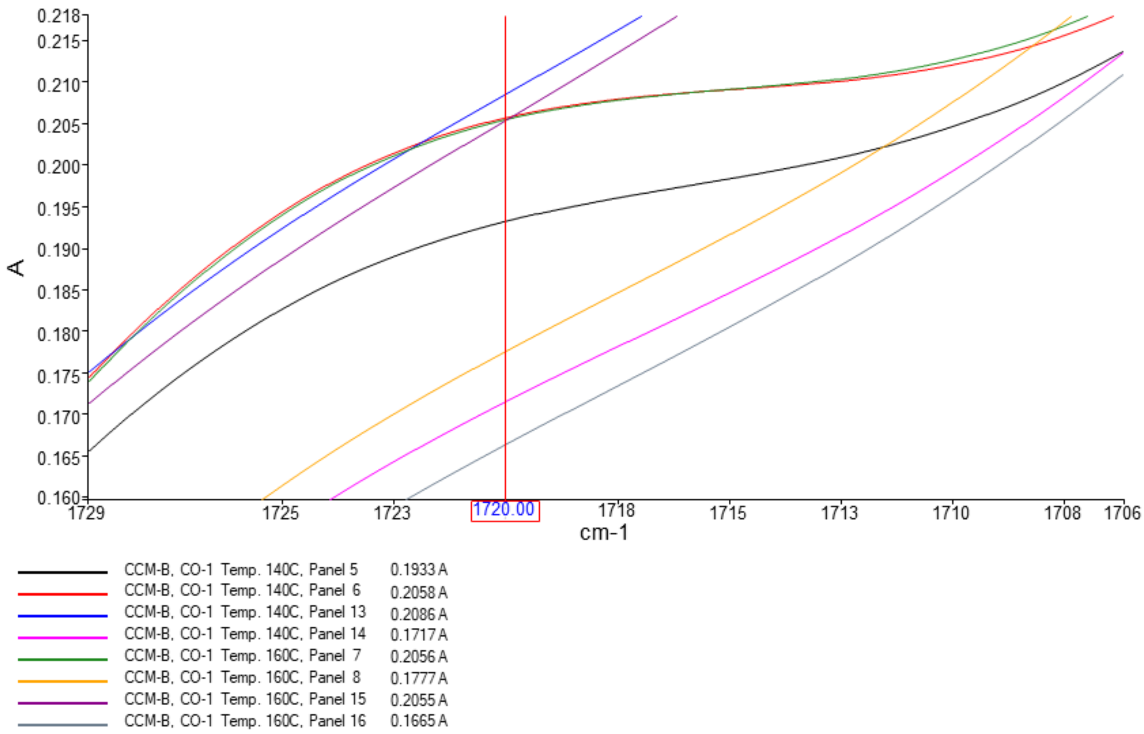
CO-1 temperature
CCM-A - 2270 cm^{-1}



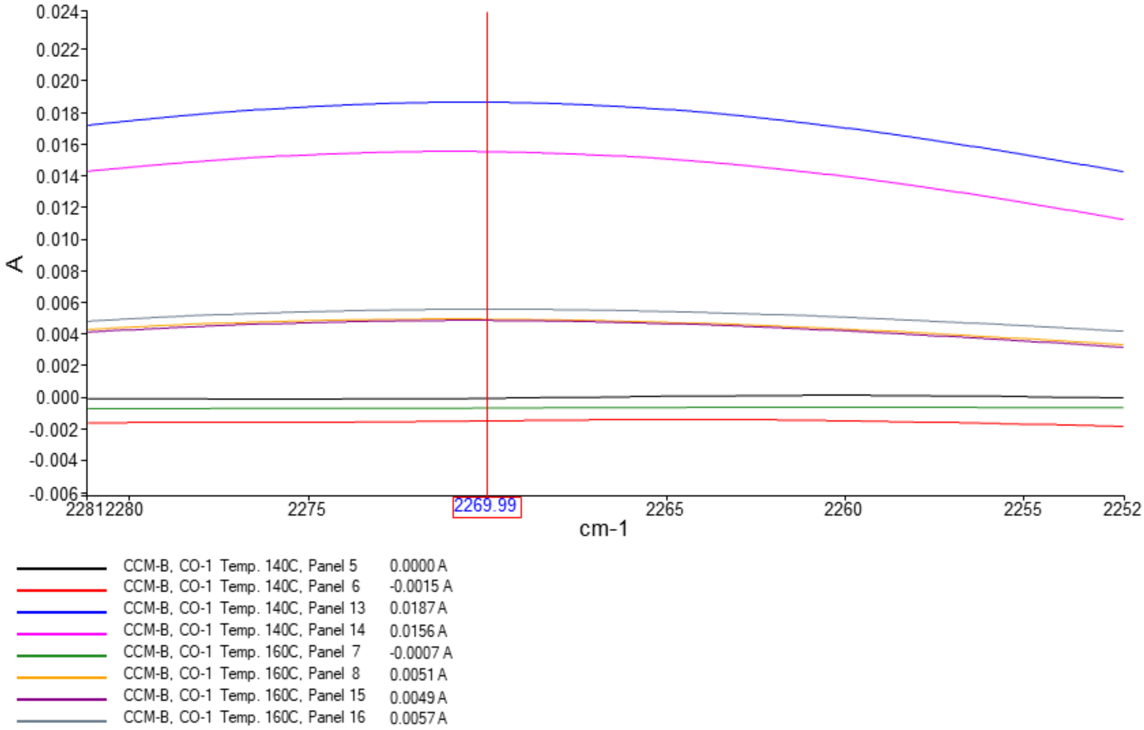
CO-1 temperature
CCM-B



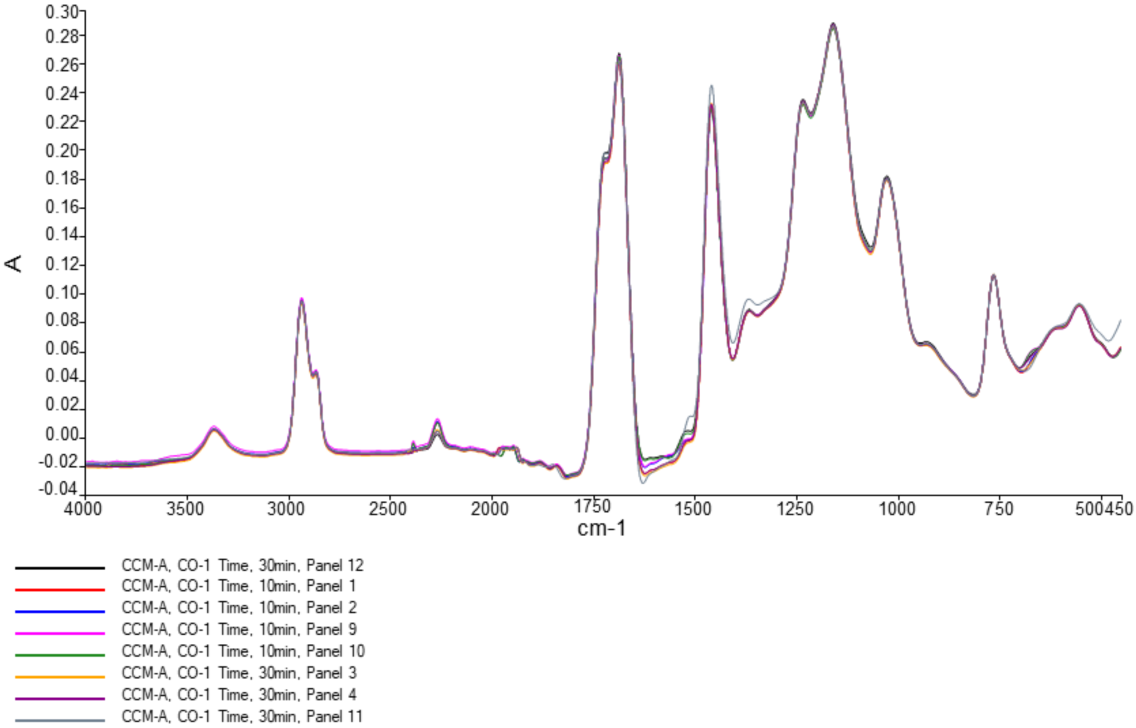
CO-1 temperature
CCM-B - 1720 cm^{-1}



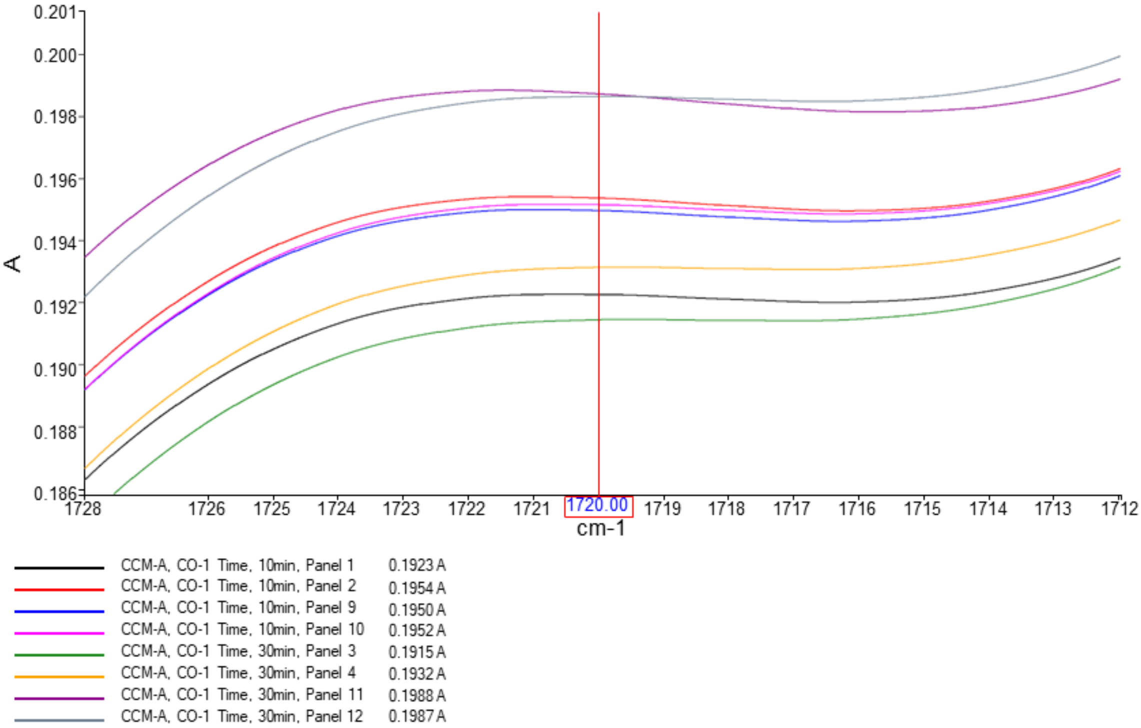
CO-1 temperature
CCM-B - 2270 cm^{-1}



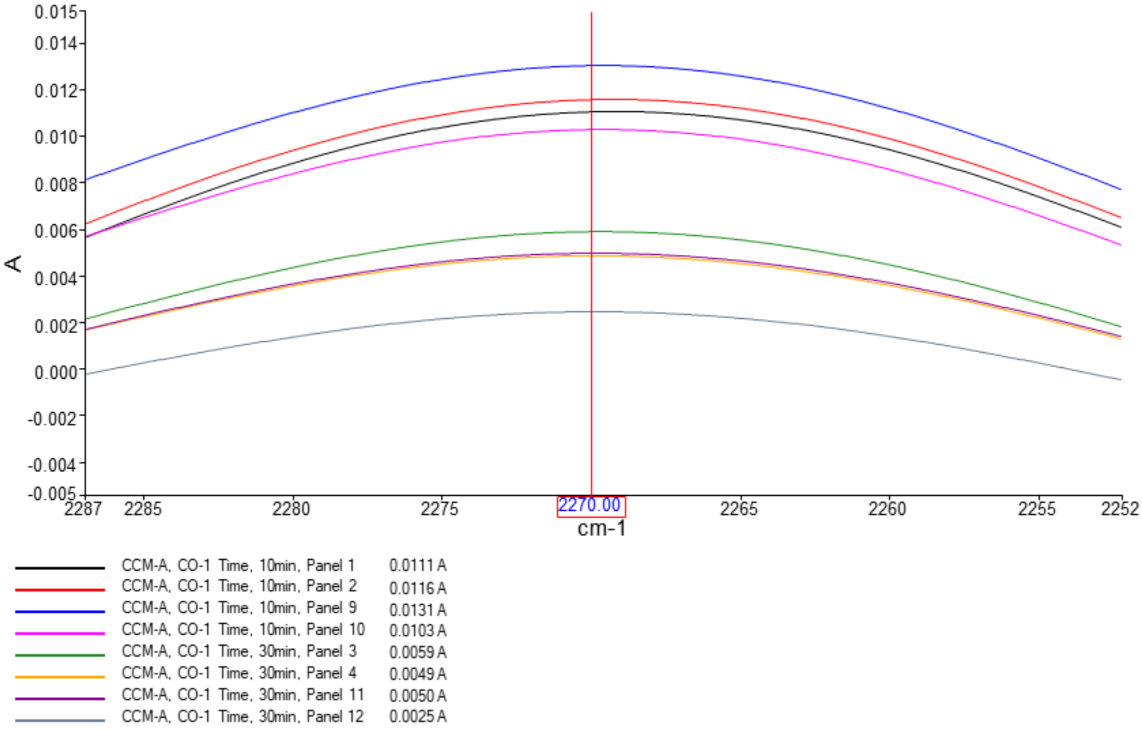
CO-1 time
CCM-A



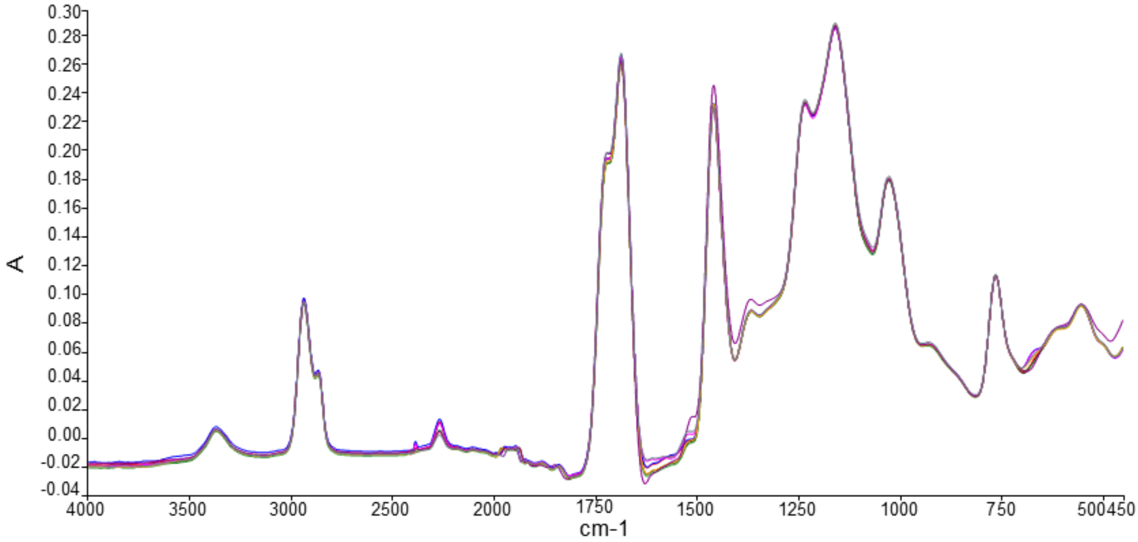
CO-1 time
CCM-A - 1720 cm^{-1}



CO-1 time
CCM-A - 2270 cm^{-1}

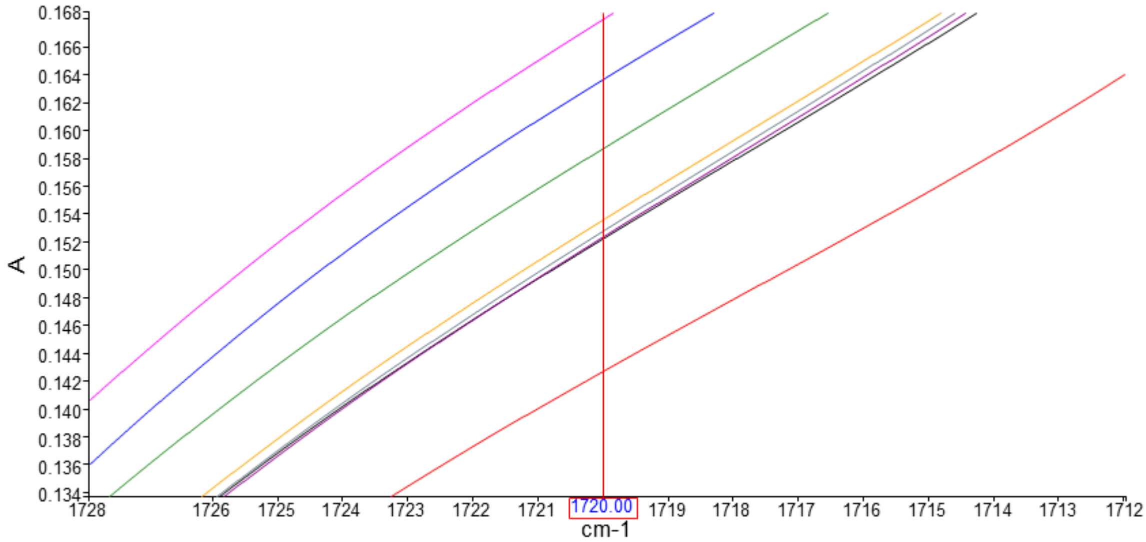


CO-1 time
CCM-B



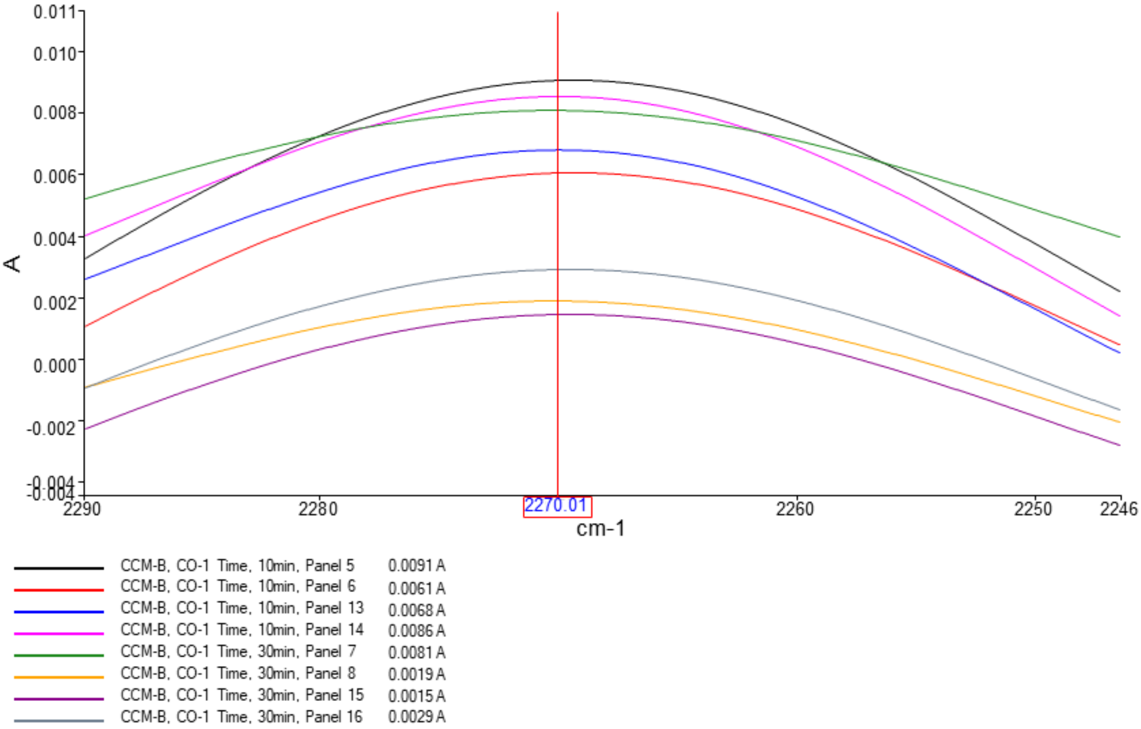
CCM-B, CO-1 Time, 10min, Panel 1
CCM-B, CO-1 Time, 10min, Panel 2
CCM-B, CO-1 Time, 10min, Panel 9
CCM-B, CO-1 Time, 10min, Panel 10
CCM-B, CO-1 Time, 30min, Panel 3
CCM-B, CO-1 Time, 30min, Panel 4
CCM-B, CO-1 Time, 30min, Panel 11
CCM-B, CO-1 Time, 30min, Panel 12

CO-1 time
CCM-B - 1720 cm^{-1}

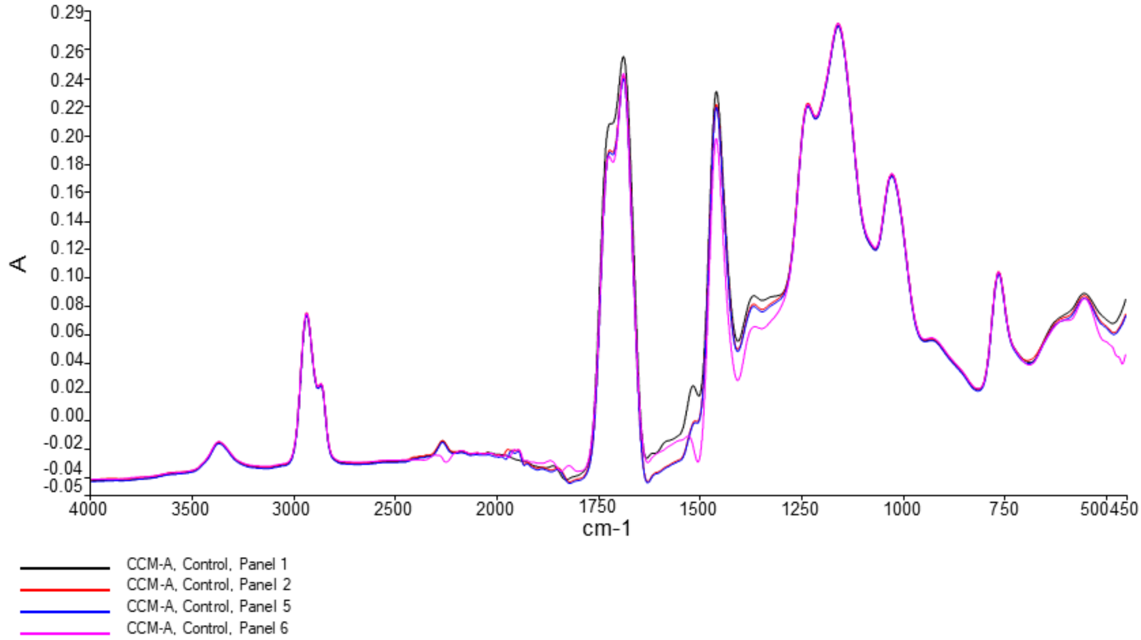


CCM-B, CO-1 Time, 10min, Panel 5 0.1523 A
CCM-B, CO-1 Time, 10min, Panel 6 0.1427 A
CCM-B, CO-1 Time, 10min, Panel 13 0.1637 A
CCM-B, CO-1 Time, 10min, Panel 14 0.1680 A
CCM-B, CO-1 Time, 30min, Panel 7 0.1587 A
CCM-B, CO-1 Time, 30min, Panel 8 0.1536 A
CCM-B, CO-1 Time, 30min, Panel 15 0.1524 A
CCM-B, CO-1 Time, 30min, Panel 16 0.1528 A

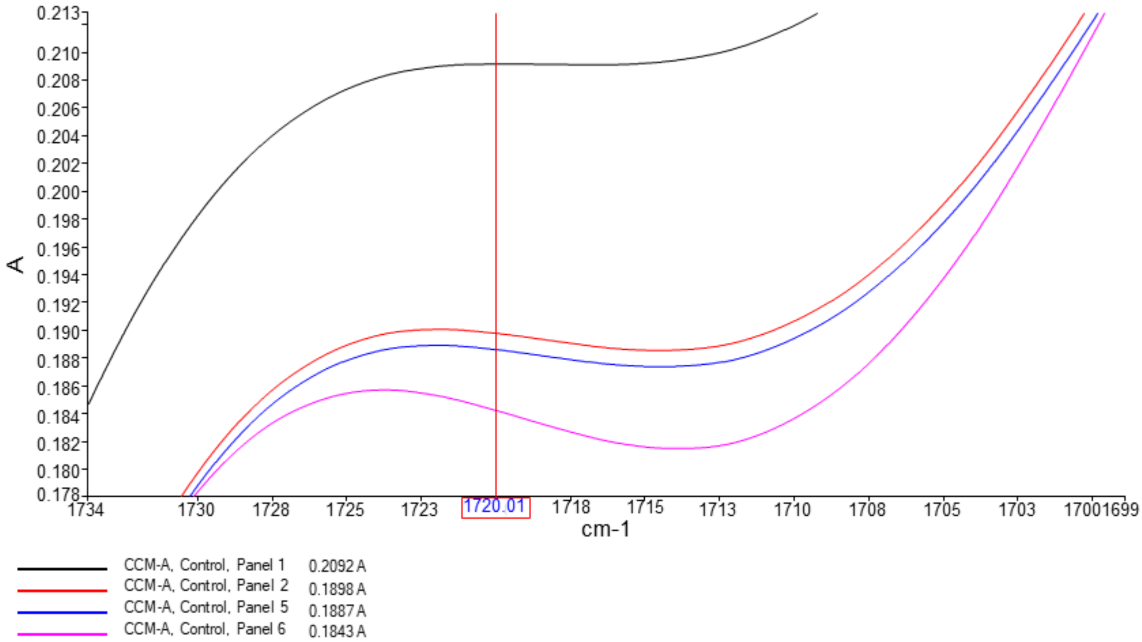
CO-1 time
CCM-B - 2270 cm^{-1}



Control
CCM-A

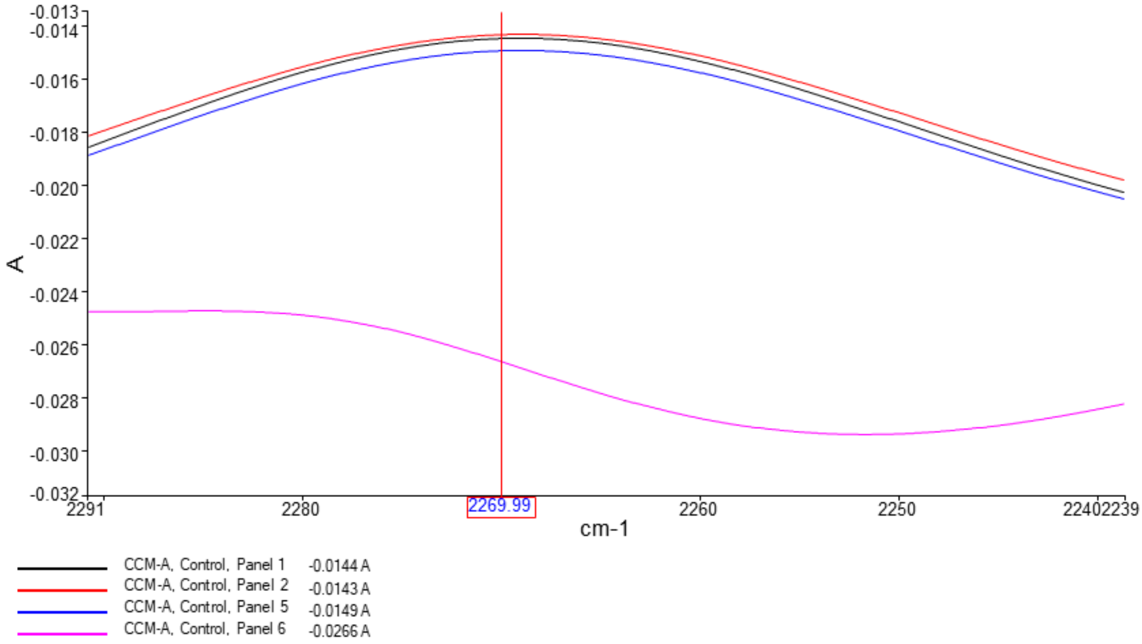


Control
CCM-A - 1720 cm^{-1}

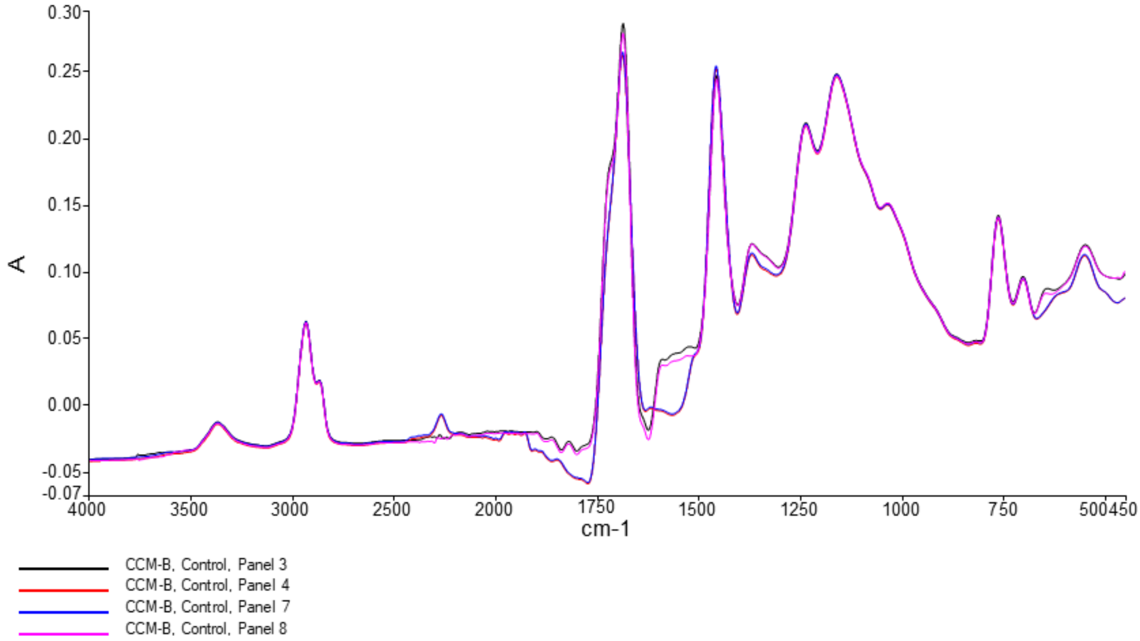


Control

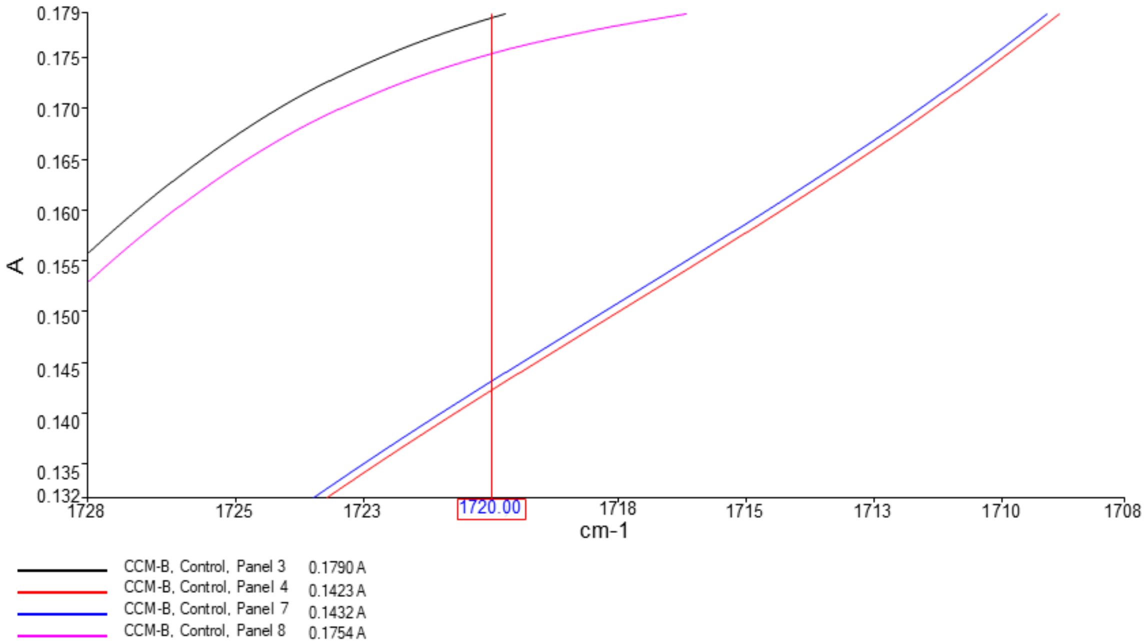
CCM-A - 2270 cm^{-1}



Control
CCM-B

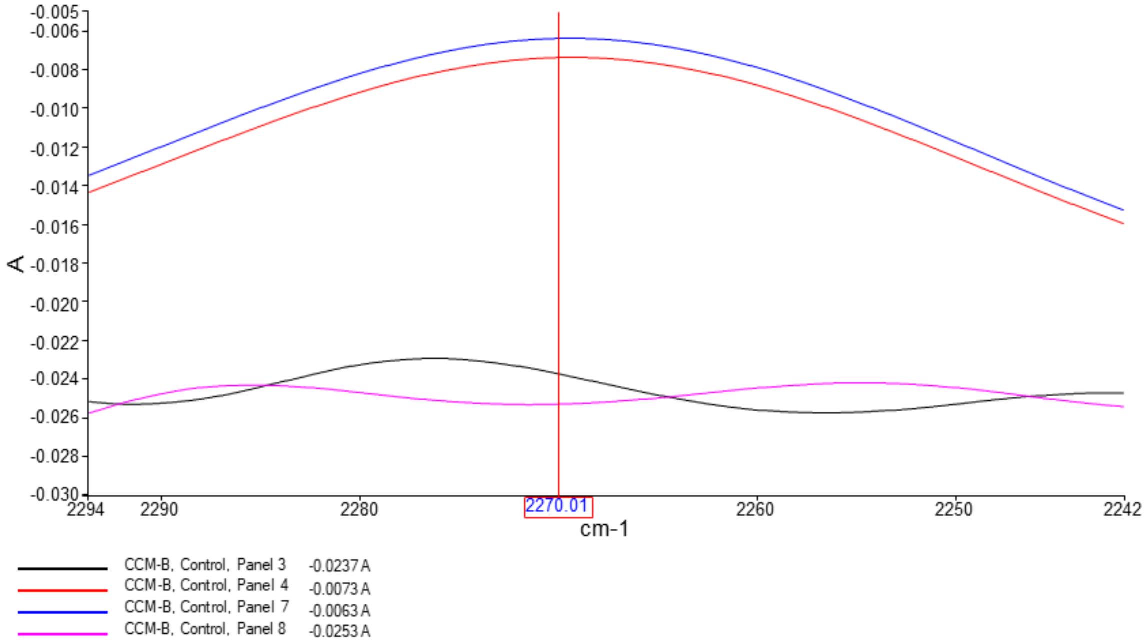


Control
CCM-B - 1720 cm^{-1}

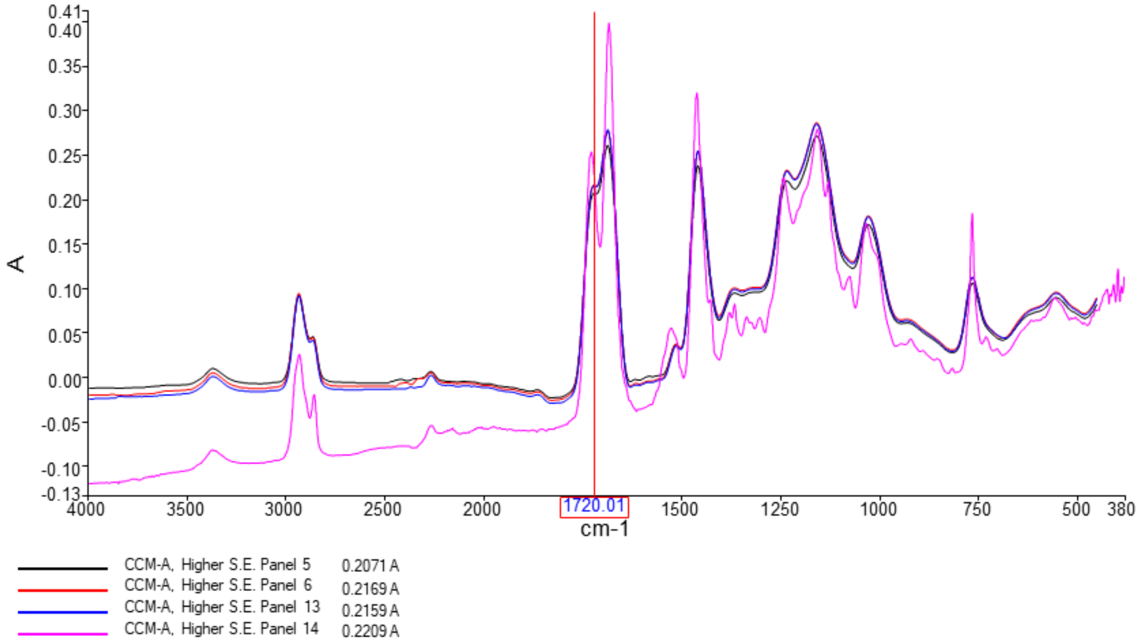


Control

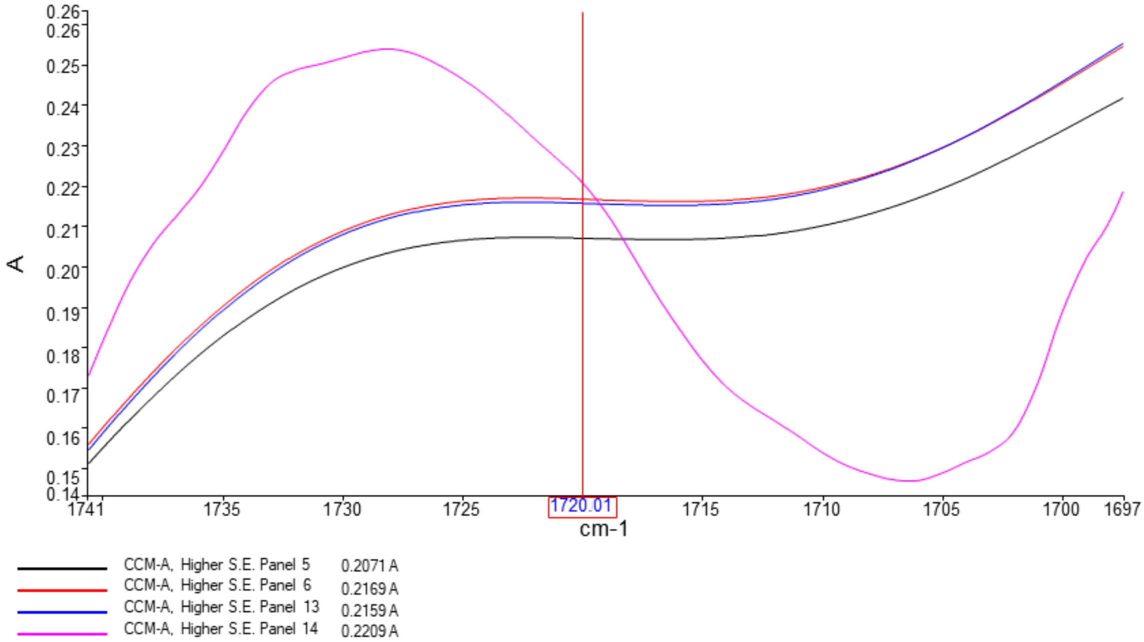
CCM-B - 2270 cm^{-1}



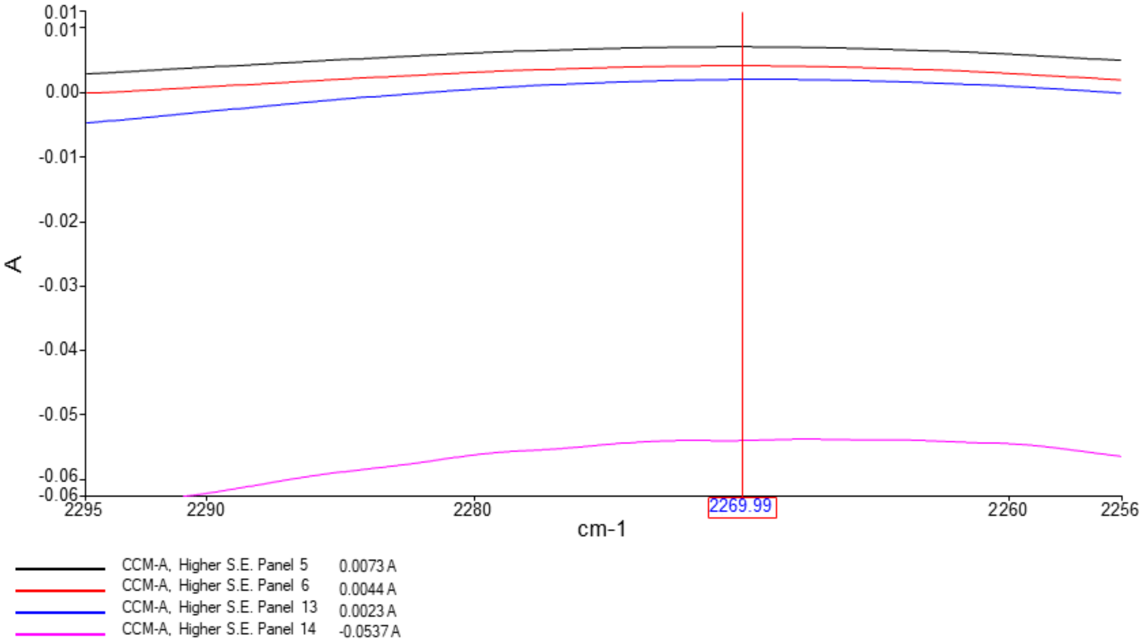
Higher S.E. - [Higher]
CCM-A



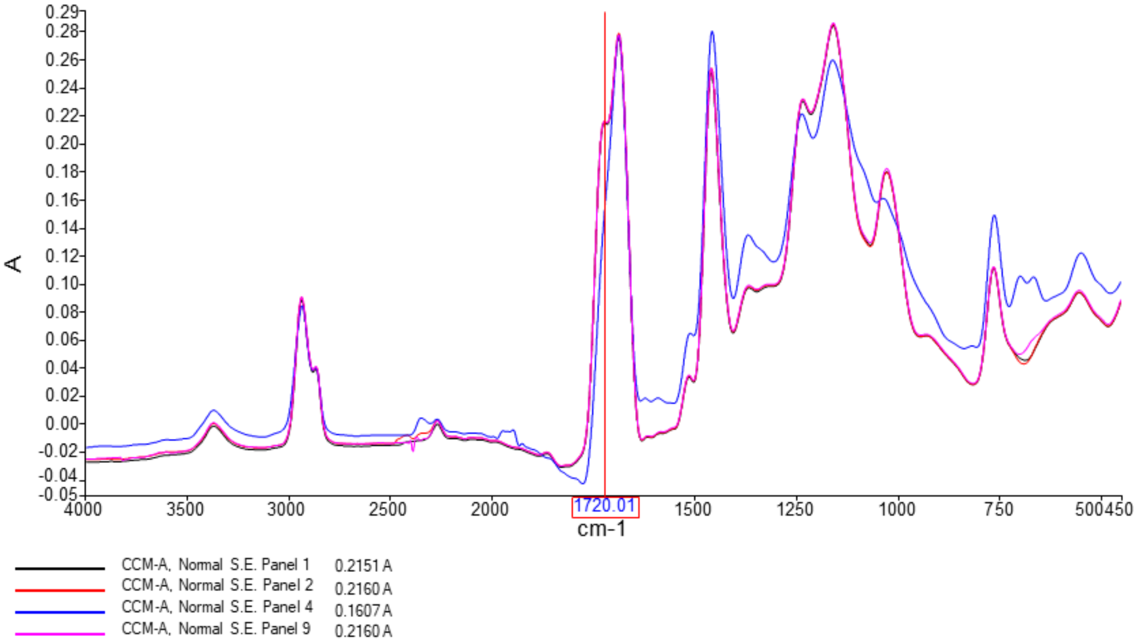
Higher S.E. - [Higher]
CCM-A - 1720 cm^{-1}



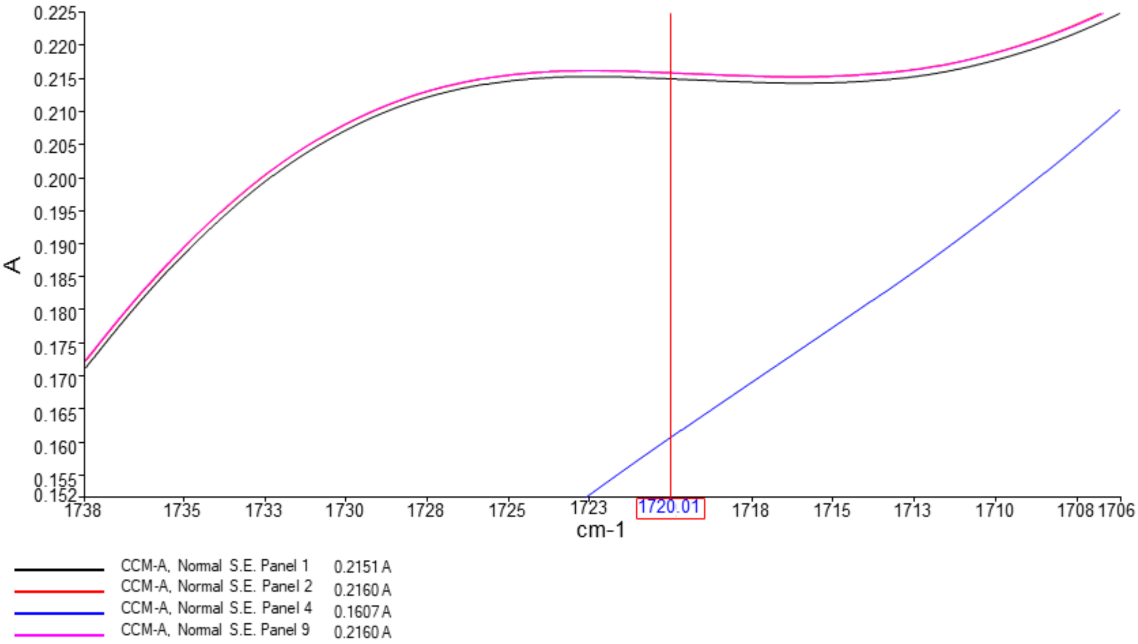
Higher S.E. - [Higher]
CCM-A - 2270 cm^{-1}



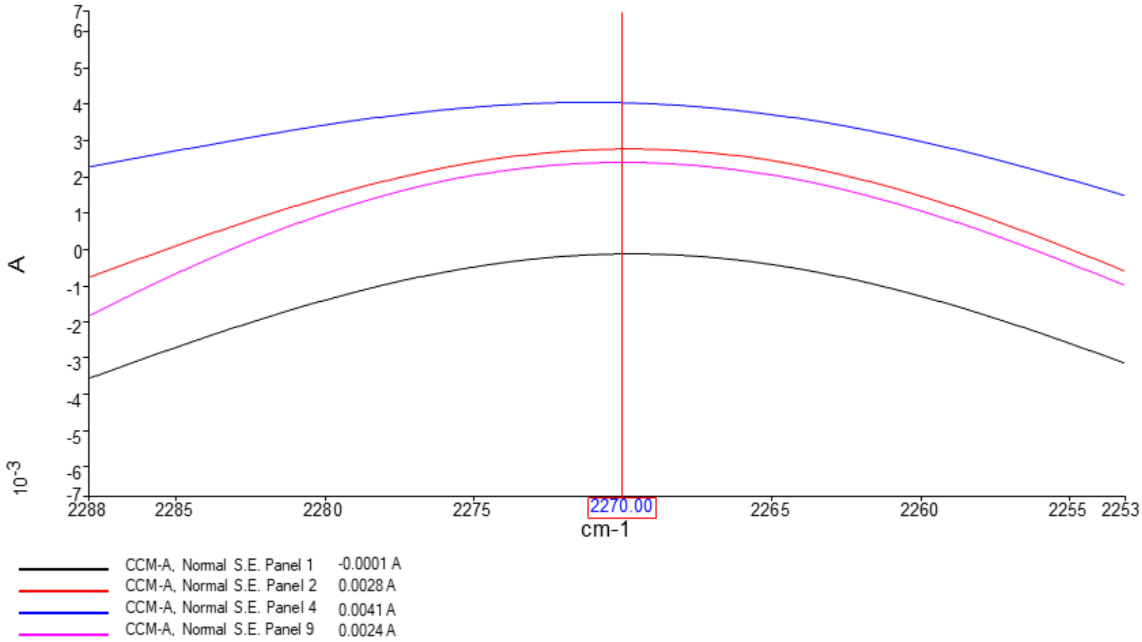
Higher S.E. - [Normal]
CCM-A



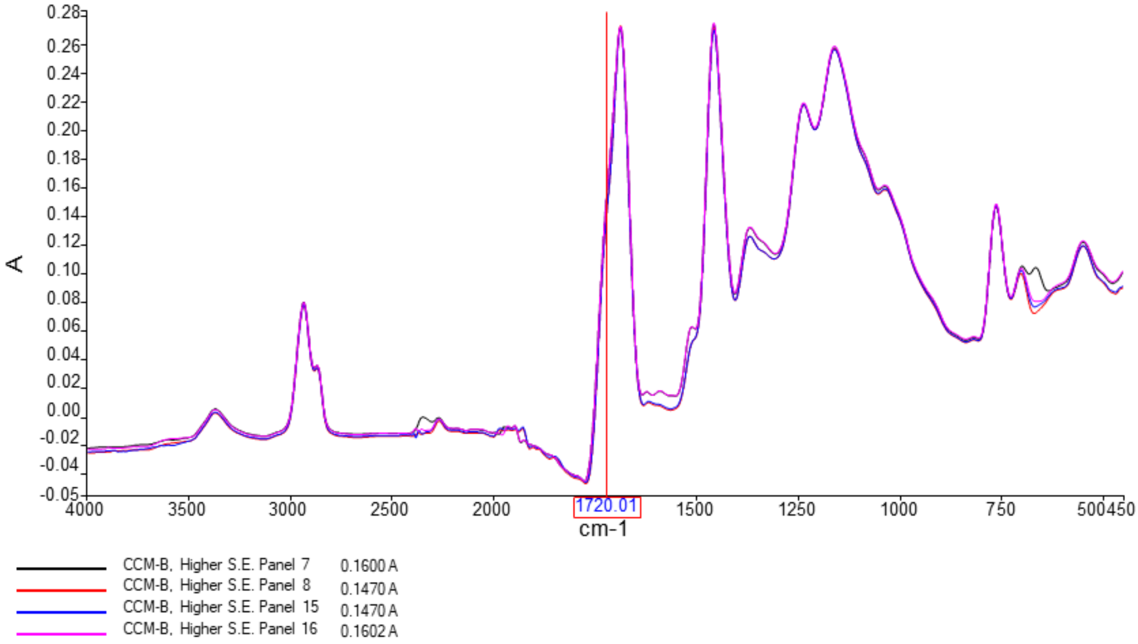
Higher S.E. - [Normal]
CCM-A - 1720 cm^{-1}



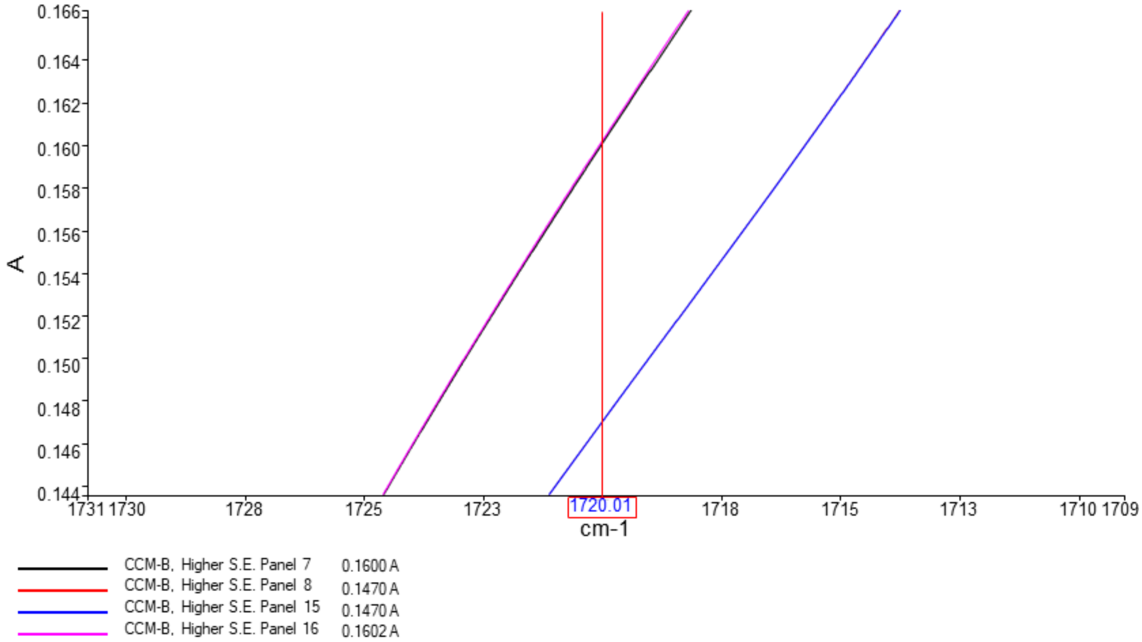
Higher S.E. - [Normal]
CCM-A - 2270 cm^{-1}



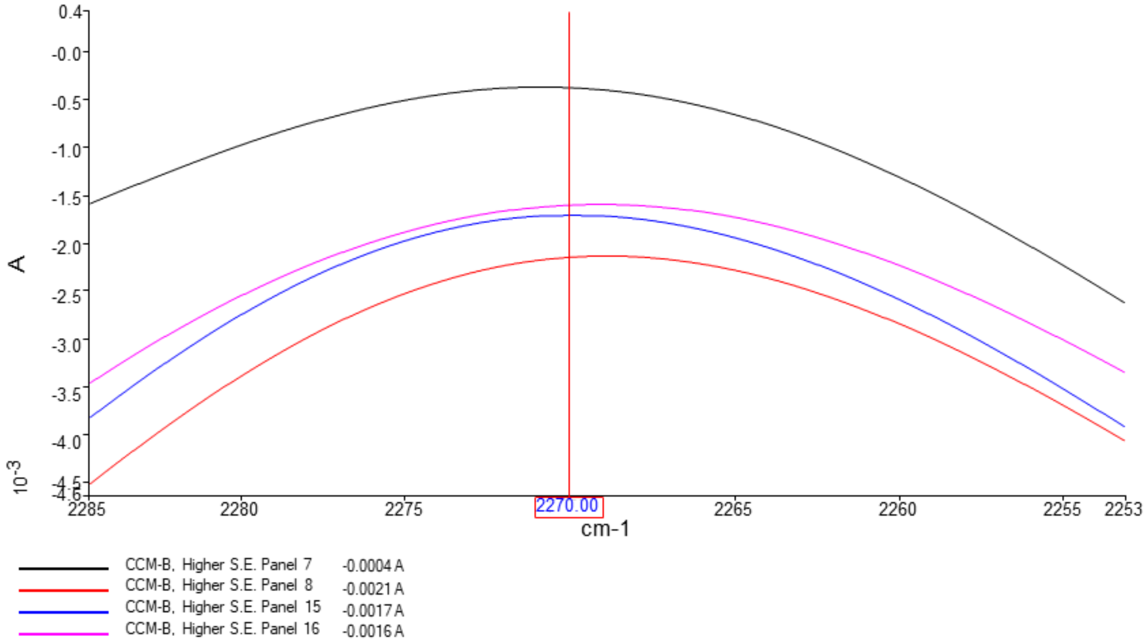
Higher S.E. - [Higher]
CCM-B



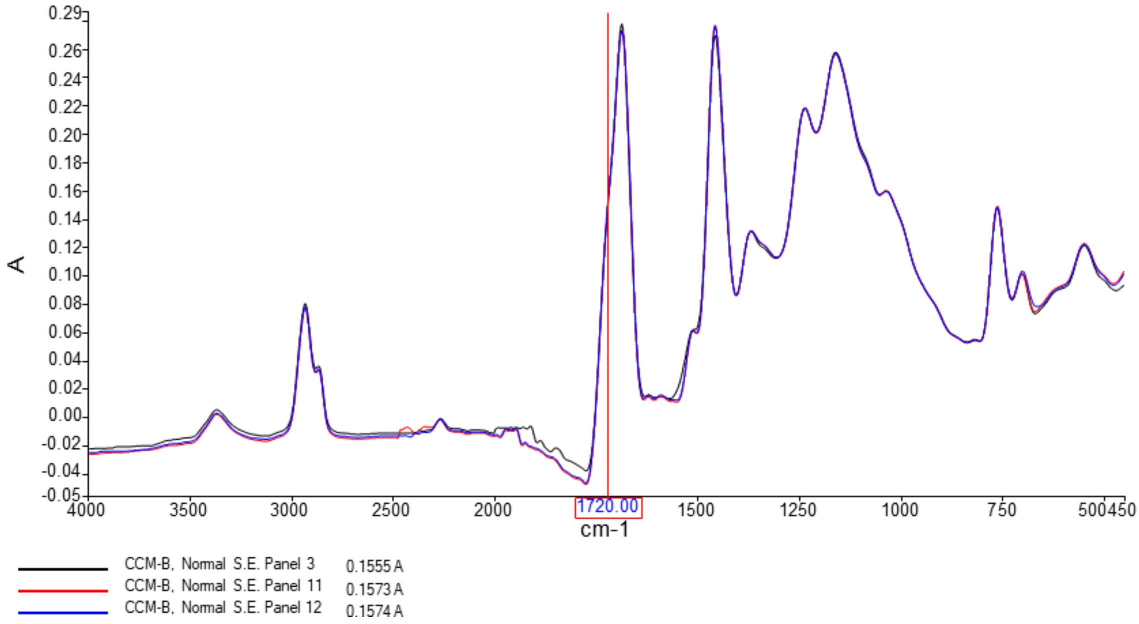
Higher S.E. - [Higher]
CCM-B - 1720 cm^{-1}



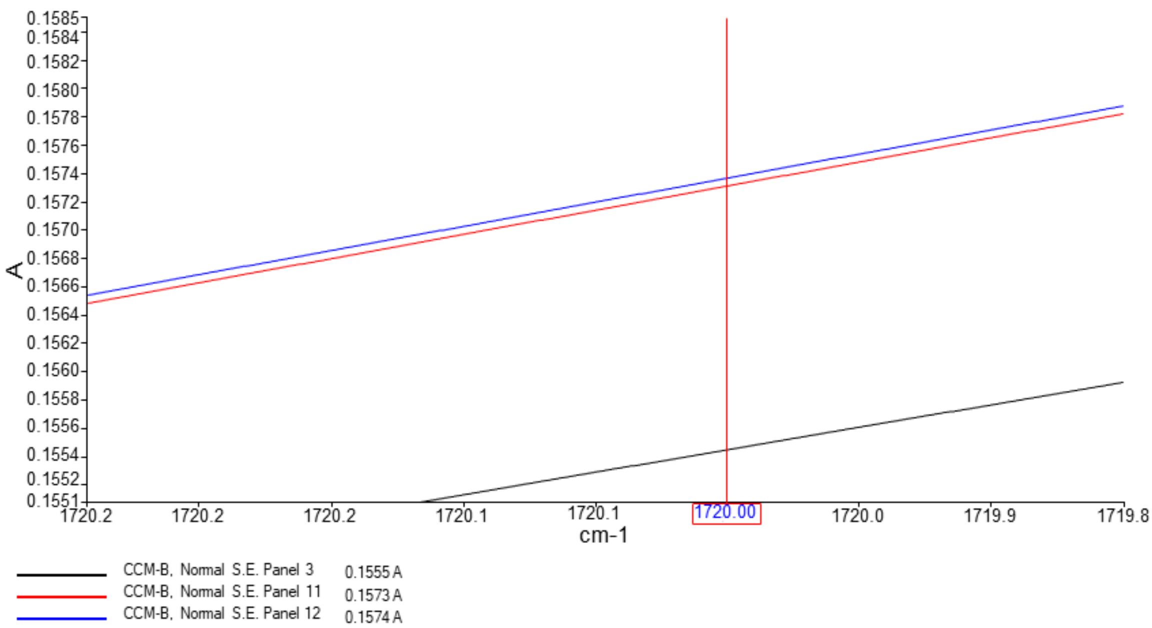
Higher S.E. - [Higher]
CCM-B - 2270 cm^{-1}



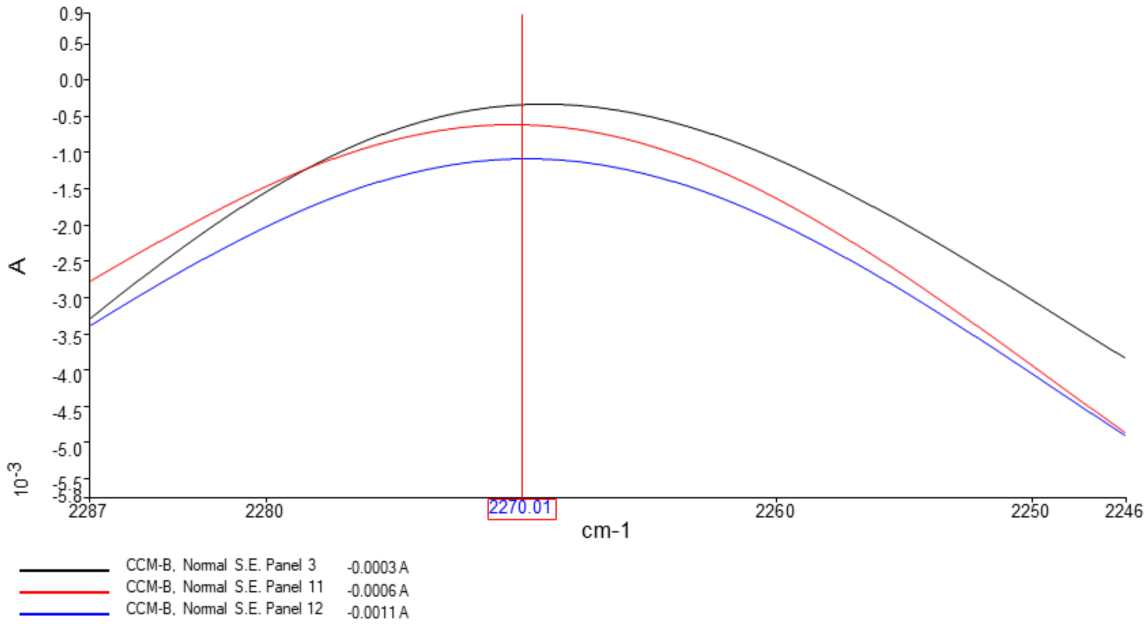
Higher S.E. - [Normal]
CCM-B



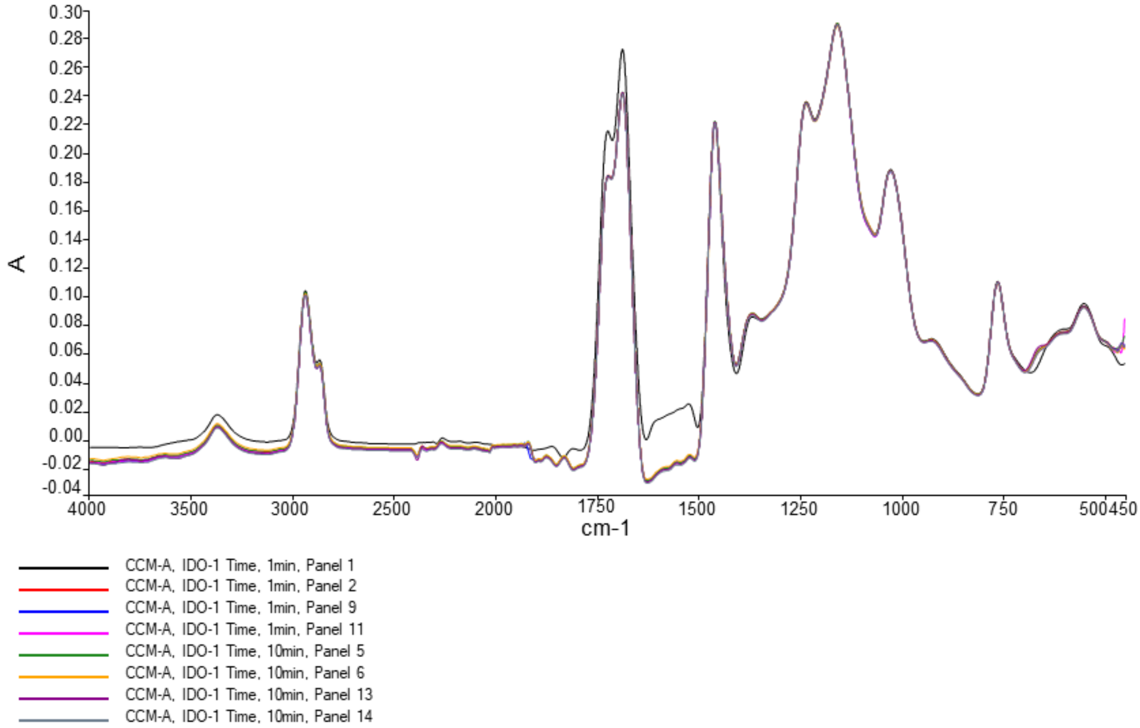
Higher S.E. - [Normal]
CCM-B - 1720 cm^{-1}



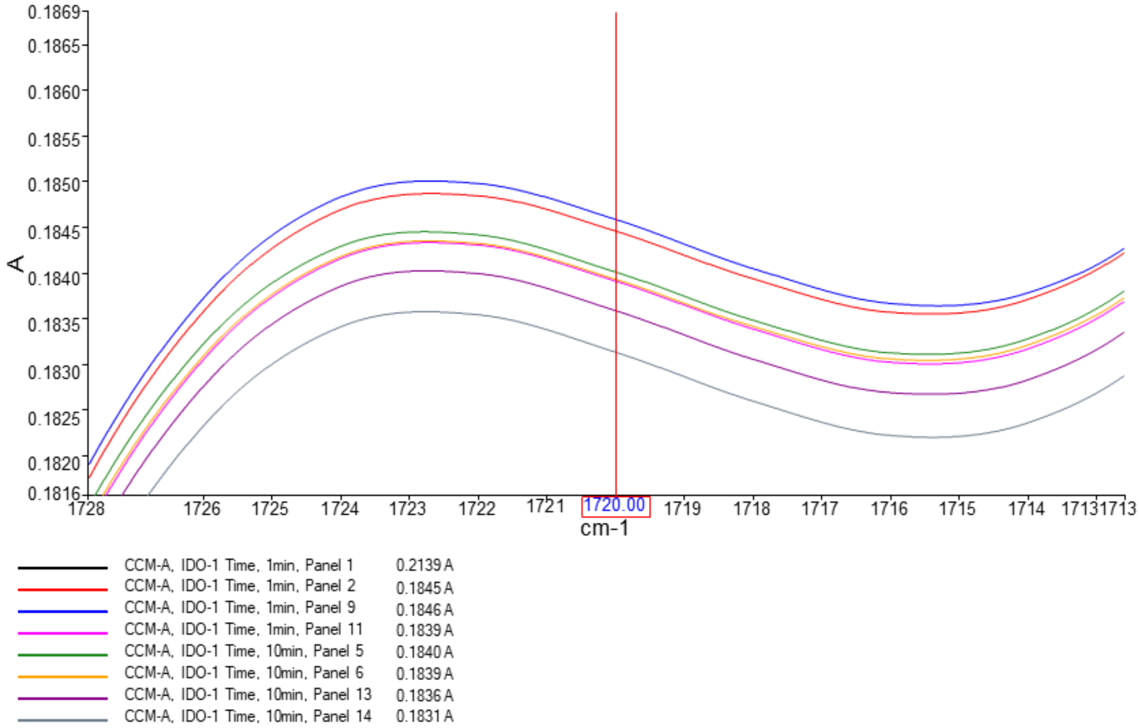
Higher S.E. - [Normal]
CCM-B - 2270 cm^{-1}



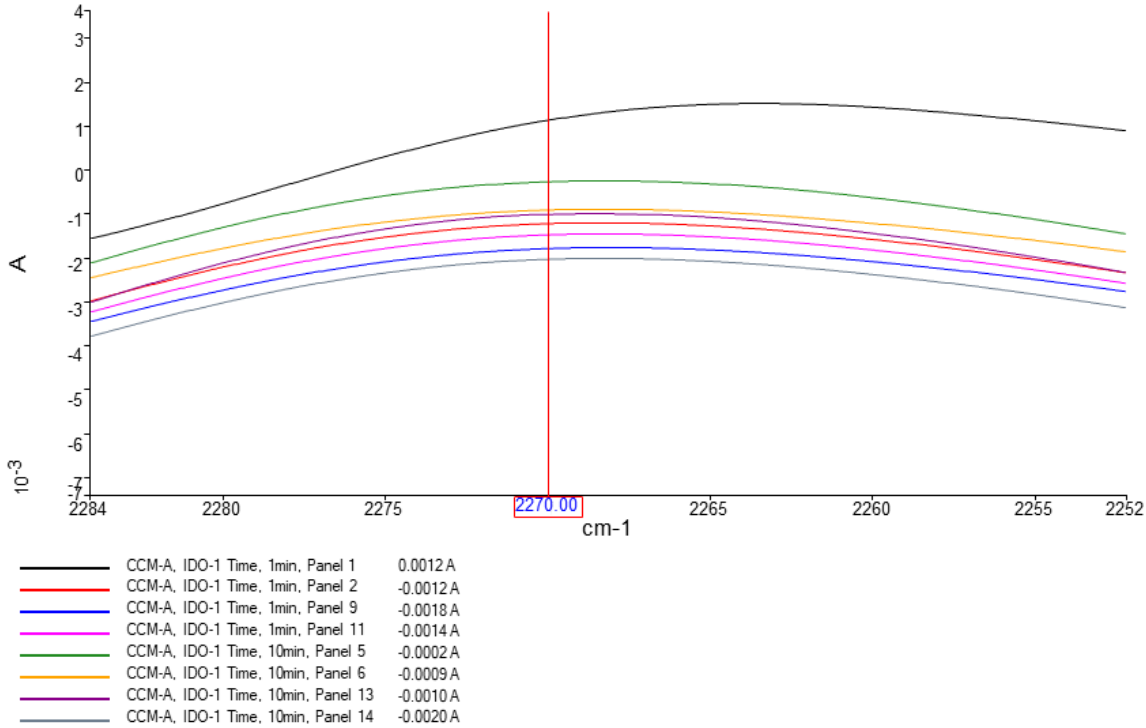
IDO-1 time
CCM-A



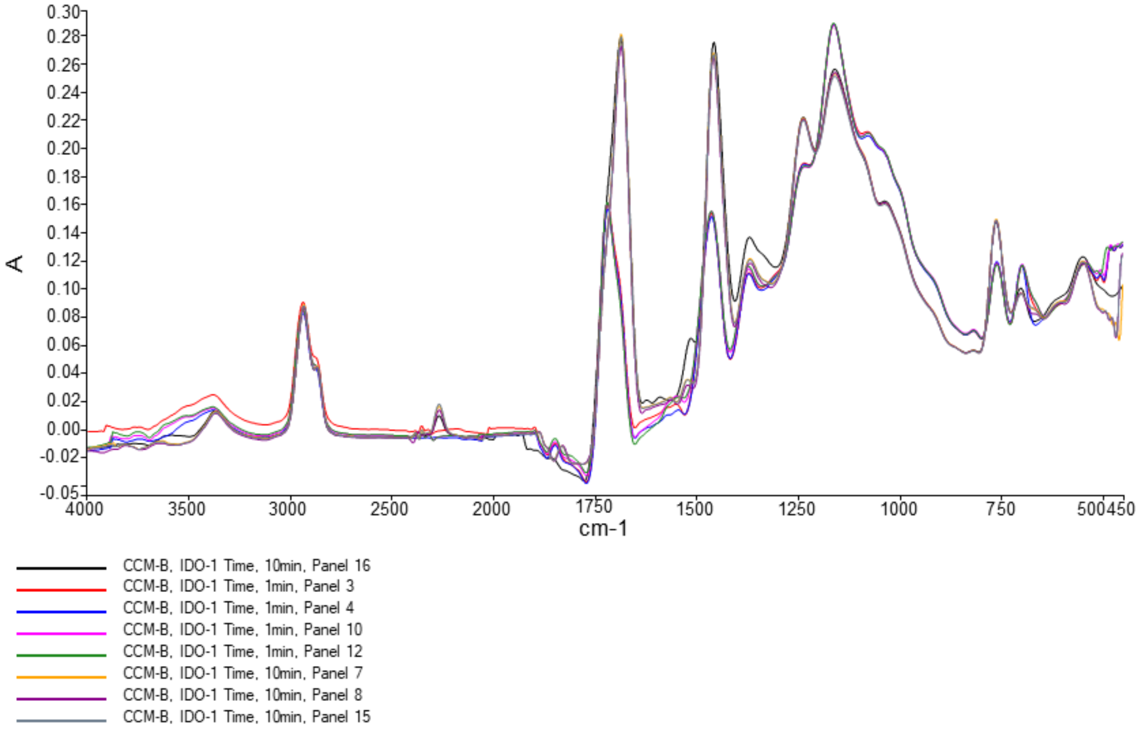
IDO-1 time
CCM-A - 1720 cm^{-1}



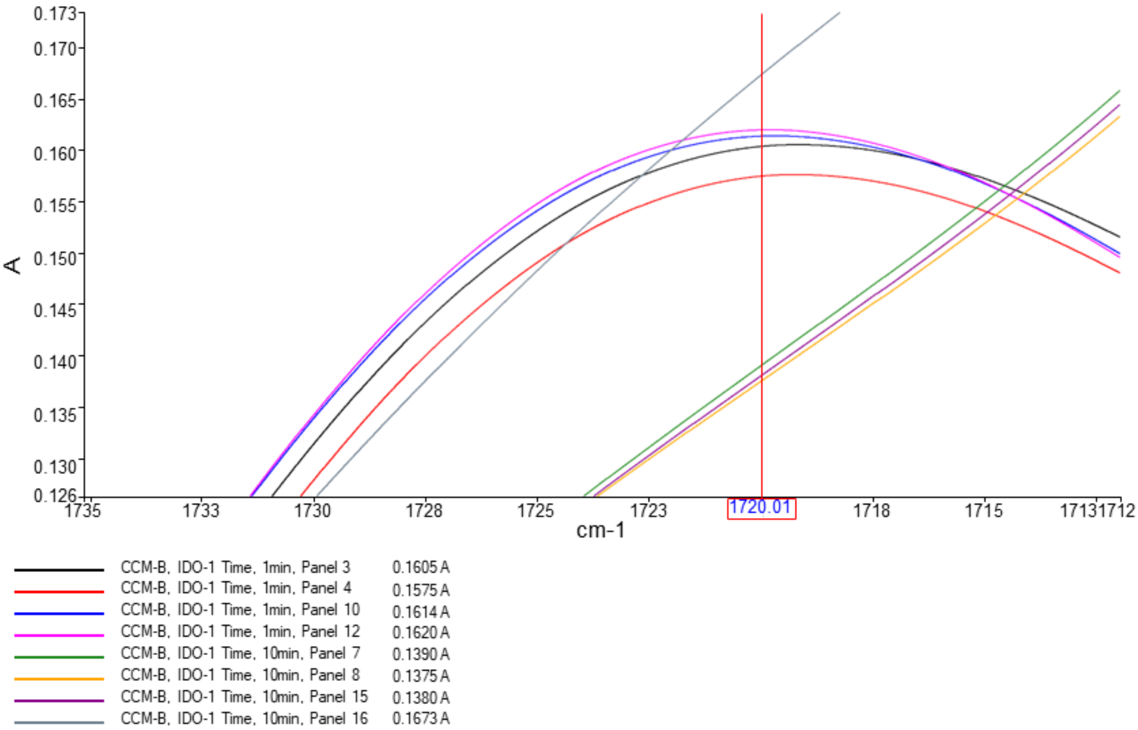
IDO-1 time
CCM-A - 2270 cm^{-1}



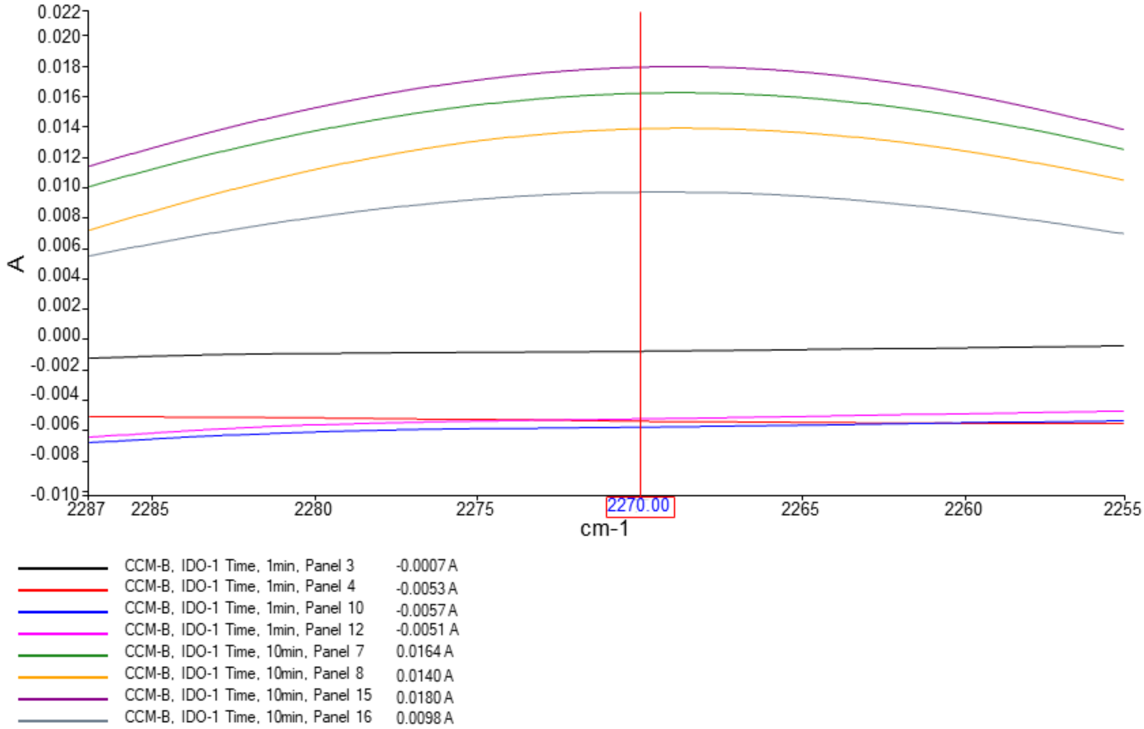
IDO-1 time
CCM-B



IDO-1 time
CCM-B - 1720 cm^{-1}



IDO-1 time
CCM-B - 2270 cm^{-1}



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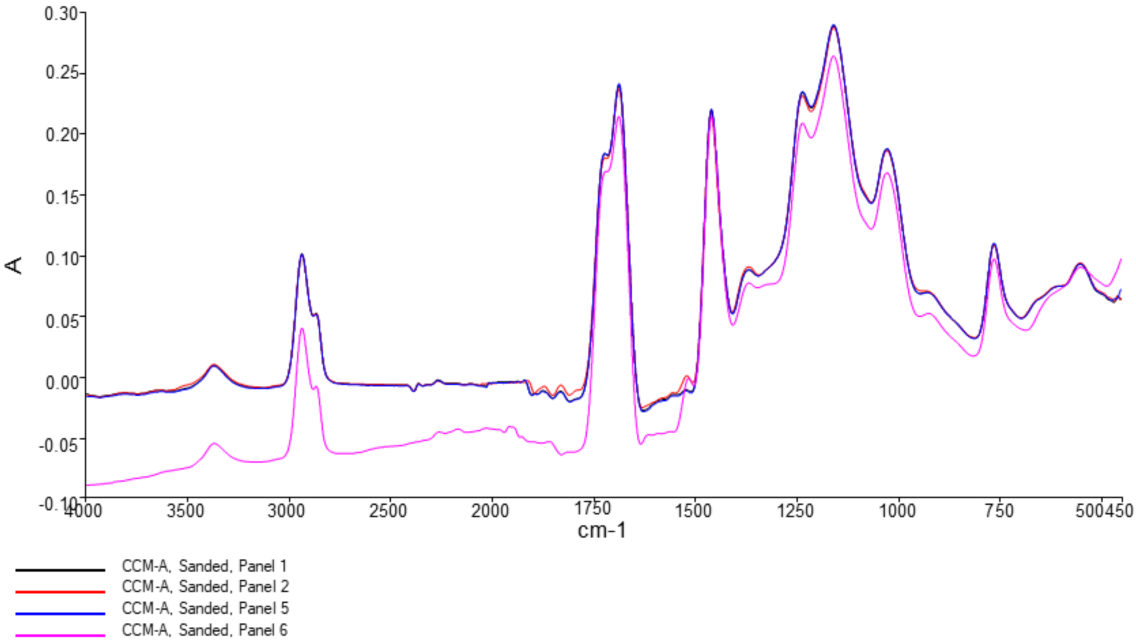

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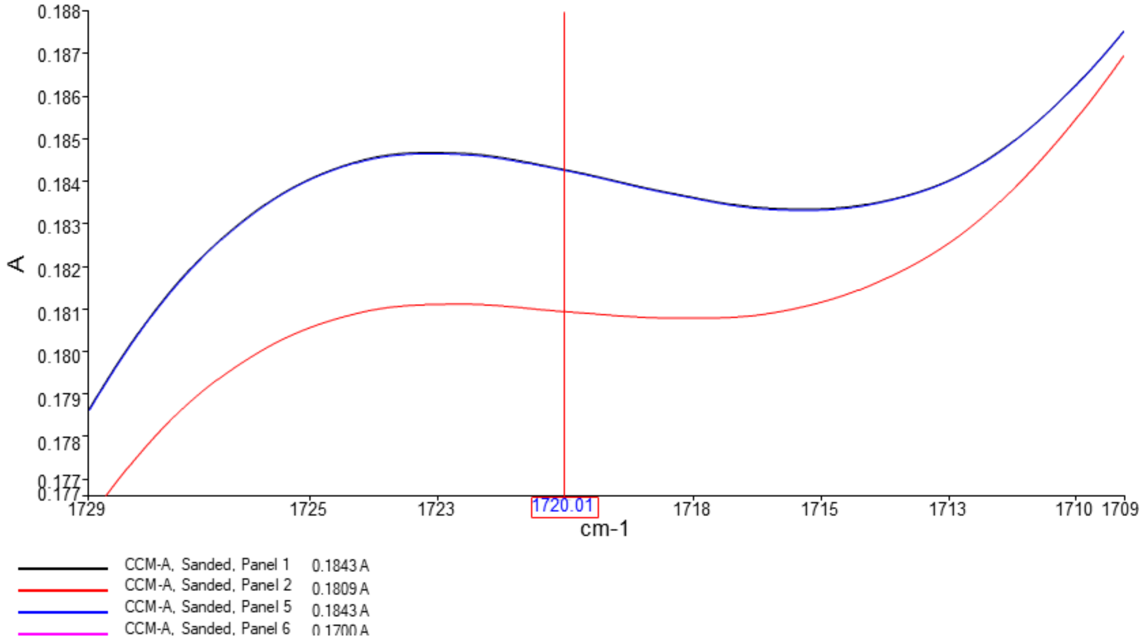

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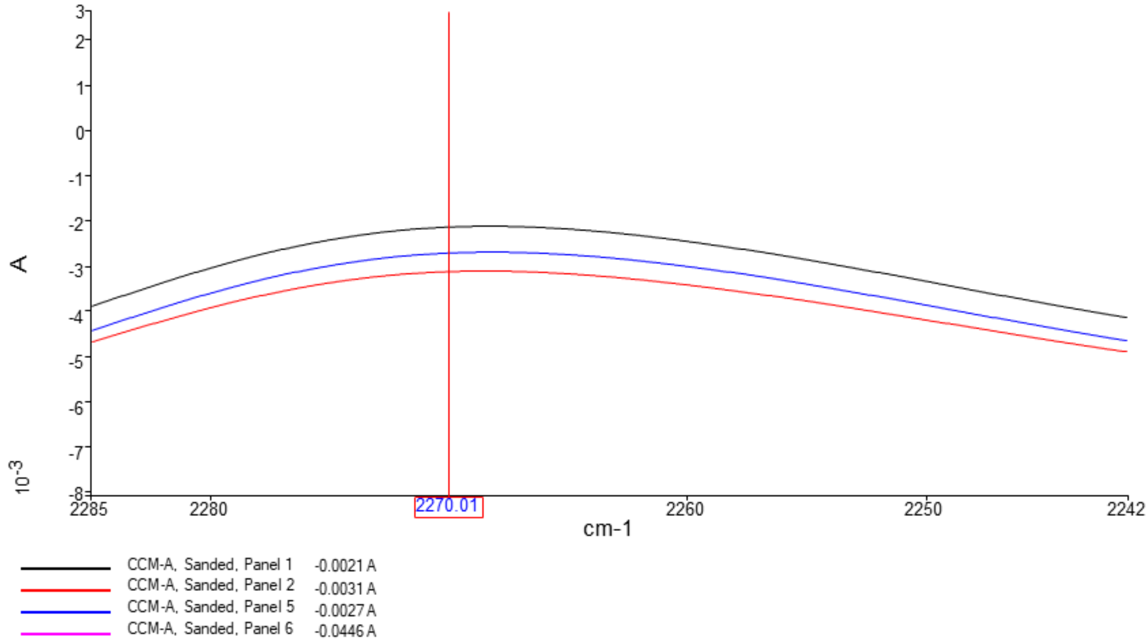

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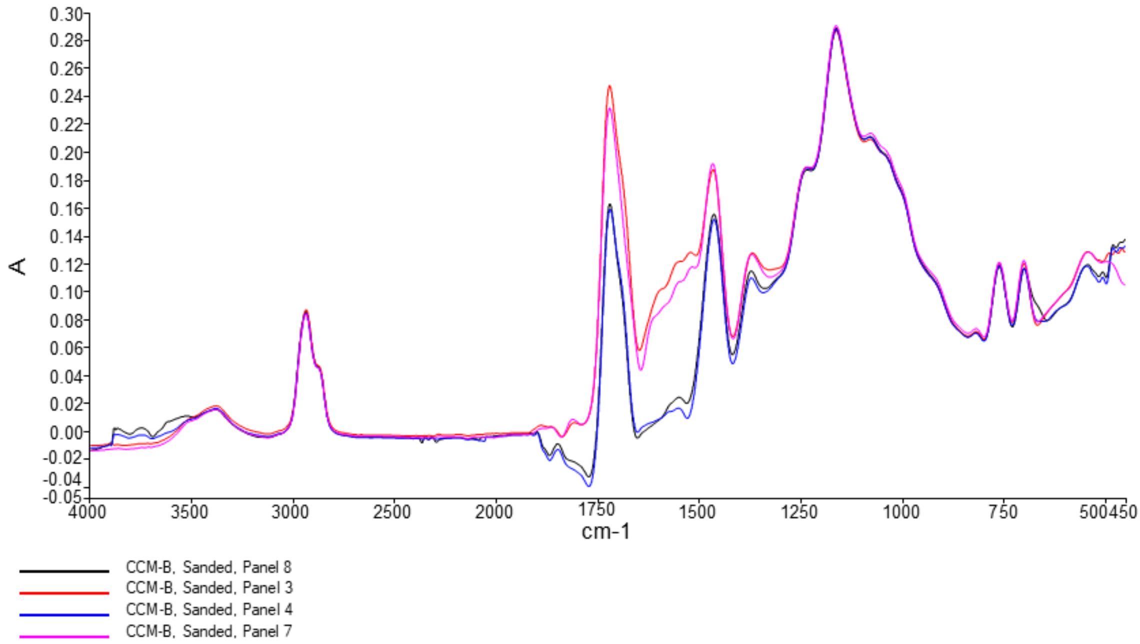

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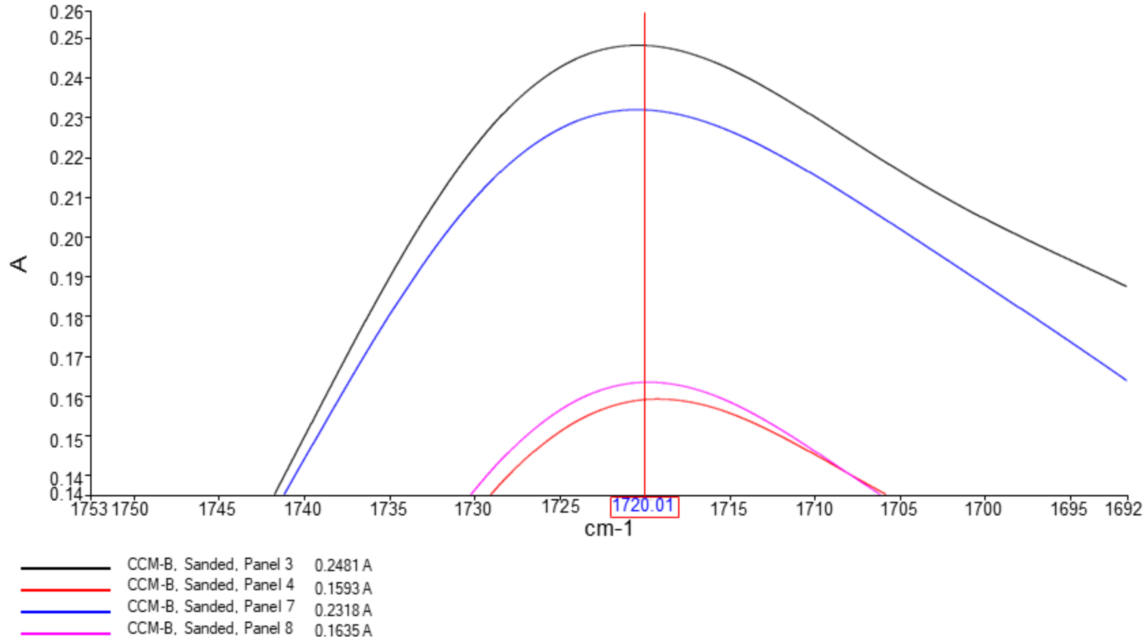

Sanded
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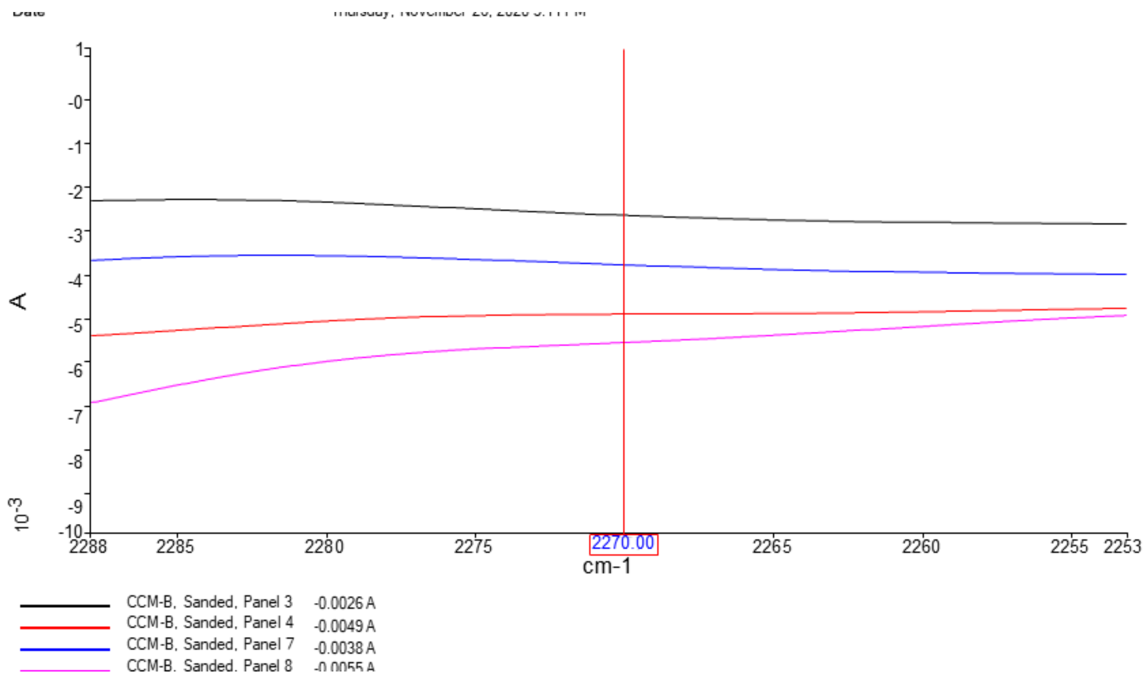
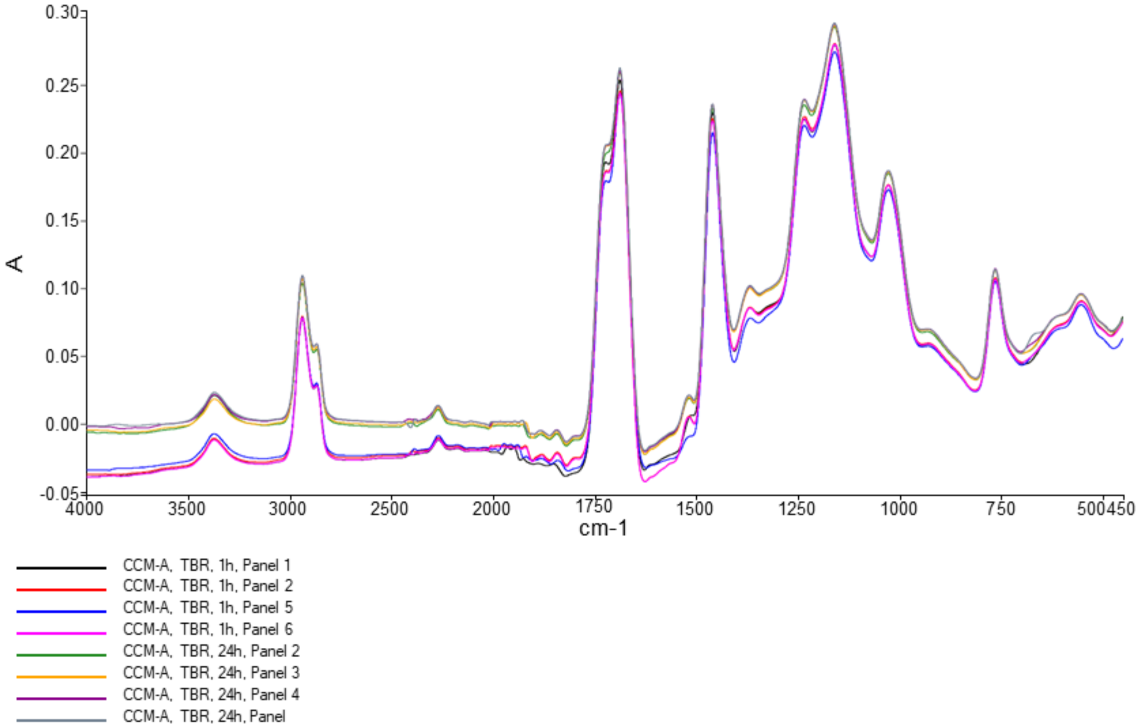


TBR
CCM-A



TBR
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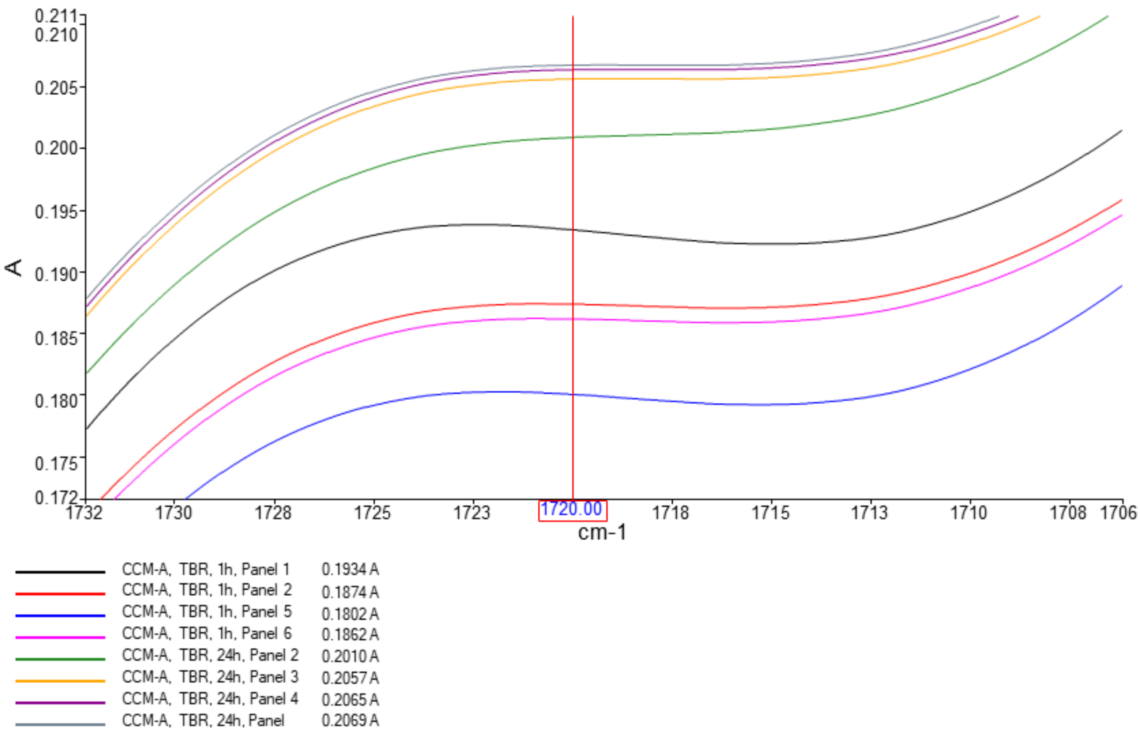

TBR
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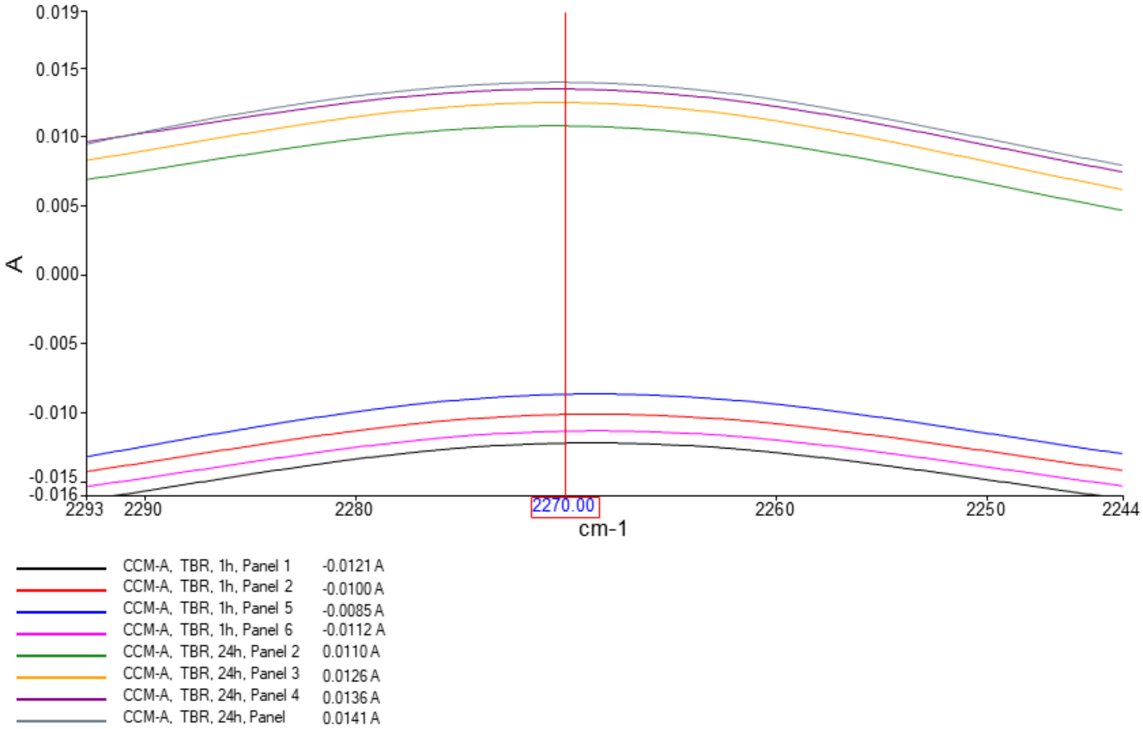

TBR
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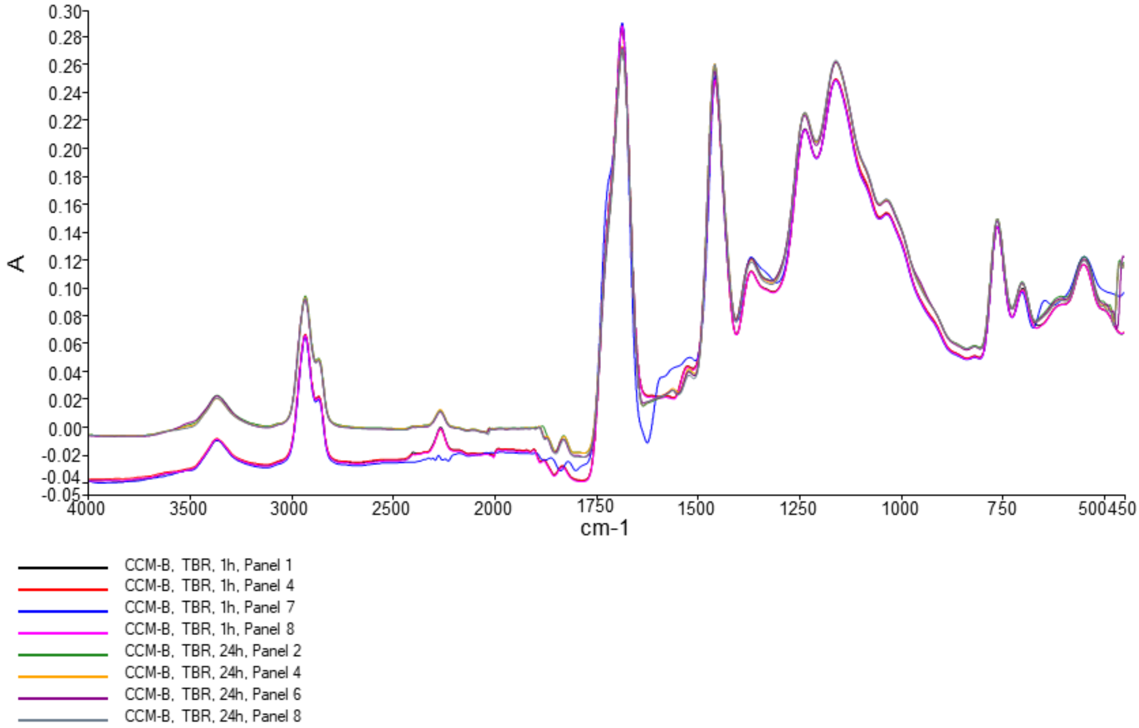

TBR
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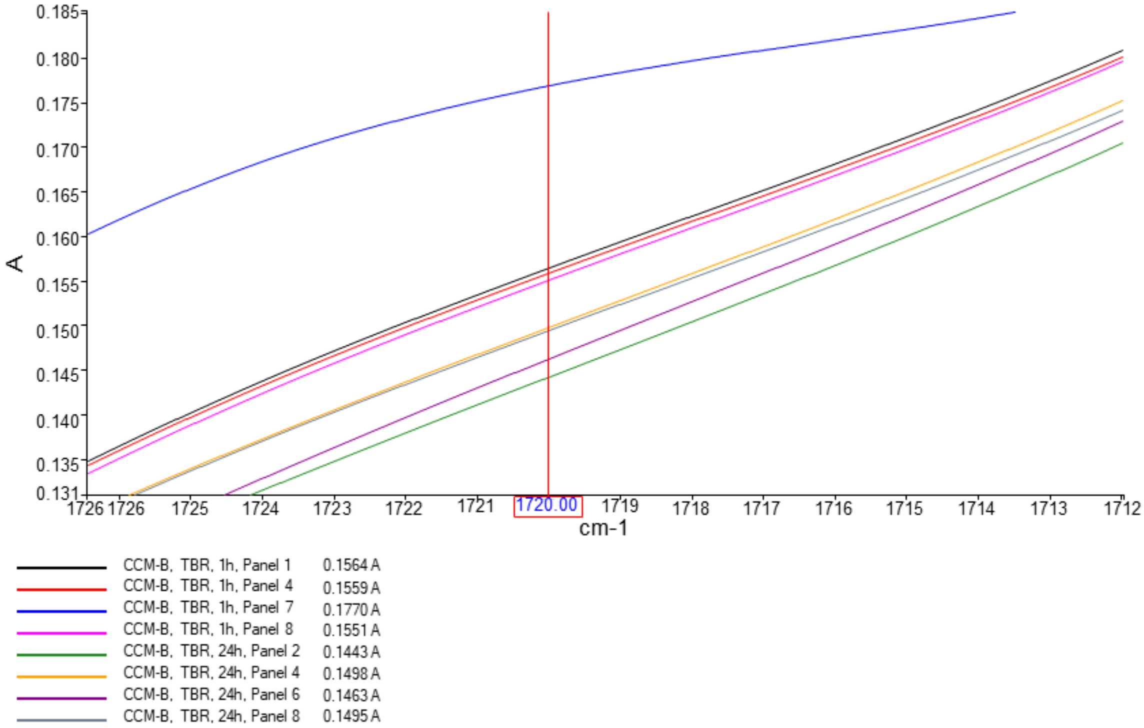

TBR
CCM-B - 2270 cm^{-1}