12-2018

Optimization of the Practice of Slow Cooling Steel Bars: A Redesign and Modernization of Materials

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Optimization of the Practice of Slow Cooling Steel Bars:

A Redesign and Modernization of Materials

An Undergraduate Honors College Thesis

in the

Department of Mechanical Engineering

College of Engineering

University of Arkansas

Fayetteville, AR

by

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July 24, 2018

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Acknowledgements

I would like to thank the Fort Smith, AR Gerdau plant for sponsoring the project and allowing me to trial materials and fabrication systems of materials within their plant. Next, I would like to thank Raymond Leasure, Michael Doss, and Gregory Leding for advising me throughout this process, assisting with data analysis, and helping me to learn how to manage different suppliers throughout the process of my thesis project. I would also like to thank my advisor, David Albers, for providing me with assistance and guidance in relation to this thesis. Finally, I would like to thank everyone else who taught me the necessary background information about this process within the plant so that I could complete this project to the best of my ability.

Abstract

Throughout the process of steel making, certain grades of steel are a higher risk for defects caused by the inability to quickly diffuse hydrogen through the steel when cooled to room temperature at a normal rate based on the ambient air temperature. To reduce the hydrogen flaking defects that are caused due to hydrogen entrapment in the steel, the process of slow cooling is utilized. This process reduces the cooling rate of steel bars by keeping them at a higher temperature for extended periods and in turn gives the hydrogen a chance to fully dissipate from the steel. In many steel mills, this process is completed using insulated boxes, however in the mill where this project is based, this is not a possibility. Storage and space issues mandate that slow cooling occur outdoors and be completed by materials that are easily managed by employees which does not allow for slow cooling to be done in insulated boxes, as the boxes would need to be heated during the winter months and stored when not in use. Additionally, the initial cost of the boxes poses an issue for the company, as fifty boxes would have to be purchased to accommodate for the maximum number of heats the company can slow cool at once. Different materials and fabrication styles were then studied based on the following requirements. First, the materials must increase the safety for employees. Secondly, the materials need to improve or retain the quality of the steel bars. Finally, the materials need to reduce the amount of waste created by the process. Due to these requirements it was determined that a new material system, specifically Material 1, was the best solution due to its inability to absorb water, weight, ease of use, and improvement in worker safety without increasing costs to the company.

List of Figures

I. Literature Review and Background Information

Definition of Terms

Slow Cooling

The process of slowing the cooling rate of a steel bar from the elevated temperature after it finishes rolling to the ambient temperature.

Hydrogen Flaking

For the purposes of this paper, hydrogen flaking will be defined as a discontinuity along the centerline of a bar caused by the entrapment of hydrogen within the steel.

Heat

A heat is a batch of steel made by Gerdau. The plant produces multiple heats per day.

Discussion and History of Hydrogen Flaking in Steel Bars

In the early 1920's, flaking was documented as a defect formed due to the presence of hydrogen within steel and a multitude of research was completed following its discovery to determine the mechanism that causes the flaking. Hydrogen flaking is defined as "an extremely complex phenomena" (Fruehan, 1997) for which "the precise mechanism is not completely understood," (Fruehan, 1997) but when simplified requires the presence of hydrogen and causes "internal hairline cracks, or shatter cracks, commonly referred to as (snow) flakes" (Fruehan, 1997). These cracks can be seen in Figure 1 below.

FIGURE 1: Hydrogen Flakes in a Steel Bar

The presence of hydrogen causes these flakes because it “tends to concentrate in the discontinuities inside the material” (Ravichandar, Nagashanmugam, & Balusamy, Slow Cooling of Hot Rolled Bars to Eliminate Hydrogen Induced Cracks in Cr-Mo Steels, 2015). When the concentration of hydrogen is high enough, and the cooling rate is too fast, the hydrogen “can recombine to molecular hydrogen and create very strong localized pressures,” (Ravichandar, Nagashanmugam, & Balusamy, Slow Cooling of Hot Rolled Bars to Eliminate Hydrogen Induced Cracks in Cr-Mo Steels, 2015) and in turn, these pressures can “exceed the strength of the steel and cause fractures or hydrogen flakes” (Ravichandar, Nagashanmugam, & Balusamy, Slow Cooling of Hot Rolled Bars to Eliminate Hydrogen Induced Cracks in Cr-Mo Steels, 2015). These hairline cracks weaken the steel, decreasing its capacity for load bearing and increasing the brittleness of the steel. This is especially crucial since the most vulnerable types of steels to hydrogen flaking are high-strength steels (Hydrogen Embrittlement, n.d.). For companies looking to buy a high-strength clean steel, hydrogen flaking can be detrimental to their processes. Therefore, companies that produce specialized steel must ensure that there is no hydrogen flaking within their bars to guarantee that the quality matches the customer specifications. When bars are inspected, and hydrogen flaking is found, the bars are scrapped, as the defects within the steel do not allow it to be a useable product. In turn, this creates a large cost for the company if the flaking is not eliminated within the processing of the steel.

For years it was thought that the degassing of steel, or the "elimination of dissolved gasses especially hydrogen and nitrogen" (Steel Degassing, n.d.) would completely eradicate the issue of hydrogen flaking in steel. This process, shown in Figure 2, requires the holding tank that contains the steel ladle to be placed under a vacuum which allows for the "heavy flow of inert gas" (Satyendra, Vacuum Degassing Processes for Liquid Steel, 2016) to be removed through the "rapid evacuation of the vacuum tank," (Satyendra, Vacuum Degassing Processes for Liquid Steel, 2016). The quality of the degassing process is based upon the remaining hydrogen content in parts per million (ppm). A quality degas has a remainder of less than 2.0 ppm, and the aim for the degassing process is to finish with a remainder of less than 1.0 ppm.

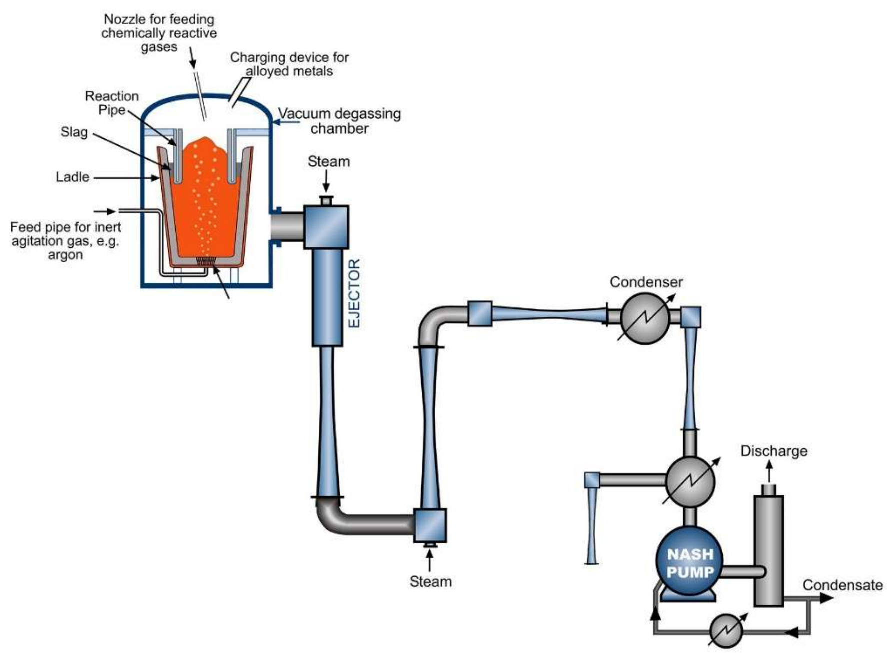

FIGURE 2: Vacuum Tank Degassing Process

Although this process removes most of the hydrogen from within the steel, it does not eliminate the issue of hydrogen flaking, as hydrogen can be reintroduced into the steel during the casting process. Instead, to assist in preventing hydrogen flaking, steel bars must undergo the process of slow cooling. This process allows for the diffusible hydrogen to move through the steel from the center to the exterior surface and out of the bars. To allow for this process to work, after the steel bars have been processed by an inline mill, the bars must be kept above 390°F but below the transition temperature for a complete bainite transformation of the steel (about 430°F) (Commission). In doing so, the hydrogen can easily diffuse while the steel is still in a Body Centered Cubic Structure, and not a Face Centered Cubic Structure. This is due to the "larger inter-atomic spacing" (Ravichandar, Nagashanmugam, & Balusamy, Slow Cooling of Hot Rolled Bars to Eliminate Hydrogen Induced Cracks in Cr-Mo Steels, 2015). This information is expanded upon by Quarrell (n.d.) where he argues that "hydrogen in steel obeys Fick's law",as shown in Equation 1 in Appendix A. Along with this, Sarkar (2016) contends that the "Solubility of hydrogen in steel increases with increasing temperature…" and "depends on the crystal structure." This is shown in the Figure 3 below where the temperature of low-alloy steel is graphed against the solubility of Hydrogen in parts per million (Hydrogen In Steels, n.d.). The phases of steel are also included within the graph.

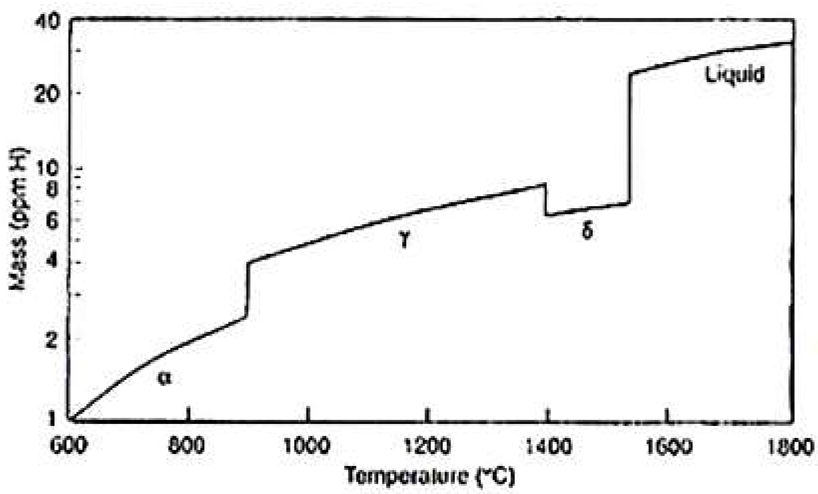

FIGURE 3: Solubility of Hydrogen in Low-Alloy Steel

In addition to temperature, the time for hydrogen to fully dissipate through the steels is crucial for reducing the chance of hydrogen flaking as the process is intrinsically slow. "It may take 12 hours to 30 hours and even more depending on the size and hydrogen content of the steel" (Sarkar, 2016). This is shown in Figure 4 below in which the temperature profiles and time to cool of slow cooled and air-cooled bars are plotted (Ravichandar, Nagashanmugam, & Balusam, Elimination of Hydrogen Induced Cracks by Slow Cooling After Hot Rolling of Medium Carbon Molybdenum Steel Blooms, 2014).

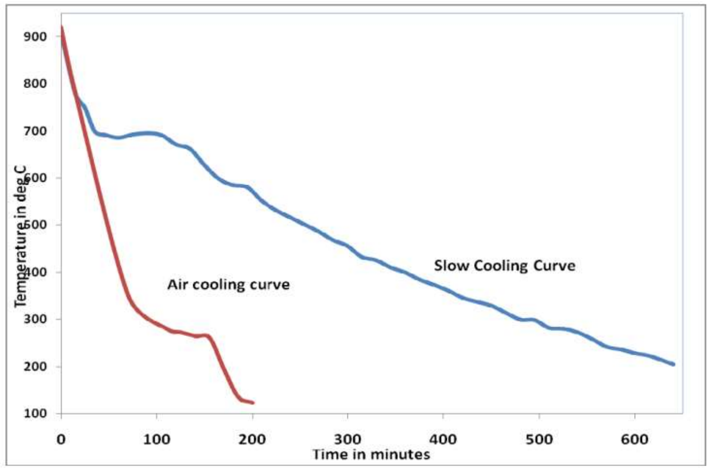

FIGURE 4: Temperature Profiles of Air and Slow Cooled Bars

Even if bars are not being slow cooled, time is a crucial factor in crack formation. "Flake cracks appear after a certain incubation time at temperatures lower than 200°C" (Eiselt, May, & Hein, 2013).. This means that if tested immediately after processing bars, the results from the testing can show that the steel bars are completely clean, and yet a week later, the bars could be tested again and show hydrogen cracking. The incubation period for crack formation "depends on the sensitivity of steel to the formation of flakes" (Smialowski, 1962) and "the cooling rate of the steel after hot-working" (Smialowski, 1962). This incubation period though, does not occur if the steel is cooled at "very low cooling rates" (Smialowski, 1962). This information leads to the conclusion that the both the temperature at which special steels are cooled (between 290°F and 430°F) and the speed at which the steel is cooled are crucial to the elimination of the occurrence of hydrogen cracking.

II. Goal and Objectives

The goals of this project were to reduce rejection rates due to hydrogen cracking for hydrogen sensitive grades, increase safety for workers within the slow cooling area, and to diminish the environmental impact of this process within the plant. To do this, the following objectives were created. The first objective was to determine the best and most cost-effective system for slow cooling materials, whether this was using a new material to cover heats that were to be slow cooled, or to create a completely new process for slow cooling materials. The second objective was to design and fabricate a cover system based on the analysis and results from the first objective. Finally, the system (or systems) would be tested, analyzed, and compared based upon the goals stated previously.

Requirements for the Project

1) The Corporate Culture within the company is to achieve the utmost level of safety. One of the goals of this project is to support that culture by finding an alternative solution that will lessen or eliminate the safety risks associated with the process of slow cooling.
2) While improving the safety of the slow cooling process, the system must increase or retain the current quality of the steel bars. Covering material must be waterproof to ensure that the bars are not cooled too rapidly in the middle of the slow cooling process. This is a current issue for the company, as rain has caused higher-than-average rates of flaking and the addition of extra waste since the wet slow cooling material cannot be reused. It also included making sure that the new system had the same or better insulative properties. This ensured that the bars will be slow cooled at the appropriate temperature. To determine this, thermal resistance (R) values for the different systems were calculated and compared to the R value of the current system that has worked for the past 30 years. The R value was selected as a discerning factor as it took the thickness of the insulation into account.
3) The new system should have less waste than the current process, in which the material is scrapped after every three uses, or after every time it rains. This attributes to over 250,000 pounds (lbs.) of waste each year. Therefore, the new system must have less than 250,000 lbs. of waste per year.

III. Design of the System

The design of materials began by a discussion with the company about different options available to slow cool the steel bars. Many plants use “boxes” such as the one below in Figure 5, (Dhakshanamoorthy, Bommannan, & Thangavel, 2016), while others lay different materials over the steel as a “blanket” as shown below in Figure 6.

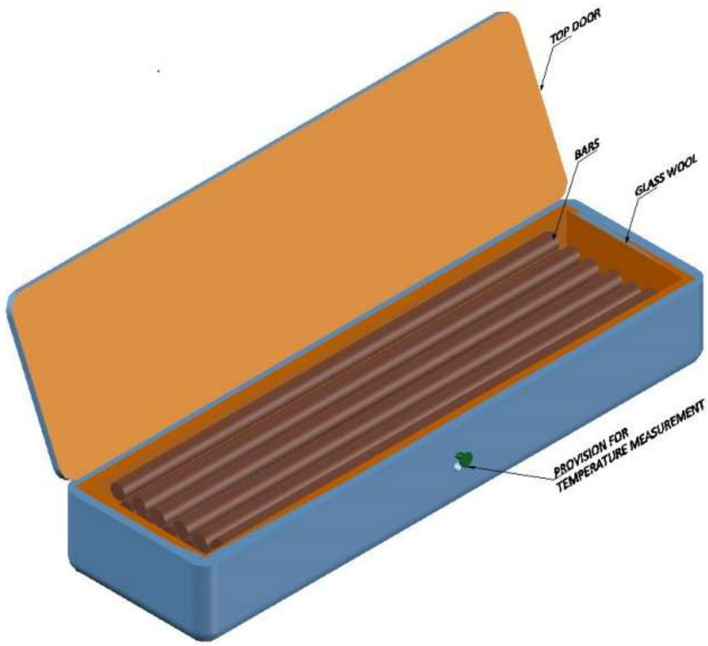

FIGURE 5: Steel Bar Slow Cool Box Schematic

FIGURE 6: Steel Bars Slow Cooling under a Blanket

Following a discussion with the company, a multitude of issues were found with each idea. Therefore, a Down Select Matrix was completed to compare the different ideas, as shown below in Figure 7.

Customer Requirement	Units	Slow Cool Box Container	Current Slow Cool Blanket	Slow Cool Blanket out of Waterproof Materials
Cost	Dollars	1	10	8
Ease of Use	Weight of System and Ease of Movement	2	8	10
Waste	Pounds	10	1	8
Robustness	The system is not easily Damagaed or torn	10	1	6
Waterproofing	Does the system absorb any water	10	1	10
Insulation Value	R-value	8	1	10
Safety Risk	How safe is the system to use	8	5	9
	TOTAL	49	27	61

FIGURE 7: Down Select Matrix

As seen above, slow cooling with a blanket made from water proof materials was considered to be the better option. Concerning the slow cool containers, they are expensive on the front end as each container can cost upwards of $25,000 and with a maximum of 50 heats slow cooling at one time, the initial cost for 50 boxes would be over a million dollars. Furthermore, pending capital improvements to the plant could render the boxes null and void in the next few years which would negate the value of this investment. In addition, the metal containers are hard to store and are required to be moved by fork trucks which could pose a safety risk to any employees nearby when boxes are being moved. Finally, in the winter, the boxes would have to be heated to ensure that the cold boxes would not increase the rate of cooling based on Newton's Law of Cooling, as determined by Equation 2 in Appendix A.

After it was determined that the best option for the project would be to continue with a waterproof blanket material, multiple suppliers were contacted for samples of high temperature waterproof material systems. Once the samples were received, they were tested to determine if it was possible that they would survive within this application. This testing is discussed more in the next section.

Following this, ultimately, the 5 materials systems were examined in comparison to the ceramic fiber blankets and their layered properties are shown below in Figures 8 and 9 below. Since Material 3 was an inch of bare insulation with an invisible waterproof coating, a cross section view is not shown.

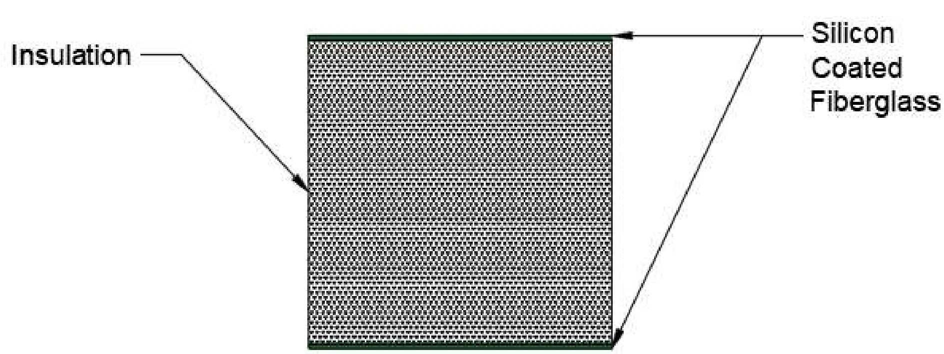

FIGURE 8: Cross Section view of Materials 1 and 2

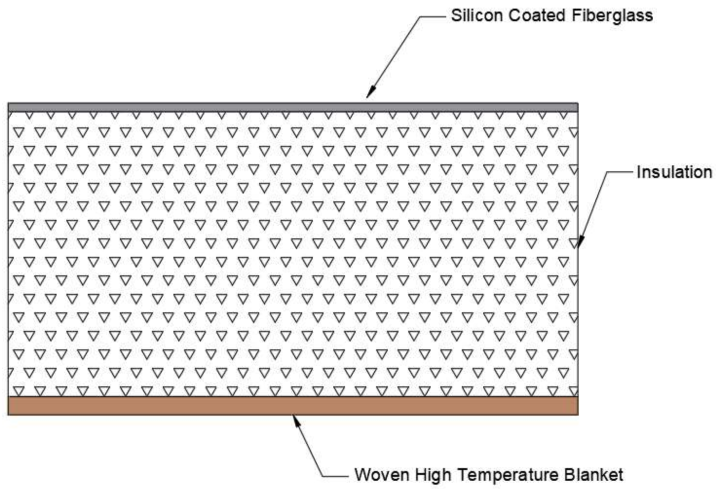

FIGURE 9: Cross Section view of Material 4

When the material systems were examined Material 4 was scrutinized as the woven high temperature blanket layer was not completely waterproof. After being assured by the supplier that this would not be an issue as the woven blanket was to be placed against the steel and therefore would not get wet, the material was included in the trials anyway. Other material systems were examined, and those that did not meet the specifications without adequate reasoning were omitted from the project.

After the sub-par materials were eliminated, the thermal resistance (R) values were calculated for the remaining materials using Equation 3 in Appendix A. In addition to this, when materials were added to the trials their R values were also calculated. The calculated values, in (hr-ft^2-°F)/Btu, were as follows: for the original material R=.625, for Material 1 R = 1.422, for Material 2 R = 1.047, for Material 3 R = .953, for Material 4 R = 2.13 and for Material 5 R = 2.735. All the materials, except for Material 2 were determined to be considerably more insulative than the original material as their R values were more than double that of the original material. Material 2 was determined to be more insulative, but not to the point in which it would impact the slow cooling of the steel bars, when the heat transfer rates were calculated based on Equation 4 in Appendix 2.

IV. Testing of Materials

Initially, the sample materials were placed on a small section of a hot steel bar within the Rolling Mill for 15 minutes. The bar temperature was 632°F which is above the absolute maximum temperature at which the hot rolled bars leave the Rolling Mill. While on the steel bar section, the temperature of the samples was tracked, and the reaction of the materials were examined to determine if they were melting or burning. After the materials had been tested on a hot steel bar section, they were held in a bowl shape and water was poured on top of them. The water was allowed to stand on the material for 30 minutes to determine if water would be absorbed by the material system. All of the trial materials were then dissected to determine if water had been absorbed. In doing this, materials that had no chance in surviving in the harsh environment outdoors were excluded from consideration.

Subsequently, once it was determined that the trial materials had the potential to withstand the slow cooling environment, they were taken outside and used in the environment under close supervision. To assist in determining if the materials performed adequately, the exterior temperature of the trial materials and the exterior temperature of the ceramic fiber blankets were recorded and monitored. (The sheets in which the data was recorded can be found in Appendix E Figures E1-E6.) This information was used as a way to monitor the trial materials and any possible deterioration in their insulative properties as the number of times the materials were used increased. Additionally, the insulative properties of the materials were tracked with infrared camera images that can be found in Appendix D, Figures D1-D2. The temperature data recorded in the trials was analyzed and is discussed in Section V, analysis of results.

During the material trials, heats that are normally slow cooled were selected to be partially covered by the trial materials and partially covered by the original material that is normally used within the process. Every 12 hours, the exterior temperatures of all the materials were recorded until the heats were "removed" from slow cool. The decision to trial the materials in this manner caused a possible source of error to occur. This source of error was the fact that the trial materials were placed on different heats and therefore the trial materials could not be as easily compared to one another as they were subject to different temperatures throughout the trial. However, this source of error seemed negligible as the new materials needed to be compared to the original material, more so than they needed to be compared to the other trial materials.

Material 1 performed well in the first trial. There were a few scorch marks on the trial material, but were easily removed by water. The edges of Material 1 were a point of concern during the trials, as they were unfinished, but later in the trials it was determined that the unfinished edges had no effect on the durability of the material. When the material was first placed upon the heat, smoke escaped from the interior side of the material, but based on the recommendation of the supplier, this was ignored. The reasoning behind this is that the smoke was caused by the binding materials used in the creation of the silicon layer on the exterior of Material 1 burning due to the high heat. Based on the temperature the material was subjected to and the open environment that the material was being used in, this smoke did not create an additional safety issue. After the steel was removed from slow cool, the material was able to be folded and stacked on the pallet to be stored.

Material 2 also performed well in the first trial. The size of the sheet, however, seemed too large for the employees to easily handle. Both materials had scorch marks after being removed from the steel, but were easily removed by rubbing them with a small amount of water. Moreover, storing the material was troublesome as the material had to be rolled and then stacked on a pallet. This could become an issue due to the weight of the material and the chance that a single employee may have to handle the material alone.

Material 3, which was like the original material with the addition of a waterproofing coating, held up through the first trial. Of note, this material let off a strange dust when being rolled and began to deteriorate, creating a fibrous dust similar to what the original material produced when handled. The material also absorbed dirt from the ground and had a few minor scorch marks. These issues caused the employees to be wary of the material and its future abilities.

The second trial of materials was completed to test the effect of rain on the materials. Since only a light rain occurred during the trial, the trial was repeated later. After this trial, the workers concluded that they prefer Materials 1 and 2. During the trial, neither material soaked up water or became waterlogged. Additionally, Material 1 was easy to use, stayed colder on the outside, and did not deposit any residue onto the employees clothing. Material 1 did obtain a small tear when it was dragged across the steel, but it did not affect the effectiveness of the material. The employees also preferred Material 2 in relation to the rest of the materials as it was easy to use, did not smoke when heating up, and the exterior stayed colder than the original material.

Material 2 also did not tear during the trial. The workers liked the idea that this material might be able to interconnect over the heats using the hooks that were incorporated in to the construction of Material 2. Along with this, the workers liked the size of the material. It was heavier, but it's large size made covering a heat faster as the employees had to place less sheets of material on the steel. Some black streaks also appeared on Material 2 during this trial, but like on Material 1, they rubbed off easily.

Material 3 was not preferred as it absorbed dirt and tore easily when rubbing against the bars. This material was removed from testing after this trial because the waterproof coating on the material was compromised and the material began to absorb water. Along with this, there were some safety concerns from the workers, due to the residue it was leaving on their clothing and the fibers it was releasing into the air when being rolled up and placed into storage. There were also concerns about the Safety Data Sheet of this material as many of the hazards listed had a statement next to them asserting the fact that the material not been tested. Finally, the material was easily damaged after rolling and storing it multiple times.

After 5 trials of Materials 1 and 2, Material 4 was introduced to the project. This material underwent the same initial trials to determine the viability of its use, and it passed. This material was composed of a waterproof outer layer, insulation, and heat resistant inner layer that was not waterproof. After the 3rd trial of Material 4, the material became waterlogged and was eliminated as a possibility for this project. Subsequently, it was also determined that Material 1 had better insulative properties than Material 2 and weighed less per square foot making it easier to handle.

As the trials continued, the main issue with Material 1 was that the small blanket size (4 feet by 8 feet) caused the employees to use more material to cover the steel, as the individual sheets of material had to be was overlapped to ensure the steel was fully blanketed in the material. Therefore, the supplier for this material was requested to develop a new material system. Material 5 was created to increase the size of the sheets of the material and reduce the cost of the material as there was no quilting. This material was introduced after 39 trials of Material 1, the initial material system from the supplier. Material 5 was also eliminated as a possibility for the project after 20 uses as sheets with and without visible damage became waterlogged and too heavy to handle. Finally, the lack of quilting and increased size of the sheets made it easy for the sheets of the material to become torn when dragged across sharp portions of the steel bars.

Other materials were tested and eliminated from the project as they did not meet the initial specifications. One material appeared to meet the specifications of the project, but when it was tested on steel bars in the slow cooling area, the threads burned and the material began to melt. When it began to look like the material was failing, it was immediately removed from the steel and fell apart completely upon removal. This supplier was also eliminated from the project as this was the third material they brought to trial that did not meet the given specifications.

As the trials progressed, and it was determined that Material 1 sustained the least damage throughout the process and was the easiest for the employees to handle, due to its light weight. Even when Material 1 was damaged, the waterproofing on the material stayed intact. Along with this, it was determined that each of the quilted squares on Material 1 could be repaired and the material could continue to be used. Material 2 was determined to be a good back up plan, but the large size of the sheet and the weight of the sheet made the material hard to handle for the employees. In addition to this, the material had lower insulative properties in comparison to Material 1 and cost more per square foot than Material 1.

V. Analysis of Results

The most important factor in this project is the safety of the process, which includes the storage, handling, and disposal aspects of the material. Due to the fact that Material 1 was the most promising material after the trials, the data sheet was most critically compared to the original material. The first difference identified was the storage requirements defined in the Safety Data Sheets for the materials. Material 1 can be stored without any precautions while the original material must be stored to minimize airborne dust. There are possible respiratory issues with both materials, but the risks are mitigated in a well-ventilated environment such as the outdoors. In the case of this process, this is true. Furthermore, in the Exposure Controls/Personal Protection section, Material 1, identifies that the individuals handling the project should wear common PPE items (gloves, long shirt, long pants) while the Safety Data Sheet for the original materials identifies these items, but also specifies that the clothes should be carefully cleaned as to minimize exposure to the product's dust.

The next requirement of the project was to improve or maintain the quality of the steel bars. To do this, the testing data for the number of bars that were rejected due to center line defects from the trial heats were surveyed in contrast to the testing data from the heats produced under normal conditions. The top 12 types of steel in the trial were initially examined in comparison to the normal heats of the same steel type to gain an overall understanding of the situation, as shown in Figure 11 below. Individual trial data in regards to centerline rejects can be found in Appendix F, Figure F1. One heat was eliminated from the data as a multitude of variables other than the trial that could have caused an increase in centerline defects were identified in relation to the heat.

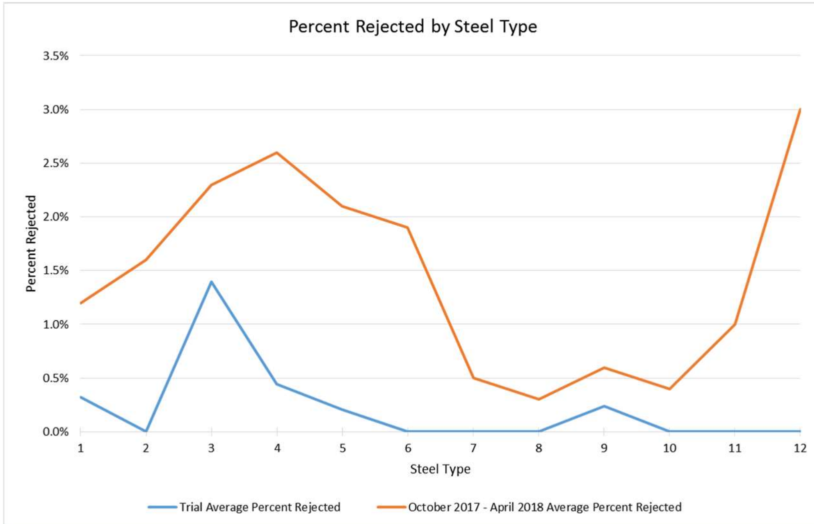

FIGURE 10: Percent of Centerline Rejects by Steel Type

The number of overall centerline rejects for the plant was then compared to the average number of centerline rejects for the same months of the previous year. This data is shown in Figure 12 below and the orange line represents the percent rejected for the months in which the trial occurred. A few trials did occur in the later months of 2017, but when the number of trials was compared to the total number of heats slow cooled during these months, it would have been impossible for the trials to have made a statistical impact.

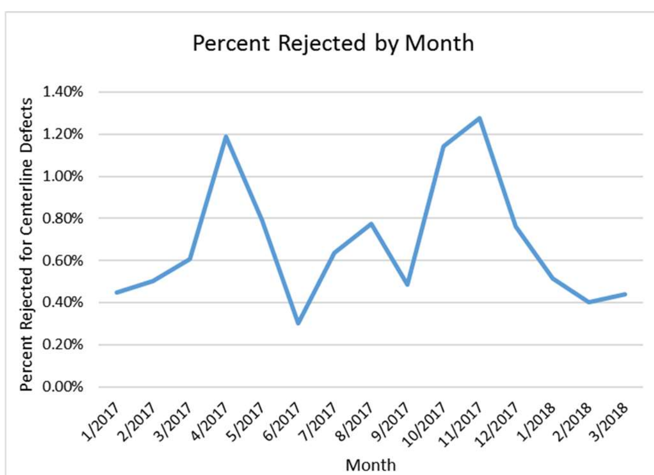

FIGURE 11: Percent Rejected by Month

Both the trial and normal data for centerline core rejections were analyzed statistically using Control Charts, Proportions tests and Mann-Whitney tests since the data was nonparametric. Due to the nature of these tests and the fact that the differences in the sampling sizes was so large, it was determined that the trial materials at this point in time have had no significant impact on the quality of the bars. Along with this, the quality of the bars covered with the trial materials may increase in the rain, but there was not enough evidence at the time of the trials to prove the quality increased. These results were discussed with a Six Sigma Black Belt within the company and it was determined that based on the variability of the process of creating the steel bars, the statistically indeterminate results may be all that is achieved.

Due to the statistically indeterminate results, an analysis of the insulative properties of the materials was conducted. Since only the exterior temperatures of the material could be tracked throughout the process in order to contain the heat within the systems and based on the stacking and bundling requirements of the heats, calculating the heat transfer rates for the materials became complicated. Therefore, worst-case scenarios were used. Newton's Law of Cooling was first used to calculate the time it would take for a single steel bar to cool in the average ambient temperature during the month that the heat was produced if no insulation was placed on the bar. These calculations yielded an average time of 10.65 hours to cool to ambient temperature, a minimum time of 4.92 hours and a maximum time of 18.88 hours. Next, Newton's Law of Cooling was used to determine the percent change in the temperature of a single steel bar to the temperature the steel bar would be five minutes after it was resting in ambient temperature. This calculation yielded an average percent change of 3.67%, a maximum change of 6.01% and a minimum change of 2.02%. The main reason for these calculations was to determine if using the initial cover temperature to calculate the heat transfer rate five minutes after the heat had been covered would be appropriate. It was determined these percent changes were negligible in this experiment as there is heat transferred from the other bars and insulation that would reduce the percent change in the temperature. The initial temperature of the bars and the exterior temperature of the material after five minutes was then used to calculate the heat flux and the heat transfer rate for five minutes through a one-meter square section of the material. The average heat transfer rates determined are shown below in Figure 12. Averages were used to compensate for deviation due to human error. Human error occurred in the temperature measurements due to not measuring the exact same areas on the heat, multiple different employees taking temperatures, and not measuring the temperatures at the prescribed times.

Heat Transfer Rate by Material (Btu/hr)	
	Average Heat Transfer Rate
Original Material	58.86
Material 1	55.86
Material 2	52.69

FIGURE 12: Heat Transfer Rate by Material

Materials 3, 4, and 5 were not examined as they were eliminated from the trial due to other reasons. The percent reduction in the heat transfer rate was then calculated for each trial individually. Based on these results, it was determined that when Material 1 was compared to the original material, it reduced the heat transfer rate on average by 30.59%, with a minimum reduction of 8.33% and a maximum reduction of 62.50%. Material 2 when compared to the original material reduced the heat transfer rate by an average of 30.51%, with a minimum reduction of 8.33% and a maximum reduction of 58.02%. This means that when the trial materials were used, less heat escaped from cover and therefore the steel bars stayed hotter. In turn, because the temperature of the steel bars stayed higher, the hydrogen within the bars should diffuse out of the steel with less difficulty.

The exterior temperatures of the bars were also examined to verify the heat transfer rate calculations. This was based on the logical thought process that if the temperature is lower on the exterior of the trial material when compared to the exterior of the original material, there is less heat transfer occurring through the trial material. Like the calculations done previously, this examination is simplified, as there is heat generation within the covered system due to the fact that the bars are bundled and the bundles are stacked closely together and the fact that the stacks of bundles do not rest on the ground. The average exterior temperatures of the test materials used and the original material on the same heat are shown below by trial in Figure 13. The raw data from which the graph was made can be found in Appendix B, Figures B1-B5.

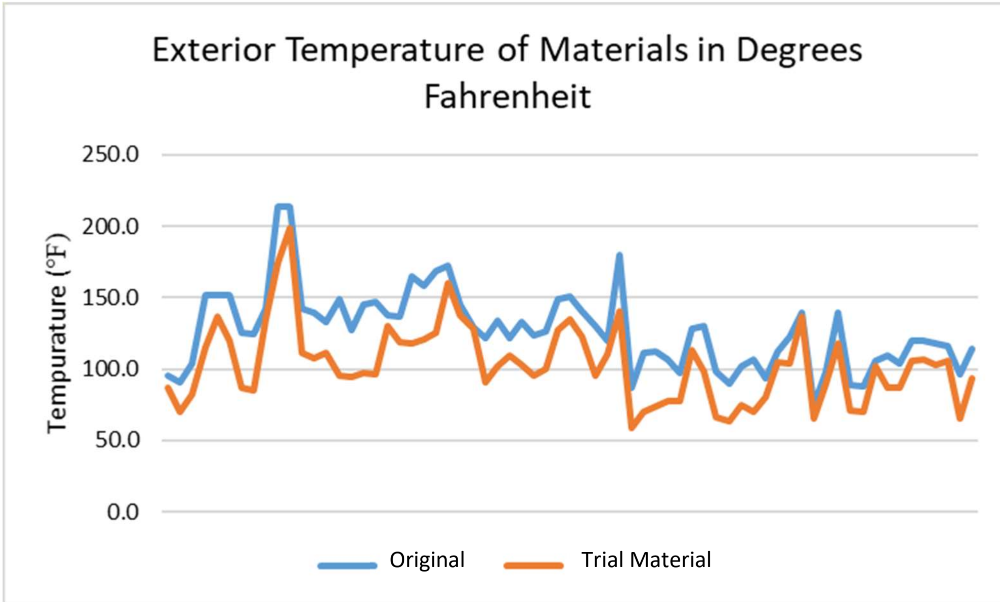

FIGURE 13: Average Exterior Temperature of Materials

It can be concluded from the graph, that the average exterior temperatures of the trial materials were colder than that of the original materials. Therefore, this information verifies the previous calculations showing that Materials 1 and 2 had a lower heat transfer rate than the original material. Due to the indeterminate statistical evidence and the decrease in the heat transfer rates, it was determined that the requirement to maintain or increase the quality of the steel bars was achieved.

The final requirement of the project was to reduce the amount of waste that occurs due to this process. At a maximum, each roll of the original material can only be used three times, if it is well cared for and not damaged by rain. Material 1 has been used over 50 times and was still in use at the conclusion of this trial. Approximately 250,000 lbs of the original material is sent to the landfill each year. If we assume that the material was dry, this weight corresponds to approximately 2605 blankets. Three uses each of 2605 blankets equals 7813 total uses. To get the same number of uses from Material 1, we would need 157 blankets the same size as the original material. Since Material 1 is 12.5 times smaller than the original material though, this equates to 1963 blankets of the new material. Each blanket of Material 1 weighs 14 lbs and therefore, the total weight of 1963 blankets is 24,475 lbs. This is a 90.21% reduction in the amount of waste sent to the landfill. Of course, the actual reduction of waste could be larger or smaller, due to the fact that some of the material sent to the landfill in either case could be wet and since there is variability in the number of uses for each blanket. The error in this calculation, based on the variability of in the number of uses and the amount of water absorbed by the material when it is delivered to the landfill, is not large enough to change the fact that there will be a future reduction in the amount of landfill waste.

Finally, the cost of materials was examined to ensure that there is not a major increase in the overall cost for the process. Material 1 is more expensive than the original material, but this is negligible when the number of uses for each material is examined in conjunction with the cost. Additionally, there will be a slight decrease of the cost with the reduction of waste from the process being sent to the landfill. Therefore, due to the ease of use, ease of storage, increase in safety, and statistically indeterminate impact on quality or cost, it was recommended that the company transition from using the original Material to using Material 1. If the company wished to do more analysis in the future though, recommendations would include experimentally calculating the temperature gradient throughout the heat of steel by taking thermal imaging photographs of each bundle individually before and after slow cooling and recording their location in the stack, as well as trying to find a way to continuously measure the temperature of the heat in multiple places to reduce the human error previously discussed.

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VII. Appendices

Appendix A: Equations Used

Fick's Law (Quarrell)

$$\frac{dm}{dt} = -D\frac{dc}{dx} \quad [Eqn. 1]$$

Where:

dm = the mass transferred across the area
dt = the time dt when the concentration gradient is dc/dx
dc/dx = the concentration gradient
D = the diffusion coefficient

Newton's Law of Cooling

$$T(t) = T_S + (T_0 - T_S)e^{-kt} \quad [Eqn. 2]$$

Where:

T(t) = the temperature of the material at a given time (Kelvin)
t = time (Seconds)
T_S = temperature of the surroundings (Kelvin)
T_0 = temperature of the object (Kelvin)
k = thermal conductivity specific to the material

Thermal Resistance

$$R = \frac{t}{k} \quad [Eqn. 3]$$

Where:

t = thickness
k = thermal conductivity specific to the material

Heat Transfer Rate Due to Conduction

$$q = k * \frac{(T_{S1} - T_{S2}) * A_C}{\frac{L}{A_C}} \quad [Eqn. 4]$$

Where:

q = the heat transfer rate in Btu/(hr*ft*°F)
k = thermal conductivity specific to the material
T_{S1} = temperature of the inner surface
T_{S2} = temperature of the outer surface
L = thickness of the material (ft)
A_C = cross sectional area of the material

Appendix B: Temperature Data

Material 1

Trial Number	Date	Initial Temperature (F)		12 Hour Temp (F)		24 Hour Temp (F)		36 Hour Temp (F)		48 Hour Temp (F)		60 Hour Temp (F)		Averages		TM-CW
		CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	
1	27-Oct	178.0	130.0	176.0	75.0	85.0	61.0	60.0	60.0	71.0	122.0	54.5	47.3	104.1	82.6	21.5
2	31-Oct	185.6	105.8	147.2	145.9	123.0	93.2							151.9	115.0	37.0
3	6-Nov	154.0	110.0	126.0	93.0	159.0	80.0	110.0	83.0	80.0	70.0			125.8	87.2	38.6
4	6-Nov	147.0	119.0	236.4	295.1	148.0	102.0	~~98.0~~	~~79.0~~	~~82.0~~	~~78.0~~			142.3	134.6	7.7
5	8-Nov	245.0	178.0	210.0	176.0	185.0	170.0							213.3	174.7	38.7
6	10-Nov	230.0	175.0	130.0	91.0	90.0	85.0	~~82.0~~	~~95.0~~					133.0	111.5	21.5
7	14-Nov	220.0	110.0			118.0	90.0			110.0	85.0			149.3	95.0	54.3
8	14-Nov	220.0	110.0			115.0	93.0			100.0	90.0			145.0	97.7	47.3
9	16-Nov	195.0	185.0			115.0	110.0			102.0	96.0			137.3	130.3	7.0
10	27-Nov	220.0	130.0	220.0	130.0	148.0	115.0	135.0	130.0	103.0	84.0			165.2	117.8	47.4
11	1-Dec	172.0	160.0											172.0	160.0	12.0
12	5-Dec	230.0	170.0	115.0	130.0	114.0	125.0	115.0	118.0	100.0	112.0	100.0	112.0	129.0	127.8	1.2
13	5-Dec	226.0	175.0	158.0	103.0	125.0	89.0	102.0	82.0	95.0	82.0	95.0	82.0	133.5	102.2	31.3
14	13-Dec	220.0	180.0	100.0	90.0	95.0	87.0	70.0	80.0					121.3	109.3	12.0
15	15-Dec	248.0	203.0	147.2	66.0	75.0	60.0	60.4	80.9					132.7	102.5	30.2
16	15-Dec	239.0	204.8	118.0	66.0	78.0	54.0	71.6	74.3					126.7	99.8	26.9
17	18-Dec	200.0	190.0	200.0	190.0	205.0	122.0	80.0	80.0	60.0	55.0			149.0	127.4	21.6
18	18-Dec	215.0	185.0	215.0	185.0	148.0	98.0	76.0	80.0	50.0	65.0			140.8	122.6	18.2
19	19-Dec	170.0	115.0	130.0	95.0	90.0	75.0							130.0	95.0	35.0
20	22-Dec	180.0	140.0	180.0	140.0									180.0	140.0	40.0
21	3-Jan	135.0	90.0	105.0	75.0	85.0	50.0	60.0	40.0	50.0	40.0			87.0	59.0	28.0
22	5-Jan	150.0	100.0					75.0	48.5					112.5	74.3	38.3
22	5-Jan	150.0	108.0					64.0	47.0					107.0	77.5	29.5
23	9-Jan	197.0	116.0	109.0	111.0	135.0	143.0	95.0	97.0	107.0	97.0			128.6	112.8	15.8
23	9-Jan	257.0	135.0	133.0	113.0	80.0	74.0	90.0	85.0	90.0	84.0			130.0	98.2	31.8
24	12-Jan	115.0	80.0	110.0	68.0	70.0	50.0							98.3	66.0	32.3
25	13-Jan	140.0	100.0			100.0	82.0	66.0	42.0					102.0	74.7	27.3
26	16-Jan	167.0	148.0	100.0	97.0	68.0	37.0	41.0	38.0					94.0	80.0	14.0
26	16-Jan	158.0	143.0	136.0	118.0	44.0	53.0							112.7	104.7	8.0
26	16-Jan	168.0	145.0	145.0	120.0	54.0	46.0							122.3	103.7	18.7
27	18-Jan	145.0	138.0	134.0	135.0									139.5	136.5	3.0
28	20-Jan	80.0	70.0	75.0	65.0	70.0	60.0							75.0	65.0	10.0
29	21-Jan	208.0	180.0	180.0	150.0	110.0	90.0	60.0	52.0					139.5	118.0	21.5
30	22-Jan	130.0	115.0	105.0	75.0	97.0	68.0	60.0	53.0	54.0	45.0			89.2	71.2	18.0
31	23-Jan	145.0	135.0	108.0	113.0			64.0	57.0					105.7	101.7	4.0
32	24-Jan	134.0	102.0	118.0	95.0	106.0	84.0	93.0	80.0	70.0	76.0			104.2	87.4	16.8
33	26-Jan	216.0	175.0	123.0	105.0	100.0	90.0	90.0	85.0	70.0	77.0			119.8	106.4	13.4
34	29-Jan	174.0	274.0	132.0	66.0	100.0	54.0	98.0	70.0	86.0	50.0			118.0	102.8	15.2
35	2-Feb	201.0	99.0	75.0	65.0	60.0	50.0	50.0	48.0					96.5	65.5	31.0
36	10-Feb	200.0	190.0													

FIGURE B1: Material 1 Temperature Data

Material 2

Trial Number	Date	Initial Temperature (F)		12 Hour Temp (F)		24 Hour Temp (F)		36 Hour Temp (F)		48 Hour Temp (F)		60 Hour Temp (F)		Averages		TM-CW
		CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	
1	27-Oct	140.0	125.0	106.0	86.0	88.0	81.0	83.0	56.0	91.0	114.0	66.0	59.0	95.7	86.8	8.8
2	31-Oct	185.6	101.9	147.2	145.9	123.0	161.0							151.9	136.3	15.7
3	6-Nov	138.0	109.0	153.0	90.0	143.0	77.0	110.0	83.0	80.0	65.0			124.8	84.8	40.0
4	8-Nov	245.0	210.0	210.0	234.0	185.0	151.0							213.3	198.3	15.0
5	10-Nov	192.0	130.0	146.0	108.0	116.0	104.0	104.0	88.0					139.5	107.5	32.0
6	14-Nov	220.0	120.0			118.0	85.0			45.0	78.0			127.7	94.3	33.3
7	14-Nov	215.0	116.0			115.0	87.0			112.0	85.0			147.3	96.0	51.3
8	16-Nov	195.0	175.0			115.0	99.0			99.0	84.0			136.3	119.3	17.0
9	27-Nov	230.0	165.0	230.0	165.0	150.0	88.0	140.0	127.0	94.0	82.0			168.8	125.4	43.4
10	5-Dec	215.0	179.0	170.0	96.0	135.0	95.0	75.0	67.0	68.0	55.0	68.0	55.0	121.8	91.2	30.7
11	15-Dec	230.0	194.0	108.0	69.0	88.0	50.0	66.5	70.4					123.1	95.9	27.3
12	18-Dec	220.0	198.0	220.0	198.0	117.0	104.0	110.0	96.0	86.0	80.0			150.6	135.2	15.4
13	22-Dec	120.0	110.0	120.0	110.0									120.0	110.0	10.0
14	3-Jan	150.0	107.0	125.0	95.0	125.0	95.0	100.0	60.0	90.0	35.0	80.0	30.0	111.7	70.3	41.3
15	5-Jan	130.0	100.0			84.0	70.0	78.0	62.0					97.3	77.3	20.0
16	12-Jan	105.0	75.0	100.0	70.0	65.0	45.0							90.0	63.3	26.7
17	14-Jan	148.0	90.0			103.0	81.0	70.0	40.0					107.0	70.3	36.7
18	20-Jan	125.0	115.0	90.0	85.0	80.0	70.0							98.3	90.0	8.3
19	22-Jan			105.0	87.0	93.0	63.0	66.0	59.0					88.0	69.7	18.3
20	24-Jan	141.0	101.0	125.0	93.0	110.0	90.0	97.0	84.0	73.0	68.0			109.2	87.2	22.0
21	26-Jan	176.0	154.0	153.0	123.0	100.0	90.0	90.0	85.0	80.0	75.0			119.8	105.4	14.4
22	29-Jan	165.0	242.0	132.0	108.0	100.0	50.0	96.0	67.0	85.0	62.0			115.6	105.8	9.8
23	2-Feb	201.0	166.0	130.0	100.0	65.0	58.0	60.0	50.0					114.0	93.5	20.5
24	13-Feb	103.0	100.0			106.0	97.0									
25	17-Feb	102.0	115.0	110.0	100.0			69.0	94.0							

FIGURE B2: Material 2 Temperature Data

Material 3

Trial Number	Date	Initial Temperature (F)		12 Hour Temp (F)		24 Hour Temp (F)		36 Hour Temp (F)		48 Hour Temp (F)		60 Hour Temp (F)		Averages		TM-CW
		CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	
1	27-Oct	150.0	98.5	117.0	70.0	90.0	81.0	64.0	47.0	73.0	77.0	53.0	49.4	91.2	70.5	20.7
2	31-Oct	185.6	118.1	147.2	145.9	123.0	96.0							151.9	120.0	31.9

FIGURE B3: Material 3 Temperature Data

Material 4

Trial Number	Date	Initial Temperature (F)		12 Hour Temp (F)		24 Hour Temp (F)		36 Hour Temp (F)		48 Hour Temp (F)		60 Hour Temp (F)		Averages		TM-CW
		CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	CW	TM	
1	10-Nov	206.0	142.0	145.0	116.0	119.0	100.0	101.0	86.0					142.8	111.0	31.8
2	27-Nov	215.0	150.0	215.0	150.0	137.0	105.0	124.0	117.0	101.0	81.0			158.4	120.6	37.8
3	1-Dec	145.0	138.0											145.0	138.0	7.0

FIGURE B4: Material 4 Temperature Data

Material 5

Trial	Date	Initial Temperature	12 Hour Temp	24 Hour Temp	36 Hour Temp	48 Hour Temp	Average Temp
1	9-Feb	94.0	84.0				89.0
2	13-Feb	64.0	84.0	62.0	77.0		71.8
3	13-Feb	71.0		73.0			72.0
4	16-Feb	82.0	68.0	76.0			75.3
5	17-Feb	82.0	51.0	40.0	36.0		52.3
6	17-Feb	88.0	79.0	69.0			78.7
7	22-Feb	74.0	69.0	63.0			68.7
8	24-Feb	150.0	104.0	100.0		86.0	110.0
9	28-Feb	82.0	82.0	79.0		67.0	77.5
10	2-Mar	83.0	81.0	60.0	60.0		71.0
12	4-Mar	200.0	180.0	73.6	65.6		129.8
13	6-Mar	146.0			60.1		103.1
15	18-Mar	76.0					76.0
16	17-Mar	130.0	88.0	81.0	70.0	67.0	87.2

FIGURE B5: Material 5 Temperature Data

Appendix C: Photographs of the Slow Cooling Process

Material 1

FIGURE C1: Material 1 Photograph 1

FIGURE C2: Material 1 Photograph 2

Material 2

FIGURE C3: Material 2 Photograph 1

FIGURE C4: Material 2 Photograph 2

Material 3

FIGURE C5: Material 3 Photograph 1

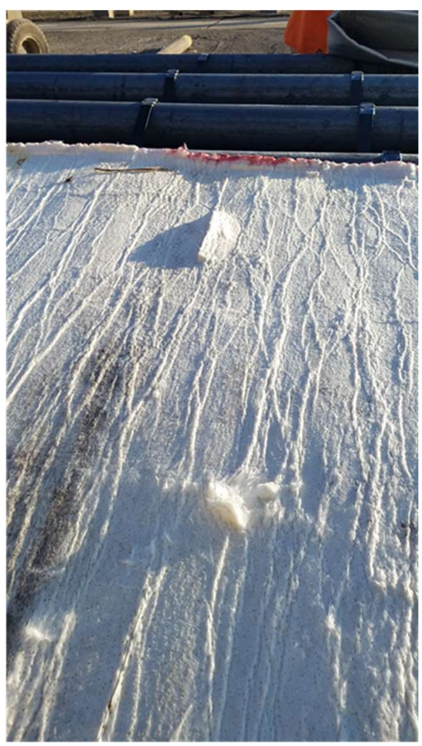


FIGURE C6: Material 3 Photograph 2

Material 4

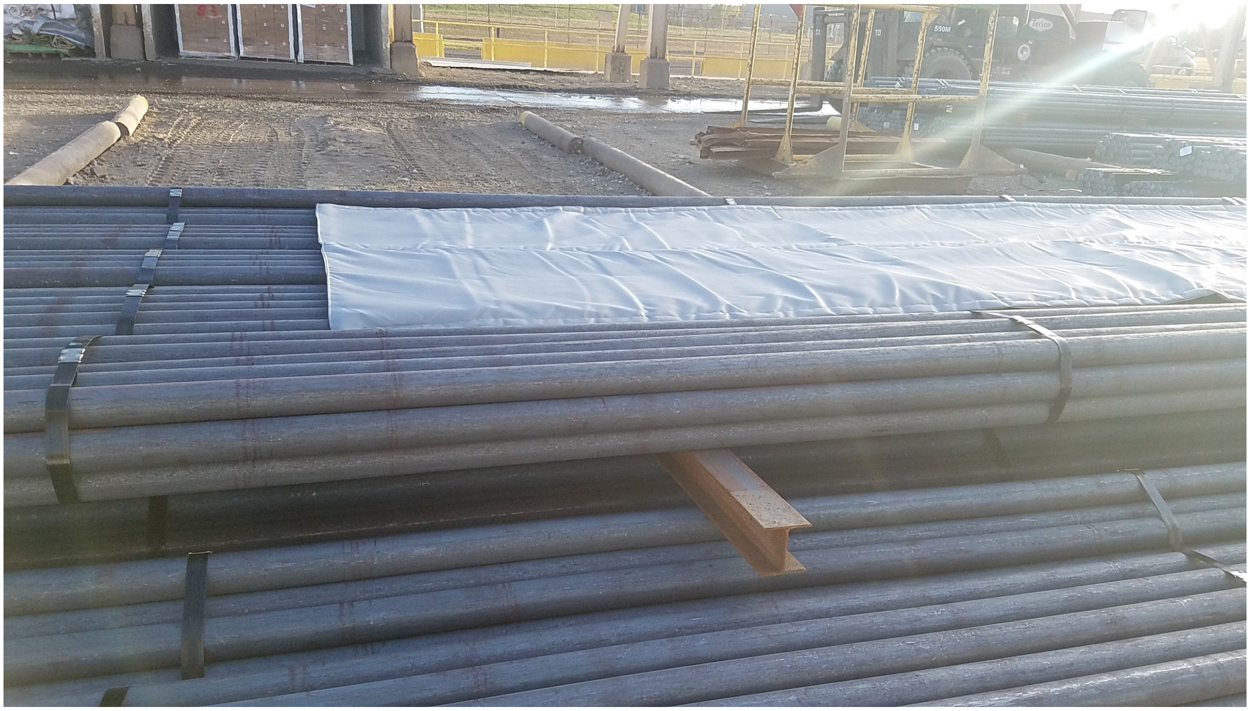


FIGURE C7: Material 4 Photograph 1

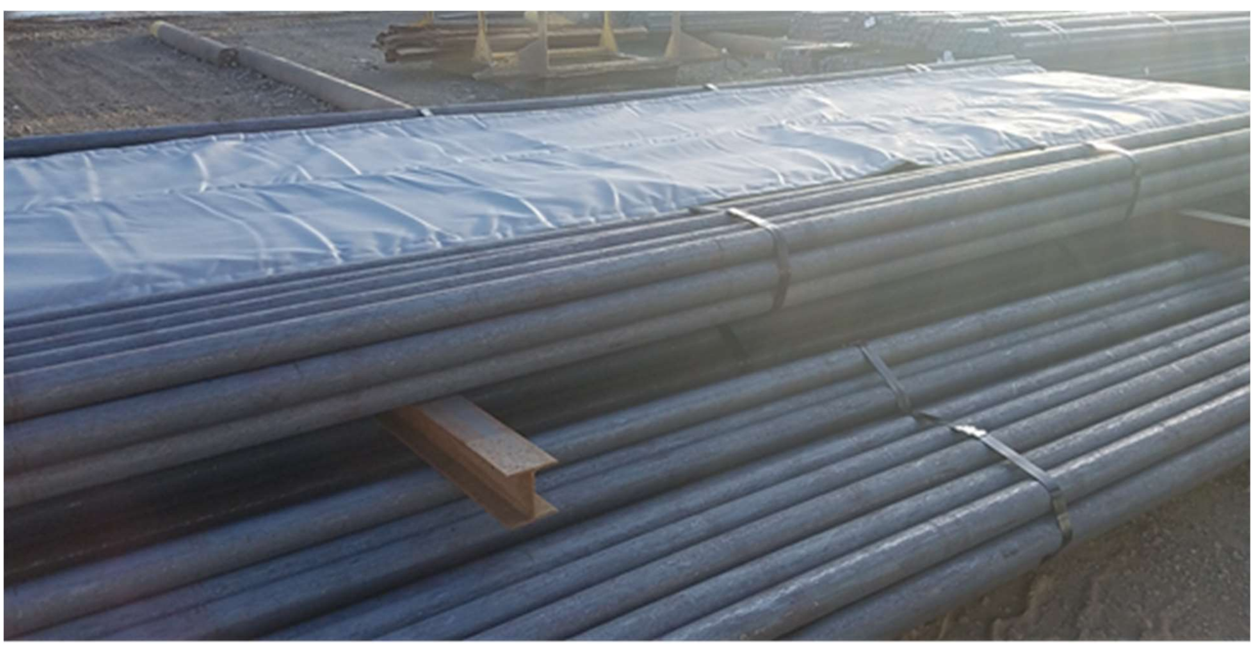


FIGURE C8: Material 4 Photograph 2

Material 5

FIGURE C9: Material 5 Photograph 1

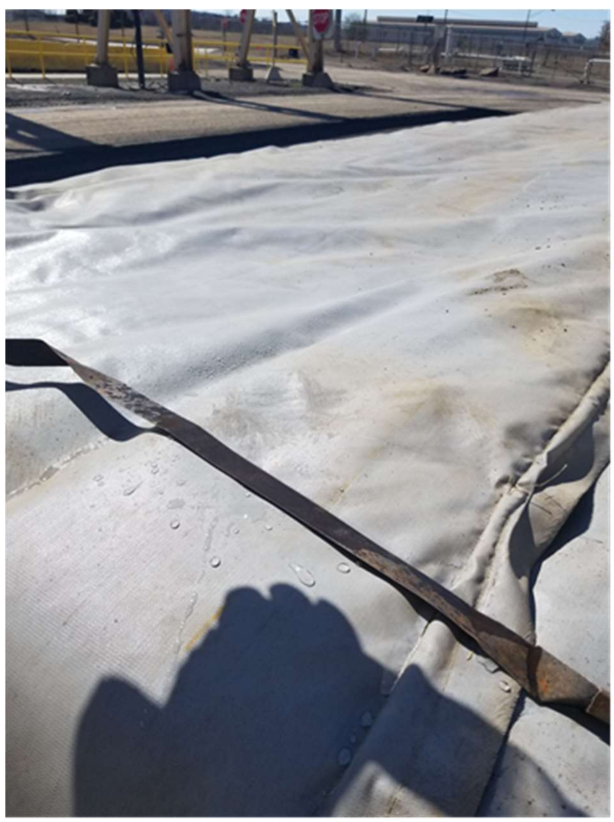


FIGURE C10: Material 5 Photograph 2

Original Material

FIGURE C11: Original Material Photograph 1

FIGURE C12: Original Material Photograph 2

Appendix D: Thermal Imaging Camera Records

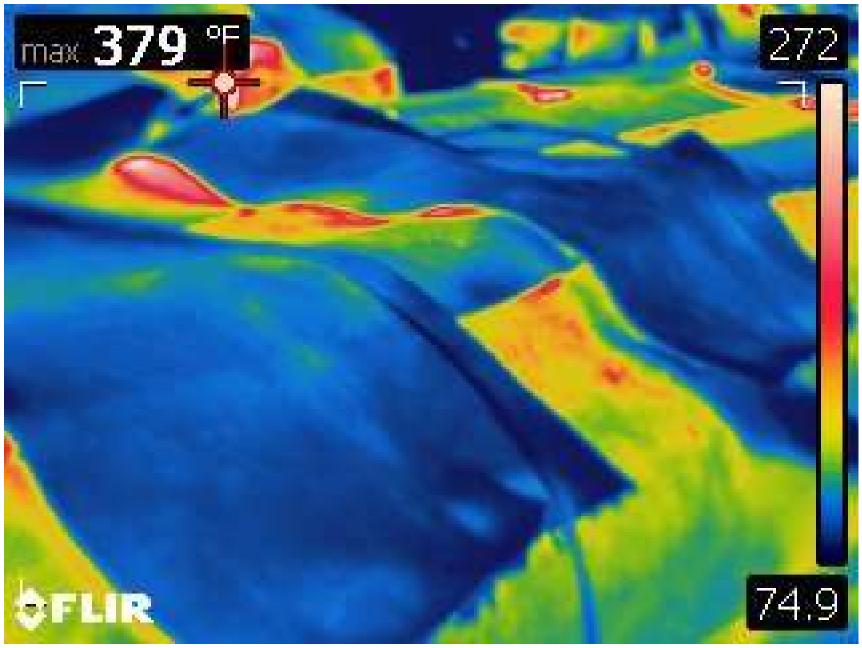


FIGURE D1: Original Material Thermal Camera Photograph

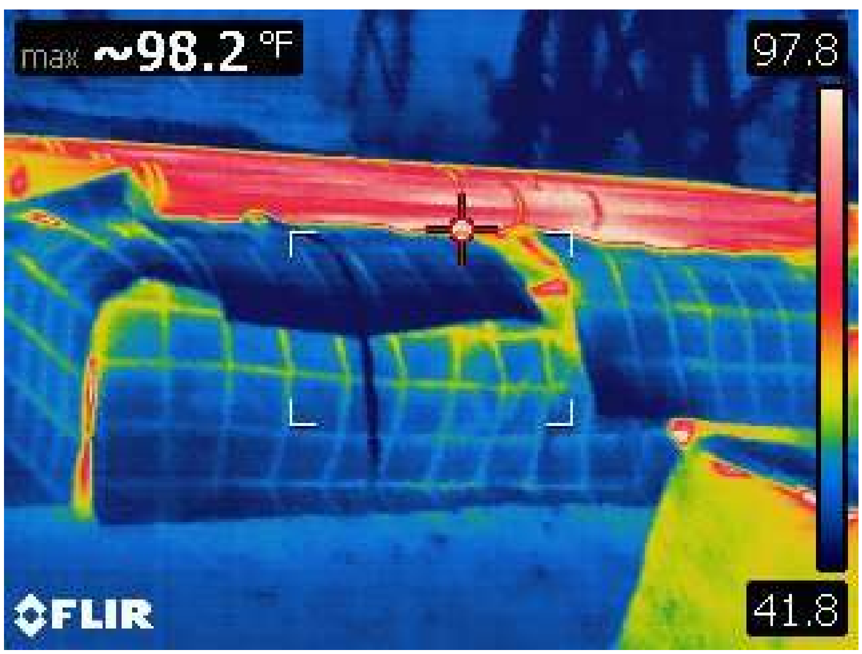


FIGURE D2: Material 1 Thermal Camera Photograph

Appendix E: Records Kept by EE's of Data

Heat Number	Test Material			Initial Temperature (5 Minutes After Cover) FiberFrax	Initial Temperature (5 Minutes After Cover) Test Material	12 Hour Temp FiberFrax	12 Hour Temp Test Material	24 Hour Temp FiberFrax	24 Hour Temp Test Material	36 Hour Temp FiberFrax	36 Hour Temp Test Material	48 Hour Temp FiberFrax	48 Hour Temp Test Material
				150°	150°	500°	500°	425°	400°	375°	400°	225°	125°
Example	✓												
73107296		✓		140	125°	106°	86°			83	56	91°	114°
74107843			✓	150°	98.5°	117°	70°F			64	47	73°	77°
73107297	✓			178°	130°	80°	75°	[illegible]		60	60	71°	122°
								85°	61°				
73107297	✓									54.5	47.3		
73107296		✓						88°	81°	66°	59°		
[illegible]										at 30m	2:00am		
74107843			✓					90°	81°	53°	49.4°		
73107360	✓	~~✓~~	~~✓~~	185.6°	105.8°	64	63.3	123	93.2				
7310 7360		✓		185.6°	101.9°	64	65	123	[illegible] 164				
73107360			✓	185.6	~~[illegible]~~ 118.1°	64	65.7	123	96				

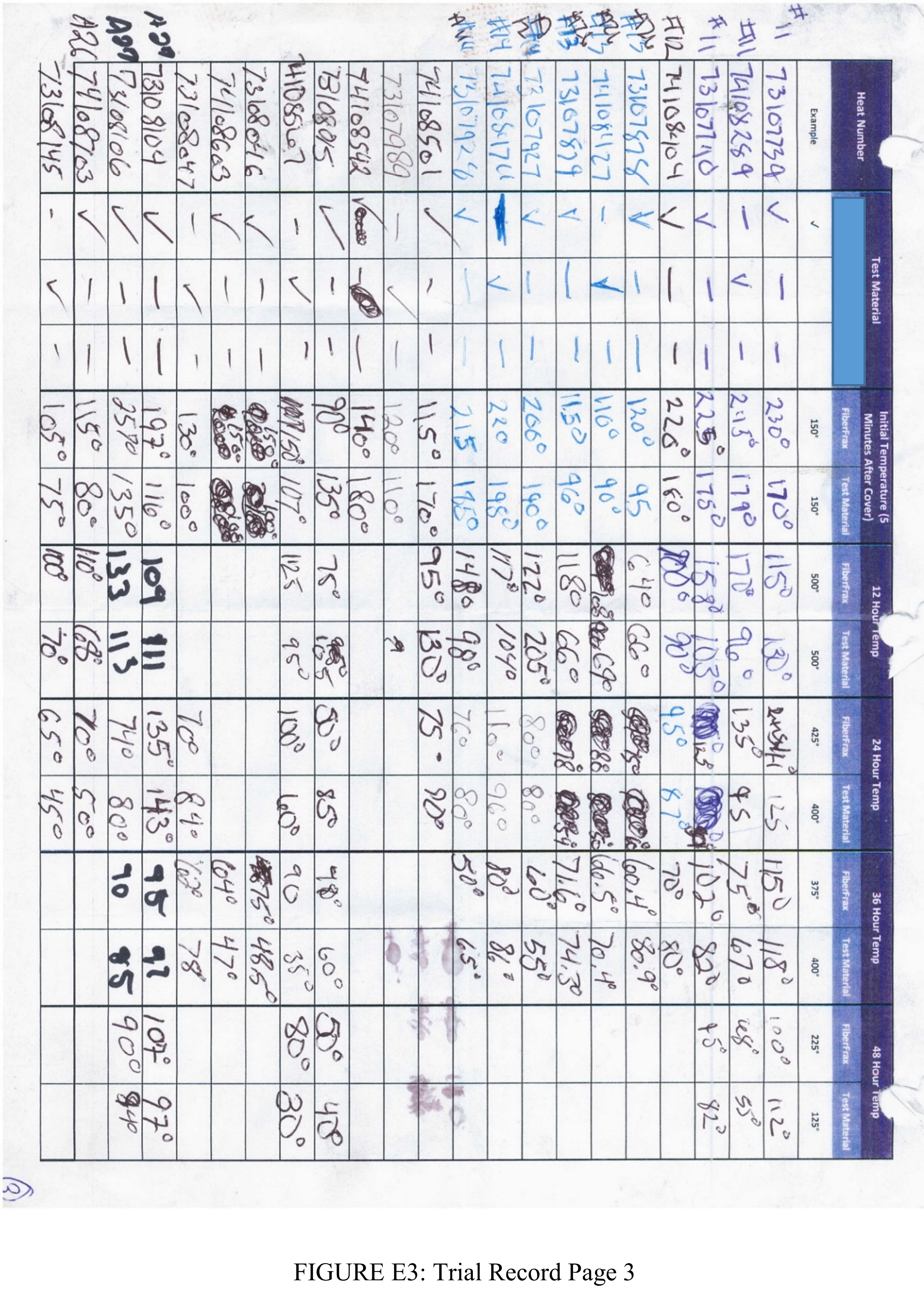
Make Sure temp gun is in °F

①

FIGURE E1: Trial Record Page 1

Heat Number	Trial Number	Date	Test Material			Initial Temperature (5 Minutes After Cover)		12 Hour Temp		24 Hour Temp		36 Hour Temp		48 Hour Temp	
						FiberFrax	Test Material	FiberFrax	Test Material	FiberFrax	Test Material	FiberFrax	Test Material	FiberFrax	Test Material
EXAMPLE	4	11/06	✓		RGA	115.6°F	89°F	156°F	100°F	285°F	150°F	100°F	60°F	98°F	50°F
7310 7450	3	11/6	✓			[illegible]	110°	126°	93°	[illegible]	80°	110	83	80	
7310 7450	3	11/6		✓			109°		78°		72°	110	83	80	
7310745Φ	3	11/7	✓					101°	93F		[illegible]	[illegible]			124F
7310745Φ	3	11/7		✓					90F			101	74	82	
73107451	4		✓					236.4F	295.1F		64°	98	79	82	
74108022	5	11/8	✓			245°	178°	210	176	185	170				
7410 8022	5	11/8		✓		245°	216°	210	234	185	[illegible] 151				
74108043	6	11/10			✓	206°	142°	145	116	119°	100°	101	86		
73107499	6	11/10		✓		192°	130°	146	108	116°	104°	104	[illegible]		
74108044	6	11/10	✓			230°	173°	130	91	90°	85°	82	95		
73107556	7	11/14	✓	[illegible]	—	220°	110°			118°	90°			110	85°
73107556	7	11/14	[illegible]	✓	—	220°	120°			118	85°			115	78°
74108810	7	11/14	✓	—	—	220°	110°			115	93°			160	90°
74108810	7	11/14	—	✓	—	215°	116°			115	87°			112	85°
73107591	8	11/16	✓	—	—	195°	185°			115°	110°			102	96°F
73107591	8	11/16	—	✓	—	195°	175°			115°	99°			99	84°F
73107632	9	11/27	✓	—	—	220	180°	108	[illegible]	135°	130°	103	84		
74108179	9	11/27	—	—	✓	215°	150°	137	[illegible]	124°	117°	101	81		
73107633	9	11/27	—	✓	—	230°	165°	130	[illegible]	140°	127°	94	82		
74108232	10	12/1	[illegible]			160°	172°								
74108232	10	12/1			[illegible]	145°	138°	[illegible]	[illegible]						

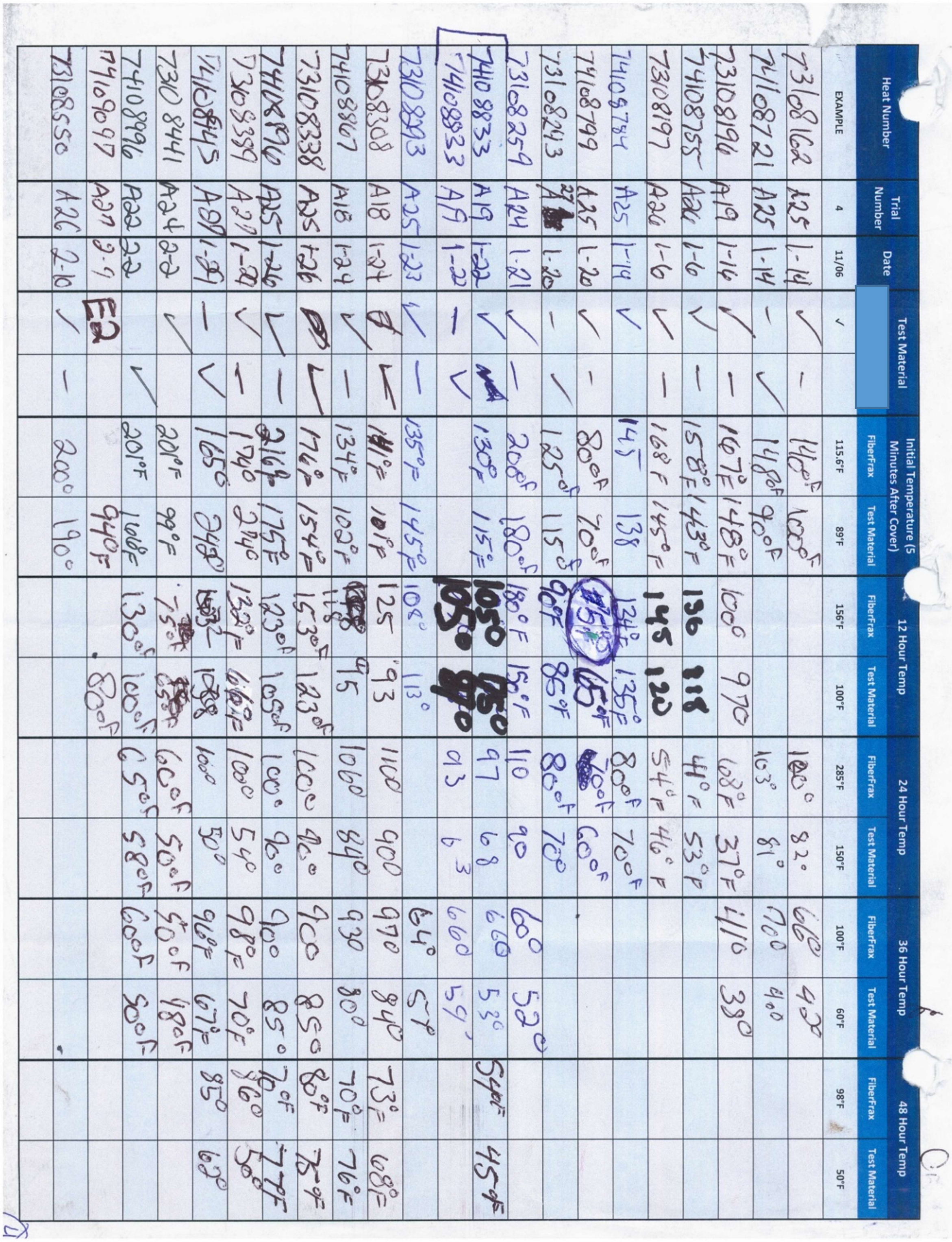
FIGURE E2: Trial Record Page 2



Heat Number	Test Material			Initial Temperature (5 Minutes After Cover) FiberFrax	Initial Temperature Test Material	12 Hour Temp FiberFrax	12 Hour Temp Test Material	24 Hour Temp FiberFrax	24 Hour Temp Test Material	36 Hour Temp FiberFrax	36 Hour Temp Test Material	48 Hour Temp FiberFrax	48 Hour Temp Test Material
Example	✓			150°	150°	500°	500°	425°	400°	375°	400°	225°	125°
#11 73107734	✓	—	—	230°	170°	115°	130°	[illegible]	125	115°	118°	100°	112°
#11 74108284	—	✓	—	215°	179°	170°	96°	135°	95	75°	67°	48°	55°
#11 73107740	✓	—	—	225°	175°	158°	103°	125	[illegible]	102°	82°	45°	82°
#12 74108404	✓	—	—	220°	160°	100°	90°	95°	87°	70°	80°		
#13 73107878	✓	—	—	120°	95	64°	66°	[illegible]	[illegible]	60.4°	80.9°		
#13 74108427	—	✓	—	110°	90°	[illegible]	69°	88	[illegible]	66.5°	70.4°		
#13 73107879	✓	—	—	115°	96°	118°	66°	78	[illegible]	71.6°	74.3°		
#14 73107927	✓	—	—	200°	190°	122°	205°	80°	80°	60°	55°		
#14 74108417	—	✓	—	220	198°	117°	104°	110°	96°	80°	86°		
#14 73107926	✓	—	—	215	185°	148°	98°	76°	80°	50°	65°		
74108501	✓	—	—	115°	170°	95°	130°	75	90°				
73107989	—	✓	—	120°	110°								
74108542	✓	—	—	140°	180°								
73108015	✓	—	—	90°	135°	75°	155	50°	85°	48°	60°	50°	48°
74108567	—	✓	—	150°	107°	125	95°	100°	60°	90	35°	80°	30°
73108046	✓	—	—	150°	100°					75°	48.5°		
74108603	✓	—	—	150°	105					64°	47°		
73108047	—	✓	—	130°	100°			70°	84°	62°	78°		
A29 73108104	✓	—	—	197°	116°	109	111	135°	143°	95	91	107°	97°
A29 73108106	✓	—	—	257°	135°	133	113	74°	80°	90	85	90°	84°
A26 74108703	✓	—	—	115°	80°	110°	68°	70°	50°				
73108145	-	✓	-	105°	75°	100°	70°	65°	45°				

(3)

FIGURE E3: Trial Record Page 3



Heat Number	Trial Number	Date	Test Material		Initial Temperature (5 Minutes After Cover) FiberFrax	Initial Temperature (5 Minutes After Cover) Test Material	12 Hour Temp FiberFrax	12 Hour Temp Test Material	24 Hour Temp FiberFrax	24 Hour Temp Test Material	36 Hour Temp FiberFrax	36 Hour Temp Test Material	48 Hour Temp FiberFrax	48 Hour Temp Test Material
EXAMPLE	4	11/06	✓		115.6°F	89°F	156°F	100°F	285°F	150°F	100°F	60°F	98°F	50°F
73108162	A25	1-14	✓	—	140°F	100°F			100°	82°	66°	42°		
74108721	A25	1-14	—	✓	148°F	90°F			103°	81°	70°	40°		
73108196	A19	1-16	✓	—	167°F	148°F	100°	97°	68°F	37°F	41°	38°		
74108755	A26	1-6	✓	—	158°F	143°F	136	118	41°F	53°F				
73108197	A26	1-6	✓	—	168 F	145°F	145	120	54°F	46° F				
74108784	A25	1-19	✓		145	138	134°F	135°F	80°F	70°F				
74108799	A25	1-20	✓	—	80°F	70°F	75°F	65°F	70°F	60°F				
73108243	A27	1-20	—	✓	125°F	115°F	90°F	86°F	80°F	70°				
73108259	A24	1-21	✓	—	200°F	180°F	180°F	150°F	110	90	60°	52°		
74108833	A19	1-22	✓	[illegible]	130°F	115°F	105°	75°	97	68	66°	53°	54°F	45°F
74108833	A19	1-22	—	✓			105°	87°	93	63	66°	59		
73108393	A25	1-23	✓	—	135°F	145°F	108°	113°			64°	57		
73108308	A18	1-24	✓	✓	141°F	101°F	125	93	110°	90°	97°	84°	73°F	68°F
74108867	A18	1-24	✓	—	134°F	102°F	118	95	106°	84°	93°	80°	70°F	76°F
73108338	A25	1-26	✓	✓	176°F	154°F	153°F	123°F	100°	90°	90°	85°	80°F	75°F
74108896	A25	1-26	✓	—	216°F	175°F	123°F	105°F	100°	90°	90°	85°	70°F	77°F
73108399	A27	1-29	✓	—	174°	274°	132°F	66°F	100°	54°	98°F	70°F	86°	50°
74108845	A27	1-29	—	✓	165°	242°	[illegible]	[illegible]	100°	50°	96°F	67°F	85°	62°
73108441	A24	2-2	✓		201°F	99°F	75°F	65°F	60°F	50°F	50°F	48°F		
74108996	A22	2-2		✓	201°F	166°F	130°F	100°F	65°F	58°F	60°F	50°F		
74109097	A27	2-9	E2			94°F		80°F						
73108550	A26	2-10	✓	—	200°	190°								

FIGURE E4: Trial Record Page 4

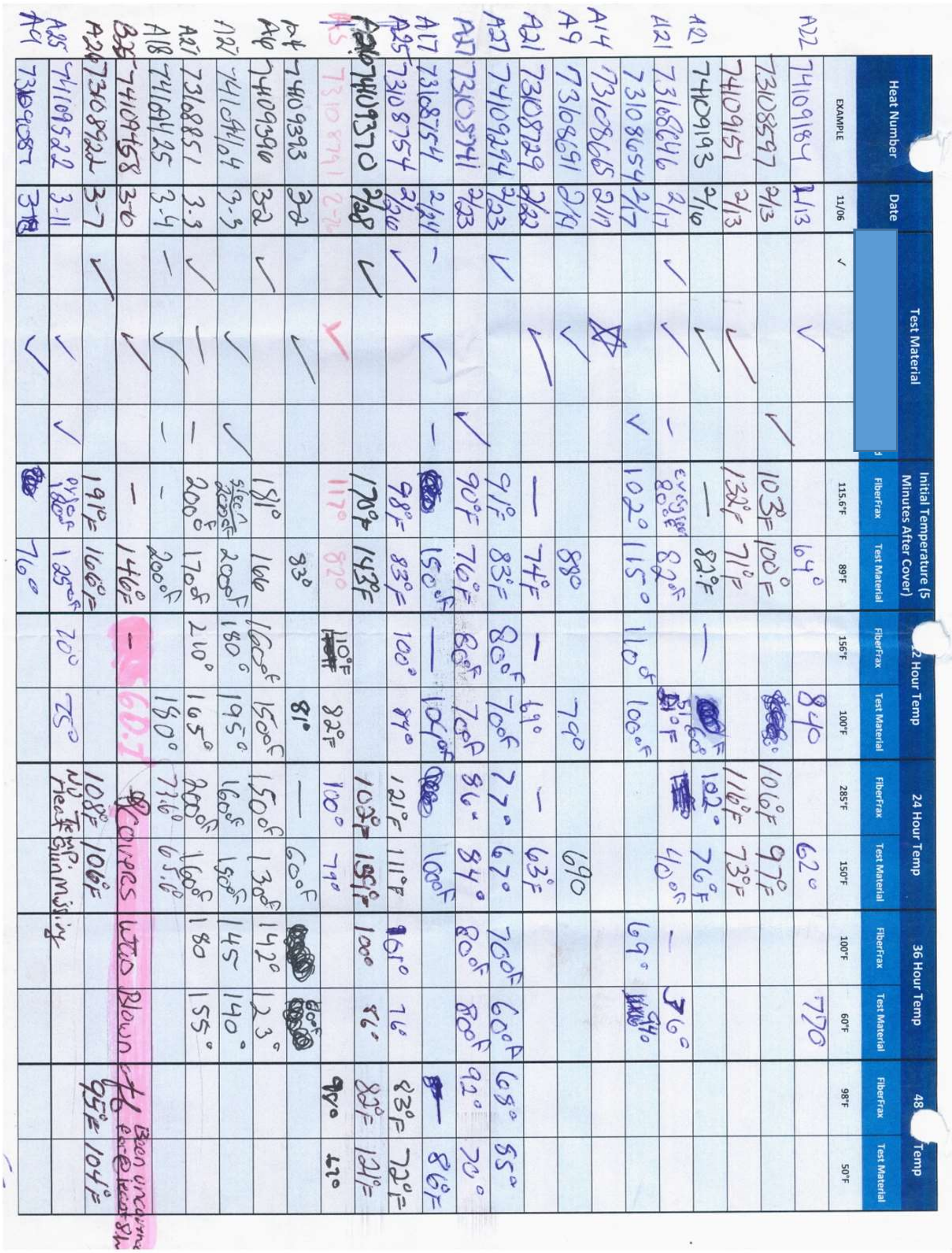


FIGURE E5: Trial Record Page 5

Appendix F: Testing Data

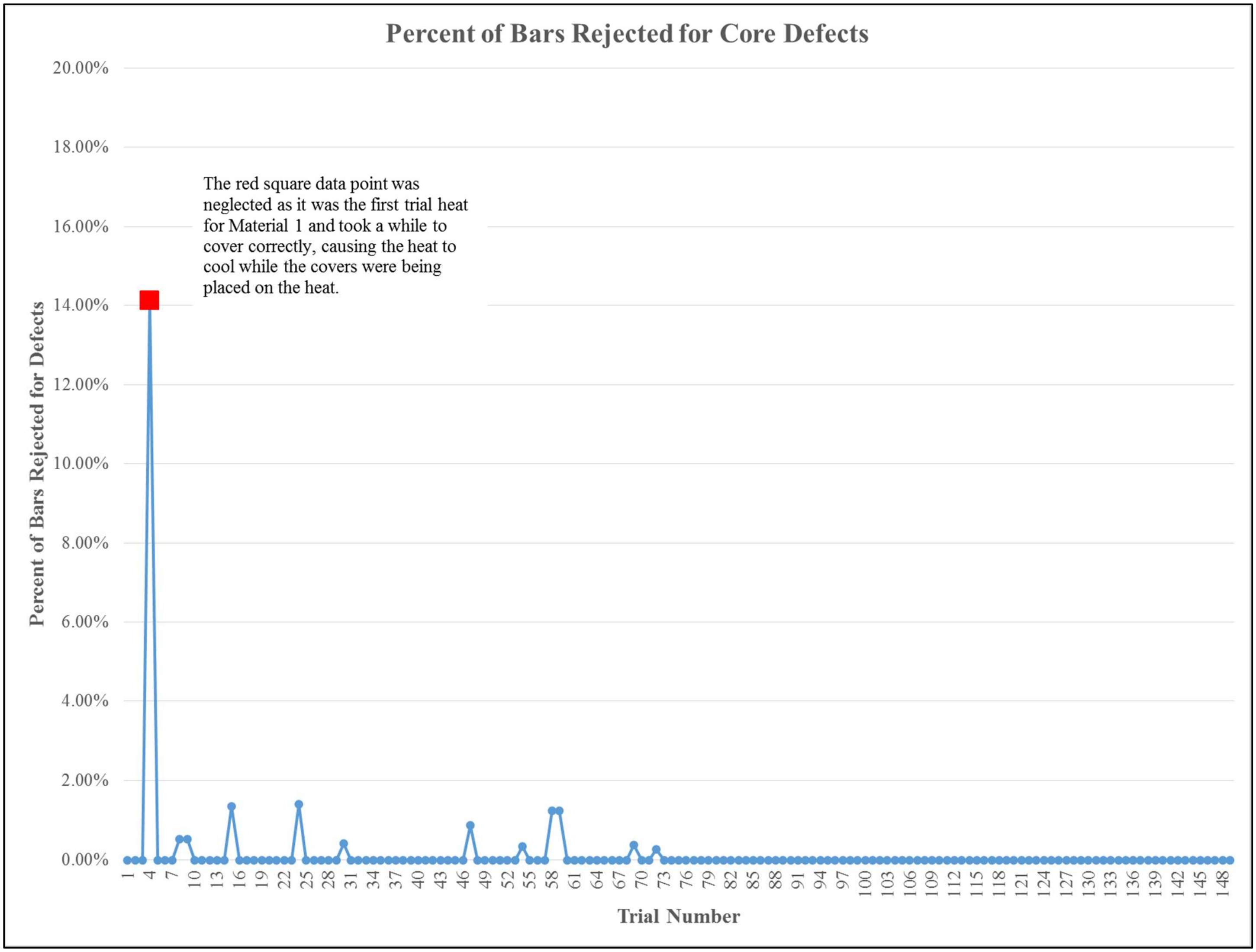


FIGURE F1: Percent of Bars Rejected for Core Defects

Appendix G: Temperature Data for Material 1

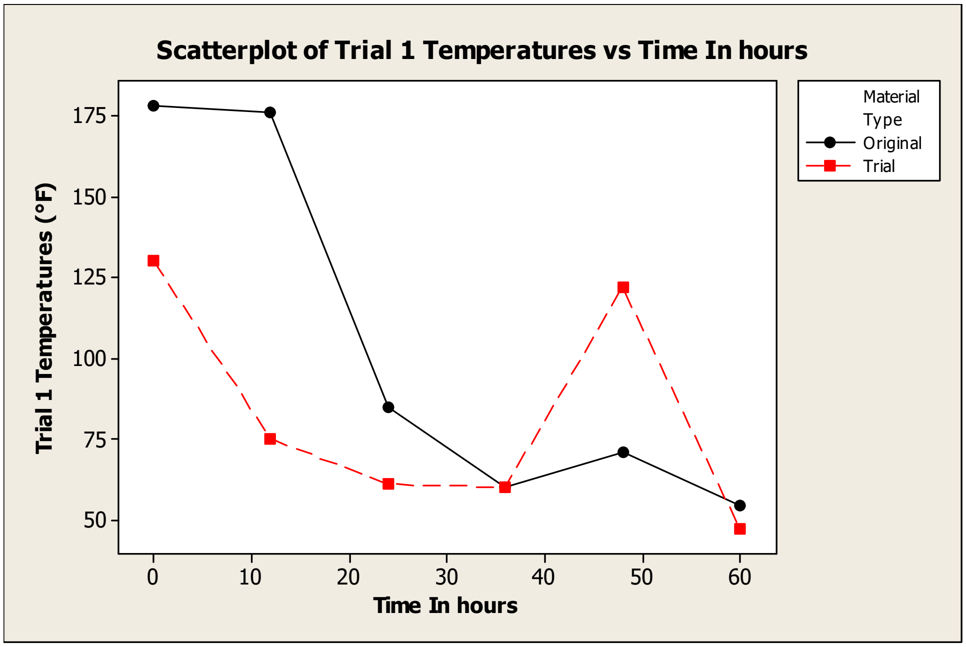


FIGURE G1: Trial 1 Temperature Data

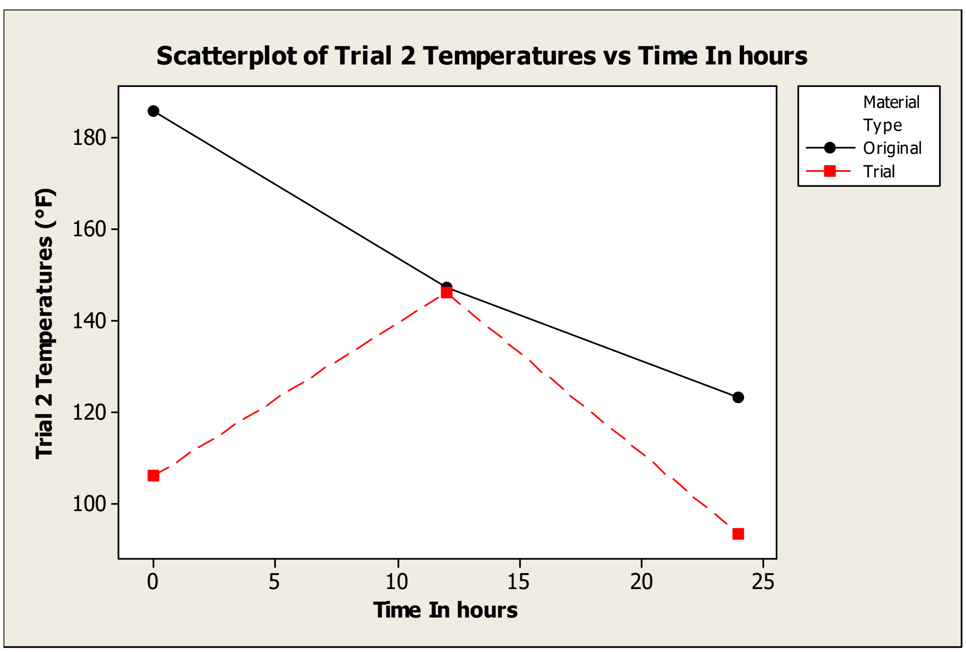


FIGURE G2: Trial 2 Temperature Data

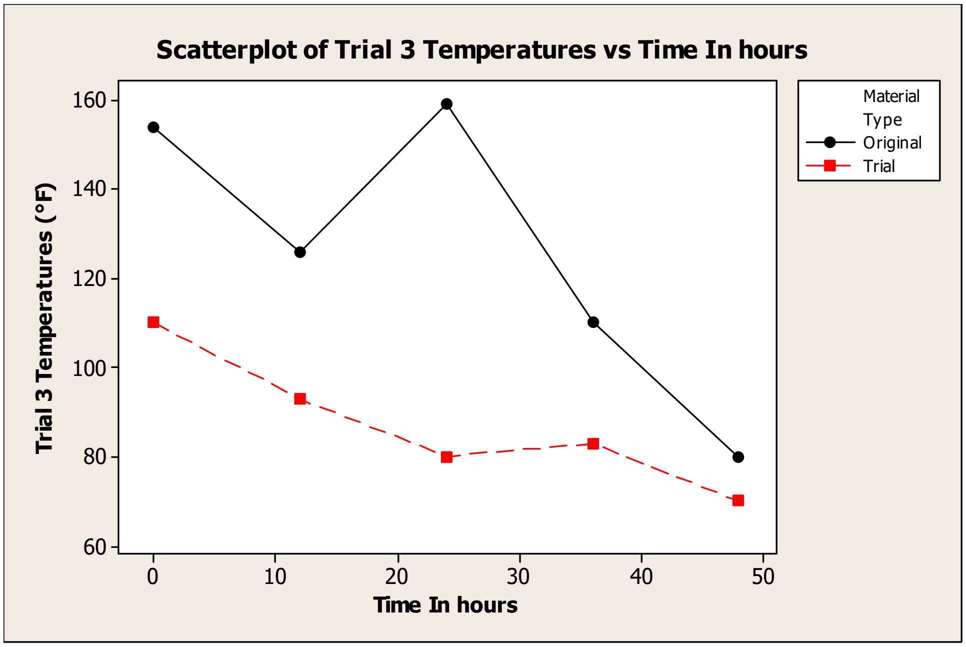


FIGURE G3: Trial 3 Temperature Data

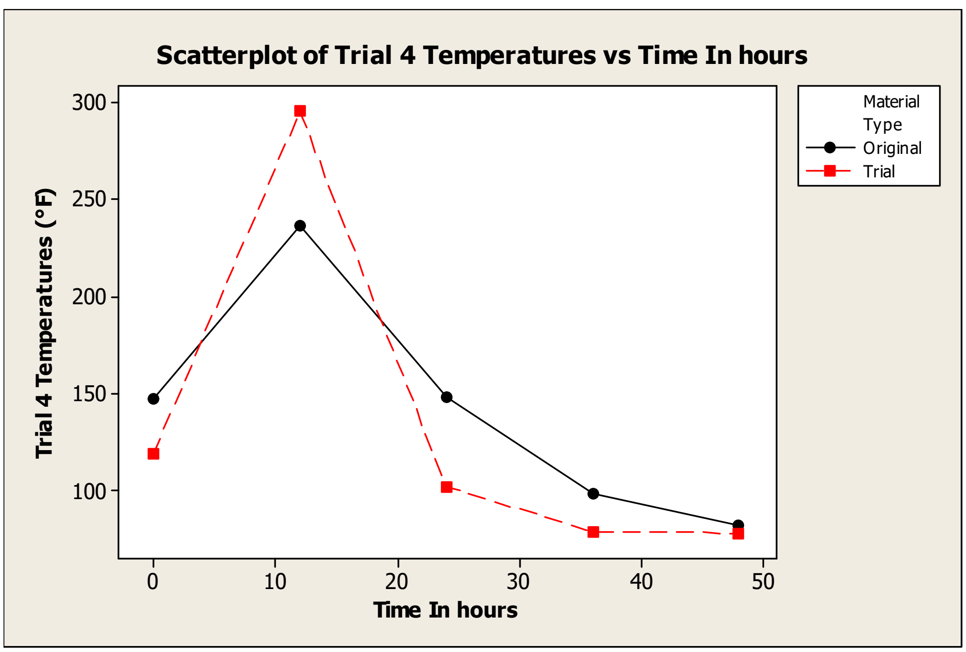


FIGURE G4: Trial 4 Temperature Data

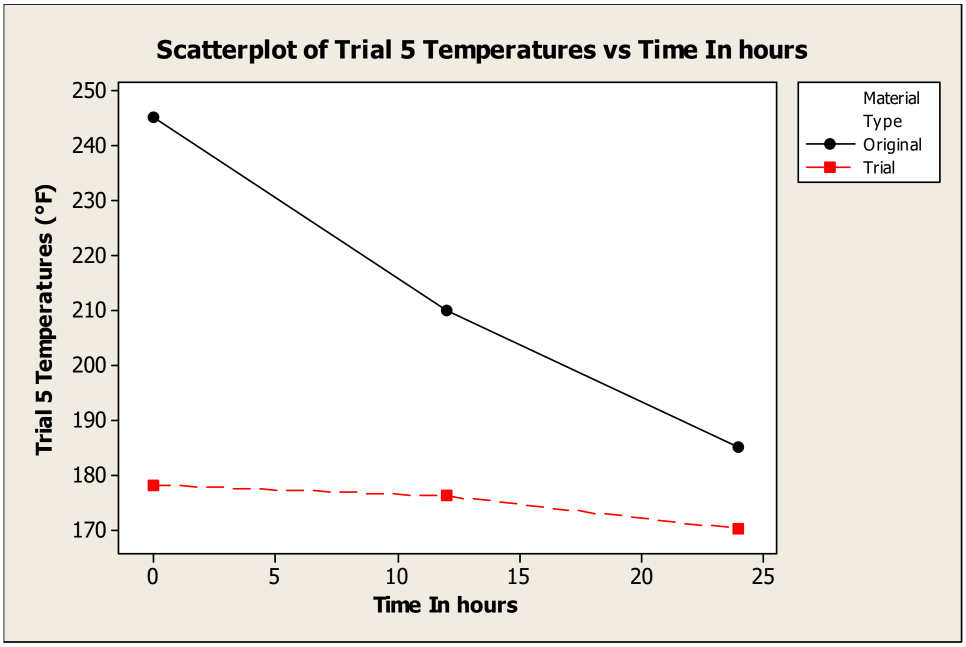


FIGURE G5: Trial 5 Temperature Data

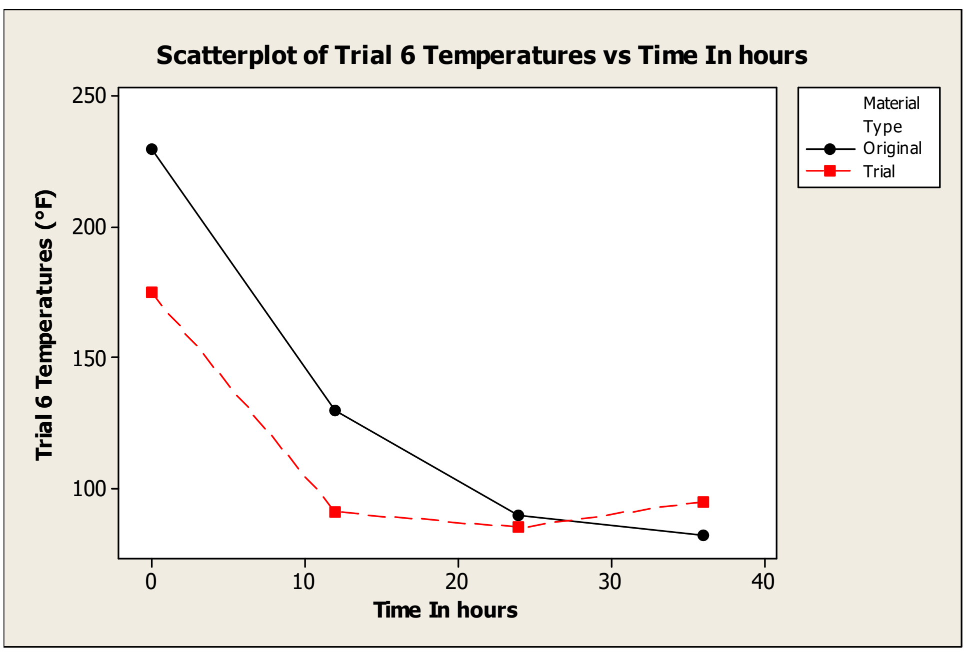


FIGURE G6: Trial 6 Temperature Data

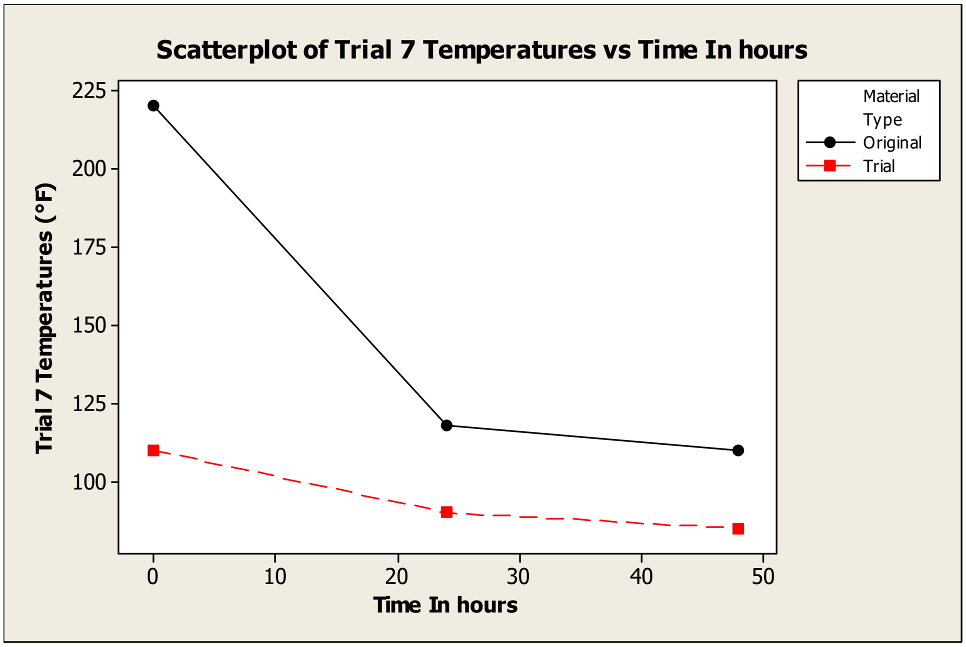


FIGURE G7: Trial 7 Temperature Data

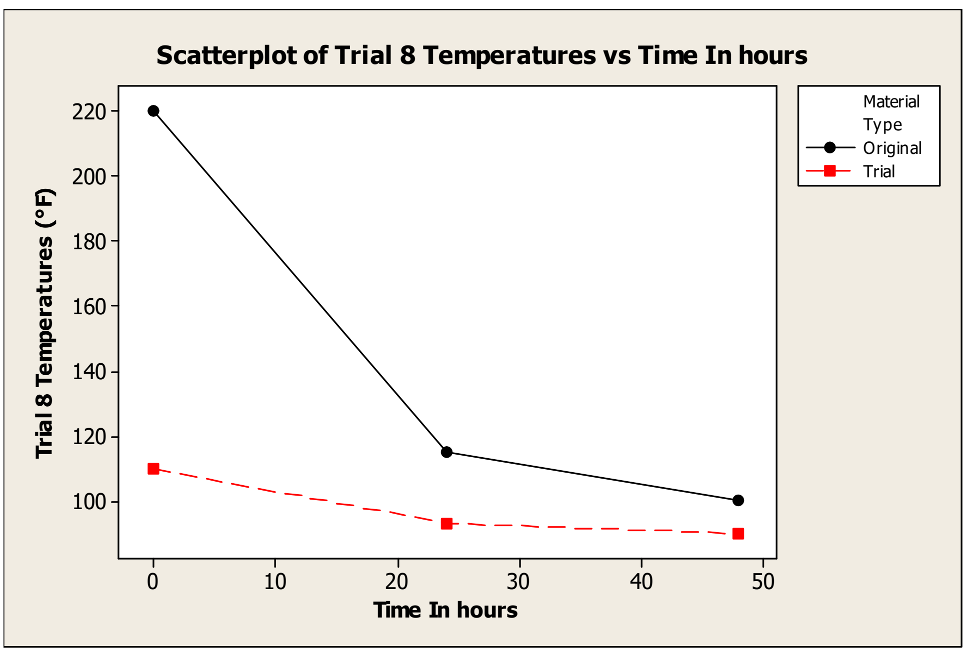


FIGURE G8: Trial 8 Temperature Data

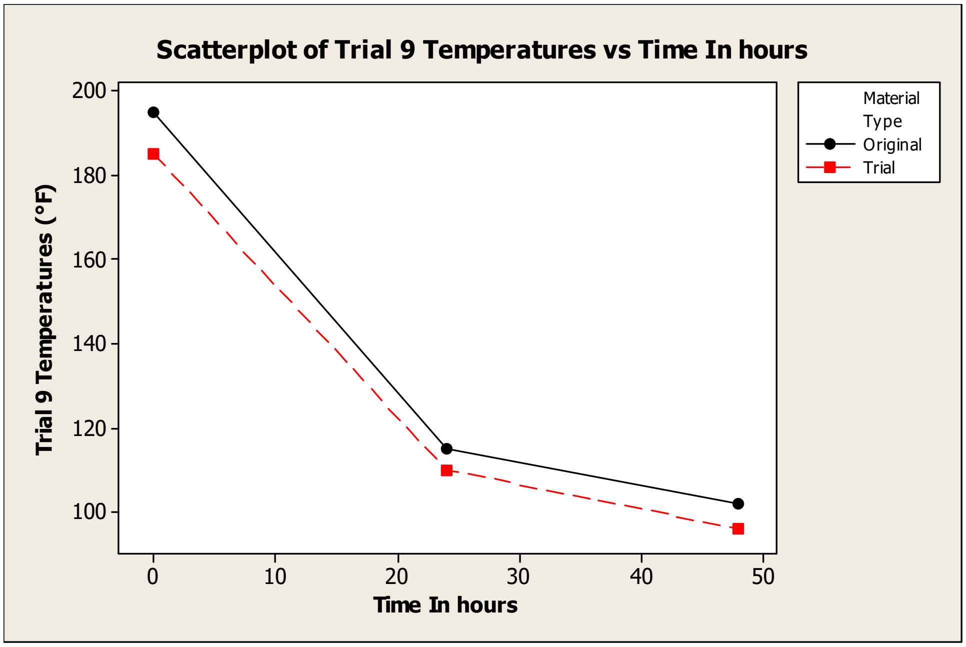


FIGURE G9: Trial 9 Temperature Data

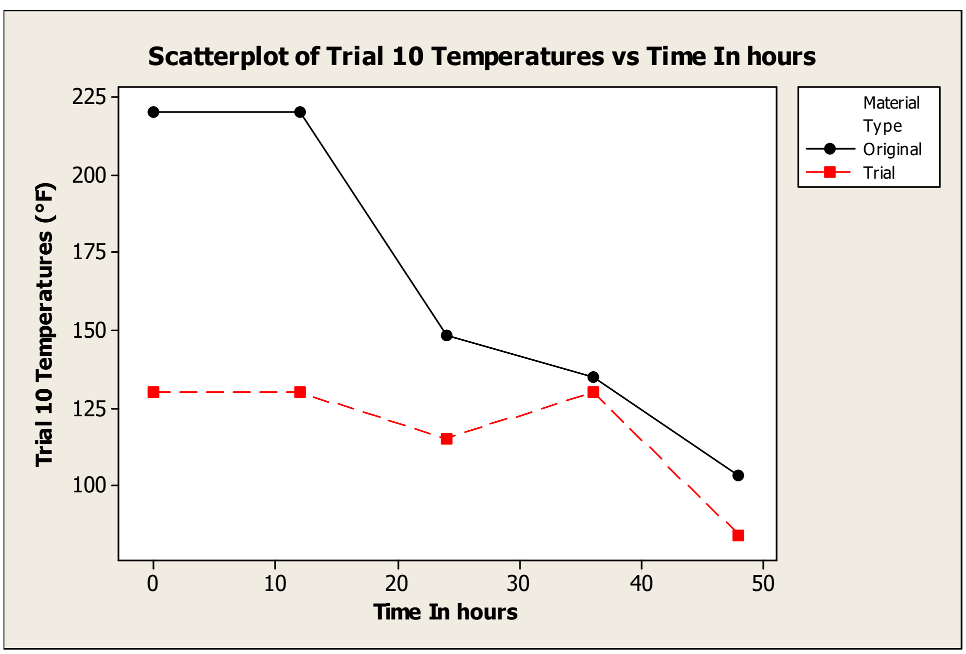


FIGURE G10: Trial 10 Temperature Data

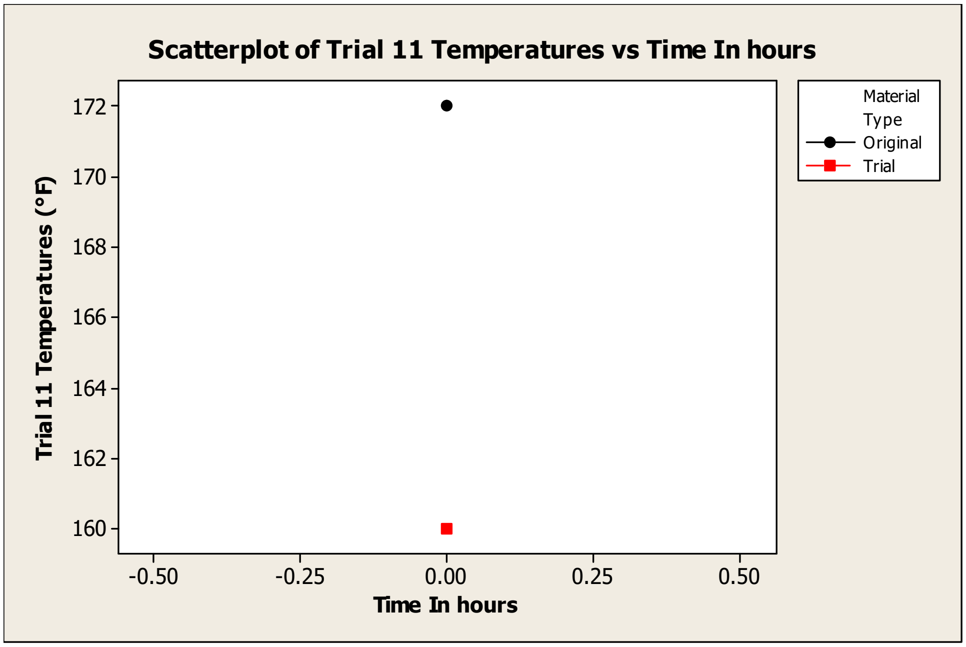


FIGURE G11: Trial 11 Temperature Data

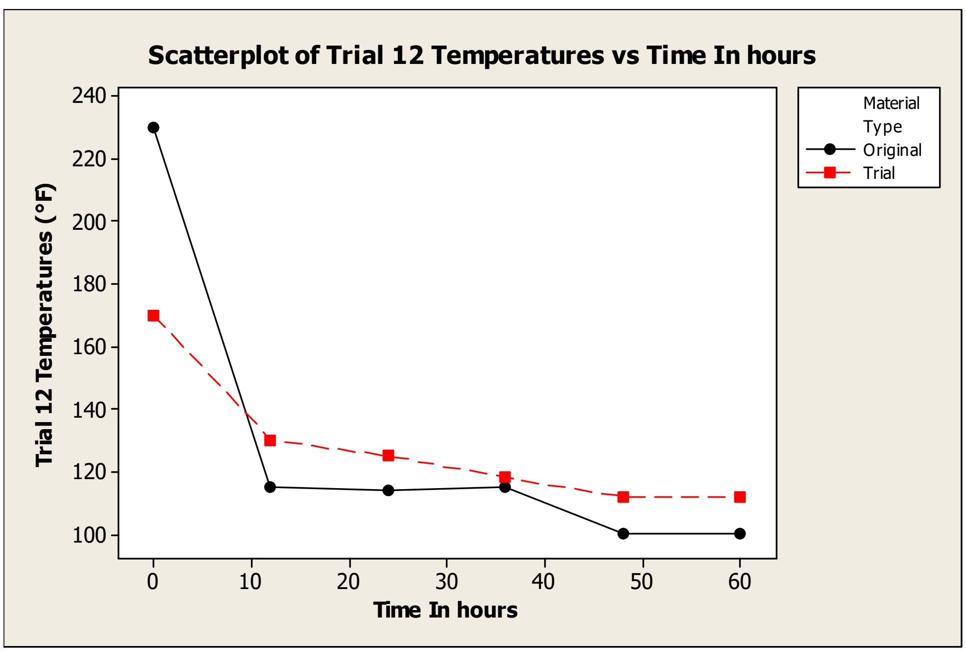


FIGURE G12: Trial 12 Temperature Data

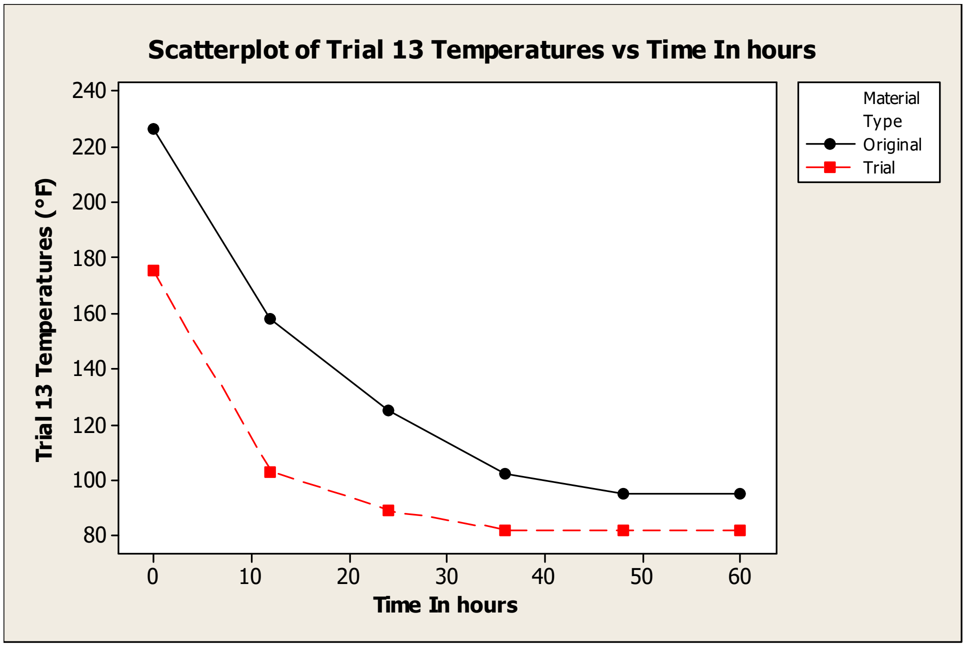


FIGURE G13: Trial 13 Temperature Data

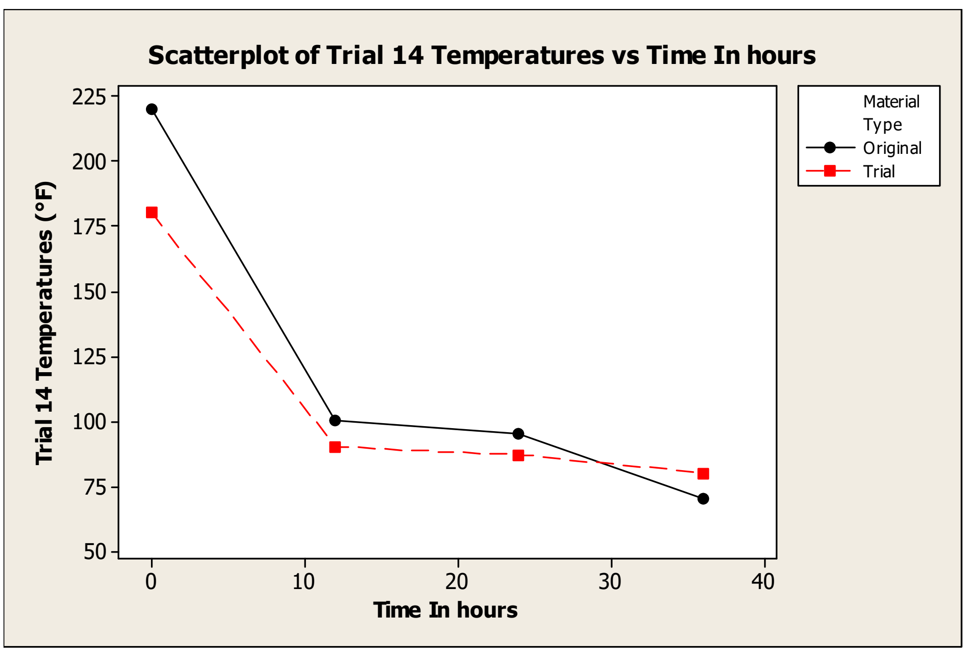


FIGURE G14: Trial 14 Temperature Data

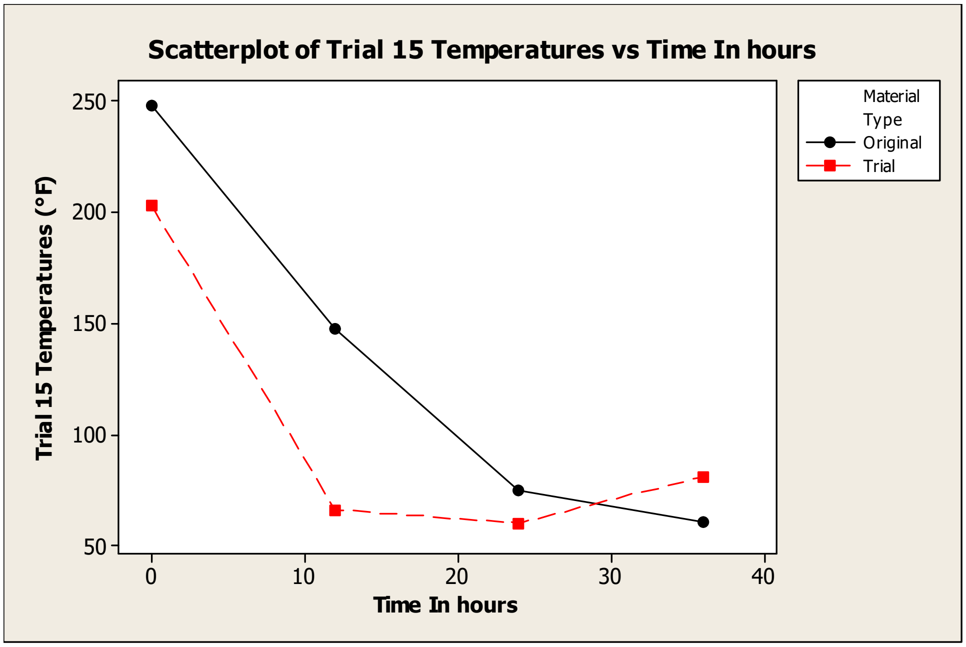


FIGURE G15: Trial 15 Temperature Data

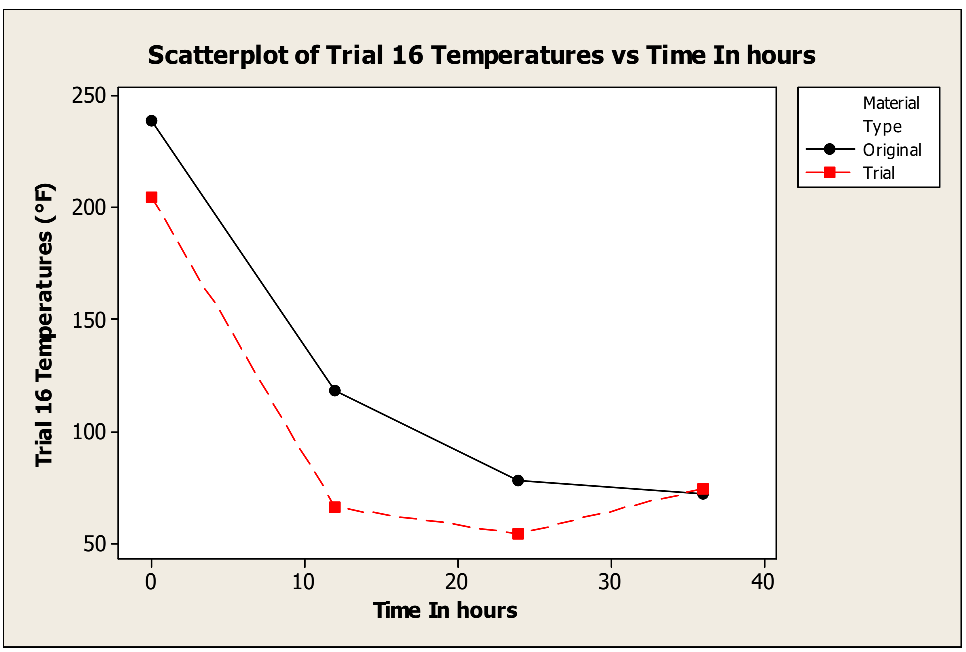


FIGURE G16: Trial 16 Temperature Data

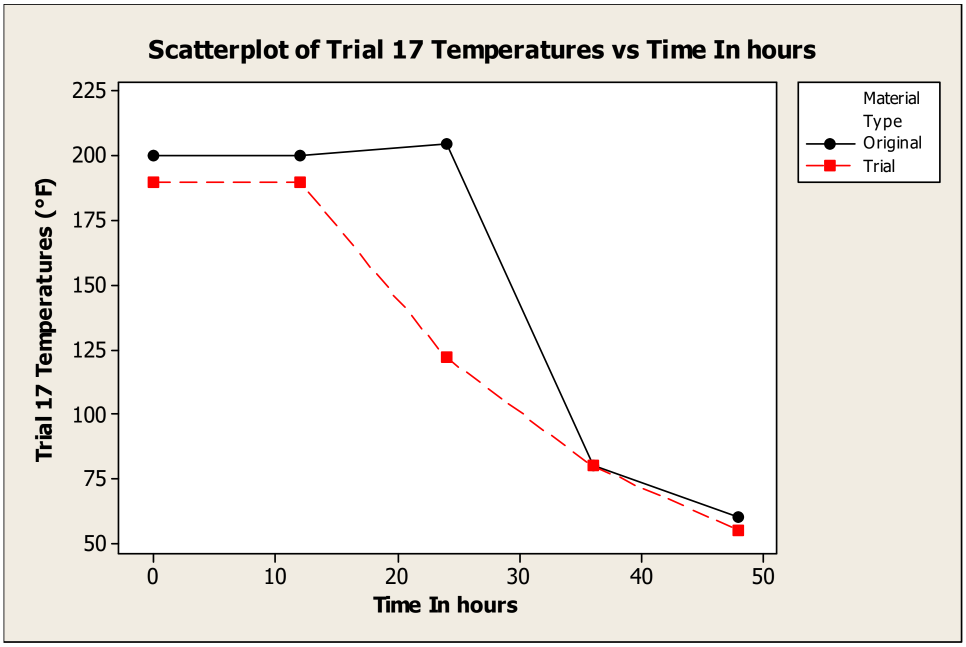


FIGURE G17: Trial 17 Temperature Data

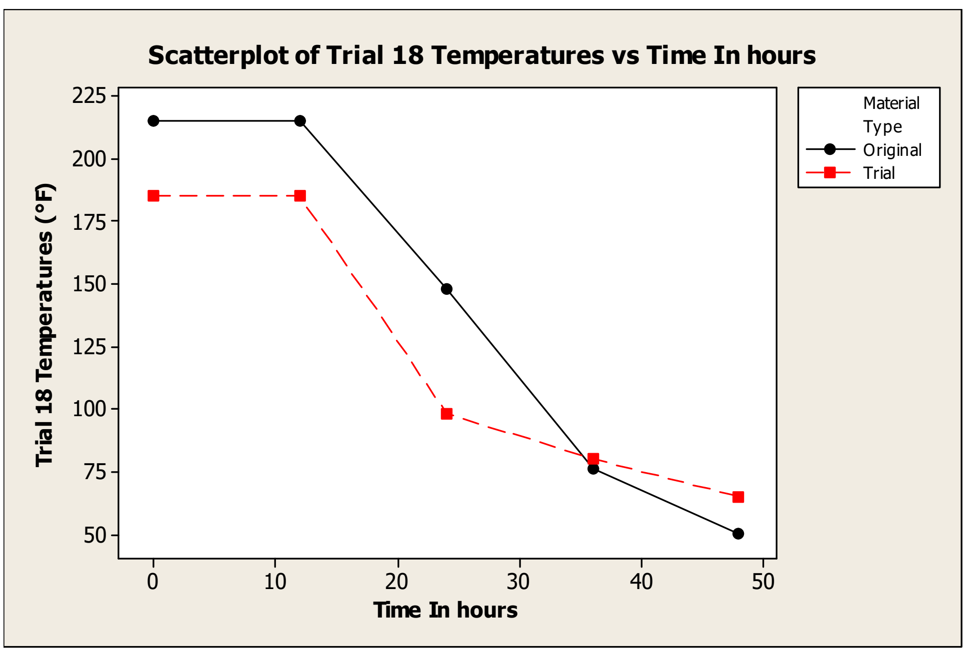


FIGURE G18: Trial 18 Temperature Data

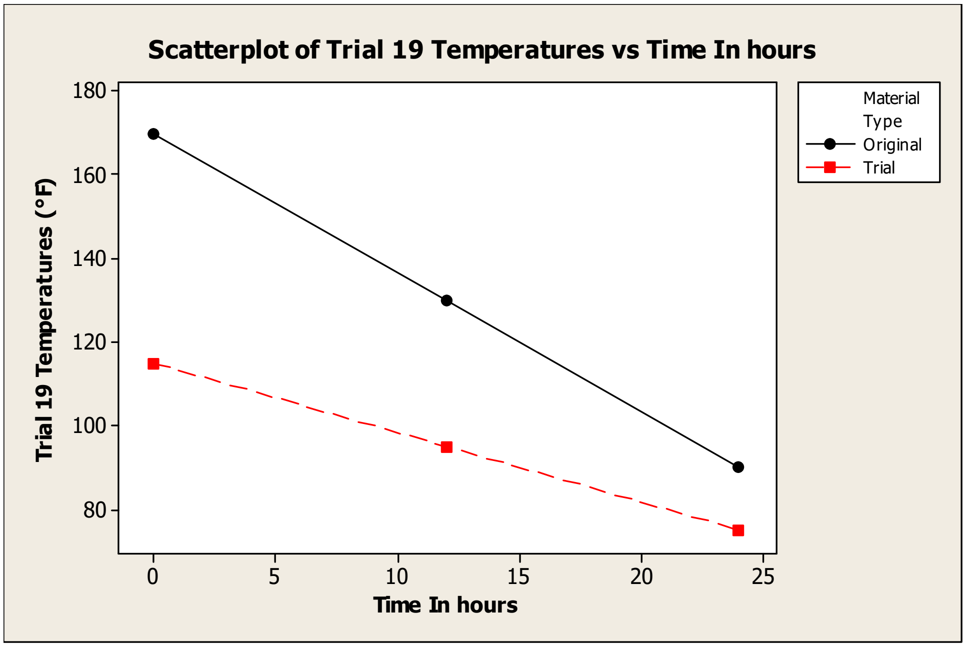


FIGURE G19: Trial 19 Temperature Data

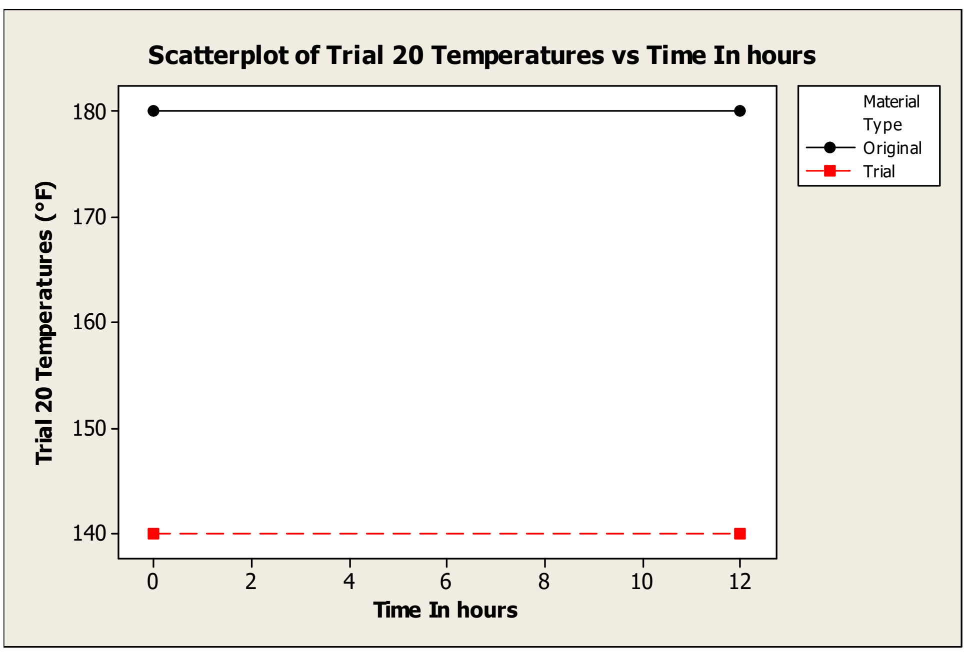


FIGURE G20: Trial 20 Temperature Data

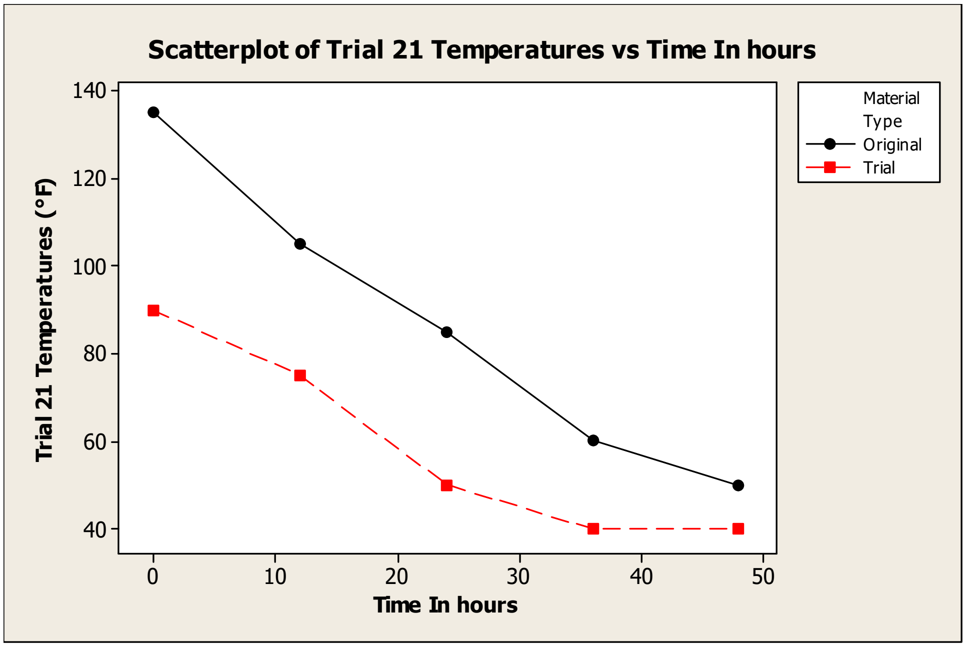


FIGURE G21: Trial 21 Temperature Data

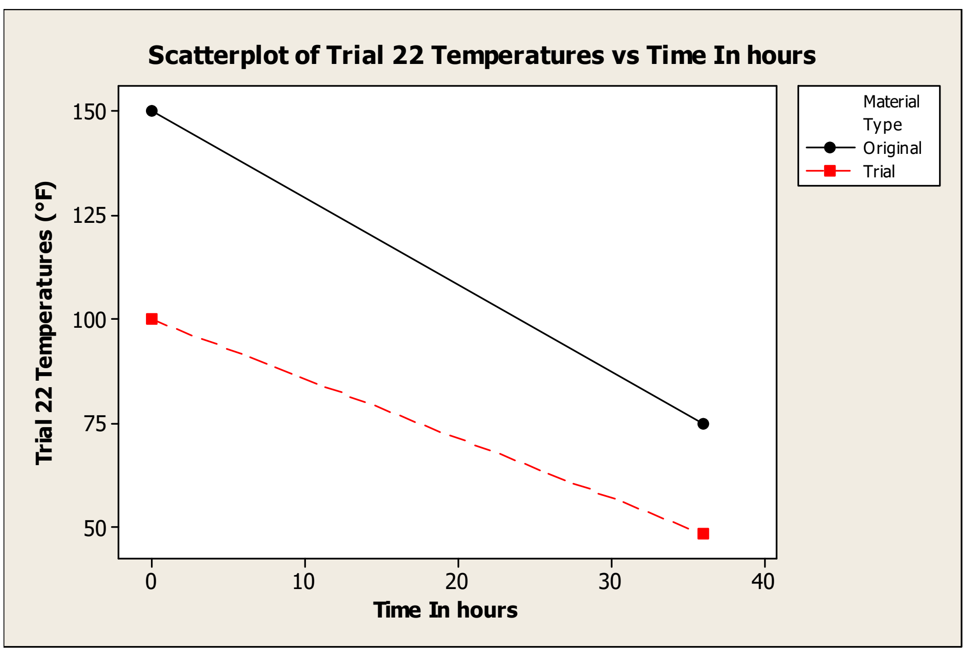


FIGURE G22: Trial 22 Temperature Data

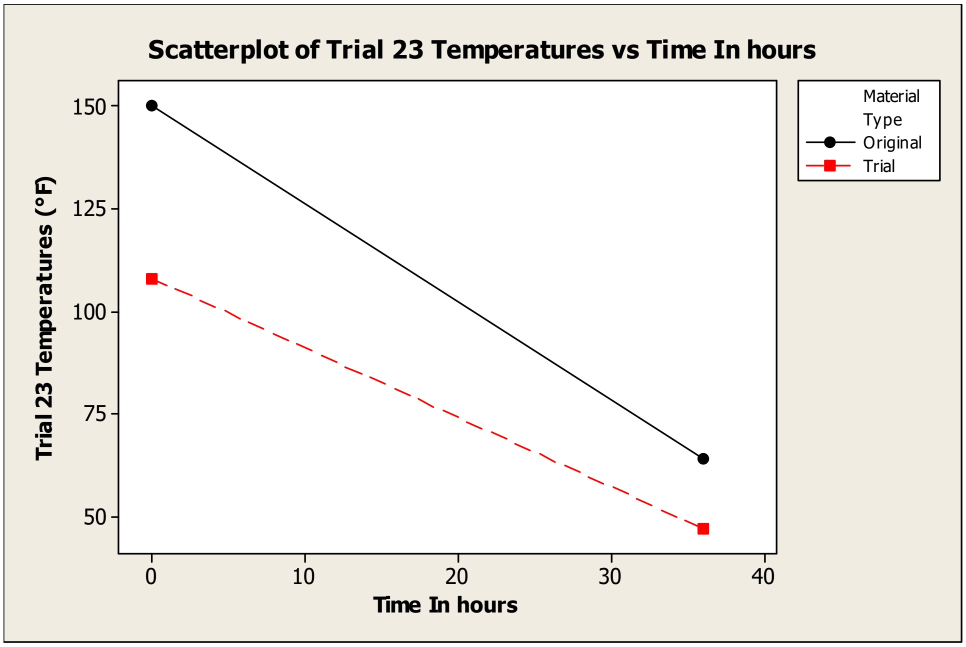


FIGURE G23: Trial 23 Temperature Data

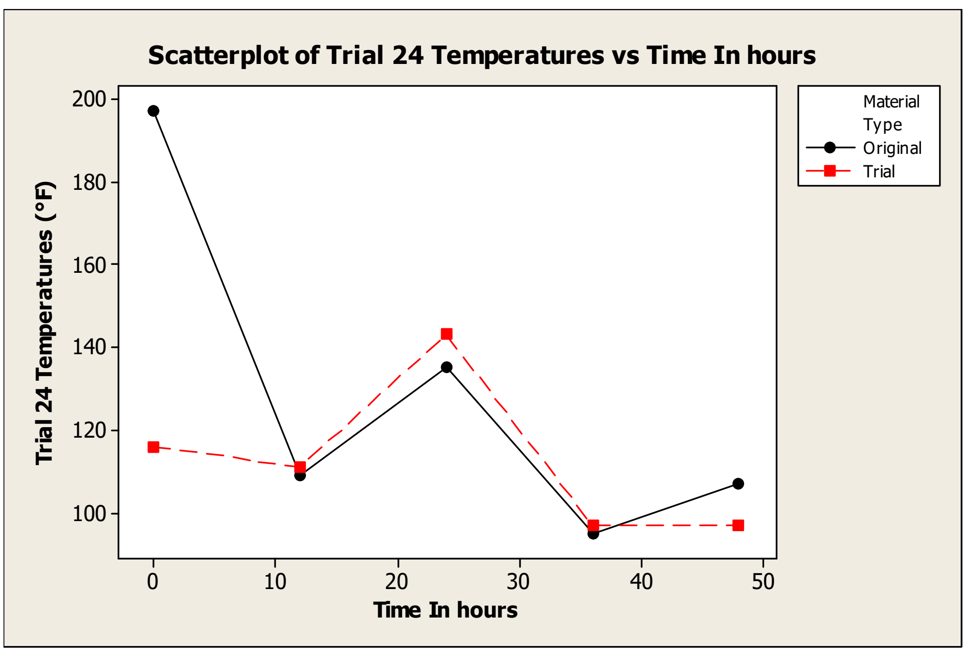


FIGURE G24: Trial 24 Temperature Data

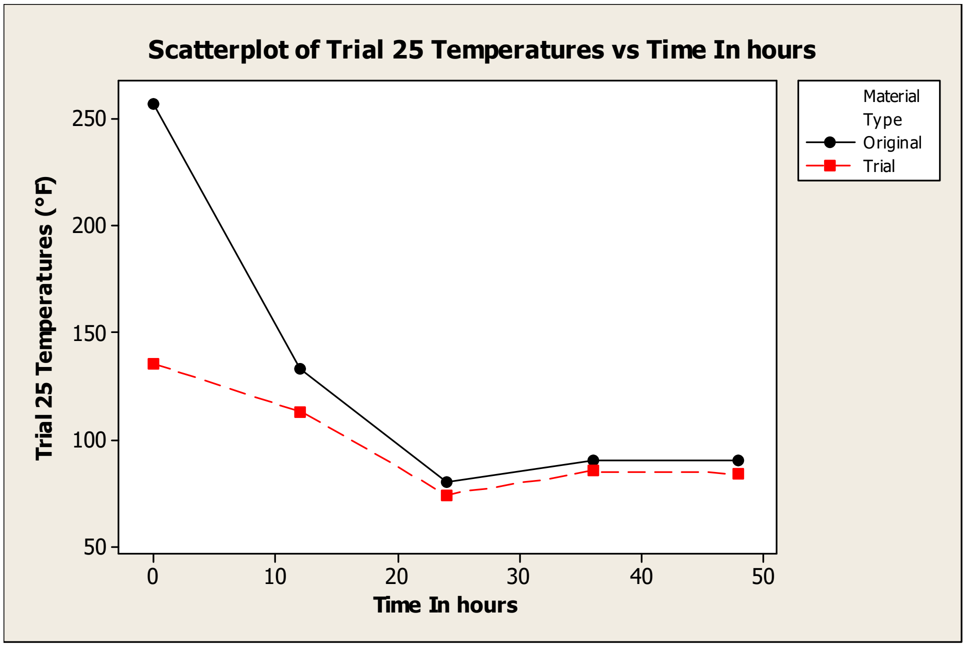


FIGURE G25: Trial 25 Temperature Data

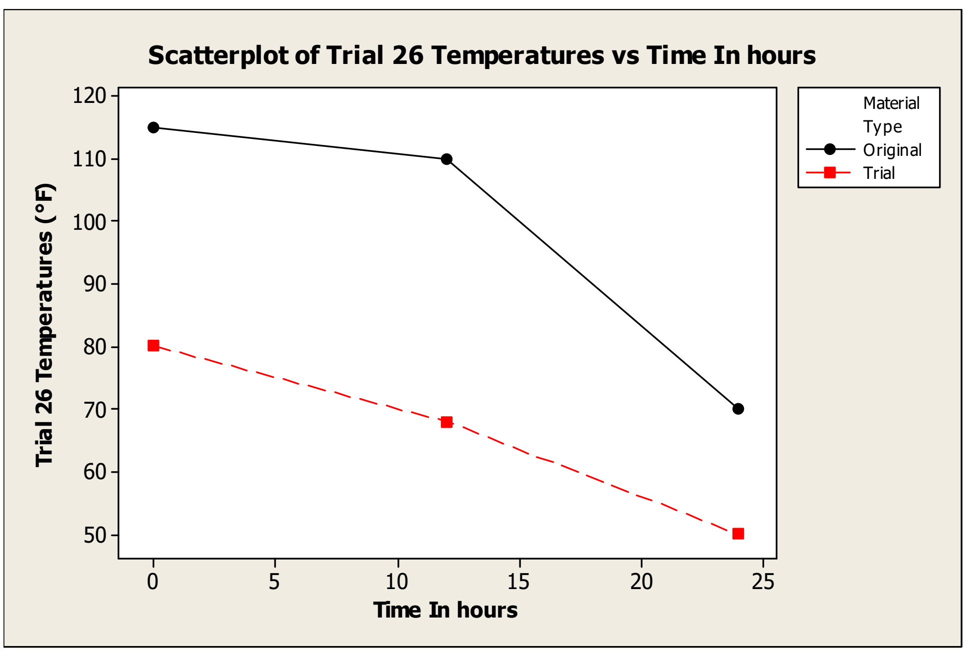


FIGURE G26: Trial 26 Temperature Data

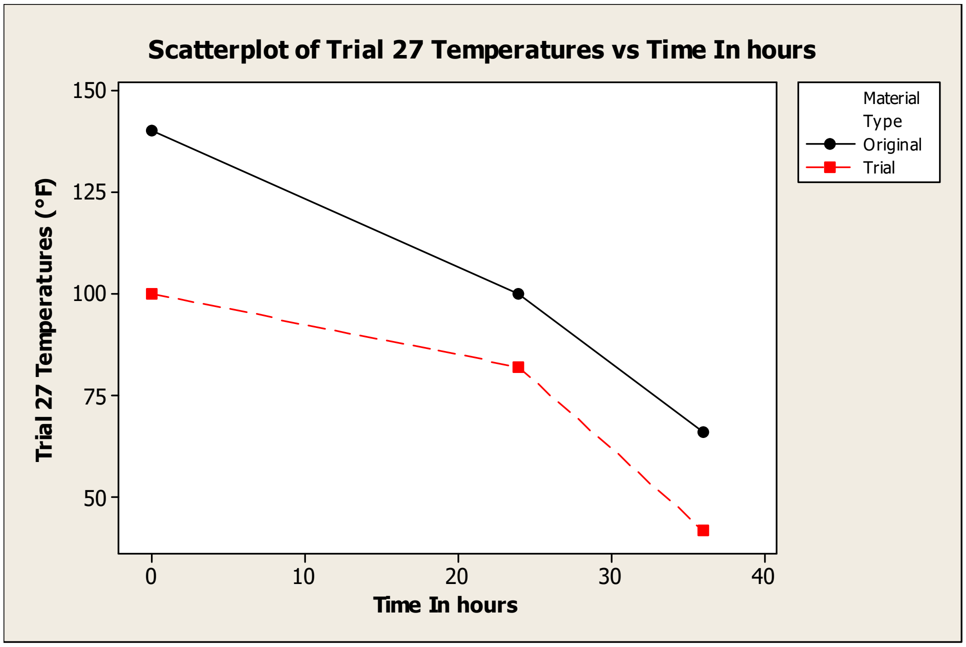


FIGURE G27: Trial 27 Temperature Data

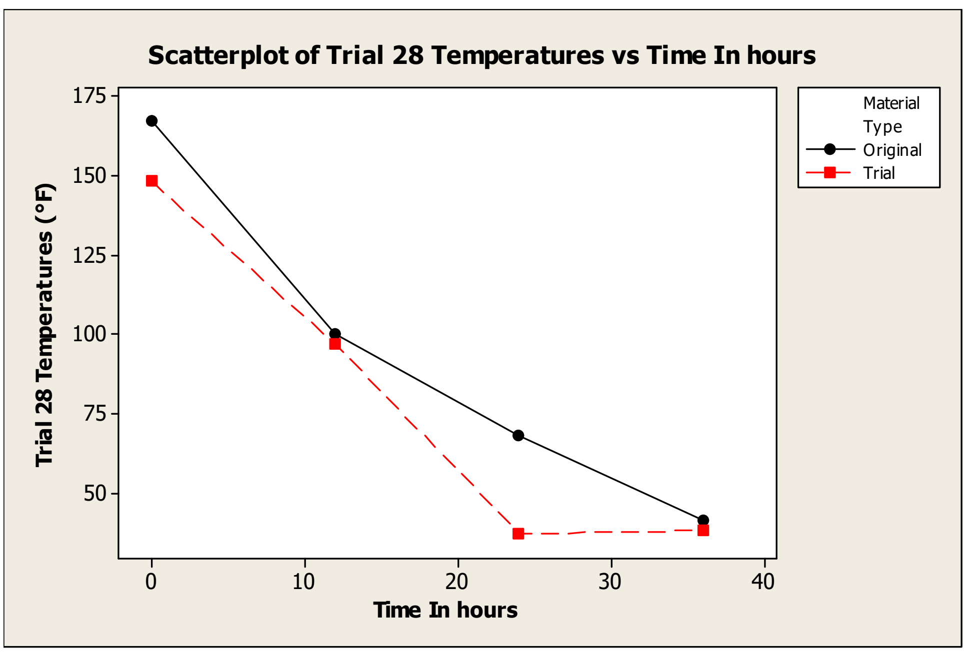


FIGURE G28: Trial 28 Temperature Data

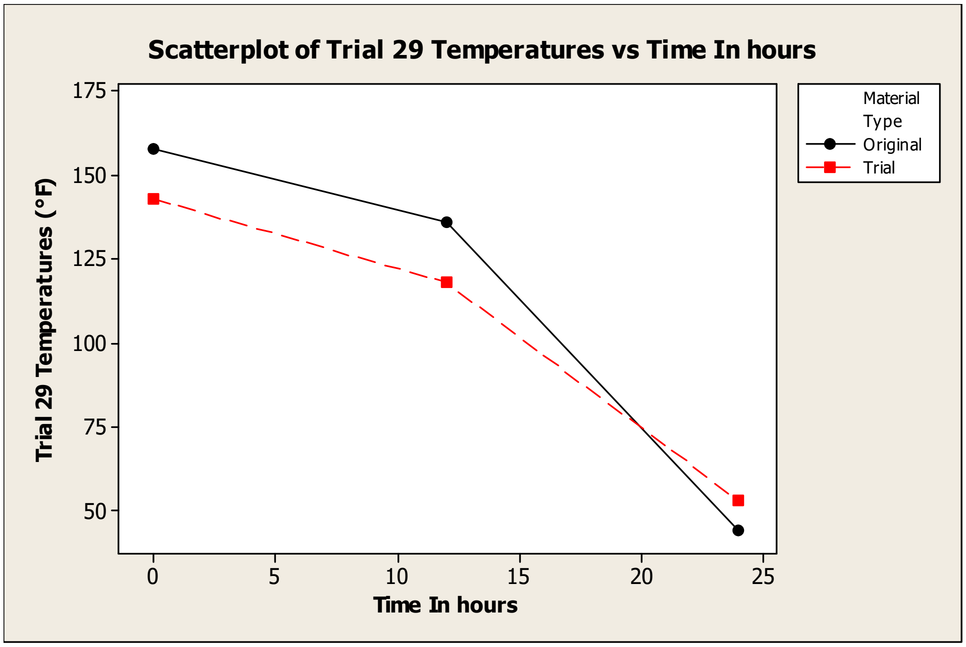


FIGURE G29: Trial 29 Temperature Data

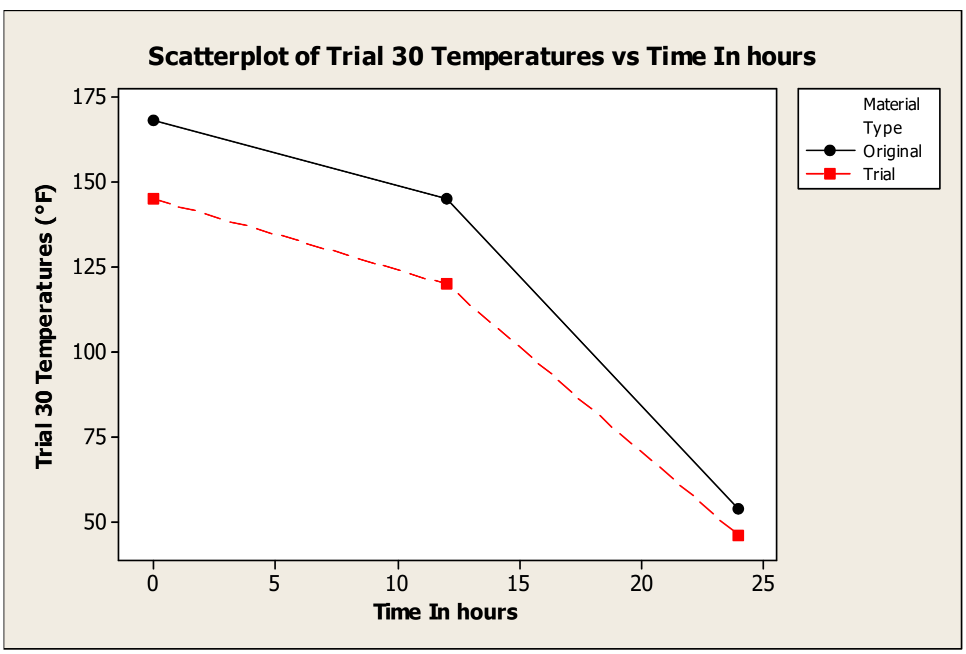


FIGURE G30: Trial 30 Temperature Data

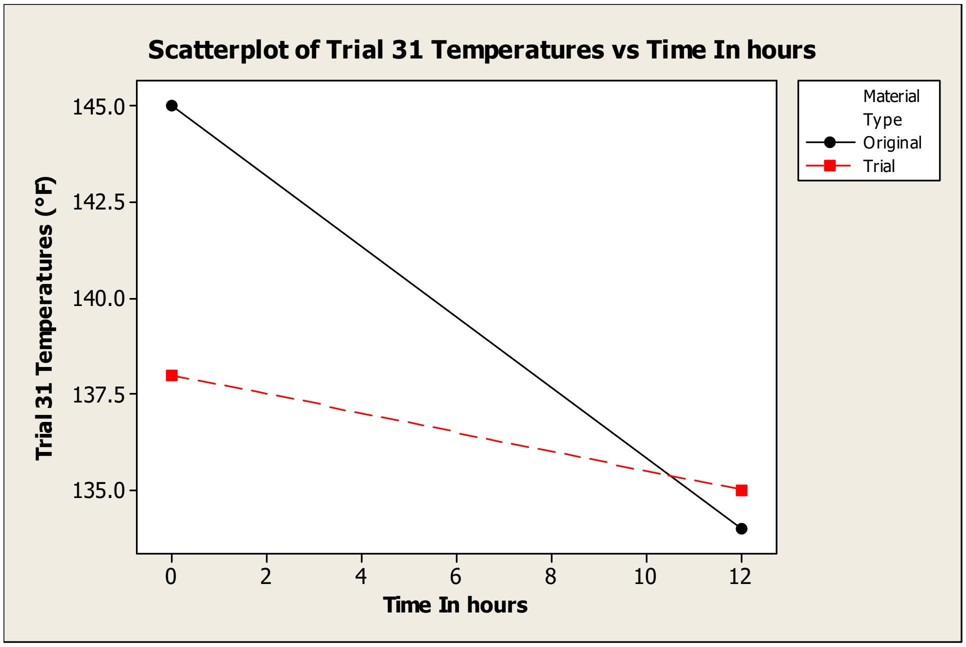


FIGURE G31: Trial 31 Temperature Data

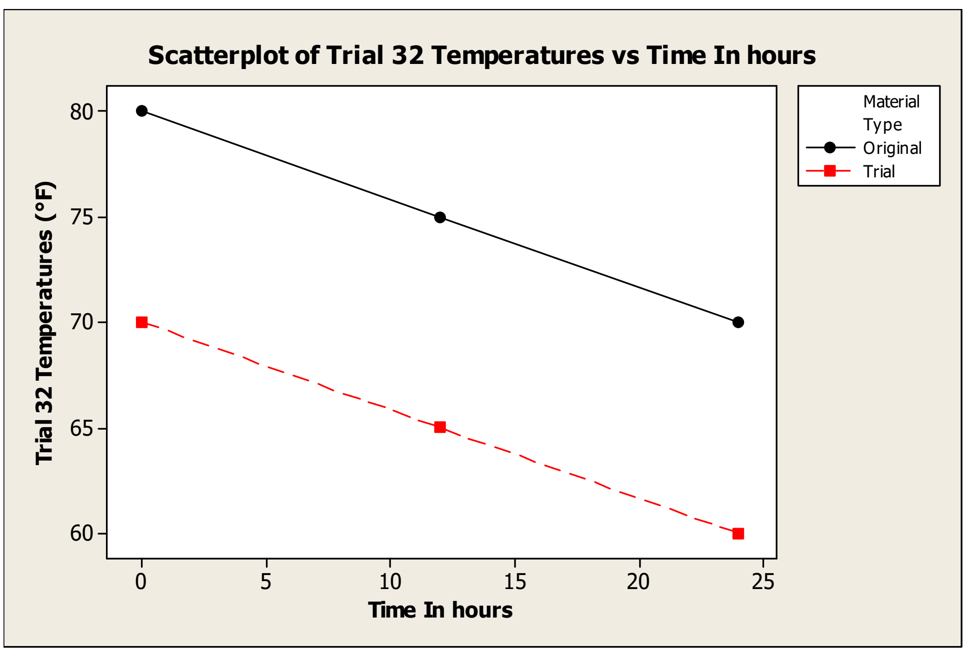


FIGURE G32: Trial 32 Temperature Data

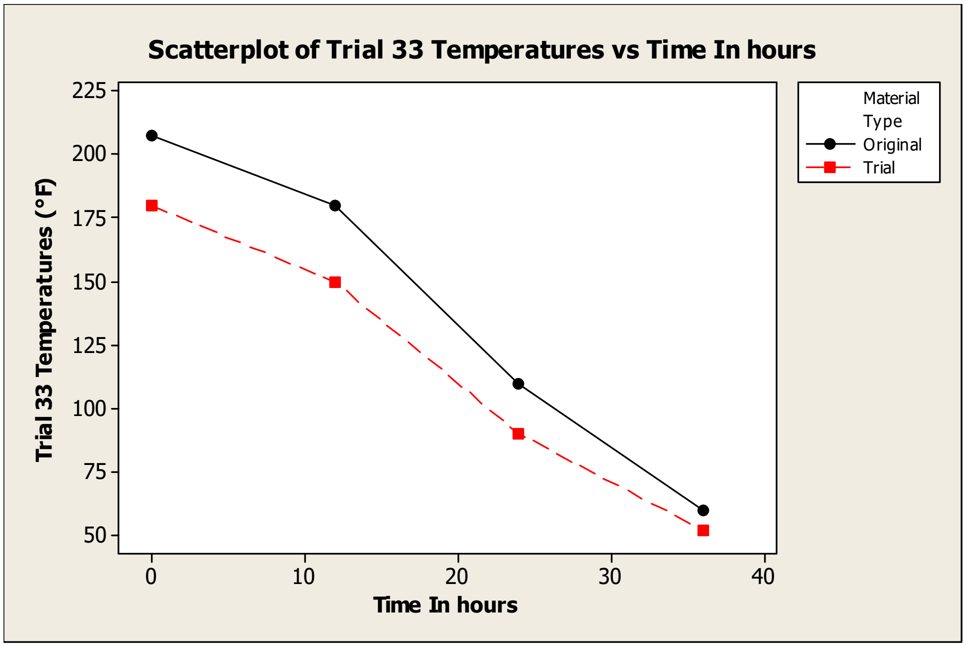


FIGURE G33: Trial 33 Temperature Data

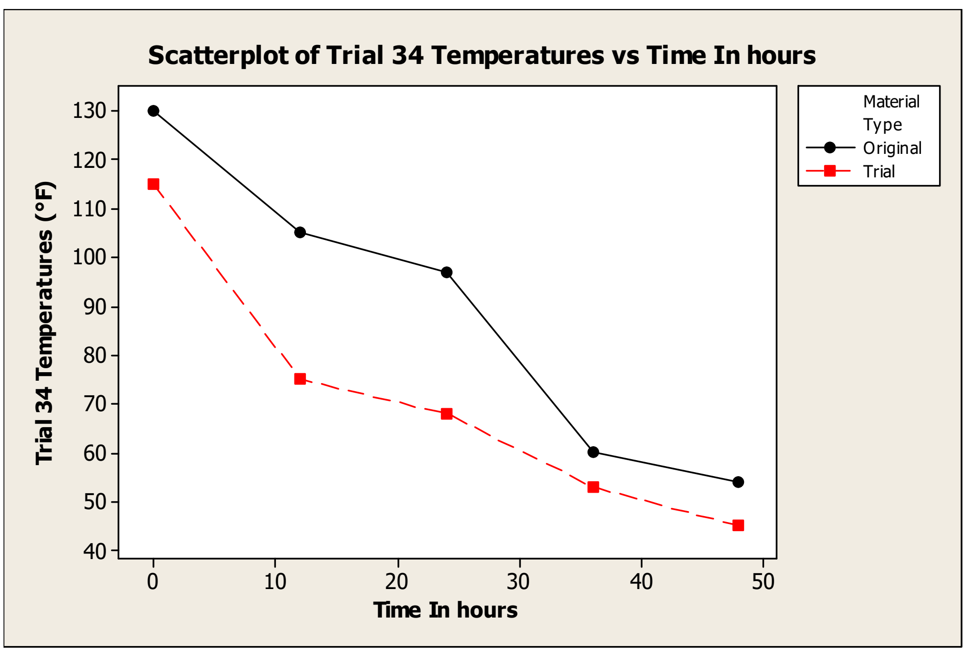


FIGURE G34: Trial 34 Temperature Data

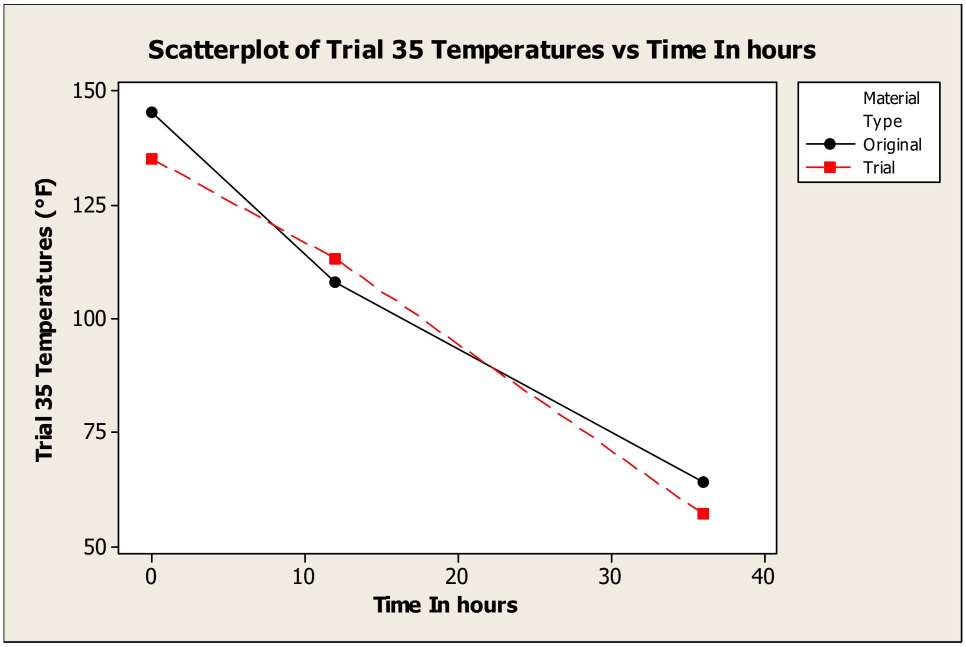


FIGURE G35: Trial 35 Temperature Data

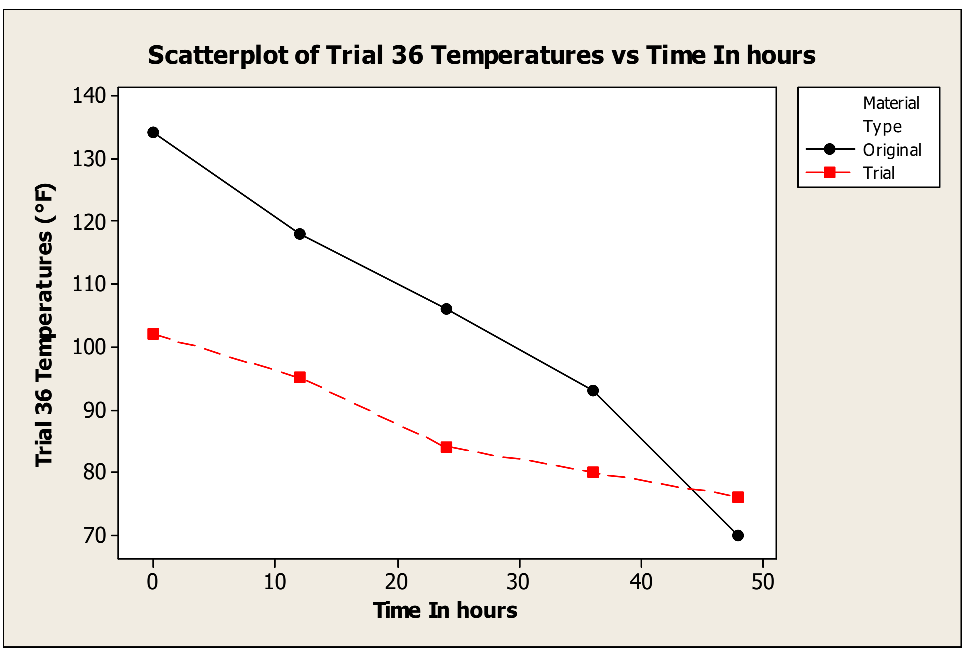


FIGURE G36: Trial 36 Temperature Data

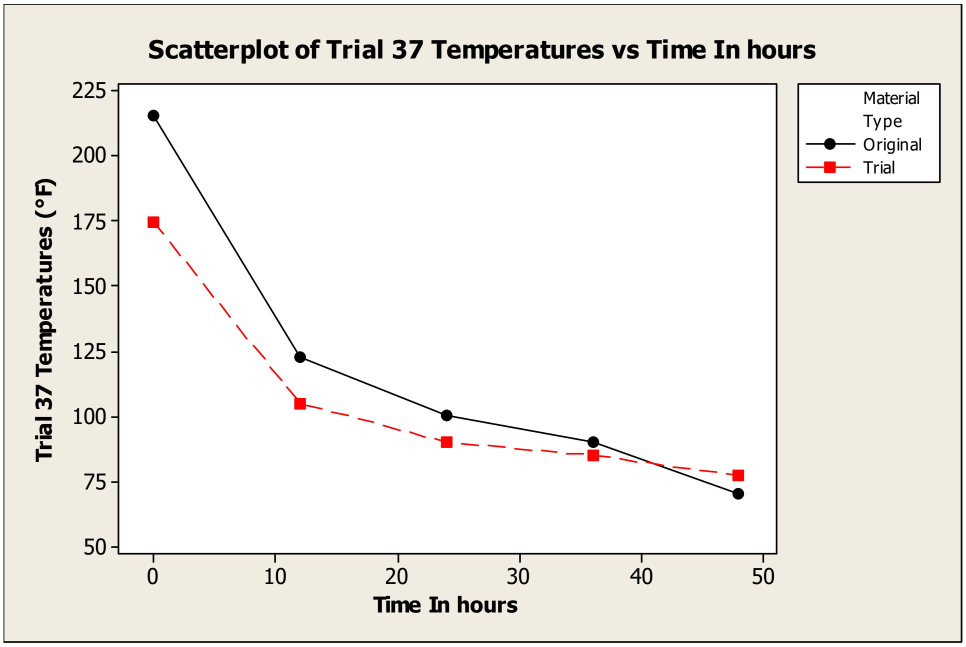


FIGURE G37: Trial 37 Temperature Data

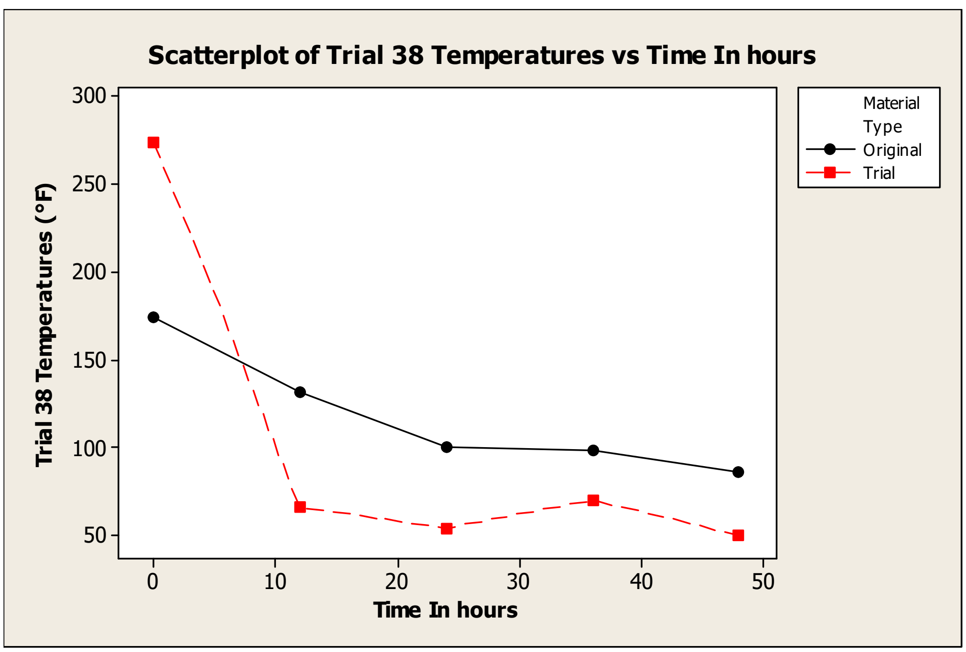


FIGURE G38: Trial 38 Temperature Data

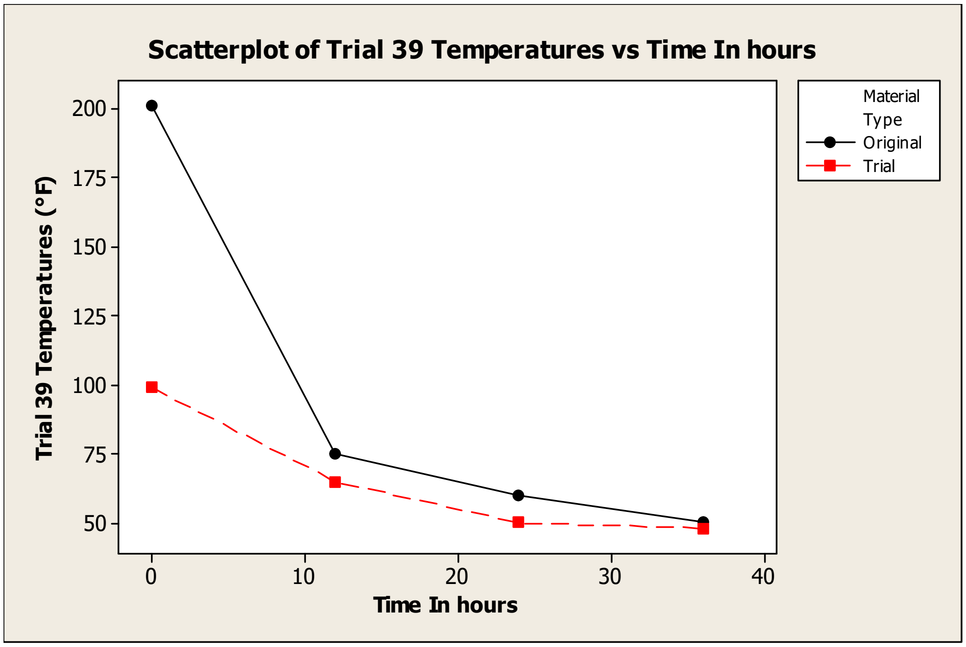


FIGURE G39: Trial 39 Temperature Data

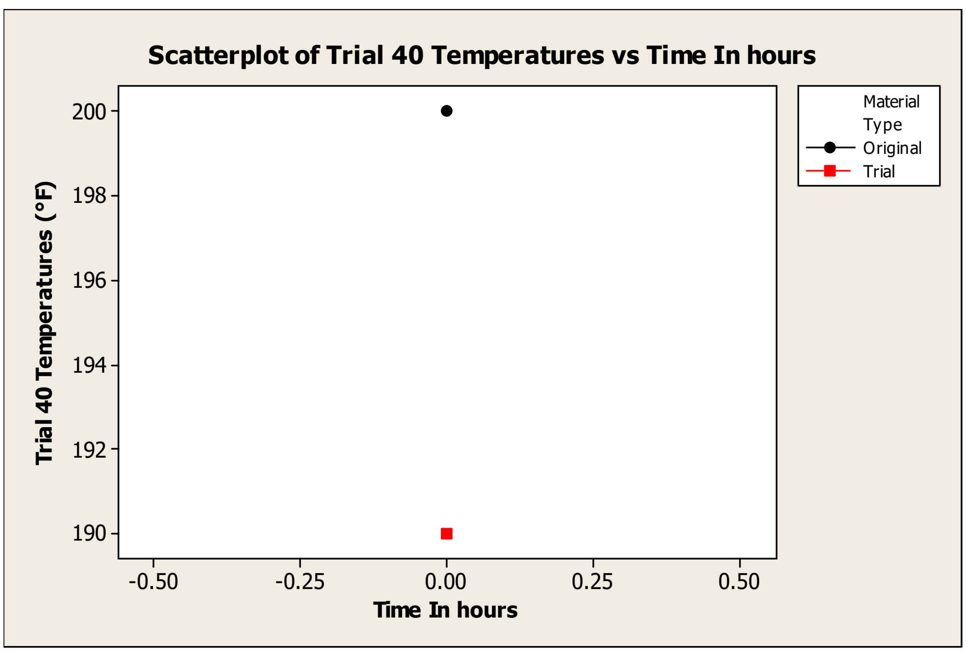


FIGURE G40: Trial 40 Temperature Data

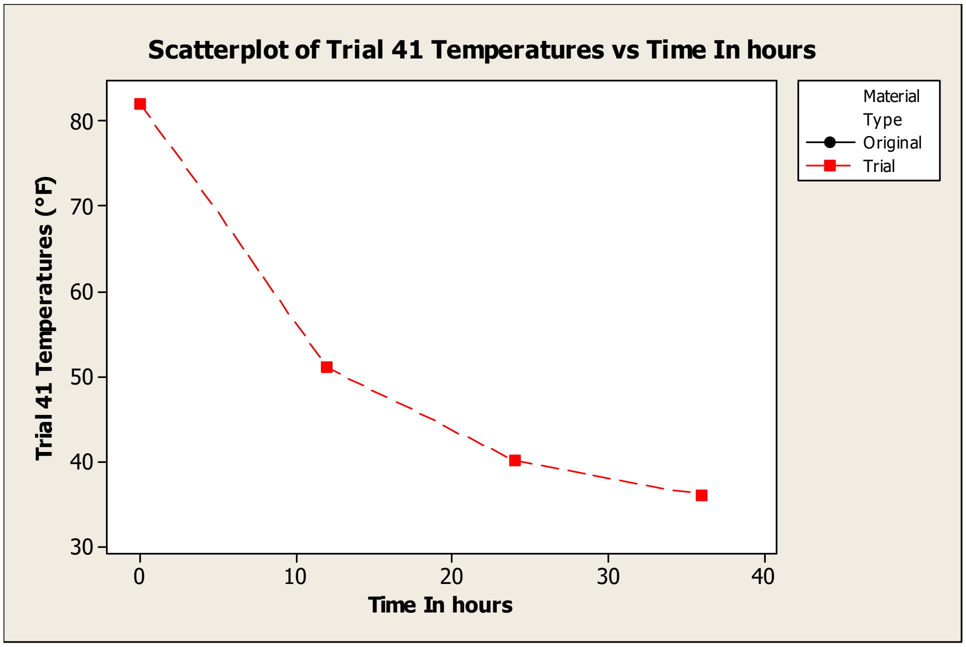


FIGURE G41: Trial 41 Temperature Data

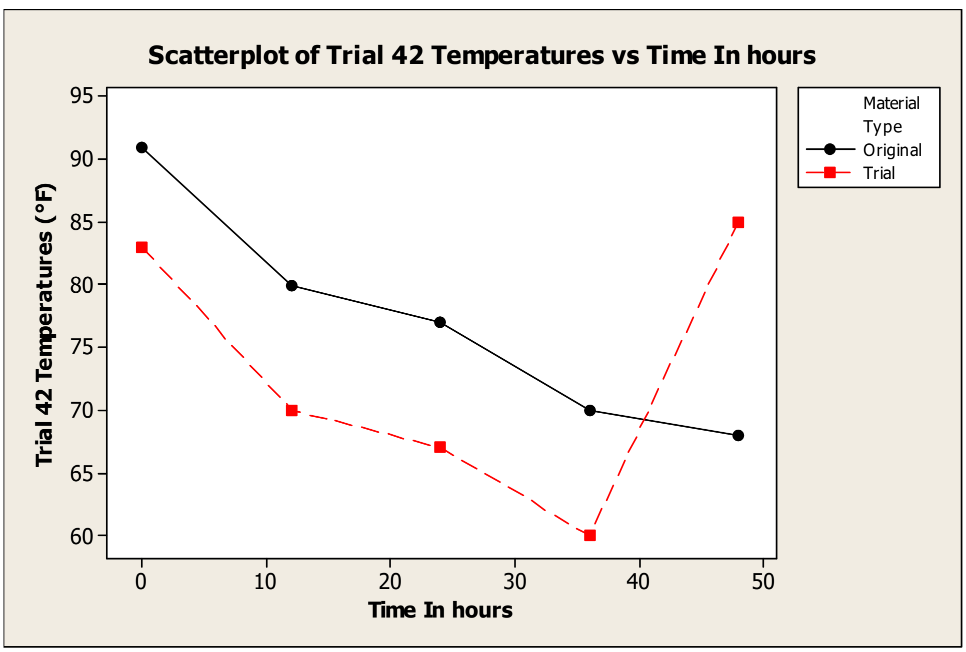


FIGURE G42: Trial 42 Temperature Data

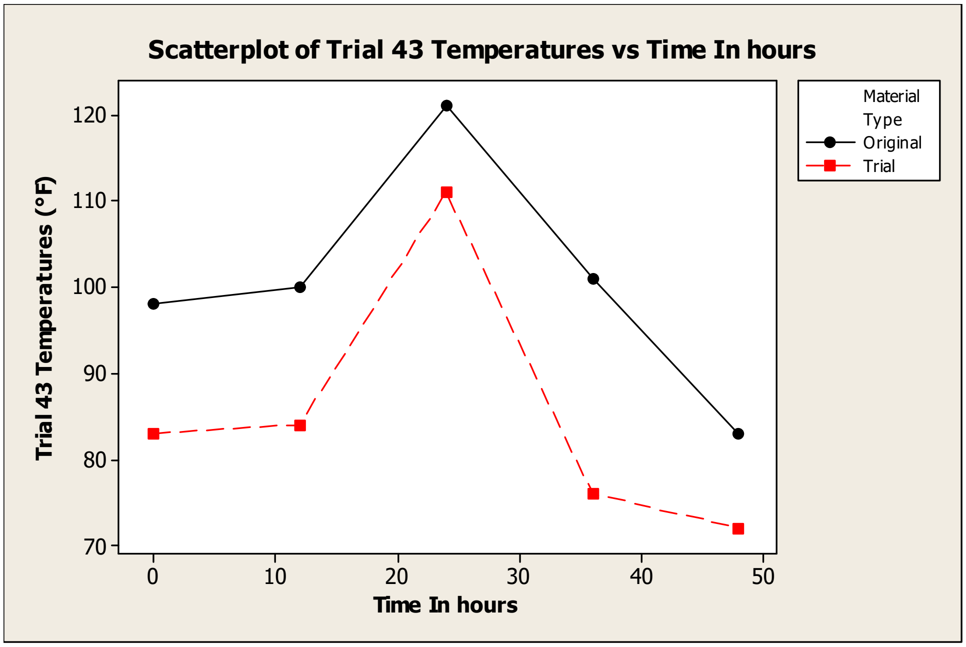


FIGURE G43: Trial 43 Temperature Data

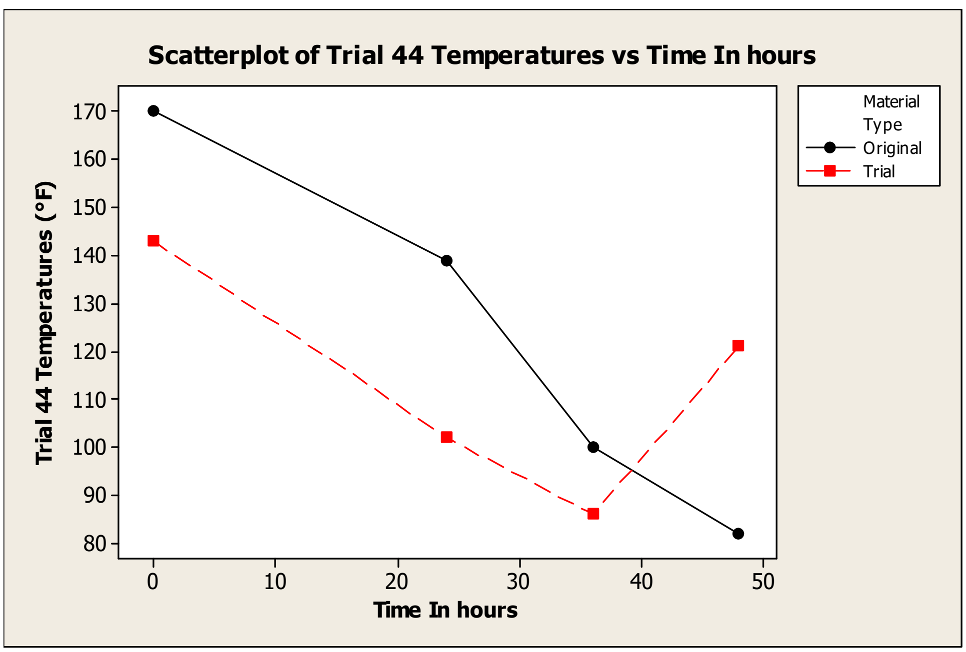


FIGURE G44: Trial 44 Temperature Data

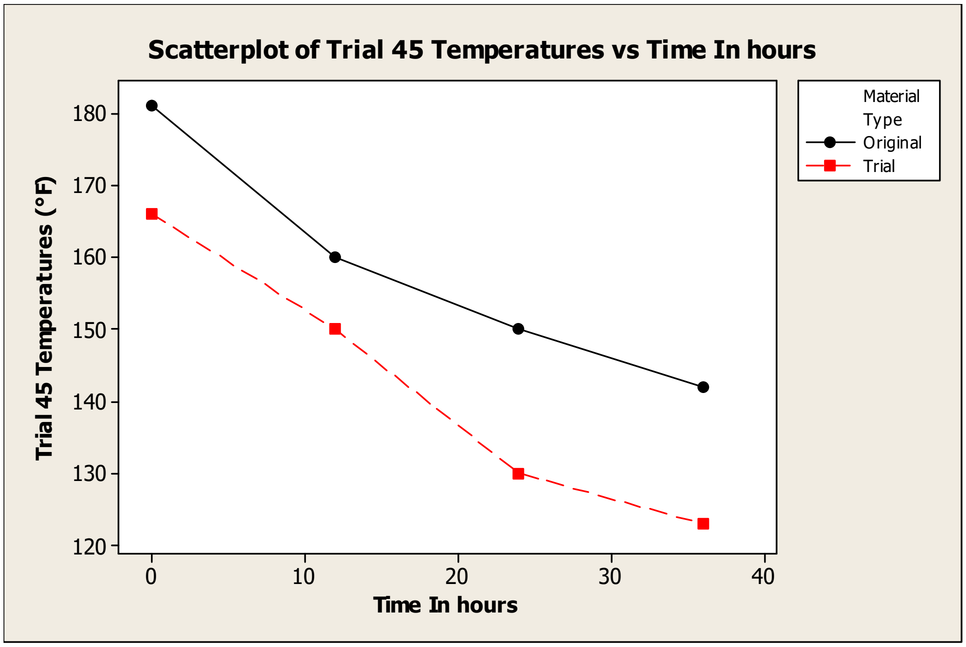


FIGURE G45: Trial 45 Temperature Data

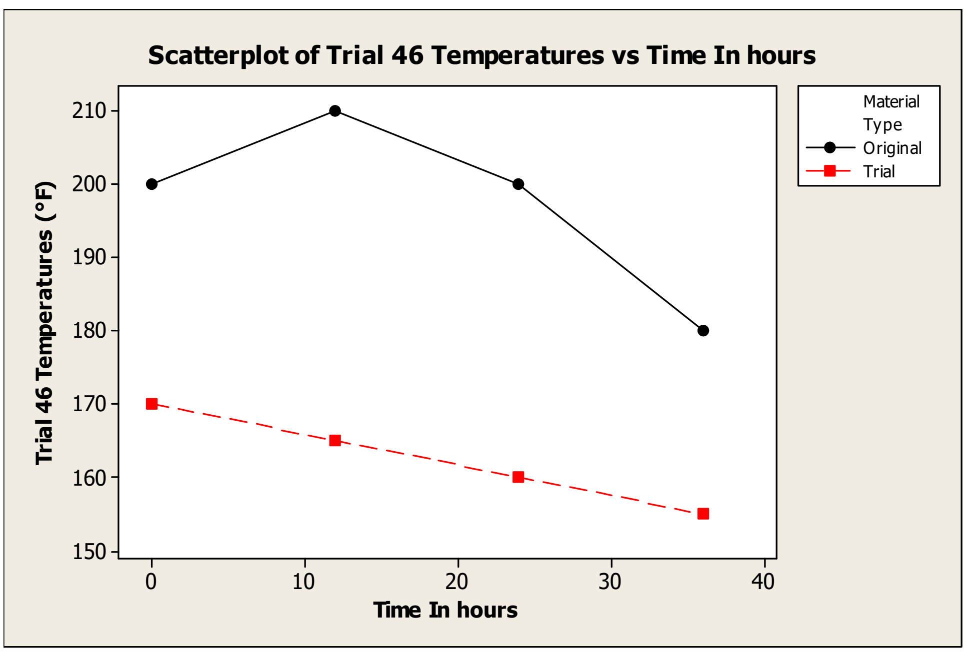


FIGURE G46: Trial 46 Temperature Data

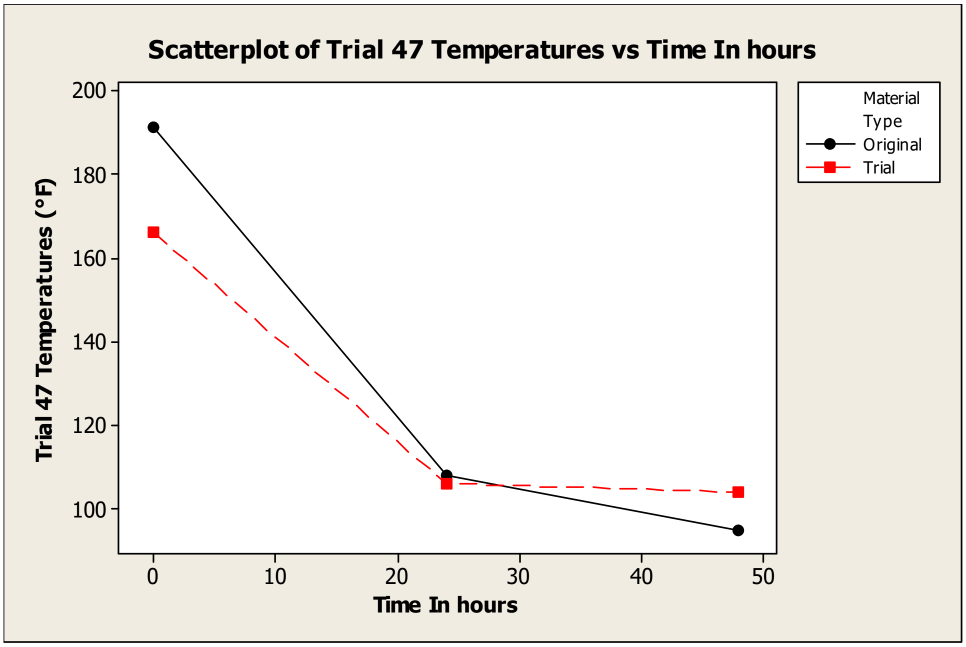


FIGURE G47: Trial 47 Temperature Data

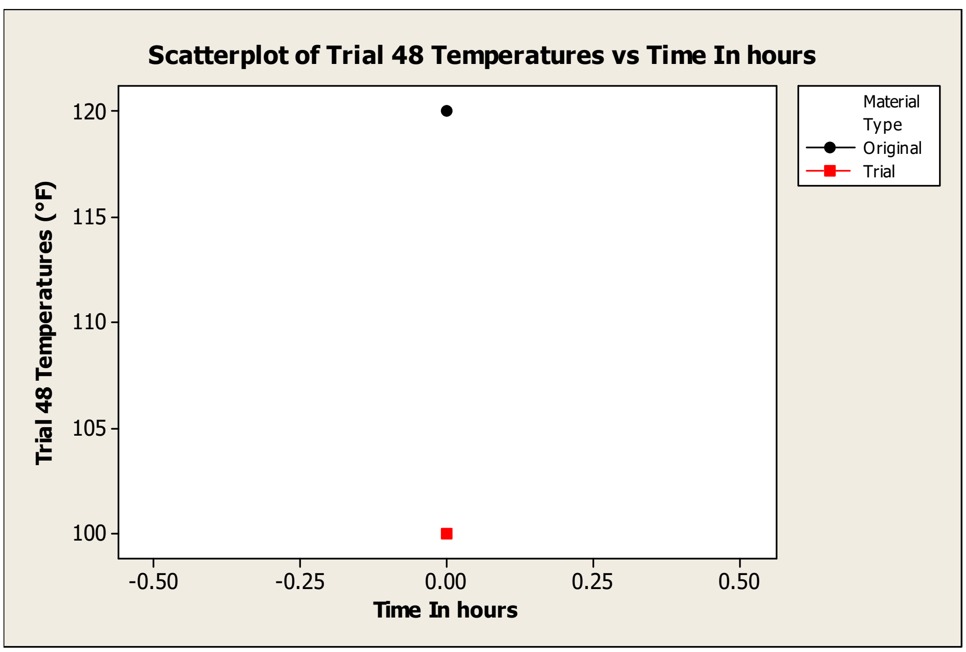


FIGURE G48: Trial 48 Temperature Data

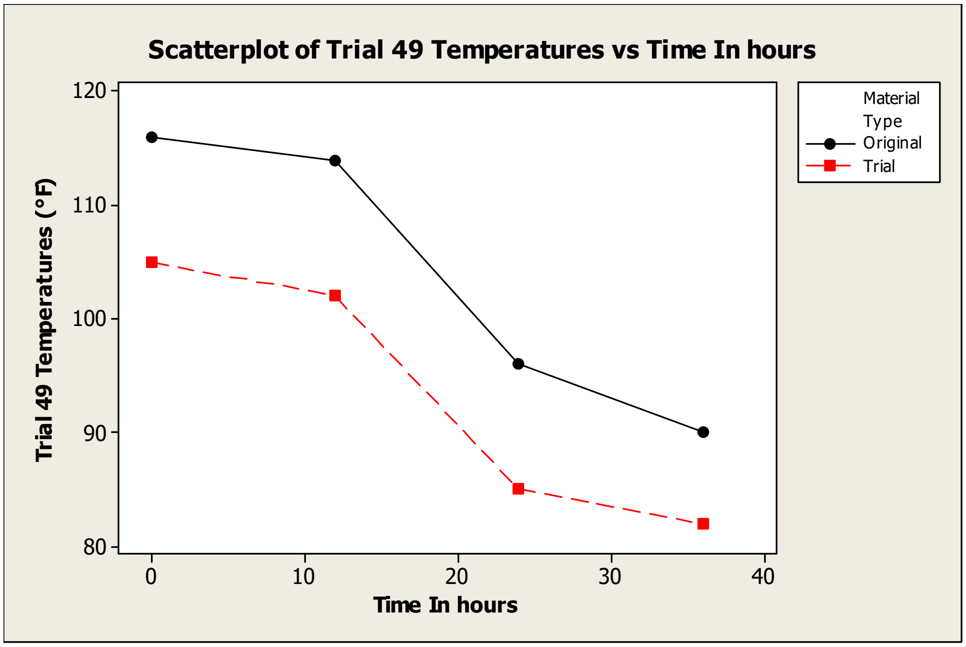


FIGURE G49: Trial 49 Temperature Data

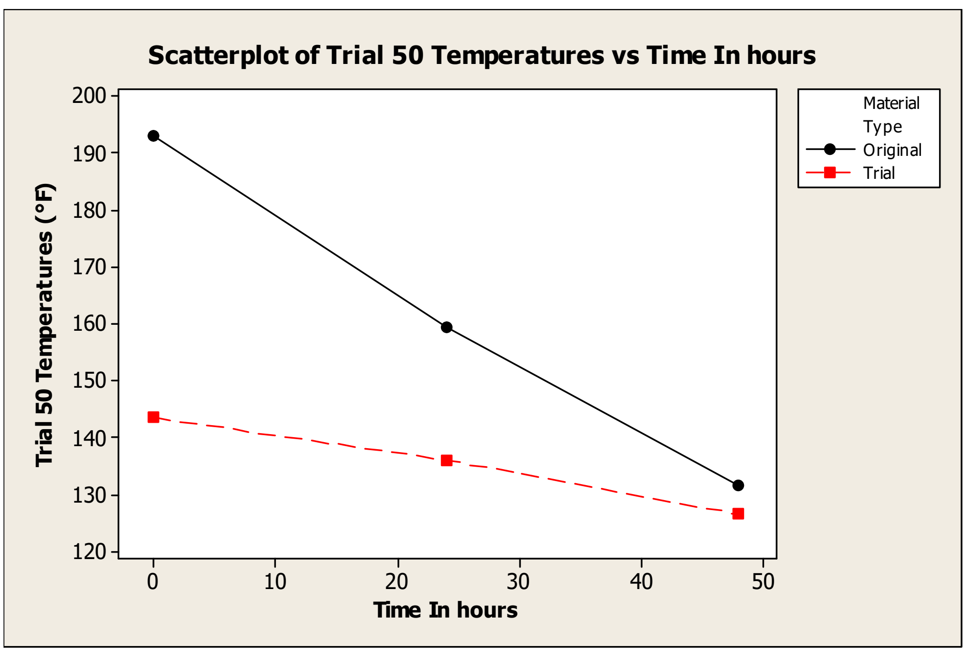


FIGURE G50: Trial 50 Temperature Data

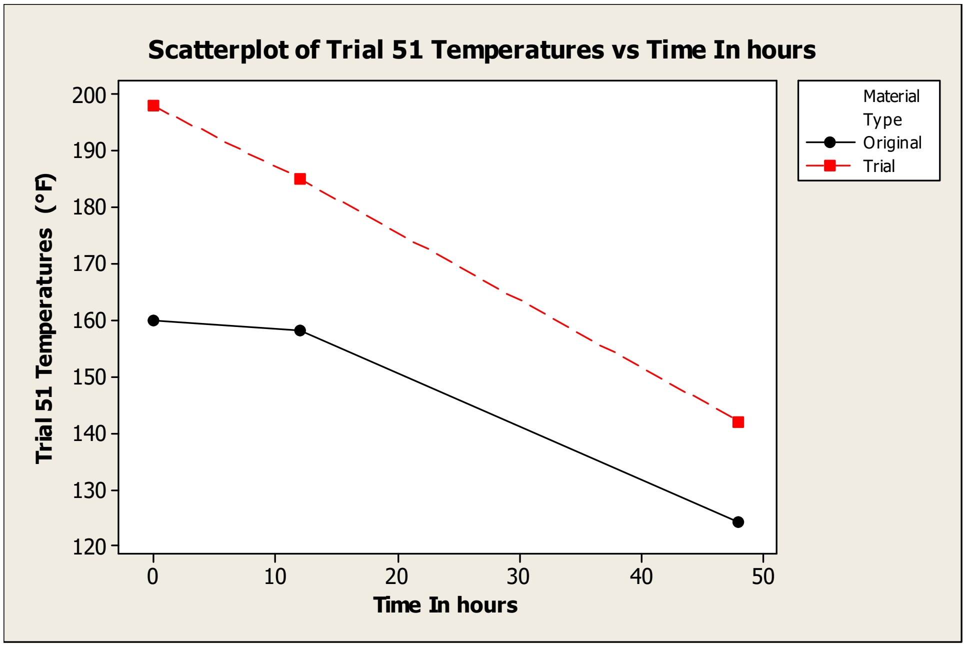


FIGURE G51: Trial 51 Temperature Data

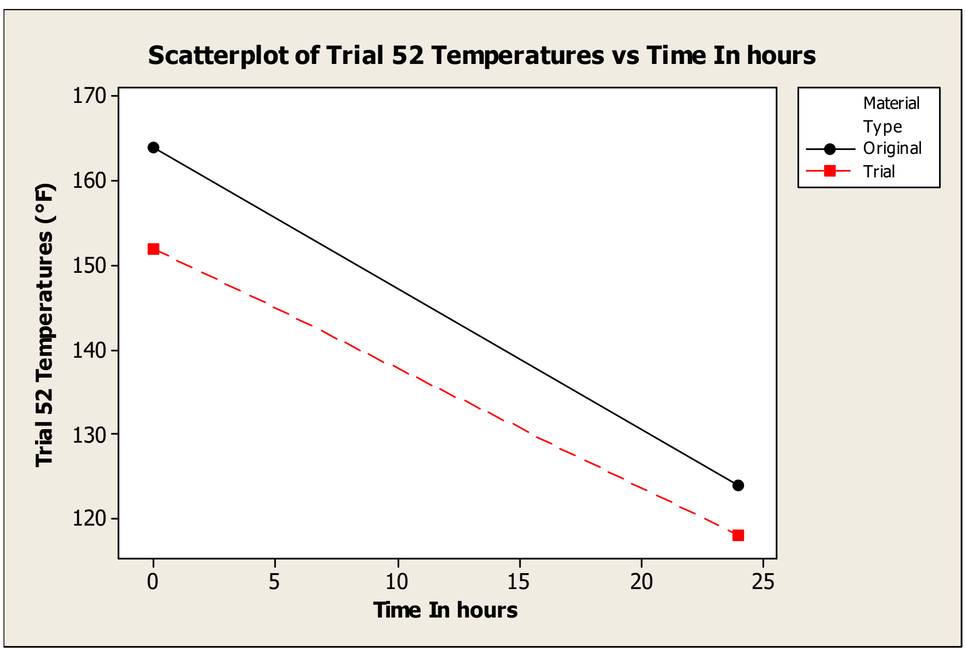


FIGURE G52: Trial 52 Temperature Data

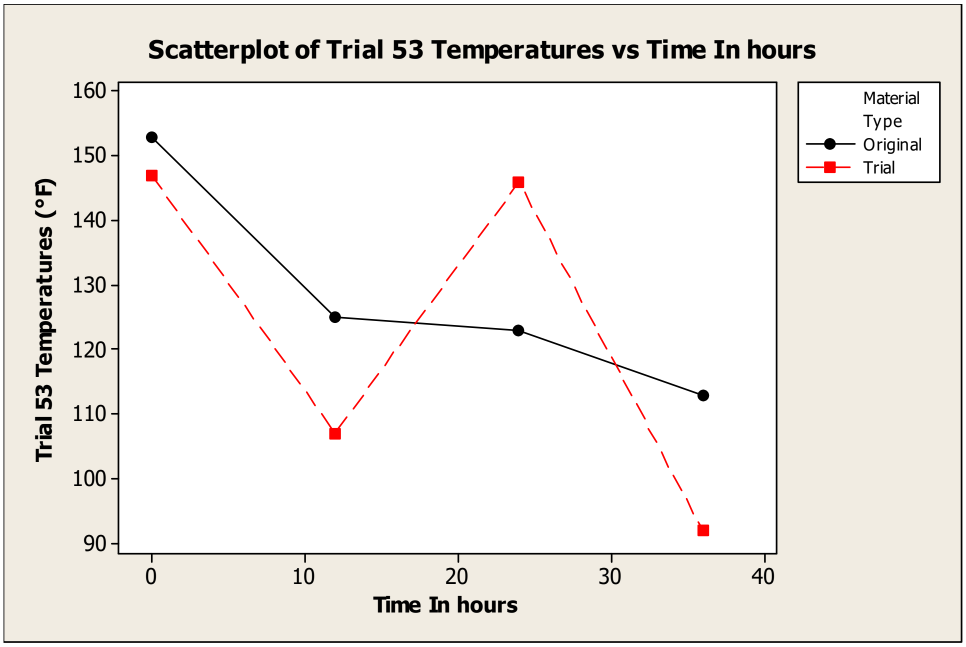


FIGURE G53: Trial 53 Temperature Data

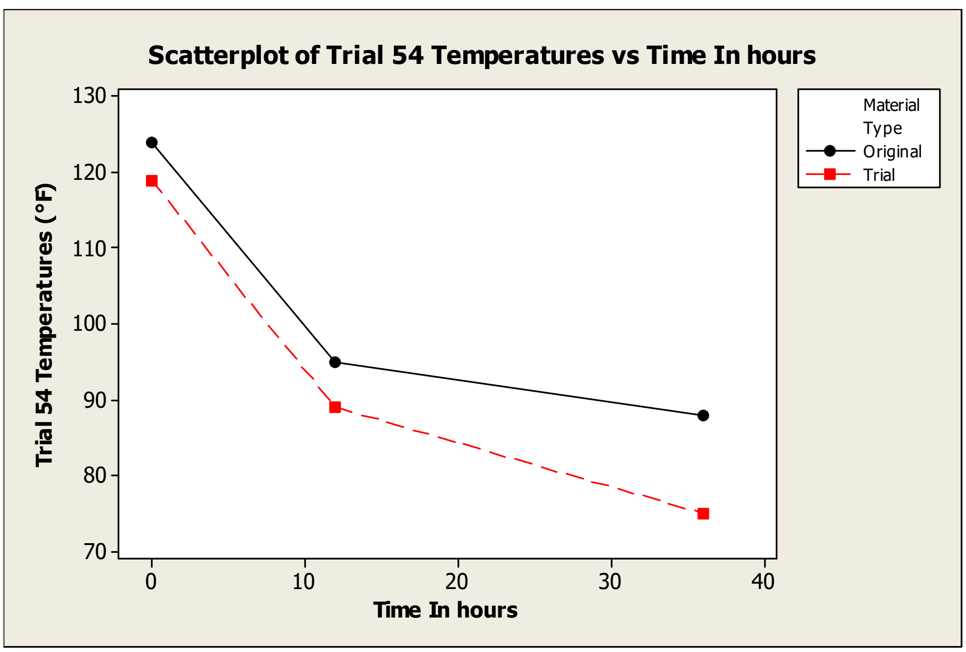


FIGURE G54: Trial 54 Temperature Data