Influence of High Intensity Mixing on Green Ball and Fired Pellet Properties

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Executive Summary

For the Minnesota Taconite Industry to compete in today's global economy, pellet quality must meet or exceed the standards being set by its competitors. Green ball quality is accepted by the industry as one of the key parameters influencing fired pellet quality and bentonite binders have been established as the industry standard for North American mines. Previous studies have shown that the opportunity exists to use high intensive mixing of binder and concentrate to reduce additive rates and enhance quality (4). Historically these units were cost prohibitive for retrofit in the taconite operations, however the economic models have changed. The type of mixing intensity required and the parameters influenced must be identified to complete cost benefit models and properly size apparatuses for further economic consideration. The objective of this project is to compare the benefits of intensive mixing with typical standard mixing procedures using the physical and metallurgical quality of both green balls and fired pellets as guidelines.

A series of tests were conducted at both the bench and pilot scale to evaluate conventional mixing practices and then compared them to intensive mixing of concentrate and binder. Standardized procedures for batch balling tests were used to evaluate green ball properties and both mini-pot and full pot grate tests were used to produce fired pellets for physical and metallurgical quality evaluation.

From batch balling testwork, intensive mixing shows a significant increase in the green ball drop number and dry compressive strength. Drop number increased 50%, (3.8 to 5.7) at 15 lbs./DLT, 69%, (5.8 to 9.8) at 20 lbs./DLT, and 90% (6.4 to 12.2) at 25 lbs./DLT. Trends with respect to dry strength also indicated a 50-65% increase at all three binder addition rates. The bench test data shows that as mixing intensity increases (increasing blade speed), green ball quality also improves. Drop number increased from 9.3 to 19.8 at 25 lbs./DLT and dry strength increased from 13.8 to 21.7 lbs. at 25 lbs./DLT, resulting in an improvement of approximately 60%.

Slight improvements in fired pellet quality in mini-pot pellets are indicated with intensive mixing over the conventional design at the lower bentonite rates. These results show that the green balls prepared with intensive mixing and a lower bentonite addition are similar or better than those with prepared at higher addition rates with conventional mixing, and resulted in higher quality pellets with respect to after tumble and compression in mini-pot pellets.

Only a slight improvement in both drop number (9.3 to 10.2) and dry strength (11.2 to 12.5 lbs) were obtained with intensive mixing with 15 lbs./DLT bentonite binder on the flux pellet blend in the pilot balling disk. The acid pellet mix shows improvement in the drop number (8.6 to 11.8), however, dry strength decreased from 14.7 to 13.7 lbs with intensive mixing. For both pot grate pellet quality comparisons, fired pellet compression decreased by approximately 10%, from 556 to 499 lbs in the fluxed pellets and 448 to 412 lbs in the standard pellet test. Since this is contradictory to the mini-pot test results and there is limited data available for evaluation, further verification of these results should be conducted, with additional testing at the pilot scale prior to making any conclusions. With the exception of a decrease in pellet contraction on fluxed pellets, no significant differences in metallurgical quality were determined in this comparison.

1 Introduction

For the Minnesota Taconite Industry to compete in today's global economy, pellet quality must meet or exceed the standards being set by its competitors. Green ball quality is accepted by the industry as one of the key parameters influencing fired pellet quality. Bentonite binders for iron ore pelletizing have been established as the industry standard for North American taconite mines. As bentonite supplies and quality decline, and binder prices increase, techniques for decreasing consumption or improving quality become of interest. Previous studies have shown that the opportunity exists to use high intensive mixing of binder and concentrate to reduce additive rates and enhance quality (4). Historically these units were cost prohibitive for retrofit in the taconite operations, however the economic models have changed. The type of mixing intensity required and the parameters influenced must be identified to complete cost benefit models and properly size apparatuses for further economic consideration. The objective of this project is to compare the benefits of intensive mixing with typical standard mixing procedures using the physical and metallurgical quality of both green balls and fired pellets as guidelines.

2 Background

2.1 Bentonite Binder Mechanism

Bentonite is an iron ore pelletizing binder that is used to maintain the physical integrity of the green ball during material handling and processing. It is a unique type of clay, composed primarily of montmorillonite. It was formed by the alteration of volcanic ash deposited from areas now occupied by the Rocky Mountains. It is composed of two tetrahedral silica platelets that results in a polar negative charge on the outside surface. This forms an ideal site for the positively charged sodium and calcium ion to bond to the surface of these platelets. Weak bonds hold the sodium, while much stronger bonds hold the calcium ions making it much easier to dissociate the sodium (2). Bentonite enhances the strength of iron ore agglomerates in two ways; 1) as colloidal material that decreases inter-particle distances and thus increases van der Waal's forces and 2) it forms a solid bridge of hardened gel that strengthens particle contact points (1, 4). In the presence of water, the sodium ions are dissociated and platelets will separate allowing the absorption of water in the interstices creating a dispersion of water and binder. Intensive mixing imposes shear forces that can cause the clay platelets to slide past one another, at low water concentrations, to form bridges between the particles (3). An understanding of the parameters that are key to influencing fired pellet quality will help to improve the quality of these products.

2.2 Batch Balling

Batch balling tests are designed to define the parameters required for production of quality green balls with a specified ore and necessary additives. It can be used to establish binder rates and can subsequently be used for comparing the influence of ore characteristics such as grind as well as binders, additives, or balling techniques on individual green ball physical quality parameters. Green balls are typically prepared in 3000 g batches, using standardized procedures, in a balling tire from iron ore concentrate, binders and any necessary additives. Green ball physical quality is evaluated by comparing green ball moisture content, 18" wet drop number, dry compressive strength, and sizing as an indicator of green ball growth rate. Figure 1 shows the standard batch balling test equipment and arrangement, consisting of a Mueller mixer, shredder, and balling tire.

Figure 1: Batch balling test equipment and arrangement

For this study, alternative mixing techniques were employed using the "V" mixer and bench scale Eirich Mixer shown in Figures 2 and 3 below:

Figure 2: "V" Mixer

Figure 3: Eirich High Intensity Mixer

2.3 Mini-Pot Furnace

Batch balling tests are commonly fired in the mini-pot furnace (Figure 4) and used to quantify the relative effect of changes in additives, agglomeration, or firing temperatures on physical pellet quality. This equipment has shown to be effective for evaluating balling additives, binders, temperatures and various firing conditions for taconite pellets.

Figure 4: Mini-Pot Furnace

A mini-pot test is designed to indurate green balls using specified cycles to produce 1700-1800g of fired pellets for physical quality analyses (%+1/4" AT and fired pellet compression). This is compared to a pot grate test that requires a starting concentrate weight of 200 lbs. and creates about 75 lbs. of green balls. The smaller size reduces material handling, green ball preparation and analysis time, therefore reducing its costs compared to full pot grate tests. Furnace cycles developed from mini-pot tests are also used to define initial parameters required for drying, pre-heat, firing and cooling stages of induration.

2.4 Pot Grate Furnace

The pot grate furnace and related test results have historically been used to design both straight-grate and grate-kiln induration machines for decades. The pot grate furnace consists of 1ft^2 pot with grate bars at the bottom to allow airflow penetration. The burner/combustion chamber arrangement and the associated ducting permit the flow of gasses using updraft and downdraft configuration while controlling temperature, pressure drop across the bed, and oxygen content. The NRRI CMRL pot grate furnace (Figure 5) has recently been upgraded with a new combustion system and blower, PLC control, PC based data collection, flow control/measurement for nat. gas, airflow, and oxygen, digital pressure and oxygen measurement, and full temperature recording capabilities up to 7 thermocouples including bed profile at 2" intervals. A thermocouple located 18 inches above the bed of pellets and is referred to as the "on-gas" or control temperature. The oxygen concentration is measured in the on-gas approximately 6 inches above the bed.

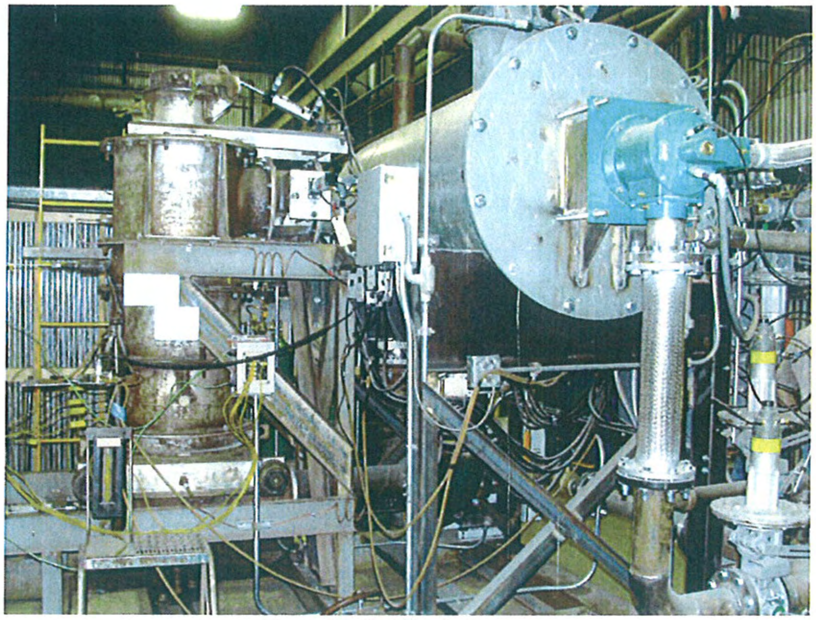

Figure 5. Pot Grate Furnace

Green balls for pot grate tests are prepared in pilot equipment using the baselines additive defined in the batch balling studies. The typical process involves filtering concentrate to approximately 9.5% moisture, blending the concentrate and binder in a Simpson Mixer Muller and balling the blended concentrate in a pilot balling disk. The pilot equipment is shown in Figures 4 and 5.

Figure 6. Simpson Muller Mixer

Figure 7. Balling Disk (3 ft. dia.)

It should be noted that the pilot scale Eirich, originally planned for use in this series was not available in the time frame it was requested, therefore, the high intensity mixing was accomplished using the bench scale Eirich mixer unit shown in Figure 3. Initial mixing tests were conducted using the pilot Littleford unit shown below (Figure 8), however no noticeable difference was observed between this unit and the Simpson Muller Mixer shown above.

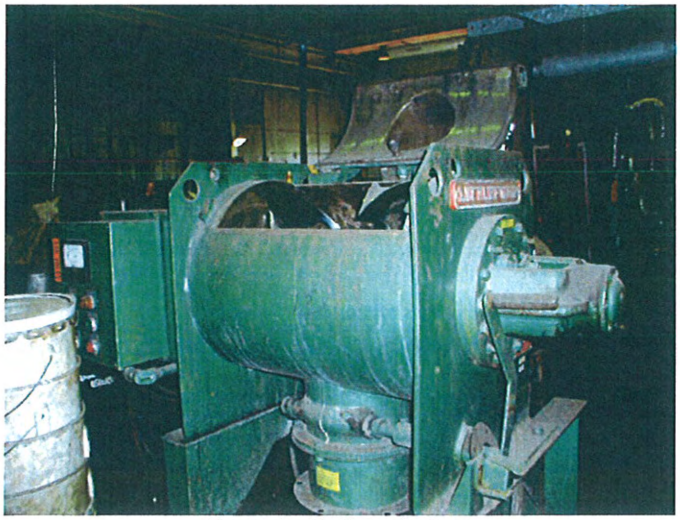

Figure 8: Littleford Mixer

3 Results and Discussion

3.1 Batch Balling Test Results

A series of batch balling tests were conducted to compare the physical quality of green balls prepared with bentonite binder at various addition rates with multiple forms of mixing techniques. The data from these tests is provided in Table 1.

						Green Ball Quality				
Test ID No.	Mixing	Time	Speed	Bentonite	Moisture	18" Drop	Dry Comp	Green Ball Sizing, %		
		(min.)	(rpm)	lbs./DLT	%	#	lbs.	+1/2"	-1/2" +7/16"	-7/16" +3/8"
Batch Balling Test M11520	Muller Mixer	2	std	15.0	9.2	3.8	5.8	2.8	48.2	48.9
Batch Balling Test M11521	Eirich Mixer	1	567	15.0	9.4	5.7	9.6	15.6	49.5	34.9
Batch Balling Test M11522	"V" Mixer	1	std	15.0	9.0	3.6	5.1	6.0	53.9	40.1
Batch Balling Test M11523	Muller Mixer	2	std	20.0	9.5	5.8	8.0	6.5	57.3	36.2
Batch Balling Test M11524	Eirich Mixer	1	567	20.0	9.6	9.8	12.0	18.4	48.9	32.7
Batch Balling Test M11525	"V" Mixer	1	std	20.0	9.4	4.9	6.9	15.4	52.4	32.3
Batch Balling Test M11526	Muller Mixer	2	std	25.0	9.6	6.4	10.0	5.6	54.0	40.4
Batch Balling Test M11527	Eirich Mixer	1	567	25.0	9.9	12.2	16.2	4.4	39.4	56.3
Batch Balling Test M11528	Eirich Mixer	1	219	15.0	9.5	4.9	7.9	2.0	47.1	50.9
Batch Balling Test M11529	Eirich Mixer	1	219	20.0	9.5	6.6	10.1	8.1	47.9	44.1
Batch Balling Test M11530	Eirich Mixer	1	219	25.0	9.8	9.3	13.8	7.4	53.5	39.1
Batch Balling Test M11532	Eirich Mixer	1	1500	15.0	9.3	7.5	11.2	28.0	47.2	24.9
Batch Balling Test M11533	Eirich Mixer	1	1500	20.0	9.6	10.4	16.0	21.9	51.4	26.7
Batch Balling Test M11534	Eirich Mixer	1	1500	25.0	10.0	19.8	21.7	11.4	55.5	33.1

Table 1: Batch Balling – Green Ball Test Results

Tests were conducted with bentonite addition rates ranging from 15 lbs./DLT to 25 lbs./DLT. All tests were initiated with a filter cake moisture content of 9.4% using identical procedures.

Balling water was used as required. The resulting moisture content ranged from 9.0 to 10.0%, understanding that some is lost during the mixing and agglomeration process. Also, no significant difference was observed between data from the bench Simpson Muller mixer and the "V" mixer with regard to green ball quality, so it was not used in subsequent testing. The Eirich mixer used for comparison was operated at a mid range blade speed of 567 rpm. The effect of intensive mixing on green ball physical quality is shown in Figures 9 and 10.

Figure 9: Green Ball Drop Number

Figure 10: Green Ball Dry Strength

Figure 9 shows a significant increase in the green ball drop number of 50%, (3.8 to 5.7) at 15 lbs./DLT, 69%, (5.8 to 9.8) at 20 lbs./DLT, and 90% (6.4 to 12.2) at 25 lbs./DLT with the use of intensive mixing. Figure 10 shows similar trends with respect to dry strength with a 50-65% increase at all binder addition rates.

In addition to changes in bentonite addition, the Eirich mixer was also examined at three different blade speeds, 219, 567 and 1500 rpm. Some of the initial tests were tried beyond 1500 rpm, however resulted in micro-balling and were not included in the data set. The corresponding trends with green ball quality are shown in Figure 11 and 12.

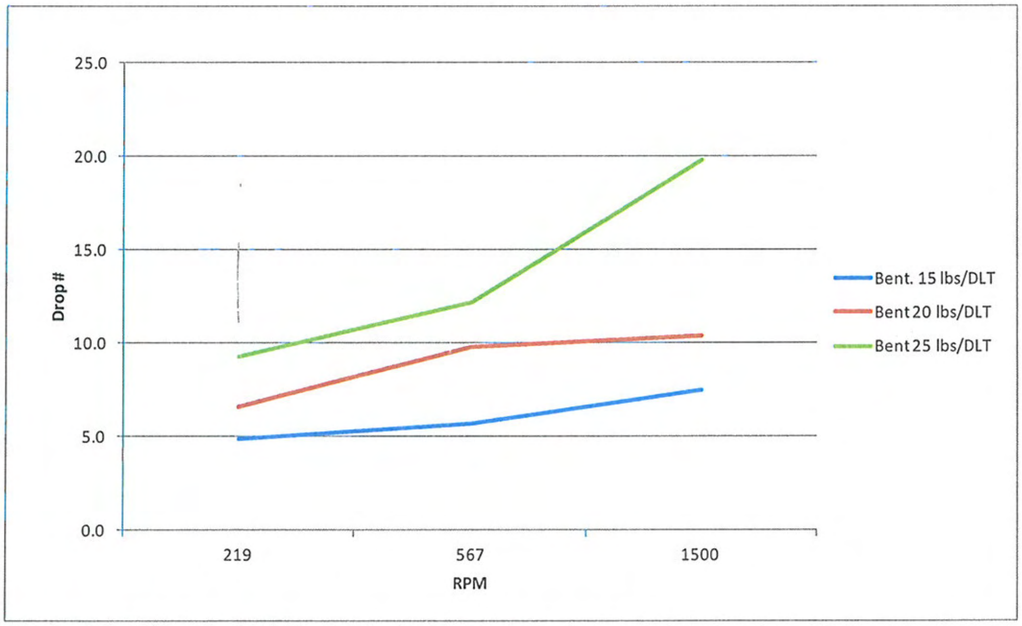

Figure 11: Influence of Mixing Intensity on Drop Number

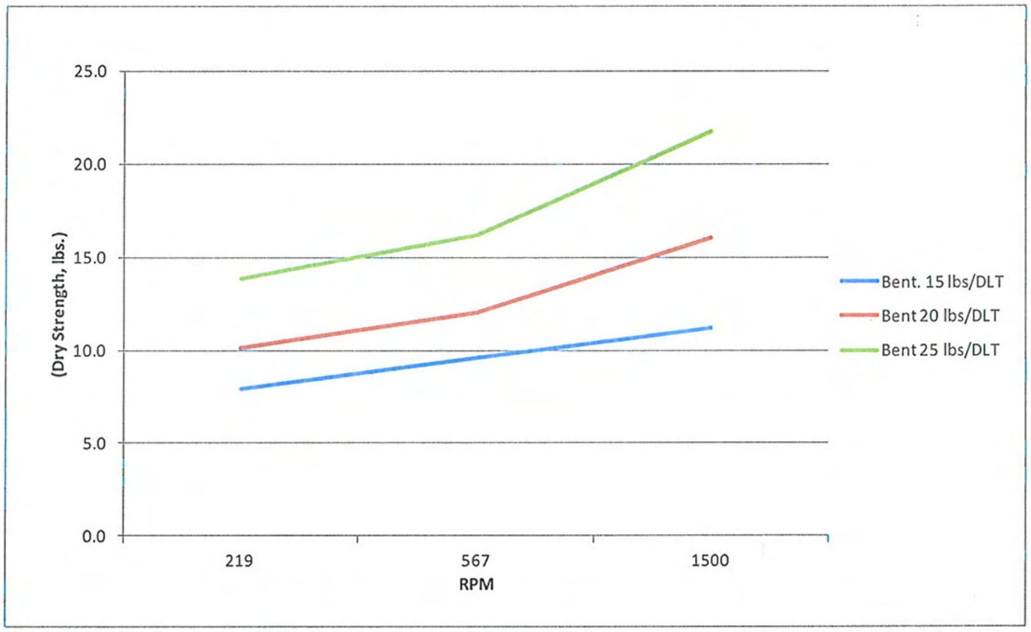

Figure 12: Influence of Mixing Intensity on Dry Strength

The bench test data shows that as mixing intensity increases (increasing blade speed), green ball quality with respect to drop number, (9.3 to 19.8 at 25 lbs./DLT) and dry strength, (13.8 to 21.7 lbs. at 25 lbs./DLT) improves by approximately 60%.

3.2 *Mini-Pot Test Results*

The batch balling tests described above were fired in the mini-pot furnace to produce a relative fired pellet quality shown in Table 2 below:

Test ID No.	Mixing	Time (min.)	Speed (rpm)	Bentonite lbs./DLT	Pellet Quality Compression Avg. lbs.	 %-300 lbs.	 %-200 lbs.	 After Tumble % + 1/4"	 % - 32M
Mini-Pot Grate Test M11520	Muller Mixer	2	std	15.0	482	7	1	95.8	3.8
Mini-Pot Grate Test M11521	Eirich Mixer	1	567	15.0	506	7	0	96.2	3.8
Mini-Pot Grate Test M11522	"V" Mixer	1	std	15.0	471	8	1	94.3	5.6
Mini-Pot Grate Test M11523	Muller Mixer	2	std	20.0	446	8	2	95.2	4.7
Mini-Pot Grate Test M11524	Eirich Mixer	1	567	20.0	482	9	0	97.1	2.9
Mini-Pot Grate Test M11525	"V" Mixer	1	std	20.0	451	11	2	93.0	3.9
Mini-Pot Grate Test M11526	Muller Mixer	2	std	25.0	457	12	0	95.8	4.1
Mini-Pot Grate Test M11527	Eirich Mixer	1	567	25.0	414	13	0	97.0	3.0
Mini-Pot Grate Test M11528	Eirich Mixer	1	219	15.0	497	5	0	95.8	4.1
Mini-Pot Grate Test M11529	Eirich Mixer	1	219	20.0	473	12	1	96.0	4.0
Mini-Pot Grate Test M11530	Eirich Mixer	1	219	25.0	459	13	0	97.0	3.0
Mini-Pot Grate Test M11532	Eirich Mixer	1	1500	15.0	540	1	0	97.4	2.6

Table 2: Mini-Pot Fired Pellet Quality

Temperature profiles for each of the mini-pot tests are provided in Appendix A to demonstrate that each test was fired under identical conditions. The corresponding trends from the table above with fired pellet compression and % +1/4"After Tumble results are shown in Figures 13 and 14.

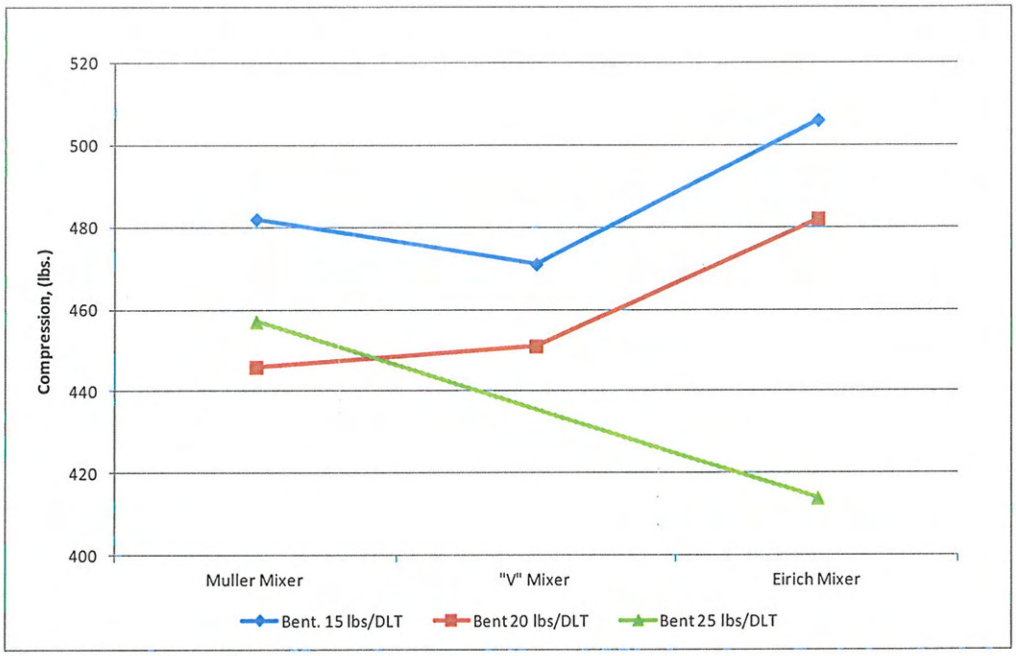

Figure 13: Mini-Pot Fired Pellet Compression

Figure 14: Mini-Pot Fired Pellet After Tumble

This shows that some slight improvements in fired pellet quality are indicated with intensive mixing over the conventional Muller design at the lower bentonite rates, however, a decrease in fired pellet compression can be noted at 25 lbs./DLT bentonite, with no significant increase in after tumble. The influence of mixing intensity (i.e. blade speed) is shown in relationship with bentonite addition in Figures 15 and 16. The trend of decreasing fired pellet compression with increasing bentonite rate was evident at 219 and 567 rpm, therefore, tests M11533 and M11534 were not fired in the study.

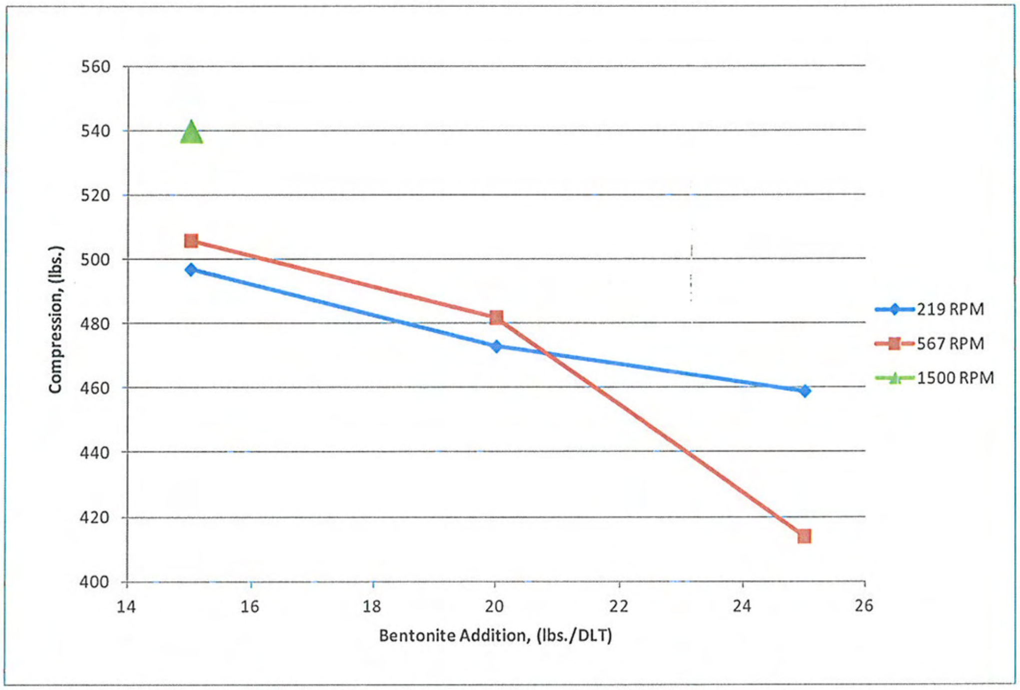

Figure 15: Influence of Mixing Intensity on Mini-Pot Fired Pellet Compression

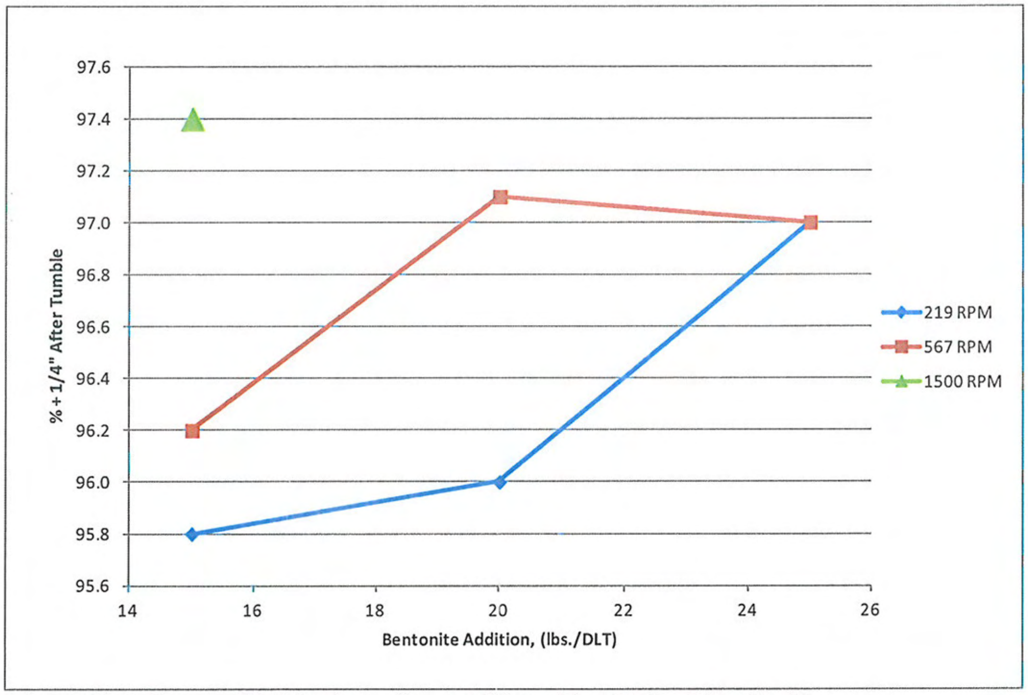

Figure 16: Influence of Mixing Intensity on Mini-Pot Fired Pellet After Tumble

These results show that 1500 RPM in the Eirich Mixer, and 15 lbs./DLT bentonite addition achieves the highest fired pellet quality in Mini-Pot fired pellets. These results were used for the subsequent pot grate fired pellet evaluation.

3.3 Pot Grate Test Results

A total of 11 pot grate furnace tests were conducted using a variety of furnace cycles. Two types of pellet were produced; 1) a standard (acid grade) pellet and 2) a fully fluxed pellet. Since the pot grate furnace fires under "ideal" conditions, achieving a high pellet quality is not difficult and often is "too good" to see any effect of other factors that may influence pellet quality. The objective was to achieve a reasonable fired pellet quality on a conventionally mixed blend of iron ore and binder without excess, to allow a cushion for improvement. The final cycles developed are shown in Tables 3 and 4. The firing temperature profiles for each these tests are provided in the Appendix B.

9.0 fpm
3.0" HL / 12.0" Green Balls

	Time (min)	Temp	Start Time (min)	End Time (min)	ΔP	O2
UDD	05:04	550	00:00	05:04	20	as-is
DDD	02:54	450	05:04	07:58	22.5	as-is
TPH	01:26	1100	07:58	09:24	23	21
PH	02:10	1850	09:24	11:34	23	21
Fire	04:19	2350	11:34	15:53	22	17
After Fire	01:48	1750	15:53	17:41	22	17
Cool	09:45		17:41	27:26	18	21

Table 3: Flux Pellet Baseline Firing Cycle

2.0" HL / 4.5" Green Balls						
	Time (min)	Temp	Start Time (min)	End Time (min)	ΔP	O2
DD1	01:14	661	00:00	01:14	12.2	as-is
DD2	01:14	892	01:14	02:28	12.2	as-is
TPH	01:26	1685	02:28	03:54	12.2	16
PH	01:50	2010	03:54	05:44	11.9	16
Fire-1	04:30	2050	05:44	10:14	5	16
Fire-2	04:30	2250	10:14	14:44	5	16
Fire-3	04:30	2350	14:44	19:14	5	16
After Fire	04:30	2250	19:14	23:44	5	16
Cool	to 400 F		23:44		18	

Table 4: Standard Pellet Baseline Firing Cycle

3.3.1 Green Ball Quality

Based on batch balling results and mini-pot data, 15 and 20 lbs./DLT bentonite were evaluated on the larger systems. From this data it was also decided that the Eirich mixer configuration most suited for application in the pilot scale was the highest achievable blade speed of 1500 RPM without micro-balling. As stated earlier, the pilot mixer originally planned for this testwork was not available at the time of testing, therefore individual batches of 5000g were blended in the bench top unit until the necessary quantity of 200 lbs was available for the pilot disk. The green ball quality results produced on the 3-foot balling disk with the various mixing systems are provided in Table 5.

				Green Ball Quality			
Test ID No.	Mixing	Speed	Pellet Type	Bentonite lbs./DLT	Moisture %	18" Drop #	Dry Comp lbs.
Pot Grate Test P11517	Muller	std	Flux	20	Blown Test - No Data		
Pot Grate Test P11518	Muller	std	Flux	20.0	9.7	15.8	15.2
Pot Grate Test P11519	Muller	std	Flux	20.0	9.6	15.7	15.1
Pot Grate Test P11520	Littleford	std	Flux	20.0	9.7	15.2	15.0
Pot Grate Test P11521	Muller	std	Flux	15.0	9.7	11.8	10.7
Pot Grate Test P11522	Littleford	std	Flux	15.0	9.6	10.5	11.7
Pot Grate Test P11523	Muller	std	Flux	15.0	9.5	7.3	11.6
Pot Grate Test P11524	Muller	std	Flux	15.0	9.3	9.3	11.2
Pot Grate Test P11525	Eirich	1500	Flux	15.0	10.2	15.3	12.5
Pot Grate Test P11527	Muller	std	Acid	14.0	9.3	8.6	14.7
Pot Grate Test P11530	Eirich	1500	Acid	14.0	9.2	11.8	13.7

Table 5: Pilot Disk Green Ball Quality Results

The data in this table show that no significant variance in results was obtained between the pilot Littleford and the Simpson Muller mixer. This is no reflection of potential results that may be obtained from Littleford in a fully optimized system or blade configuration for this application, and should be regarded as the available configuration of Littleford mixer at CMRL. Since optimization of the Littleford mixer was not part of this study, further testing with this unit was abandoned. This data shows that with 15 lbs./DLT bentonite, a slight improvement in both drop number (9.3 to 10.2) and dry strength (11.2 to 12.5 lbs) were obtained with the intensive mixing on the flux pellet blend. The standard pellet results only indicate improvement in drop number (8.6 to 11.8) where dry strength decreased from 14.7 to 13.7 lbs. It is not known if mixing in the bench scale unit had any influence on these results.

3.3.2 Fired Pellet Quality

Using the firing profiles described above, baseline tests were established for both flux and standard pellets. Test ID P11524 and P11525 were established as the baseline tests for fluxed pellets and test ID P11527 and P11530 were established as the baseline tests for standard pellets. Fired pellet quality results from these tests are provided in Table 6.

				Pellet Physical Quality				
Test ID No.	Mixing	Speed	Pellet Type	Compression			After Tumble	
				Avg. lbs.	%-300 lbs.	%-200 lbs.	% + 1/4"	% - 32M
Pot Grate Test P11524	Muller	std	Flux	556	4	0	96.5	2.6
Pot Grate Test P11525	Eirich	1500	Flux	499	5	1	95.6	3.6
Pot Grate Test P11527	Muller	std	Acid	448	14	1	96.1	1.9
Pot Grate Test P11530	Eirich	1500	Acid	412	13	2	92.5	1.4

Table 6: Fired Pellet Physical Quality

All physical quality testing was conducted according to ASTM standards. The results show that in both pellet types, fired pellet compression decreased by approximately 10%, from 556 to 499 lbs in the fluxed pellets and 448 to 412 lbs in the standard pellet test. Fired pellet % +1/4" after tumble also decreased in both cases with the intensive mixing. Since this is contradictory to the mini-pot test results and there is limited data available for evaluation, further verification of these results should be conducted prior to making any conclusions.

3.3.3 Metallurgical Quality

Fired pellet metallurgical tests were conducted according to ISO standard procedures for the baseline pot grate pellets and the results are provided in Table 7. Contraction testing was conducted by the laboratory at the ArcelorMittal Minorca Mine.

Pellet Metallurgical Quality

Test ID No.	Mixing	Speed	Pellet Type	Porosity	LTD - ISO 4696-1			R40 ISO 4695	Swelling ISO 4698	Contraction*
				%	% +1/4"	% -1/4" + 32M	% - 32M	$\%O_2$ /min	%	
Pot Grate Test P11524	Muller	std	Flux	25.1	98.2	0.3	1.5	1.12	7.8	9.28
Pot Grate Test P11525	Eirich	1500	Flux	23.2	98.2	0.3	1.5	1.10	8.1	8.14
Pot Grate Test P11527	Muller	std	Acid	21.8	95.2	3.1	1.7	0.61	10.1	
Pot Grate Test P11530	Eirich	1500	Acid	21.4	92.6	5.8	1.6	0.62	12.0	

* Contaction Testing was conducted by ArcelorMittal Minorca Mine, Virginia, MN

Table 7. Fired Pellet Metallurgical Results

The results for fluxed pellet show no significant difference between conventional and intensive mixing with regards to LTD (ISO-4696-1), Reducibility, (R40-ISO 4695) or Swelling, (ISO 4698). The data shows that porosity decreased slightly (25.1 to 23.2) as well as the contraction value (9.28 to 8.14). The standard pellet metallurgical tests showed a slight decrease in the LTD (95.2 to 92.8 % +6.3mm) and potentially a slight increase in the Swelling, however this is well within the margin of error for this test. Reducibility and porosity are essentially equivalent. The data from this metallurgical testwork is provided in Appendix C.

4 Conclusions and Recommendations

From batch balling testwork, intensive mixing shows a significant increase in the green ball drop number and dry compressive strength at three separate bentonite rates. Drop number increased 50%, (3.8 to 5.7) at 15 lbs./DLT, 69%, (5.8 to 9.8) at 20 lbs./DLT, and 90% (6.4 to 12.2) at 25 lbs./DLT. Trends with respect to dry strength indicated a 50-65% increase at all three binder addition rates. The bench test data shows that as mixing intensity increases (increasing blade speed), green ball quality also improves. Drop number increased from 9.3 to 19.8 at 25 lbs./DLT and dry strength increased from 13.8 to 21.7 lbs. at 25 lbs./DLT, resulting in an improvement of approximately 60%.

Slight improvements in fired pellet quality in mini-pot pellets are indicated with intensive mixing over the conventional design at the lower bentonite rates. These results show that the green balls prepared with intensive mixing and a lower bentonite addition are similar or better than those with prepared at higher addition rates using conventional mixing practices, and resulted in higher quality pellets with respect to after tumble and compression in mini-pot pellets. From this data it was decided that the Eirich mixer configuration most suited for application in the pilot scale was the highest achievable blade speed of 1500 RPM without micro-balling.

Three individual mixers were evaluated on the pilot scale, 1) Simpson Muller Mixer, 2) Littleford Mixer and 3) Eirich Mixer. The data shows that no significant difference was observed between the pilot Littleford and the Simpson Muller mixer. This is no reflection of potential results that may be obtained from Littleford in a fully optimized system or blade configuration for this application and therefore additional testing should be considered to further evaluate these systems. Since optimization of the Littleford mixer was not part of this study, the results are not included in this evaluation. Using the intensive Eirich mixer, a slight improvement in both drop number (9.3 to 10.2) and dry strength (11.2 to 12.5 lbs) were obtained with 15 lbs./DLT bentonite binder on the flux pellet blend. The standard pellet mix with the Eirich shows improvement in drop number (8.6 to 11.8) where dry strength decreased from 14.7 to 13.7 lbs. Since the larger pilot scale intensive mixer was not available for this testing, it is not known if the bench scale unit had any influence on these results. For both pot grate pellet comparisons, fired pellet compression decreased by approximately 10%, from 556 to 499 lbs in the fluxed pellets and 448 to 412 lbs in the standard pellet test. Since this is contradictory to the mini-pot test results and there is limited data available for evaluation, further verification of these results should be conducted, with additional testing at the pilot scale prior to making any conclusions. With the exception of a decrease in pellet contraction on fluxed pellets, no significant differences in metallurgical results were determined in this comparison.

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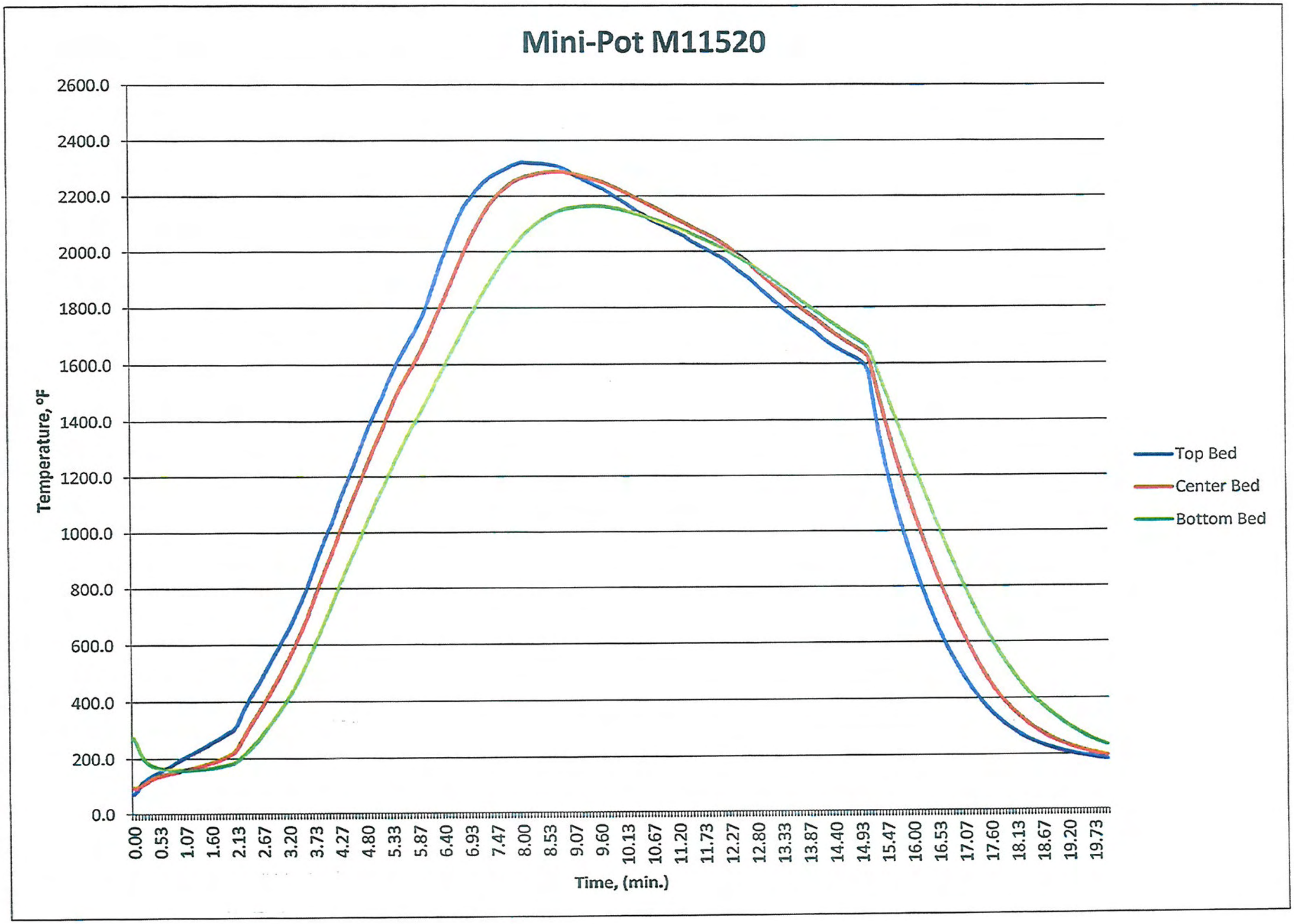
2. Kapur, P.C., and D.W. Fuerstenau, "Minerals Beneficiation – Kinetics of Green Pelletization", Society of Mining Engineers, AIME Transactions, December, 1964, pp 348-355

3. Ripke, S.J. and S.K. Kawatra, "Fibrous Bonding Mechanisms for Reducing Bentonite Dosage", American Foundry Society Transactions, 2000, Vol. 108, pp. 101-104

4. Wilson, J. M. D., "The role of Binders in Iron Ore Pelletizing - A Review", Canada Centre for Mineral and Energy Technology. Mineral Sciences Laboratories Division Report MRP/MSL 80-52 (OP&J), December, 1980, 40 pp.

APPENDIX A

MINI-POT FIRING TEMPERATURE PROFILES


Mini-Pot M11520
Temperature, °F
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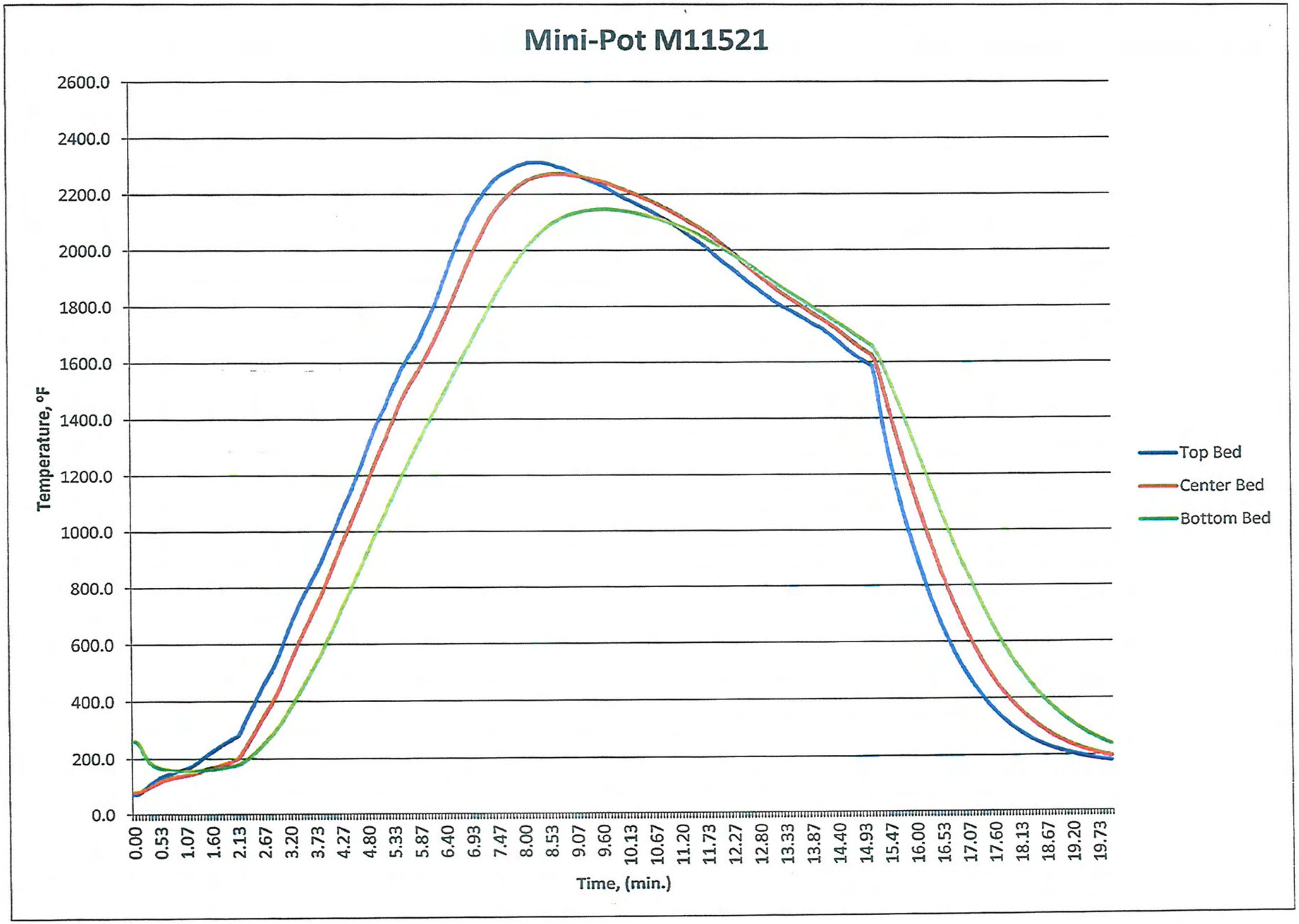
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed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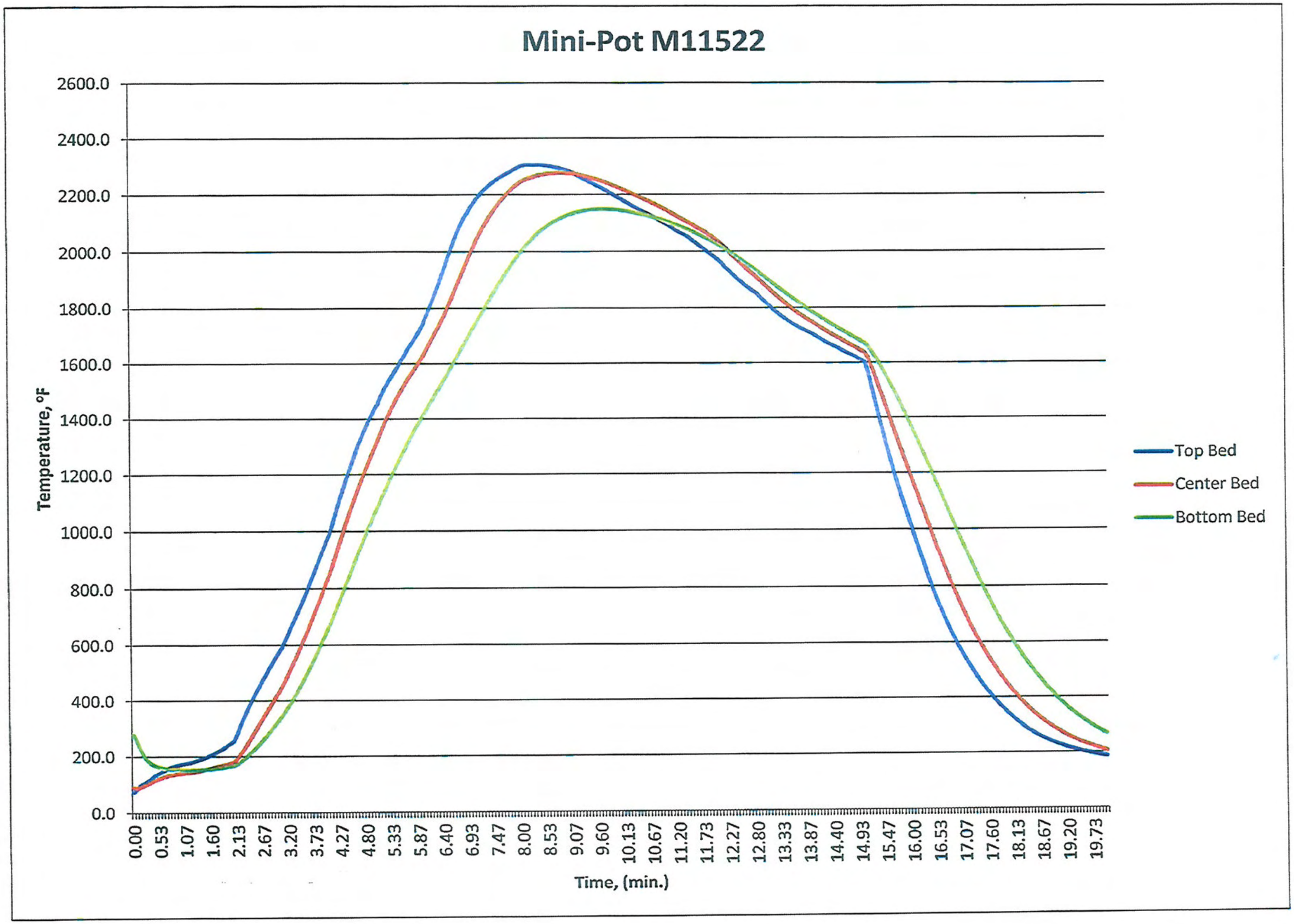
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed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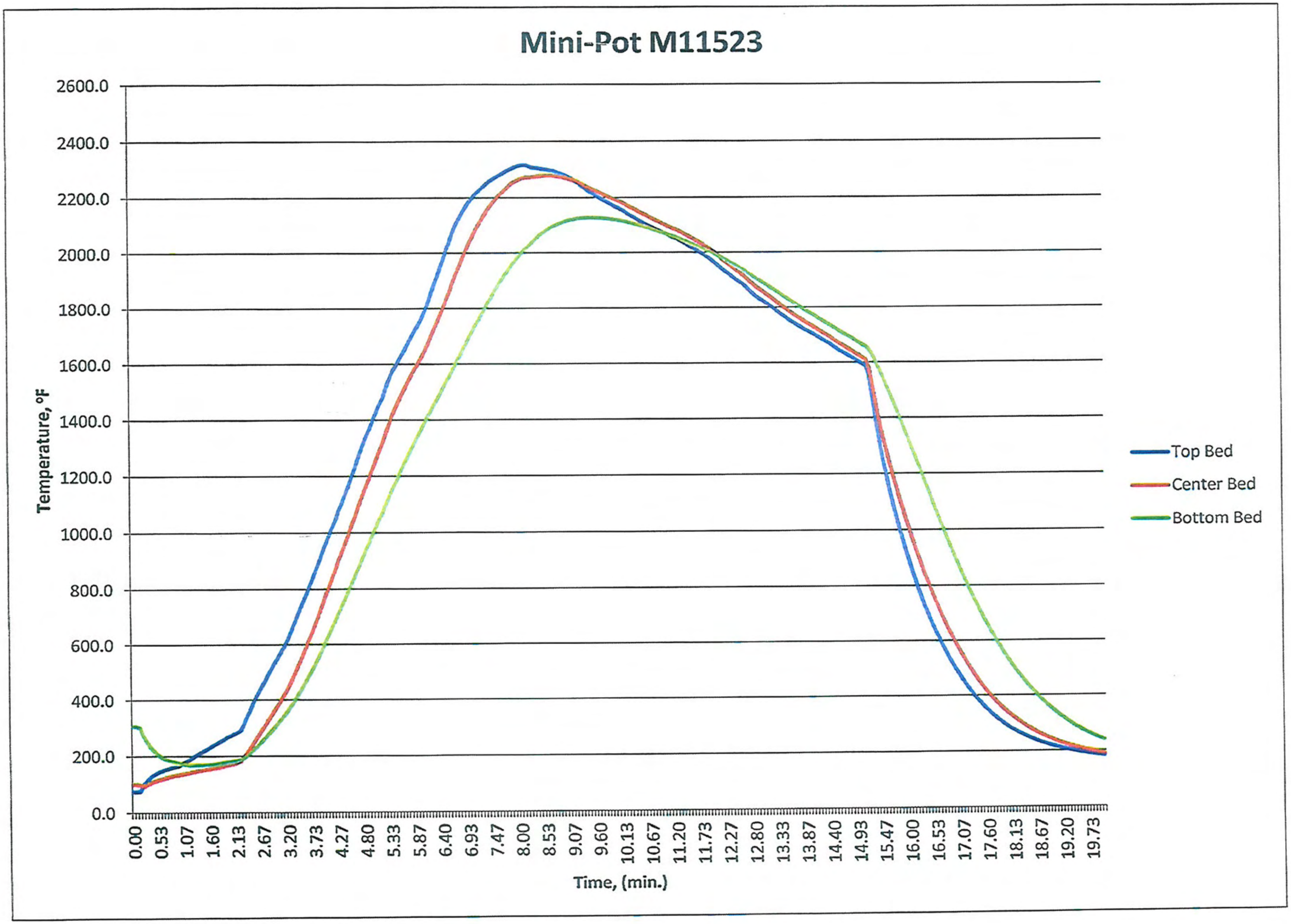
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Temperature, °F
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed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Temperature, °F
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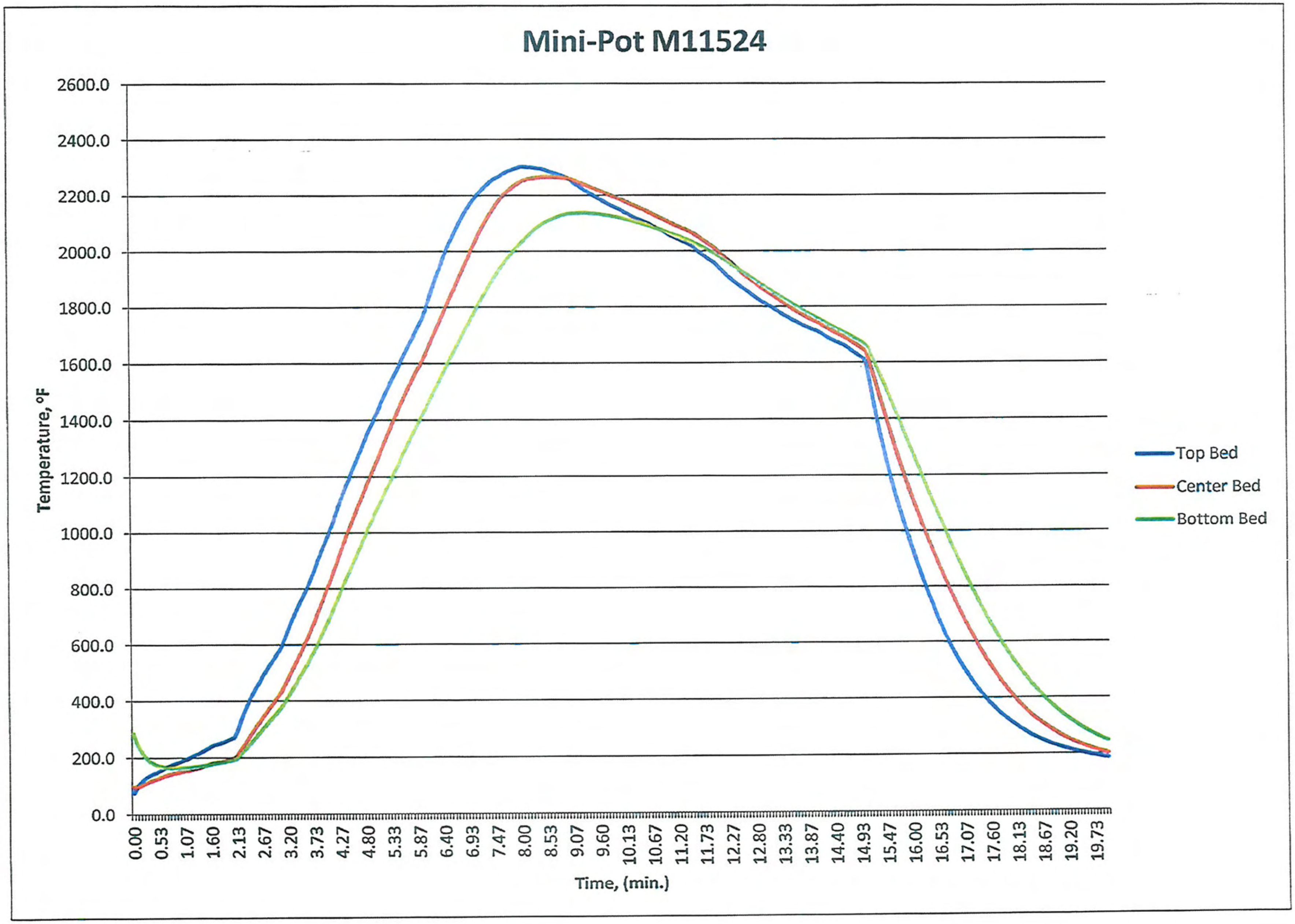
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed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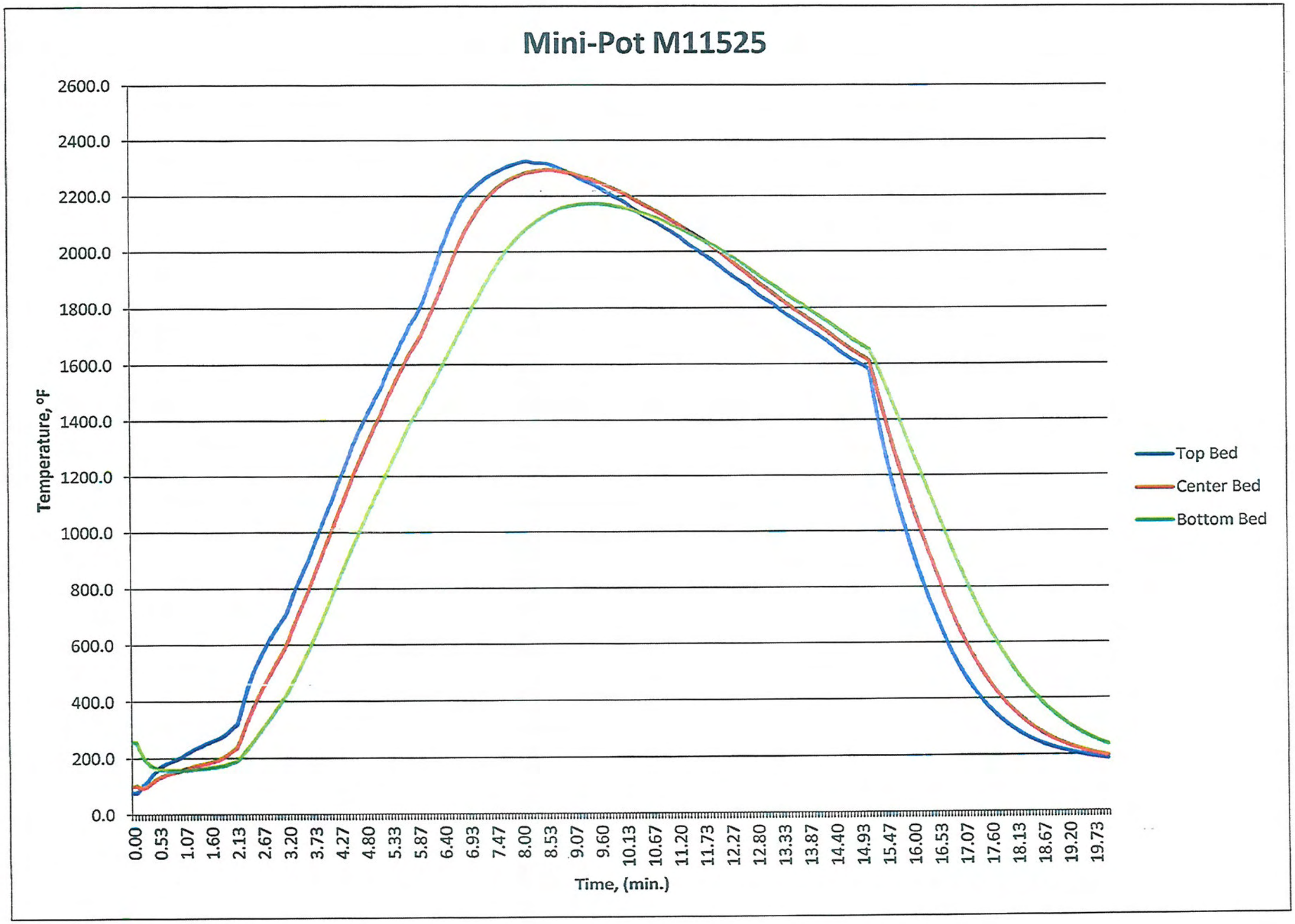
Mini-Pot M11525
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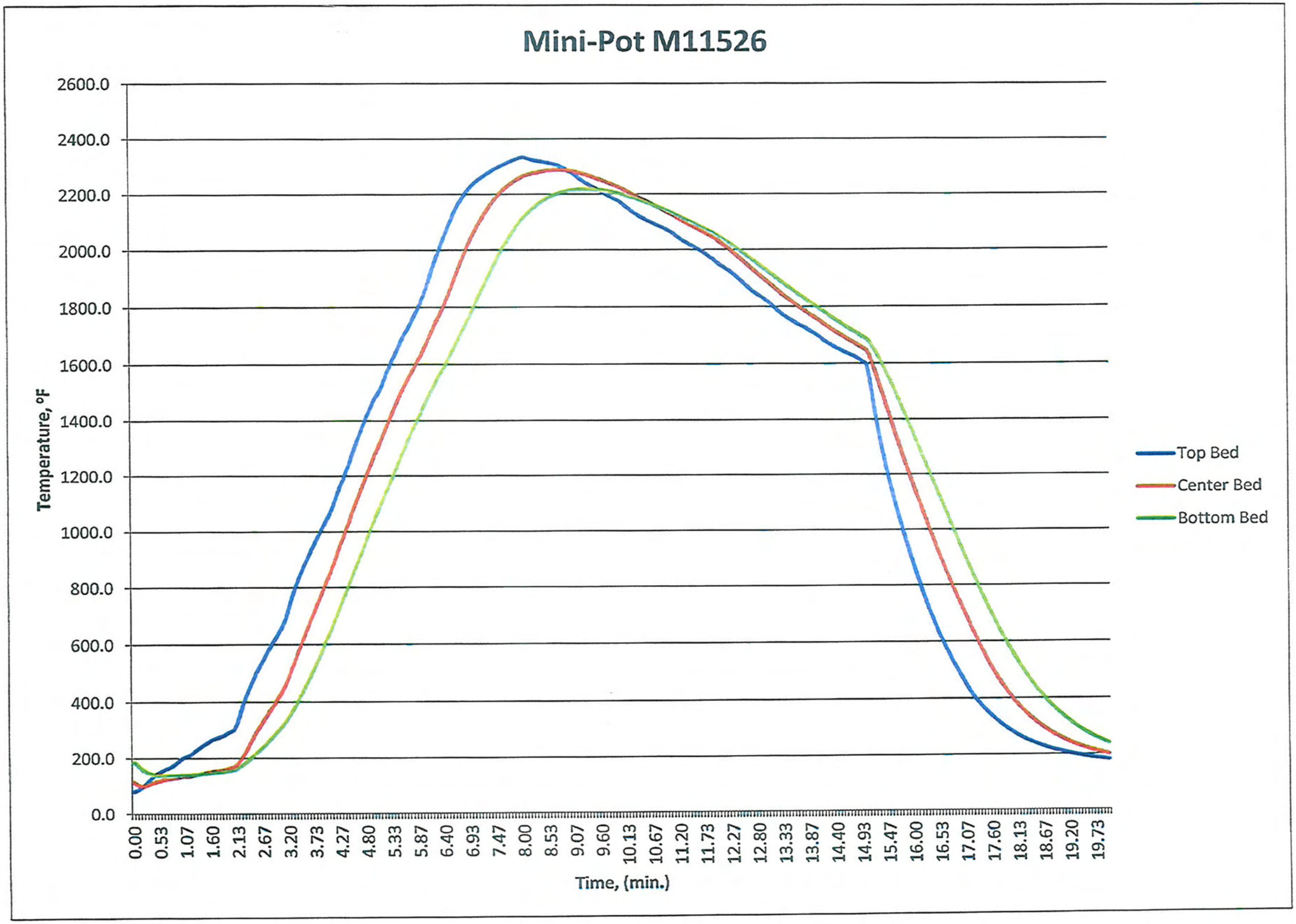
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
Temperature, °F
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed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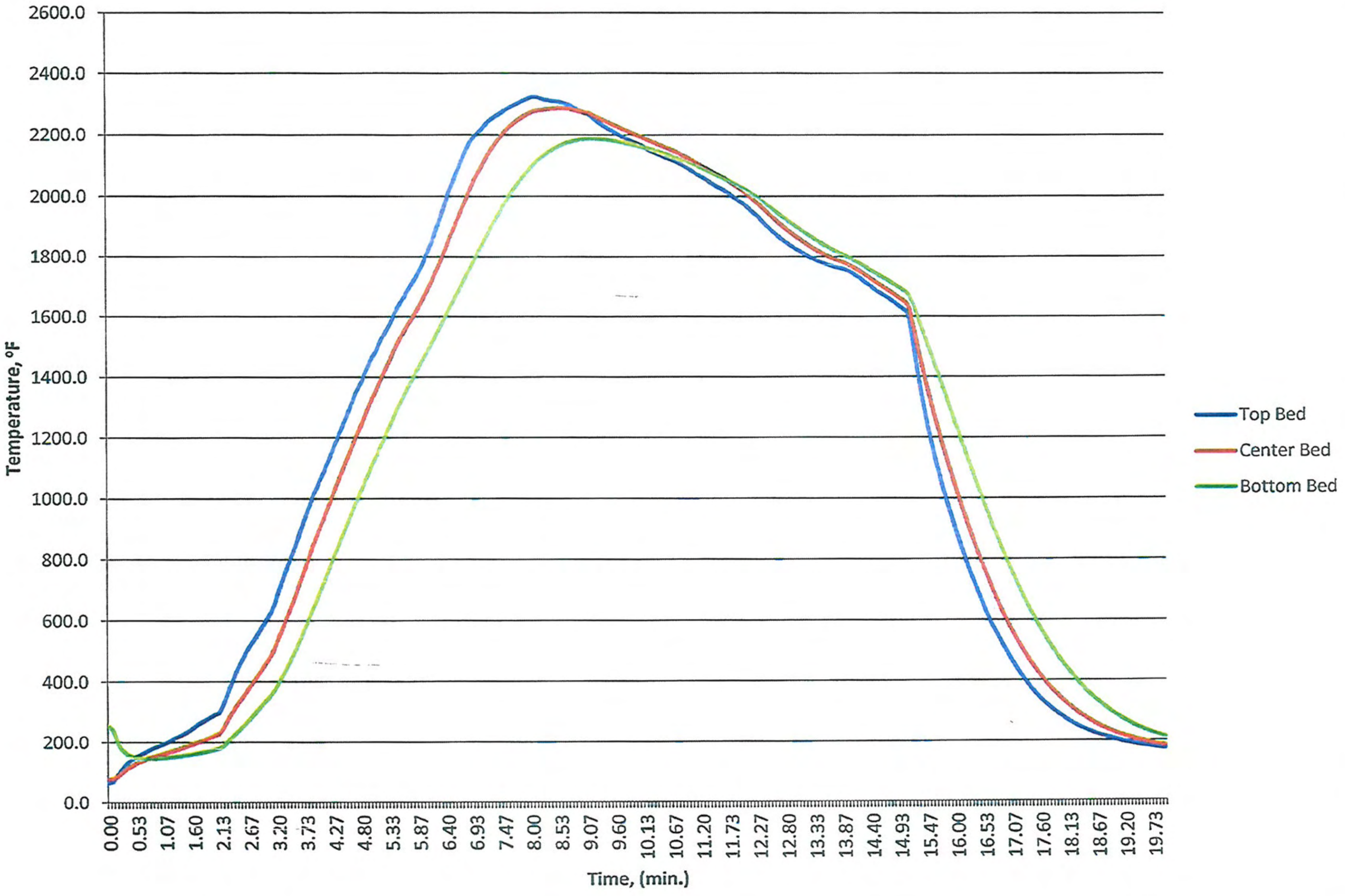
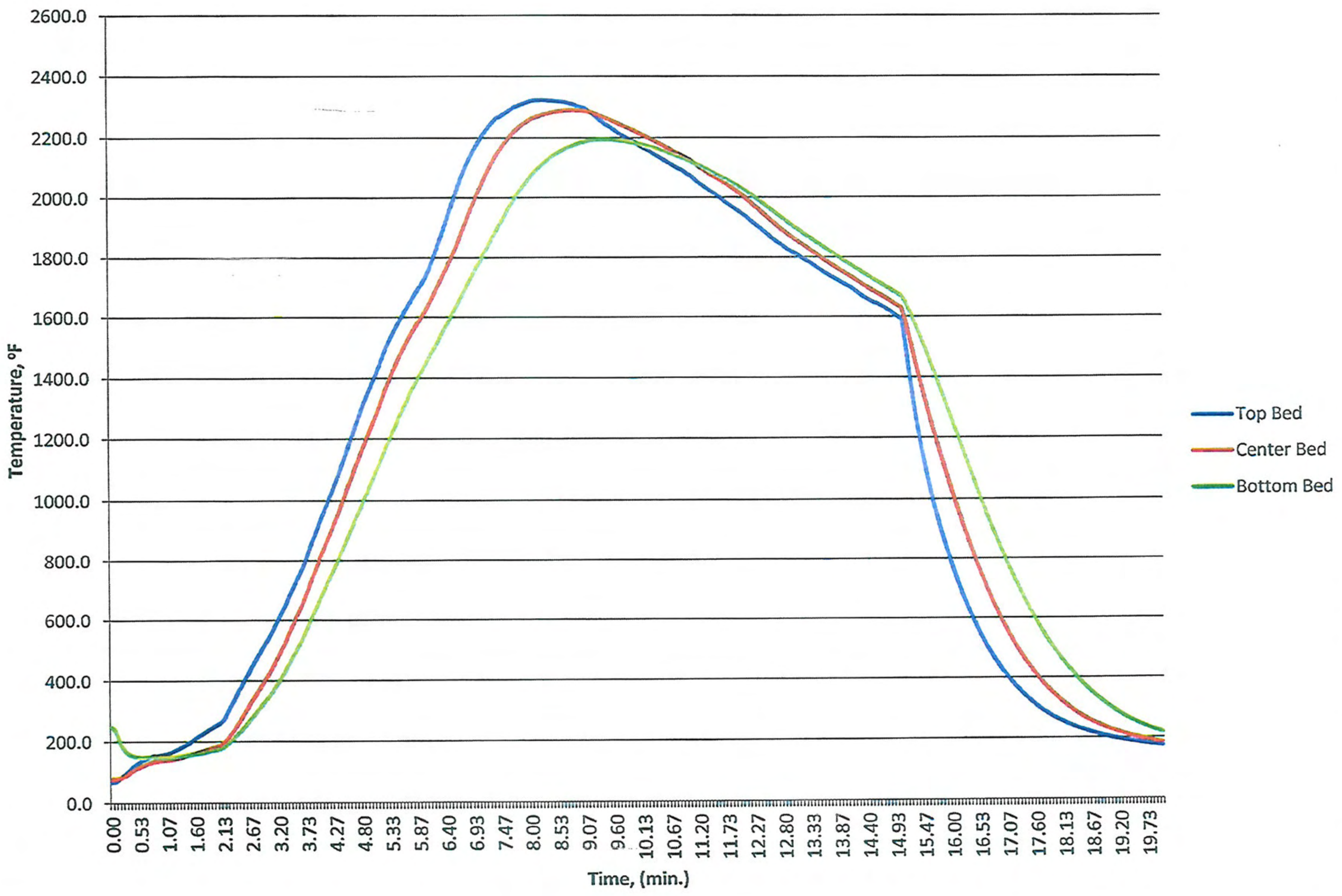


Mini-Pot M11527

Mini-Pot M11528



NRRI # P11525 Special Pot Grate Pellet Sample

Month June

Year 2011

XRF Chemistry

	SiO2	Tot. Fe	CaO	MgO	C/S	M/S	T/Ox	Al2O3	MnO	P	Satmagan Mag. Fe
Sample	4.19	62.72	4.60	1.30	1.10	0.31	99.77	0.166	0.131	0.008	5.97
Monthly Avg.											

Tumble Test

Before Tumble

Screen Size		% On Screen	Monthly Average
.+5/8"		#DIV/0!	NA
.+1/2"		#DIV/0!	
.+3/8"		#DIV/0!	
.+1/4"		#DIV/0!	
.+100M		#DIV/0!	
.-100M		#DIV/0!	
BT +1/2"		#DIV/0!	
BT -1/4"		#DIV/0!	

After Tumble

Screen Size		% On Screen	Monthly Average
.+5/8"		#DIV/0!	NA
.+1/2"		#DIV/0!	
.+3/8"		#DIV/0!	
.+1/4"		#DIV/0!	
.+100M		#DIV/0!	
.-100M		#DIV/0!	
AT +1/2"		#DIV/0!	
AT -1/4"		#DIV/0!	

Q Index

CCS Pellet Strength

Sample	Test #1	Test #2	Average
CCS	515		515
<200 lbs	0.00%		0.00%
<300 lbs	6.00%		6.00%
>600 lbs	31.00%		31.00%

Monthly Avg.	CCS
CCS	NA
<200 lbs	NA
<300 lbs	NA
>600 lbs	NA

Contraction

		% size
Test #1	8.14	38.23 / 61.77
Test #2		
Sample Avg.		
Monthly Avg.		

Contration Pellet Sizing

Raw Wt.	1759.25		
.+1/2"	83.38	4.74%	
.+7/16"	624.43	35.49%	
.+3/8"	756.52	43.00%	
.-3/8"	294.92	16.76%	100.00%
Sorted Wt.	967.12		
.+7/16"	369.74	38.23%	
.+3/8"	597.38	61.77%	100.00%

COLERAINE MINERALS RESEARCH LABORATORY
ISO 4696 REDUCIBILITY(DRDT40)

06/01/11

SAMPLE NO. : P11524
SAMPLE DESCRIPTION Flux Pot Grate Pellet - Muller Mixer

INITIAL WT G: 499.6
WT DELTA G:
PRESSURE IN HG:

DR/DT 40, %/MIN: 1.12

PELLET %FE %: 63.18
PELLET %FE++ %: 1.73

TIME	WT LOSS (g)	
3	13.00	13.00
6	20.00	7.00
9	27.00	7.00
12	34.00	7.00
15	39.00	5.00
18	45.00	6.00
21	50.00	5.00
24	54.00	4.00
27	59.00	5.00
30	63.00	4.00
33	67.00	4.00
36	70.00	3.00
39	74.00	4.00
42	77.00	3.00
45	80.00	3.00
48	83.00	3.00
51	86.00	3.00
54		-86.00
57		0.00
60		0.00
63		0.00
66		0.00
69		0.00
72		0.00
75		0.00
78		0.00
81		0.00
84		0.00

BRACKET TIME & WT @ RT30 : 39.49 GMS LOSS

TIME LO = 15
TIME HI = 18
X30 AVE = 16.5

WT LO = 39.0
WT HI = 45.0
Y30 AVE = 42.0

BRACKET TIME & WT @ RT60 : 80.20 GMS LOSS

TIME LO = 45
TIME HI = 48
X60 AVE = 46.5

WT LO = 80.0
WT HI = 83.0
Y60 AVE = 81.5

06/02/11

COLERAINE MINERALS RESEARCH LABORATORY
ISO 4696 REDUCIBILITY(DRDT40)

SAMPLE NO. : P11525
SAMPLE DESCRIPTION Flux Pot Grate Pellet - Eirich Mixer

INITIAL WT G: 499.7
WT DELTA G:
PRESSURE IN HG:

DR/DT 40, %/MIN: 1.10

PELLET %FE %: 63.20
PELLET %FE++ %: 1.51

TIME	WT LOSS (g)	
3	14.00	14.00
6	22.00	8.00
9	30.00	8.00
12	36.00	6.00
15	42.00	6.00
18	47.00	5.00
21	52.00	5.00
24	57.00	5.00
27	61.00	4.00
30	65.00	4.00
33	68.00	3.00
36	72.00	4.00
39	75.00	3.00
42	78.00	3.00
45	81.00	3.00
48	84.00	3.00
51	87.00	3.00
54		-87.00
57		0.00
60		0.00
63		0.00
66		0.00
69		0.00
72		0.00
75		0.00
78		0.00
81		0.00
84		0.00

BRACKET TIME & WT @ RT30 : 39.66 GMS LOSS

TIME LO = 12
TIME HI = 15

X30 AVE = 13.5

WT LO = 36.0
WT HI = 42.0

Y30 AVE = 39.0

BRACKET TIME & WT @ RT60 : 80.40 GMS LOSS

TIME LO = 42
TIME HI = 45

X60 AVE = 43.5

WT LO = 78.0
WT HI = 81.0

Y60 AVE = 79.5

06/09/11

COLERAINE MINERALS RESEARCH LABORATORY
ISO 4696 REDUCIBILITY(DRDT40)

SAMPLE NO. : P11527
SAMPLE DESCRIPTION Std Pot Grate Pellet - Muller Mixer

INITIAL WT G: 499.8
WT DELTA G:
PRESSURE IN HG:

DR/DT 40, %/MIN: 0.61

PELLET %FE %: 66.42
PELLET %FE++ %: 0.41

TIME	WT LOSS (g)	
3	10.00	10.00
6	18.00	8.00
9	24.00	6.00
12	29.00	5.00
15	35.00	6.00
18	39.00	4.00
21	43.00	4.00
24	46.00	3.00
27	49.00	3.00
30	52.00	3.00
33	55.00	3.00
36	58.00	3.00
39	60.00	2.00
42	62.00	2.00
45	65.00	3.00
48	67.00	2.00
51	69.00	2.00
54	71.00	2.00
57	73.00	2.00
60	76.00	3.00
63	77.00	1.00
66	79.00	2.00
69	81.00	2.00
72	83.00	2.00
75	85.00	2.00
78	87.00	2.00
81		-87.00
84		0.00

BRACKET TIME & WT @ RT30 : 42.53 GMS LOSS

TIME LO = 18
TIME HI = 21
X30 AVE = 19.5

WT LO = 39.0
WT HI = 43.0
Y30 AVE = 41.0

BRACKET TIME & WT @ RT60 : 85.36 GMS LOSS

TIME LO = 75
TIME HI = 78
X60 AVE = 76.5

WT LO = 85.0
WT HI = 87.0
Y60 AVE = 86.0

COLERAINE MINERALS RESEARCH LABORATORY
ISO 4696 REDUCIBILITY(DRDT40)

06/15/11

SAMPLE NO. : P11530
SAMPLE DESCRIPTION Std Pot Grate Pellet - Eirich Mixer

INITIAL WT G: 499.7
WT DELTA G:
PRESSURE IN HG:

****
DR/DT 40, %/MIN: 0.62
****

PELLET %FE %: 66.21
PELLET %FE++ %: 0.41

TIME	WT LOSS (g)	
3	9.00	9.00
6	17.00	8.00
9	24.00	7.00
12	29.00	5.00
15	34.00	5.00
18	39.00	5.00
21	42.00	3.00
24	46.00	4.00
27	49.00	3.00
30	52.00	3.00
33	54.00	2.00
36	57.00	3.00
39	59.00	2.00
42	62.00	3.00
45	64.00	2.00
48	66.00	2.00
51	69.00	3.00
54	71.00	2.00
57	73.00	2.00
60	75.00	2.00
63	77.00	2.00
66	79.00	2.00
69	81.00	2.00
72	83.00	2.00
75	85.00	2.00
78	87.00	2.00
81		-87.00
84		0.00

BRACKET TIME & WT @ RT30 : 42.39 GMS LOSS

TIME LO = 21
TIME HI = 24
X30 AVE = 22.5

WT LO = 42.0
WT HI = 46.0
Y30 AVE = 44.0

BRACKET TIME & WT @ RT60 : 85.07 GMS LOSS

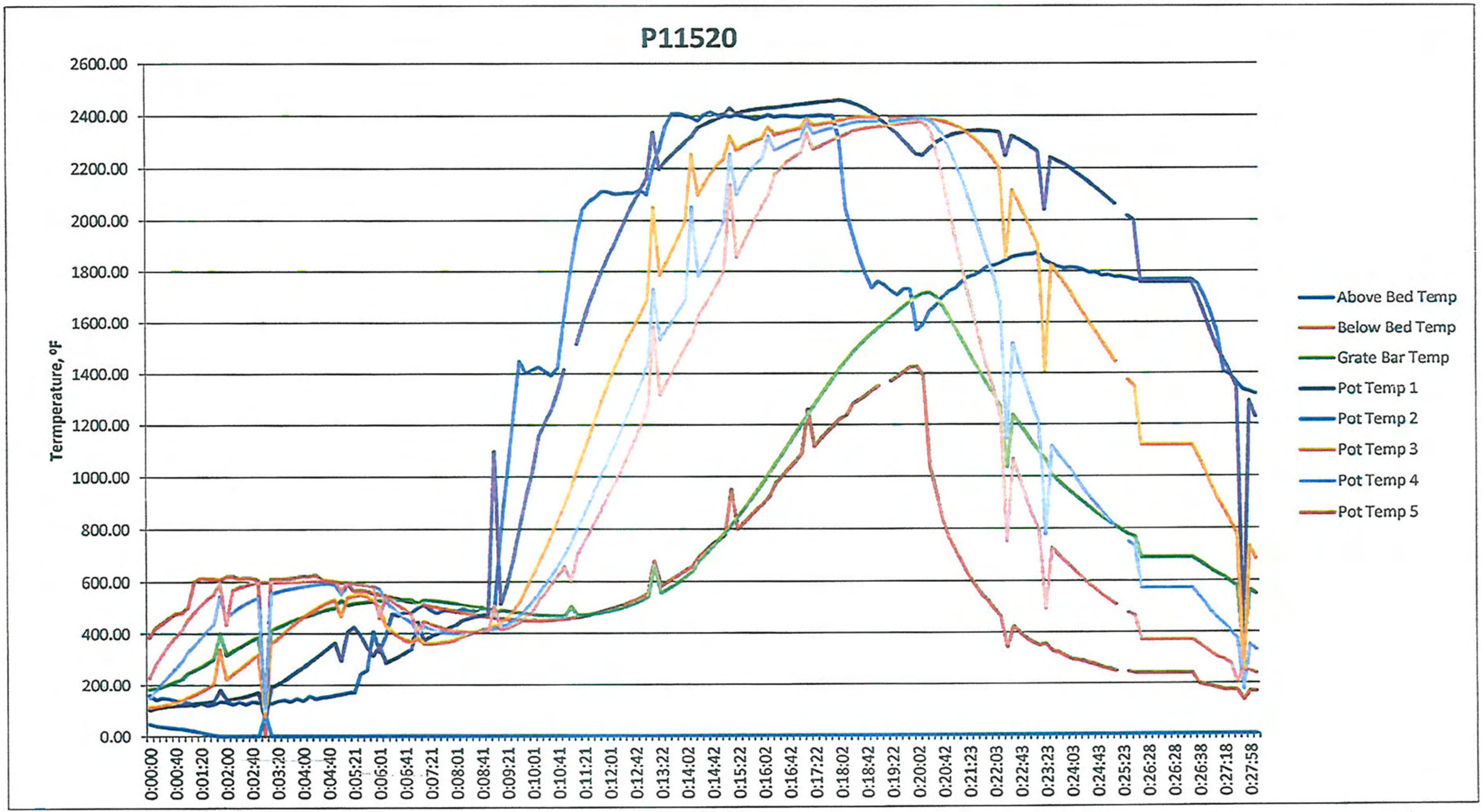
TIME LO = 75
TIME HI = 78
X60 AVE = 76.5

WT LO = 85.0
WT HI = 87.0
Y60 AVE = 86.0

Pellet Porosity Procedure

		P11524 Core	P11525 Core	P11527 Core	P 11530 Comp.
A	Weight of Dry Pellets, (g)	161.55	162.13	162.74	162.21
B	Weight of Flask and Water, (g)	257.28	257.28	257.28	257.28
C	Weight of Flask, Water and Pellets, (g)	382.96	383.42	385.18	384.74
D	Weight of "Wet" Pellets, (g)	171.88	171.65	170.69	170.00
E	(B + D – C) / 0.998	46.29	45.60	42.88	42.63
F	A / E - Apparent Specific Gravity	3.49	3.56	3.80	3.81
G	True Specific Gravity	4.6596	4.6378	4.8591	4.8482
H	Porosity	25.1	23.2	21.80	21.41

Porosity % = True – App / True


P11520
Termperature, °F
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2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:40
0:01:20
0:02:00
0:02:40
0:03:20
0:04:00
0:04:40
0:05:21
0:06:01
0:06:41
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0:20:42
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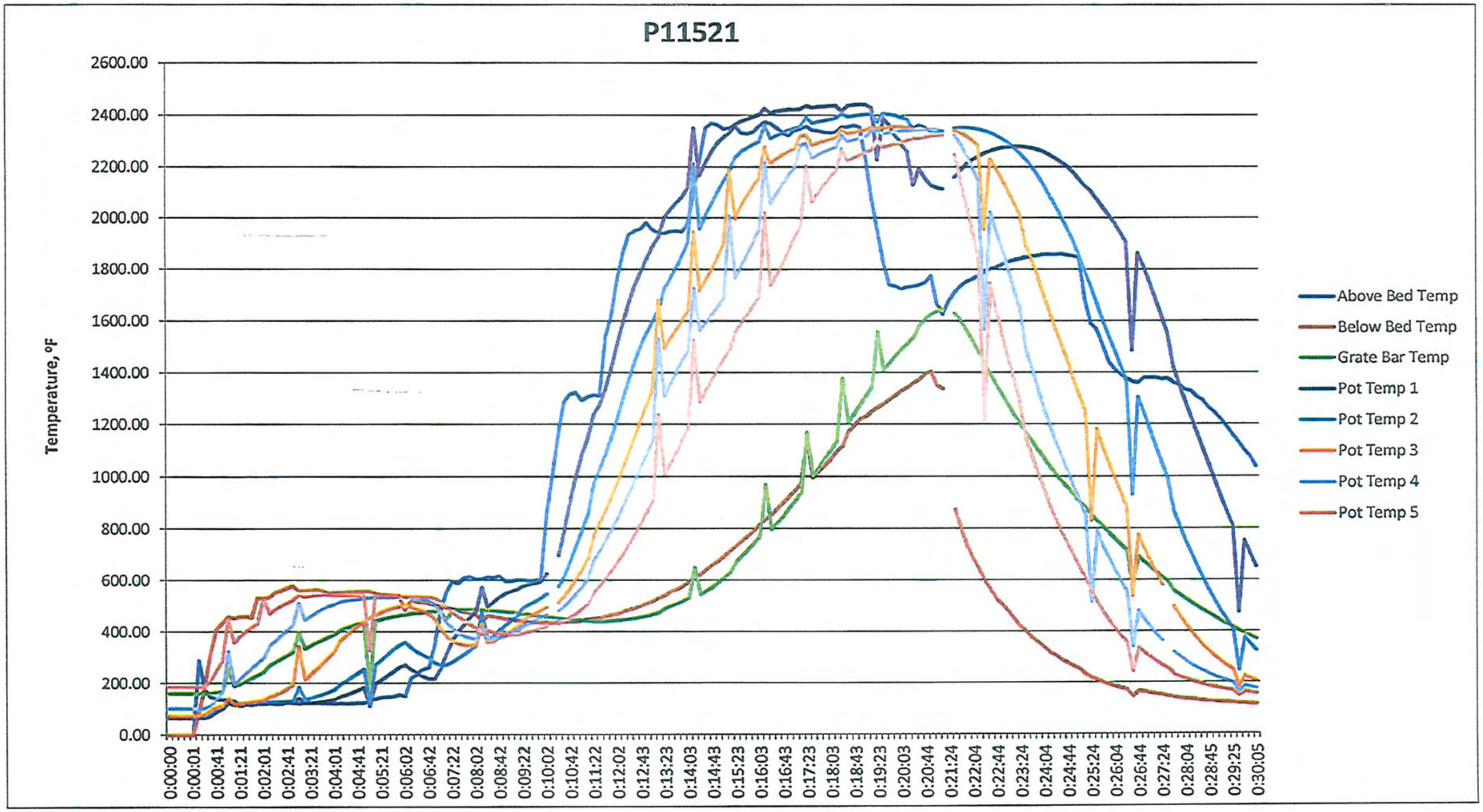
0:22:03
0:22:43
0:23:23
0:24:03
0:24:43
0:25:23
0:26:28
0:26:28
0:26:38
0:27:18
0:27:58
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 3
Pot Temp 4
Pot Temp 5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Temperature, °F
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2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:01
0:00:41
0:01:21
0:02:01
0:02:41
0:03:21
0:04:01
0:04:41
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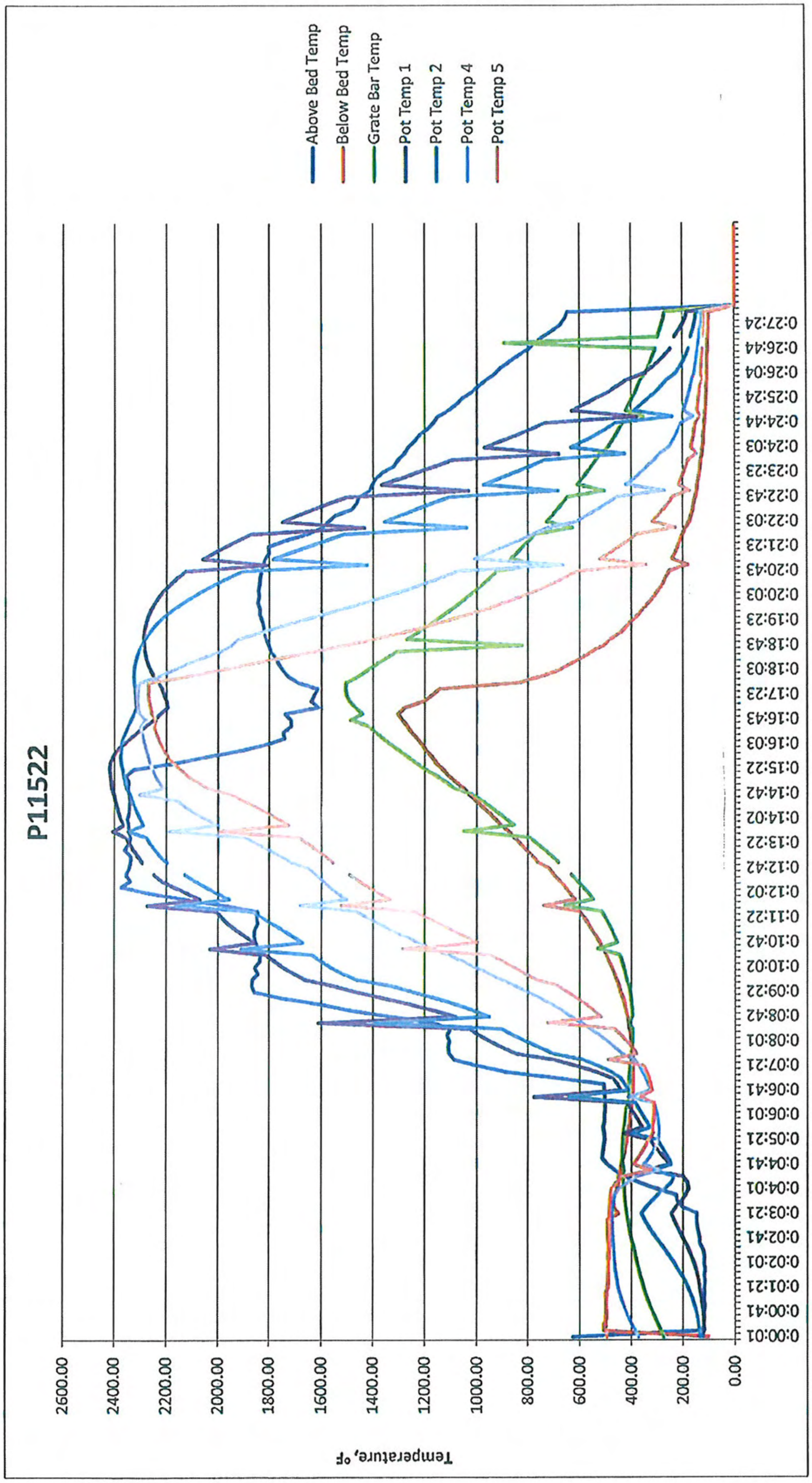
0:25:24
0:26:04
0:26:44
0:27:24
0:28:04
0:28:45
0:29:25
0:30:05
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 3
Pot Temp 4
Pot Temp 5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Temperature, °F
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2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:01
0:00:41
0:01:21
0:02:01
0:02:41
0:03:21
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0:04:41
0:05:21
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0:13:22
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0:14:42
0:15:22
0:16:03
0:16:43
0:17:23
0:18:03
0:18:43
0:19:23
0:20:03
0:20:43
0:21:23
0:22:03
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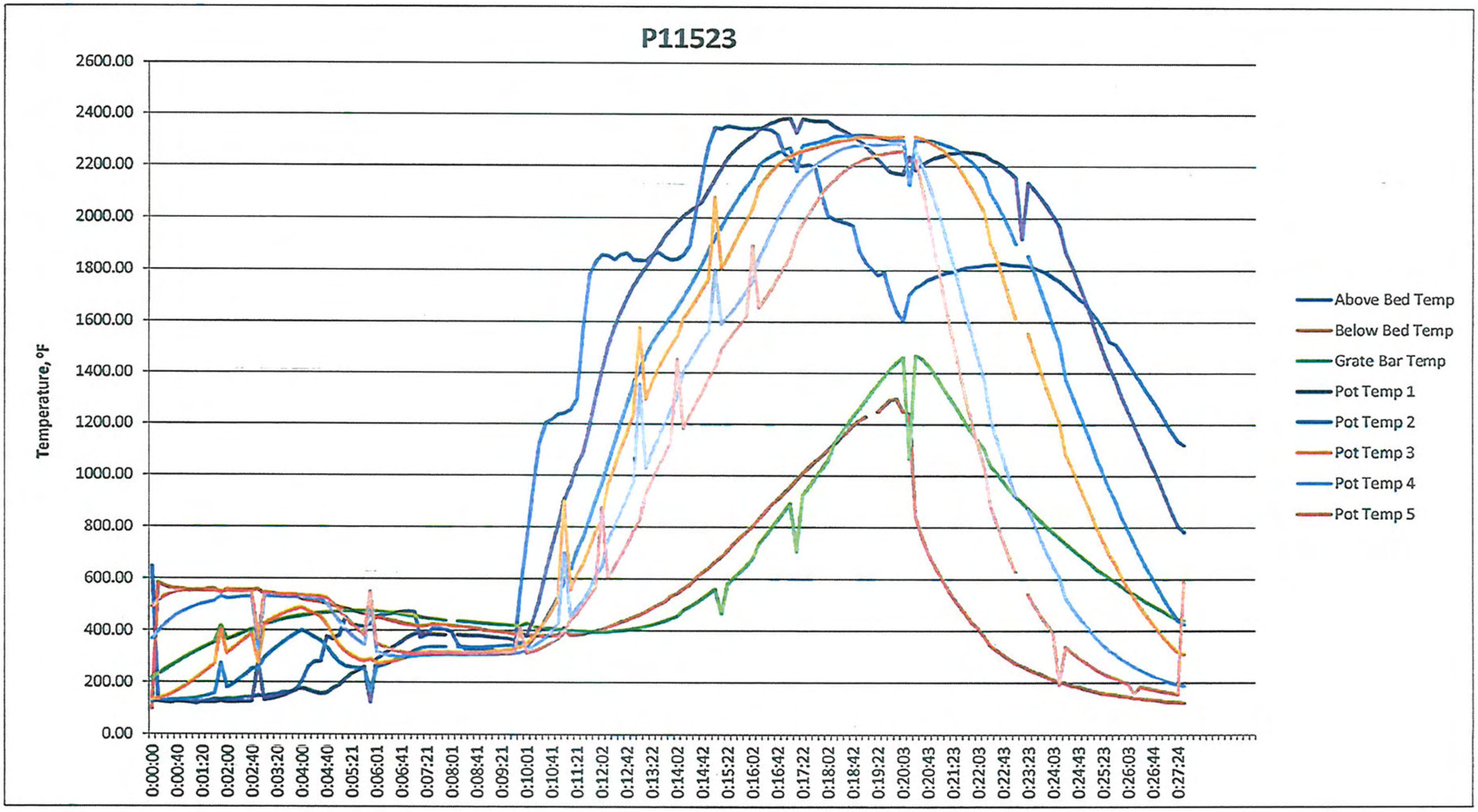
0:24:03
0:24:44
0:25:24
0:26:04
0:26:44
0:27:24
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 4
Pot Temp 5


P11523

Temperature, °F
2600.00
2400.00
2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:40
0:01:20
0:02:00
0:02:40
0:03:20
0:04:00
0:04:40
0:05:21
0:06:01
0:06:41
0:07:21
0:08:01
0:08:41
0:09:21
0:10:01
0:10:41
0:11:21
0:12:02
0:12:42
0:13:22
0:14:02
0:14:42
0:15:22
0:16:02
0:16:42
0:17:22
0:18:02
0:18:42
0:19:22
0:20:03
0:20:43
0:21:23
0:22:03
0:22:43
0:23:23
0:24:03
0:24:43
0:25:23
0:26:03
0:26:44
0:27:24
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 3
Pot Temp 4
Pot Temp 5

APPENDIX C

FIRED PELLET METALLURGICAL RESULTS

NRRI # P11524 Special Pot Grate Pellet Sample

Month June
Year 2011

XRF Chemistry

	SiO2	Tot. Fe	CaO	MgO	C/S	M/S	T/Ox	Al2O3	MnO	P	Satmagan Mag. Fe
Sample	4.29	62.71	4.62	1.27	1.08	0.3	99.84	0.162	0.13	0.008	7.58
Monthly Avg.											

Tumble Test

Before Tumble

Screen Size		% On Screen	Monthly Average
.+5/8"		#DIV/0!	NA
.+1/2"		#DIV/0!	
.+3/8"		#DIV/0!	
.+1/4"		#DIV/0!	
.+100M		#DIV/0!	
.-100M		#DIV/0!	
	BT +1/2"	#DIV/0!	
	BT -1/4"	#DIV/0!	

After Tumble

Screen Size		% On Screen	Monthly Average
.+5/8"		#DIV/0!	NA
.+1/2"		#DIV/0!	
.+3/8"		#DIV/0!	
.+1/4"		#DIV/0!	
.+100M		#DIV/0!	
.-100M		#DIV/0!	
	AT +1/2"	#DIV/0!	
	AT -1/4"	#DIV/0!	

Q Index 83.37

CCS Pellet Strength

Sample	Test #1	Test #2	Average
CCS	555		555
<200 lbs	0.00%		0.00%
<300 lbs	3.00%		3.00%
>600 lbs	38.99%		38.99%

Monthly Avg.	CCS
CCS	NA
<200 lbs	NA
<300 lbs	NA
>600 lbs	NA

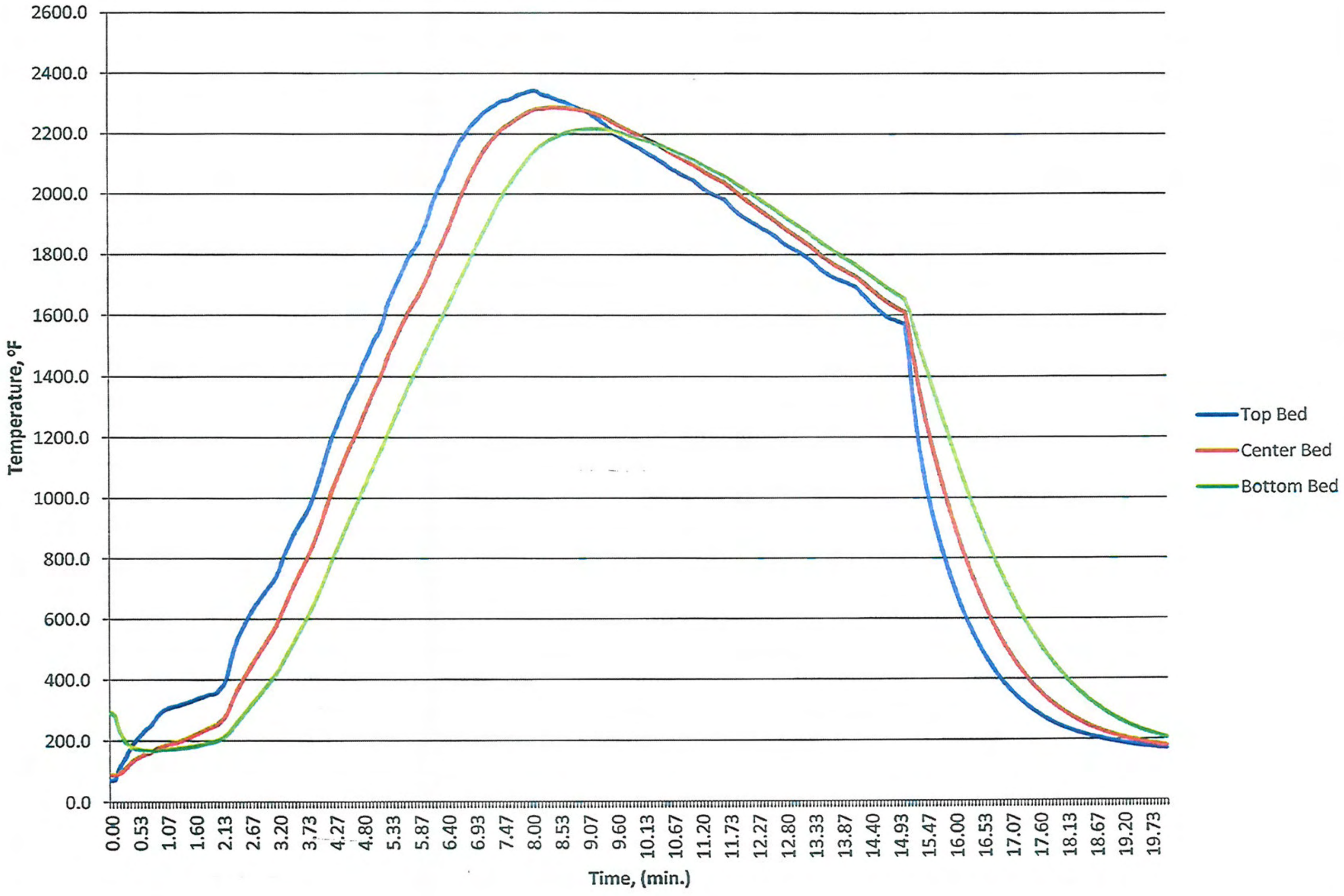
Contration Pellet Sizing

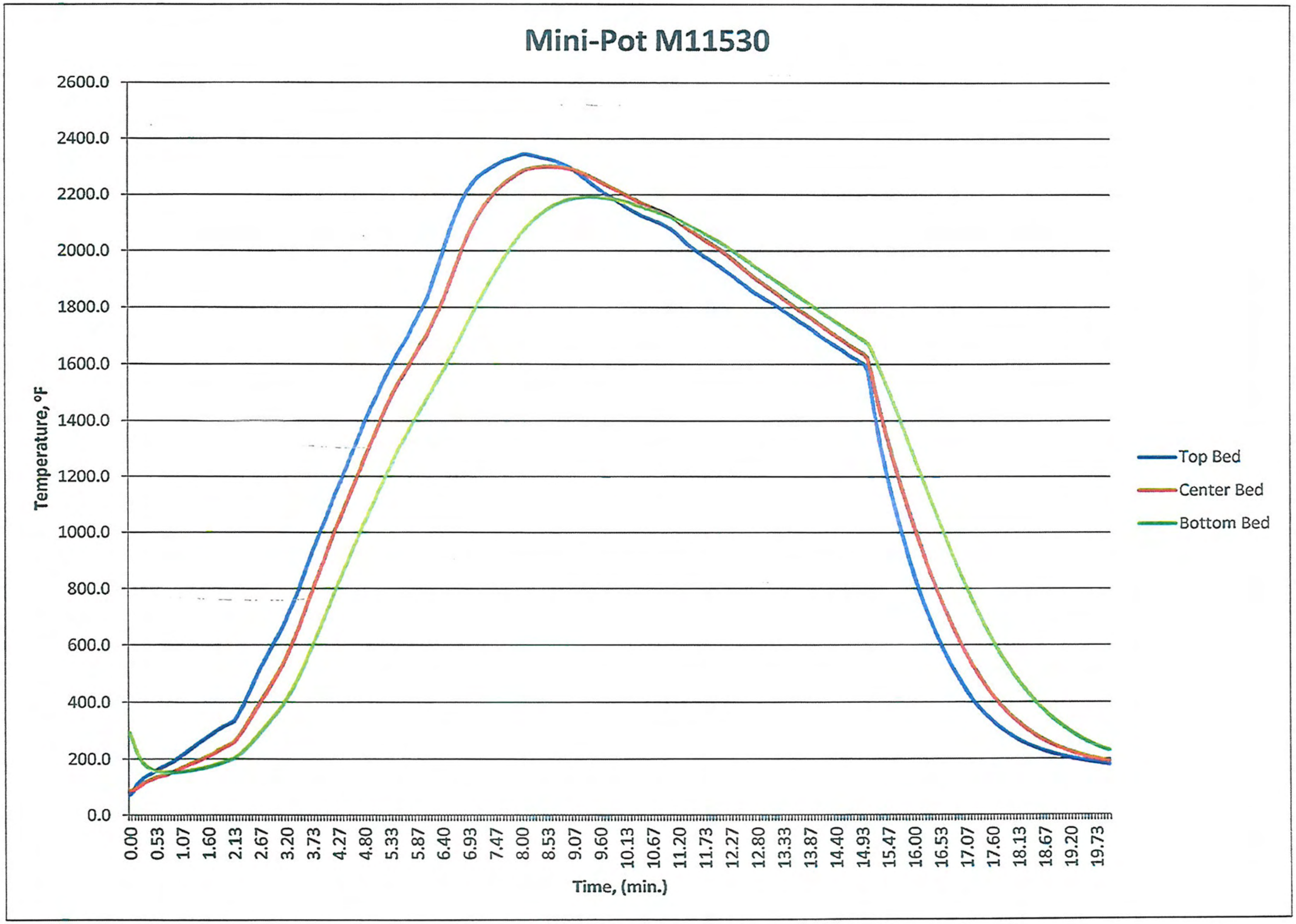
Raw Wt.	2085.76		
.+1/2"	100.02	4.80%	
.+7/16"	850.84	40.79%	
.+3/8"	935.75	44.86%	
.-3/8"	199.15	9.55%	100.00%
Sorted Wt.	1503.31		
.+7/16"	654.7	43.55%	
.+3/8"	848.61	56.45%	100.00%

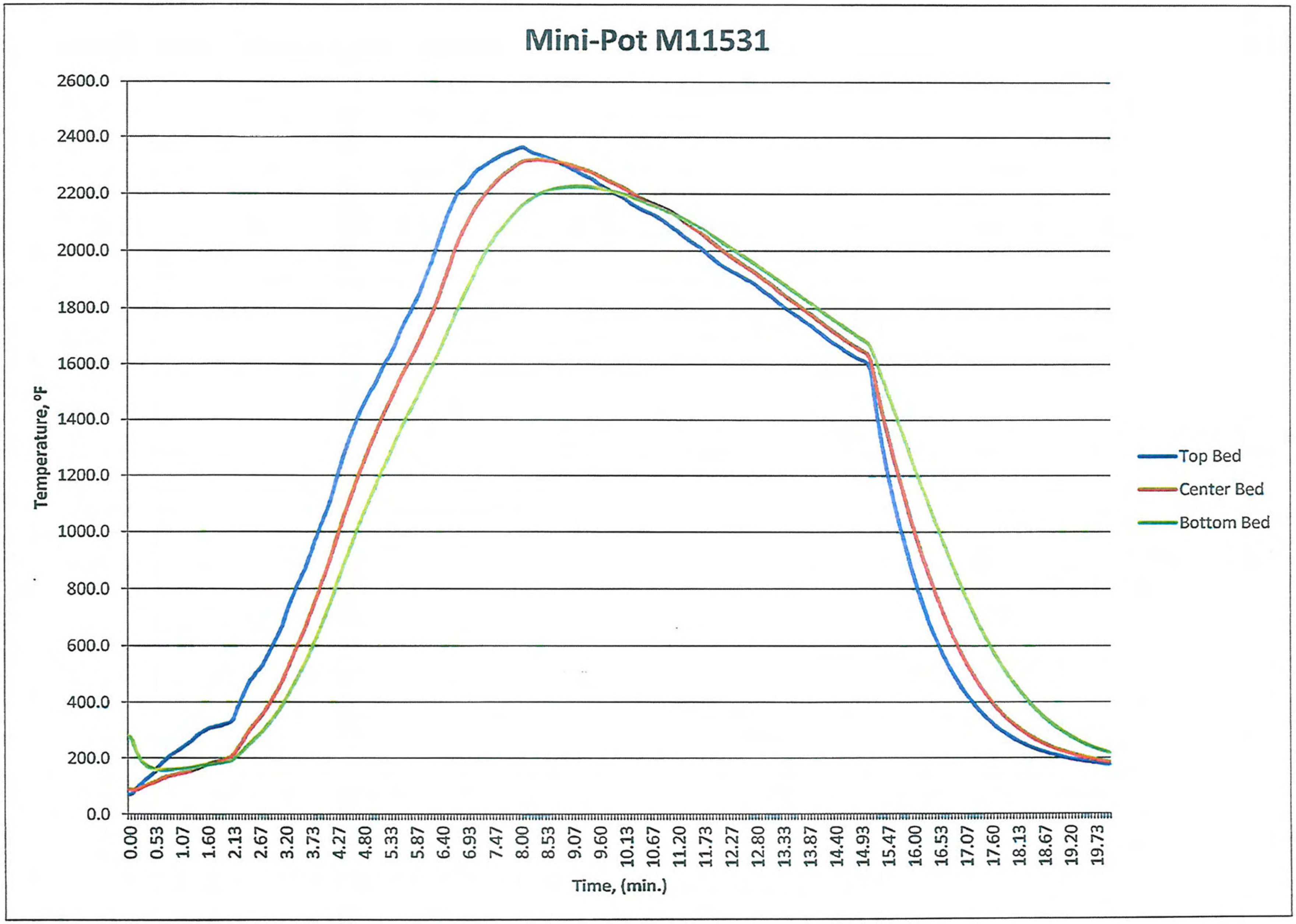
Contraction

		% size
Test #1	9.28	43.55 / 56.45
Test #2		
Sample Avg.		

Mini-Pot M11529



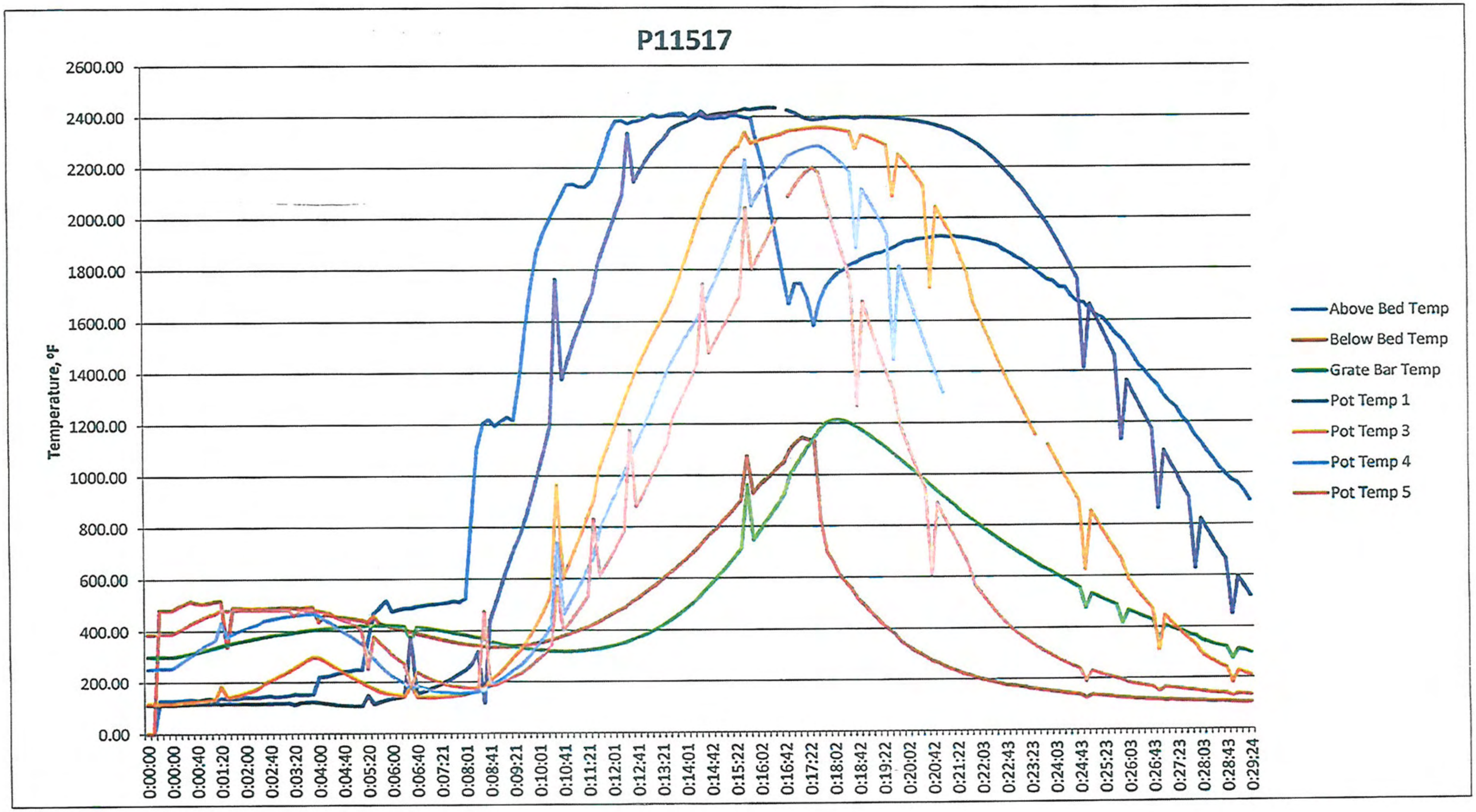

Mini-Pot M11530
Temperature, °F
2600.0
2400.0
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.00
0.53
1.07
1.60
2.13
2.67
3.20
3.73
4.27
4.80
5.33
5.87
6.40
6.93
7.47
8.00
8.53
9.07
9.60
10.13
10.67
11.20
11.73
12.27
12.80
13.33
13.87
14.40
14.93
15.47
16.00
16.53
17.07
17.60
18.13
18.67
19.20
19.73
Time, (min.)
Top Bed
Center Bed
Bottom Bed



Mini-Pot M11531

APPENDIX B

POT GRATE FIRING TEMPERATURE PROFILES


P11517

Temperature, ºF
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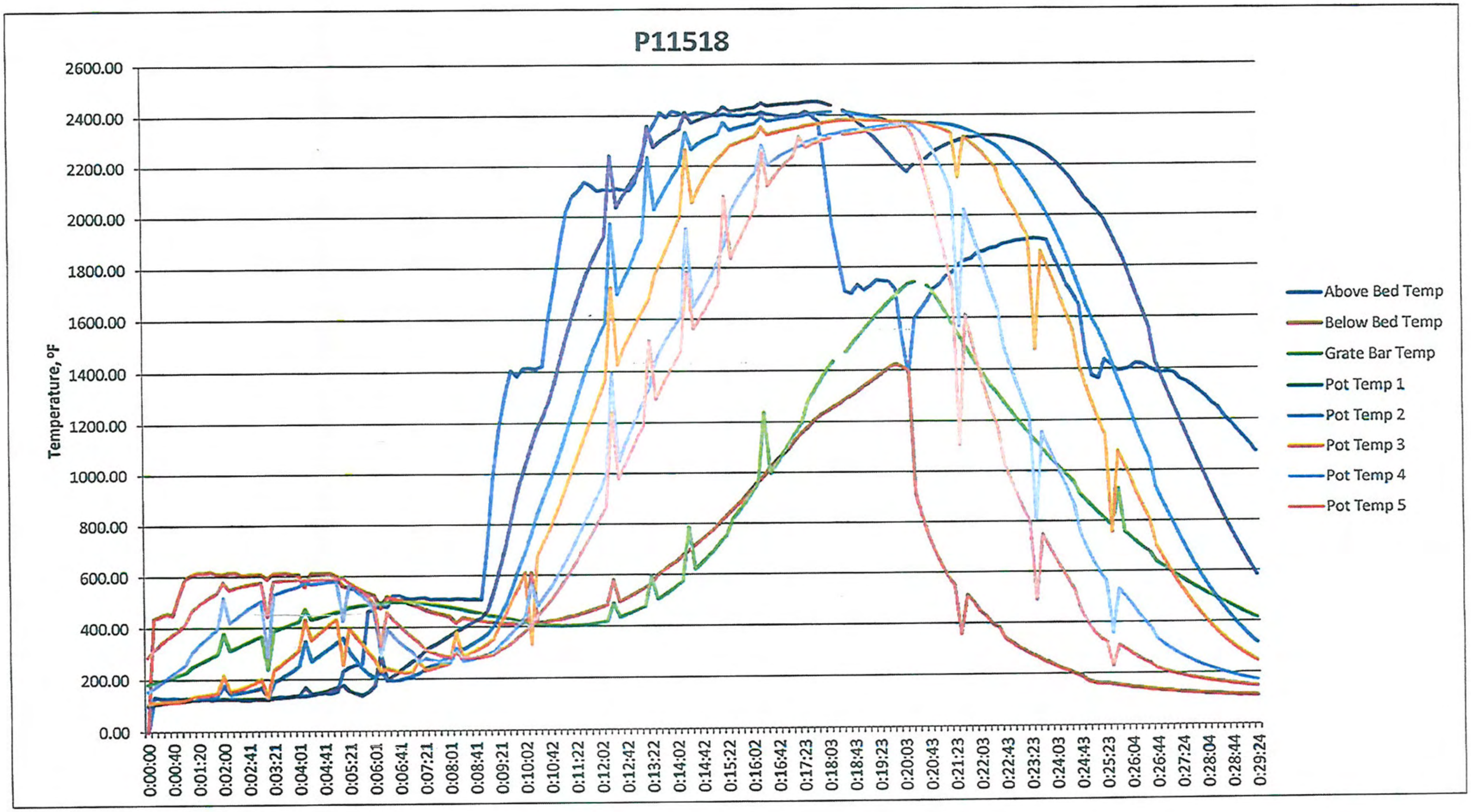
2400.00
2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:00
0:00:40
0:01:20
0:02:00
0:02:40
0:03:20
0:04:00
0:04:40
0:05:20
0:06:00
0:06:40
0:07:21
0:08:01
0:08:41
0:09:21
0:10:01
0:10:41
0:11:21
0:12:01
0:12:41
0:13:21
0:14:01
0:14:42
0:15:22
0:16:02
0:16:42
0:17:22
0:18:02
0:18:42
0:19:22
0:20:02
0:20:42
0:21:22
0:22:03
0:22:43
0:23:23
0:24:03
0:24:43
0:25:23
0:26:03
0:26:43
0:27:23
0:28:03
0:28:43
0:29:24
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 3
Pot Temp 4
Pot Temp 5



P11518

Temperature, ºF
2600.00
2400.00
2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:40
0:01:20
0:02:00
0:02:41
0:03:21
0:04:01
0:04:41
0:05:21
0:06:01
0:06:41
0:07:21
0:08:01
0:08:41
0:09:21
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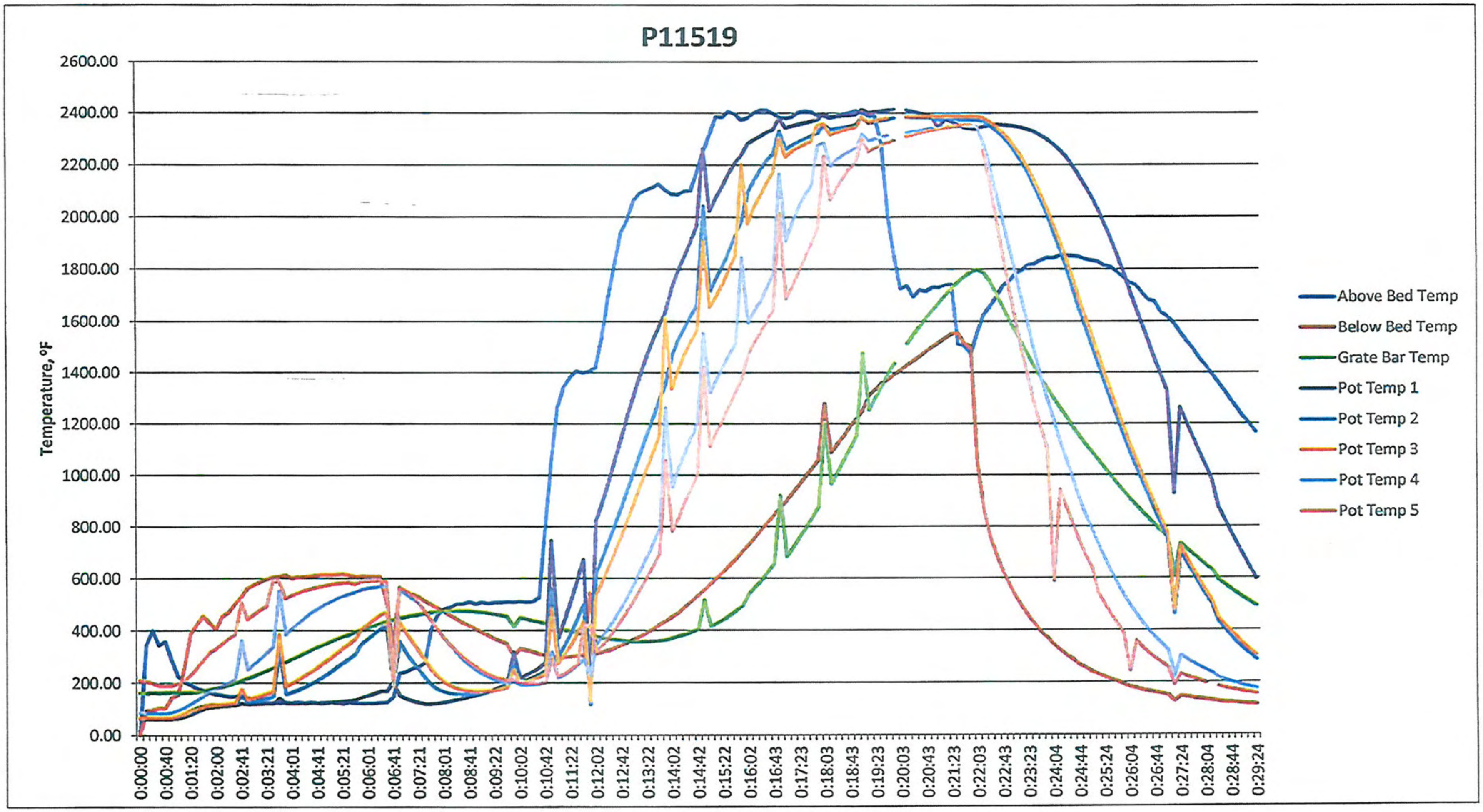
0:12:42
0:13:22
0:14:02
0:14:42
0:15:22
0:16:02
0:16:42
0:17:23
0:18:03
0:18:43
0:19:23
0:20:03
0:20:43
0:21:23
0:22:03
0:22:43
0:23:23
0:24:03
0:24:43
0:25:23
0:26:04
0:26:44
0:27:24
0:28:04
0:28:44
0:29:24
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 3
Pot Temp 4
Pot Temp 5


P11519
Temperature, °F
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2200.00
2000.00
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
0:00:00
0:00:40
0:01:20
0:02:00
0:02:41
0:03:21
0:04:01
0:04:41
0:05:21
0:06:01
0:06:41
0:07:21
0:08:01
0:08:41
0:09:22
0:10:02
0:10:42
0:11:22
0:12:02
0:12:42
0:13:22
0:14:02
0:14:42
0:15:22
0:16:02
0:16:43
0:17:23
0:18:03
0:18:43
0:19:23
0:20:03
0:20:43
0:21:23
0:22:03
0:22:43
0:23:23
0:24:04
0:24:44
0:25:24
0:26:04
0:26:44
0:27:24
0:28:04
0:28:44
0:29:24
Above Bed Temp
Below Bed Temp
Grate Bar Temp
Pot Temp 1
Pot Temp 2
Pot Temp 3
Pot Temp 4
Pot Temp 5

COLERAINE MINERALS RESEARCH LABORATORY

LABORATORY REPORT OF SCREEN ANALYSIS

ENGINEER ____________ DATE ____________ OPERATOR ____________

Sample of Sample Desc P11524 Center Comp

Screen Set Color

Mesh	Weight Pounds Grams	Wt %	Passing Retained Cum %
+6.3	479.6	98.2	
6.3/3.15	1.3	0.3	
3.15/32	0.3	}	
-32	7.0	} 1.5	
	488.2		
Sample Desc P11527 Center Comp			
6.3	460.7	95.2	
6.3/3.15	13.5	2.8	
3.15/32	1.5	0.3	
-32	8.2	1.7	
	483.9	100%	

Sample of Sample Desc P11525 Center Comp

Screen Set Color

Mesh	Weight Pounds Grams	Wt %	Passing Retained Cum %
+6.3	479.0	98.2	
6.3/3.15	1.5	0.3	
3.15/32	0.3	}	
-32	7.0	} 1.5	
	487.8	100%	
Sample Desc P11530 Center Comp			
6.3	448.5	92.6	
6.3/3.15	25.4	5.2	
3.15/32	2.8	0.6	
-32	7.6	1.6	
	484.3	100%	

Sample of Sample Desc

Screen Set Color

Mesh	Weight Pounds Grams	Wt %	Passing Retained Cum %
+6.3			
6.3/3.15			
3.15/32			
-32			
Sample Desc			
6.3			
6.3/3.25			
3.15/32			
-32			