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YEAR 1 HEAT EXTRACTION BARRIER PERFORMANCE REPORT

BRIDGETON LANDFILL

BRIDGETON, ST. LOUIS COUNTY, MISSOURI

Prepared For:
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Project No.: BT-142

STATE OF MISSOURI
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Year 1 Heat Extraction Barrier Performance Report

Bridgeton Landfill, LLC

TABLES

APPENDICES

1 INTRODUCTION

Bridgeton Landfill, LLC (Bridgeton Landfill) submitted the *Technical Evaluation of a Heat Extraction Barrier* on November 1, 2015 to the Missouri Department of Natural Resources (MDNR) which:

- demonstrated the pilot study heat removal system removed heat and could reduce temperatures in temperature monitoring devices near the pilot study wells;
- provided thermal modeling to predict the effectiveness of a Heat Extraction Barrier (HEB);
- provided installation guidance for the HEB; and
- proposed a system of Temperature Monitoring Probes - System Performance Monitoring (TMP-SPM) to monitor temperatures in the neck area.

The MDNR approved the November 1, 2015 submittal on December 4th, 2015. The approval letter listed 10 comments to the submittal. The United States Environmental Protection Agency (USEPA) ordered the Bridgeton Landfill to install the HEB via an April 28th, 2016 Administrative Settlement Agreement and Order on Consent for Removal Actions (ASAOC). Section VIII.35.c of the April 28th, 2016 ASAOC incorporated the November 1, 2015 submittal and the December 4, 2015 approval letter except for Comment #1.

In accordance with Comment No. 9 of the December 4th, 2015 MDNR letter (incorporated into the April 28, 2016 ASAOC), this report will summarize the HEB's performance and include a revised thermal model based upon the observations from the previous year. The heat extraction data have been submitted within monthly reports submitted per Comment #8 of the December 4, 2015 MDNR comment letter, and is not included in this report.

2 HEAT EXTRACTION BARRIER INSTALLATION

The 16 HEB elements – called Heat Extraction Wells (HEW) were installed between July 11, 2016 and September 17, 2016. The installation of the piping and manual instrumentation were installed by September 25, 2016. Operations of the HEB commenced on October 11, 2016 once the grout was allowed to cure and background SPM-TMP readings were obtained. As built record drawings detailing the installation of the HEB was submitted to the USEPA and MDNR on November 23, 2016.

The Gas Inceptor Wells (GIW) pilot system (GIW-2, GIW-3, GIW-4, GIW-5, GIW-6, GIW-7, GIW-8, GIW-9, GIW-10, GIW-11, GIW-12, and GIW-13) has been removing heat since

November 2014, and remained in operation during the installation of the HEWs. The GIW system was incorporated into the entire HEB system. The twenty-eight (28) heat extraction units, the cooling tower, the cooling liquid storage tank, the pump, and the instrumentation system comprise the Neck Heat Extraction System as defined in the April 28th, 2016 ASAOC. The as-built update of the Neck Heat Extraction System is included in **Appendix A**.

Automated Barrier System Data Collection

At the time of system startup on October 11th, 2016, heat extractor units were outfitted with inlet and outlet temperature sensors and flow meters that required manual recording of temperature and flow. Those sensors and flow rate meters were read and recorded once per day during the initial startup period then once every other day after the startup period (October 21st, 2016). During November 2016 the heat extraction system was outfitted with an automated data collection system to calculate the thermal energy removed directly from a database of temperature and flow rate measurements.

The heat extractors are each outfitted with a flow rate meter that provides measurement results for inlet temperature and flow rate and a wireless Resistance Temperature Detector (RTD) that provides measurement results for outlet temperature. The measurement results are transmitted (via wired connections for the flow meters and via wireless transmission for the outlet RTDs) to a centralized data collection system. The data collection system records measurement results at ten (10) minute intervals. The exception to this is GIW-5, which is outfitted with a wireless RTD for inlet temperature data collection but does not have an automated flow rate meter data collector due to the limited number of data input channels available on the wired connection chart recorder. Flow rate measurements for GIW-5 are currently recorded manually once per week.

Temperature and flow rate measurement results have been provided in previous Neck Heat Extraction System Monthly Reports.

3 HEAT EXTRACTION BARRIER PERFORMANCE

The HEB has been in operation since October 11, 2016. The Year 1 report contained herein analyzes data through the end of August 2017. Based upon the following empirical data collected, the Neck Heat Extraction System (as defined in the April 28, 2016 ASAOC) is performing effectively:

- The measured amount of thermal energy from the system during the above time period has been measured to be over 2.7 Billion BTUs (See **Table 1**).
- The TMP-SPMs 3 and 4 (TMPs north of the HEB line) are trending downward in temperature, a direct effect of the Neck Heat Extraction System. (See **Appendix B**).

- The 220 degree F isotherm line has either been stationary or has retreated south in the vicinity of GIW-10 (See **Appendix E**).

Calculation of amount of thermal energy removed

Thermal energy is removed from the landfill via the extraction points. Energy is transferred to the cool liquid as it travels through the extractor. The liquid is warmed in a closed loop system by the surrounding waste mass and is pumped to the reservoir tank to complete the cooling cycle. The rate of energy removal is equal to the mass of the fluid mixture passing through the extractor per given time, multiplied by the heat capacity of the fluid mixture, multiplied by the change in temperature that occurred as it passed through the extractor, and is expressed by Equation 1:

$$HRR = C_p(T)\ x\ Q\ x\ \delta(T)\ x\ (T_o - T_i) \qquad (1)$$

Where:

HRR = Heat Removal Rate (kilowatts);

$C_p(T)$= Heat Capacity of Fluid Mixture as a function of Temperature;

Q = Flow Rate (gpm, corrected from the recorded reading for viscosity variation);

$\delta(T)$= Mass Density of Fluid Mixture as a function of temperature;

T_o = Outflow Temperature (°F); and

T_i = Inflow Temperature (°F)

The calculation of amount of thermal energy removed and the supporting data are submitted every month to the USEPA and MDNR within the Neck Heat Extraction System Monthly Reports. A summary of the thermal energy removed since October 11, 2016 is included in **Table 1**. In the time period, over 2.7 billion BTUs of heat have been removed from the system.

Review of Northern TMP-SPMs

TMP-SPM3 is located approximately 14 feet north of the HEB line, and TMP-SPM4 is located approximately 19 feet north of the HEB line. Both of these TMPs are showing reductions in temperature. The temperature verses depth graphs for all four System Performance Monitoring TMPs are provided in **Appendix B.** These graphs show the gray shaded historical temperatures, along with the starting temperature, and the most recent 5 weeks of temperature data collected. Please note TMP-SPM-1 and TMP-SPM-2 are south of the HEB, which is closer to the reaction.

Review of 220 degree F Isotherm

An additional gauge of Neck Heat Extraction System performance can be observed by a comparison of the 220 degree F subsurface isotherm previously provided in Appendix C of the November 2015 *Technical Evaluation of a Heat Extraction Barrier* with a 220 degree F subsurface isotherm prepared by interpolation using current (July – August 2017) maximum measured temperatures observed at TMPs near the heat extraction system. This 220 degree F subsurface isotherm has been used historically as a limit of the maximum northern extent of the possible reaction, if significant settlement was also measured. The July – August 2017 220 degree F subsurface isotherm was taken from TMP data that is reported weekly to the MDNR. The temperature verses depth graphs for the neck area and North Quarry TMPs are provided in **Appendix C**, while the temperature verses depth graphs for the pilot study TMPs are provided in **Appendix D**.

The figure provided in **Appendix E** illustrates the 2015 subsurface conditions versus July – August 2017 subsurface conditions. As can be observed, the location of the 220 degree F subsurface isotherm has moved slightly south, suggesting the heat extraction system is having a positive effect on subsurface temperatures near the system.

4 MODELING

An update to the finite element analysis thermal model has been prepared by P.J. Carey & Associates, P.C. (Carey) and is provided in **Appendix F**. The updated thermal model incorporates monitoring data provided by measurements obtained from the Neck Heat Extraction manual and automated data collection system and incorporates measurement results from TMPs at the facility.

Details regarding the derivation of input assumptions, the model function, and results are presented in **Appendix F** and summarized below:

- Waste thermal properties have been calculated using results from the heat removal. The earlier model under predicted the amount of thermal energy that would be removed; therefore, the actual data supports revising some of the model input parameters. As a result, the thermal conductivity value of 1.4 watts per meter-degree Kelvin was increased to 1.6 watts per meter-degree Kelvin, and the waste heat capacity of 2.4 mega joules per cubic meter was increased to 2.6 mega joules per cubic meter.
- Northern boundary conditions were based upon data from TMPs 16 and 19. The boundary conditions for the south were based upon TMPs 7R, 8, 31 and 32.
- The model does not account for heat loss into the quarry walls, which is a significant conservative assumption, which is consistent with the original modeling effort.

- Retardance factors were used to allow sufficient heat into the heat extractors to model the actual measured heat removal for the collectors.
- For all dates the model depicts lowering temperatures within the vicinity of the HEW line and temperatures below 170 degrees F at all locations from 40 feet south of the HEB line northward. The model results also show the HEB line acts as a line with overlapping zones of influence, negating the need for any additional heat exchange devices between the current HEB units.

5 HEAT EXTRACTION BARRIER AUGMENTATION

As described in Section 4 and the *Evaluation of Heat Extraction Barrier Model – One Year of Operation* by PJ Carey and Associates, P.C. in **Appendix F**, since the model results show the HEB acts as a line with overlapping zones of influence, no additional heat extraction augmentation is needed at this time. As long as the northern TMP-SPMs (3 and 4) show temperatures below a 185 degree F threshold, no augmentation will be needed.

6 SYSTEM PERFORMANCE MONITORING

System performance monitoring is intended to verify that the heat removal system is achieving a target temperature in the neck area north of the HEB and to assess the presence and trend of heat input from south of the HEB. As discussed in Section 3, the northern two TMP-SPMs illustrate temperature reductions. It is proposed that the following criteria be used as criteria for no additional thermal modeling:

- All thermocouples within TMP 1, 2R, 3R, and 4R and TMP -SPMs 3 and 4 are at or below 185 degrees F.

The 185 degree F threshold is well below the 200 degree F “trigger criteria” within TMPs 1, 2R, 3R, and 4R. If a thermocouple exceeds this 185 degree F threshold, then the thermal model will be reassessed to determine if additional heat extraction points are needed. Monitoring of conditions south of the HEB will continue which will allow determination of when heat extraction may be slowed, terminated, or even—if necessary—supplemented with additional points to achieve performance goals.

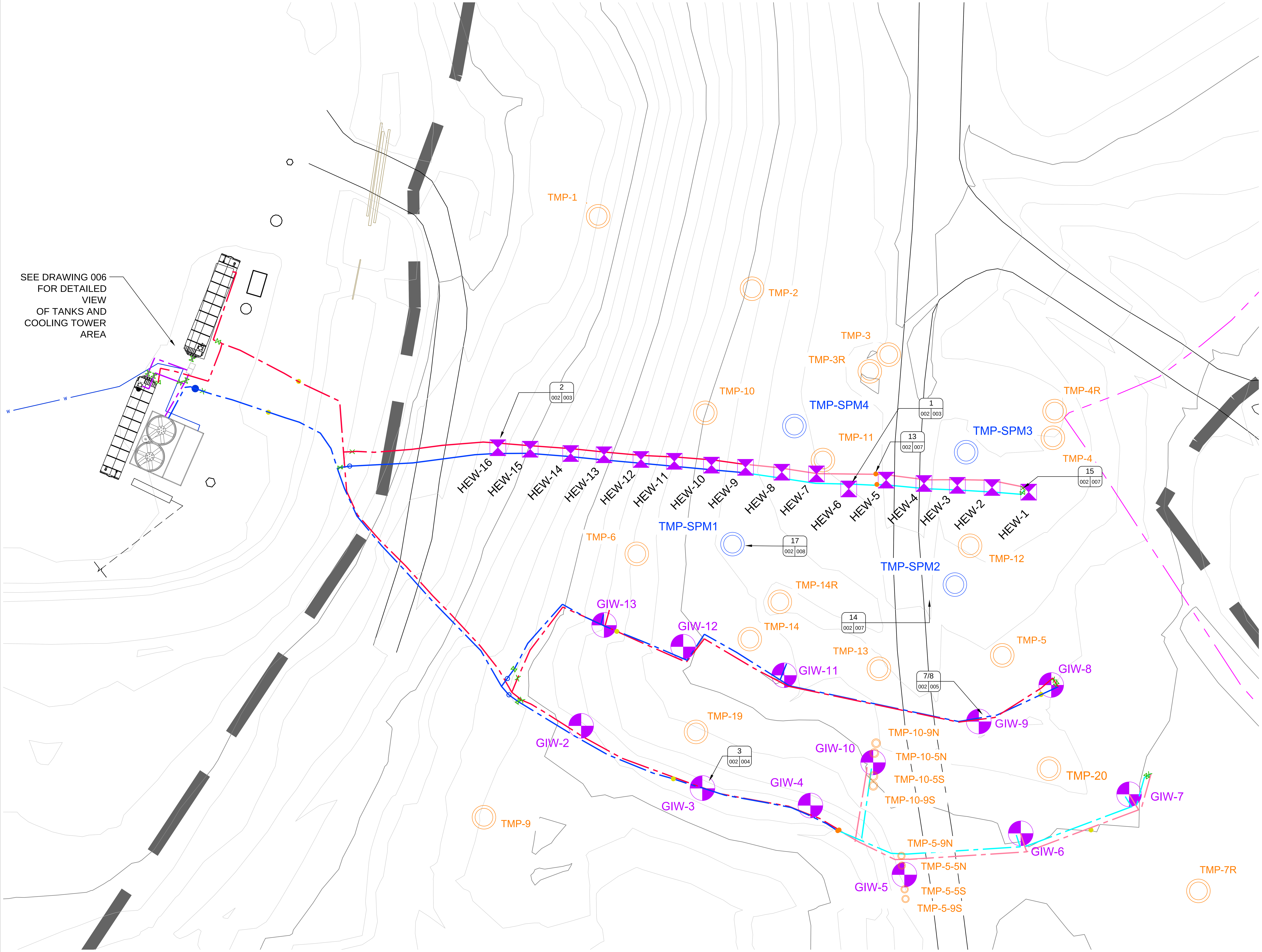
TABLE 1

CALCULATED REMOVED THERMAL ENERGY
(PERIOD 10-16-2016 TO 8-31-2017)

TABLE 1 Period 10-16-2016 to 08-31-2017 Calculated Removed Thermal Energy		
Unit	kW-hr	BTU
October 2016	69,424	236,875,785
November 2016	99,680	340,108,964
December 2016	105,697	360,638,164
January 2017	73,187	249,715,748
February 2017	50,326	171,710,730
March 2017	82,234	280,580,707
April 2017	68,140	232,493,844
May 2017	69,684	237,762,040
June 2017	68,067	232,242,976
July 2017	65,728	224,262,959
August 2017	68,172	232,603,896
Total October 2016 - August 2017	**820,339**	**2,798,995,813**

APPENDIX A

NECK HEAT EXTRACTION SYSTEM AS-BUILT PLAN VIEW DRAWING



LEGEND

- TOPOGRAPHY (2' CONTOUR)
- 500 — TOPOGRAPHY (10' CONTOUR)
- QUARRY WALL
- PERMITTED WASTE BOUNDARY
- HEAT EXTRACTION WELL
- TEMPERATURE MONITOR PROBE - SYSTEM PERFORMANCE MONITORING
- HEB 4" HEAT EXTRACTION INFLUENT PIPING
- HEB 2" HEAT EXTRACTION INFLUENT PIPING
- HEB 4" HEAT EXTRACTION EFFLUENT PIPING
- HEB 2" HEAT EXTRACTION EFFLUENT PIPING
- SYSTEM CONTROL VALVE
- SYSTEM CHECK VALVE
- SYSTEM FLOW METER
- AIR BLEED VALVE
- EXISTING TEMPERATURE MONITORING LOCATION
- EXISTING HEAT EXTRACTION LOCATION
- EXISTING TEMPERATURE MONITOR PROBE
- EXISTING 4" HEAT EXTRACTION INFLUENT PIPING
- EXISTING 2" HEAT EXTRACTION INFLUENT PIPING
- EXISTING 4" HEAT EXTRACTION EFFLUENT PIPING
- EXISTING 2" HEAT EXTRACTION EFFLUENT PIPING

0 16 32 Feet

SCALE - 1" = 16'

NOTES:

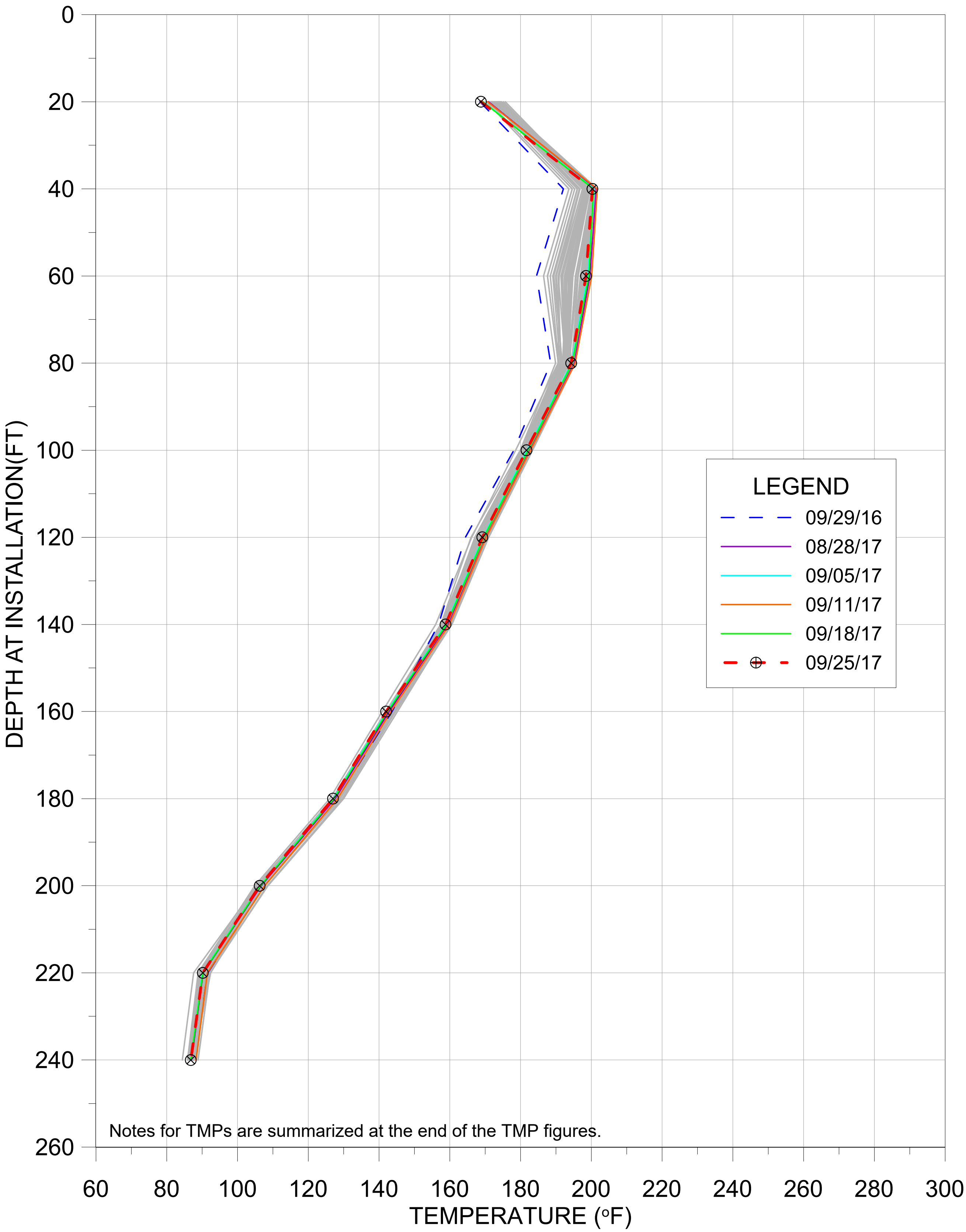
1.) AERIAL TOPOGRAPHY IS DATED FEBRUARY 27, 2016. PROVIDED BY COOPER AERIAL SURVEYS CO.

BRIDGETON LANDFILL LLC 13570 ST. CHARLES ROCK ROAD BRIDGETON, MO 63044	BRIDGETON LANDFILL NECK HEAT EXTRACTION SYSTEM AS-BUILT DRAWINGS	Engineering for a Better World FEEZOR ENGINEERING, INC.	DATE: NOVEMBER 2016 DESIGNED BY: AMR APPROVED BY: DRF	DRAWING NO.:
NECK HEAT EXTRACTION SYSTEM - PLAN VIEW			9-11-17	PML	**002**
PROJECT NUMBER: BT-096	FILE PATH: E:\Dropbox (Feezor Engineering)\BT-086 Heat Extraction Barrier Construction\Report\AB Drawings\BT-096-AB-002 (Heat Extraction Barrier - Plan View) Rev-9-11-17.dwg		REVISION	DATE	

APPENDIX B

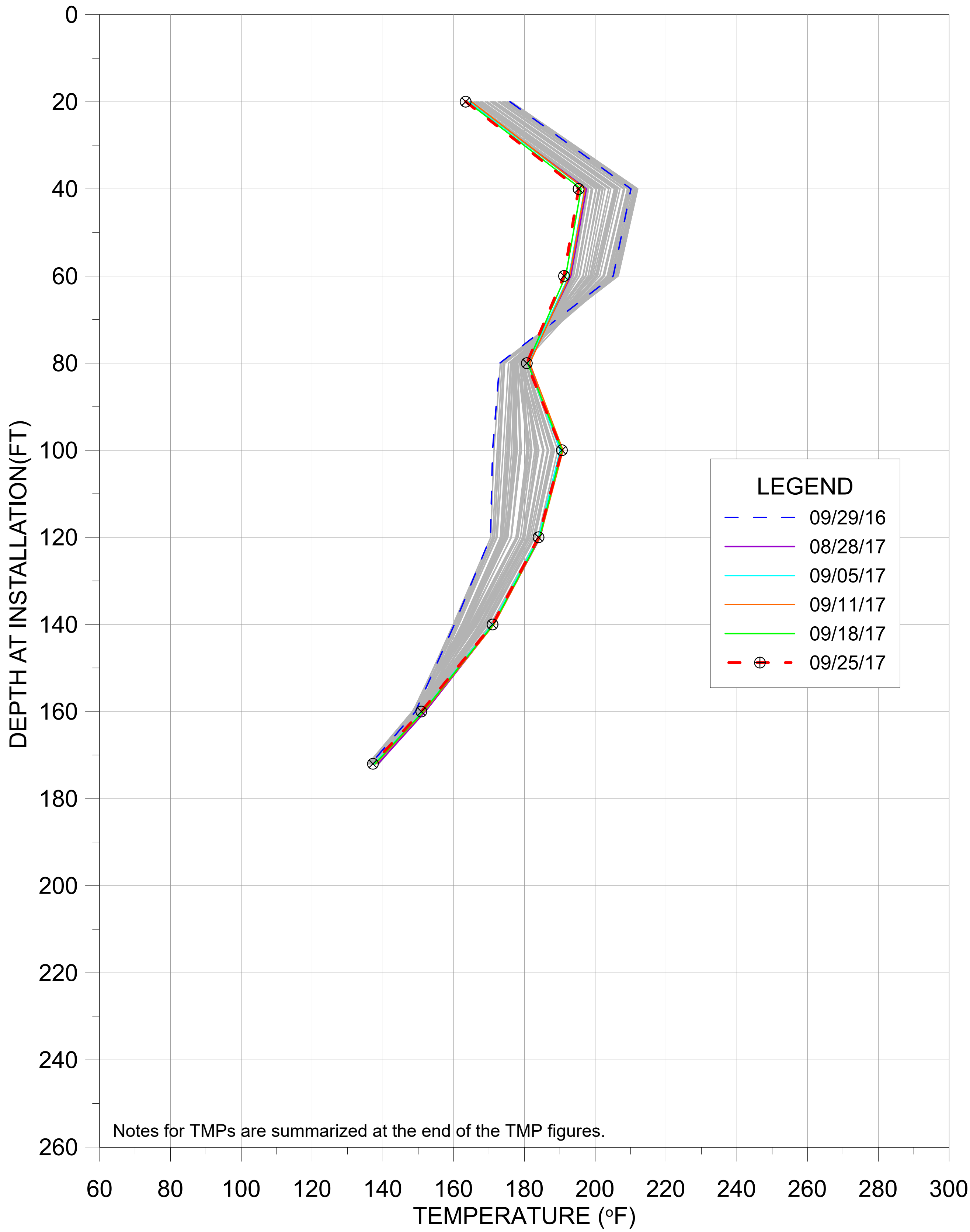
SYSTEM PERFORMANCE MONITORING TMPS GRAPHS AS OF 09/25/17

TMP-SPM1



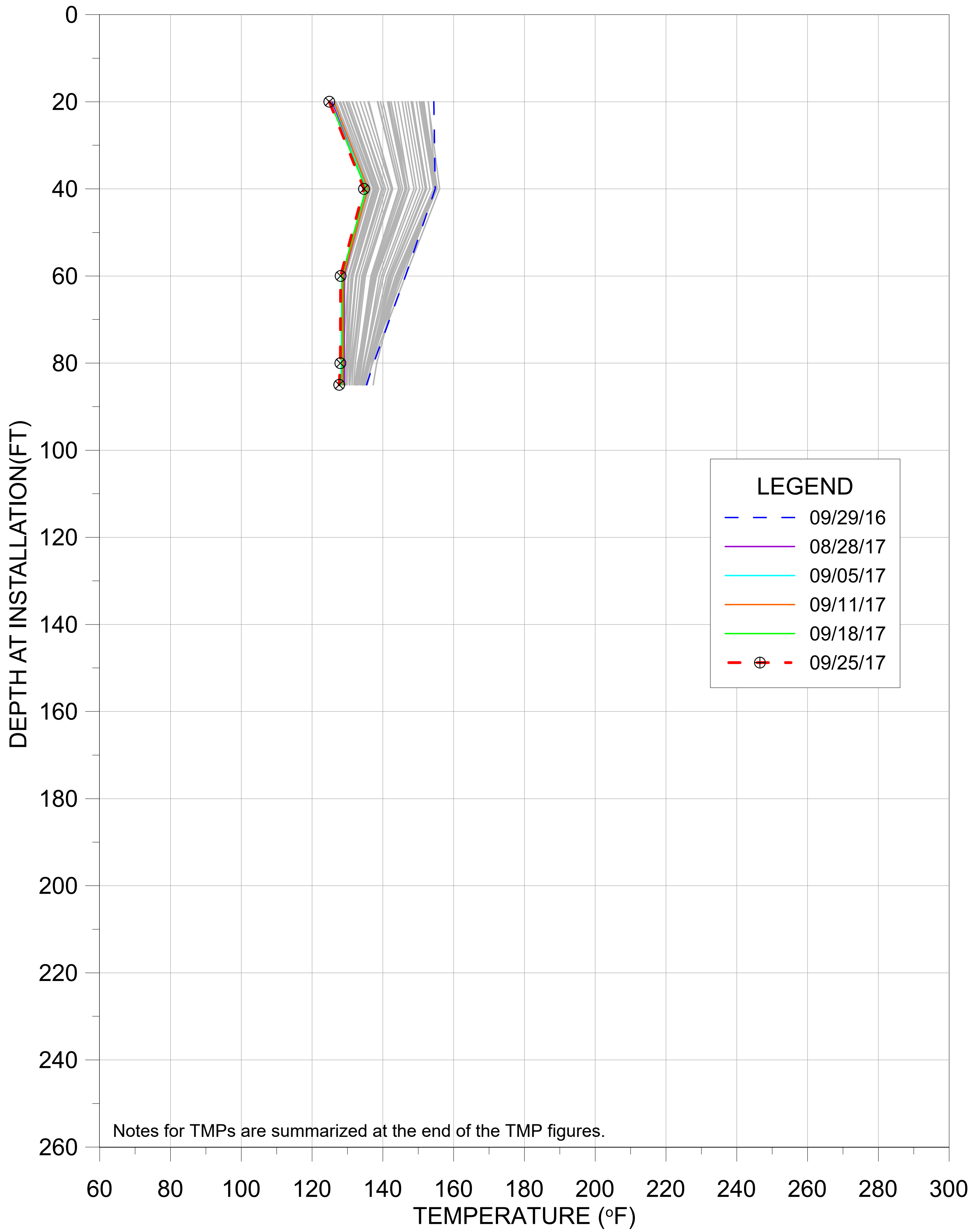
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-SPM2



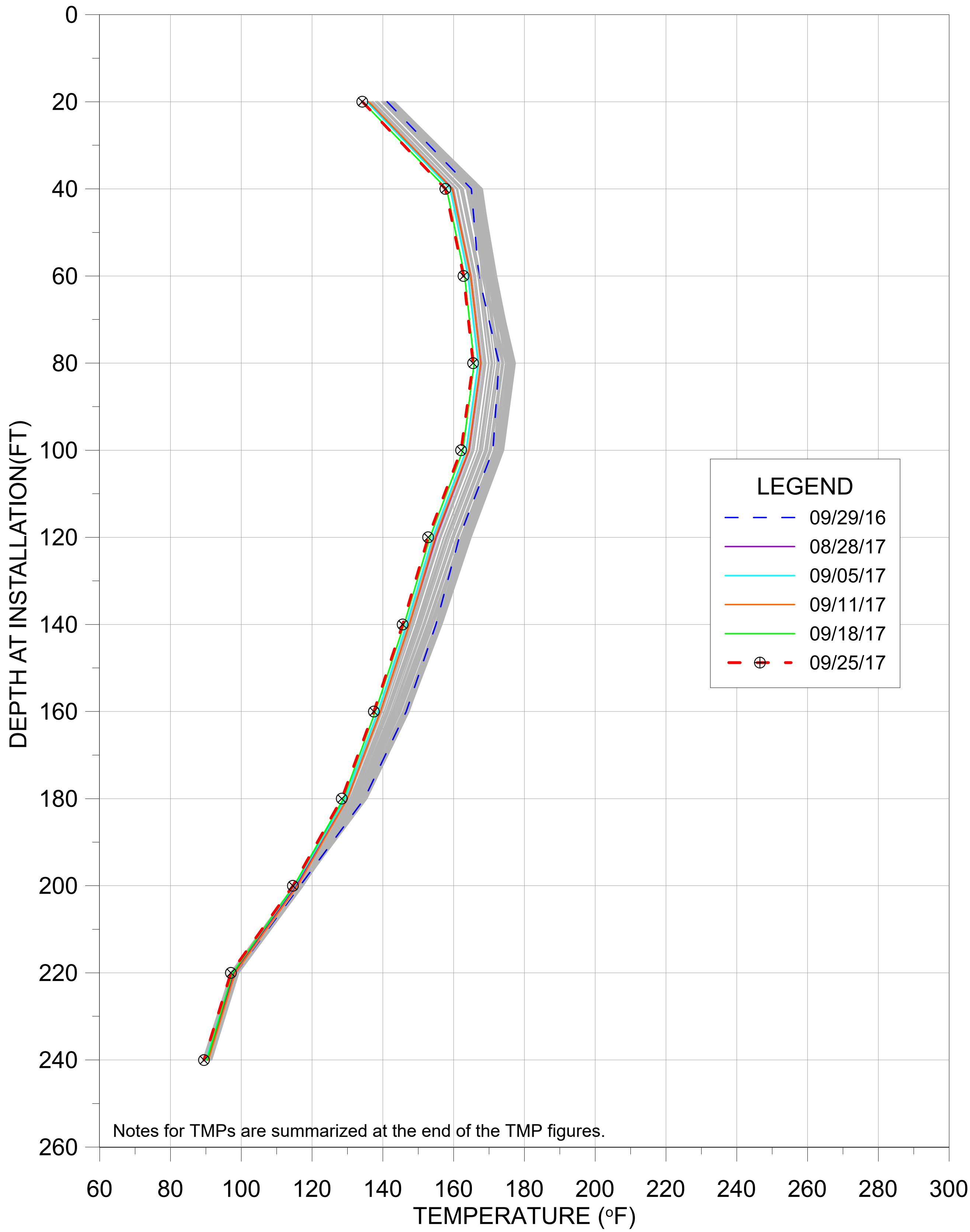
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-SPM3



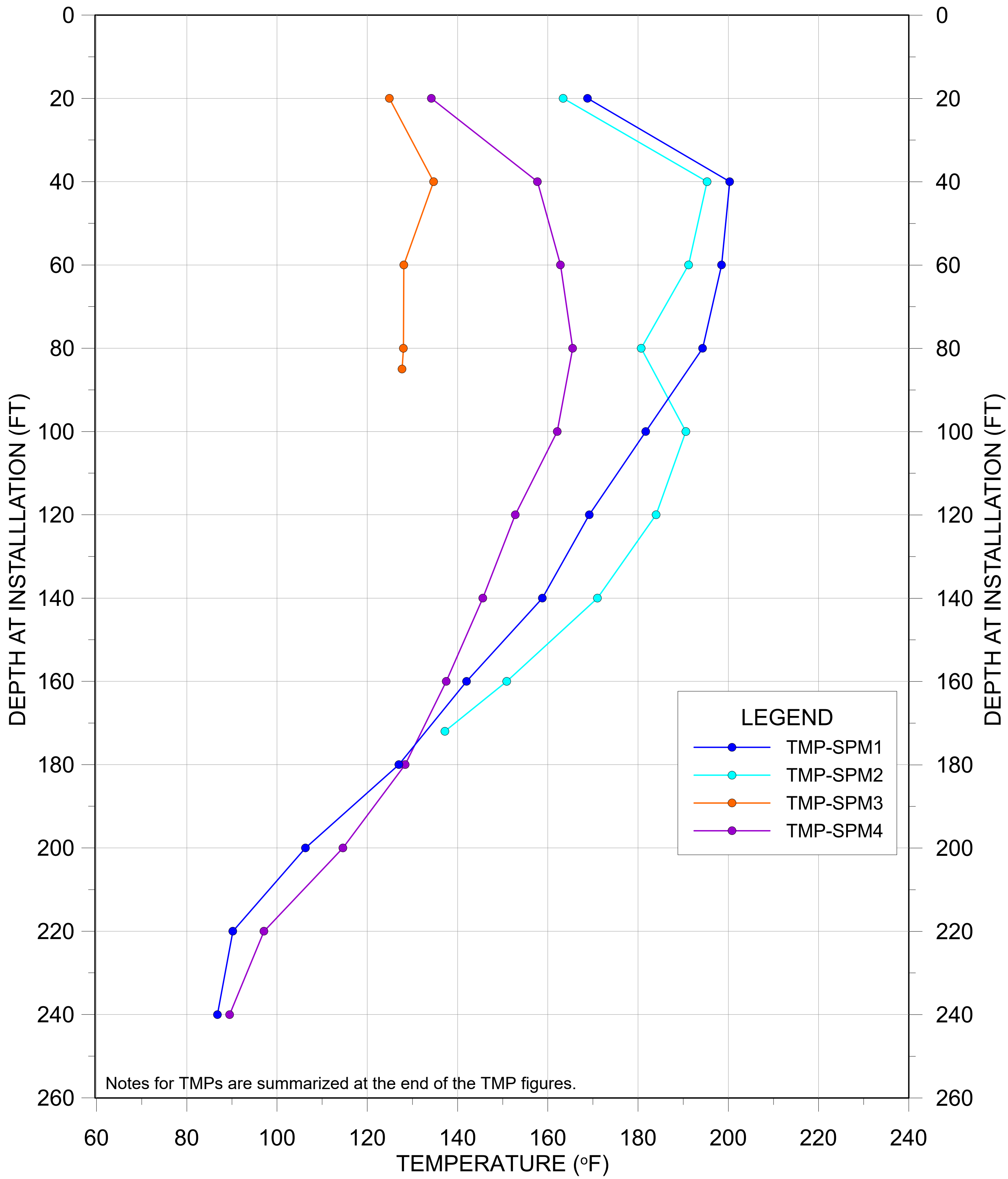
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-SPM4



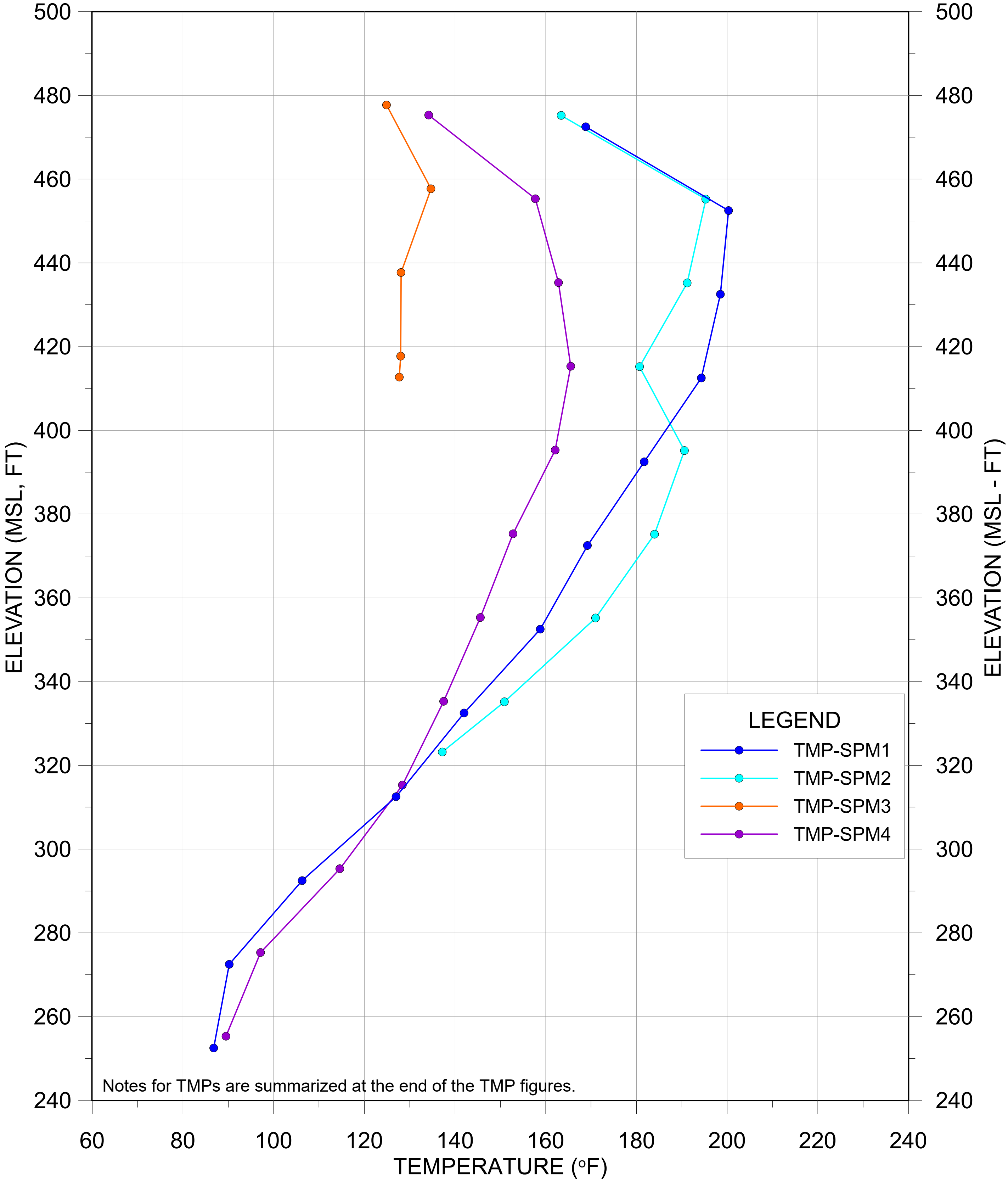
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

9/25/2017 - SPM



TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

9/25/2017 - SPM



TEMPERATURE VS ELEVATION
BRIDGETON LANDFILL

SPM BRIDGETON LANDFILL NOTES

Notes that are new for the reporting week are in **bold**.

SPM-1: NONE

SPM-2: NONE

SPM-3: NONE

SPM-4: NONE

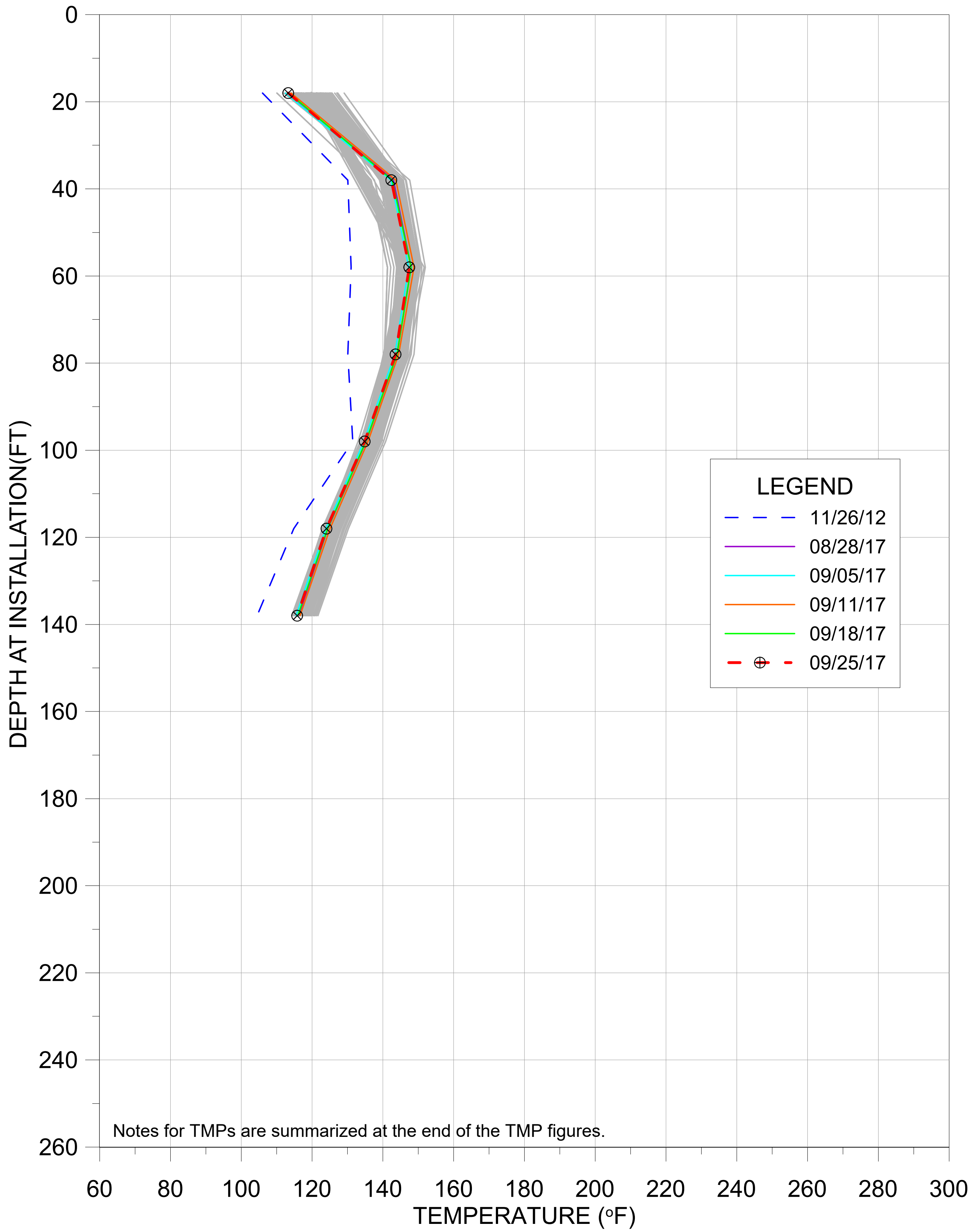
SPM- TEMP VS DEPTH & DEPTH VS ELEVATION (**09/25/17**)

NONE

APPENDIX C

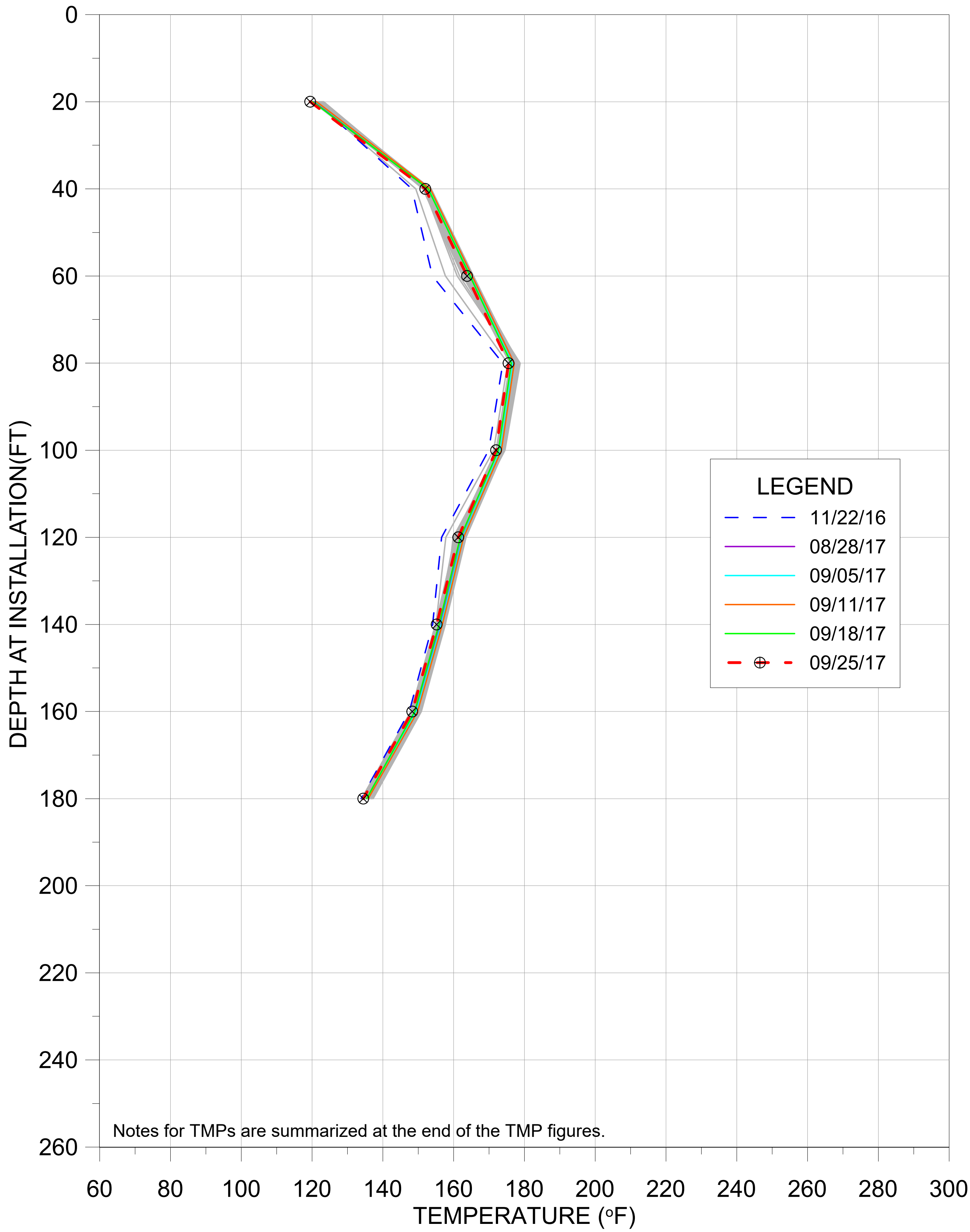
NECK AREA AND NORTH QUARRY TMPS GRAPHS AS OF 09/25/17

TMP-1



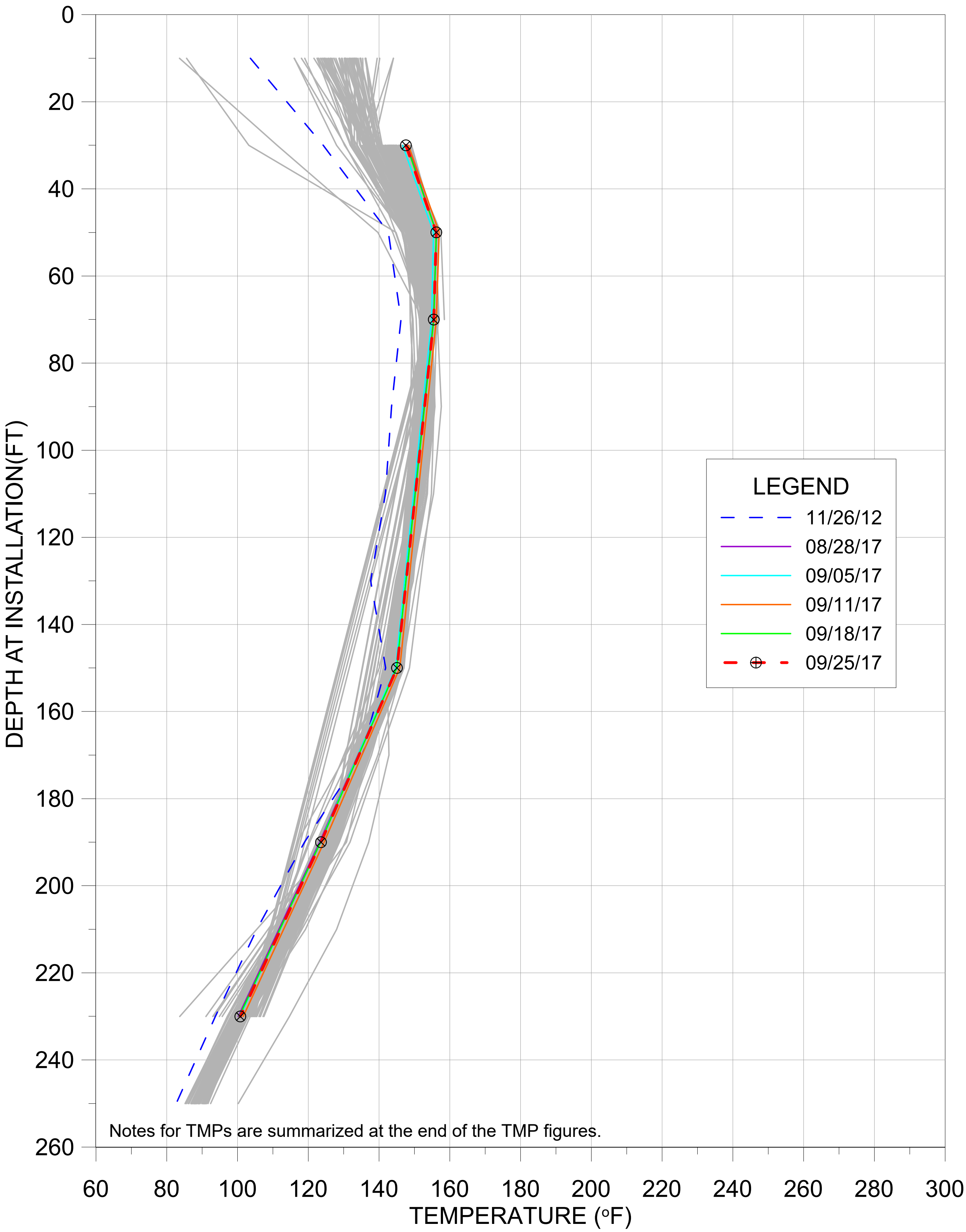
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-2R



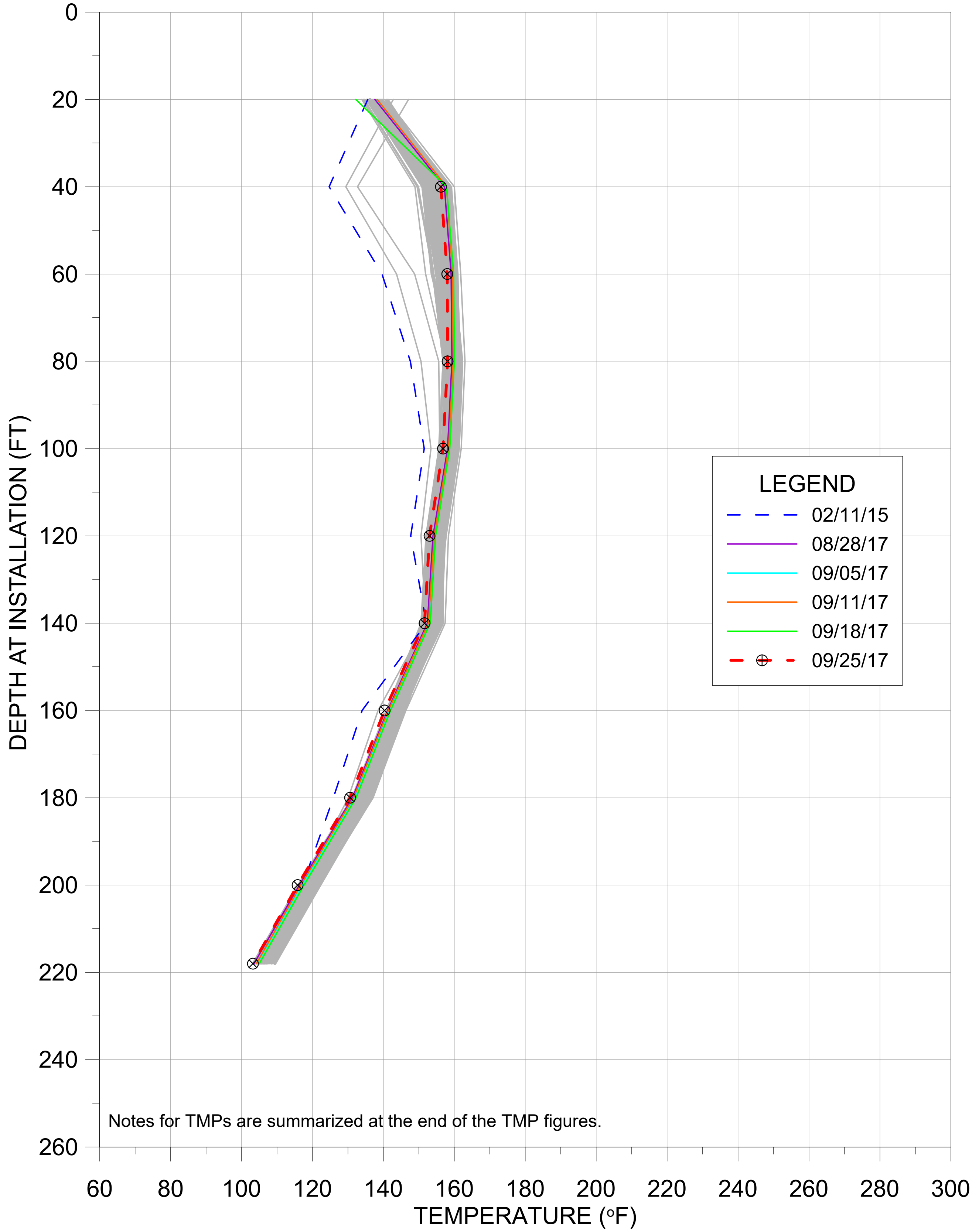
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-3



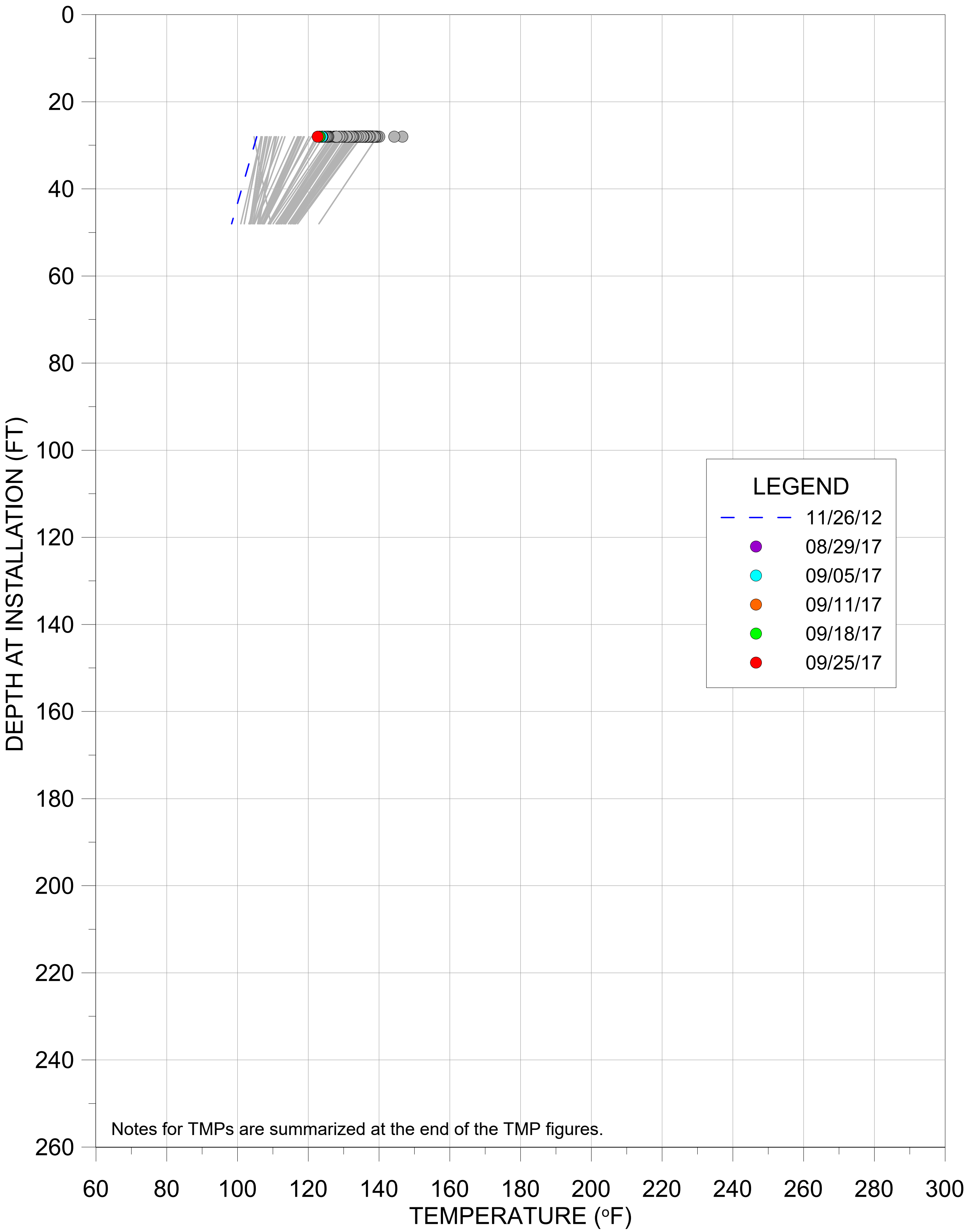
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-3R



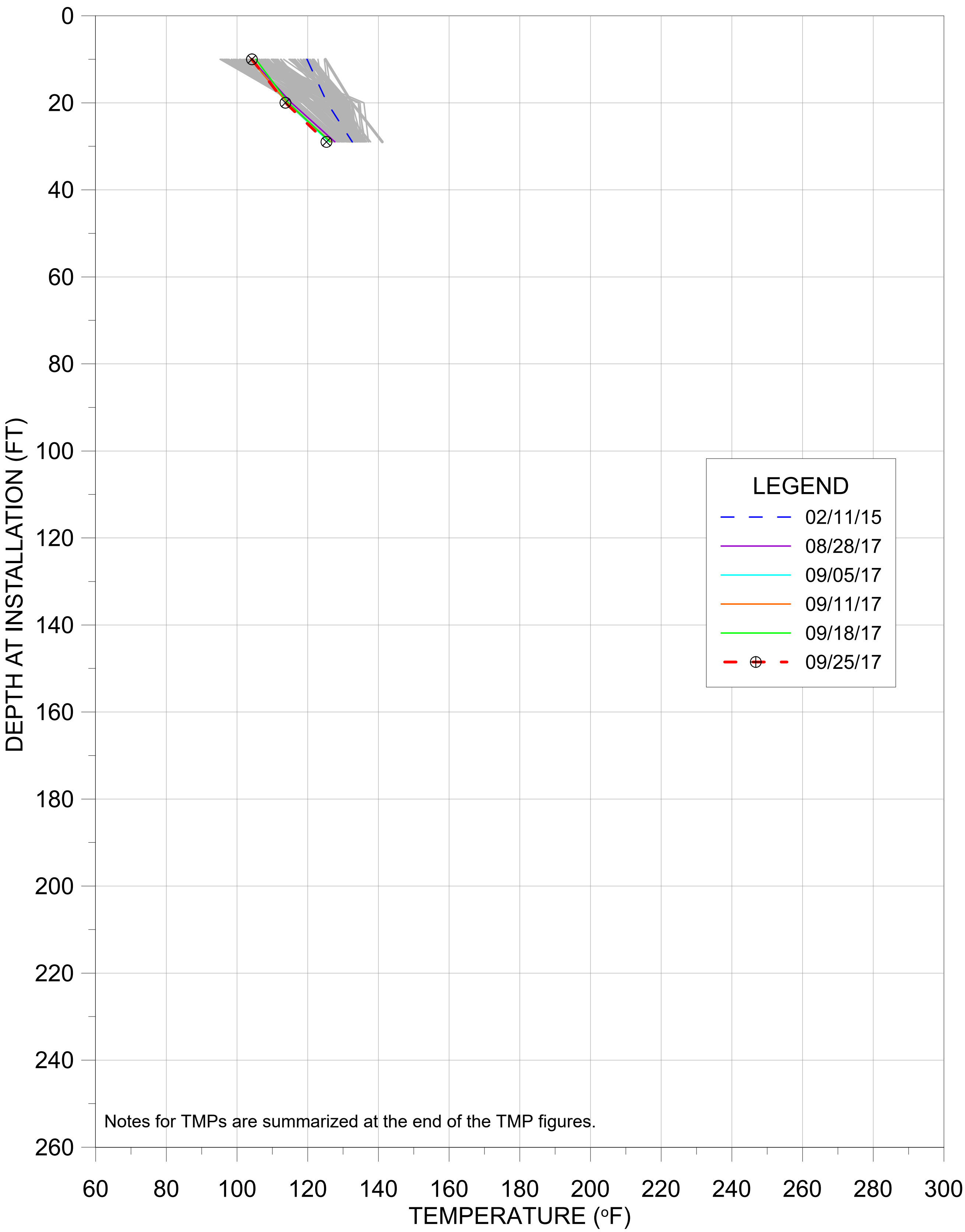
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-4



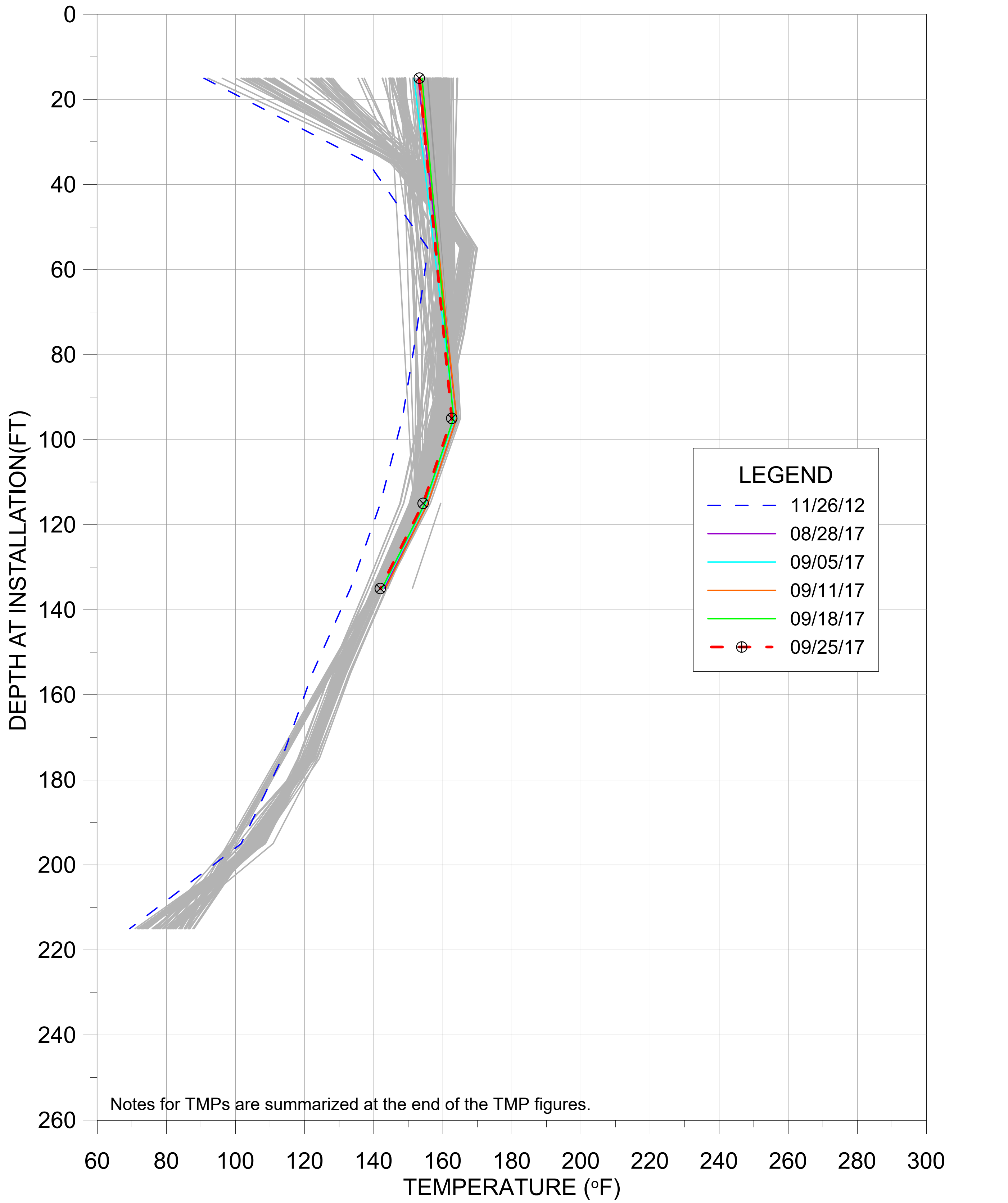
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-4R



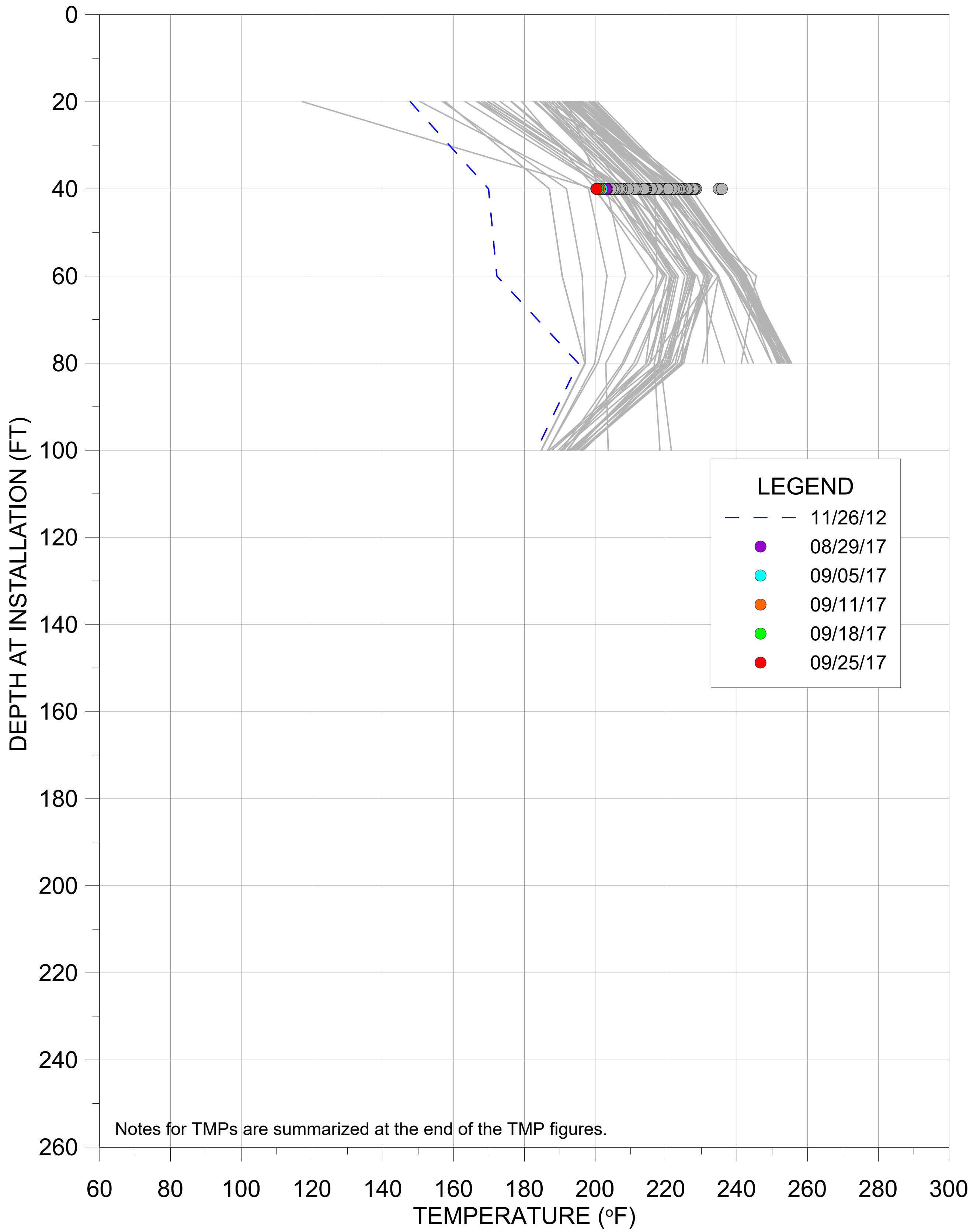
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-6



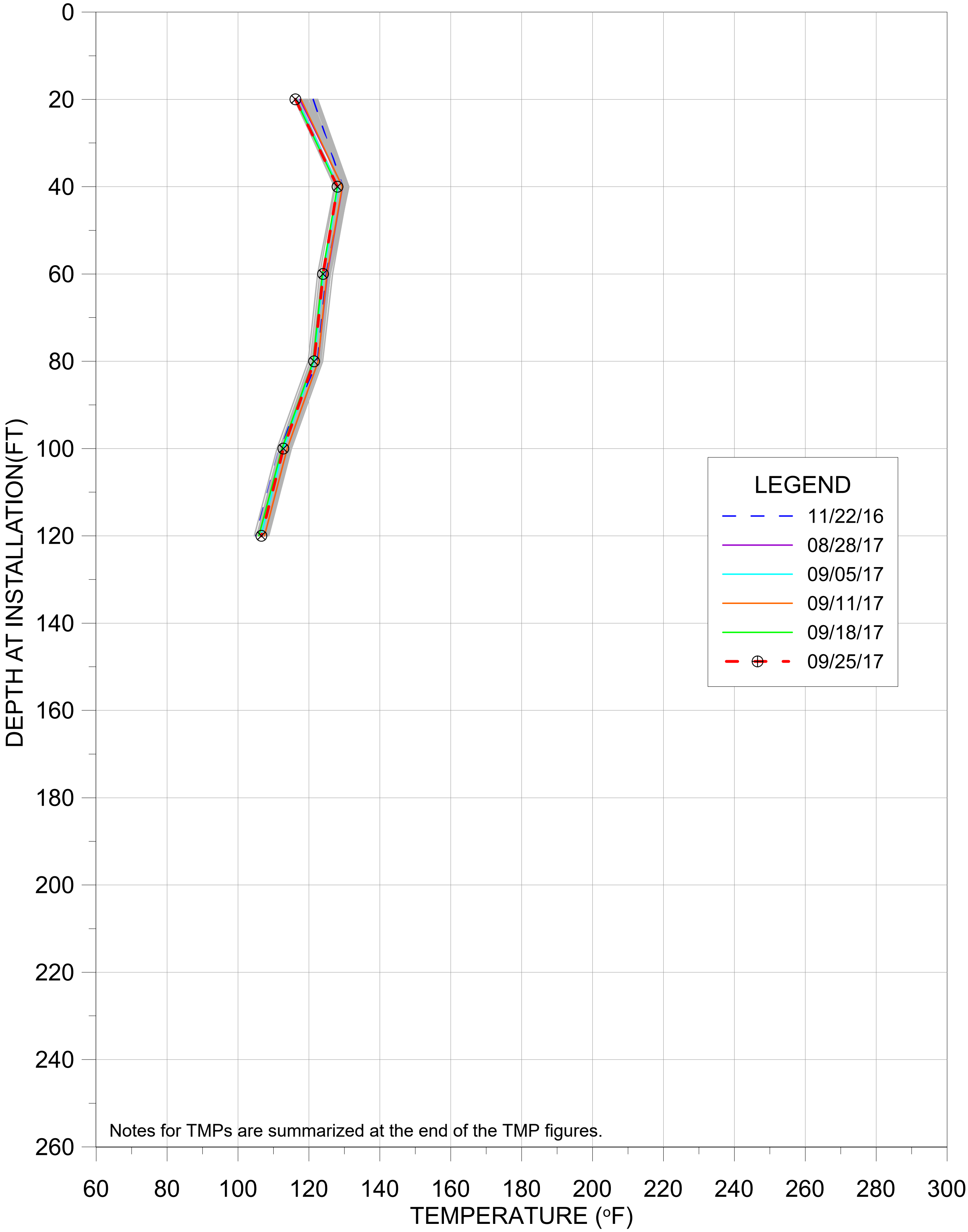
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-9



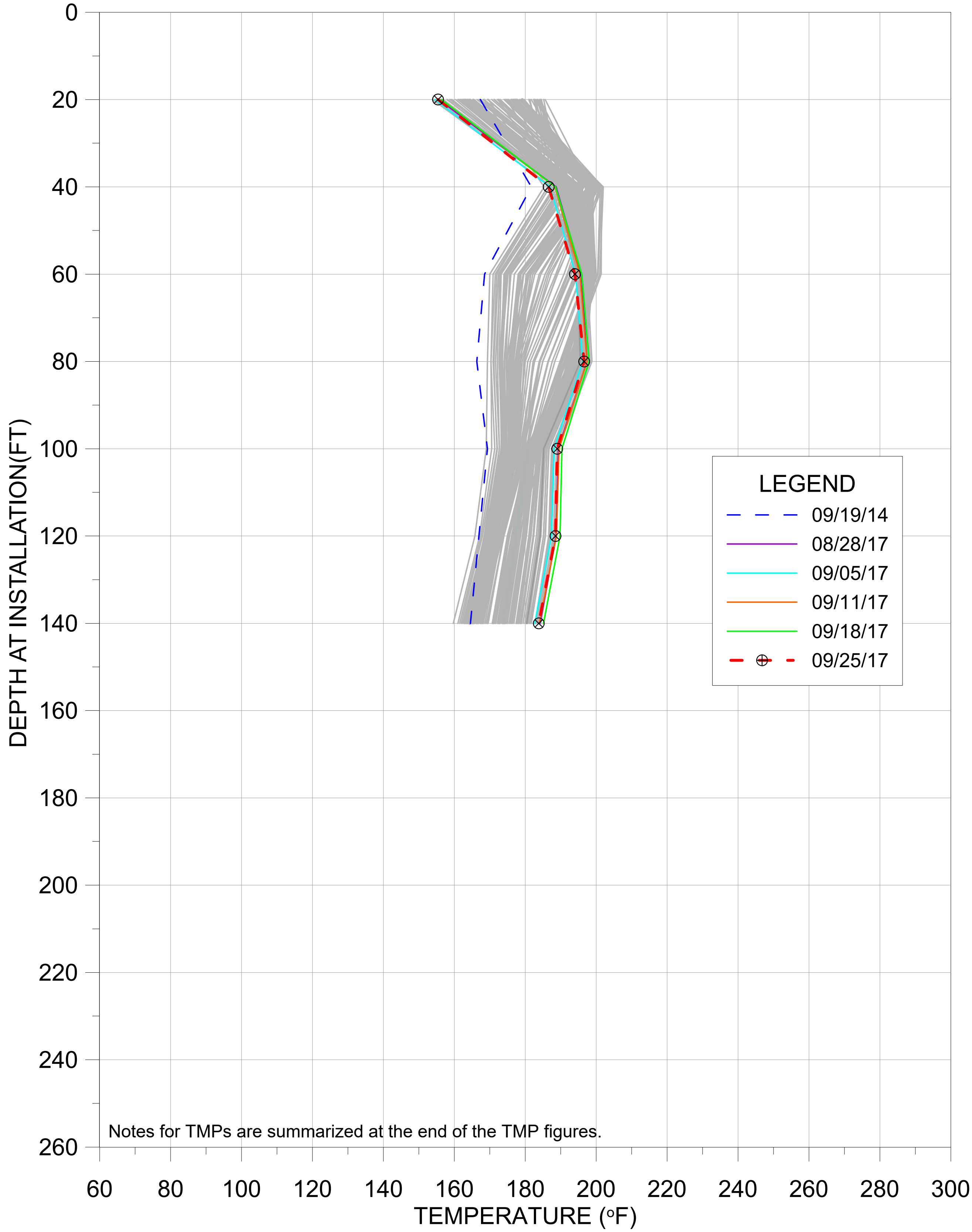
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-11R



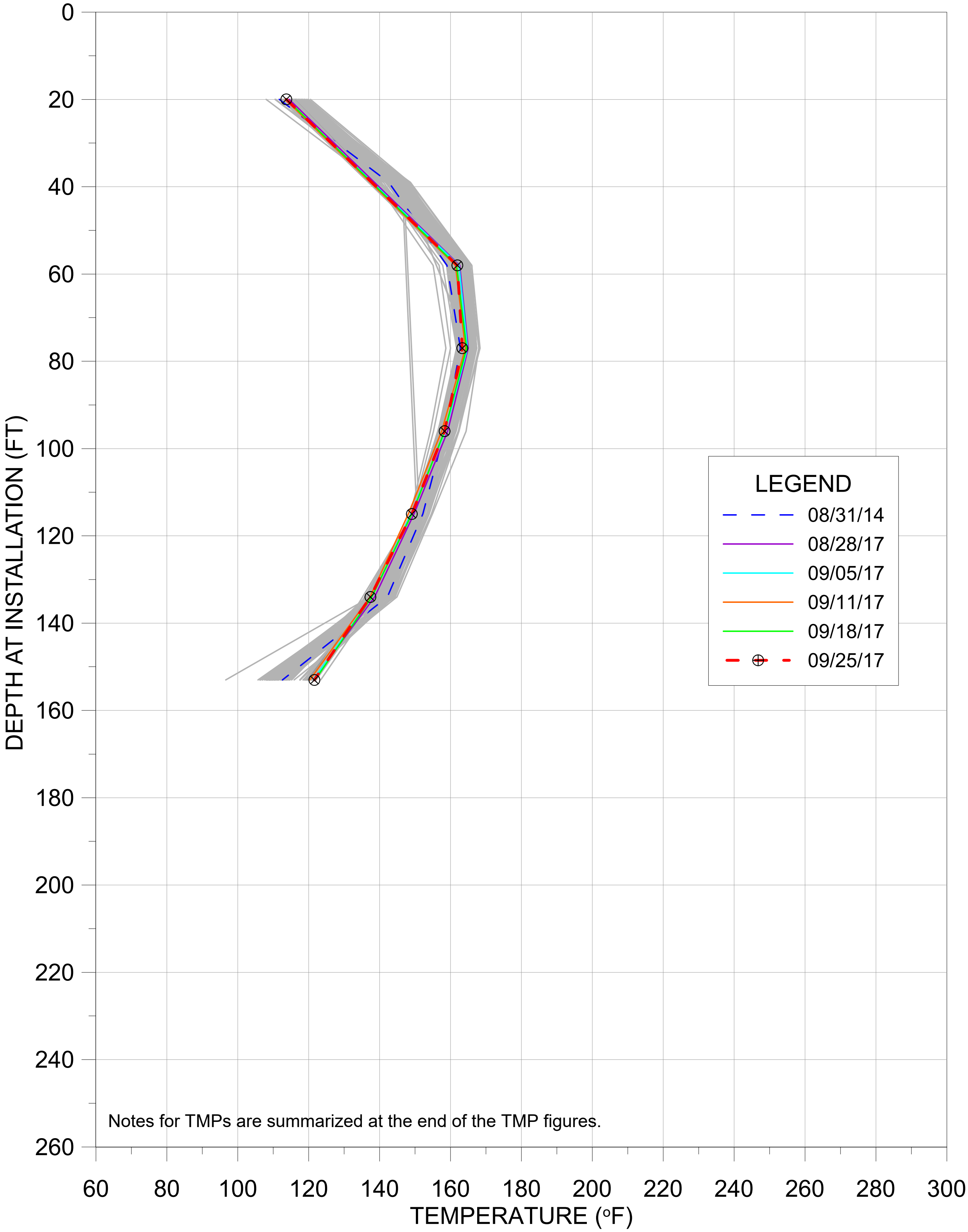
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-14R



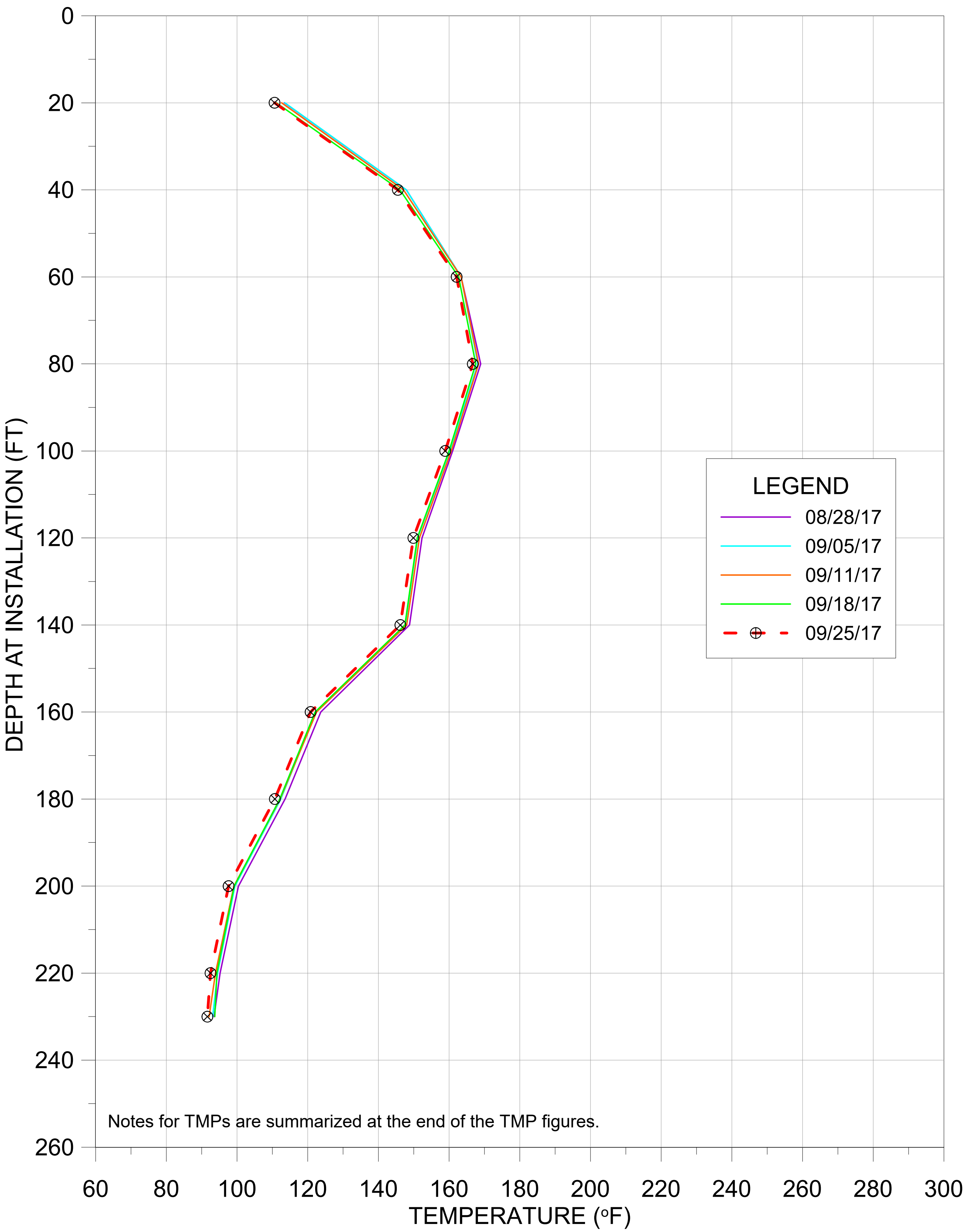
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-16



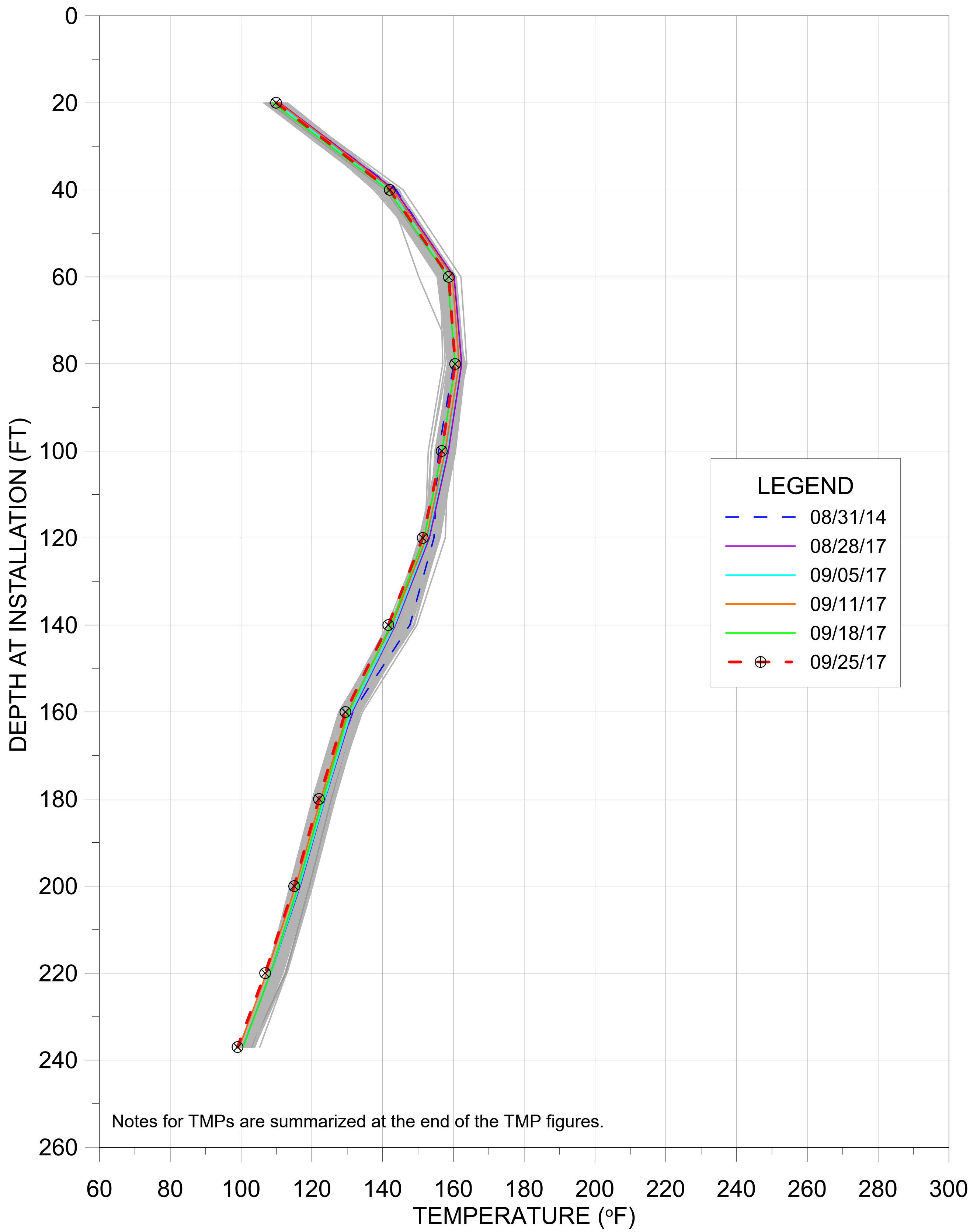
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-16R



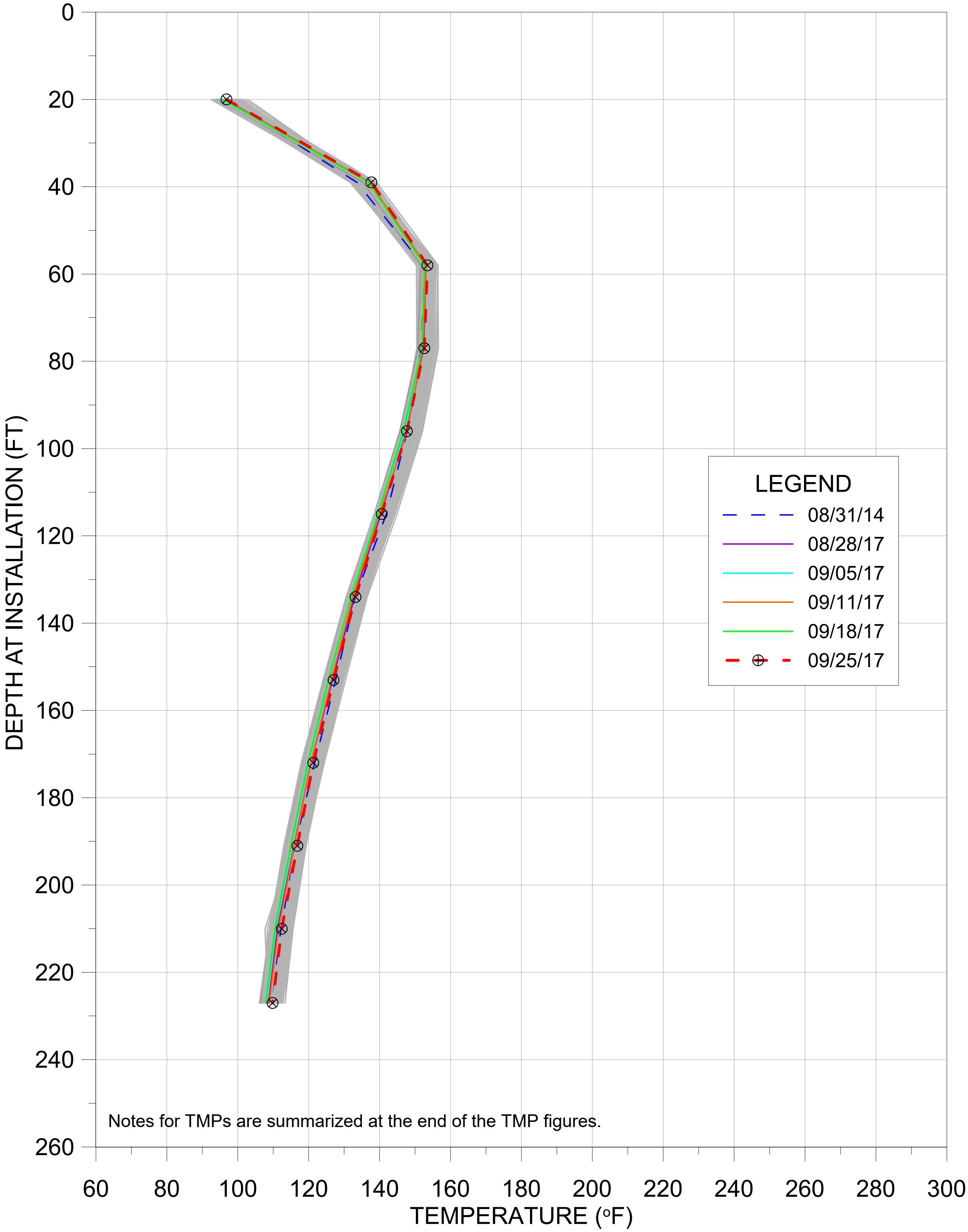
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-17



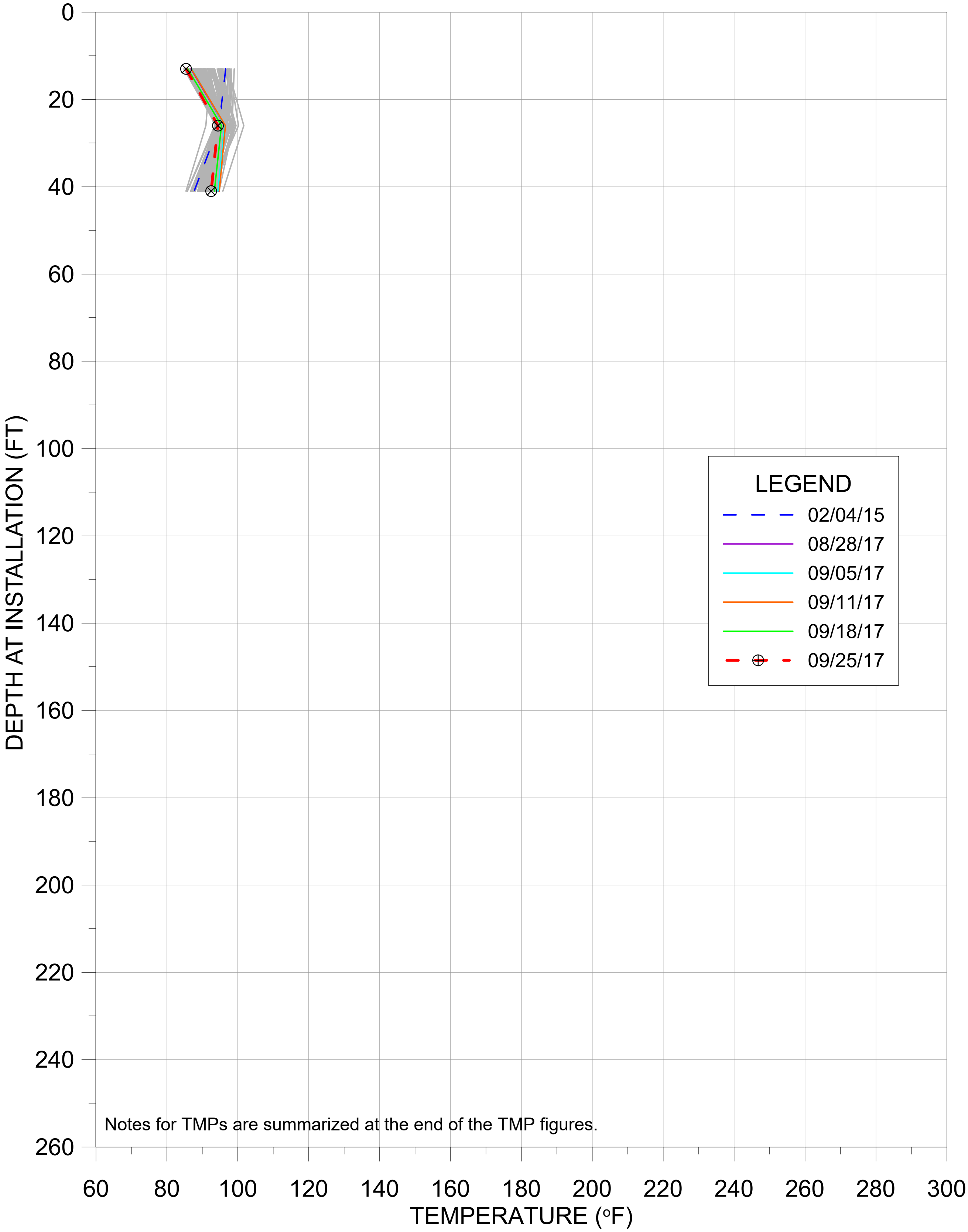
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-18



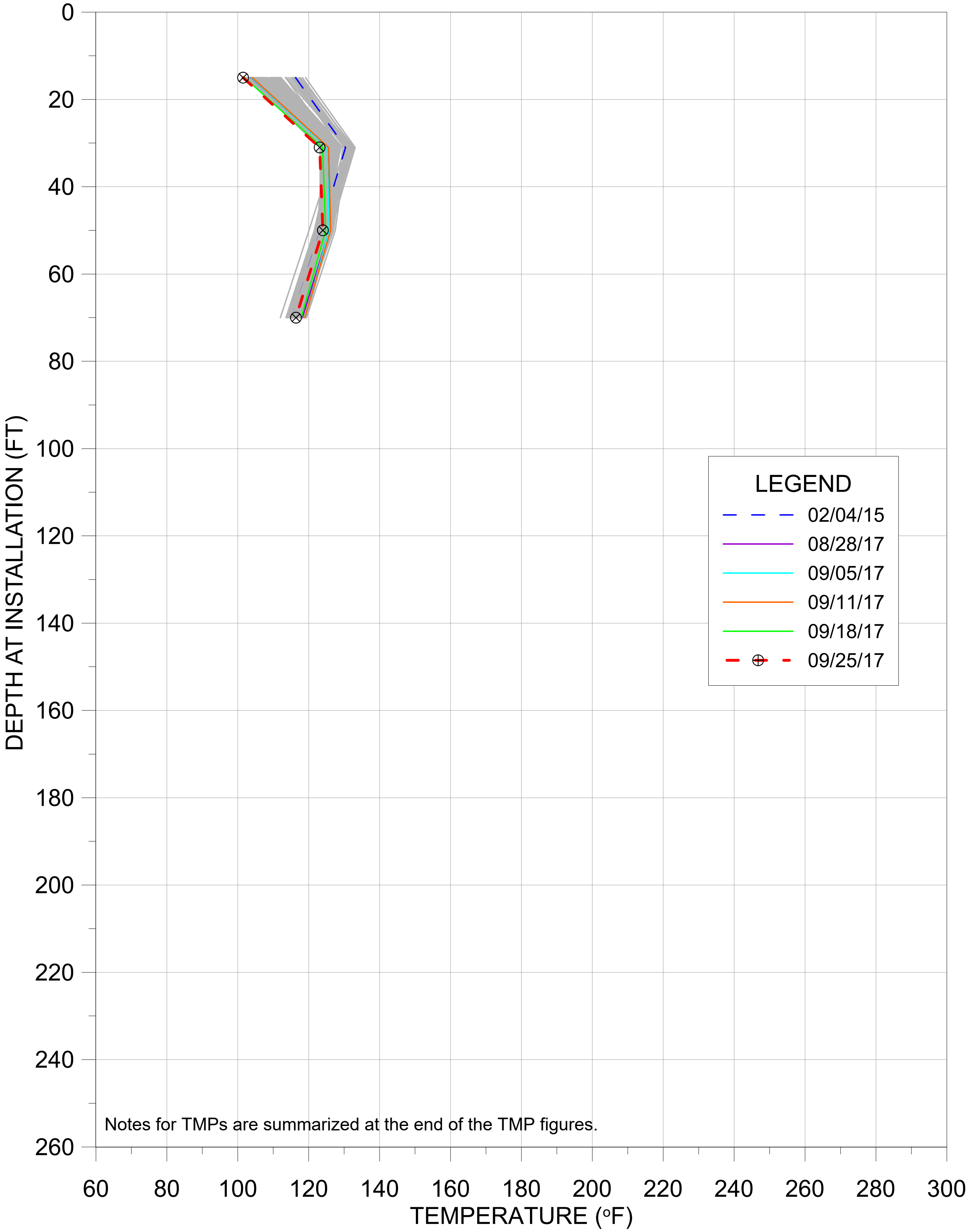
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-21



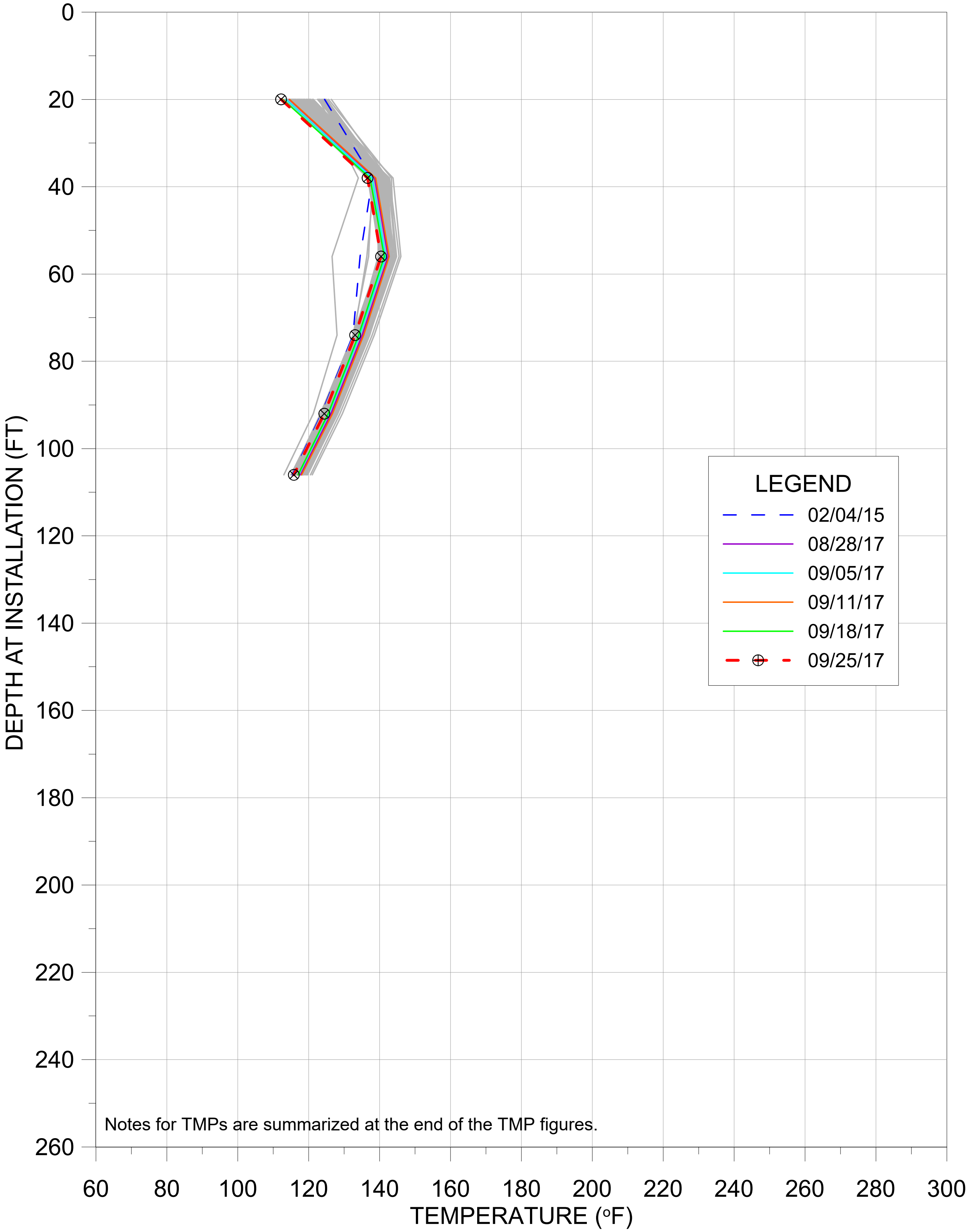
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-22



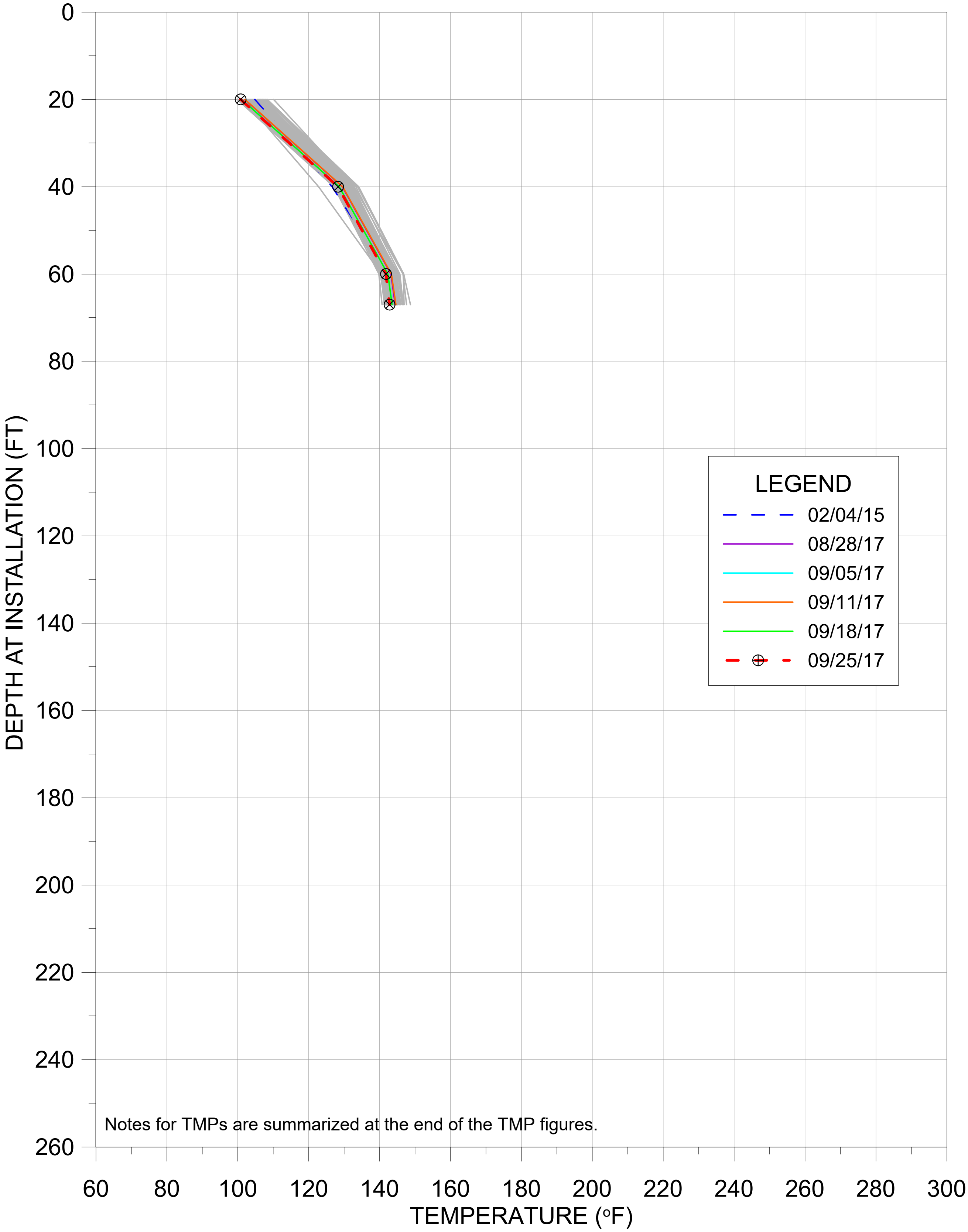
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-23



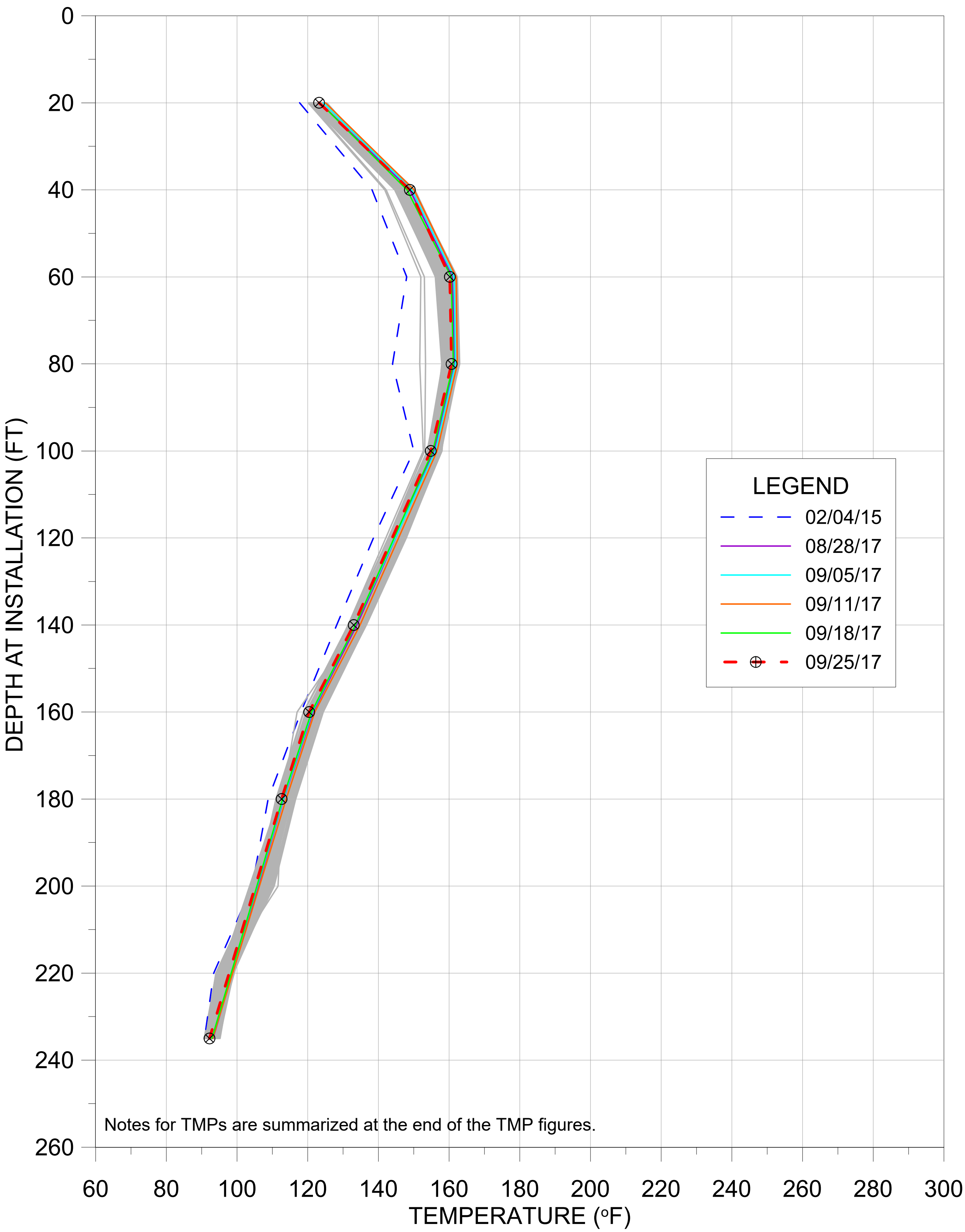
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-24



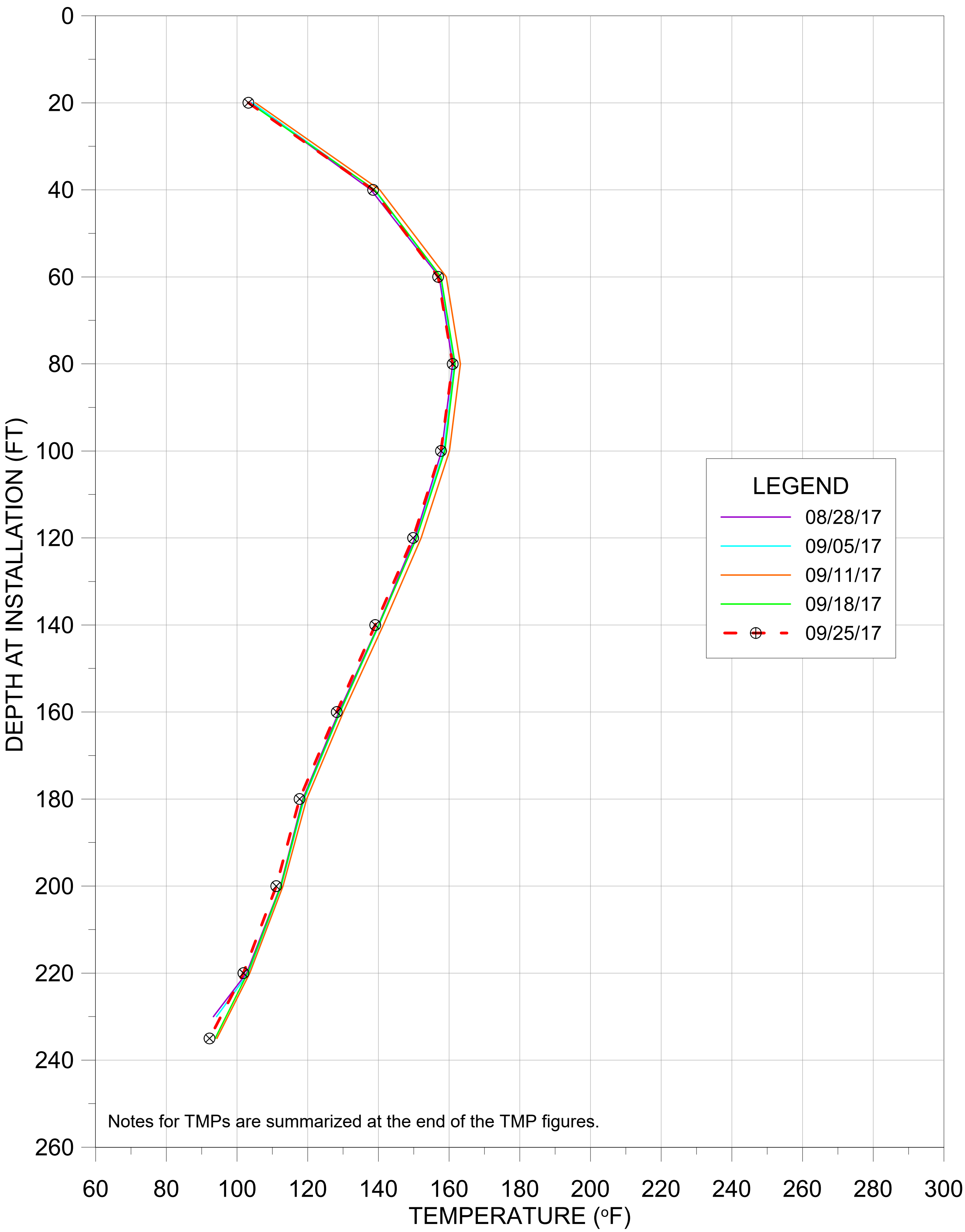
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-25



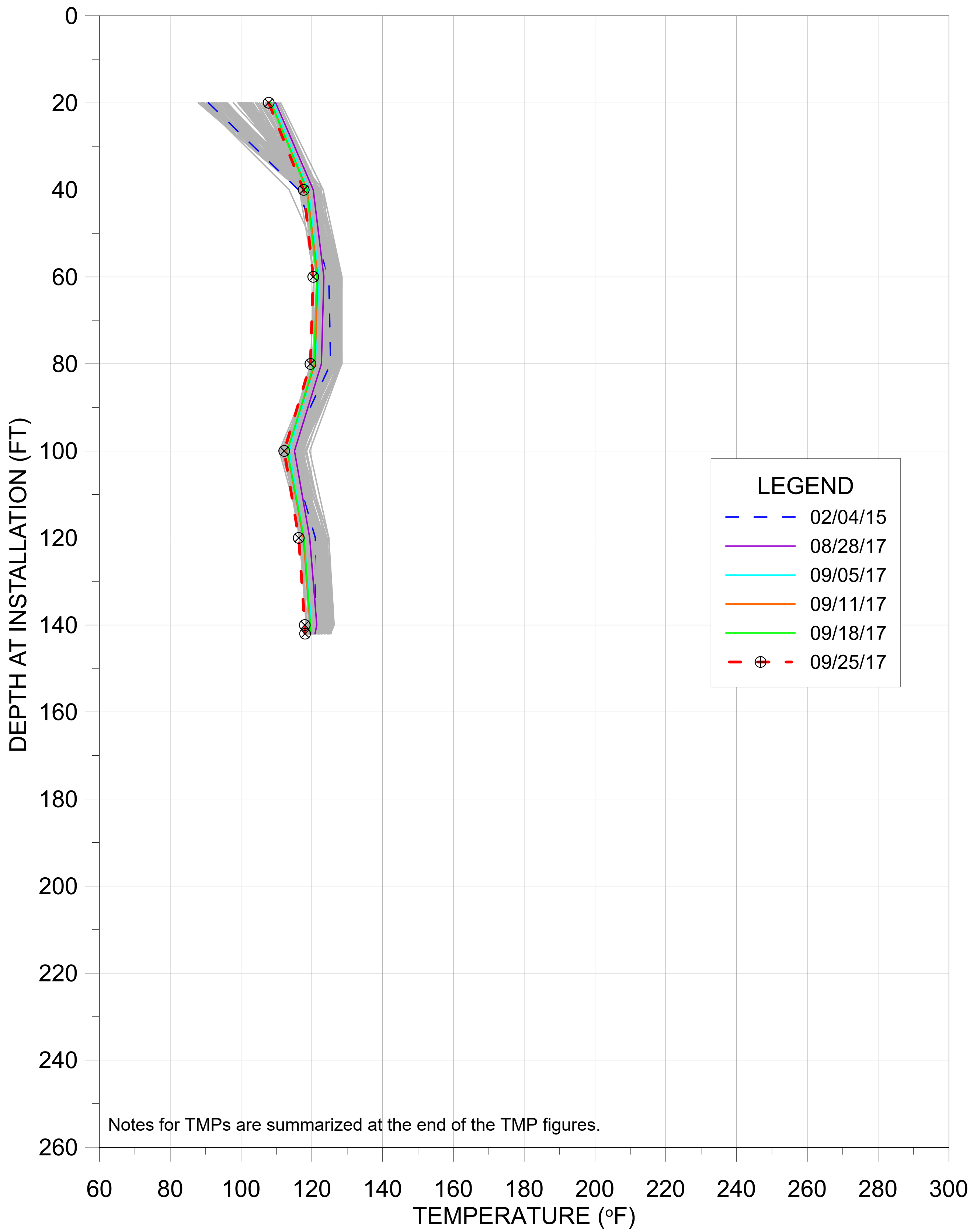
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-25R



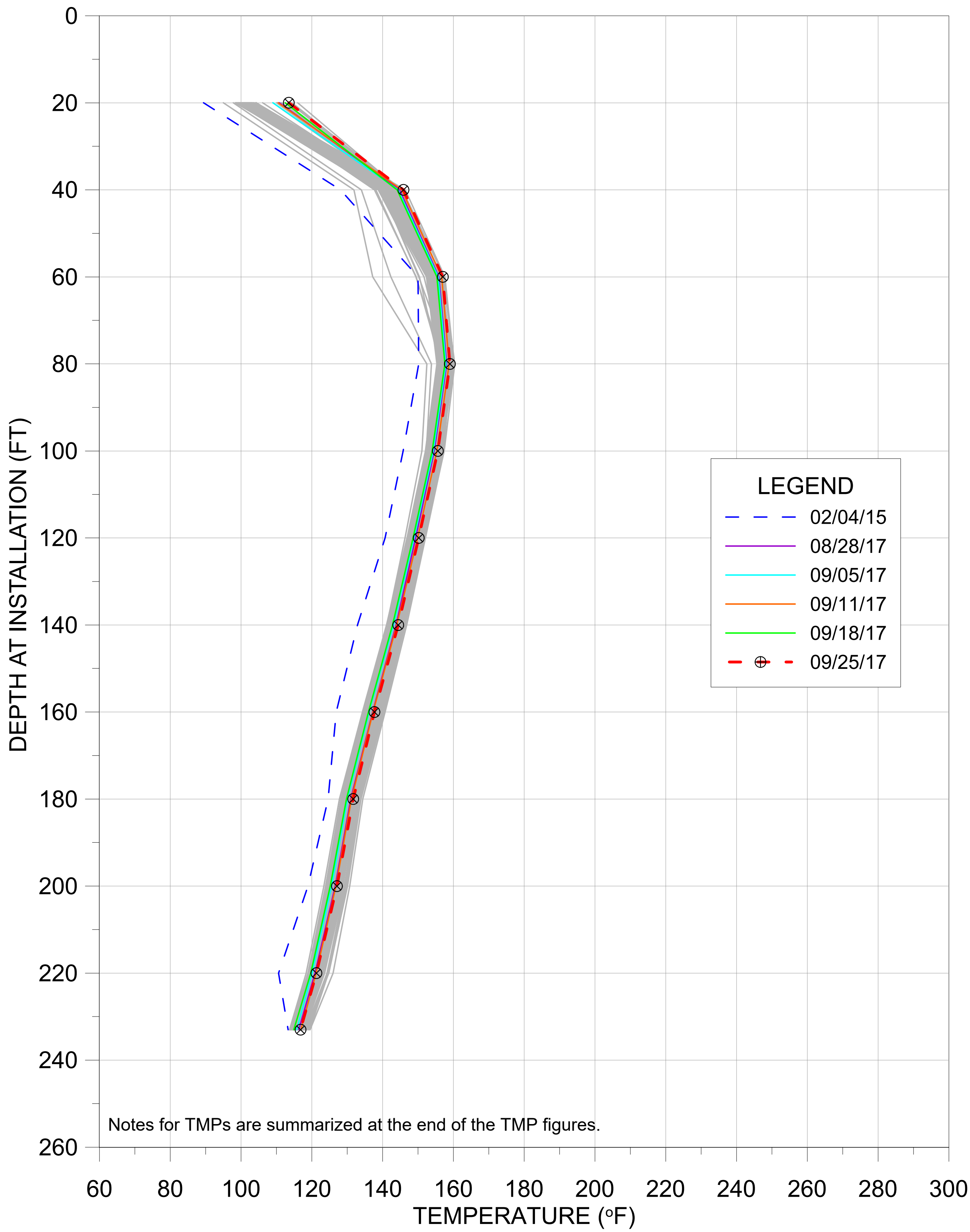
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-26



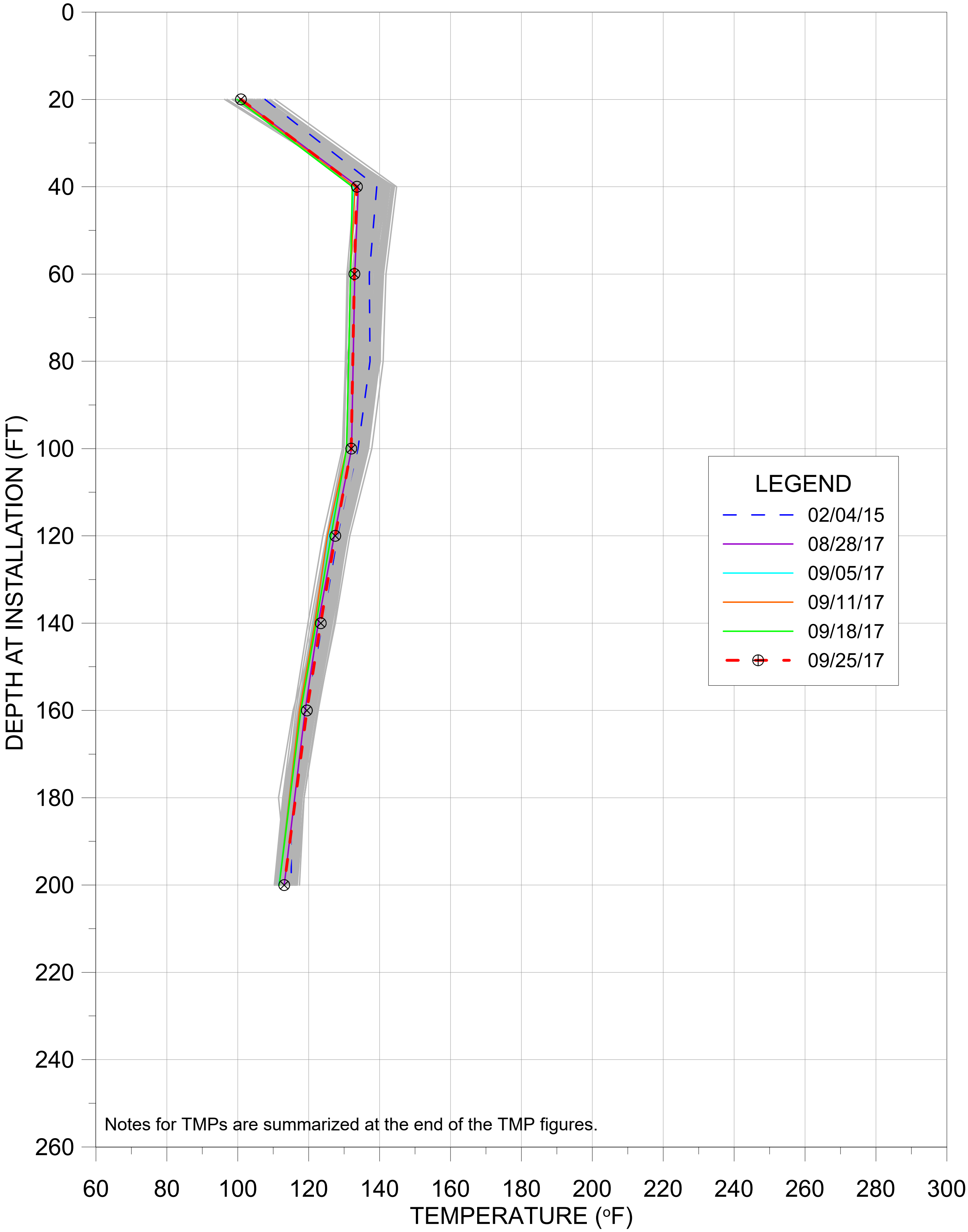
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-27



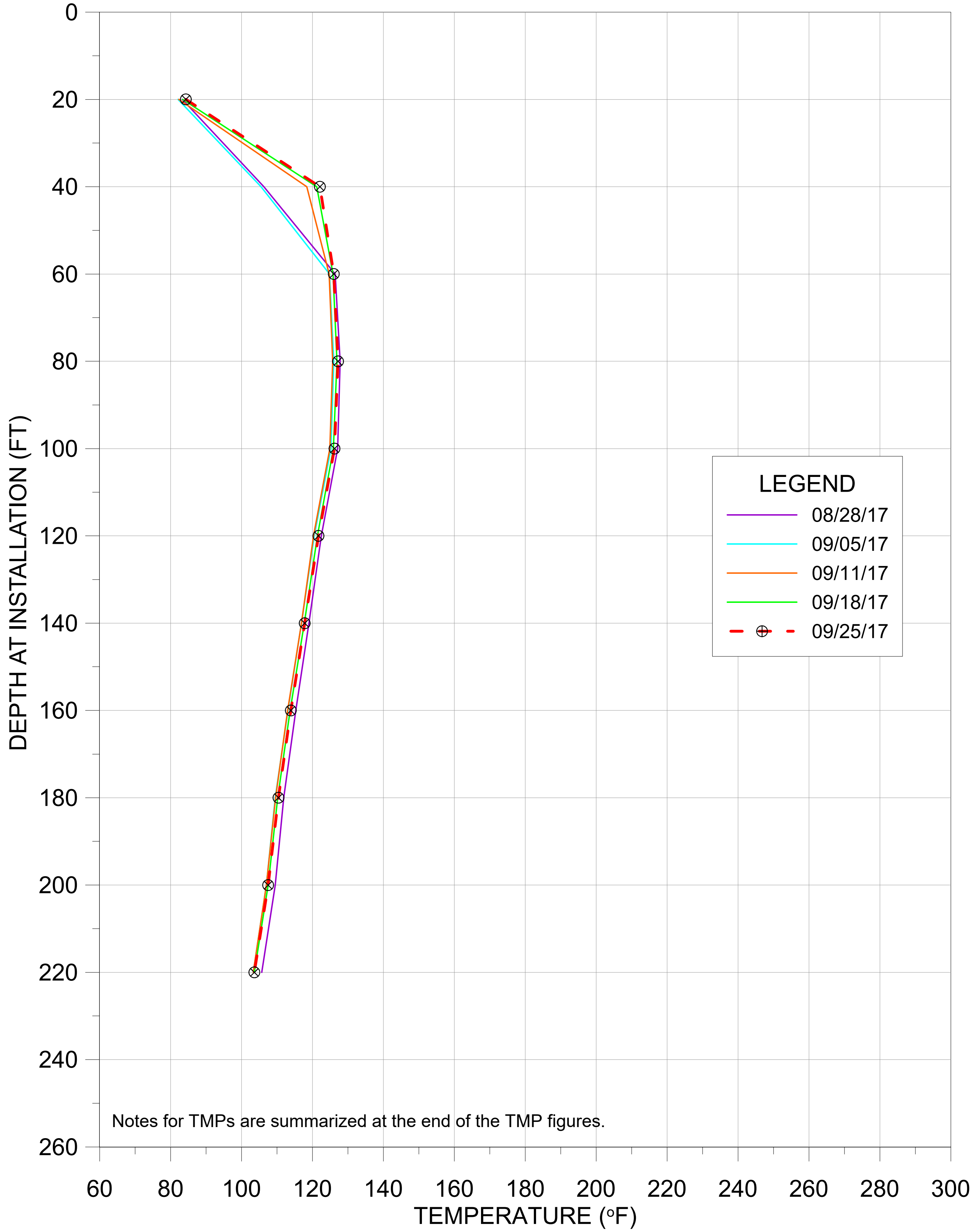
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-28



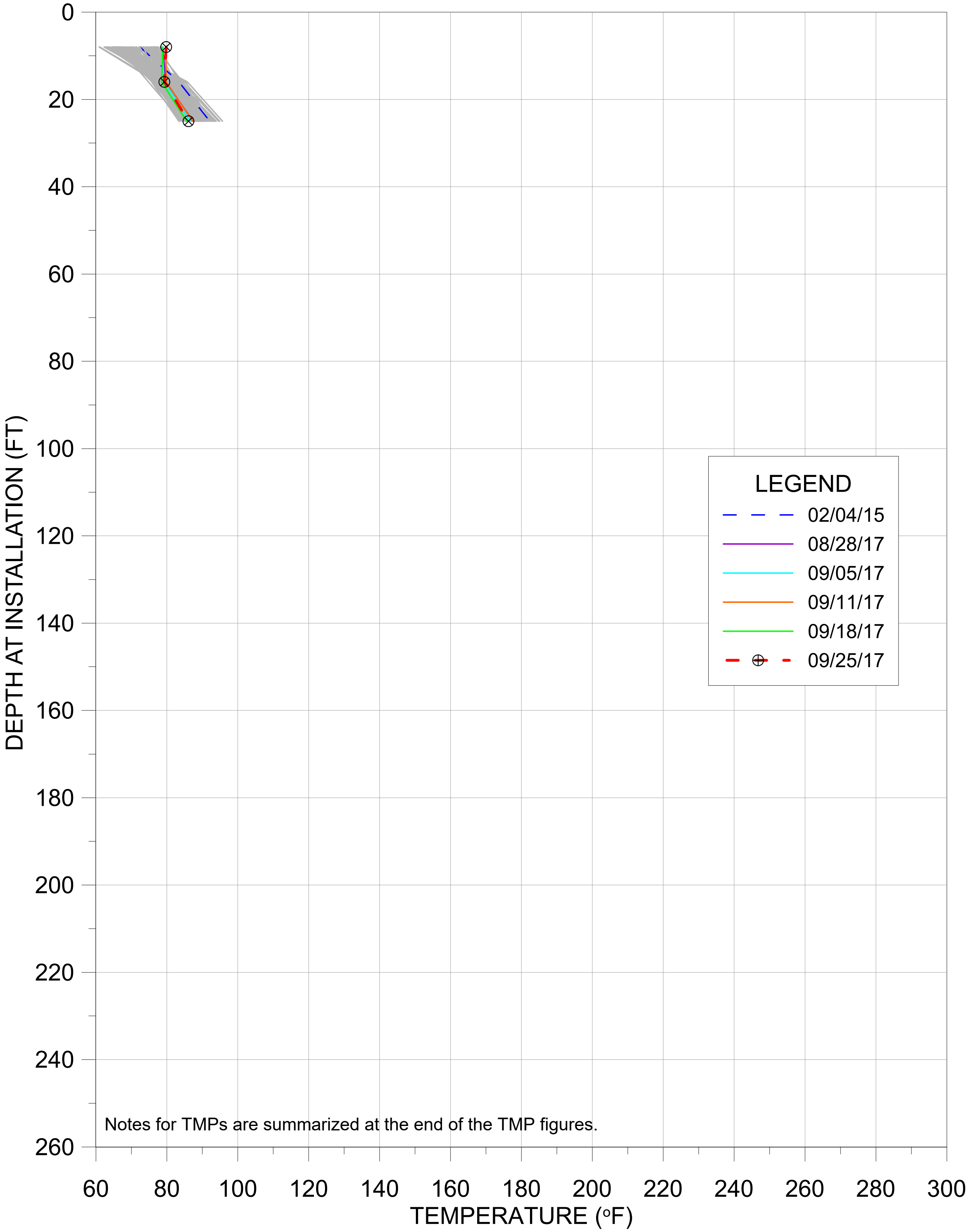
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-28R



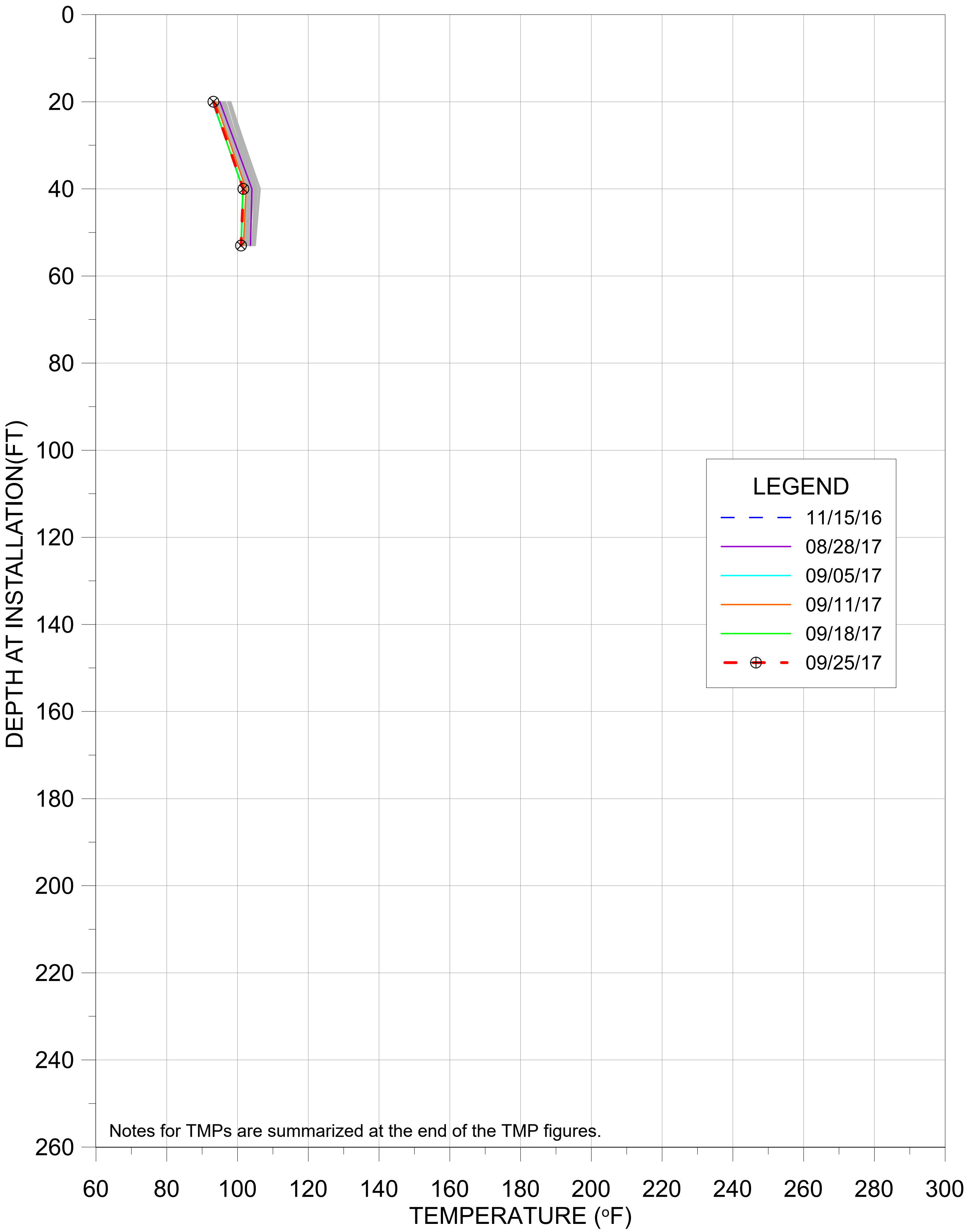
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-29



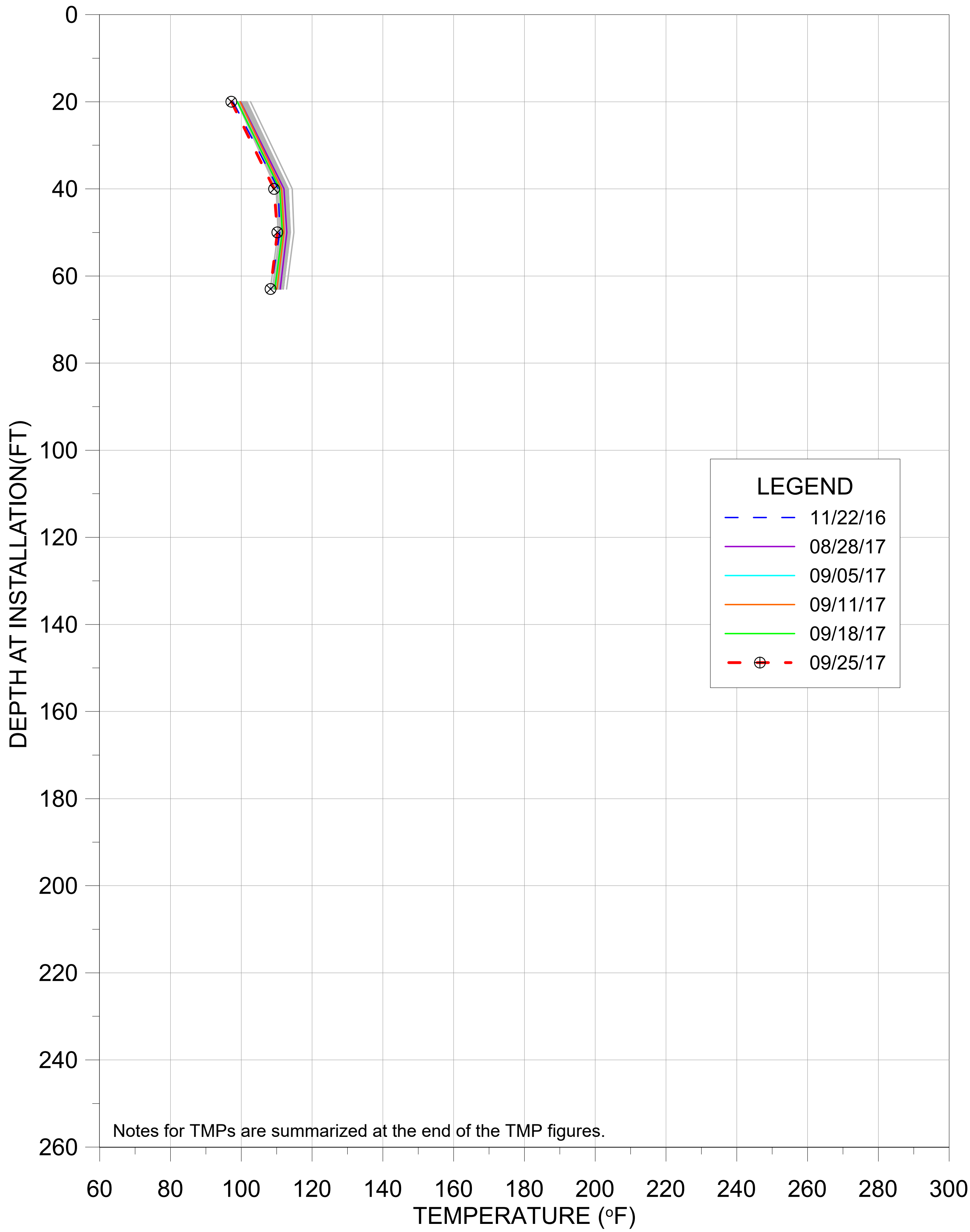
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-33



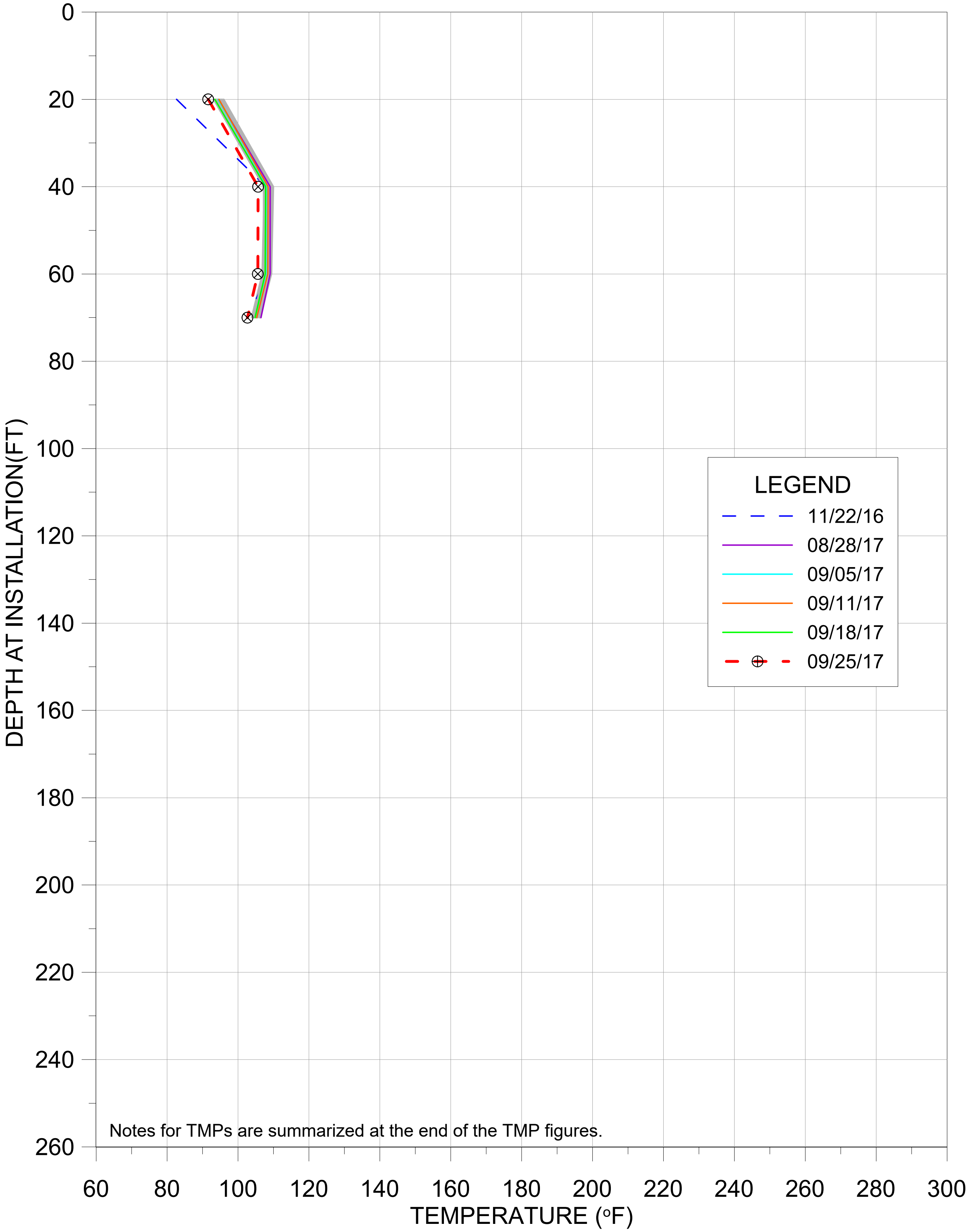
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-34



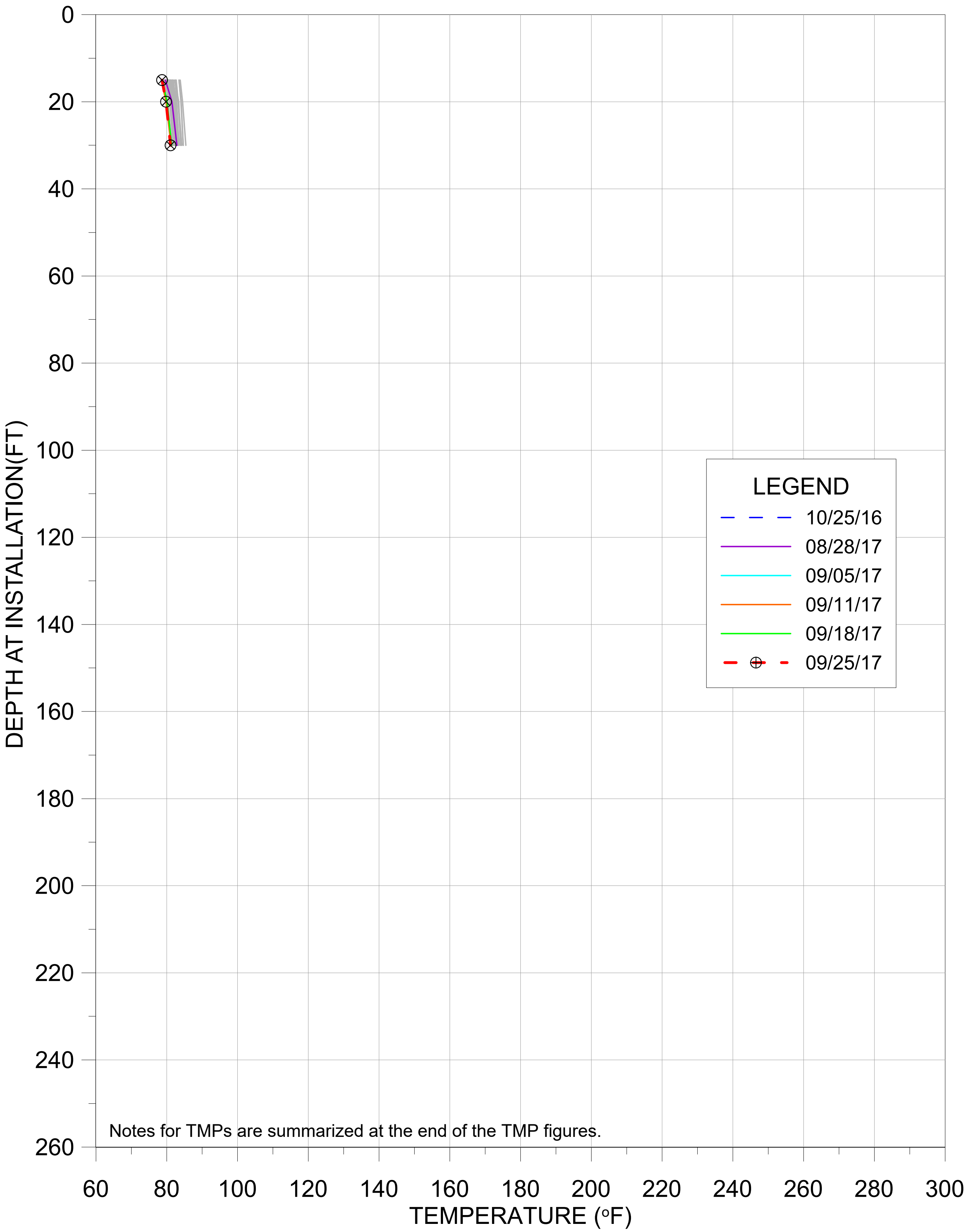
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-35



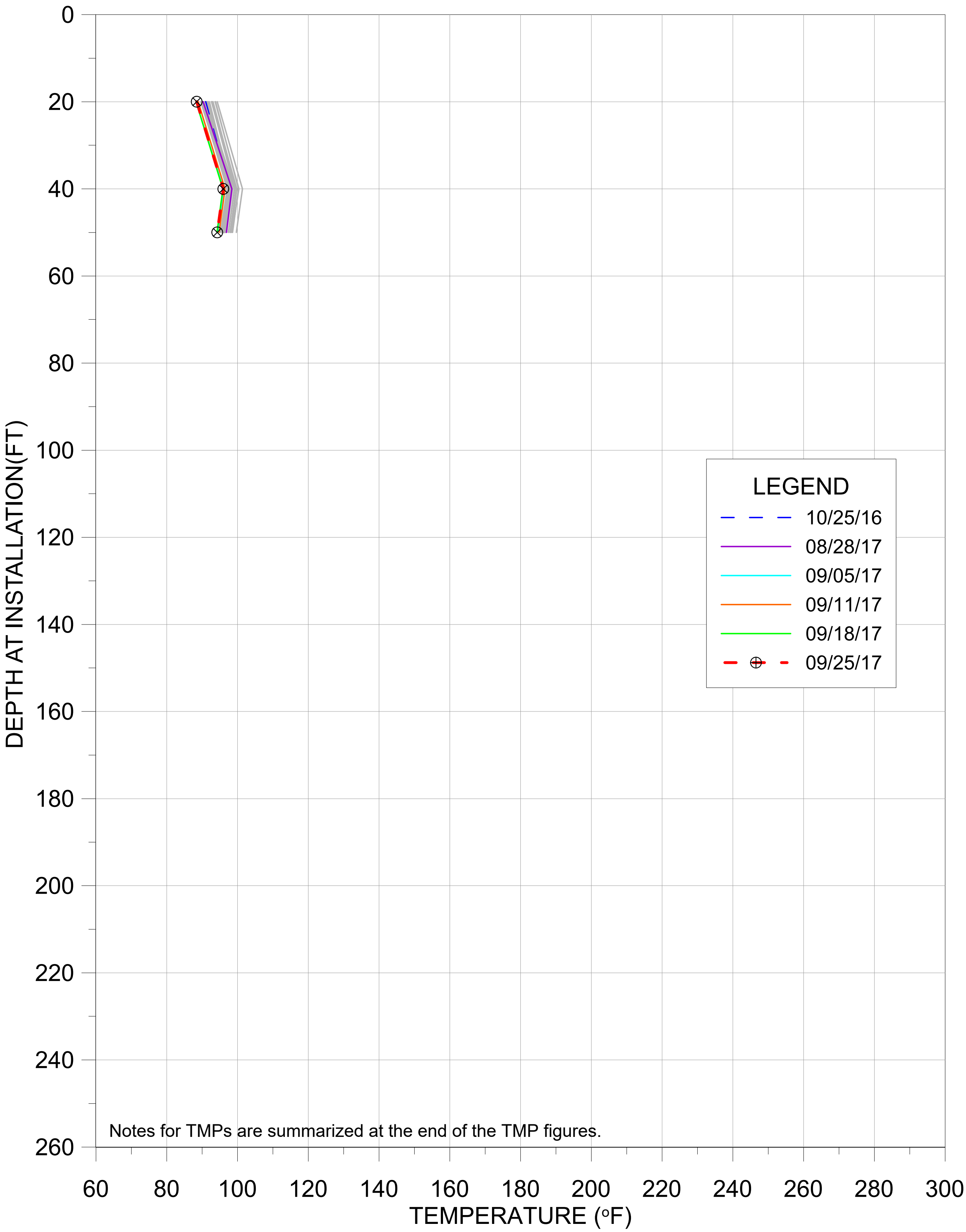
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-36



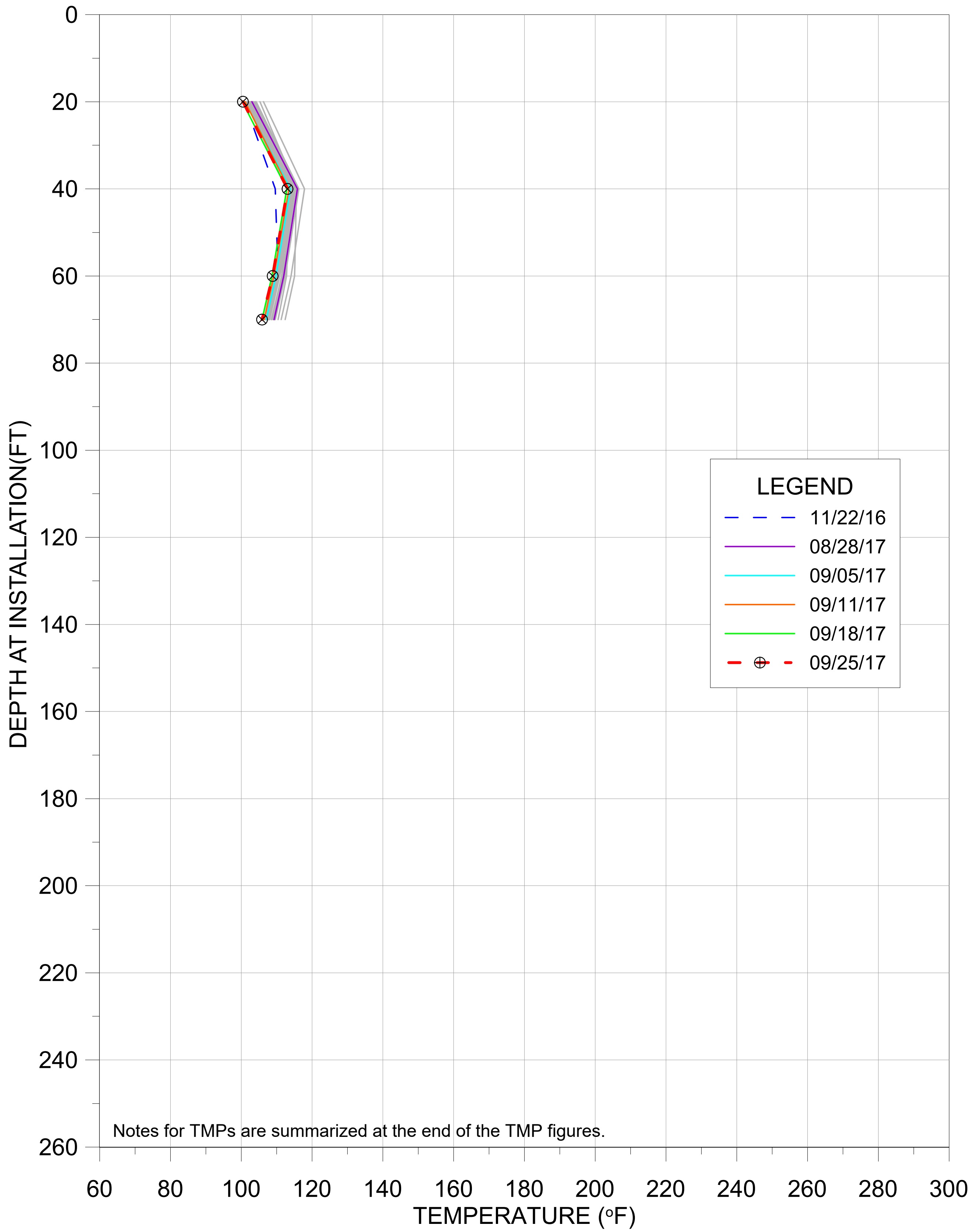
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-37



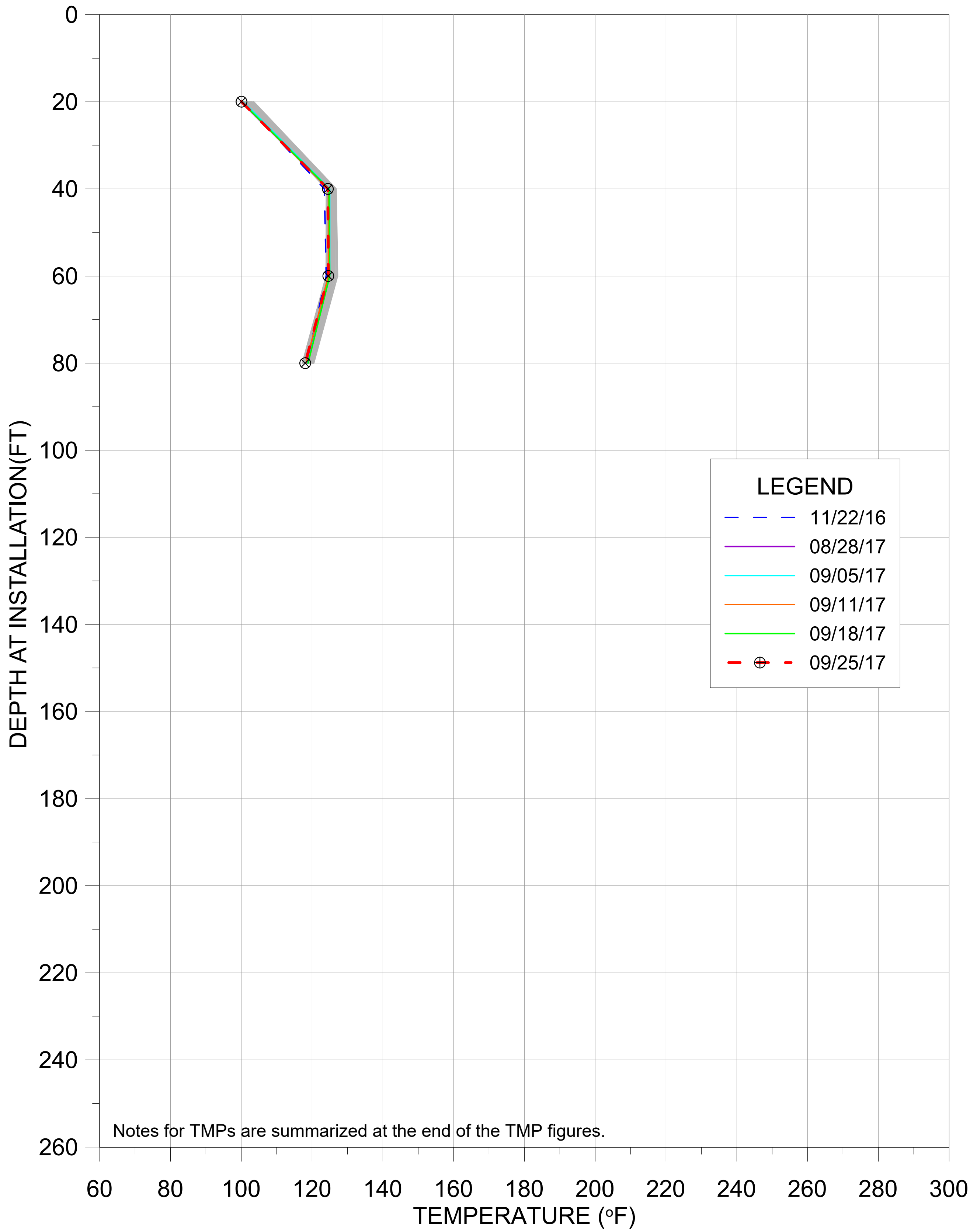
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-38



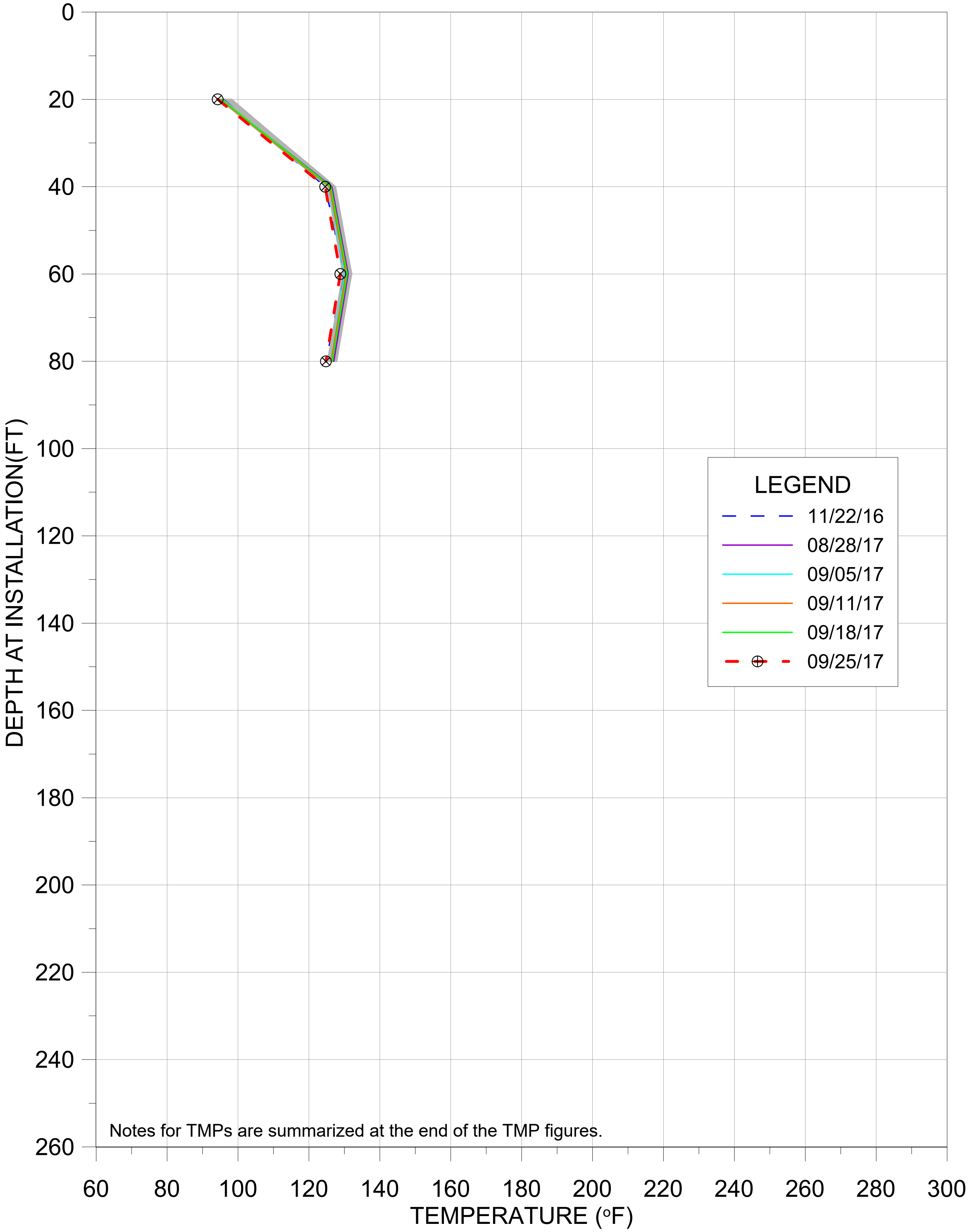
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-39

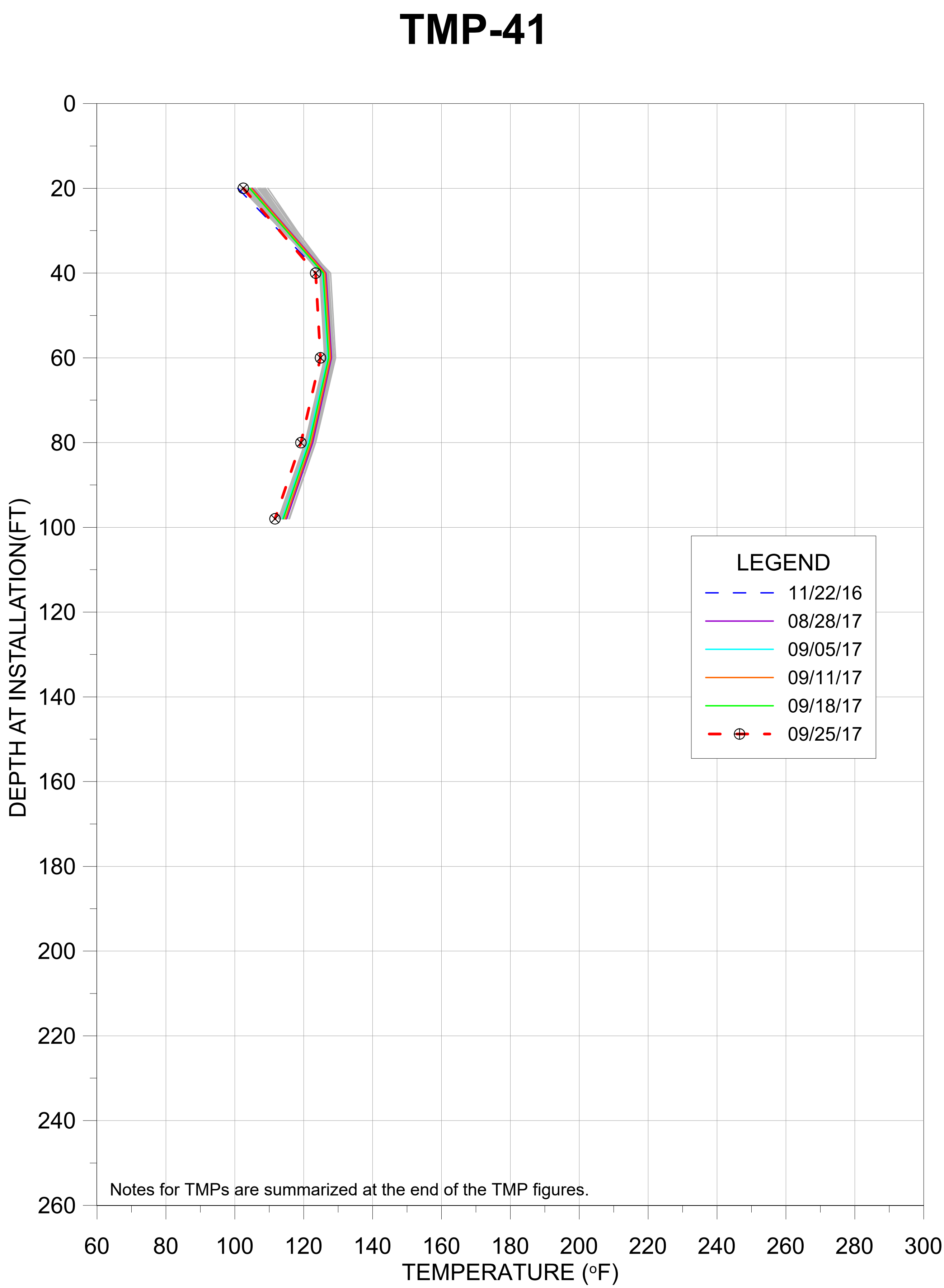


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-40

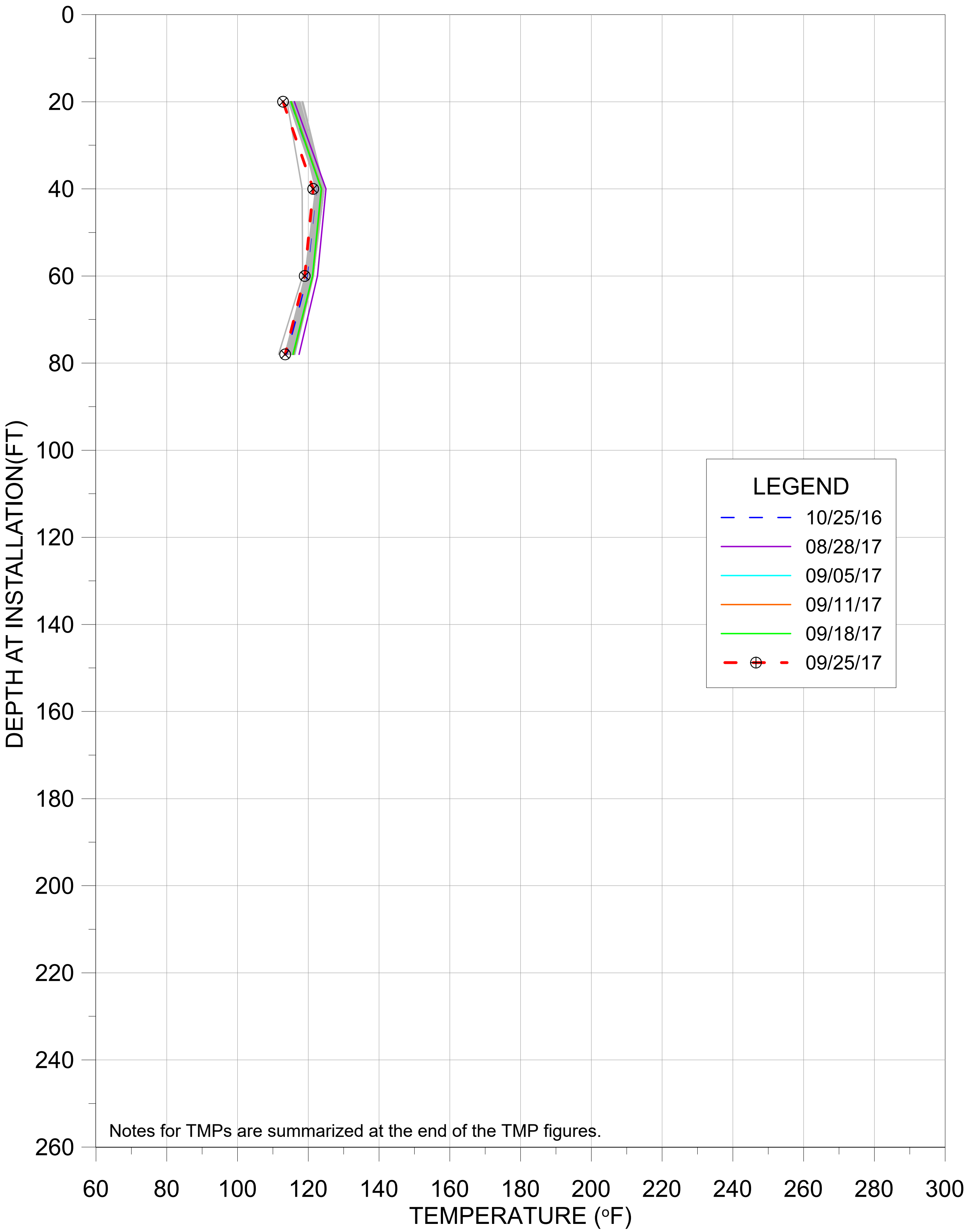


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL



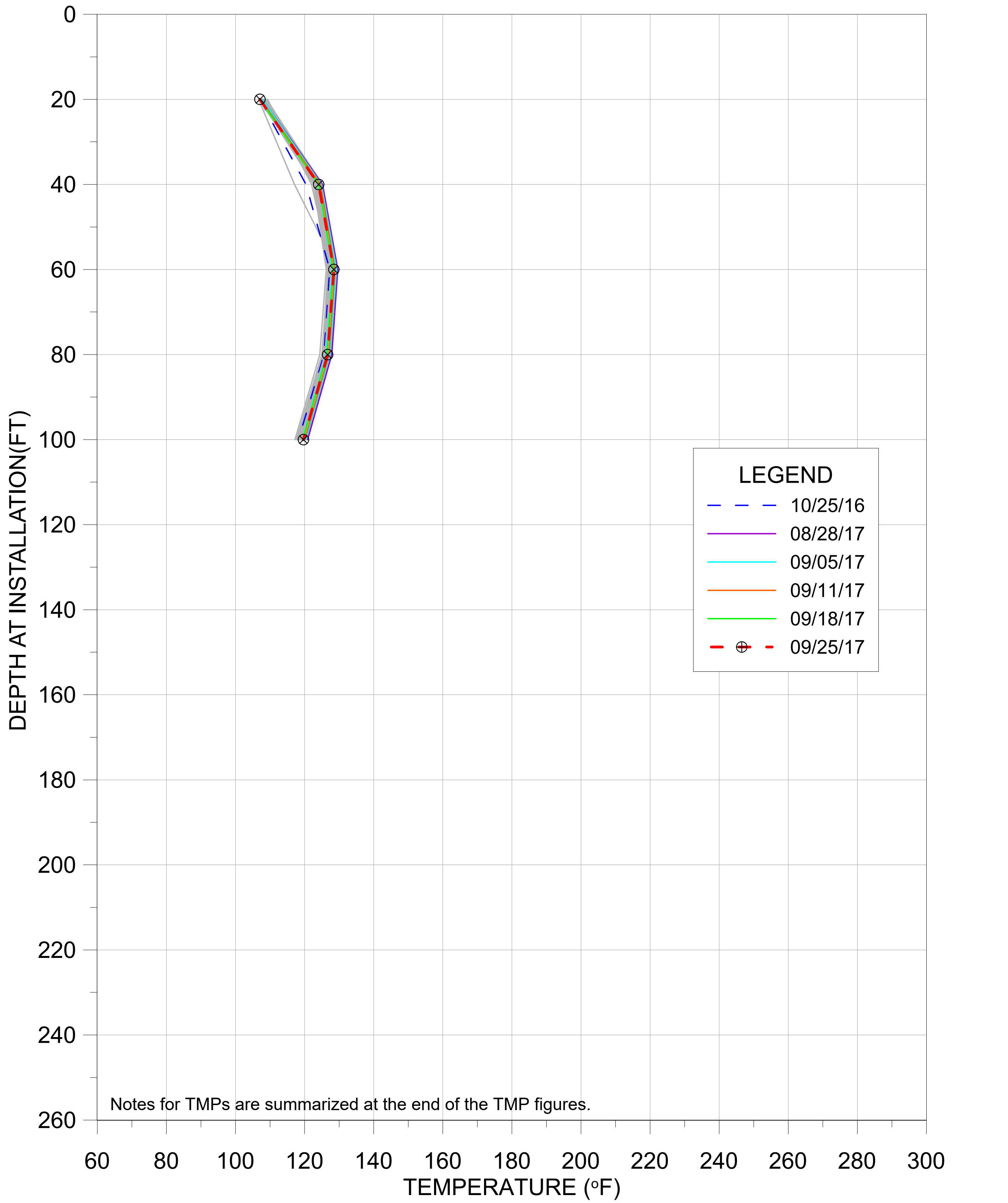
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-42



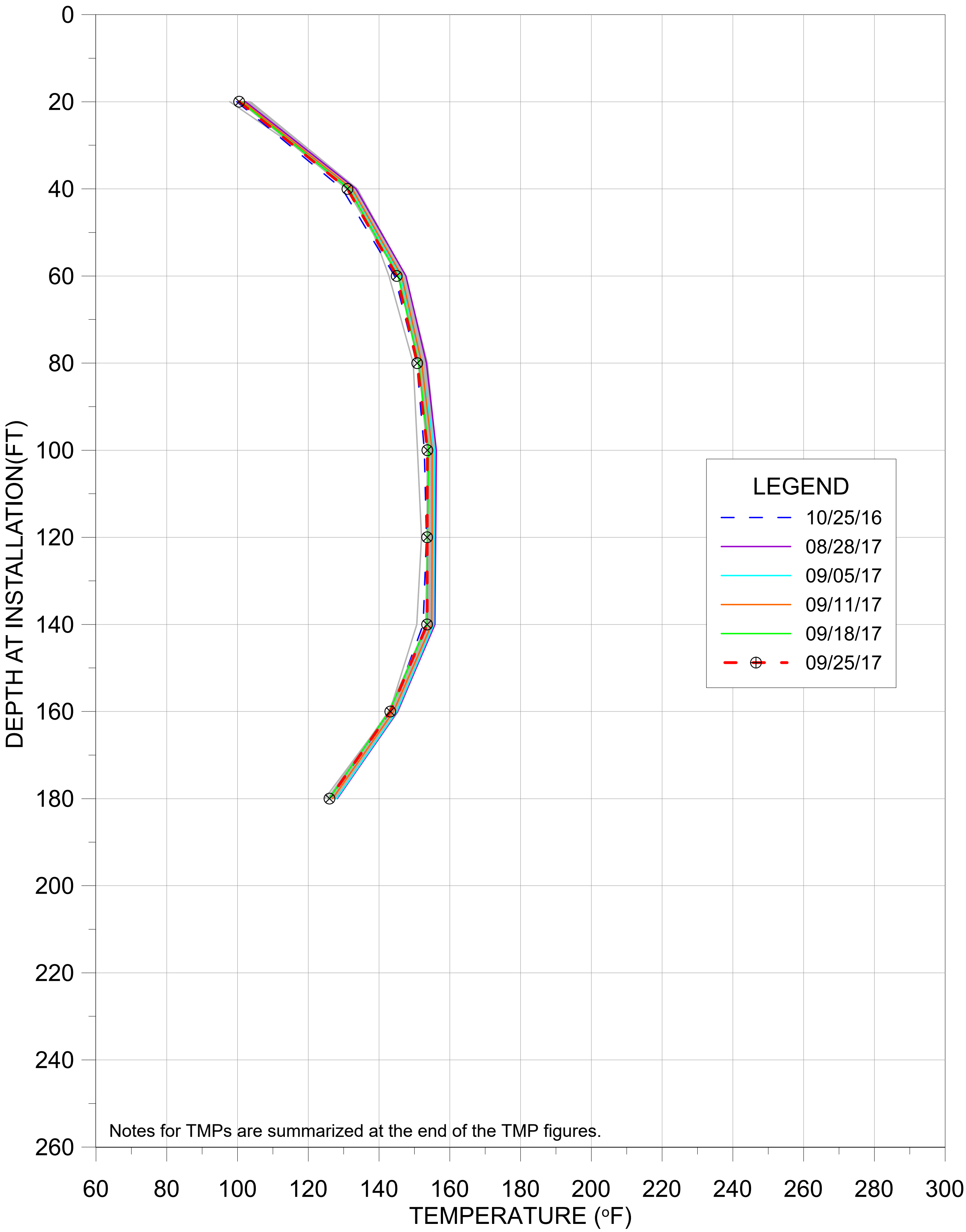
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-43



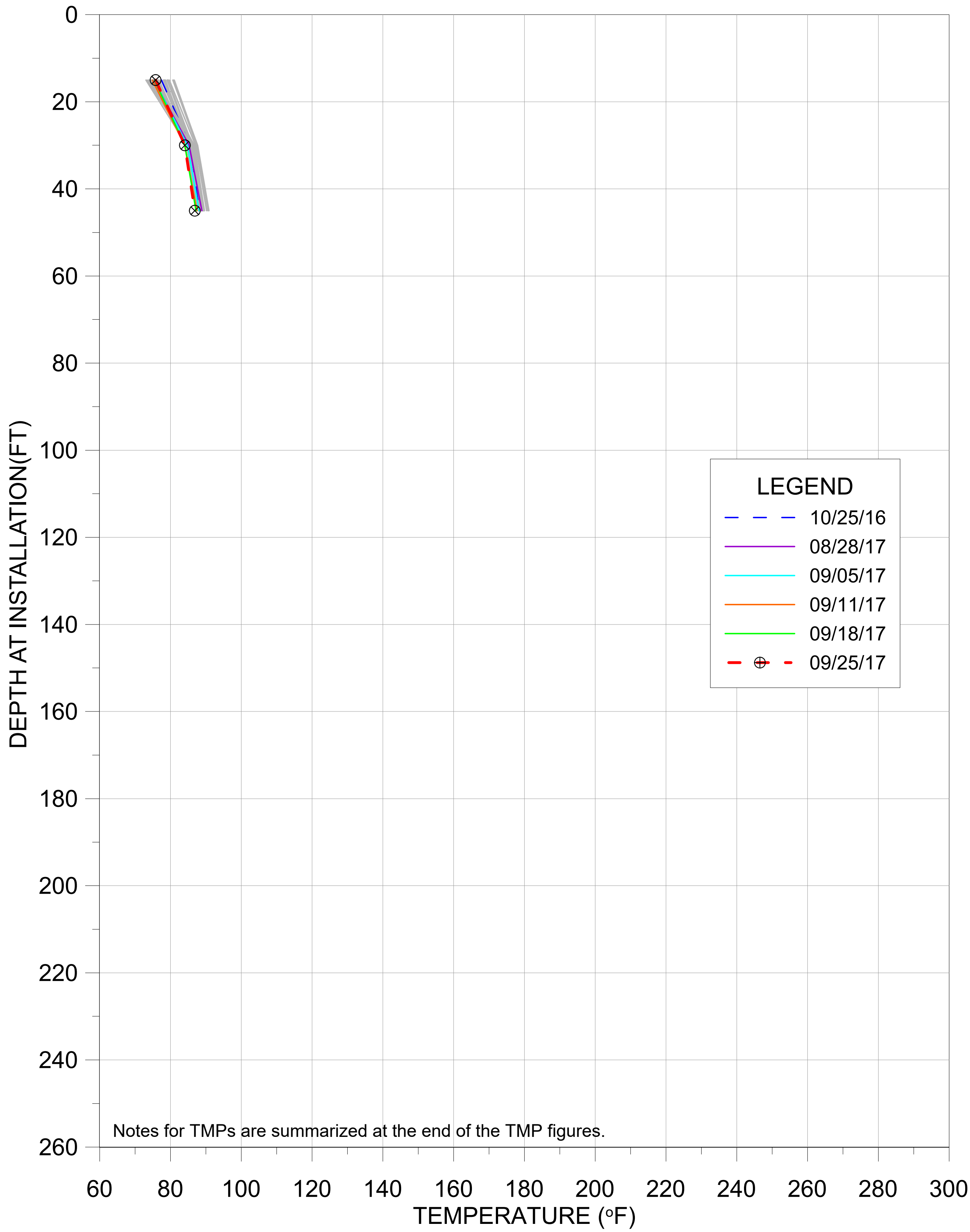
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-44



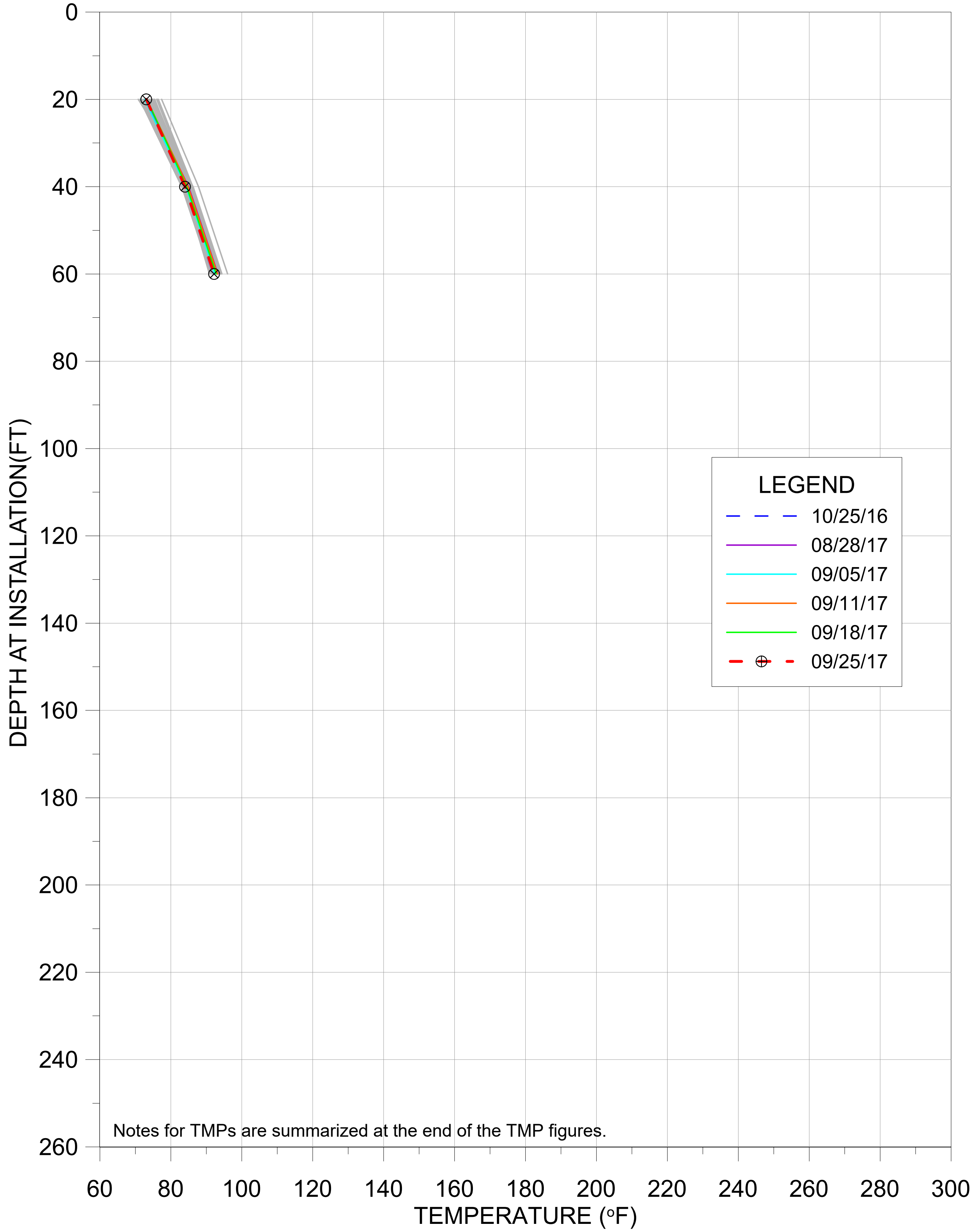
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-45

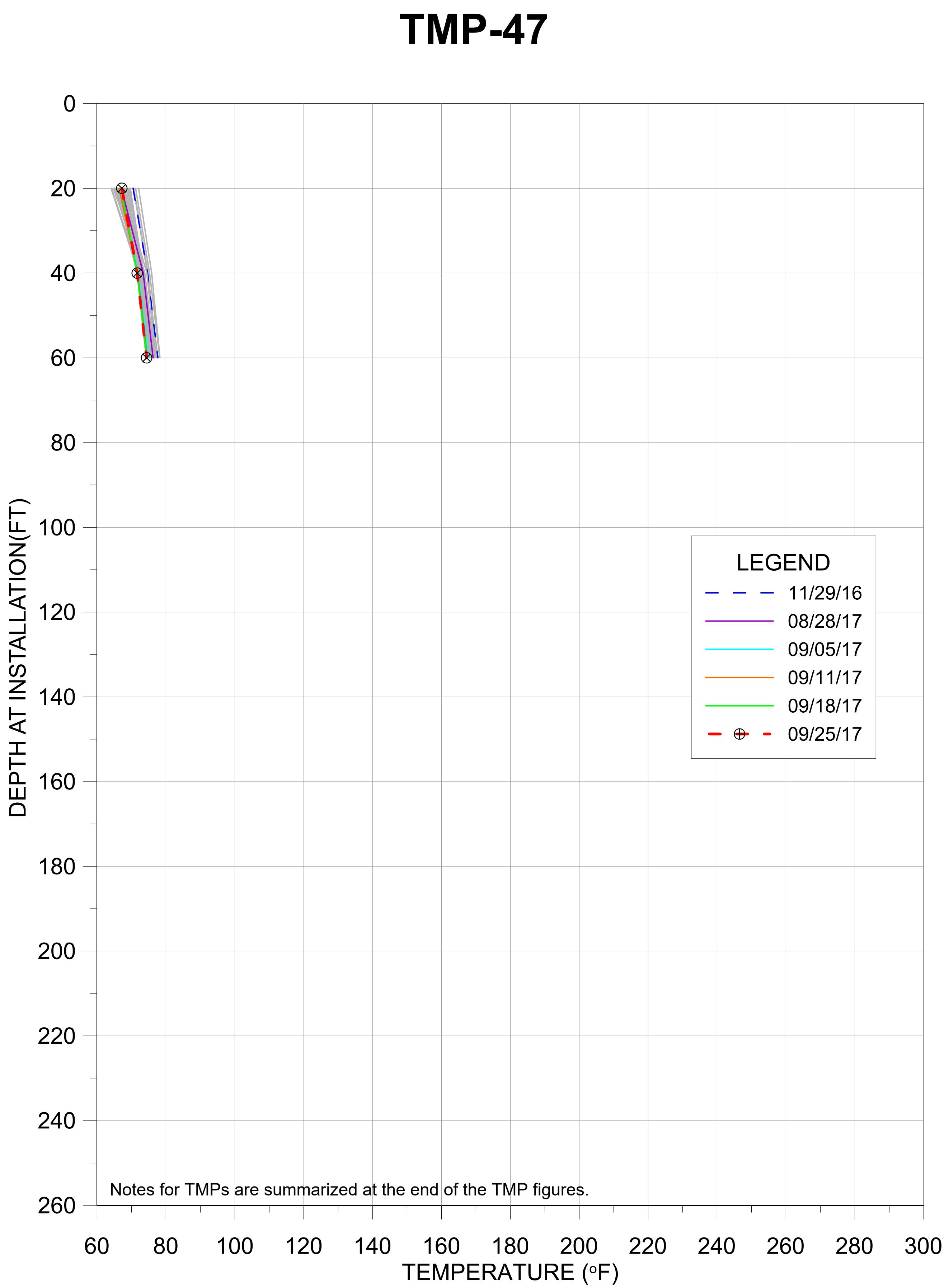


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-46

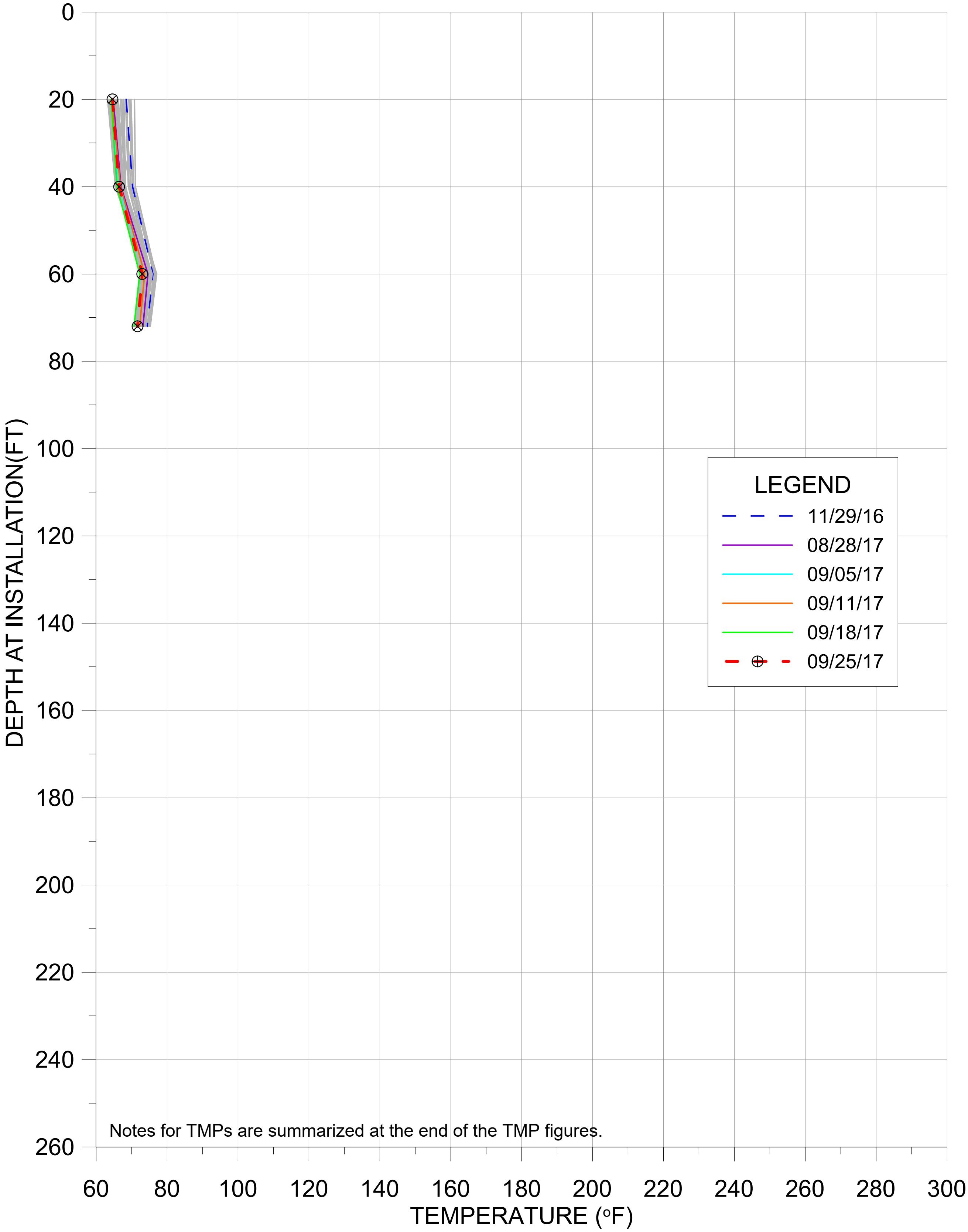


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL



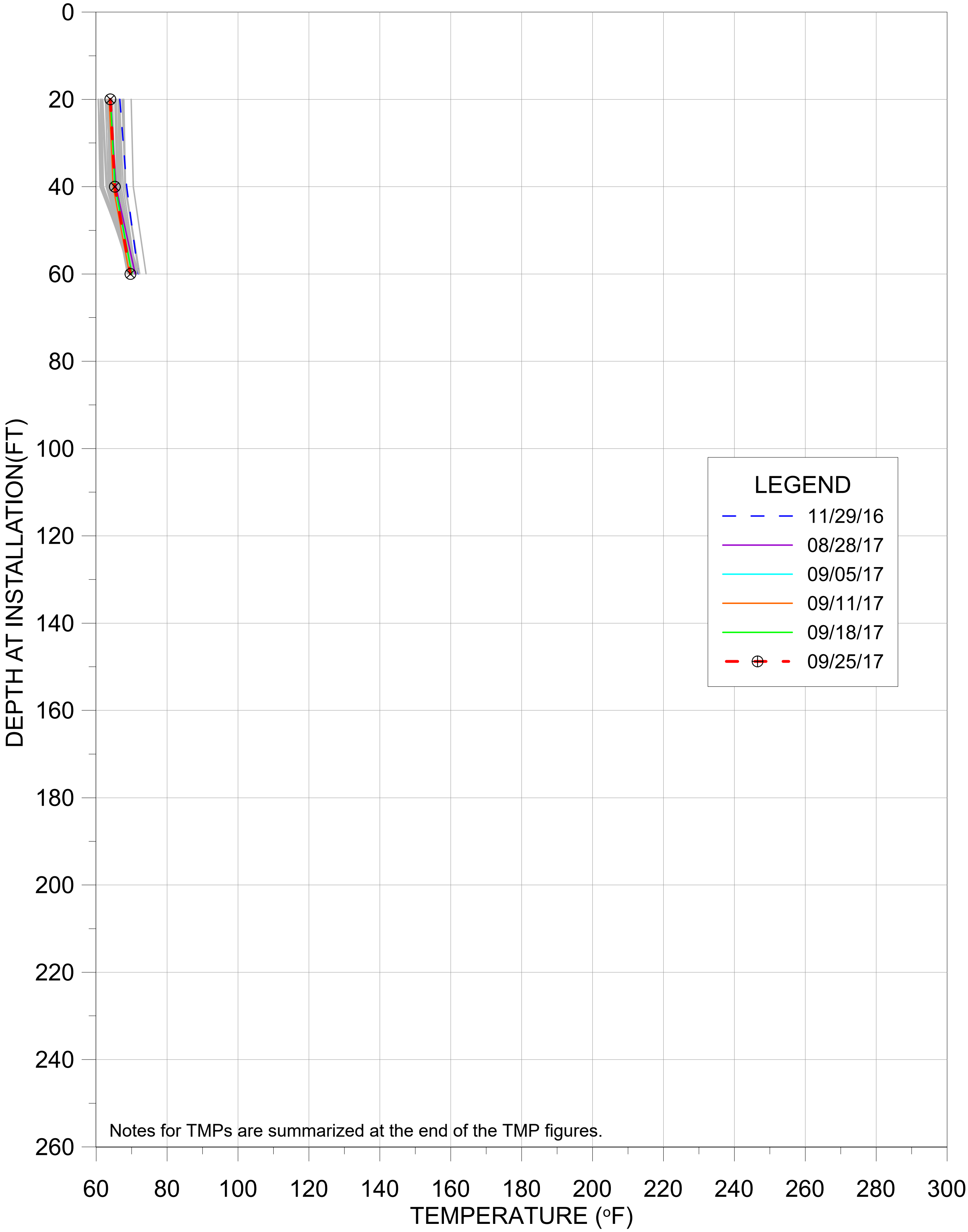
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-48



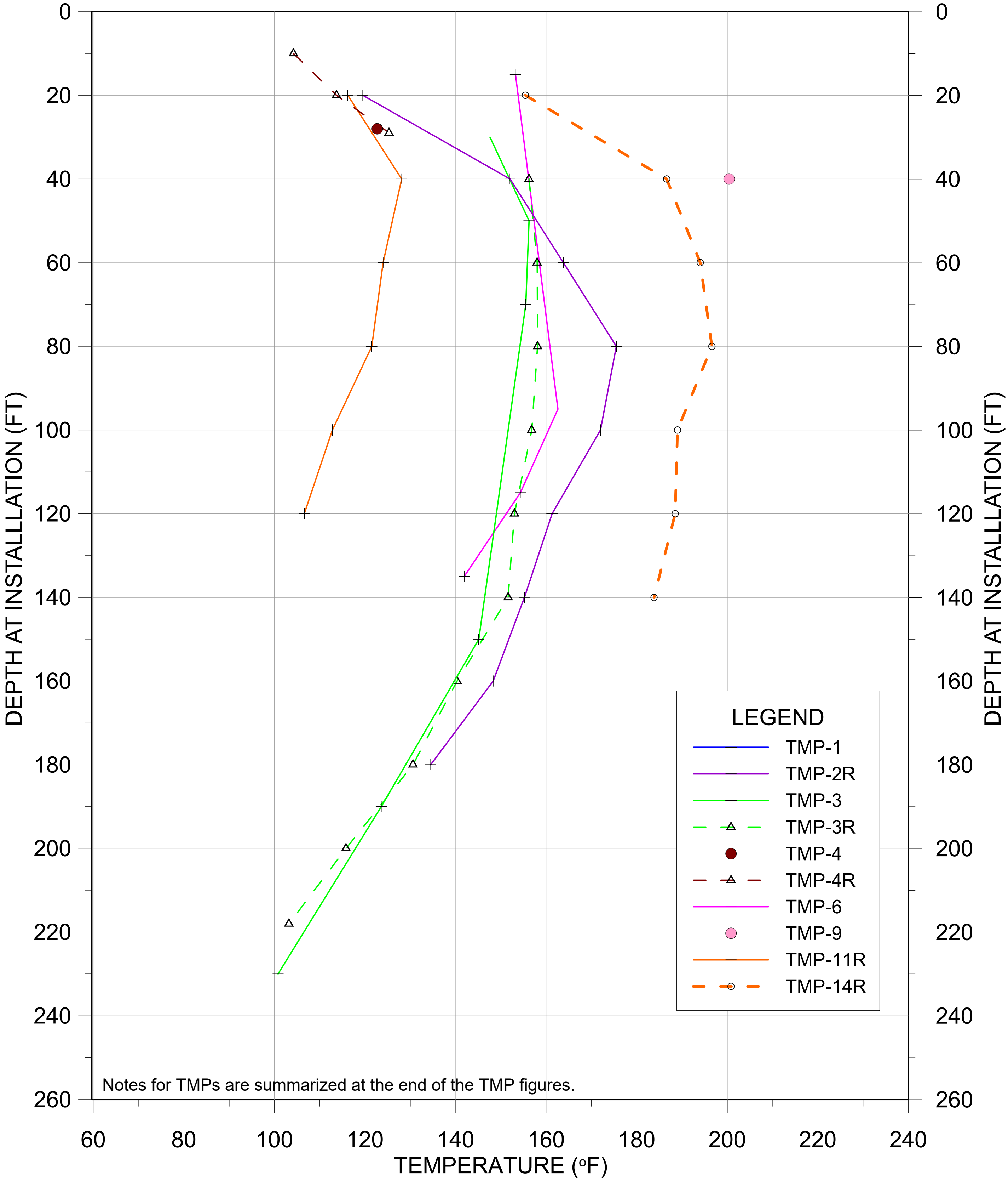
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-49



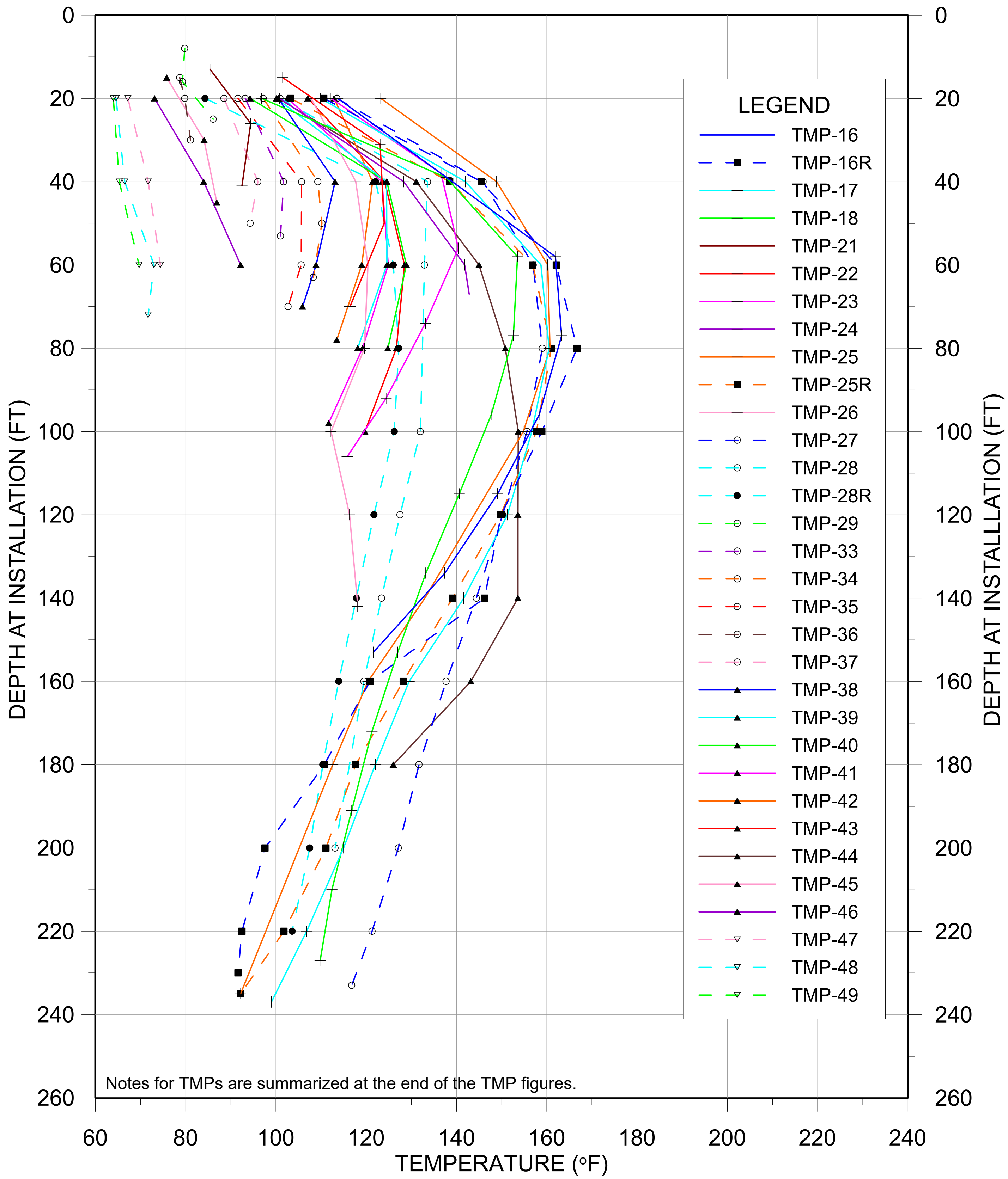
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

9/25/2017



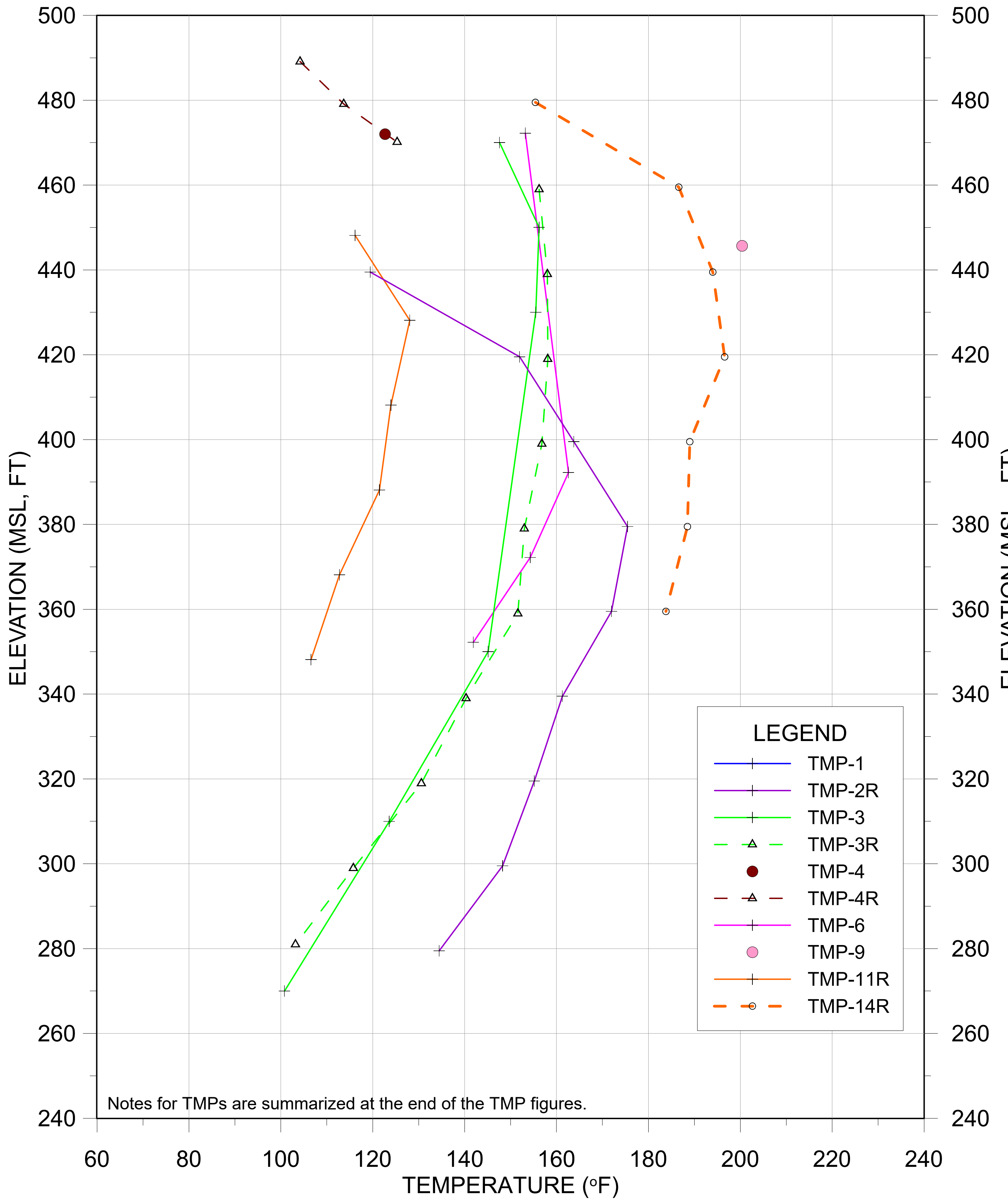
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

9/25/2017 - NORTH QUARRY



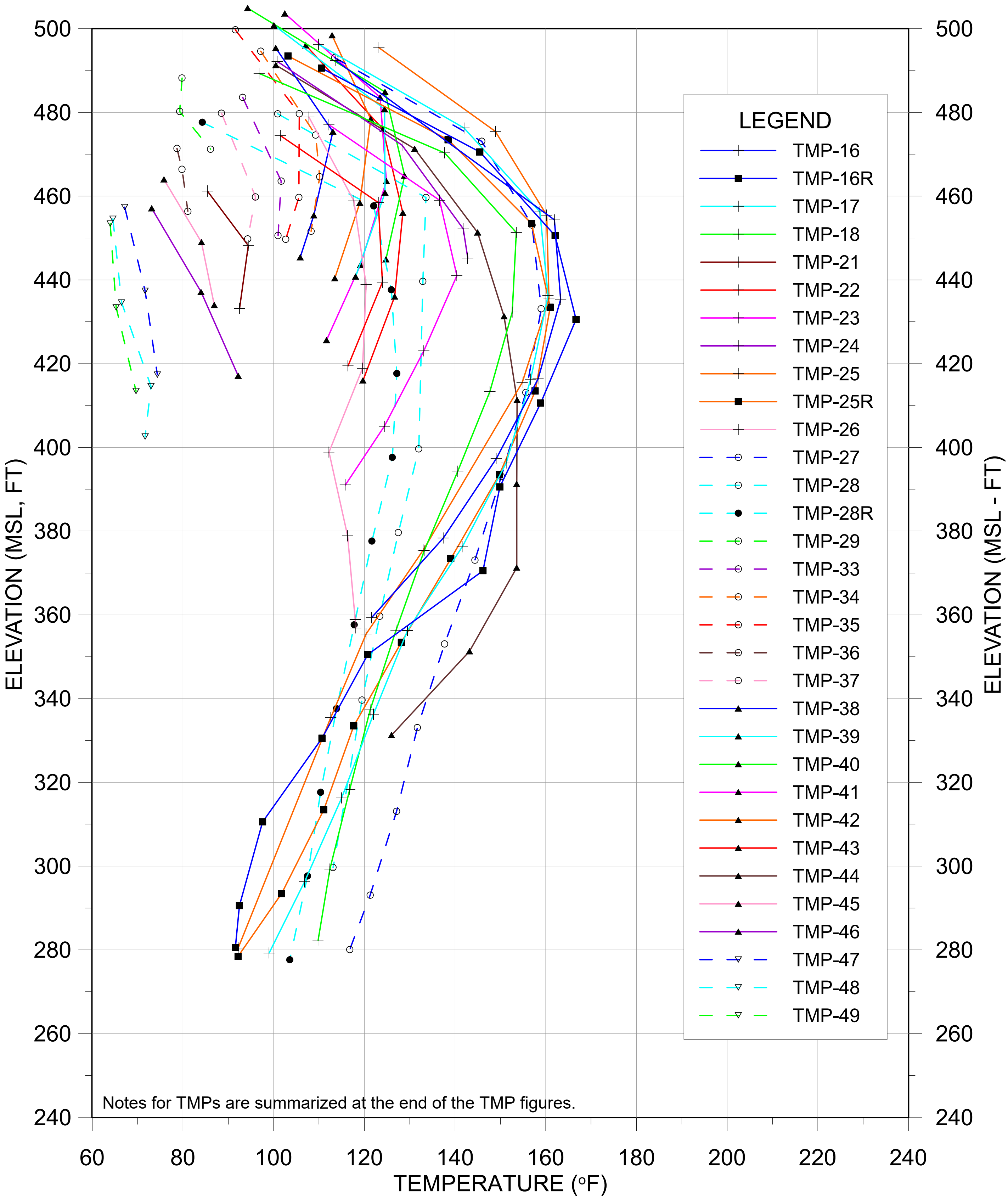
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

9/25/2017



TEMPERATURE VS ELEVATION
BRIDGETON LANDFILL

9/25/2017 - NORTH QUARRY



TEMPERATURE VS ELEVATION
BRIDGETON LANDFILL

TMP BRIDGETON LANDFILL NOTES

TMP notes that are new for the reporting week are in **bold.**

TMP-1: NONE

TMP-2:

1. TMP-2 has been replaced by TMP-2R and will no longer be monitored or included in the presentation.

TMP-2R:

1. Data reported on 11/29/2016 was inadvertently left as the 11/22/2016 data. This was corrected on 12/5/2016 reading submittal.

TMP-3:

1. No reliable temperature readings have been obtained at 170 ft depth since 1/29/2014, except on 3/13/2014.
2. The connectivity tests on 4/11/2014 conducted by CEC showed that units at 10, 90, 130, 210 and 250 ft depths are no longer reliable.
3. The connectivity tests on 10/28/2014 conducted by Feezor Engineering showed that units at 10, 90, 110, 130, 210 and 250 ft depths are not reliable.

TMP-3R:

1. **The unit at 20 ft depth had a fluctuating resistance on 9/25/2017. Therefore the temperature is determined to be unreliable.**

TMP-4:

1. The connectivity tests on 4/11/2014 conducted by CEC showed that the unit at 48 ft depth is no longer reliable.

TMP-4R: NONE

TMP-5: TMP NO LONGER IN SERVICE– Verified by Connectivity testing by Feezor Engineering in March 2015.

TMP-6:

1. The connectivity tests on 4/11/2014 conducted by CEC showed that units at 35, 55, 75, 155, 175, and 195 ft depths are no longer reliable.
2. No reliable temperature readings have been obtained at the unit at 215 ft depth since 6/13/2014.

TMP-7R: TMP NO LONGER IN SERVICE

TMP-8: TMP NO LONGER IN SERVICE

TMP-9:

1. Unit at 100 ft depth had an inaccurate temperature reading on 8/1/2013 and no reading since 8/6/2013.
2. The connectivity tests on 4/11/2014 conducted by CEC showed that units at 20, 60, 80, and 100 ft depths are no longer reliable.

TMP-10:

1. All units were verified by connectivity testing by Feezor Engineering on 6/1/2017 to be unreliable.

TMP-11:

1. All units were verified by connectivity testing by Feezor Engineering on 11/23/2016 to be unreliable.
2. TMP-11 is no longer in service and will not be included in the presentation.

TMP-11R: NONE

TMP-12:

2. All units were verified by connectivity testing by Feezor Engineering in October 2015 to be unreliable.

TMP-13: TMP NO LONGER IN SERVICE

TMP-14:

1. All units were verified by connectivity testing by Feezor Engineering in March 2016 to be unreliable.

TMP-14R:

1. Due to the connectivity test results by Feezor Engineering on TMP-14 (see note above), TMP-14R is added to this reporting data set as of 3/7/2016.

TMP-15: TMP WAS NEVER IN SERVICE

TMP-16:

1. A connectivity test conducted by Feezor Engineering showed that the units on TMP-16 may not be reliable since 9/9/2015. Further testing at the end of September 2015 showed possible connectivity on some of the units.
2. The unit at 153 ft depth had a low resistance reading and unreliable temperature since 12/21/2015.

3. The unit at 39 ft depth had a higher than acceptable resistance reading and unreliable temperature since 2/7/2017.

TMP-16R: NONE

TMP-17: NONE

TMP-18: NONE

TMP-19: NOT PART OF THIS SUBMITTAL (HEAT EXTRACTION TMP)

TMP-20: NOT PART OF THIS SUBMITTAL (HEAT EXTRACTION TMP)

TMP-21: NONE

TMP-22: NONE

TMP-23: NONE

TMP-24: NONE

TMP-25:

1. The unit at 200 ft provided an apparent anomalous reading on 3/28/2017. Subsequent readings on 4/4/2017 showed the unit to have failed (see below). The unit is no longer working and the reading of 3/28/2017 was likely unreliable.
2. The unit at 200 ft depth had a resistance reading greater 4000 ohms on 4/4/2017. A connectivity test conducted by Feezor Engineering on 4/7/2017 showed that this unit also had cross-connectivity. The unit is therefore determined to be no longer working as of the 4/4/2017 reading.
3. The unit at 120 feet had a higher than acceptable limit on 7/10/2017. Also, a connectivity test conducted by Feezor Engineering on 4/7/2017 showed that this unit may be unreliable. Therefore, this unit is determined to be unreliable.
4. The unit at 220 ft has been reported as unable to attain a reading of any kind since June 19, 2017. The unit is considered to be on no longer working as of that date.

TMP-25R: NONE

TMP-26: NONE

TMP-27: NONE

TMP-28:

1. The unit at 217 ft depth has had no resistance or temperature readings since installation.
2. The unit at 80 ft depth had a resistance drop and an unreasonable temperature decrease on 6/1/2016. The temperature has since fluctuated and is determined to be unreliable.
3. The unit at 180 feet has had a higher than acceptable limit since 3/28/2017 and is therefore determined to be unreliable as of the 4/4/2017 reading.

TMP-28R: NONE

TMP-29: NONE

TMP-33: NONE

TMP-34: NONE

TMP-35: NONE

TMP-36: NONE

TMP-37: NONE

TMP-38: NONE

TMP-39: NONE

TMP-40: NONE

TMP-41: NONE

TMP-42: NONE

TMP-43: NONE

TMP-44: NONE

TMP-45: NONE

TMP-46: NONE

TMP-47: NONE

TMP-48: NONE

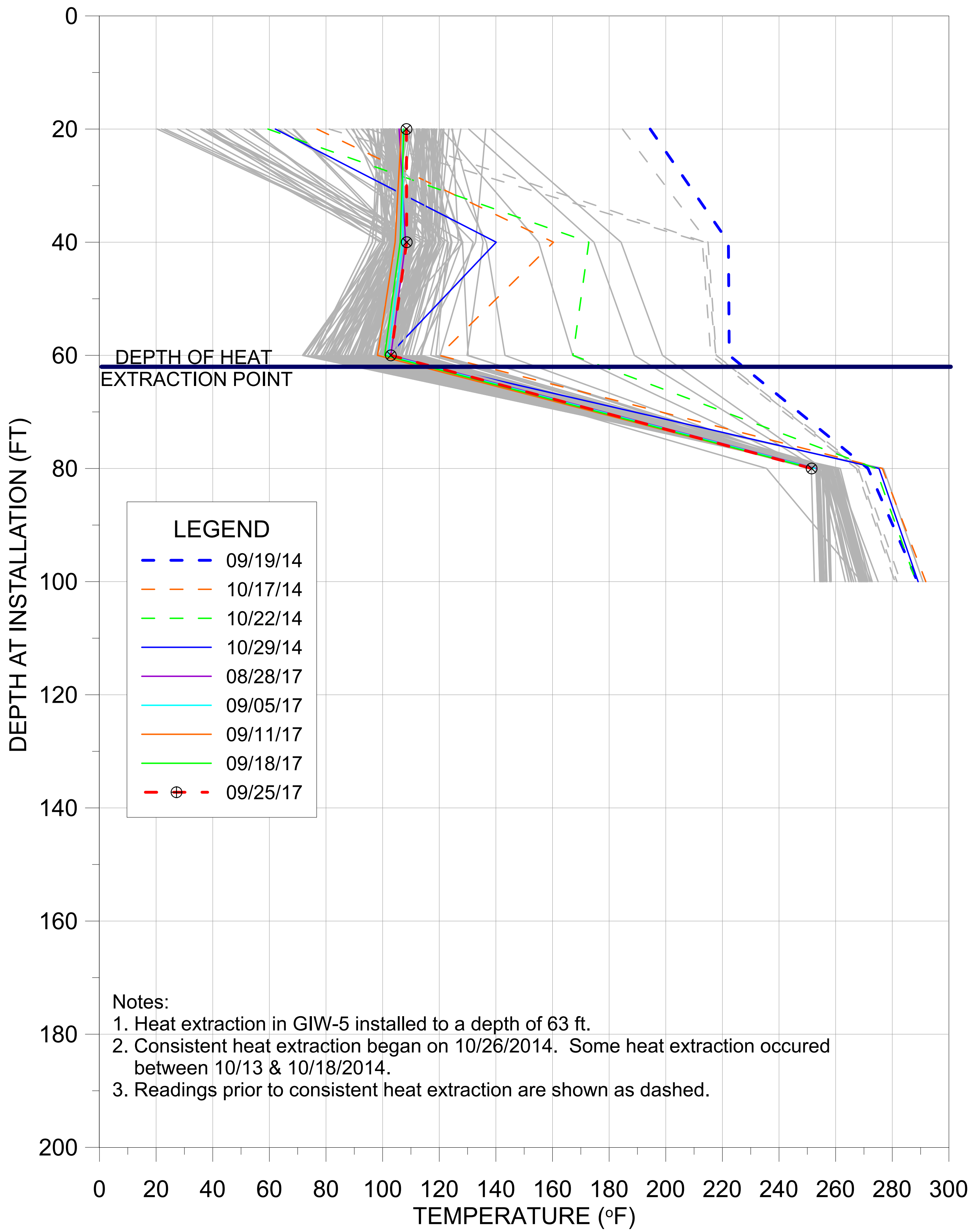
TMP-49: NONE

TMP vs DEPTH and TMP vs ELEVATION (for **09/25/17**):

1. There were no reliable temperature readings for TMP-13 since 3/19/2014.
2. There were no reliable temperature readings for TMP-7R, as determined by the connectivity test on 4/11/2014.
3. There were no reliable temperature readings for TMP-5 since 11/5/2014.
4. There were no reliable temperature readings for TMP-12 since 9/28/2015.
5. There were no reliable temperature readings for TMP-8 since 9/9/2015.
6. There were no reliable temperature readings for TMP-14, confirmed since 3/7/2016.
7. There were no reliable temperature readings for TMP-11 as determined by the connectivity test on 11/23/2016.
8. TMP-2 has been replaced by TMP-2R and will no longer be monitored.
9. TMP-11 is no longer in service and will not be included in the presentation.
10. There were no reliable temperature readings for TMP-10 since 5/30/2017.

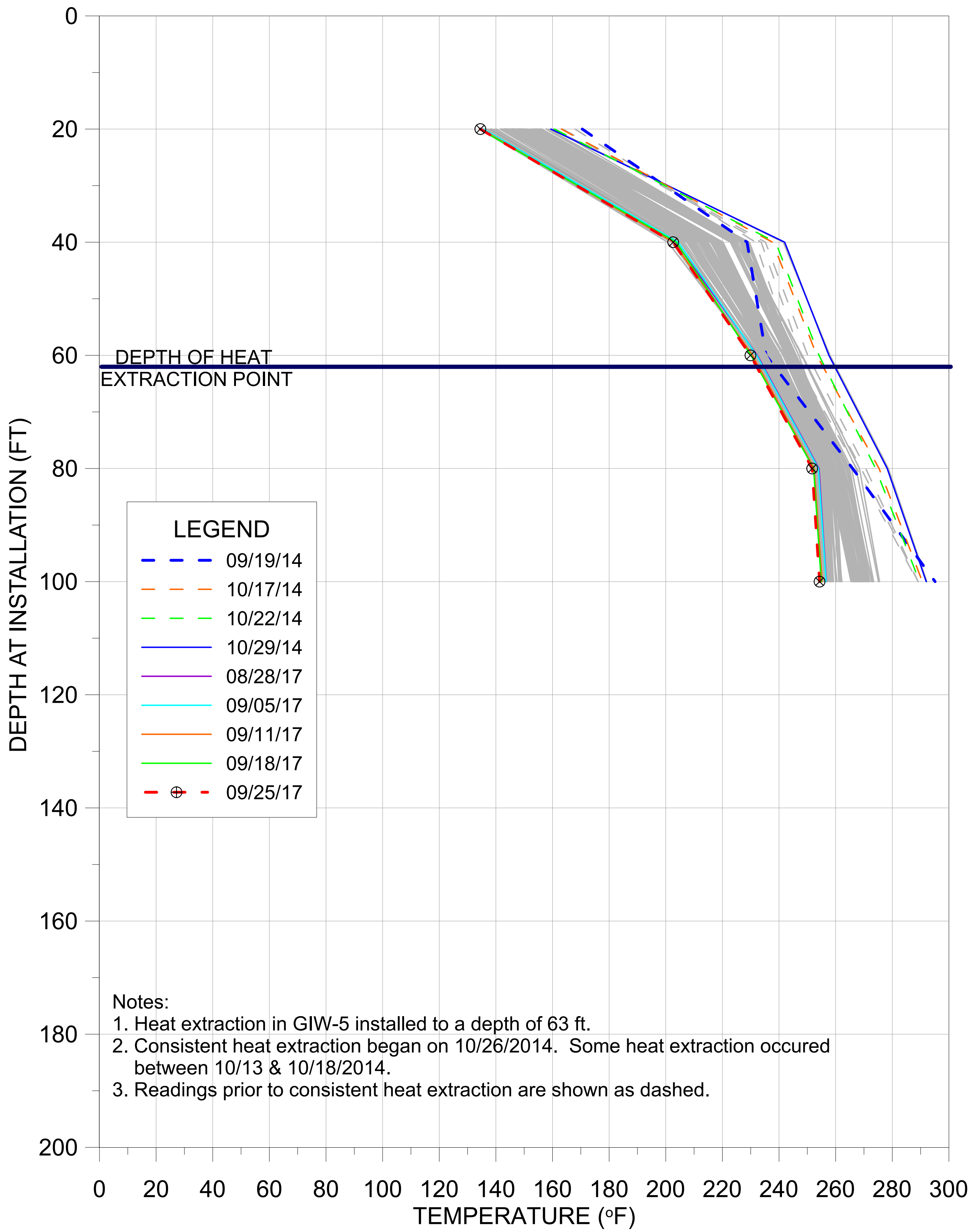
APPENDIX D
GIW PILOT SYSTEM TMPS GRAPHS AS OF 09/25/17

TMP-5-5N



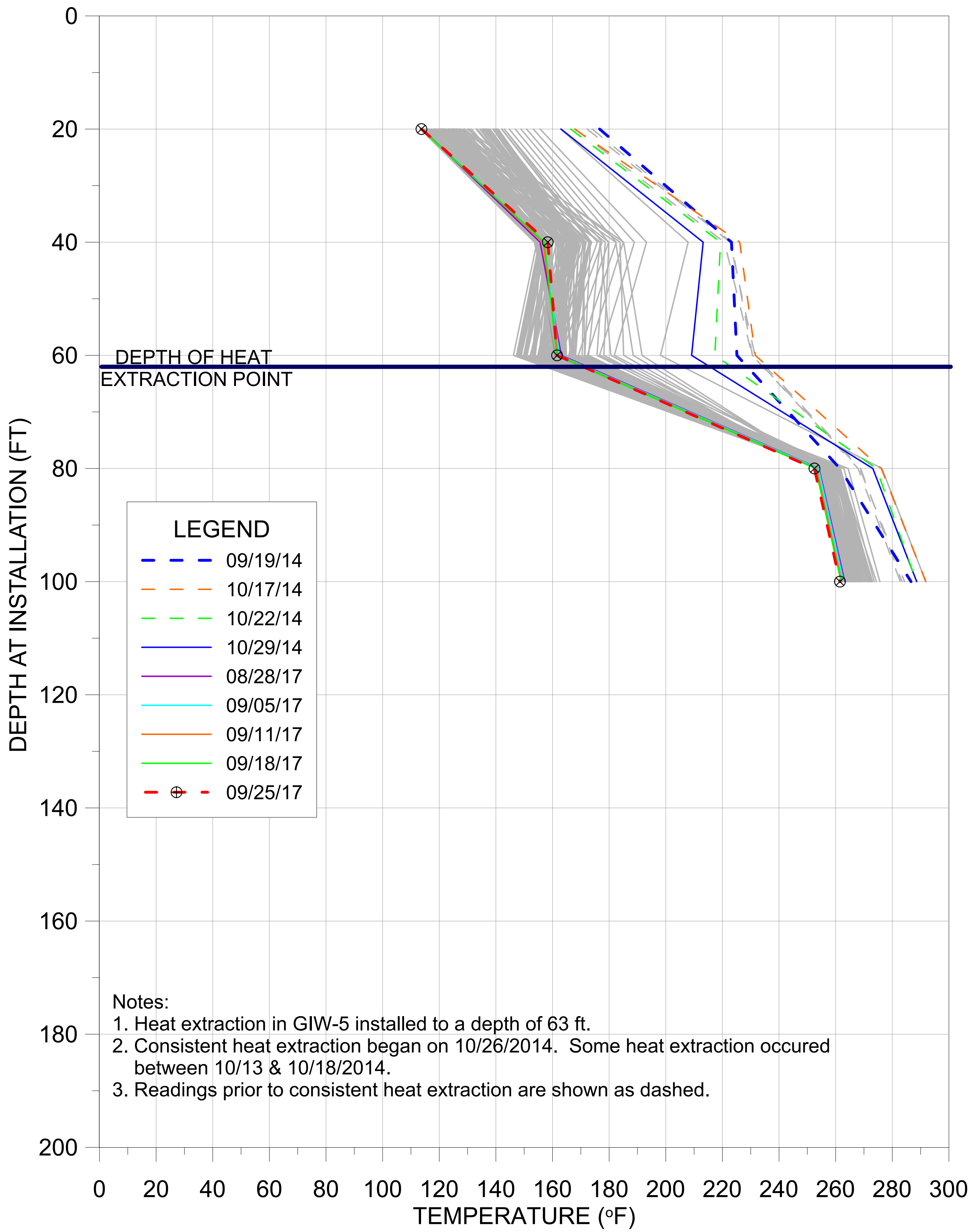
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-5-5S



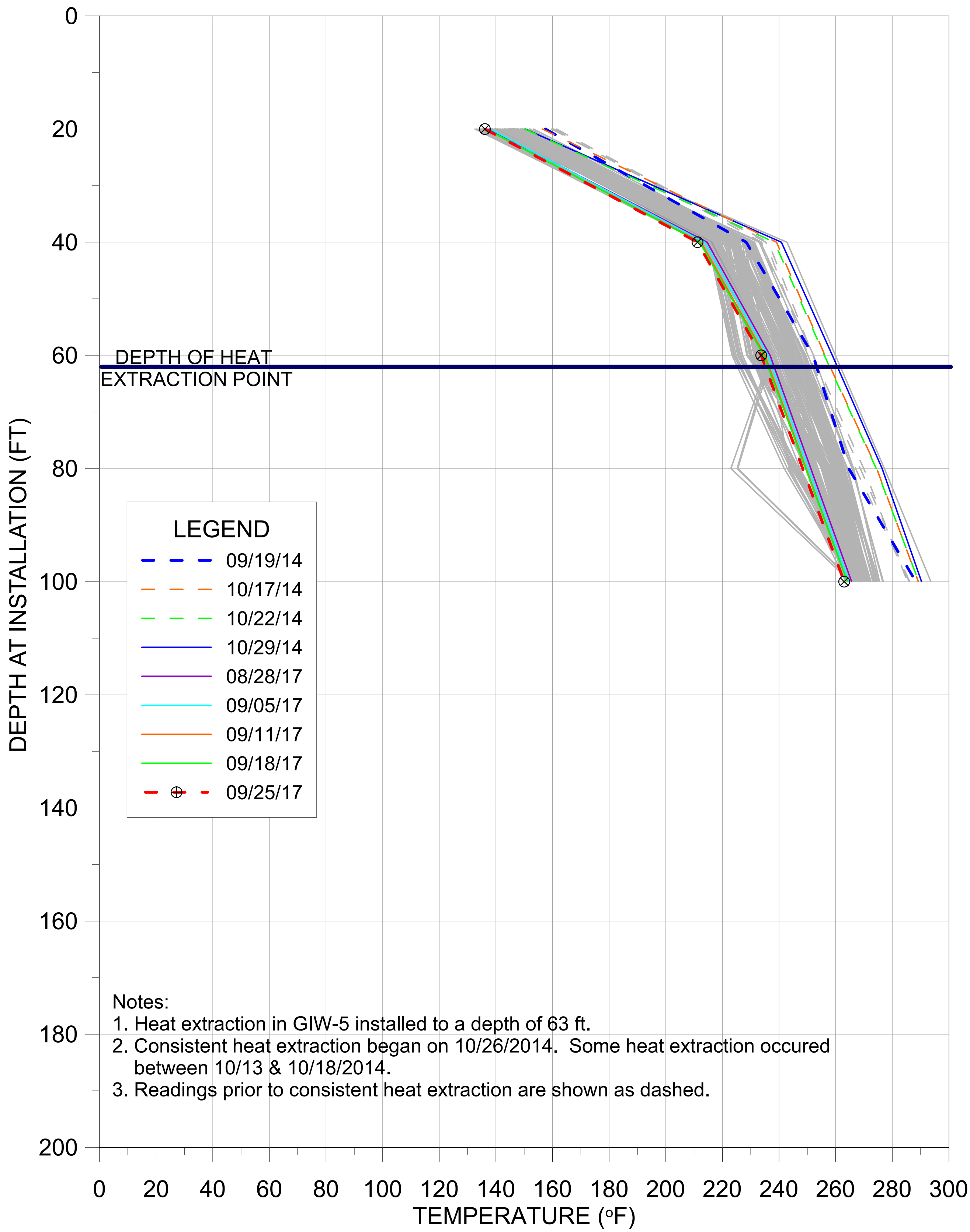
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-5-9N



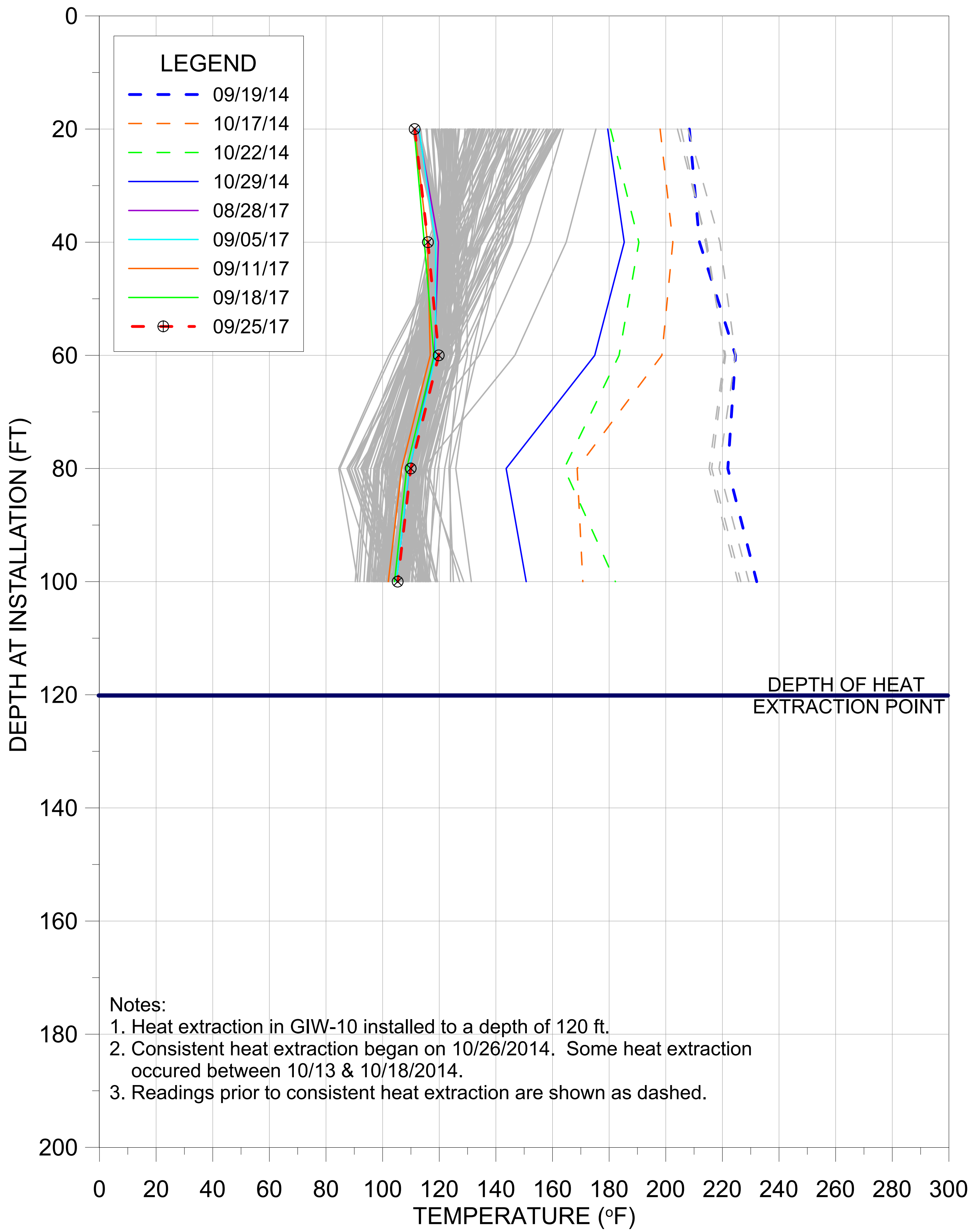
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-5-9S



TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

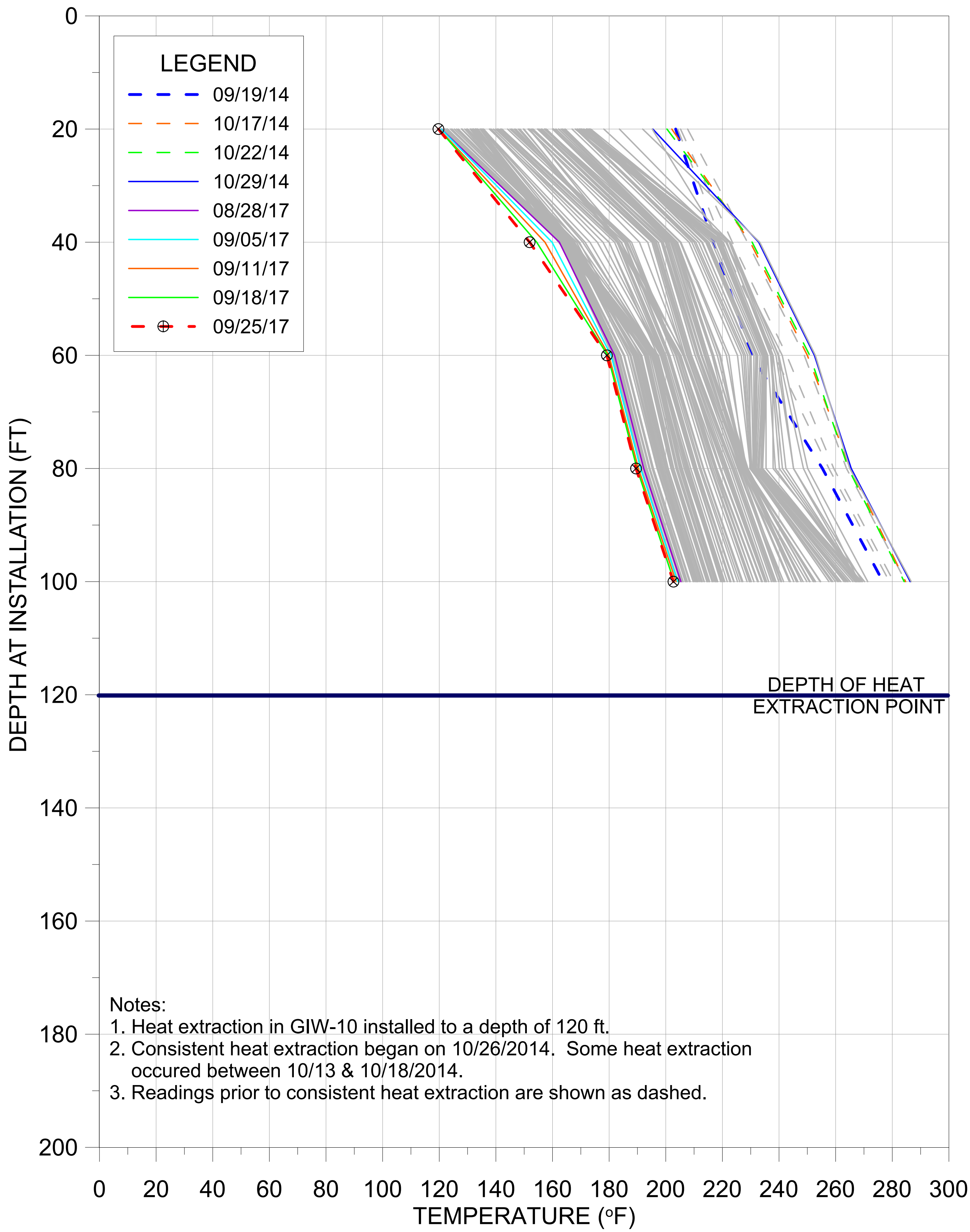
TMP-10-5N



Notes:
1. Heat extraction in GIW-10 installed to a depth of 120 ft.
2. Consistent heat extraction began on 10/26/2014. Some heat extraction occured between 10/13 & 10/18/2014.
3. Readings prior to consistent heat extraction are shown as dashed.

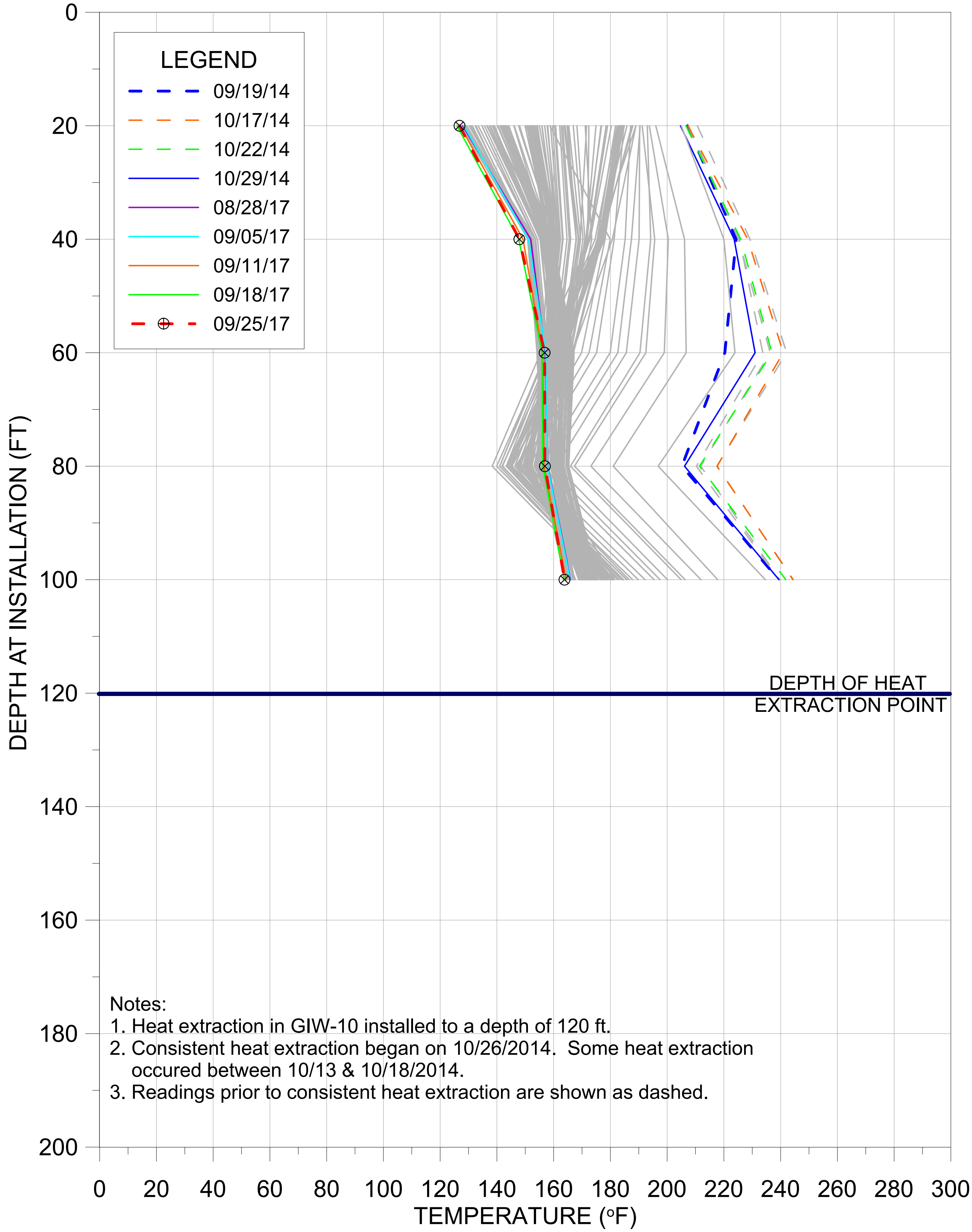
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-10-5S



TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

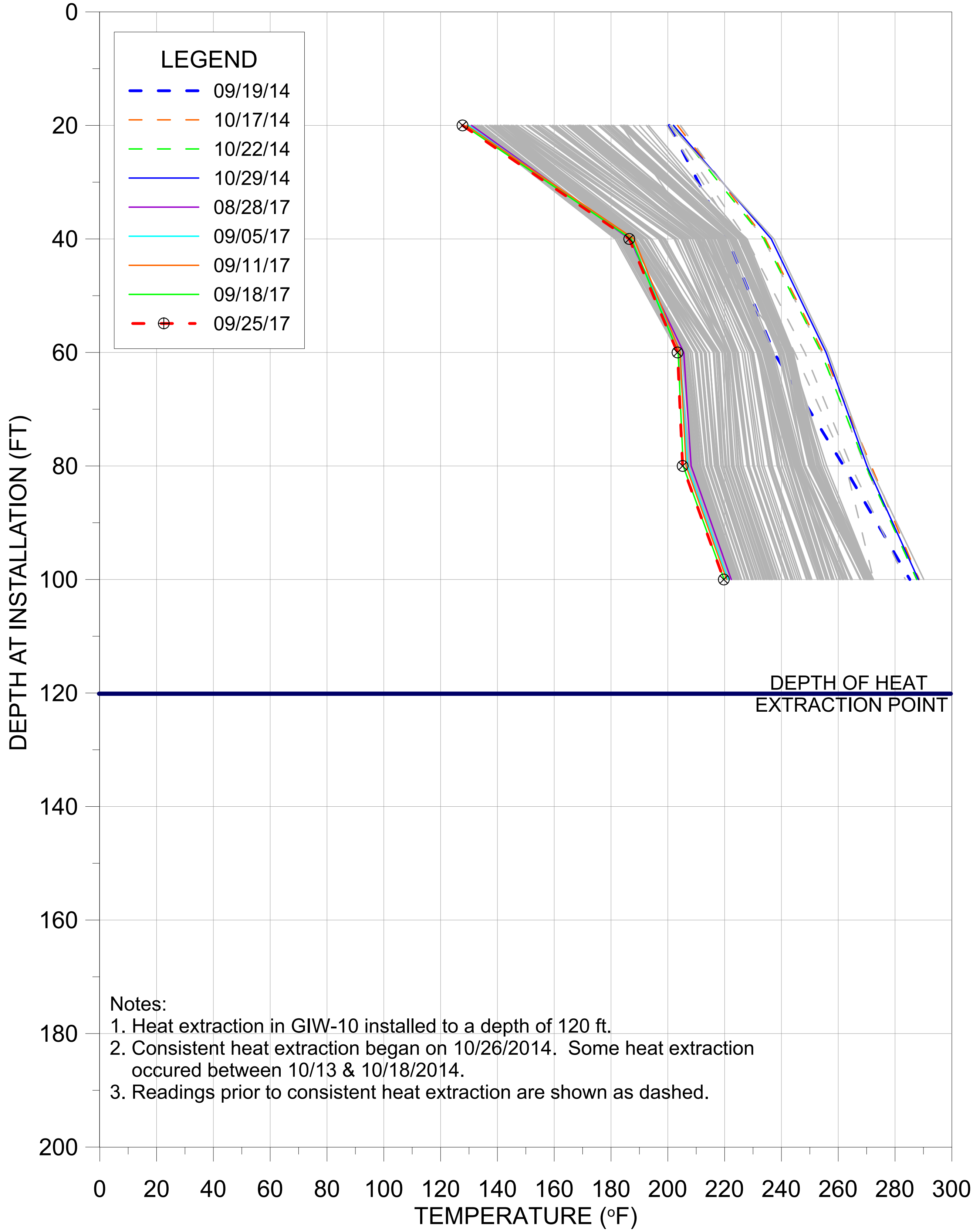
TMP-10-9N



Notes:
1. Heat extraction in GIW-10 installed to a depth of 120 ft.
2. Consistent heat extraction began on 10/26/2014. Some heat extraction occured between 10/13 & 10/18/2014.
3. Readings prior to consistent heat extraction are shown as dashed.

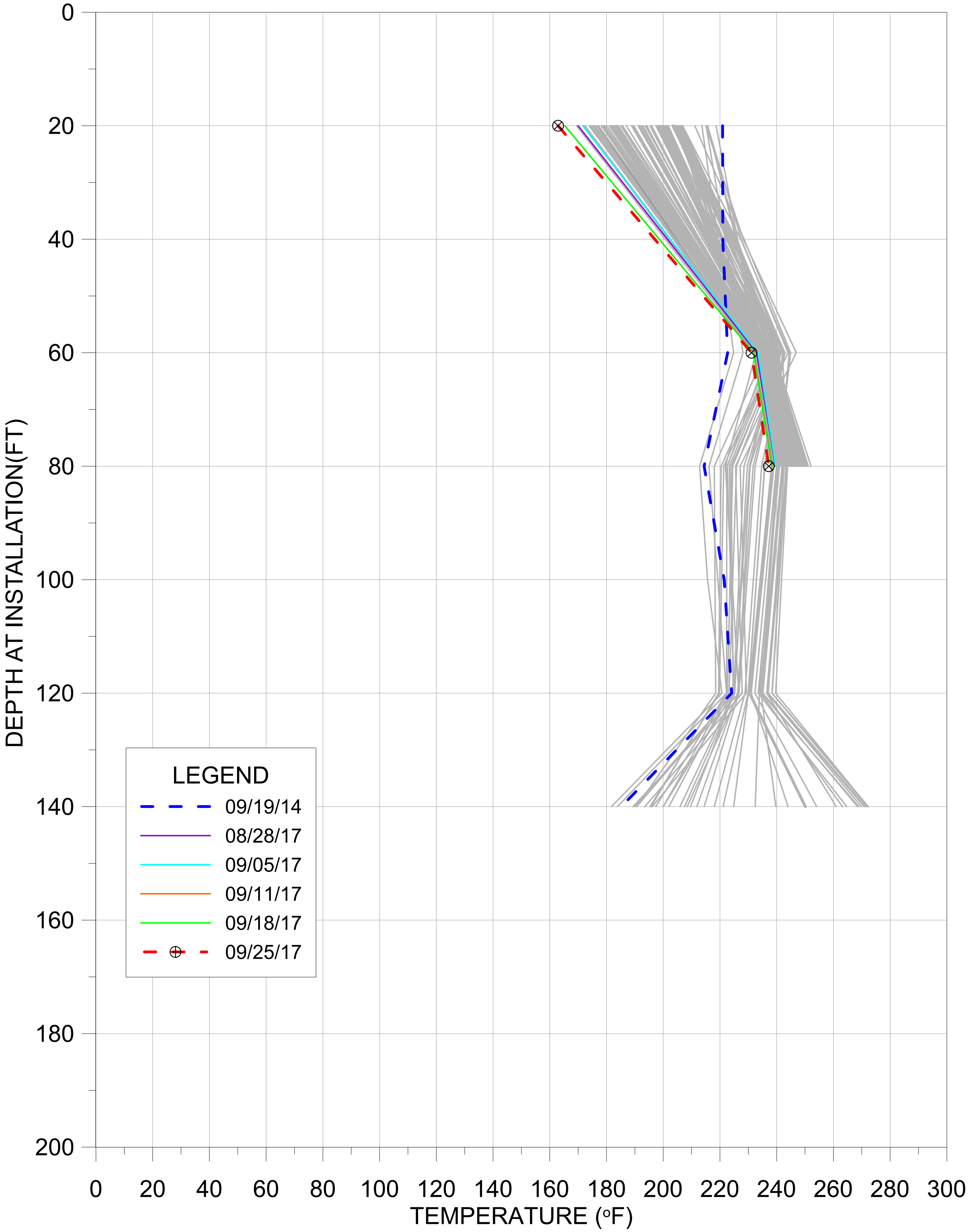
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-10-9S

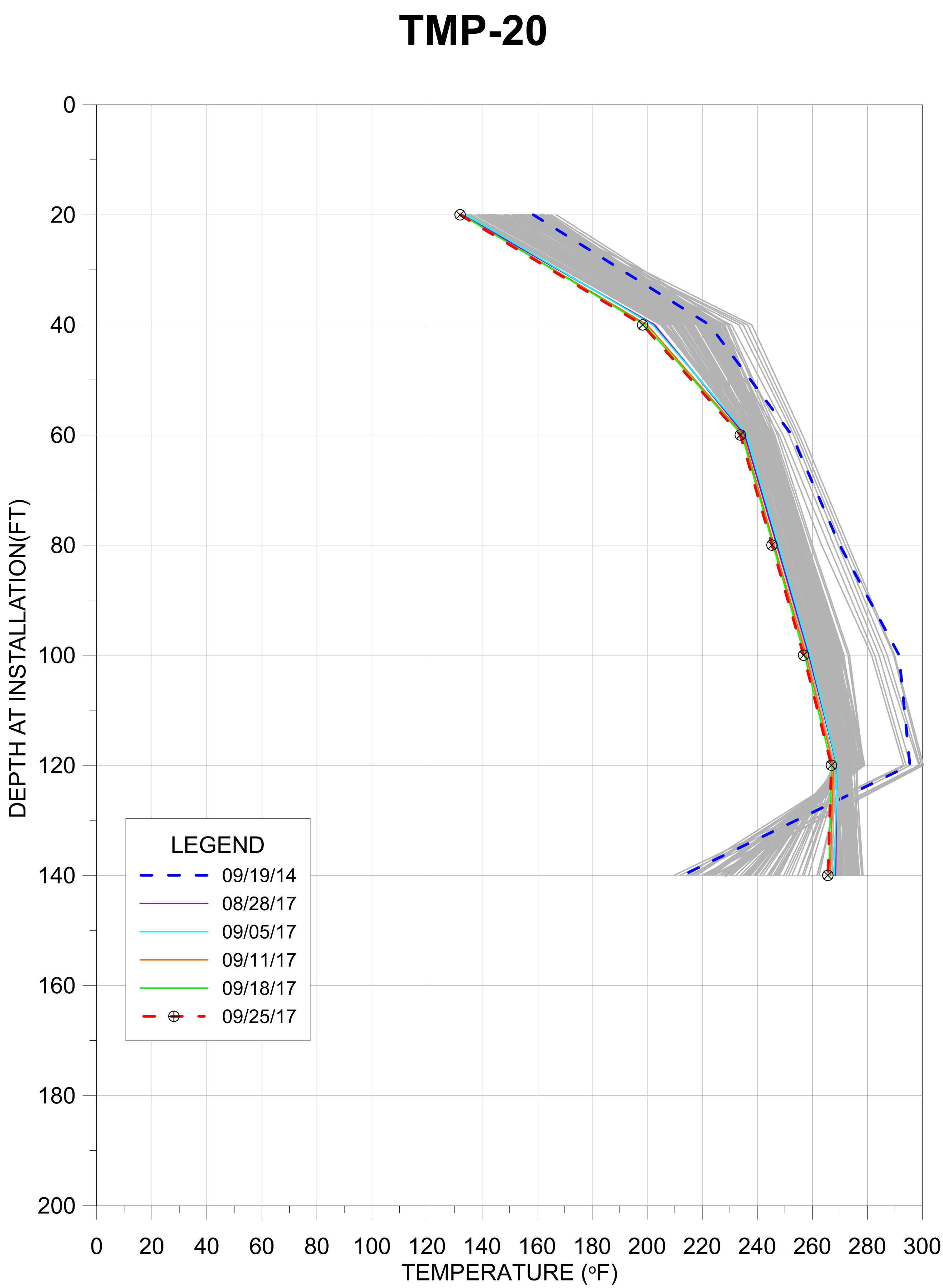


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-19

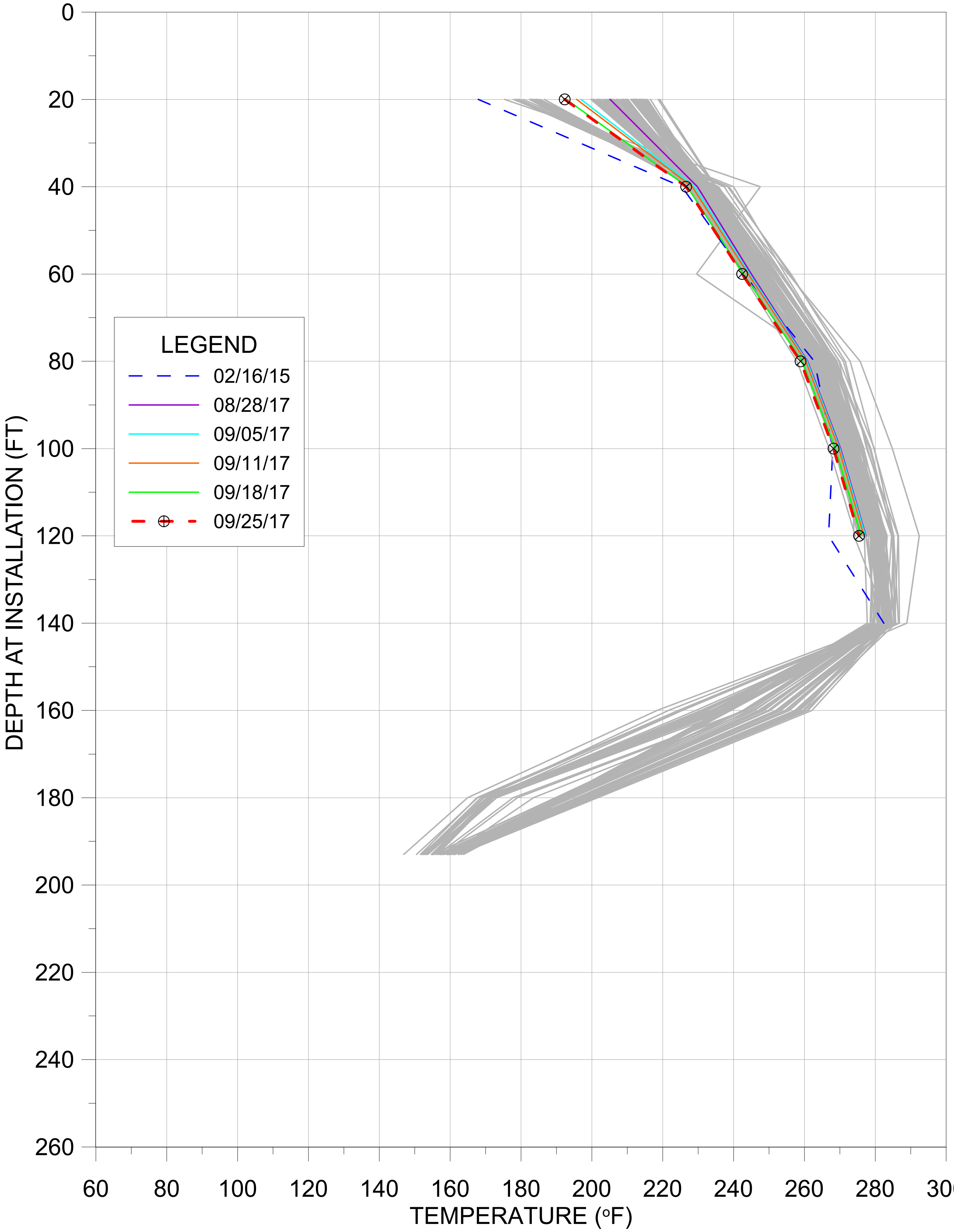


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL



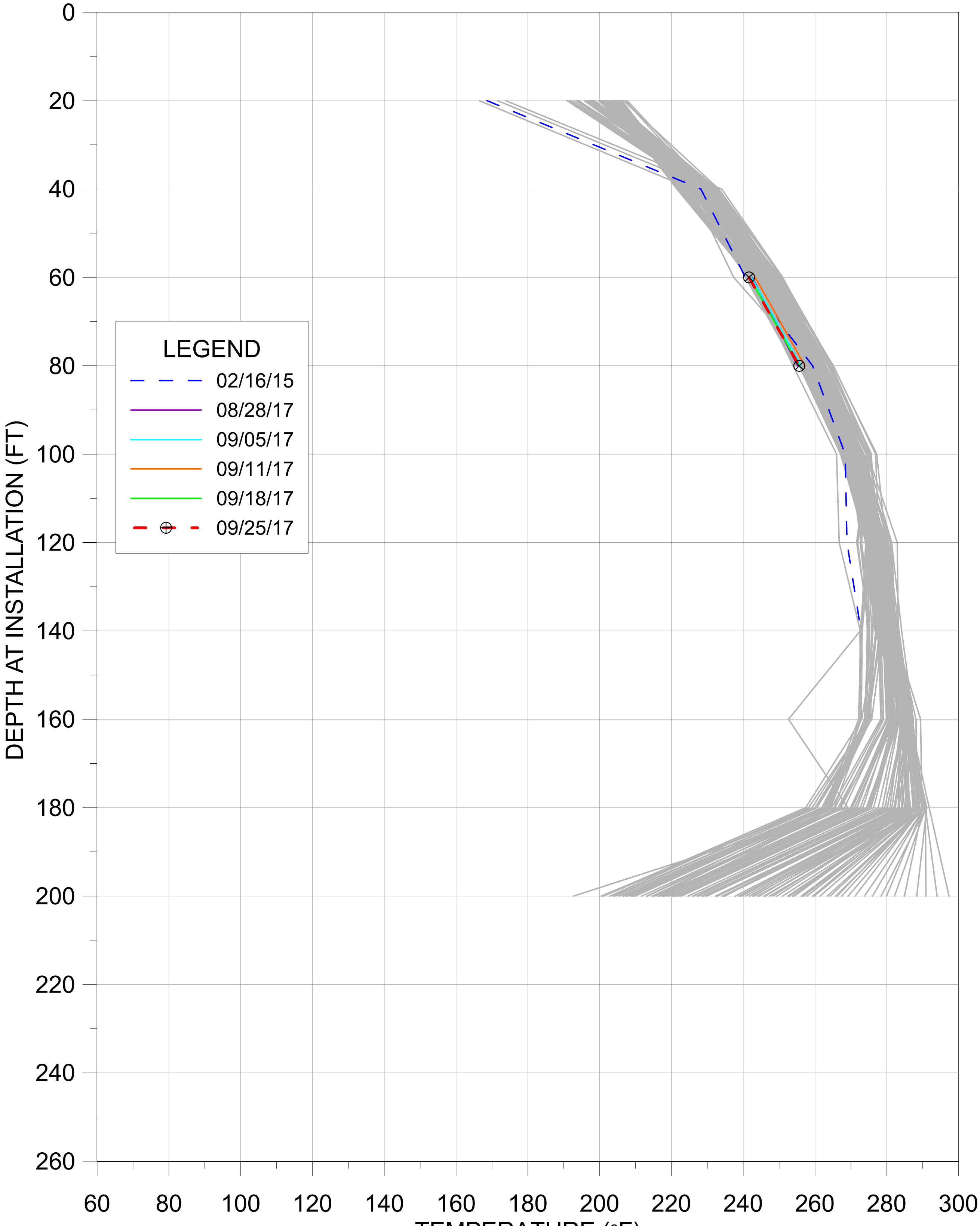
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-31



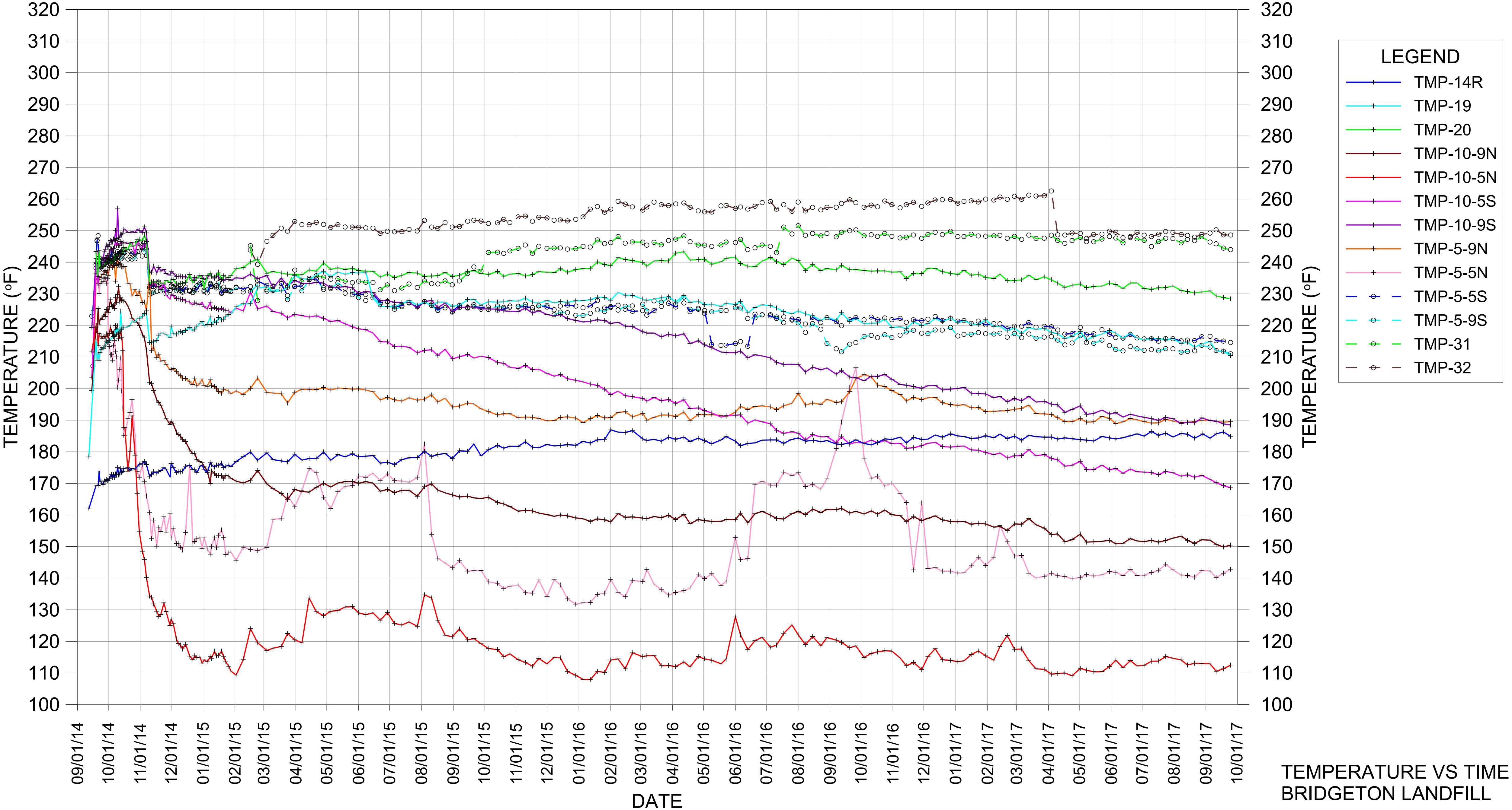
TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

TMP-32

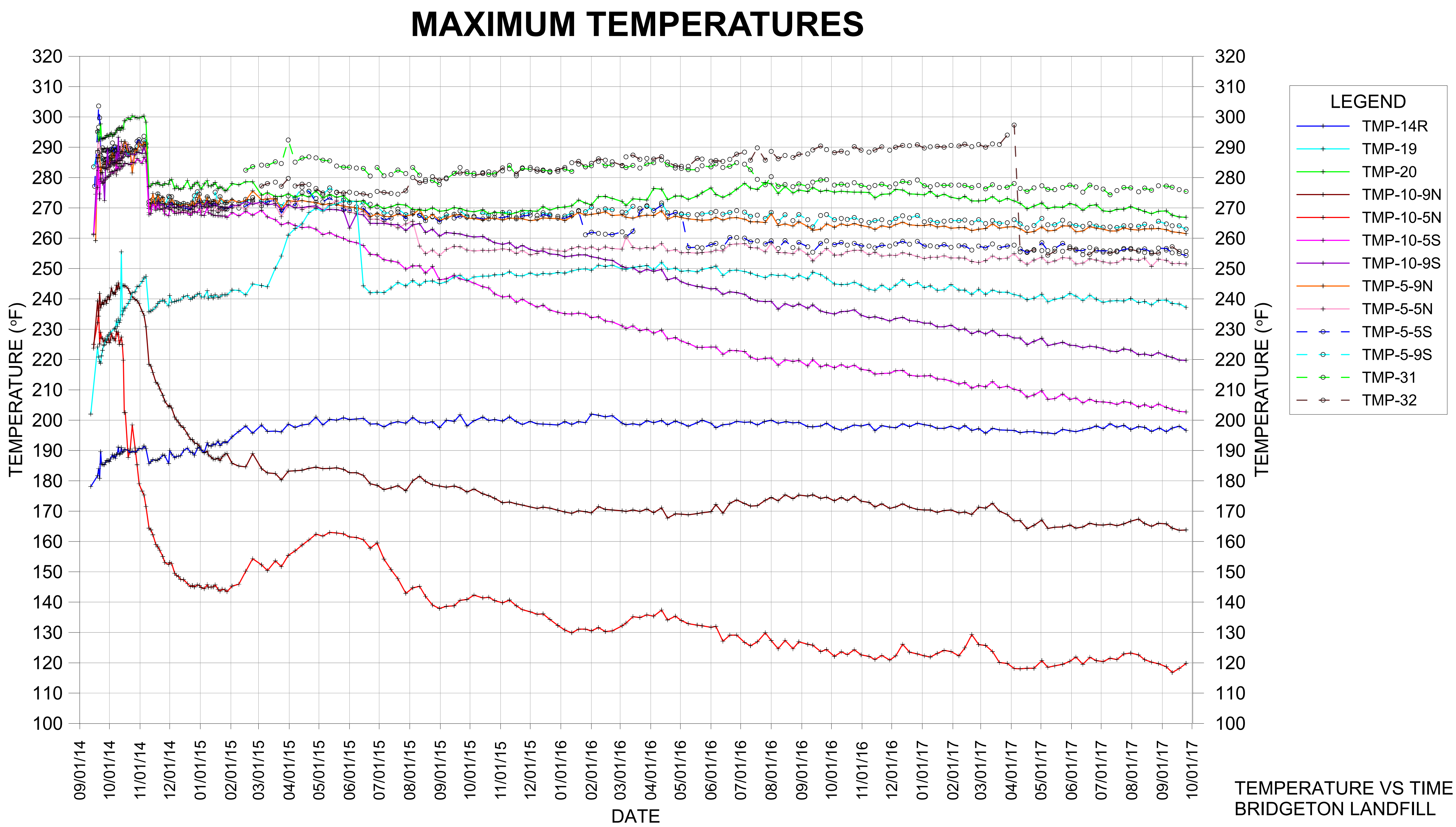


TEMPERATURE VS DEPTH
BRIDGETON LANDFILL

AVERAGE TEMPERATURES



TEMPERATURE VS TIME
BRIDGETON LANDFILL



MAXIMUM TEMPERATURES
TEMPERATURE (°F)
DATE
LEGEND
TMP-14R
TMP-19
TMP-20
TMP-10-9N
TMP-10-5N
TMP-10-5S
TMP-10-9S
TMP-5-9N
TMP-5-5N
TMP-5-5S
TMP-5-9S
TMP-31
TMP-32
TEMPERATURE VS TIME
BRIDGETON LANDFILL

APPENDIX E

NECK AREA CONDITIONS DRAWING

NOTE:
AERIAL TOPOGRAPHY PROVIDED BY COOPER AERIAL SURVEYS, INC. AND IS DATED DECEMBER 2, 2016

BRIDGETON LANDFILL, LLC 13570 ST. CHARLES ROCK ROAD BRIDGETON, MISSOURI 63044	BRIDGETON LANDFILL	Engineering for a Better World FEEZOR ENGINEERING, INC.	SEPTEMBER 2017 DESIGNED BY: IN/PML APPROVED BY: DRF	DRAWING NO.: C
NECK AREA CONDITIONS			REVISION / DATE	
PROJECT NUMBER: BT-142	FILE PATH: E:\Dropbox (Feezor Engineering)\BT-142 Heat Extraction Report\working\draft Drawings\BT-142 C Neck Area Conditions 9-29-2017.dwg			

APPENDIX F

EVALUATION OF HEAT EXTRACTION BARRIER MODEL – ONE YEAR OF OPERATION

BY PJ CAREY AND ASSOCIATES, PC

EVALUATION OF HEAT EXTRACTION BARRIER MODEL

ONE YEAR OF OPERATION

PREPARED FOR:

BRIDGETON LANDFILL LLC

Prepared by

P.J. Carey & Associates, P.C.

Sugar Hill, Georgia

10/5/2017

TABLE OF CONTENTS

FIGURES

DRAWING SIZE FIGURES

NONE

APPENDICIES

None anticipated at this time – we could add some reference materials if desired

1 EXECUTIVE SUMMARY

The measured values obtained from operation of the Heat Extraction Barrier (HEB) system were utilized to evaluate the idealized heat removal model developed for the design of the current system. The idealized model was developed in October 2015 and predicted conditions at the start of HEB operations on or about November 2016 going forward.

The predicted versus actual conditions at the beginning of operations suggested some differences in temperatures, typically at depth in the neck being lower than predicted and near surface higher than predicted. The original model also predicted rising temperatures in the region between the southern line of Gas Interceptor well extractors (GIW) and the line of heat extractor well (HEW) units. Further, original design model (ODM) presumed a steady generation of energy due to reaction in the area south of the HEW line and rising temperatures in that area to the southern extent of the model. Observations of the in ground temperature suggest that energy generation rates are reducing in this area by some amount. Heat generation in the region between the GIW and HEW lines was reduced to reflect these findings in the idealized evaluation model (IEM) relative to those used in the ODM.

The operational conditions assumed in the ODM the same as operational conditions, except for the inflow temperature. In general the inflowing water to the exchange units was warmer than assumed, and varied hourly as opposed to monthly. No other operational differences were significant.

Using the ODM it was identified that the retardance factors assigned to the HEW units were too high and that energy removed was approximately 70% of the actual measured amounts on the HEW line even when the factors of initial temperature, heat conduction and Cp were increased beyond reasonable values. Reduction in the retardance coefficients for the HEW units resolved this apparent issue and heat capacity and conductance values used in the ODM result in reasonable model behavior. Improved fit between predicted versus measured during the period between October 11, 2016 and August 31, 2017 was obtained by increasing the heat conduction of the waste from 1.4 to 1.6 W/mK and the heat capacity of the waste from 2.4 to 2.6 Mjoule/m^3. Balance between energy recovered in the central HEW units and the model predicted energy removed vary by less than 10% and show similar pattern with time.

Future prediction of the HEB performance, using IEM was performed with two different data sets of material properties. A cooling liquid inflow temperature versus time function based on the last years' experience was applied to the IEM along with the assumption that boundary conditions and heat generation rates remained the same to simulate performance into September 2019. This modeling predicted continuing reduced temperatures in vicinity of the HEW line and a reduction in the rate of energy extraction. No indication of the need to add more HEW units or to change the means of cooling was indicated.

2 INTRODUCTION

2.1 PURPOSE

The purpose of this evaluation is to examine the original design model ODM against the actual conditions indicated by site measurements and to make changes to the ODM that include consideration of significant differences. In addition future projections using the ODM or its modified successor, are used to identify any significant modifications that may be needed to prevent a rise in temperature in the areas south of the HEW line associated with the reaction heat to the south of the HEW line.

2.2 SCOPE OF WORK

The scope of work consists of:

- Examining the data from the site consisting of ;
    - In ground temperature records,
    - Exchange Unit in, out temperatures, and flow rates, and
    - Calculated energy removal totals.
- Generate a body of data representing starting conditions and operation output.
- Modify the ODM accordingly
- Perform addition simulations with the modified model (IEM) that show the model is reasonably predictive of the observed behavior under actual or conservative conditions
- Perform simulations showing that show predicted behavior for the next two years.
- Report the results

2.3 BACKGROUND

The HEB system was designed using the ODM as an integral part of determining unit spacing and depth as well as allowing the

- amount and approximate location of heat generation,
- heat conduction properties of waste materials, and
- heat capacity of waste materials

to be estimated based on the behavior observed during the pilot study. The modelling was performed with data obtained prior to September 2015. Conditions that would be present in October or November of 2016 were projected using the model. HEB operations were assumed to begin in November of 2016. Actual HEB operations began in October 2016. This evaluation begins by the examination of the starting conditions and utilizes data through the end of August 2017 for the basis of work.

3 MODELING METHODS

3.1 SOFTWARE

The modeling of heat flow and removal was performed using the program FEFLOW, developed by DHI-Wasy GMB of Germany and commercially available in the US through MIKE Powered by DHI. FEFLOW is a finite element based software that allows modeling of groundwater, heat and mass transport in two and three dimensions. The ODM (reported in 2015) utilized the latest release avaible,Version 6.2 (P11) issued late September 2015. The 64 bit version of the software was employed. The current modelling evaluations were performed using FEFLOW Version 7.1 update 4 issued in September 2017.

The updates to the software between 2015 and 2017 did not change any of the methodology the model uses for the simulation of heat extraction, but were mostly in the numerical methods for convergence, meshing improvements and pre and post processing.

3.2 MODEL CONSTRUCTION

3.2.1 GENERAL APPROACH

The model used utilized the same geometry and simplifying assumptions as the provided in the original design report. The primary difference between the current modelling and that previously reported previously[1], was that the model was broken into 5 foot thick vertical slices instead of 20 foot to allow for greater vertical discretization and the same properties for waste porosity, thermal conductance and heat capacity were assigned to all waste layers. In all ways the modeling geometry and general methods were the same. The model discretization in plan and section is depicted in Figure 1 and Figure 2, respectively.

3.2.2 SIMPLIFYING ASSUMPTIONS

3.2.2.1 Quarry Geometry

The shape of the neck area along with the varying elevation of the top of waste and depth to the quarry bottom, together with an incomplete record of temperatures along the edge of the waste made it convenient and conservative to ignore the variation in depth of waste and interaction with the quarry walls. Given that the quarry walls and floor represent non-reactive surfaces and heat sinks, this is a very conservative assumption. Using this assumption the

- model sides (nominally the east and west sides) were assumed to parallel and vertical,
- the bottom of the waste/floor of quarry was assumed to be at elevation 235 ft (approximately 5 feet lower than the lowest spot identified thus far in the neck area, and

[1] (P. J. Carey & Associates, P.C., 2015)

- the top of the waste was assumed to be at a constant elevation of 495 ft .

The models were also constructed to be symmetrical about the north/south center axis with respect to any bore hole extractor (BHE) insertions, allowing a nominal width of 150 ft to be utilized.

Boundary conditions were applied uniformly across the model in an east west direction. These simplifying assumptions for geometry resulted in quasi 2 dimensional model that allowed for discrete extraction features to be evaluated. No changes to the model shape were made, relative to that used in the ODM

3.2.2.2 Boundary Conditions

As in the ODM boundary conditions were applied to all exterior model faces. The east and west faces were assigned no flow conditions by default (no specific assignments in FEFLOW create a no flow interface to fluid, heat or mass). The north and south boundary of the model were assigned constant temperature values at each node. The temperature varied with depth only and was based on observed temperatures measured at the landfill. The top of the landfill was treated as a heat loss boundary by assigning a fixed reference temperature with addition heat transmission coefficient (3rd kind/Cauchy boundary condition). This assignment allowed the transmission of heat at the surface to account for the solid /gas interface along with allow adjustments to account for some heat losses associated with vapor removal under the cap due to near surface gas transmission. The bottom of the model was assigned a constant boundary temperature of 75°F, a conservative estimate of the ground temperature 40 feet (or more) below the bottom of waste.

3.2.2.3 Material Assignments

The materials in the model were divided into waste and bedrock. Each material was assigned a value for permeability, porosity with respect to flow, porosity with respect to heat, heat conductivity of the solid, heat capacity (C_p) of the solid, internal heat generation (referred to in FEFLOW as Source/Sink) for the solid. All other assignments used by the model were left to the default settings as they did not impact the modeling were required to be assigned.

The internal heat generation value (energy per unit volume) was used to represent energy release in decomposition of the waste as well as any release of energy by the processes referred to as the “reaction” in the south quarry. It should be noted that the assignments were made as constants for various regions of the waste mass. This is a conservative assumption in that it presumes that the energy generation is a constant with time and does not diminish. Observations at the site strongly suggest that the energy released in the “reaction” diminishes after some time. This can be observed in the lowering of temperatures in TMP 31 and 32, for example. In addition, the energy released via decomposition of the waste under normal conditions diminishes with time and becomes near zero when temperatures elevate above 167 °F, above this temperature the bacteria responsible for generating methane die. Therefore, energy assignments to non-reacting waste, especially in the neck area and north would reduce as the temperature increased. At the present time, a function that would account for either of these time or temperature related phenomena has not been developed. Therefore, predicted temperatures resulting from modeling using this set of heat generation assumption should be viewed as conservatively high with time, as the excess energy per unit time is cumulative. Material assignments in the made to the evaluation model are depicted in Figure 3, Figure 4, and Figure 5 for thermal conductivity, C_p, and internal heat. The figures depict the assignments in sectional view. No variation in assignments was made in the direction perpendicular to the sections shown.

3.2.2.4 *Groundwater Considerations*

FEFLOW requires that groundwater levels and other hydraulic related properties need to be entered to perform heat flow analysis. To simplify matters, the porosity with respect to heat flow was assumed to be an nominal 0.01 for all model layers. Ground water level within the model was assigned a uniform elevation of 495. No flow gradient results from this assignment, making the permeability of the material of no consequence. The assignment of a porosity value of 0.01 for the solid removes any dependence on the water level in the model. The assignment of water levels is not intended to suggest a piezometric surface but only to allow the assignment of a uniform set of heat properties without concern for composition or saturation in the waste.

3.2.3 BOREHOLE EXTRACTION UNITS

BHE of the type used or proposed for use at the site are commonplace in type and were contained in the BHE data base contained in the FEFLOW software. Screen shots of the data input page for the units are provided in figures of this report. A detailed explanation as to how the model uses these heat exchange features are used in the model can be found in chapter 13.5 of the FEFLOW reference book [2]. The use of these elements allows the variables of

- boring diameter,
- grout or backfill conductivity,
- pipe or tubing size and conductivity,
- flow rate, and
- varying or constant temperature of fluid circulated

to be included in the analysis with ease.

The ODM back calculated the approximate exchange properties of the GIW units based on the pilot study. These were left unchanged for this evaluation. The properties of the HEW were model default calculated based on the diameter and materials anticipated. The evaluation examined the HEW exchange properties based on the measurements taken during the operational period. This resulted in a change of the properties used as is explained later in this report.

[2] (Diersch, 2014)

4 EVALUATION OF ENERGY EXTRACTION

4.1 INITIAL TEMPERATURES

The initial time of the HEB options was October 11, 2016. At that time a number of added TMP units had been installed in the area of the quarry neck and the HEW line became operational along with the GIW extractors.

4.2 TEMPERATURE BOUNDARY CONDITION ASSIGNMENT

Boundary conditions on the north and south face of the model were identical to those presented in the ODM and reported in (P. J. Carey & Associates, P.C., 2015). The north boundary condition was based on TMPs-16 and 17. A 6th order polynomial function was used to approximate the variation with depth. The function was modified to convert depth to elevation and temperature from F to C and used to assign the boundary conditions across the north model face. The south face boundary condition was computed similarly using current readings from TMP -31, TMP-32 and readings from TMP-8 and TMP-7R from earlier dates (prior to failure of the units).

4.3 INFLOW TEMPERATURE

The inflow temperature, outflow temperature, flow rate and concentration of glycol in the circulating fluid have been monitored since the beginning of the HEB operations in October. Beginning in mid-November of 2016 readings were recorded automatically at 10 minute intervals, excepting power outages and when power surges damaged recording instruments. These recorded values were used to compute energy extraction rates and total energy extracted for each extraction unit. This information has been summarized in monthly reports and has been used as the basis of evaluating this heat extraction model. Specific discussion of flow temperatures used in the modeling are discussed below.

4.3.1 RECORDED INPUT TEMPERATURE CONDITIONING

The ODM was performed using an idealized cooling liquid inflow temperature model that was based on offset from the average monthly dew point and a lower temperature constraint of 40 °F. Examination of the actual circulation temperatures are depicted along with the idealized temperatures in Figure 6. As can be seen, the minimum temperature for the inflow was 45 °F. The recorded temperature used was that from the GIW 5 inlet temperature wireless device, supplemented by the initial data recorder on HEW 8 during October and HEW 5 recorded values when temperature records were not available from GIW 5. Actual temperatures were also significantly higher than assumed when the spray unit was not operating. As can be seen in Figure 6, temperature varied constantly. The constant change in temperature cannot be used in the modeling of the bore hole extractors (BHE) using the quasi-static Eskilson & Claesson's solution without significant error. Attempts to use a fully transient solution for the BHE simulation (Al-Khoury et al) were not successful as they required time steps of less than 1x 10^{-5} per day during the periods of change and experienced convergence failures prior to one day of elapsed time. This issue of fluctuation in temperature is only of interest if one trying to match the energy recovery over short, i.e. less than 1 day time intervals. Use of a smoothed inflow temperature that provides the same average temperature over time and eliminates significant rates of change avoids this issue and does not material impact the rate extraction computed over time.

The input temperature record was processed using a Gaussian kernel method with a bandwidth. This is a built in data processing function in the commercially available software Mathcad. The band width was varied from 1 to 14 and the resulting smoothed time /temperature records were evaluated to see if the average time weighted average smoothed temperature was comparable to the time weighted average recorded temperatures. Based on review of the smoothed values with varying bandwidth it was decided that a bandwidth of 7 provided adequate smoothing and allowed for a time history record based on 0.25 day time steps to represent the smoothed data. The interpolated temperature values at the time steps were generated by the linear interpolation function in Mathcad for the time beginning on October 11, 2016 and ending on August 31, 2017. The interpolated temperature values are shown graphically in Figure 7 along with the recorded time history.

4.3.2 PROJECTED FUTURE INFLOW TEMPERATURE

The temperature flowing into the BHE beyond the recorded time was estimated based on the assumption that the cooling system would remain in its current state. As such, the minimum temperature during the cooler months was increased from 40 °F, assumed in the ODM, to 45 °F and the average temperature during the warm months was assumed to be 76.4 °F, which assumes the spray system remains operational. The temperatures were assumed to be cyclic, repeating annually. The time temperature function is shown in Figure 8.

4.4 STARTING TEMPERATURE ASSIGNMENT

The initial starting temperatures used for the Day 222, referenced to an arbitrary date of March 3, 2016. This time offset allows running of the model in pre-operation of HEB mode to allow changes in properties and adjustment of starting conditions more simply. The model was allowed to progress in time until the temperatures in the vicinity of the HEW units were similar to those existing in October 2016. Focus was placed on this line as opposed to the southern portion of the model, given the closer proximity to the area of compliance and intent to allow over estimation of the in situ temperatures to occur in the vicinity of the GIW units and southward. The initial starting temperatures along a N-S section line are depicted in Figure 9 – HEB Initial Temperature Section ViewFigure 9 , which include the impact of operation of the southern GIW units since the fall of 2015 and the northern GIW units since June 2016. The temperature is also depicted in plan view for depths of 100 and 210 feet in Figure 10 and Figure 11, respectively.

4.5 MODELLING PROCEDURE

The procedure used to check the ODM against the measured conditions at the site consisted of a comparing the energy extracted from a central HEW unit depicted with the label g on the plan figures (used through this evaluation as the BHE of comparison) with the average of the energy extracted from HEW units 7 through 12. In addition, four temperature observation points were inserted in the model to reflect those in the field located near the center zone of the neck area. These are labeled A – (depth below top of model in ft). The relationship to the in ground temperature points are shown below.

Model Observation Point	Similar TMP in Field
A-*	TMP-2R
B-*	SPM-4
C-*	SPM-1
D-*	TMP-14R

All other neck area tmps are located outside of the central zone and impacted by the quarry wall or shallower waste thickness.

These observation points allow the tracking of temperature at the model locations are were shown as scatter plots for times of interest to look at model versus actual temperatures as an aid in understanding how the various model assignments impact the model results.

No attempt to specifically "calibrate" the model to the tmp values given that the model is idealized and the tmps are in a non-idealized setting. Further, variation is waste composition, locally variability of heat related properties and local variation in both reaction generated heat, heat conduction from warm areas, heat moved via gas collection and or vapor transport and condensation, and biologically generated heat through methanogenesis in the area north of the HEW line are all variables that cannot be specifically defined at any one time or projected in any detailed fashion into the future. Therefore, the assignment of heat generation and variation of material properties has been done to achieve a closer agreement with actual heat removed and the pattern of temperatures measured only. A comparison between model predicted temperatures and the observed temperatures in the similar TMP are shown in Figure 12 just prior to beginning operation of the HEB.Figure 12

4.6 DISCUSSION OF HEW UNIT HEAT RELATED PROPERTIES

As mentioned earlier in this report, it was found that the BHE properties computed by the software in the default mode did not allow sufficient heat into the extractors (approximately 50% of measured). This remained the case regardless of the grout conductivity assigned. It was found that manual assignment of retardance factors shown below.

HEW RETARDANCE VALUES

ITEM	**Model Computed**	**Assigned Manually**
Grout to Soil	0.03211 m sec K/joule	0.04 m sec K/joule
Pipe In to Grout	0.4479 m sec K/joule	0.02 m sec K/joule

Pipe Out to Pipe in	0.1389 m sec K/joule	0.08 m sec K/joule

Resulted in an extraction rates consistent with the measured behavior and responsive to changes in waste heat conductivity and waste specific heat. It should be mentioned that grout testing for thermal conductivity resulted in a conduction of approximately 1.7 W/mK, which was used by FEFLOW in the model computed values. The manually assigned values were used for all the simulations presented in this report for the HEW line units. The GIW unit properties were evaluated previously for the ODM and were not changed for this report modelling effort.

4.7 MODIFICATION OF HEAT RELATED MATERIAL PROPERTIES

In addition to change from assignments made in the ODM for the inflow temperature and properties of the, heat conduction of the waste, heat capacity of the waste, heat generation within the waste and surface conduction rate constant were also evaluated.

A drop off in heat removal rate following the initial 6 months in the model indicated that the heat capacity and heat conduction properties of the waste were likely a bit low. These were increased from 1.4 to 1.6 W/mK and 2.4 to 2.6 Mjoule/m^3K to obtain better fit with observed behavior. In addition, the heat generation rate within the waste in the area between the GIW and north and of the HEW line as increased altered to reduce the heat generation rate to the south of the HEW line and slightly increase it to the north of the HEW line. A value of 0.32 W/m^3 was used for this region instead of 0.28 in the ODM. The final change was the lowering of the surface out transfer rate that is used in the 3rd kind (Cauchy) heat transport boundary condition control for the ground surface. This value was lowered from 600 Joule/m^2 sec K to 550 to result in a slight increasing of the temperatures closer to the ground surface.

5 HEAT EXTRACTION MODEL EVALUATION

The original design model (ODM) with minor adjustments as described in the preceding sections was run to simulate the period from October 11, 2016 through September 11, 2017 while making minor changes in the variables discussed in Section 4.7. After some initial exploration of the impact of various variables three model runs were selected for presentation. They are referred to Model Run 4, Run 5 and Run 6. Model Run 6 was extended 2 years into the future and is referred to as Run 7.

TABLE OF ASSIGNED VALUES PER RUN

RUN	Waste Heat Conductivity	Waste Heat Capacity	Heat Generation Rate in Zone Proximate to HEW Line
Run 4	1.5	2.4	0.28
Run 5	1.8	2.6	0.30
Runs 6 and 7	1.6	2.6	0.32

5.1 DISCUSSION OF RESULTS

The model runs 4 5 and 6 all showed general agreement with total energy removed during the period from October 11, 2016 through August 31, 2017, yielding 87%, 90% and 94% of the extracted energy for the runs, respectively. A plot of the energy extracted for each run is are shown in Figure 13, Figure 14, Figure 15, and Figure 16. A review of the plots shows that in all model runs the actual energy removed was higher than the model predictions. This is most likely the result of changing local heat generation rates in the waste materials in the area proximate to the HEW line as opposed to heat conduction or heat capacity issues. Localized heat generation rates would account the deviation in rate following the initial drawdown period and could result from reaction generated heat, biological heat generation in waste that has cooled to below 167 °F and possible heat transfer from condensation as moisture saturated gasses condense in the cooler temperatures near the HEW line.

The results of the modeling for runs 6 & 7 provide the best fit for the model relative to observed behavior while still conservatively including higher heat generation and temperatures south of the HEW line. The resulting model computed temperatures and scatter plots are presented in Figure 17 through Figure 31. These figures depict the temperatures calculated the model for Runs 6 and 7 at

- May 2017
- September 2017
- September 2018 and

- September 2019

For all dates the model depicts lowering temperatures within the vicinity of the HEW line and temperatures below 170 at all locations from 40 feet south of the HEW line northward. The model results also show the HEW line acts as a line with overlapping zones of influence, negating the need for any additional heat exchange devices between the current HEW units.

6 SUMMARY

The use of the approximately 10 months of data collected since the beginning of HEB operations was used to update the idealized neck are model used for the original system design. The data suggested some minor revisions in the some of the parameters assigned to the heat properties of the waste, and decrease in the retardance values for the HEW bore hole extraction units (BHE) were appropriate. Following making of those adjustments the current model predicted heat removal rates that were in good agreement with the measured data.

The data collected, along with the actual in ground temperatures, suggest that overall the higher heat generation within the waste due to the reaction appears to be lessening. Model predicted temperatures remained higher in the areas where the 0.7 W/m^3 heat generation rate has been assigned than measured in the ground.

The prediction of the model for the next two years presuming the heat generation rates in the hotter areas of the model show that temperatures within the area north of the HEW line will continue to drop and some reduction in temperature should occur in the areas south of the HEW line (within 40 of HEW line or further). Model predictions of heat at depth in the neck area appear higher than measured while model predictions at shallow depths are lower than actually measured.

Based on model predictions no change in the heat removal system is suggested.

7 WORKS CITED

Diersch, H.-J. G. (2014). *FEFLOW - Finite Element Modeling of Flow, Mass and Heat Transport in Porous and Fractured Media.* Heidelberg: Springer.

P. J. Carey & Associates, P.C. (2015). *Bridgeton-Neck Area Heat Barrier Design Report.*

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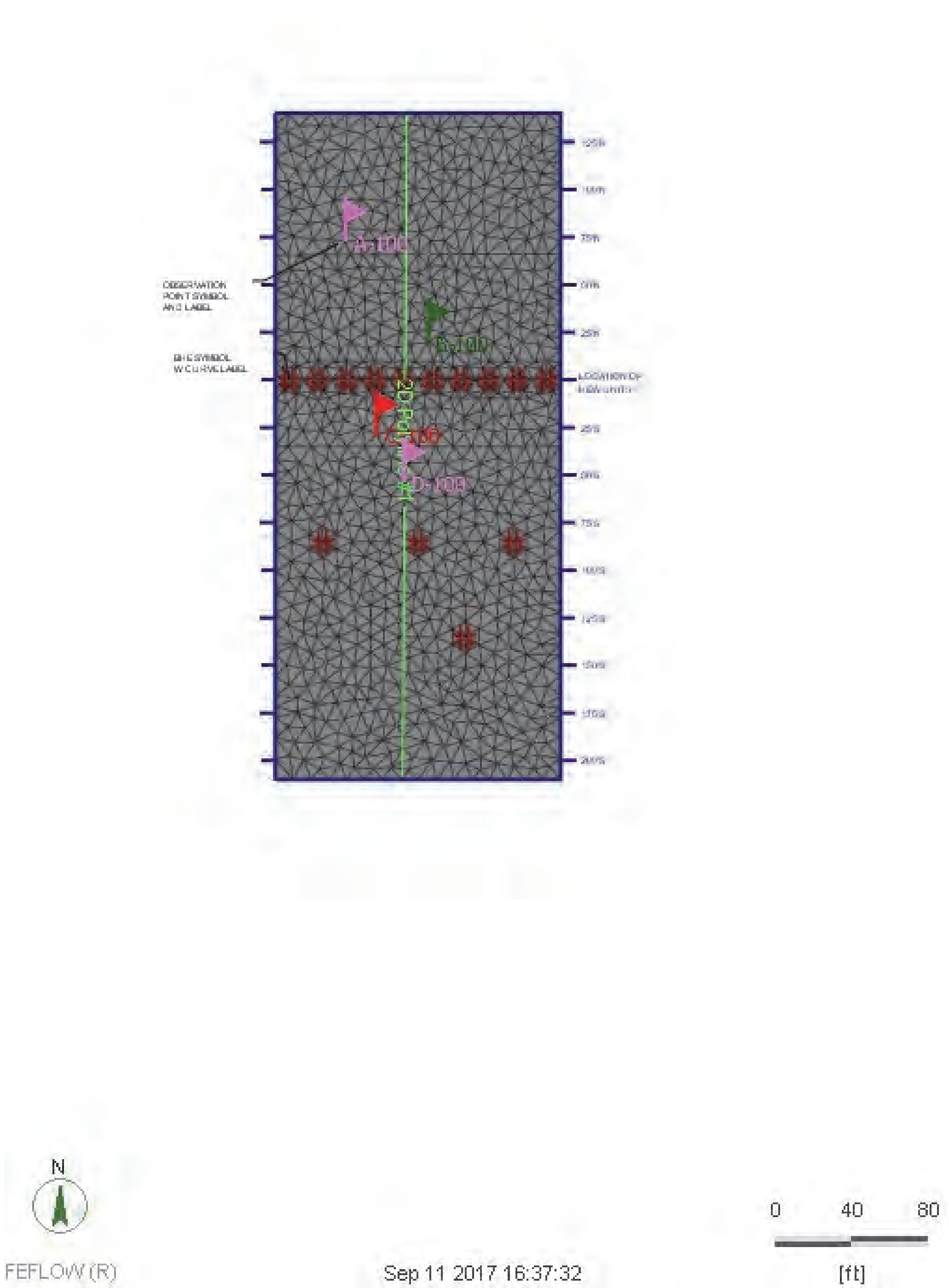
Figures

FIGURE - 1

Model Plan View Discretization

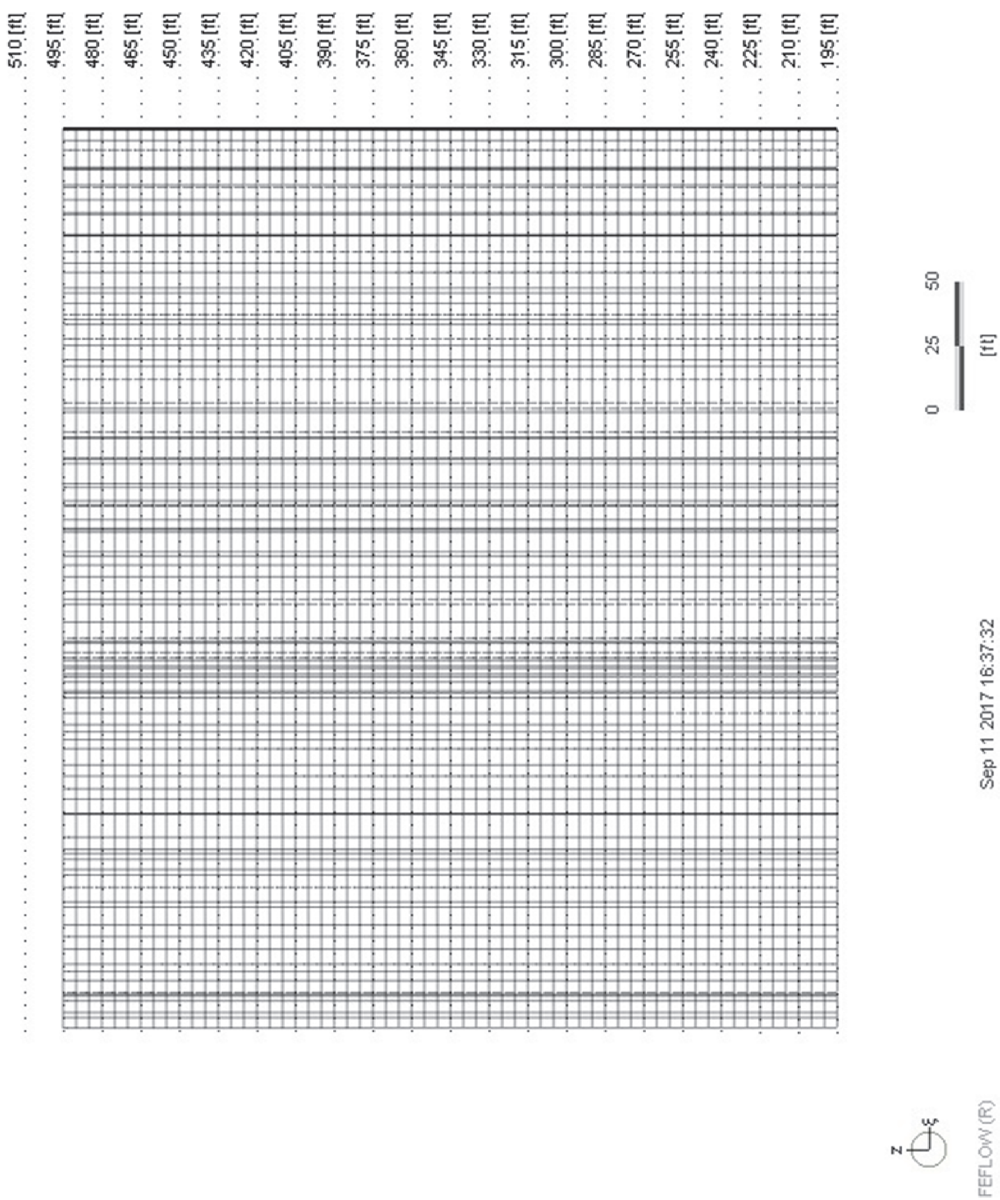


Model Discretization – Remeshed for this Evaluation

Also shows location of N-S section line

FIGURE - 2

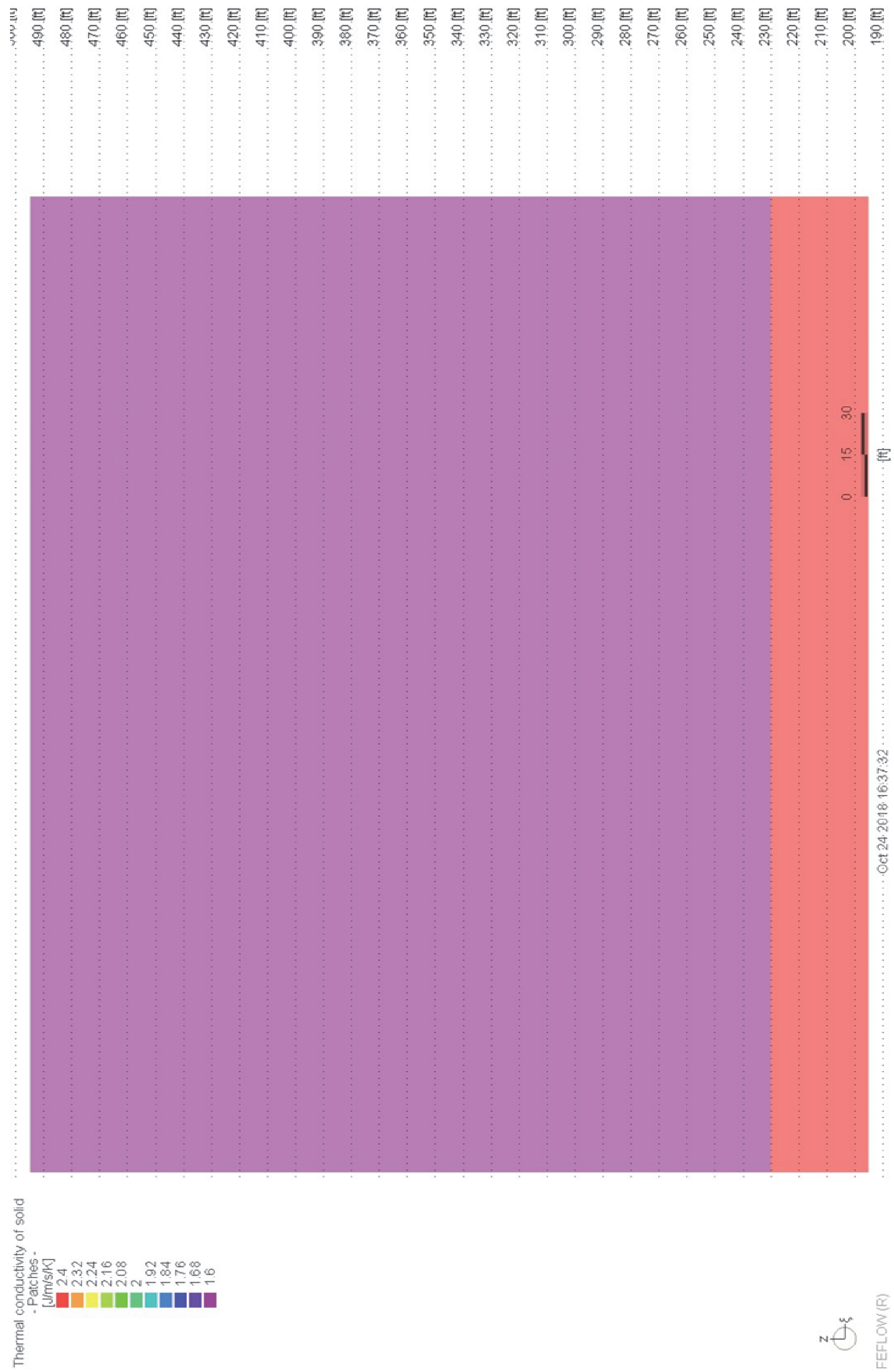
Model Section View Discretization



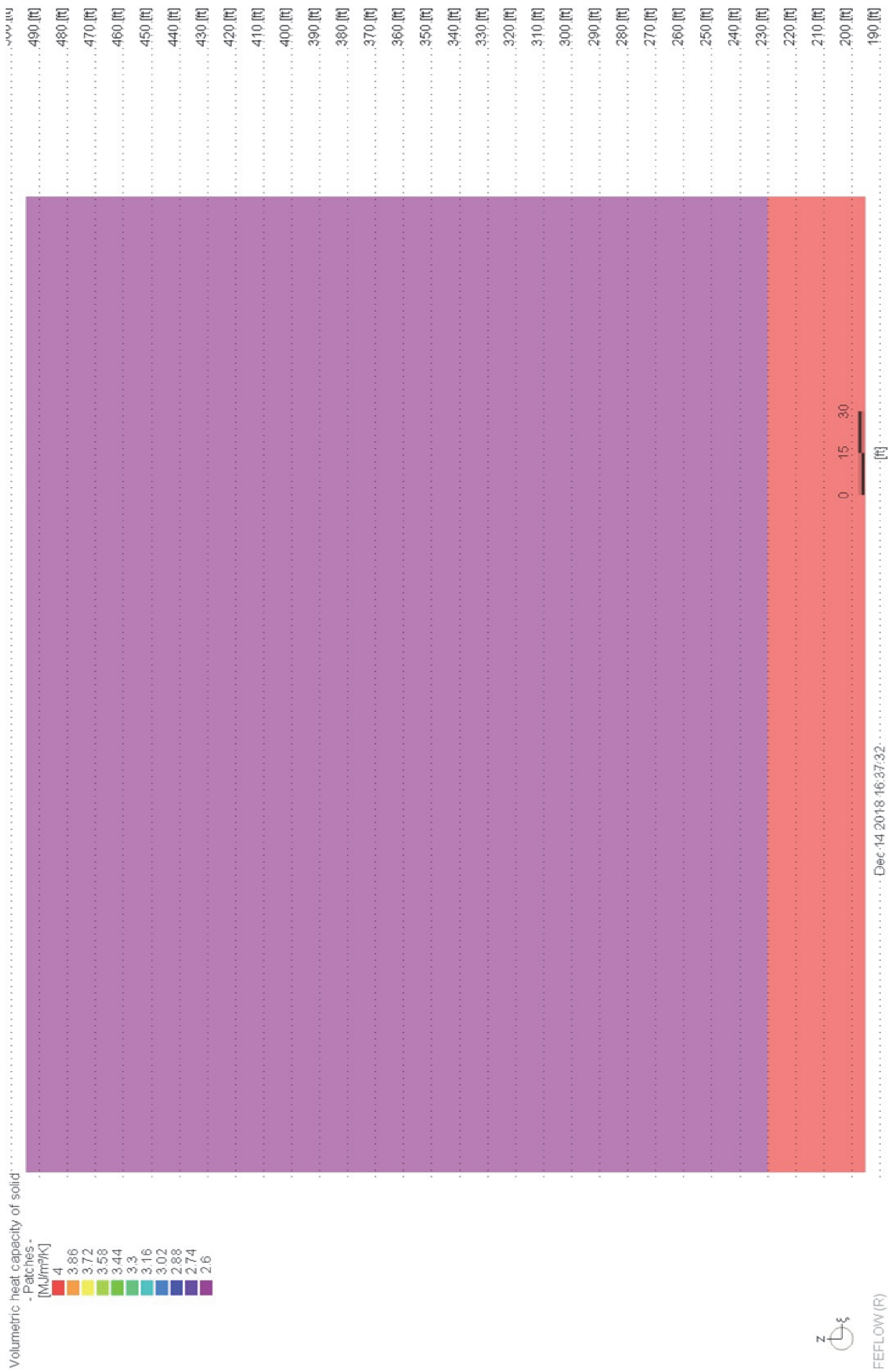
Model Vertical Discretization, used for this evaluation. North-South section shown. East side labels represent model elevations. Solid horizontal lines depict slice boundaries defining the 5 foot thick layers. Vertical lines represent element boundaries in along the section

FIGURE - 3

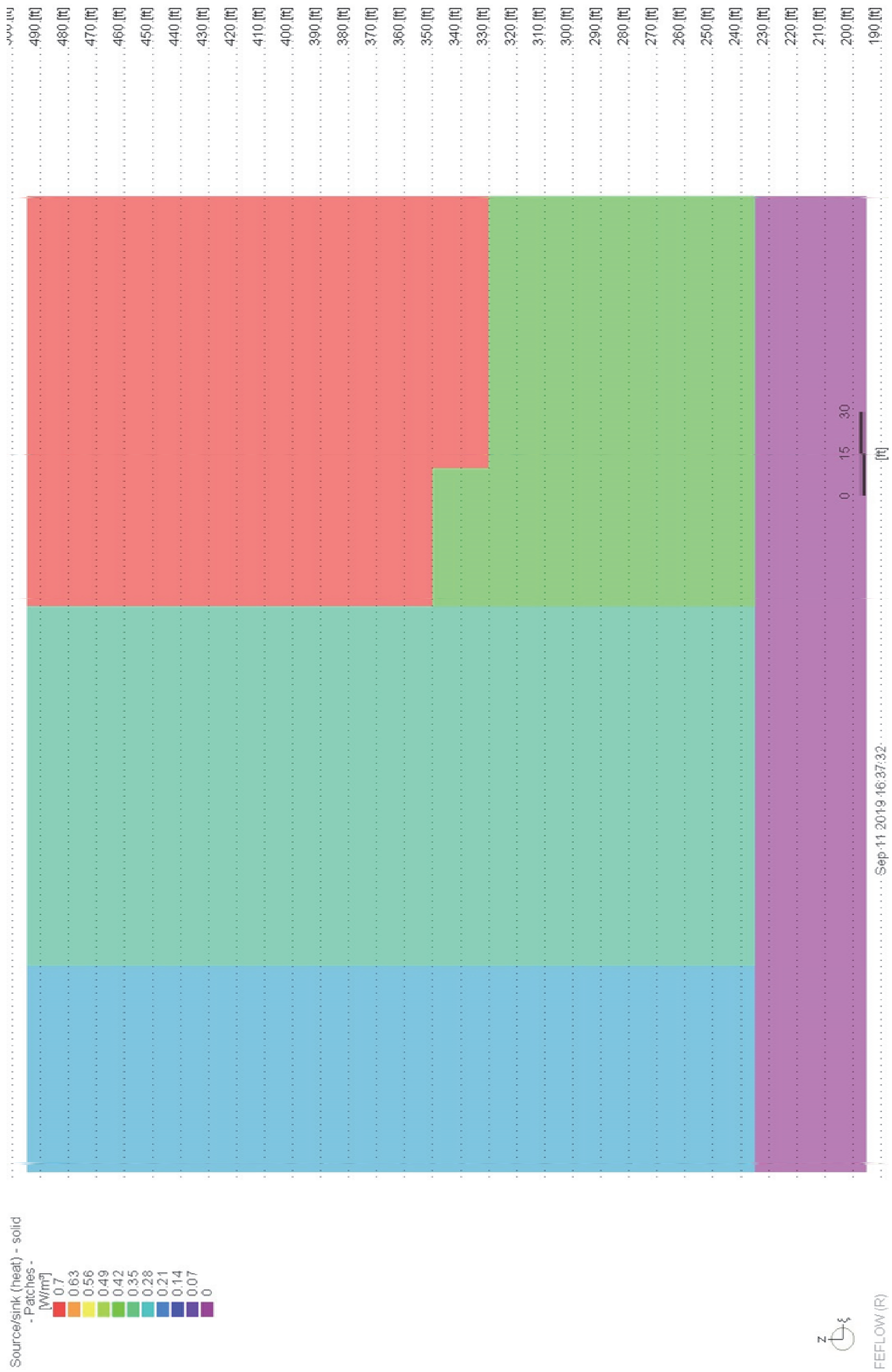
Model Heat Conductivity Assignment (Run6&7)



Model - Heat Capacity Assignments (Run 6&7)



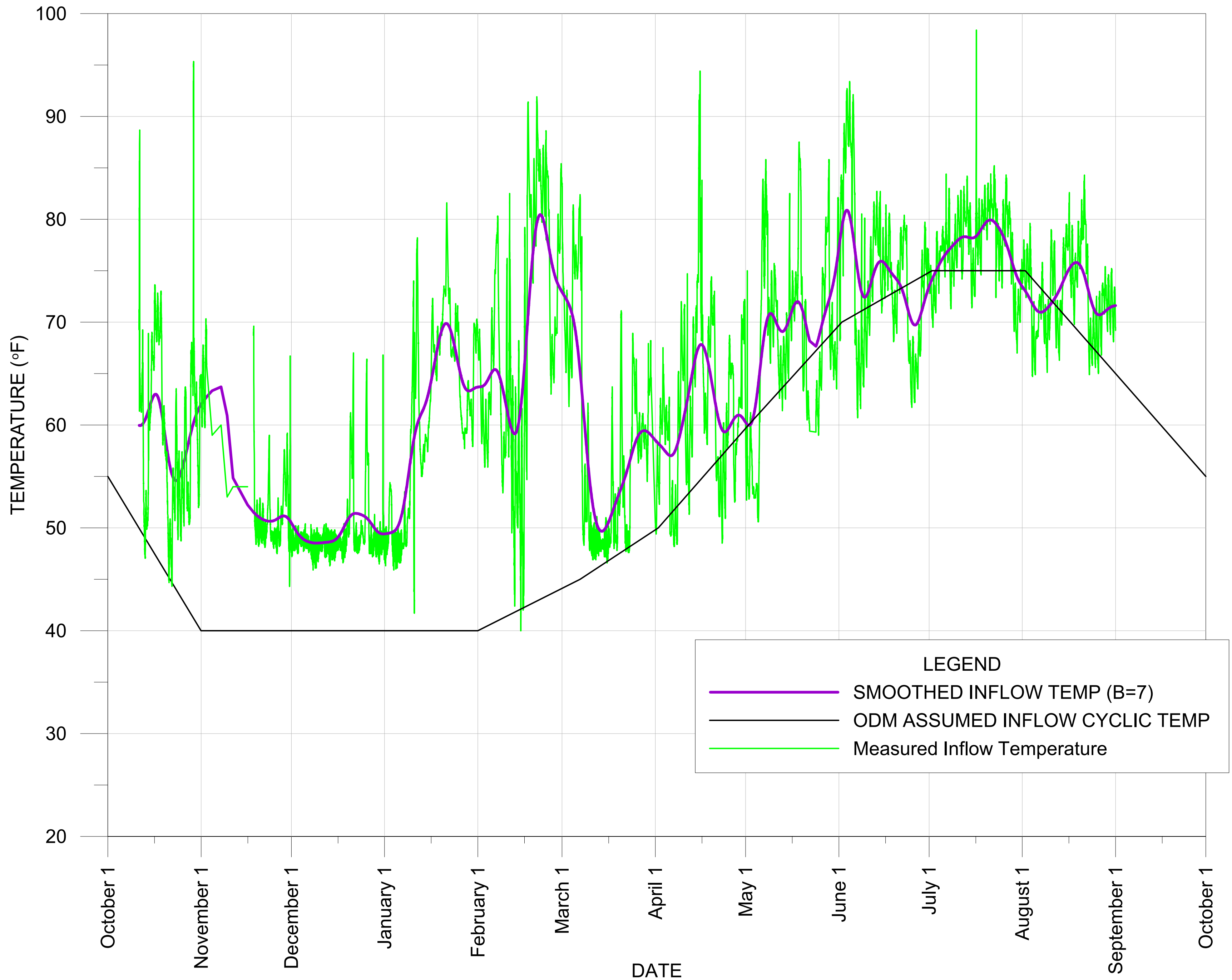
Model Internal Energy Assignments (Run 6&7)



Heat Source (Locally Generated Heat in Waste)

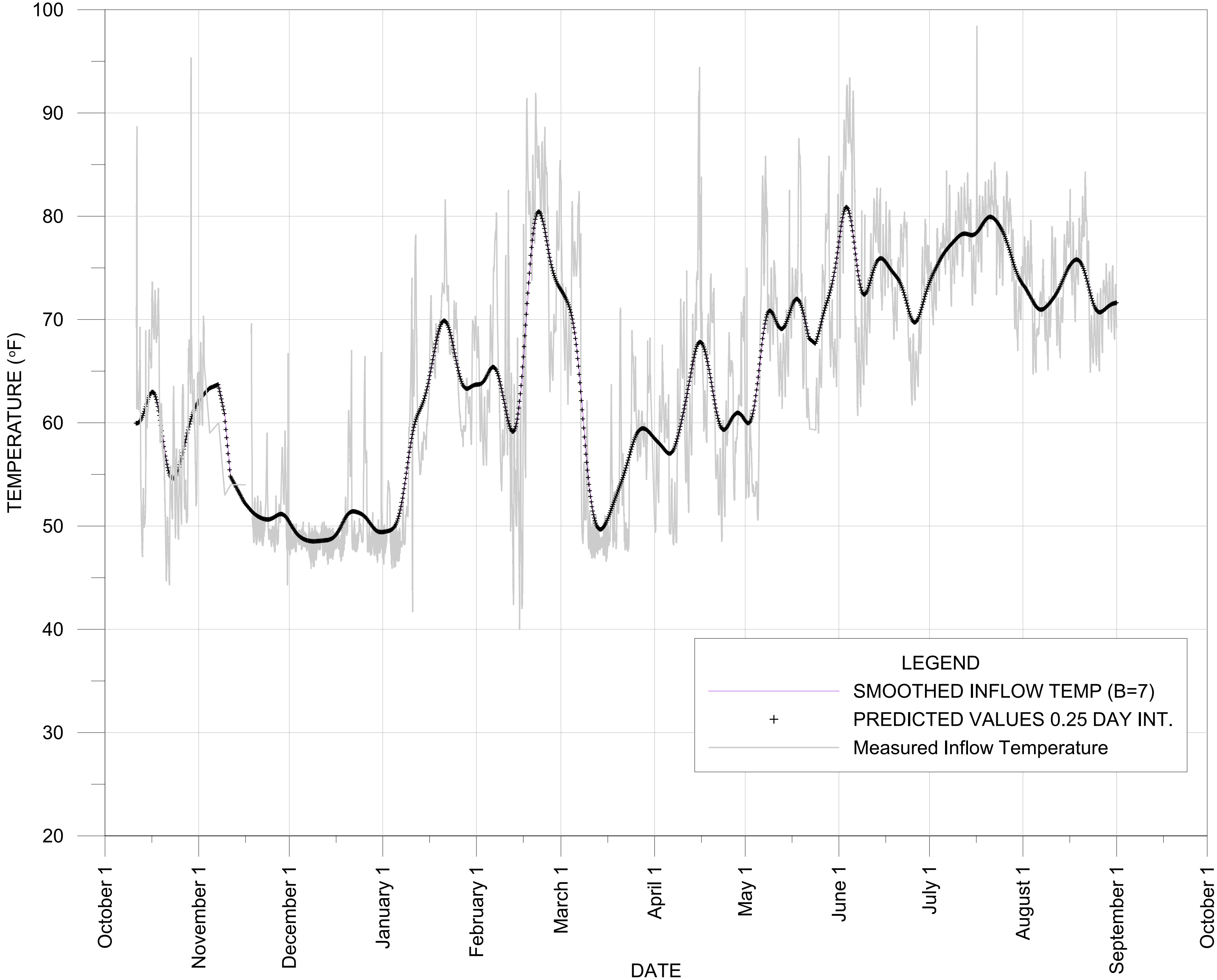
INFLOW TEMPERATURES - OCTOBER 11, 2016 TO SEPTEMBER 2017

FIGURE - 6

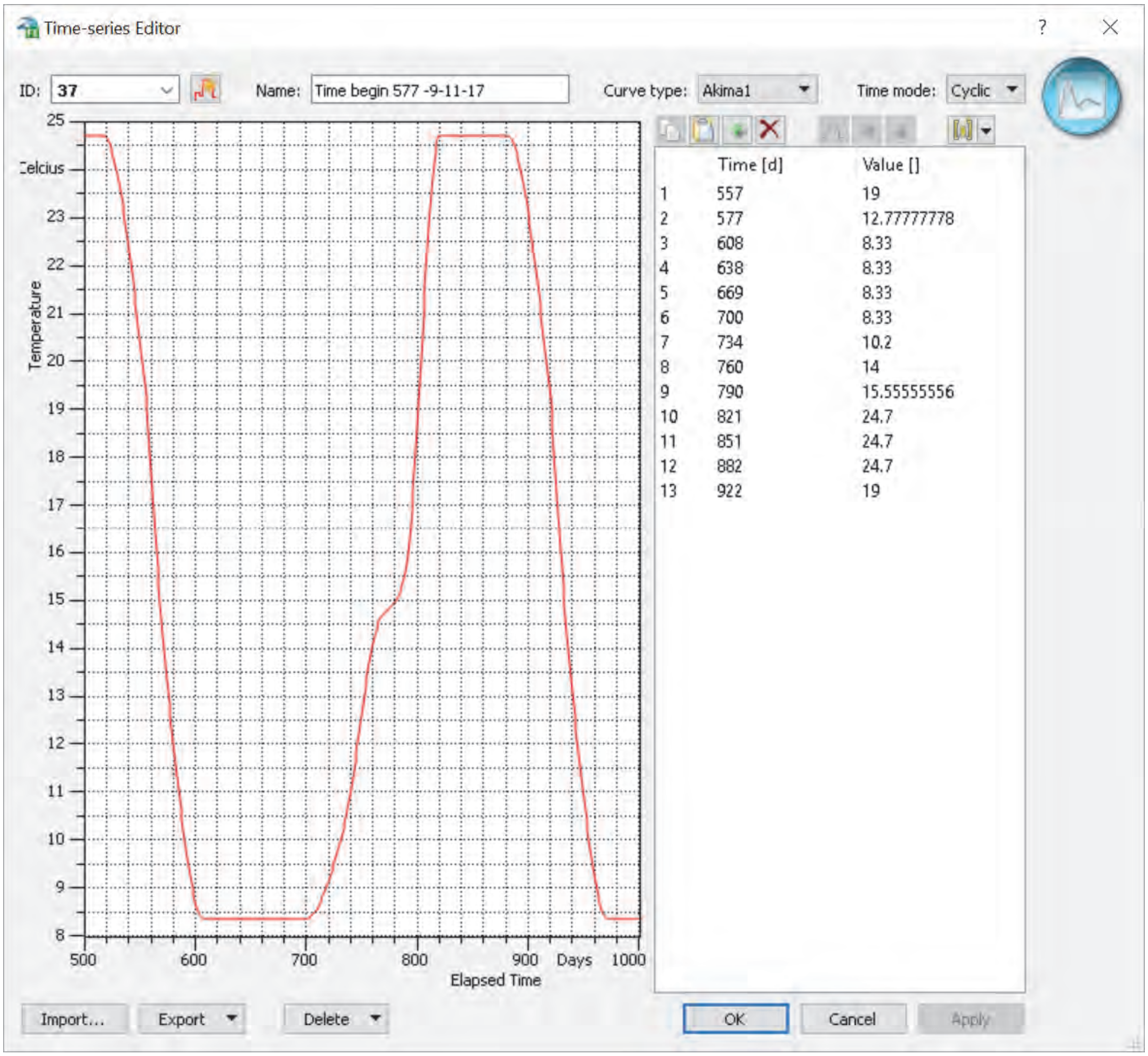


SMOOTHED INFLOW TEMPERATURES - OCTOBER 11, 2016 TO SEPTEMBER 2017
PROJECTED AT 0.25 DAY INTERVALS

FIGURE - 7

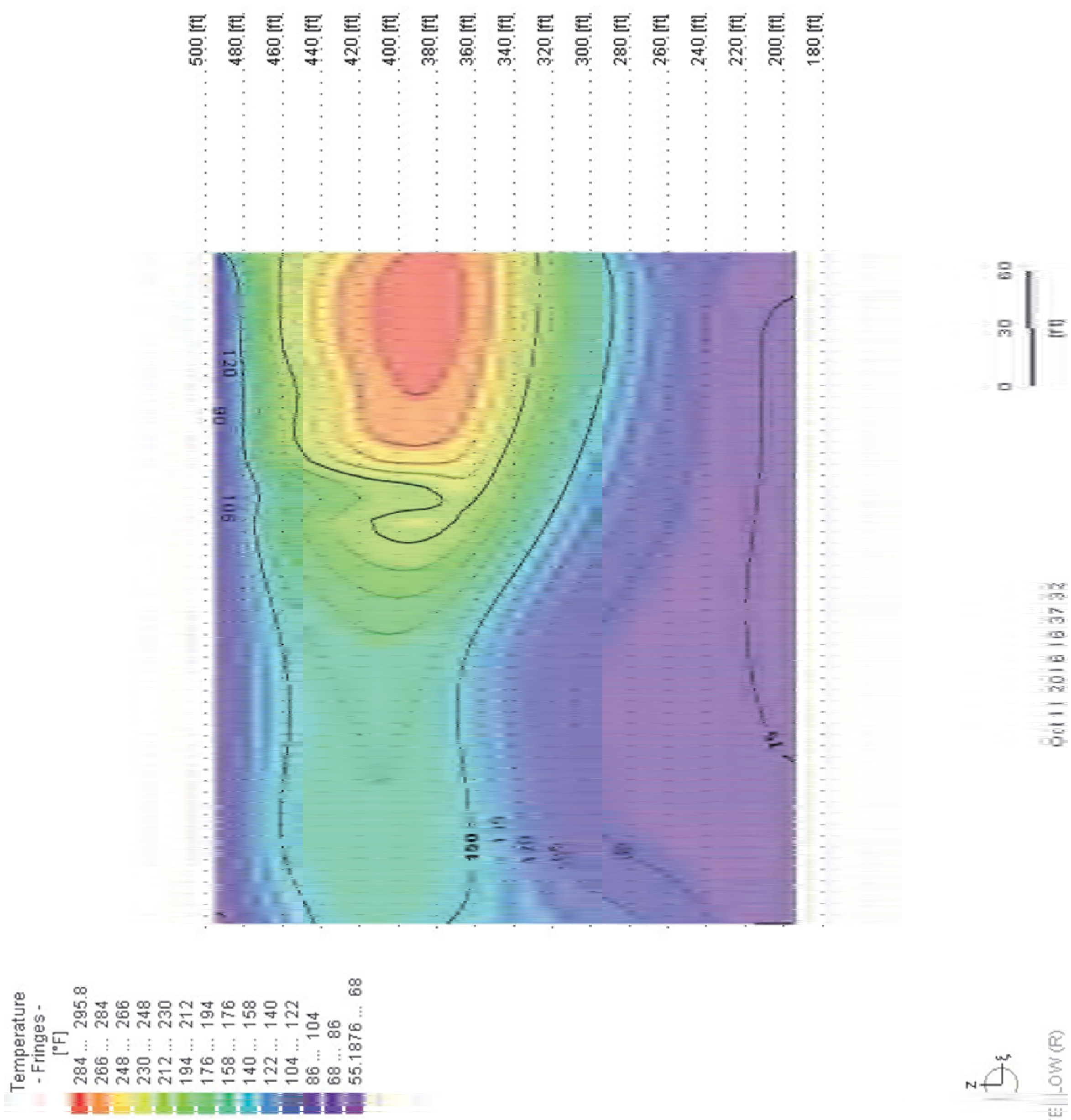


Future Inflow Temperature Variation with Time



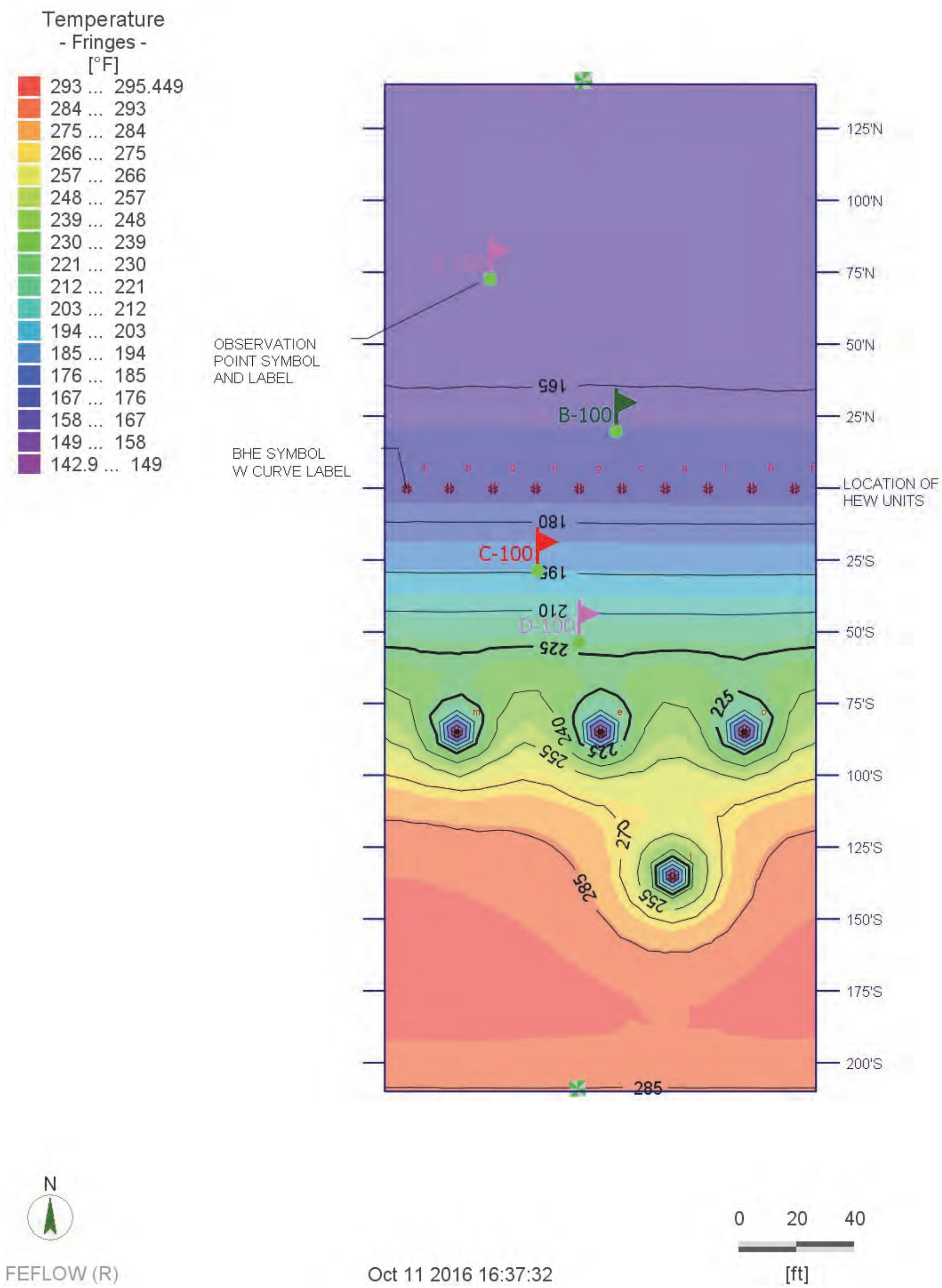
Extended Model Time Cyclic Temperature Function – Temperatures in Celsius

HEB Initial Temperature Section View



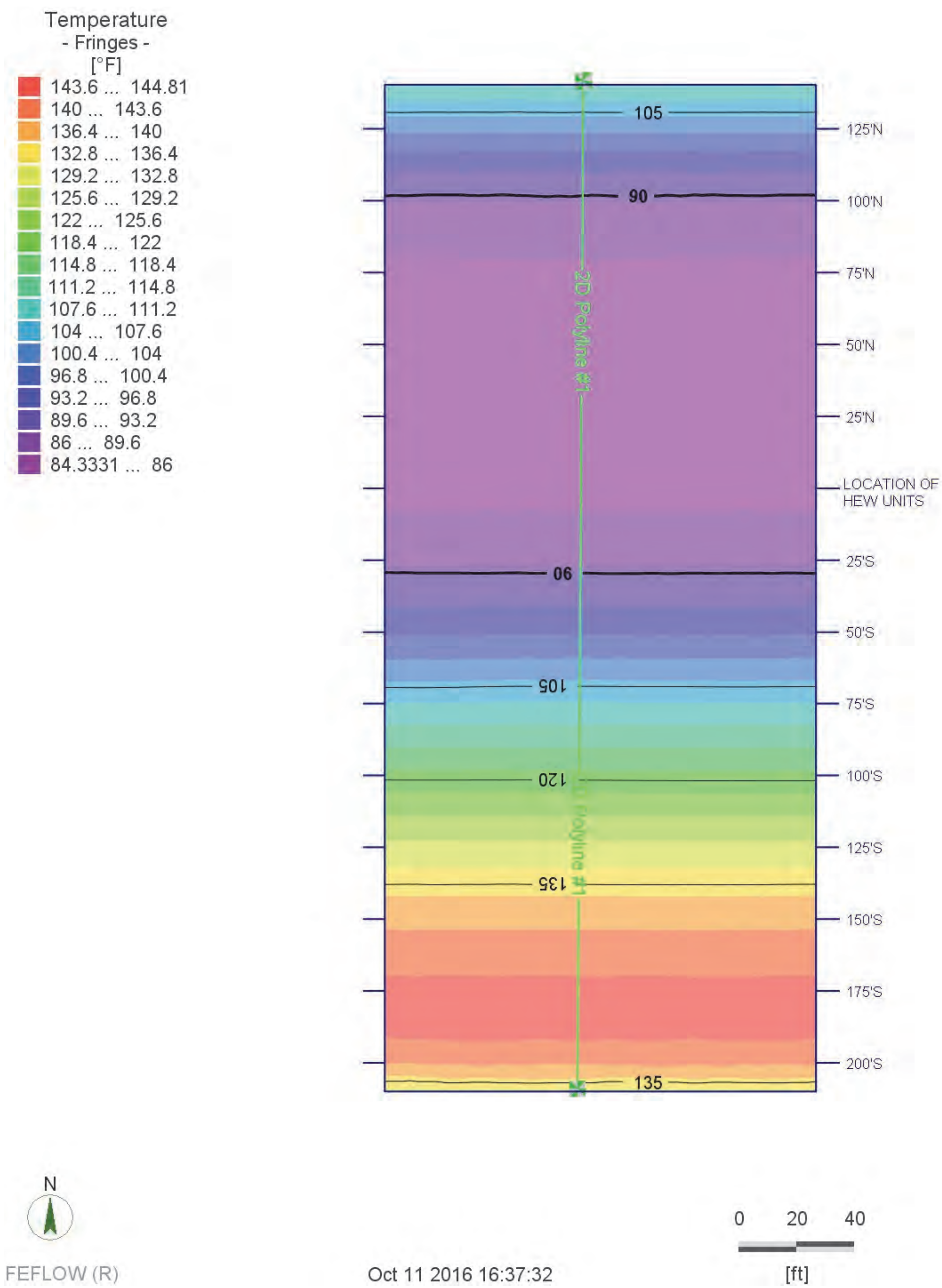
Plot of temperature, October 11/ 2016

HEB Initial Temperatures Plan View – Depth 100 ft



Run 6 Depth 100 feet Temperatures

HEB Initial Temperatures Plan View – Depth 210 ft



Run 6 Depth 210 feet Temperatures

FIGURE - 12

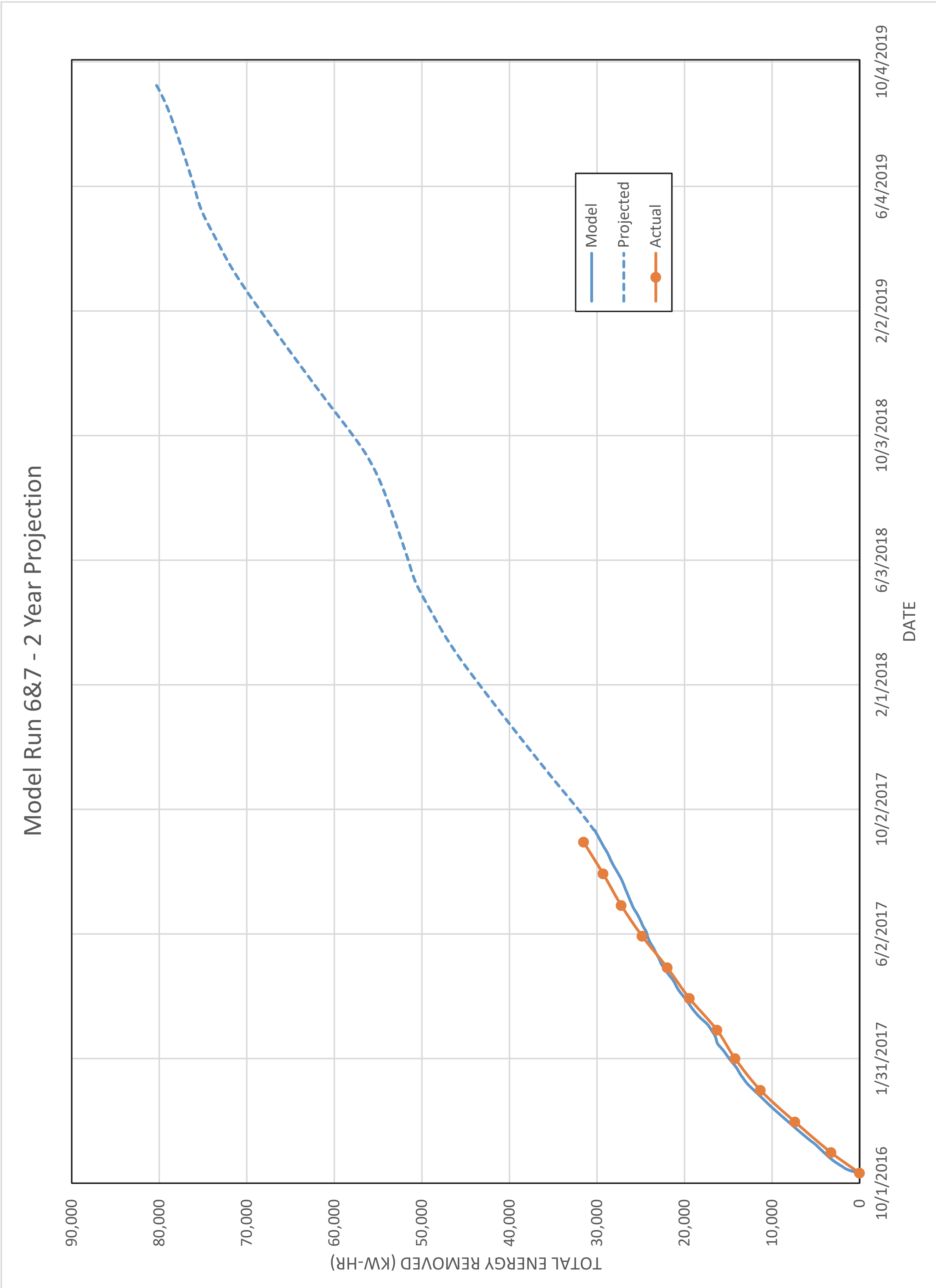
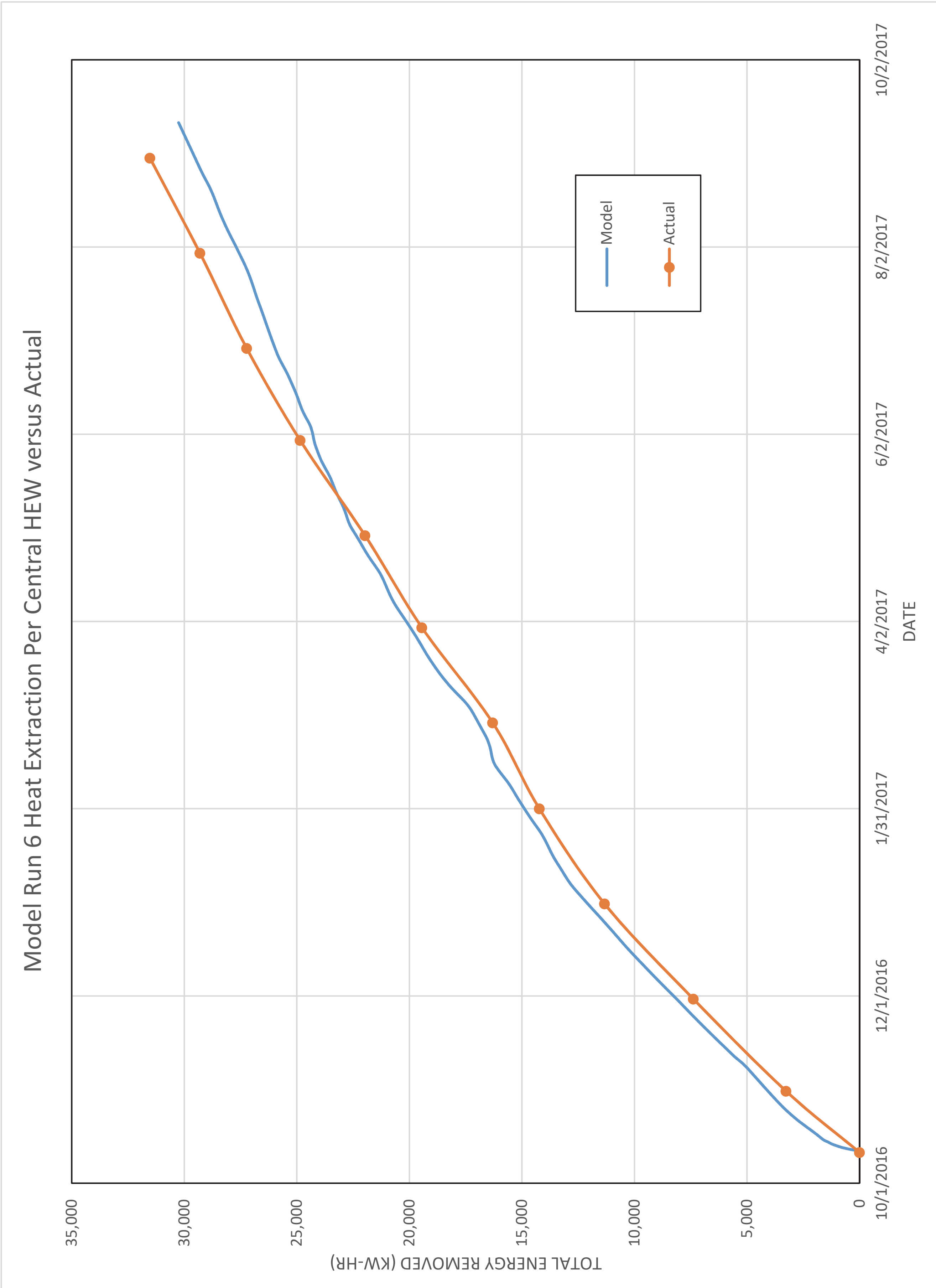
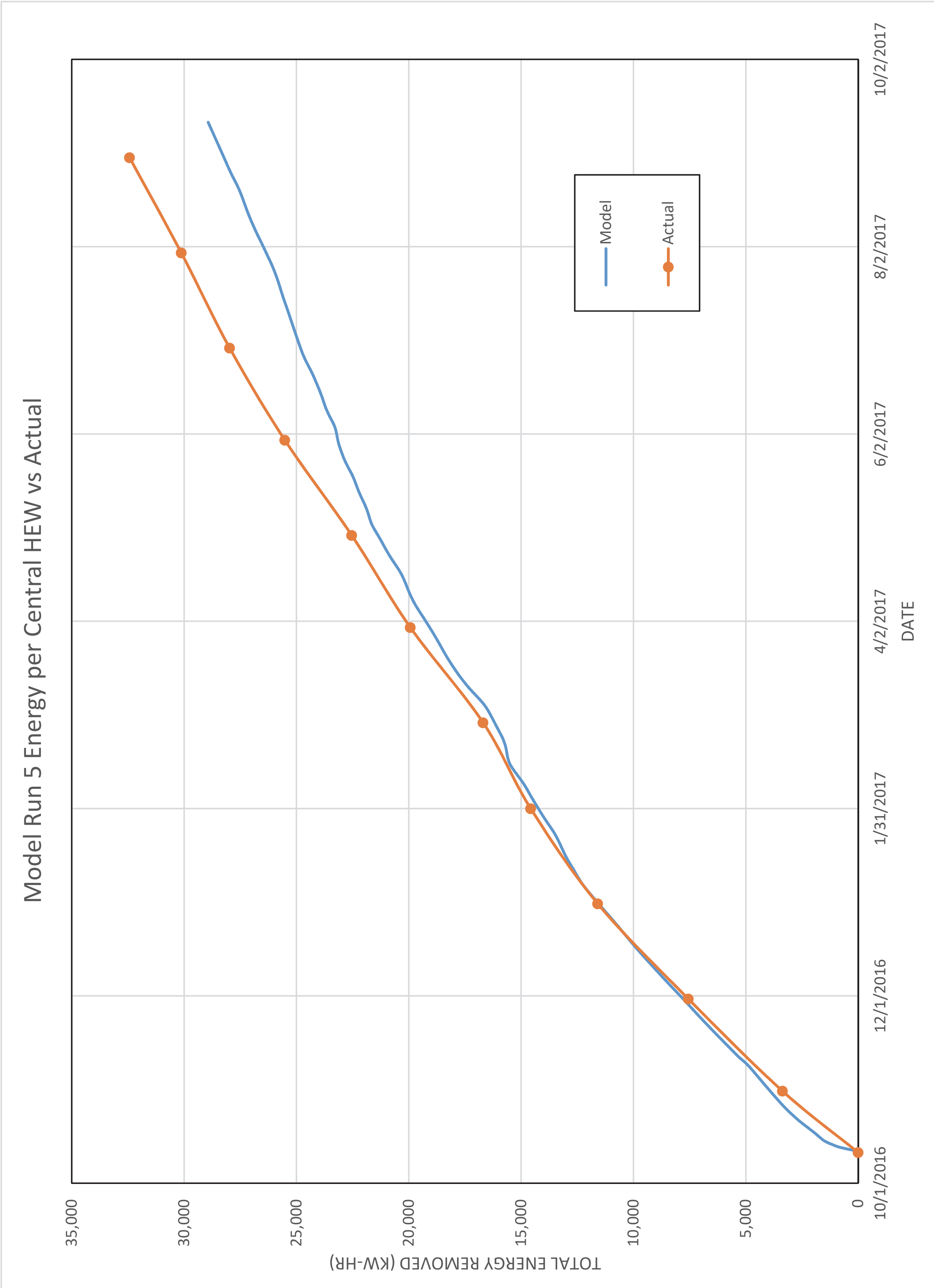

Model Run 6&7 - 2 Year Projection
TOTAL ENERGY REMOVED (KW-HR)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
DATE
10/1/2016
1/31/2017
6/2/2017
10/2/2017
2/1/2018
6/3/2018
10/3/2018
2/2/2019
6/4/2019
10/4/2019
Model
Projected
Actual

FIGURE - 13



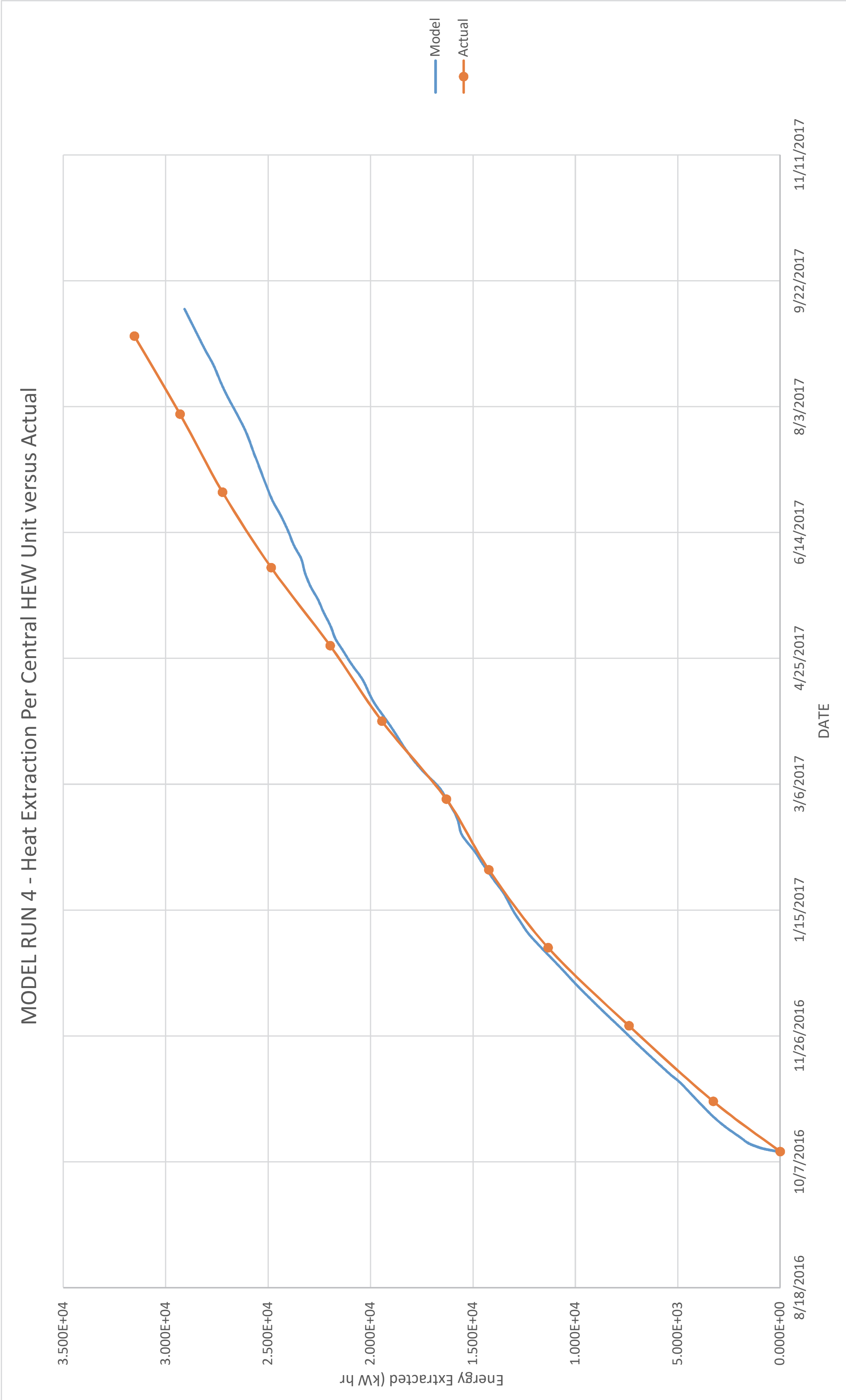
Model Run 6 Heat Extraction Per Central HEW versus Actual
TOTAL ENERGY REMOVED (KW-HR)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/2016
12/1/2016
1/31/2017
4/2/2017
6/2/2017
8/2/2017
10/2/2017
DATE
Model
Actual

FIGURE - 14



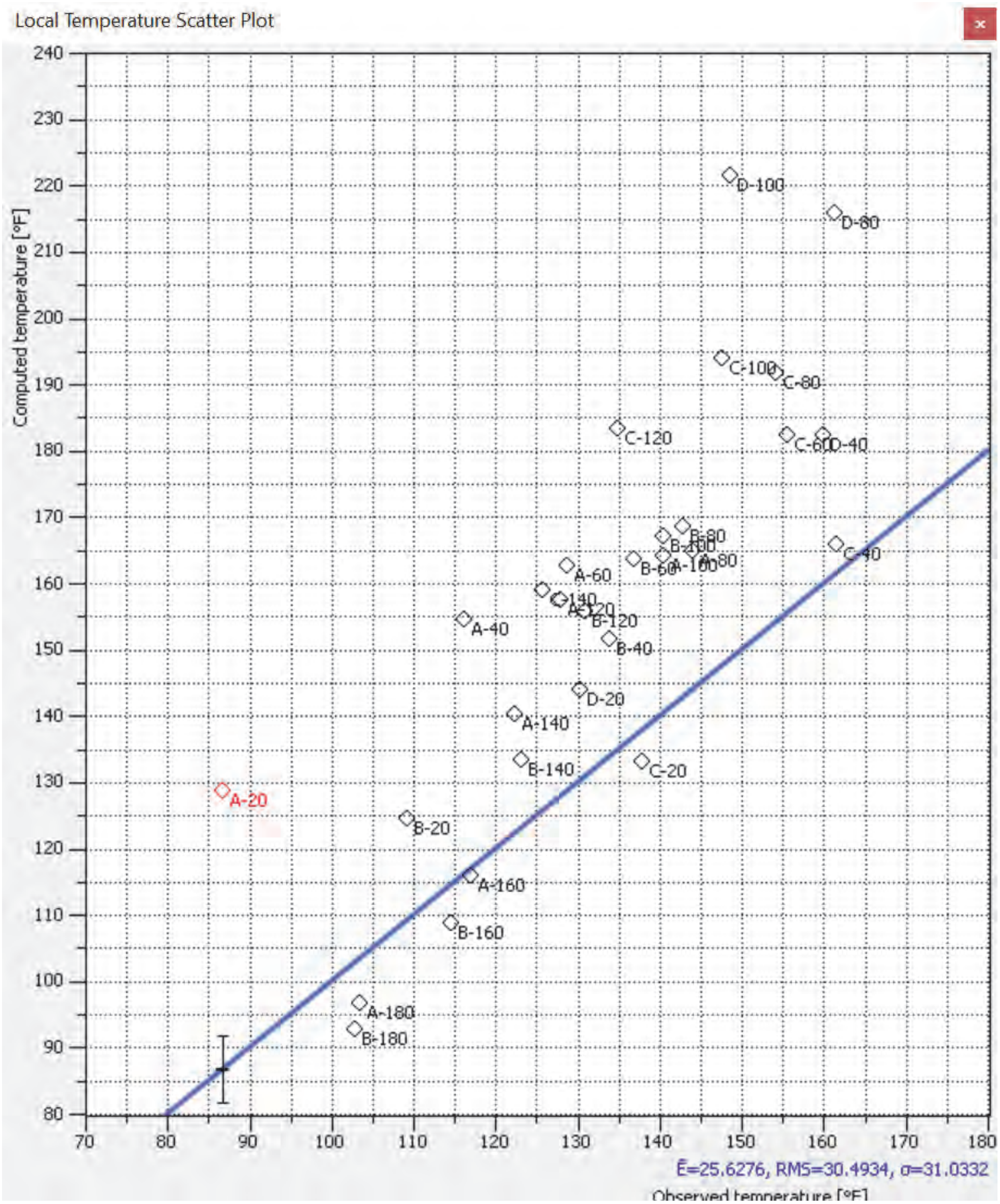
Model Run 5 Energy per Central HEW vs Actual
TOTAL ENERGY REMOVED (KW-HR)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
10/1/2016
12/1/2016
1/31/2017
4/2/2017
6/2/2017
8/2/2017
10/2/2017
DATE
Model
Actual

FIGURE - 15



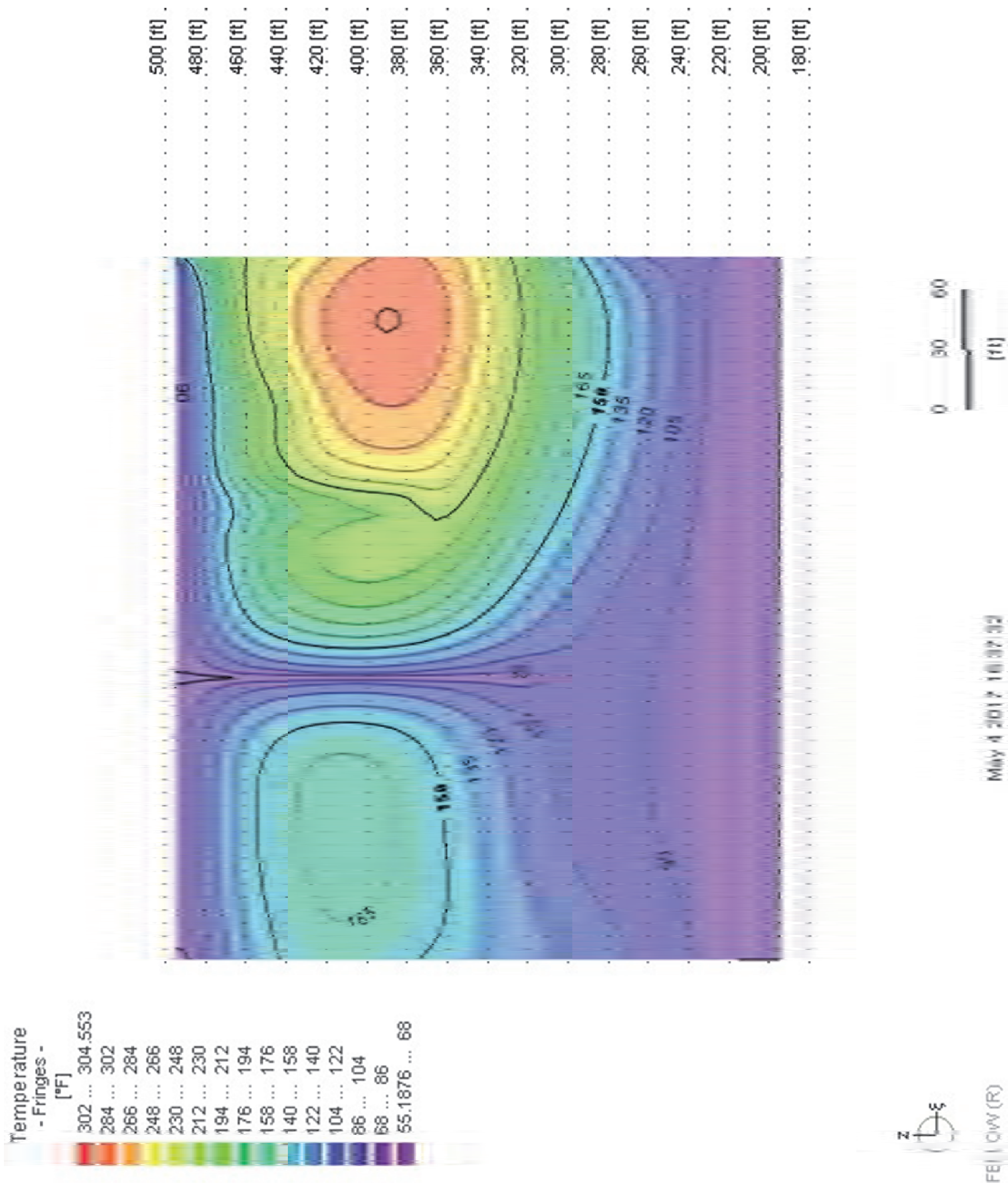
MODEL RUN 4 - Heat Extraction Per Central HEW Unit versus Actual
Energy Extracted (kW hr
3.500E+04
3.000E+04
2.500E+04
2.000E+04
1.500E+04
1.000E+04
5.000E+03
0.000E+00
8/18/2016
10/7/2016
11/26/2016
1/15/2017
3/6/2017
4/25/2017
6/14/2017
8/3/2017
9/22/2017
11/11/2017
DATE
Model
Actual

Observation Point Scatter Plot – October 11, 2016



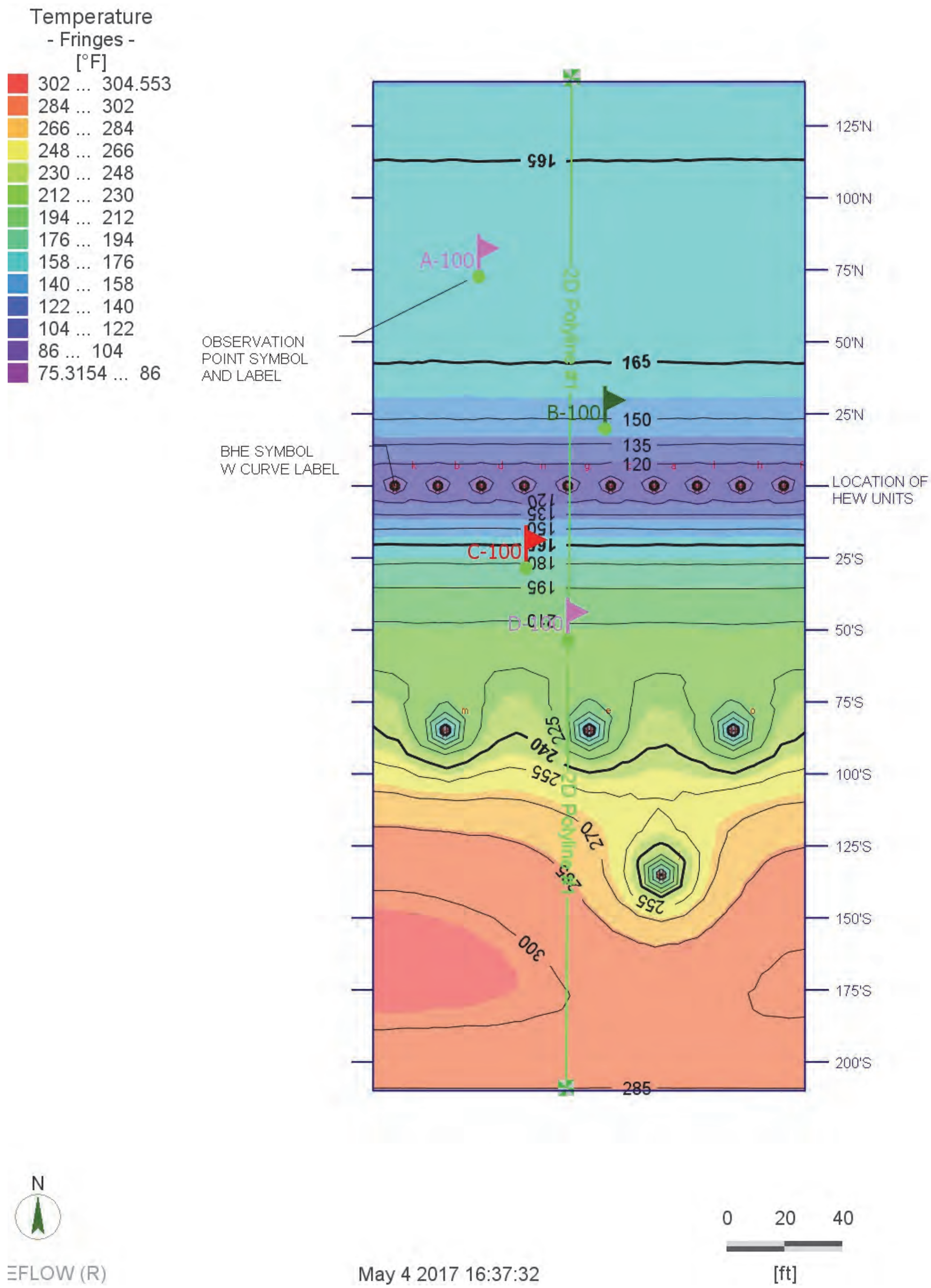
Scatter Plot – Observed Temperatures and Model Temperatures at Observation Point Series A through D - At beginning of HEB operations, October 11, 2016 – Blue Line for Reference where observation and computed values are equal

HEB Temperatures Section View May 4, 2017



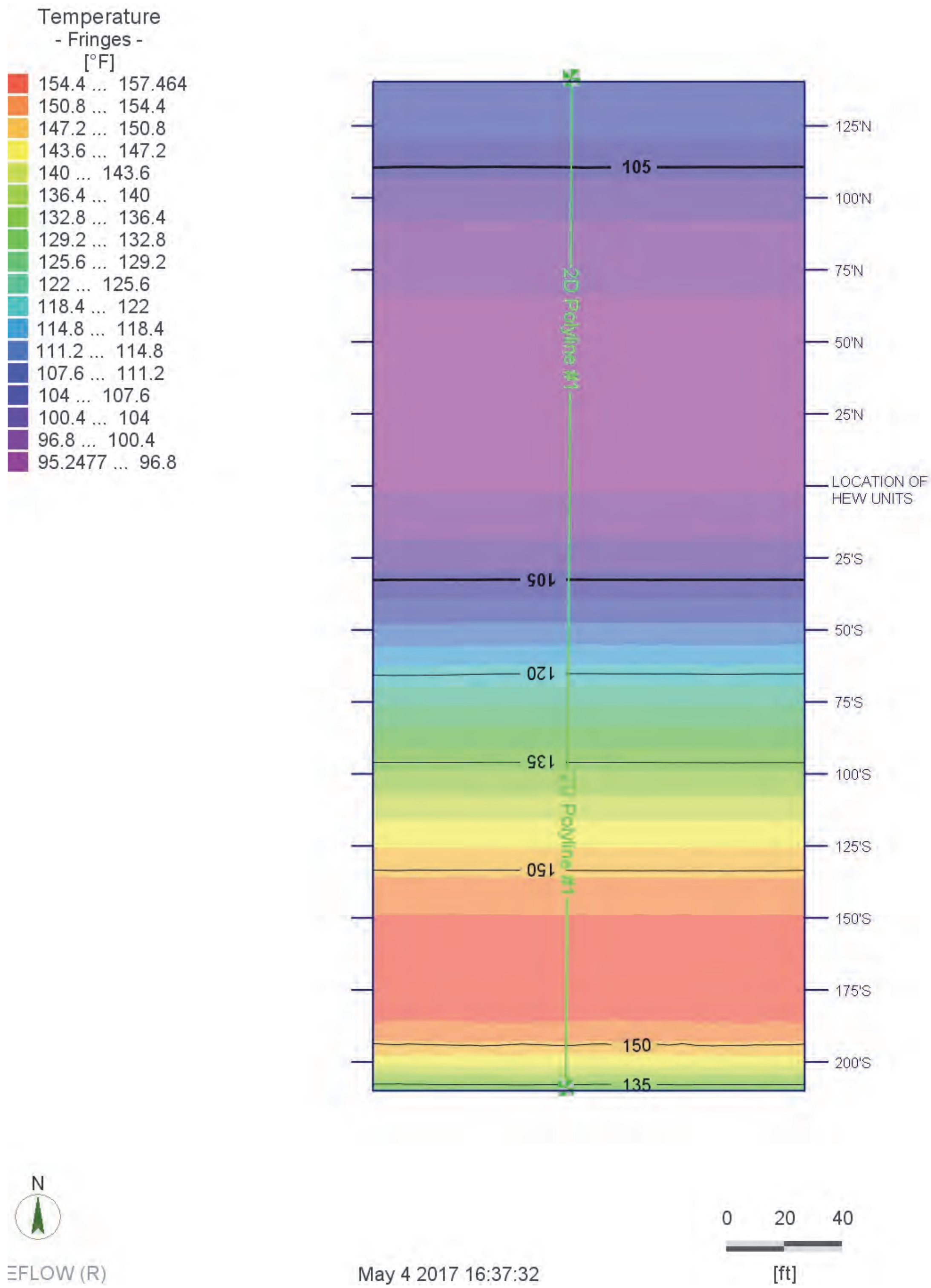
Run 6 Temperatures May 4, 2017 Section view

HEB Temperatures 100 ft Deep May 4, 2017



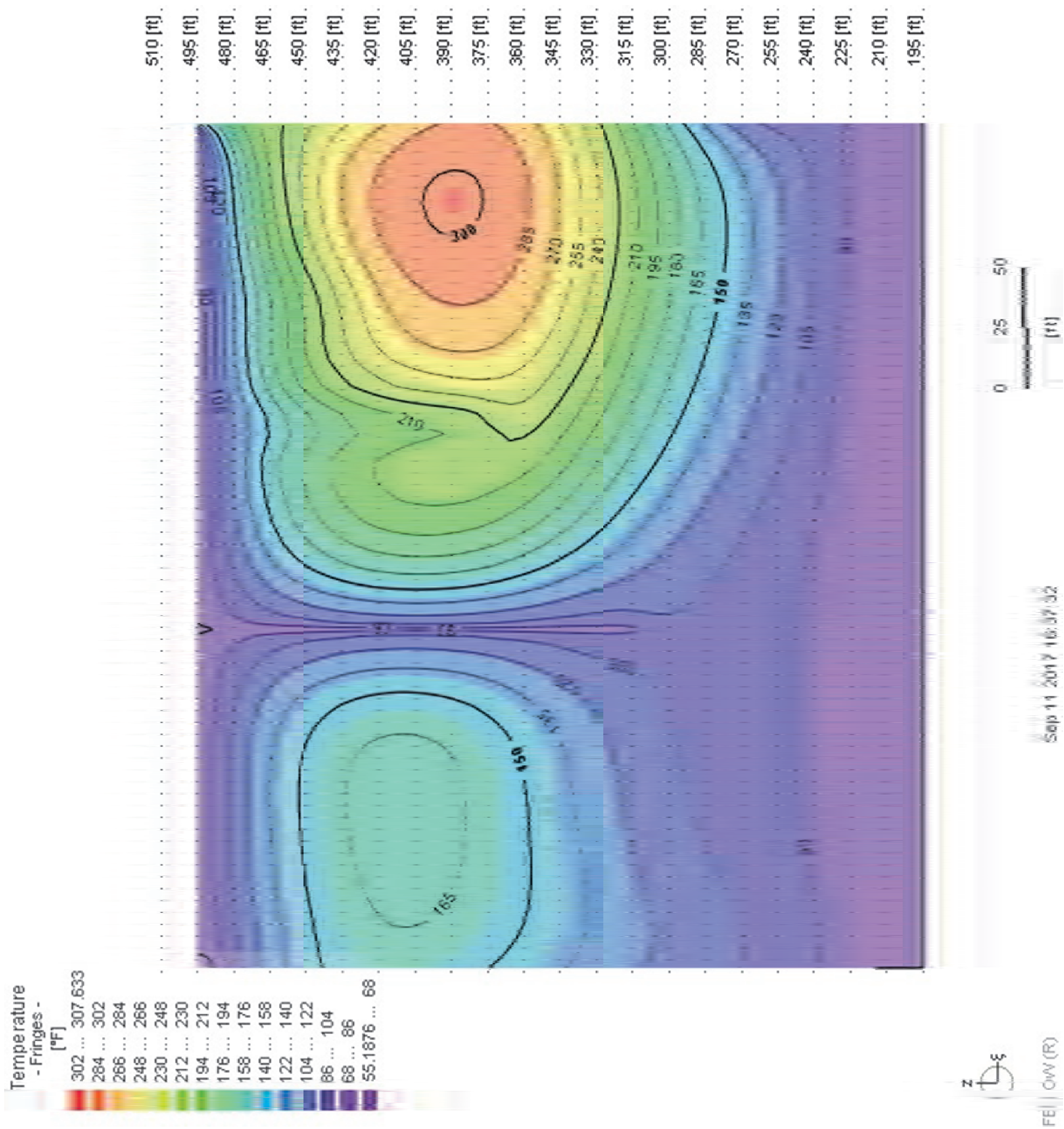
Run 6 Depth 100 ft Temperatures, May 4, 2017

HEB Temperatures 210 ft Deep May 4, 2017



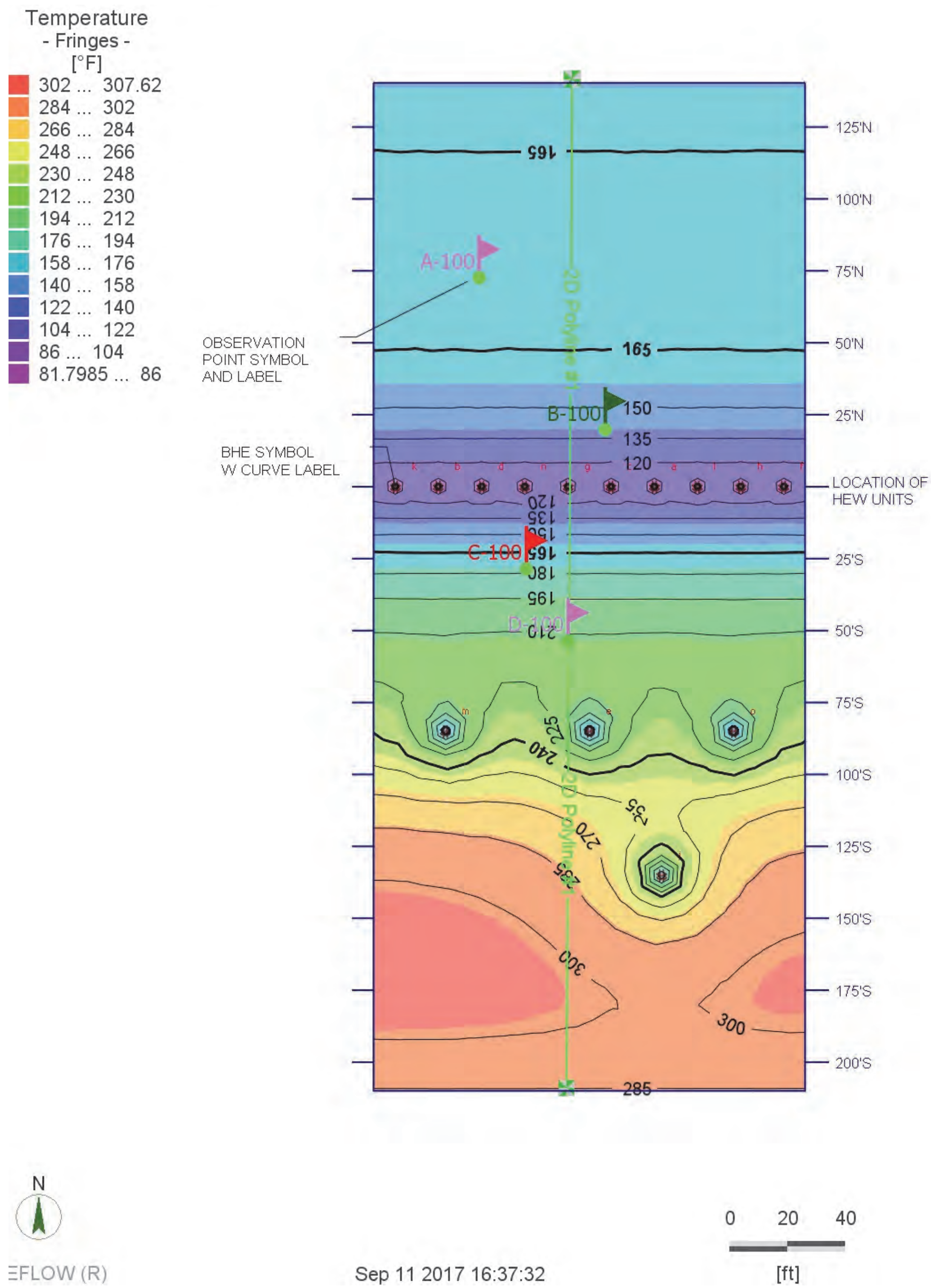
Run 6 Temperature at Depth 210 ft May 4, 2017

HEB Temperatures Section View Sept. 11, 2017



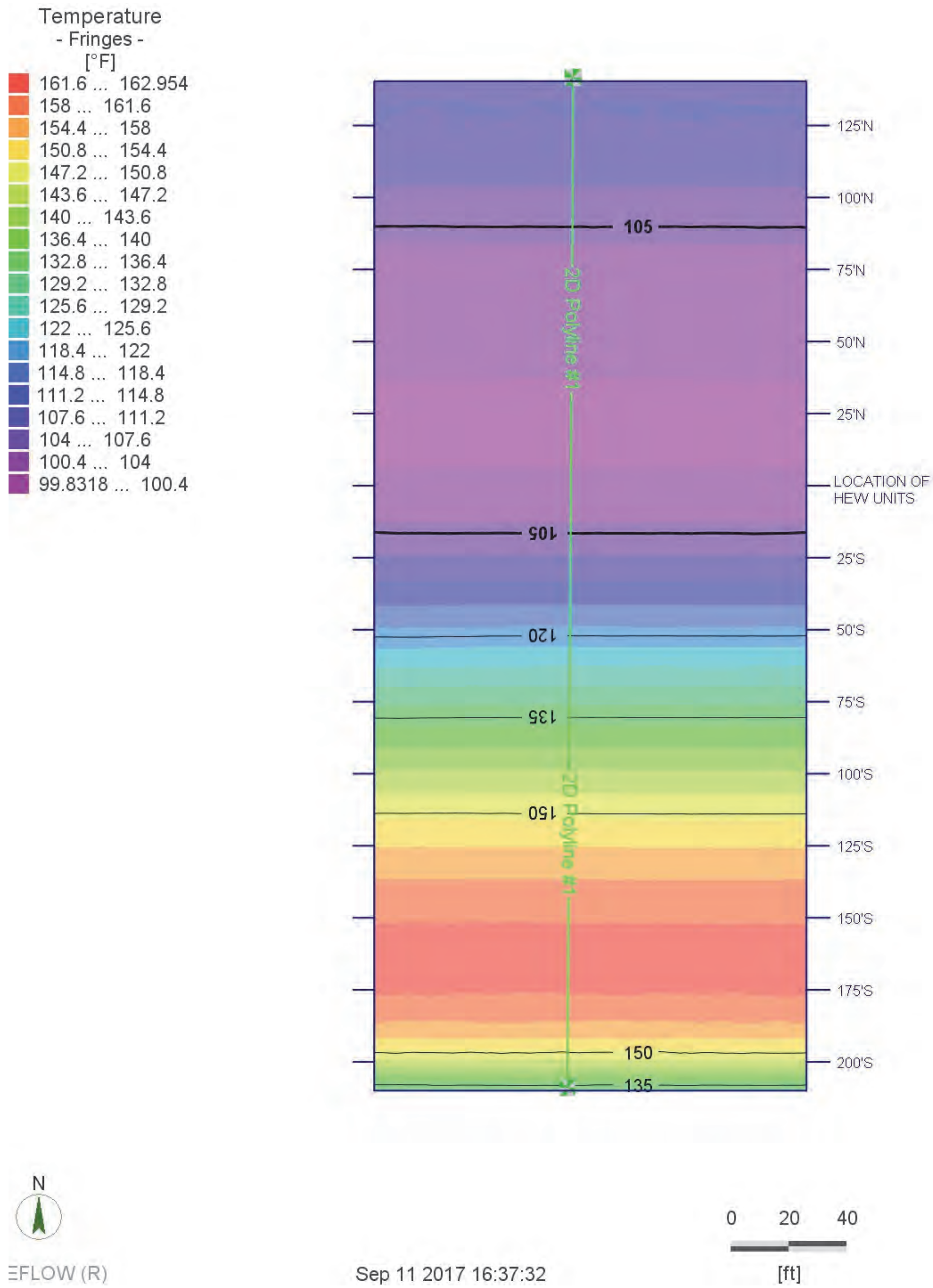
Run 6 Temperatures September 11, 2017 Section view

HEB Temperatures 100 ft Deep Sept. 11, 2017



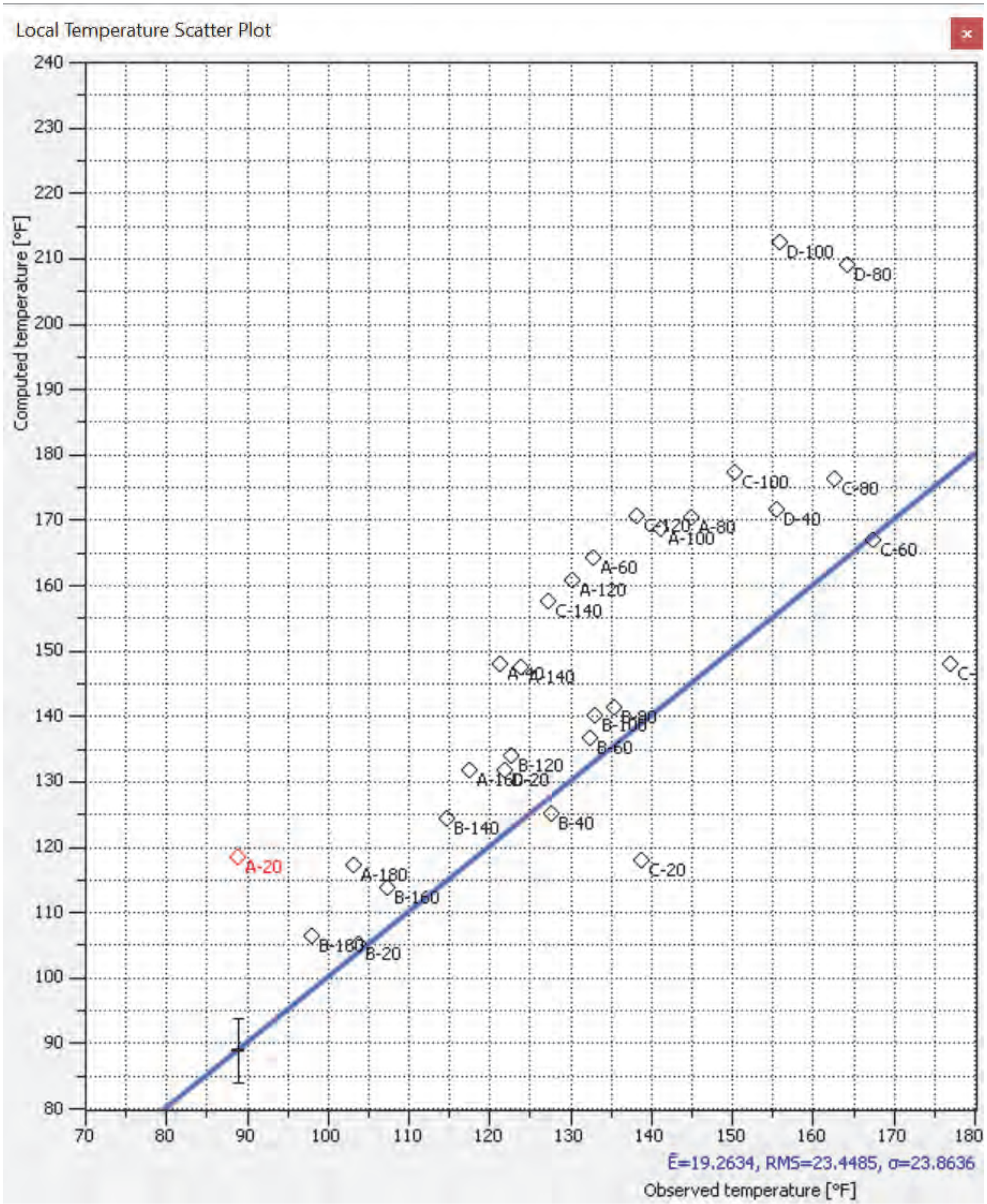
Run 6 Depth 100 ft Temperatures, September 11, 2017

HEB Temperatures 210 ft Deep Sept. 11, 2017



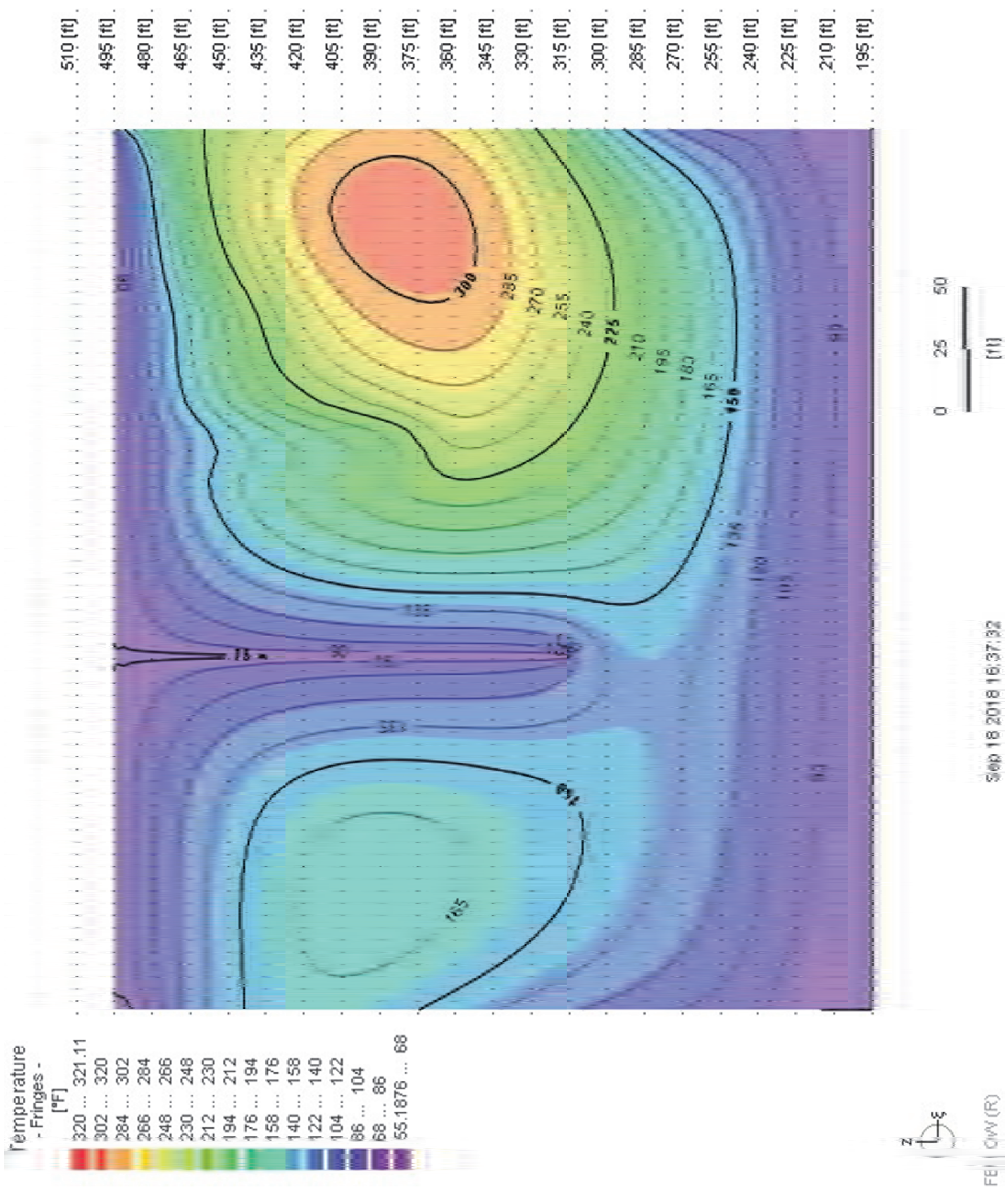
Run 6 Temperatures at Depth 210 ft September 11, 2017

Observation Point Scatter Plot – Sept. 11, 2017



Run 6 Scatter Plot September 11, 2017

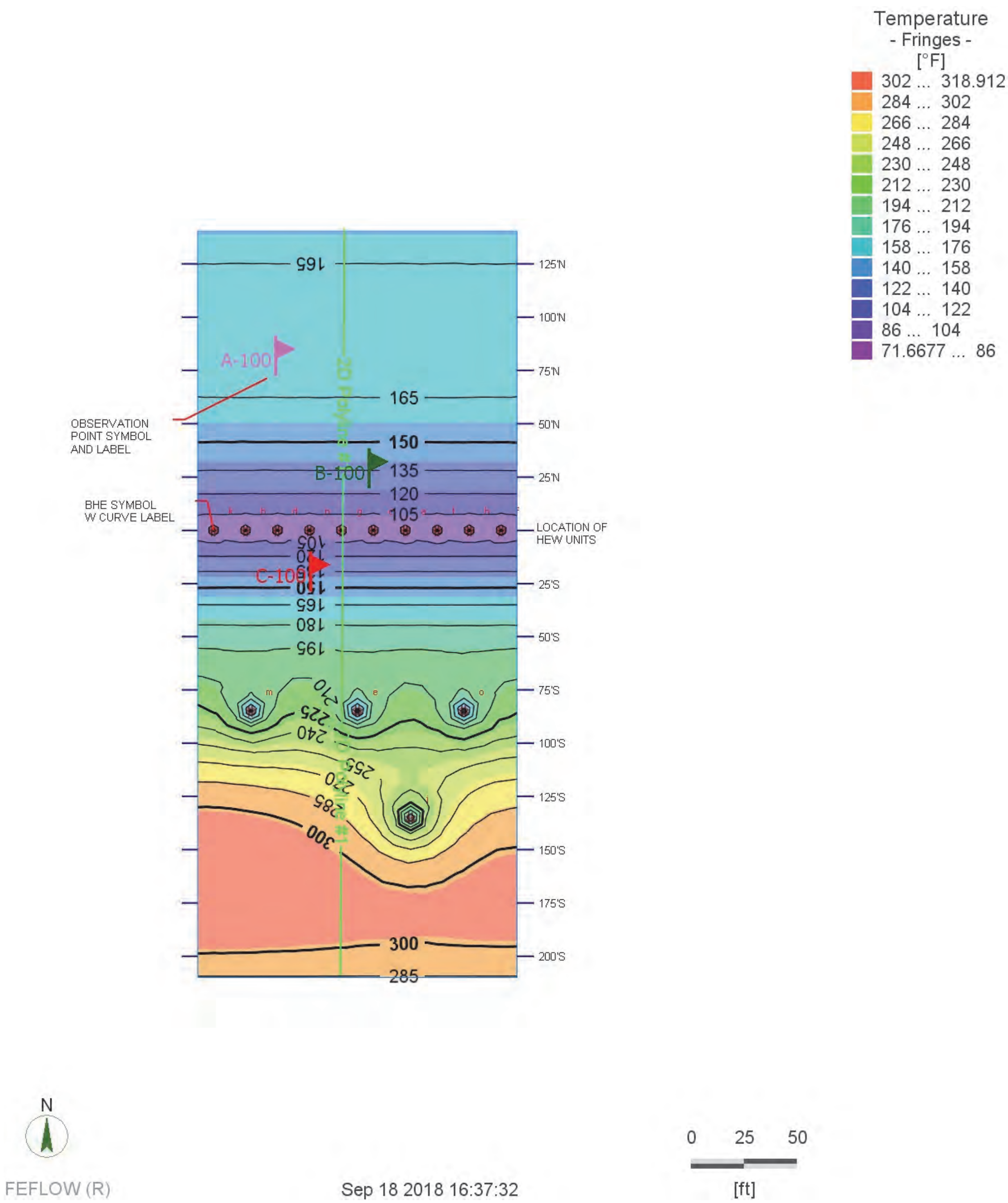
HEB Temperature Sept. 18, 2017–Section View



RUN 7 North South Section Temperatures 9-18-18

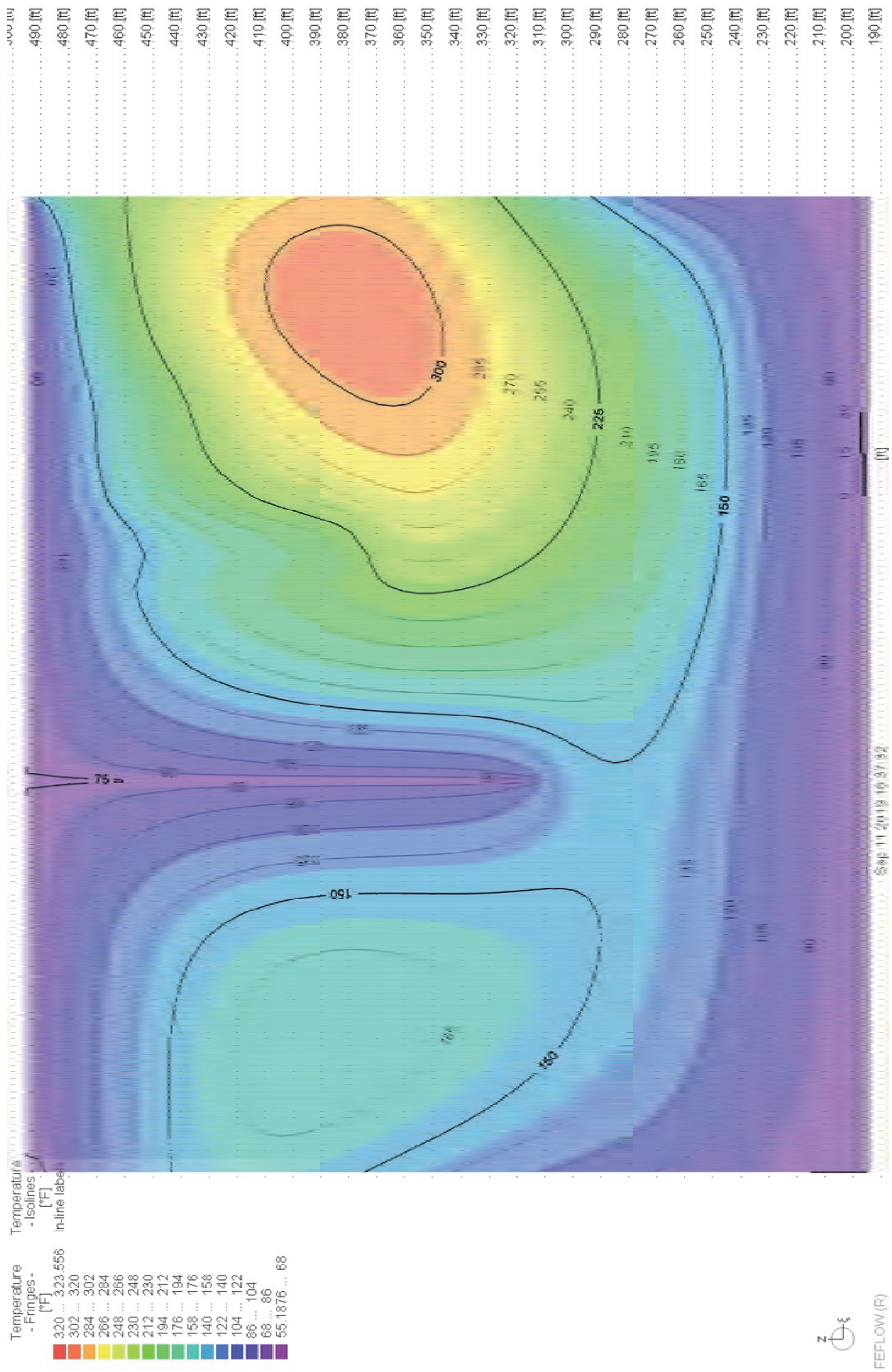
FIGURE - 25

HEB Temperature 100 ft. Deep Sept. 18,2018



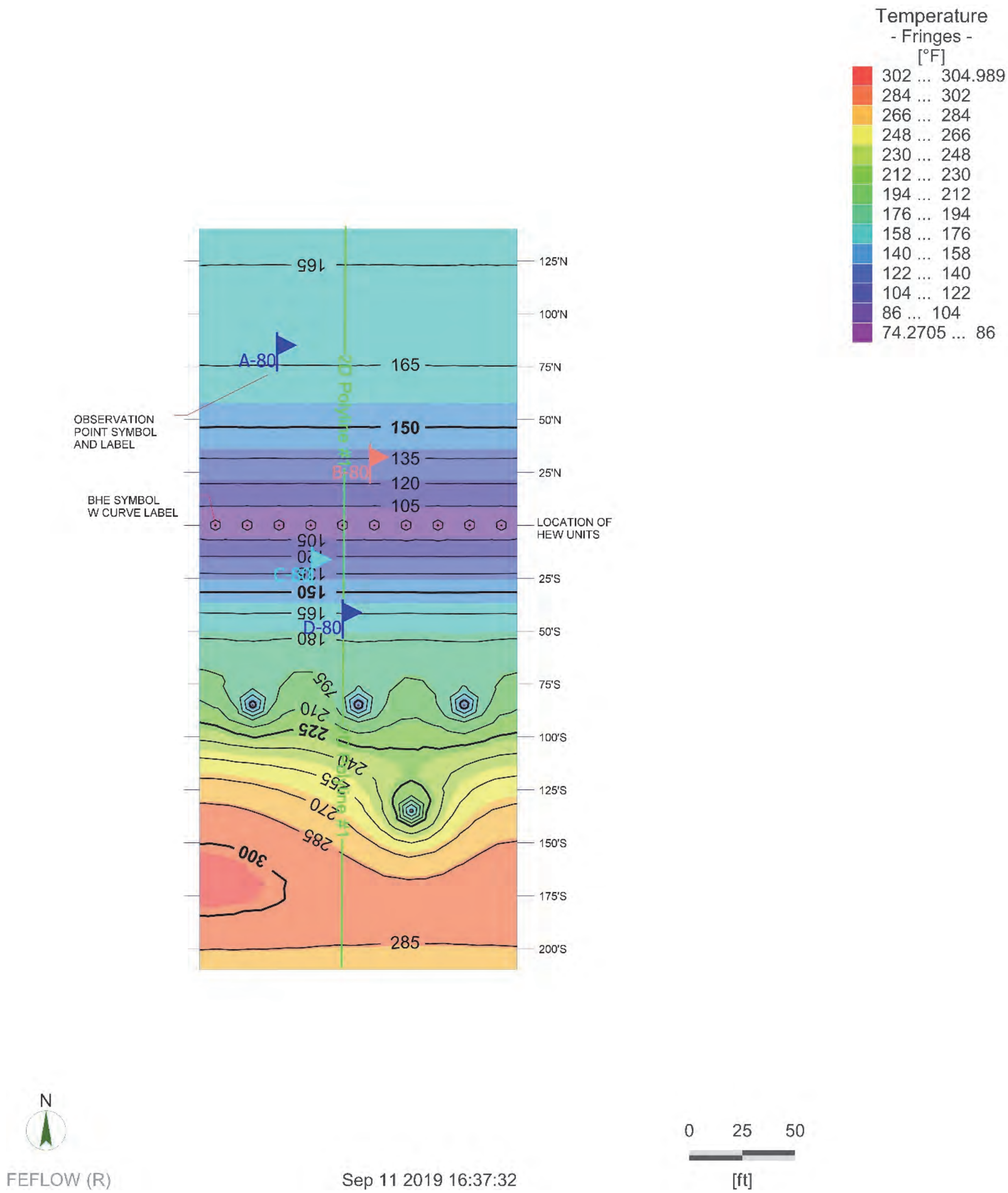
Temperatures Run 7 at 100 ft depth 9/18/2018

HEB Temperature Sept 11, 2019 – Section View



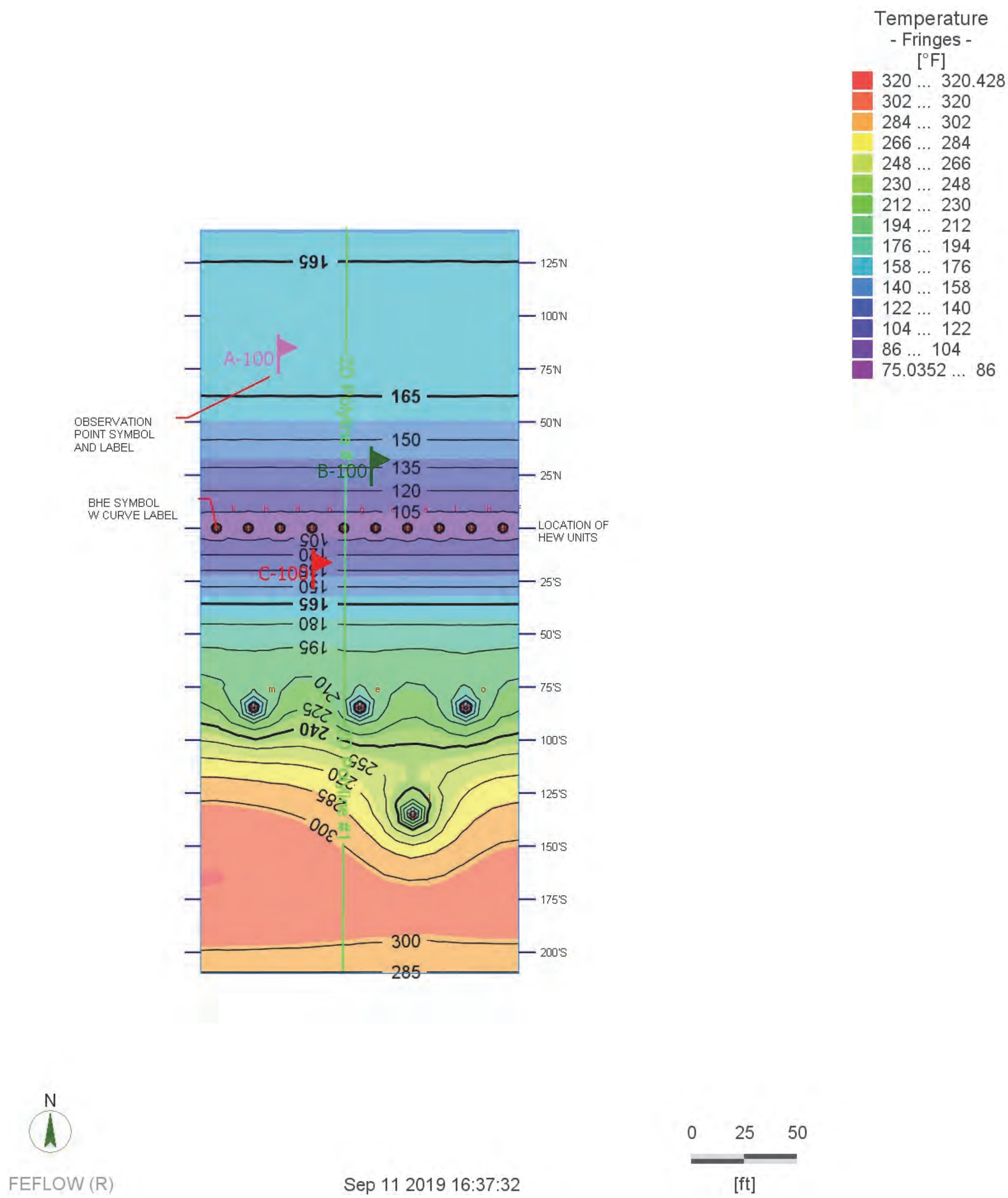
Run 7 9/11/19 Temperatures

HEB Temperature Depth 80 ft Sept 11, 2019



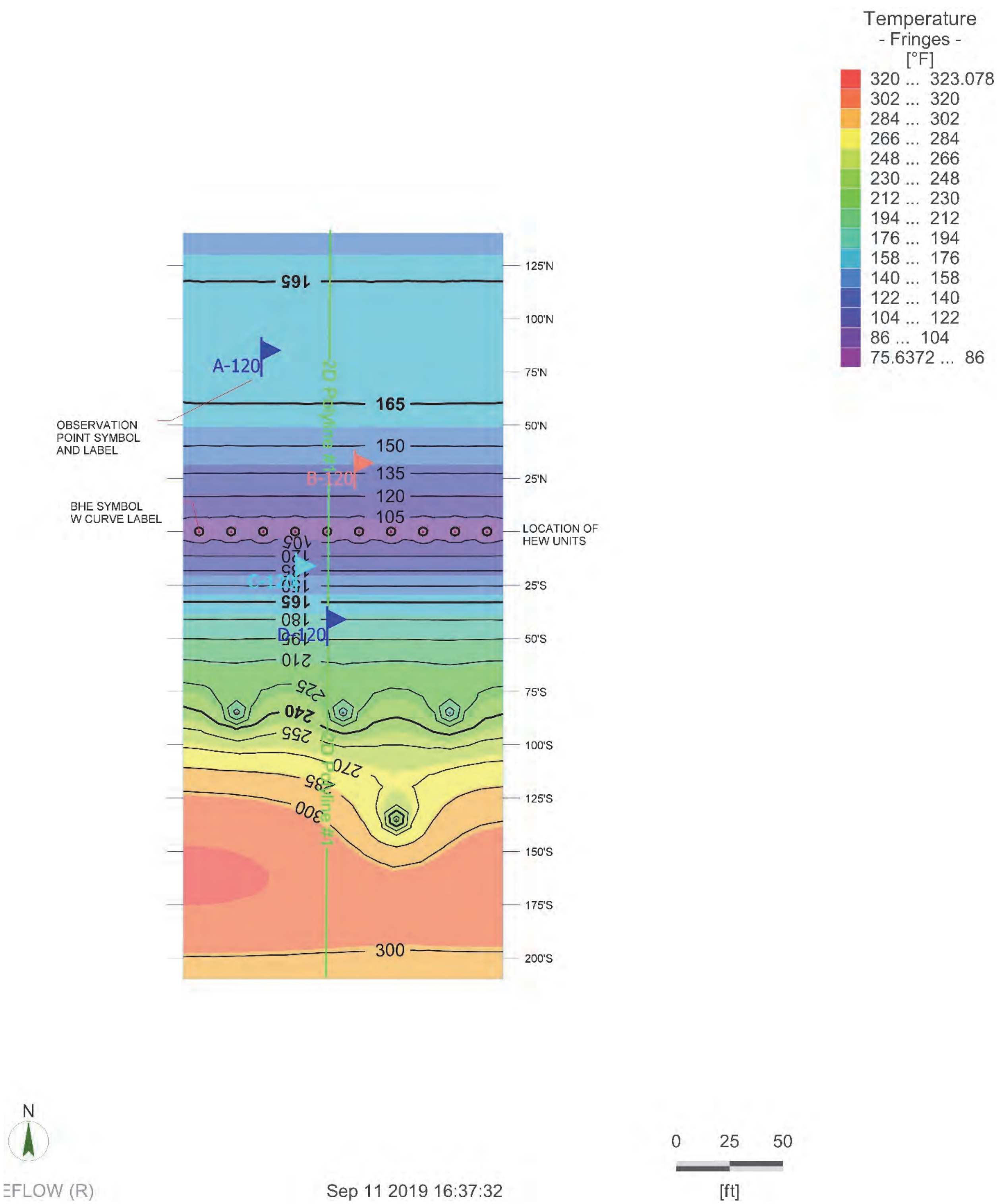
Run 7 Temperatures at depth of 80 ft.

HEB Temperature Depth 100 ft Sept 11, 2019



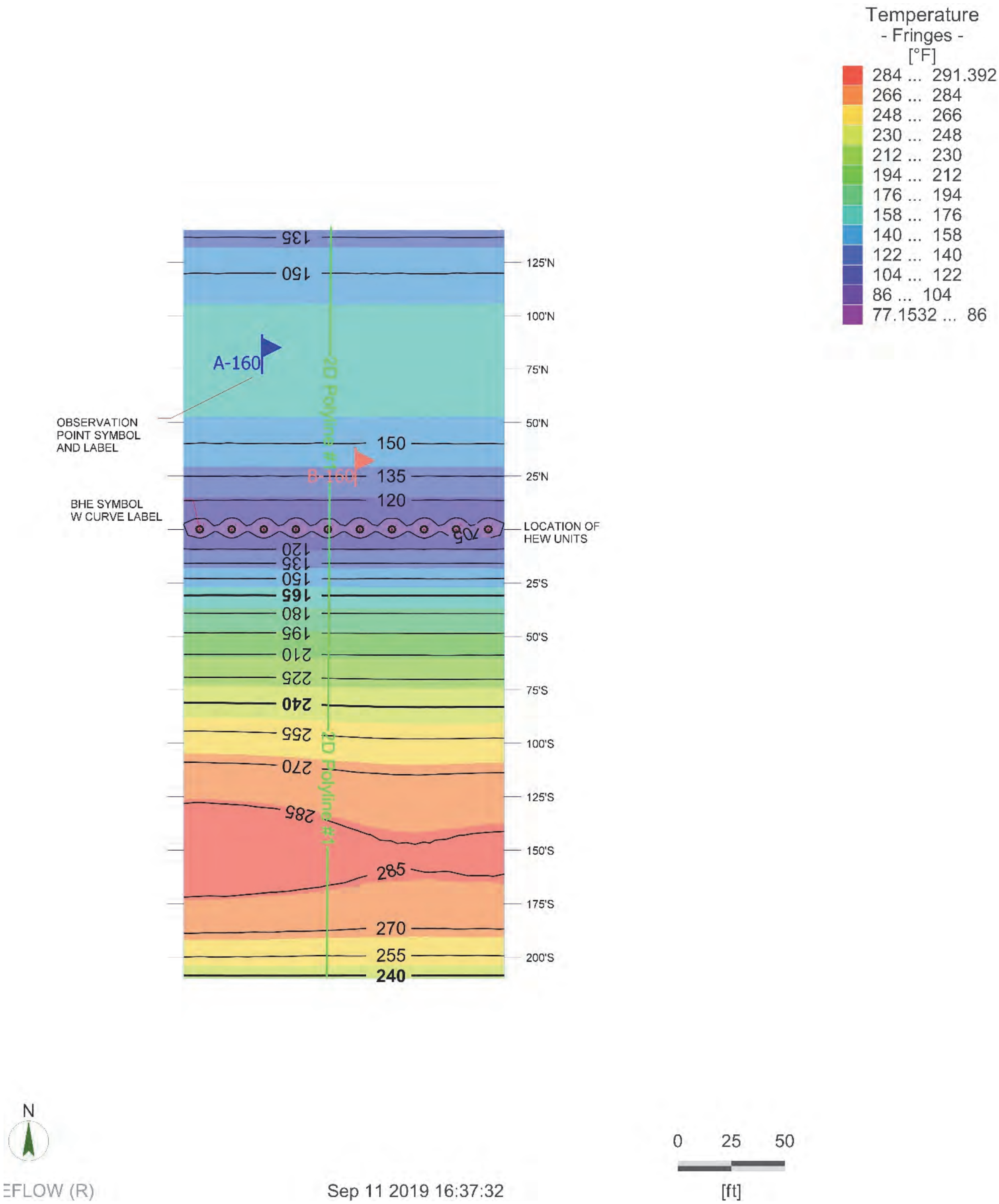
Temperatures Run 7 at 100 ft depth (el 395) 9/11/2019

HEB Temperature Depth 120 ft Sept 11, 2019



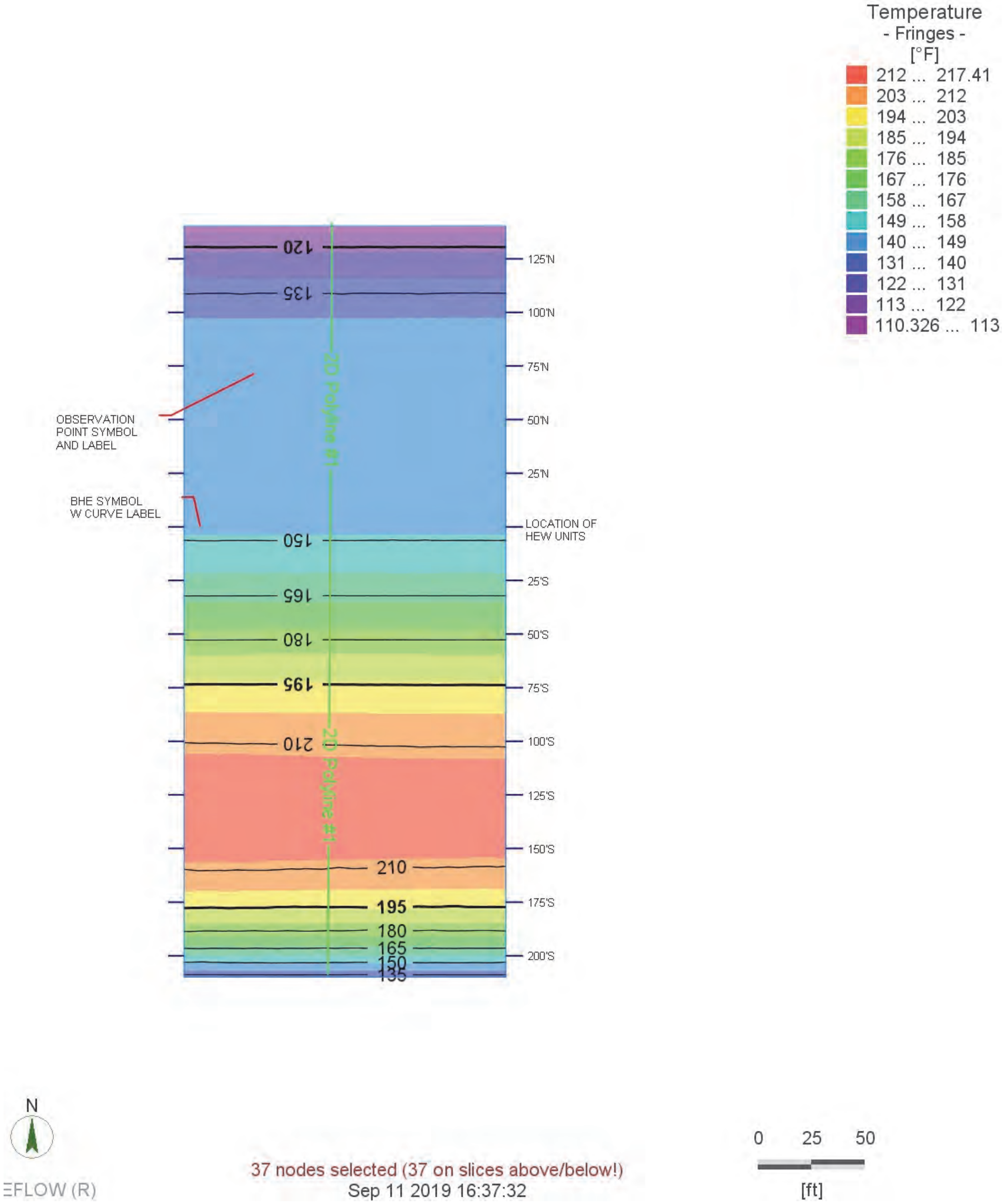
Run 7 Temperatures at Depth 120

HEB Temperature Depth 160 ft Sept 11, 2019



Run 7 Temperatures at depth of 160 ft.

HEB Temperature Depth 210 ft Sept 11, 2019



APPENDIX 1

P.J.Carey & Associates, P.C.

CLIENT Bridgeton Landfill

PROJECT Year 1 Model Review

CALCULATION BY Peter Carey

ORIGIN := 1

DATE 9/30/2017

OBJECT **create smoothing function for the inflow temp that is good approximation of measured inflow from a modeling perspective**

Date2 := READEXCEL("\\PJCA-SERVER\Projects\\Bridgeton\\Monitoring\\HEB Startup\PJCA\CompiledData\2016-2017.xlsx" ,"GIW5!T3:T40678" ,99999)

$TGIW5_{in}$:= READEXCEL("\\PJCA-SERVER\Projects\\Bridgeton\\Monitoring\\HEB Startup\PJCA\CompiledData\2016-2017.xlsx" ,"GIW5!s3:s40678" ,–999)

Date1 := READEXCEL("\\PJCA-SERVER\Projects\\Bridgeton\\Monitoring\\HEB Startup\PJCA\CompiledData\2016-2017.xlsx" ,"HEW-8!A1:A3243" ,99999)

$Thew8_{in}$:= READEXCEL("\\PJCA-SERVER\Projects\\Bridgeton\\Monitoring\\HEB Startup\PJCA\CompiledData\2016-2017.xlsx" ,"HEW-8!B1:B3243" ,–999)

create a single array for both date and temperature by stacking the data logger information on top of the wireless data through August 31

$Date := stack(Date1, Date2)$ $\qquad$ $T_{in} := stack\left(Thew8_{in}, TGIW5_{in}\right)$

$rows(Date) = 43919$ $\qquad$ $n := 1 .. rows(Date)$ $\qquad$ $Time_n := Date_n$ $\qquad$ $z_n := 1 \cdot n$

$\text{rows}(T_{in}) = 43919$

Use Gaussian Smoothing with a window width b (time in days) to generate a series f smoothed functions

$b := .25, .5 .. 10$

$\text{SmoothTIN}(b) := \text{ksmooth}(\text{Date}, T_{in}, b)$ This generates a function of smoothed values based on input values

$\text{rows}(\text{Date}) = 43919$

create a smoothed output file for graphing at various window widths(b)

$\text{time} := \text{Date}$

$TI_1 := \text{SmoothTIN}(1)$ $TI_7 := \text{SmoothTIN}(7)$ $TI_{14} := \text{SmoothTIN}(14)$

associate the time and 3 smoothed outputs in one output matrix and save

$\text{smoothedout} := \text{augment}(\text{Time}, TI_1, TI_7, TI_{14})$

smoothedout.txt

smoothedout

checking variation from area between average temp for the various smoothed values versus the actual value from recorded data

$$\text{AverageTin} := \frac{\displaystyle\sum_{z=1}^{\text{rows}(T_{in})} T_{in_z}}{\text{rows}(T_{in})} = 64.671$$

$$\frac{\sum_{z=1}^{rows(T_{in})} TI14_z}{rows(T_{in})} = 64.658$$

numerical average is very similar

Time weighted average   Average Tin*time increment

$$Date_{rows(T_{in})} - Date_1 = 324.592$$

$$AverageTin := \frac{\sum_{z=1}^{rows(T_{in})-1} \left[\left(\frac{T_{in_z} + T_{in_{z+1}}}{2}\right)\cdot\left(Date_{z+1} - Date_z\right)\right]}{Date_{rows(T_{in})} - Date_1} = 64.065$$

$$AverageSmoothTIN14 := \frac{\sum_{z=1}^{rows(T_{in})-1} \left[\left(\frac{TI14_z + TI14_{z+1}}{2}\right)\cdot\left(Date_{z+1} - Date_z\right)\right]}{Date_{rows(T_{in})} - Date_1} = 64.309$$

$$AverageSmoothTIN7 := \frac{\sum_{z=1}^{rows(T_{in})-1} \left[\left(\frac{TI7_z + TI7_{z+1}}{2}\right)\cdot\left(Date_{z+1} - Date_z\right)\right]}{Date_{rows(T_{in})} - Date_1} = 64.369$$

if a 4 time a day timing unit is used with same starting date, a reduced number of points can be used to simulate the smoothed curve

$\text{Date}_{\text{rows}(T_{in})} - \text{Date}_1 = 324.592$

$i := 1 .. 325 \cdot 4$

$(TD)_i := \text{Date}_1 + (i - 1)(.25)$

$\text{Date}_1 = 4.265 \times 10^4$

$ET := TD - TD_1 + 221$ to make the starting date time referenced to the model time 0 of March 3 2016

linear interpretation between times are computed using the smooth function - use the b=7 values

$csp7 := \text{linterp}(\text{Date}, TI_7, TD)$

check the average (no need to be time weighted since all times are same interval

$$\text{Averagecsp7} := \frac{\sum_{z=1}^{\text{rows}(TD)-1} \left(\frac{csp7_z + csp7_{z+1}}{2} \right)}{(\text{rows}(TD) - 1)} = 64.372$$

close to the actual values

$\text{rows}(TD) = 1.3 \times 10^3$

$\text{rows}(ET) = 1.3 \times 10^3$

create a time and temp output file using 0.25 day increments

$CSP7 := \text{augment}(ET, csp7)$

....\4QED7STIN.text

CSP7