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Appendix F – NOEF Temperature Update

NOEF Temperature Monitoring

24/11/2017

HSEC Environmental Projects

EIS Site Technical Team

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1 EXECUTIVE SUMMARY

In order to gain information as to the current conditions within the NOEF, drilling campaigns were undertaken in 2015, 2016 and 2017 as part of the Overburden Management Project EIS (OMP EIS), concentrating on the existing NOEF PAF cell. Groundwater monitoring wells were installed in 7 locations in 2015, while a total of 21 temperature and gas monitoring wells (12 in 2016, 9 in October 2017) were drilled through the PAF cell. Locations were selected based on the current understanding of the NOEF architecture and knowledge gaps in groundwater monitoring. Groundwater drilling extended through the entire NOEF profile and into the basement to intersect the first shallow aquifer, while the temperature and gas monitoring bores were drilled through the PAF cell only and stopped short of the lower clay liner (CCL) underlying the PAF cell, so as to not compromise its integrity.

Temperature monitoring at 10 locations instrumented in 2016 on the NOEF from October 2016 to November 2017 indicates that significant temperature decreases have already occurred over the monitoring period:

- Three locations which had significantly elevated temperatures in late 2016 can now be considered as approaching background temperature levels.
- None of the originally cool locations have recorded an increase in temperature over the monitoring period, indicating that high temperatures are not prevalent or spreading through the core of the NOEF
- The principal remaining area of elevated temperatures is located on the eastern side of the northern batter, a zone which coincides with the last remaining batter and berm configuration and has only been remediated in September 2017.
- While high temperatures remain on the eastern half of the northern NOEF batter, significant temperature decreases of ca 65°C have already occurred locally. The average temperature of the hot locations has significantly decreased over the monitoring period from 118°C in October 2016 to 85°C in 2017.
- The placement of the low air permeability advection barrier is expected to have a significant effect on the temperatures of the northern batter. Work on the barrier has already commenced and it is expected to be in fully completed by the end of March 2018.
- The equilibrium background temperature of the NOEF core is close to 73°C. While elevated in absolute terms, it is only ca 40°C warmer than ambient temperatures at the site. This value is not exceptional for a sulphidic dump, and while indicative of ongoing oxidation, it is not indicative of exceptional conditions within the NOEF.

2 INTRODUCTION

The North Overburden Emplacement Facility (NOEF) is the principal waste rock stockpile of the McArthur River Mine (MRM). The facility is located north of the open cut (see Figure 1), and is accessed by a bridge over Barney Creek. It has been in continuous operation since May 2008 and to date covers a surface area of ca 228ha, and holds approximately 58M m^3 of waste rock material (excluding the Central west stage) dominated by dolomitic shales, dolomitic breccias and pyritic shales.

The waste rocks are classified and placed according to their geochemical properties, and the correct placement of the respective rock types is crucial for the NOEF to perform as per its initial design. However, increased geochemical understanding of the MRM waste rock gained as part of the Phase 3 further works commitments has resulted in a fundamental revision and update of waste classification criteria since the original criteria were established in 2005 by URS. This has resulted in a need to update waste management practices at MRM and upgrade the design of future NOEF expansions, while designing and implementing potential mitigation strategies for the existing NOEF.

In order to gain information as to the current conditions within the NOEF, drilling campaigns through the NOEF were undertaken in 2015, 2016 and 2017 as part of the Overburden Management Project EIS (OMP EIS), concentrating on the existing NOEF PAF cell. Groundwater monitoring wells were installed in 7 locations, while a total of 21 temperature and gas monitoring wells were drilled through the PAF cell. Locations were selected based on the current understanding of the NOEF architecture and knowledge gaps in groundwater monitoring. Groundwater drilling extended through the entire NOEF profile and into the basement to intersect the first shallow aquifer, while the temperature and gas monitoring bores were drilled through the PAF cell only and stopped short of the lower clay liner (CCL) underlying the PAF cell, so as to not compromise its integrity.

The current report presents a summary of the temperature and gas monitoring program undertaken on the NOEF since 2016.

3 BACKGROUND

3.1 Waste rock classification

The MRM/KCB (2016) AMD classification criteria are presented in Table 1. The classification was implemented in January 2014 and is currently in use. Prior to the introduction of the new waste classification, MRM was using the URS(2005) classification which did not segregate between environmentally benign NAF (LS-NAF(HC)) and Metalliferous Saline NAF (MS-NAF HC and LC). Hence, NAF areas of the NOEF built prior to 2014 are composed of a mixture of LS-NAF(HC) and MS-NAFs.

TABLE 1: MRM/KCB 2017 WASTE CLASSIFICATION CRITERIA

NPR	Sulphur		Metals	Class	Description
NPR ≥ 2	S < 1%	and	Zn < 0.12 % Pb < 0.04% As < 50 ppm Cd < 10 ppm	LS-NAF(HC)	Low Salinity High Capacity NAF. Material considered at low risk of generating Acid Mine Drainage and Saline Metalliferous drainage. Provides high acid consumption capacity.
NPR ≥ 2	S ≥ 1%	and/or	Zn ≥ 0.12 % Pb ≥ 0.04% As ≥ 50 ppm Cd <10 ppm	MS-NAF(HC)	Metalliferous Saline High Capacity NAF. Material considered at low risk of generating Acid Mine Drainage but higher risk of generating Saline Metalliferous drainage Provides high acid consumption capacity. Requires some form of encapsulation
1 ≤ NPR < 2			N/A	MS-NAF(LC)	Metalliferous Saline Low Capacity NAF. Material considered at low risk of generating Acid Mine Drainage but higher risk of generating Saline Metalliferous drainage Provides limited to no acid consumption capacity. Requires some form of encapsulation
NPR < 1	S < 20%		N/A	PAF(HC)	High Capacity PAF. Material considered at higher risk of generating Acid Mine Drainage, and is likely to have a significant capacity to do so. Requires encapsulation.
NPR < 1	S ≥ 10%	and	BbH	PAF(RE)	Reactive PAF Material considered at higher risk of generating Acid Mine Drainage, and at a higher risk of spontaneous combustion. Requires encapsulation.
NPR < 1	S ≥ 20%		N/A	PAF(HW)	Hanging wall PAF. Material considered at higher risk of generating Acid Mine Drainage, and at a higher risk of spontaneous combustion. Segregated for in-pit sub-aqueous disposal .

3.2 NOEF Location

The location of the NOEF in relation to other MRM infrastructure is presented in Figure 1. Key infrastructure in the NOEF area includes the three operational Perimeter Runoff Dams (PRODs) which are designed to capture and store contaminated runoff waters from the NOEF: the South PROD (SPROD); the South East PROD (SEPROD); and the West PROD (WPROD).

FIGURE 1: NOEF LOCATION

3.3 NOEF Structure and Composition

The current as-built NOEF physical structure conforms to the original URS 2008 NOEF design. The basic structure with the location of the various material types is shown in Figure 2. An east-west cross section through the NOEF is shown in Figure 3, with the location of the internal Compacted Clay Liner (CCL) visible between the NAF wedge (the NAF base, equivalent to lift 1) and the PAF cell.

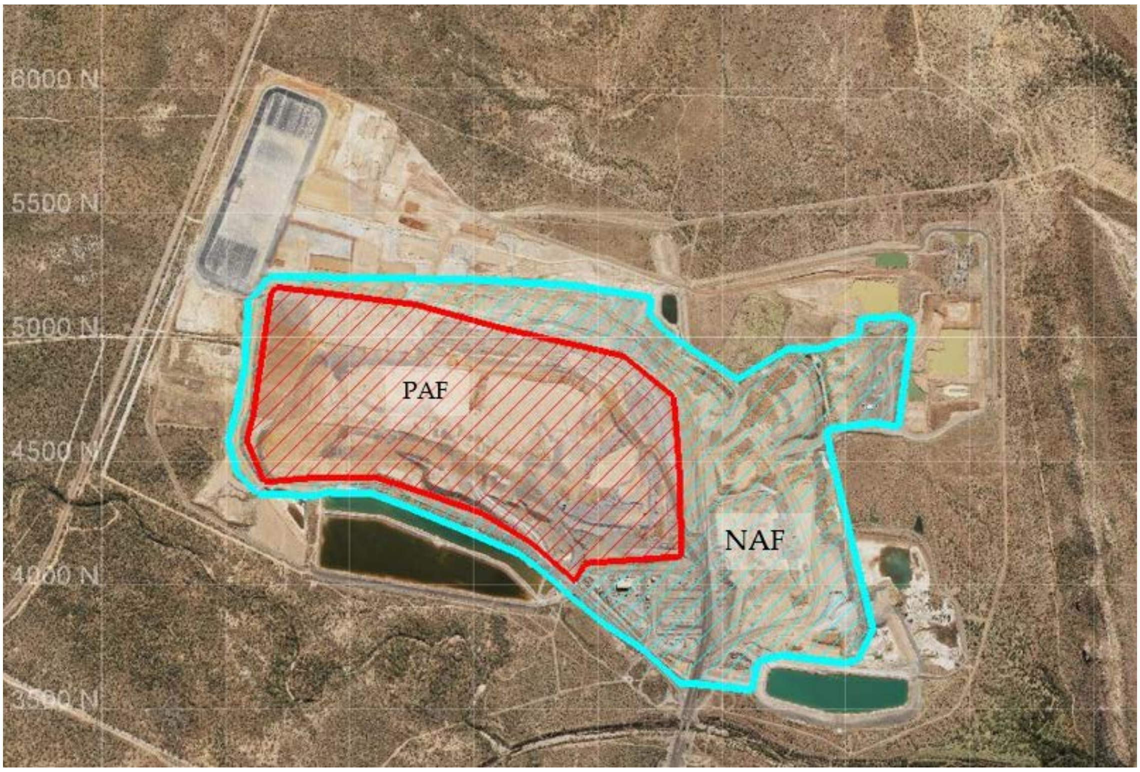


FIGURE 2: NOEF STRUCTURE AND COMPOSITION

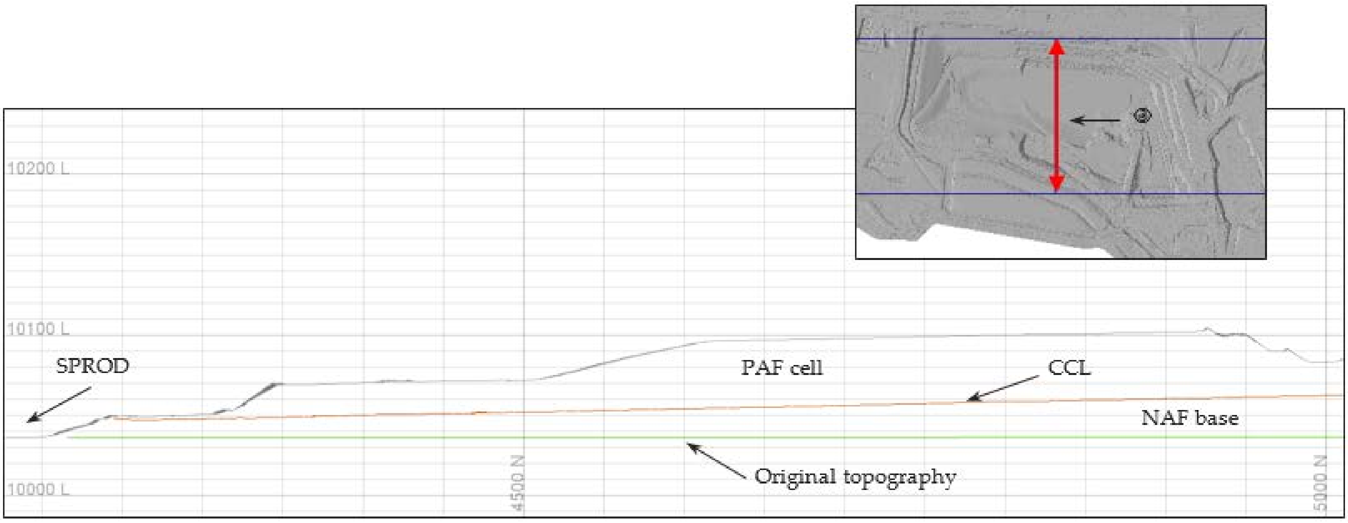


FIGURE 3: CROSS SECTION THROUGH THE NOEF

3.4 NOEF Investigations

As part of the Overburden Management EIS, MRM has undertaken several investigations into the existing NOEF. The study focussed on three separate lines of investigations to gain as much data as possible, in order to gain a better understanding of the structure and composition of the existing NOEF.

- **Historical reconstruction**: the available historical data on waste rock movement and placement since the beginning of construction has enabled a detailed reconstruction of the NOEF from May 2008 to 2016. The reconstruction used detailed survey records, mining production database and geological block model estimations.
- **NOEF block model**: based on the historical data, a fully updatable geological block model of the NOEF itself was constructed.
- **NOEF Drilling**: drilling campaigns through the NOEF were undertaken in 2015, 2016 and 2017, concentrating on the existing NOEF PAF cell. Groundwater monitoring wells were installed in 7 locations, while total of 21 temperature and gas monitoring wells were drilled through the PAF cell with 140 thermocouples and 113 gas ports installed.

3.5 NOEF Remediation works

Following the commencement of spontaneous combustion on the NOEF in 2013, major remediation works were undertaken on the NOEF PAF cell. The works focussed on the removal of hot spots primarily on the northern batter of the NOEF, which was the most affected. Remediation works included the re-excavation, cooling, relocation and compaction of shallow combusting material; flattening of the outer batter to 1V:4H gradient; and placement of a fine-grained wet season cover over the PAF cell.

The remediation works of the northern batter initiated in 2014 are ongoing, with the final shallowing of the northern batter and the placement of a low air permeability layer (advection cover) over the full PAF cell to inhibit the advection of oxygen into the stockpile, which is only partially complete at time of writing. Figures 4 to 6 show the progress of remediation works undertaken between July and September 2017, prior to the placement of the advection cover. Completion of the advection cover is expected by the end of March 2018.

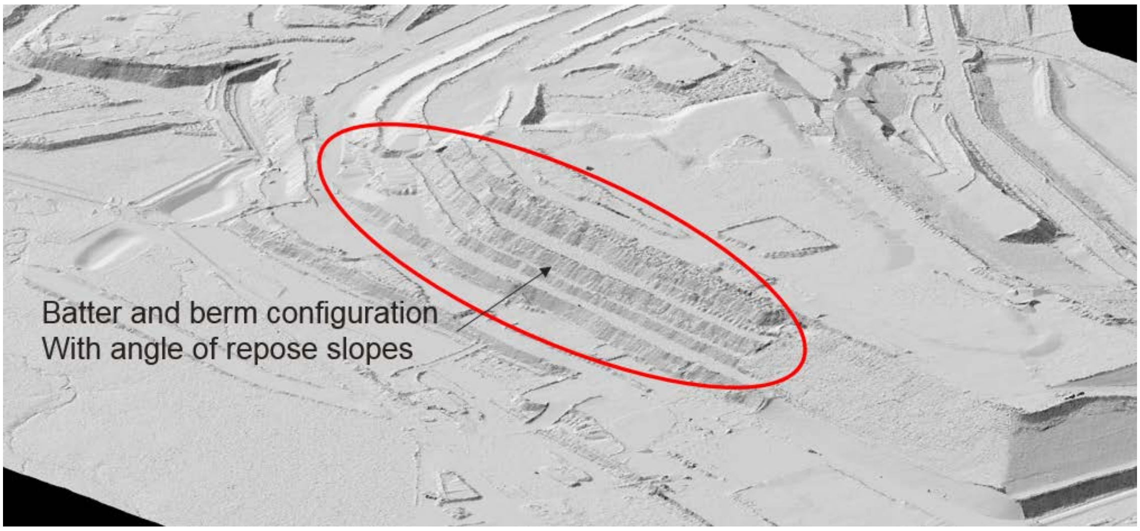


FIGURE 4: NORTHERN BATTER JULY 15TH 2017

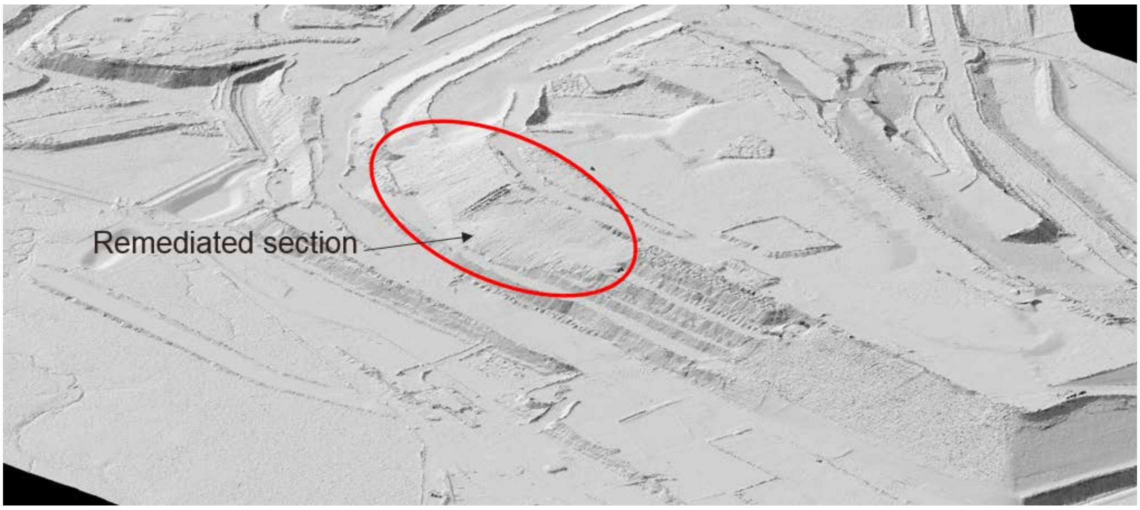


FIGURE 5: NORTHERN BATTER JULY 29TH 2017

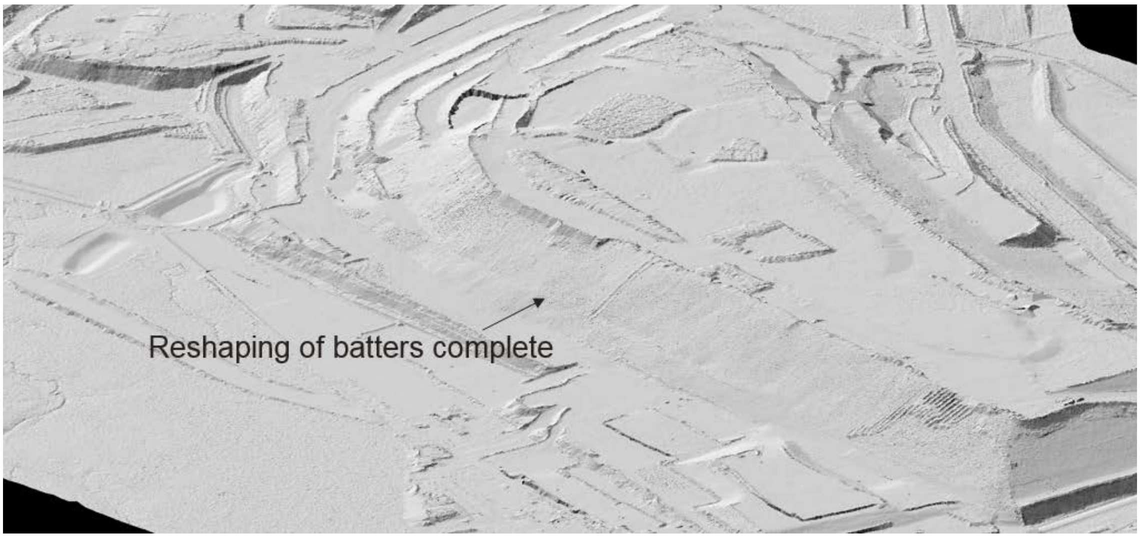


FIGURE 6: NORTHERN BATTER SEPTEMBER 23RD 2017

Figures 7 and 8 show the remediated northern batter in September 2017. The removal of the batter and berm configuration has been completed, and the placement of the advection barrier is advancing. Completion of the low air permeability layer on the northern and western batter is continuing and is expected to be completed by March 2018.

FIGURE 7: NORTHEAST BATTER ALLUVIAL COVER IN PROGRESS

FIGURE 8: REMEDIATED NORTHERN BATTER IN SEPTEMBER 2017

4 NOEF TEMPERATURE MONITORING

4.1 NOEF 2016 monitoring program

4.1.1 Locations

The 2016 NOEF drilling locations are presented in Figure 9. A total of 12 locations were drilled through the PAF cell down to the underlying CCL. Another location (8T/G) was drilled in 2015 as part of the water monitoring program. Of the 12 bores drilled, 10 were permanently instrumented with temperature sensors, while gas ports were installed in two locations. Not all drilled locations were instrumented: priority was given to bores showing elevated temperatures at time of drilling. Bores 1A and 14A were therefore not instrumented, owing to the cool temperatures recorded. All other bores were instrumented.

FIGURE 9: LOCATION OF 2016 TEMPERATURE WELLS

4.1.2 Instrumentation

All monitoring wells are instrumented with industrial grade high temperature K-type thermocouples with an operational range to 1000°C. For gas measurements, stainless steel gas ports connected to Teflon tubing rated to 380°C were placed at different levels, which enable the measurement of internal pore gas composition. The gas ports are embedded in permeable coarse sand, and each interval is sealed by bentonite clay to limit preferential vertical movement of gases along the monitoring well.

A total of 32 thermocouples and 8 gas ports were installed. The locations and depths are presented in Table 2:

TABLE 2: NOEF 2016 MONITORING WELLS

Monitoring bore	Depth	Instrument type	Status	Comment
1A		Not instrumented		
2A	10m	T	Operational	
	24m	T	Operational	
	39m	T	Operational	
5A	10m	T	Operational	
	26m	T	Operational	
	39m	T	Operational	
7A	15m	T	Operational	
	30m	T	Operational	
8A	10m	T	Operational	
	20m	T	Operational	Close proximity to
	30m	T	Operational	NOEF2017-19A
	39m	T	Operational	
8G	10m	G	Operational	
	20m	G	Operational	
	30m	G	Operational	
	50m	G	Operational	
9A	10m	T	Operational	
	18m	T	Operational	
	30m	T	Operational	
	39m	T	Operational	
10A	9m	T	Operational	
	16m	T	Operational	Close proximity to
	26m	T	Operational	NOEF2017-22A
	39m	T	Operational	
11A	10m	T, G	Out of service	
	19m	T, G	Out of service	Replaced by
	29m	T, G	Out of service	NOEF2017-20A
	38m	T, G	Out of service	
12A	10m	T	Operational	
	19m	T	Operational	
	30m	T	Out of service	
14A		Not instrumented		
15A	8m	T	Operational	Close proximity to
	17m	T	Operational	NOEF2017-25A
	30m	T	Operational	
16A	13m	T	Operational	Close proximity to
	39m	T	Operational	NOEF2017-24A

4.2 NOEF 2017 monitoring program

4.2.1 Locations

The 2017 NOEF drilling locations are presented in Figure 10. A total of 9 locations were drilled through the PAF cell down to the underlying CCL. Locations were selected based on several criteria:

- 17A, 18A and 23A were selected to increase the area of the PAF cell being monitored.
- 20A essentially replaces the non-functional 11A bore
- 21A increases the spatial resolution along the critical northern batter
- 24A, 19A, 22A and 25A provide increased vertical data resolution for areas identified as having highly variable temperature profiles.

Drilling and well construction was completed in October 2017, and final adjustments to the well heads and instrumentation were ongoing in November. Results were not available at time of writing and will be reported in 2018.

FIGURE 10: 2017 NOEF MONITORING WELLS

4.2.2 Instrumentation

Instrumentation for the 2017 wells is identical to the 2016 program (high temperature thermocouples and gas ports). Unlike the 2016 monitoring wells which were instrumented at various levels, all 2017 bores were instrumented at similar levels. The vertical resolution was significantly increased with 12 thermocouple/gas ports pairs per well. Instruments were installed:

- Every metre to 5m; so 1, 2, 3, 4, and 5m
- Every 5 metres from 5 to 39m; so 10, 15, 20, 25, 30, 35, and 39m

5 RESULTS

5.1 Vertical Temperature Profiles

Vertical temperature profiles are classed in two broad categories:

- Background temperature profiles: these temperature profiles are characterised by temperatures close to the average background temperature of the NOEF and a maximum temperature of 100°C. The 100°C cut-off value corresponds to the temperature beyond which, under oxic conditions, self-heating and spontaneous combustion may develop. A total of 6 monitoring wells show background temperatures.
- Elevated temperature profiles: These temperature profiles are characterised by the presence of temperatures in excess of 100°C. A total of 6 monitoring wells show elevated temperatures. The number of elevated temperature wells reflects the higher density of wells installed in these areas compared to cooler areas, as they require closer monitoring.

The temperature profiles are presented in the form of monthly curves from October 2016 to November 2017, as in Figure 9:

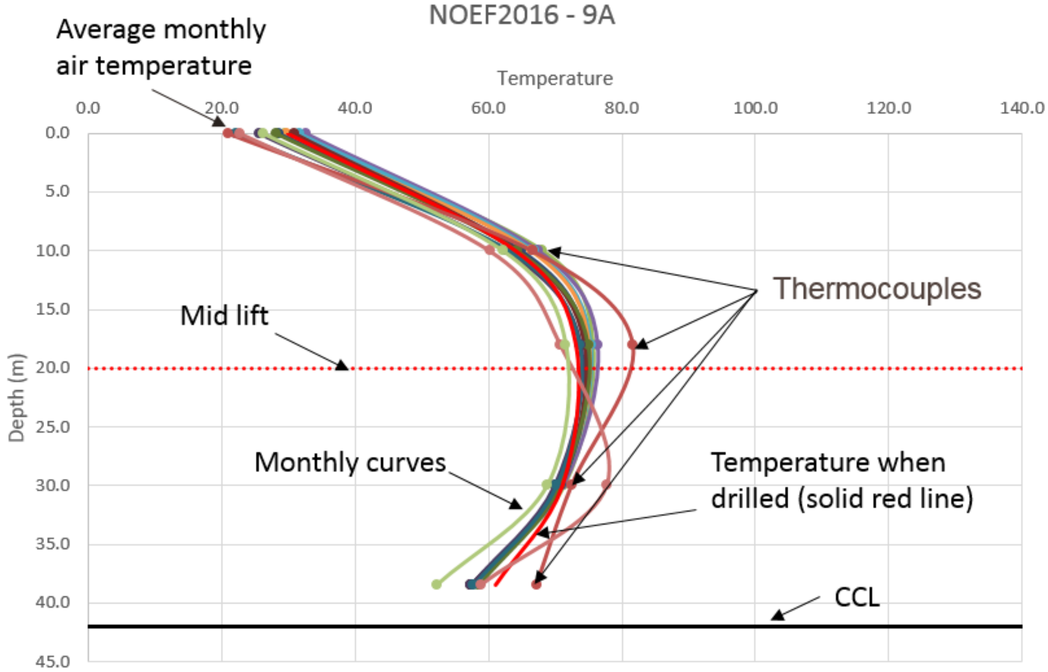


FIGURE 11: NOEF2016-9A TEMPERATURE PROFILE

Temperature measurements taken during drilling are shown by the solid red lines, while the horizontal solid black line indicates the depth of the CCL at the base of the PAF cell, and the dotted red line shows the approximate position of the middle of the PAF cell.

Surface temperatures are the mean monthly air temperature for the site. Note that these temperatures are expected to be somewhat cooler than the surface of the NOEF, and also cooler than the rock temperatures ex-pit (40°C to 60°C depending upon insolation), but provide a good indication of the expected seasonal variation in temperatures at the site and of the long-term mean annual temperature of the site.

5.1.1 Background temperature profiles

Figure 11 presents the results of the 6 monitoring wells from the 2016 monitoring program exhibiting background temperatures. NOEF 2016-1A and 14A were not instrumented so only temperatures at drilling are available. For all other wells, monthly temperature profiles from October 2016 to November 2017 are presented.

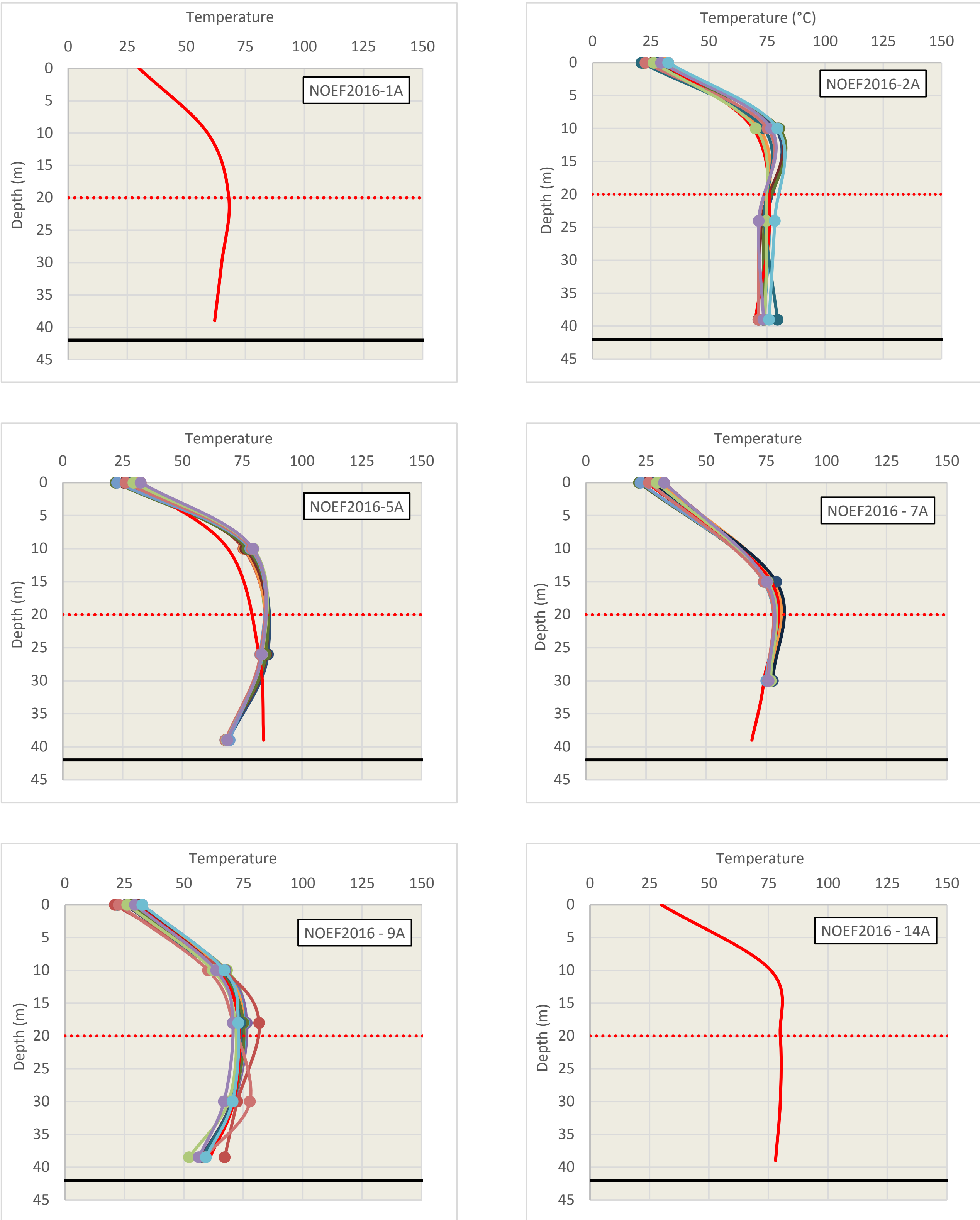


FIGURE 12: NOEF 2016 MONITORING TEMPERATURE PROFILES

All monitoring wells show very similar vertical profiles:

- Temperature increases rapidly is in the first 10m to reach values close to the average temperature of 73.5°C. This is about 40°C warmer than surface air temperatures at the site.
- Temperatures below 10m remain broadly constant and close to the average temperature value. Some profiles show cooler values closer to the base (see NOEF 2016-5A and 9A in Figure 11).
- The temperature profiles obtained from the thermocouple readings are consistent with the temperature profiles obtained at the time of drilling, indicating that the temperatures are very stable over time. The profiles show an almost complete absence of seasonal variation.
- None of the background temperature wells have shown significant increases in temperatures from October 2016 to November 2017, i.e. zones of elevated temperatures are not spreading within the existing NOEF PAF cells.

5.1.2 Elevated temperature profiles

Figure 12 presents the results of the 6 monitoring wells from the 2016 monitoring program exhibiting elevated temperatures.

Unlike the cooler temperature profiles, the elevated temperature profiles show some significant individual variations, indicating they are highly influenced by very local conditions within the NOEF:

- Zones of elevated temperatures appear localised and constrained to specific depths within each profile. They do not appear to spread vertically within a given profile.
  - In NOEF2016-8A, the high temperatures (175°C) occurred at 30m, associated with the lower half of the PAF cell, and do not appear to spread to the upper half. Temperatures at 39m and 20m appear a lot cooler (ca 85° and 60°C respectively) and a lot more stable over time.
  - NOEF2016-10A shows elevated temperatures at 15m (140°C), while temperatures at 10m are invariant and close to the background temperature of the NOEF (75°C). Temperatures at 25m remain elevated (85° to 106°C) with some reduced variability, while the temperatures at the base of the profile appear invariant and significantly cooler at ca 55°C.
  - NOEF2016-12A show high temperatures at 10m (max 160°C) and 20m (max 189°C), while temperatures closer to the base appear cooler and less variable (max 91°C).
  - While NOEF2016-11A ceased to function, the obtained temperature record show a consistent increase in temperature with depth to a maximum of 200°C.
  - NOEF2016-15A is distinct in showing highly variable temperatures at 8m (56 to 140°C) and 30m (83 to 150°C), while temperatures at the centre of the profile at ca 17m appear stable at 115°C.
  - NOEF2016-16A shows highly variable and elevated temperatures at 13m (80 to 165C) while at 39m the temperature is constant between 88° and 99°C.

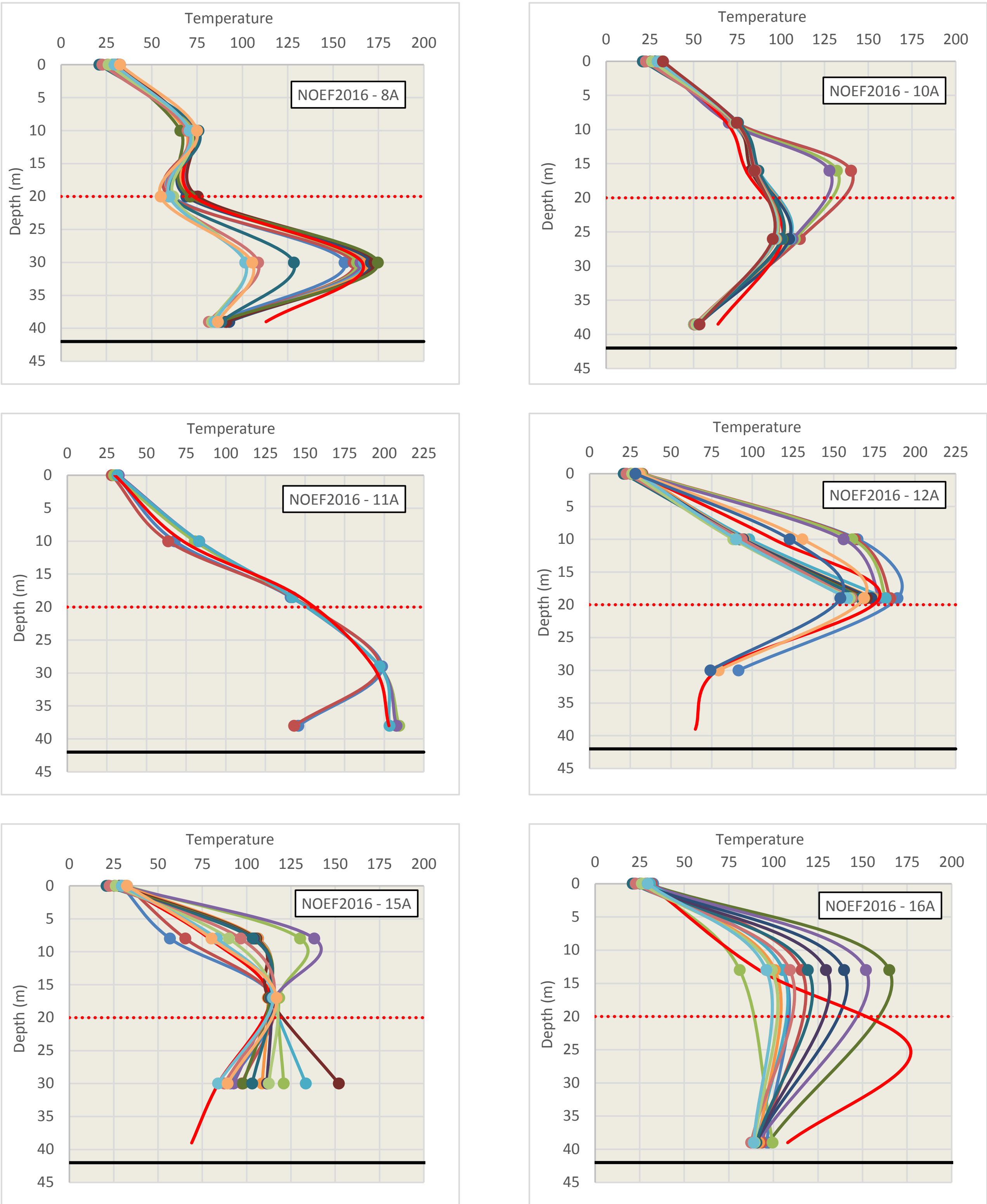


FIGURE 13: NOEF 2016 MONITORING WELLS

5.2 Temperature Trends Over Time

5.2.1 Background temperature profiles

Background temperature monitoring wells are characterised by very stable temperature profiles with internal temperatures being almost invariant over time. Temperatures have remained essentially constant over the monitoring period. These bores show an absence of seasonal variation in temperatures.

5.2.2 Elevated temperature profiles

The elevated temperature profiles show a much greater variability over time. Significantly, 4 out of the 6 2016-series monitoring wells have recorded significant temperature decreases over the monitoring period.

NOEF2016-8A (Figure 13) shows a progressive temperature decrease at 30m from March 2017 to October 2017, with a temperature decrease from 165°C to 101°C, a cooling of 64°C in 5 months. Similarly, the 20m interval has cooled from 73°C to 55°C, an 18°C cooling.

NOEF2016-8A can essentially be considered cool, with a maximum temperature at ca 100°C since September 2017.

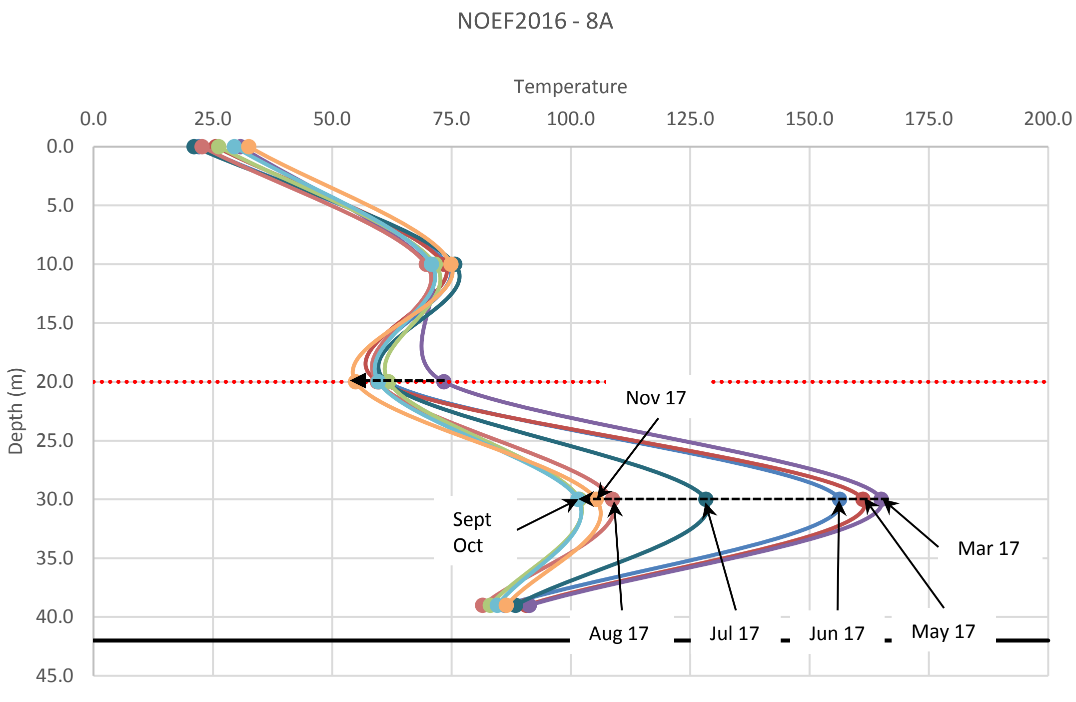


FIGURE 14: NOEF2016-8A TEMPERATURE PROFILE

NOEF2016-10A (Figure 14) shows a rapid temperature decrease at 16m between November 2017 and February 2017, with a temperature decrease from 140°C to 85°C, a cooling of 55°C in 4 months. Significantly, most of the cooling occurred in a single month between January and February 2017. Similarly, the 26m interval has cooled from 110°C to 95°C, and 15°C cooling.

NOEF2016-10A can essentially be considered cool, with a maximum temperature at ca 95°C since September 2017.

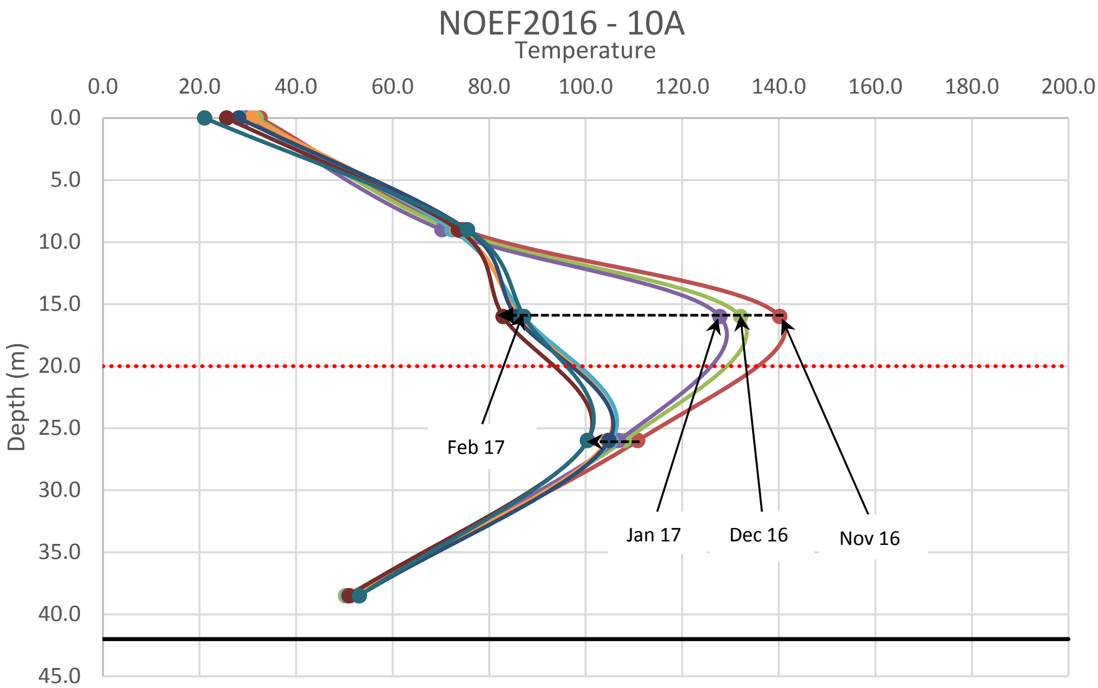


FIGURE 15: NOEF2016-10A TEMPERATURE PROFILE

NOEF2016-16A (Figure 15) shows highly variable temperatures at 13m between October 2016 and November 2017. For clarity, only the October 2016 and September and October 2017 are shown on the graph. While the cooling was not progressive over time, an overall temperature decrease of 76°C from 165°C to 88.3°C was achieved from October 2016 to November 2017. Temperatures at 39m have remained relatively constant between 88° and 95°C.

NOEF2016-16A can essentially be considered cool, with a maximum temperature at ca 96°C since September 2017.

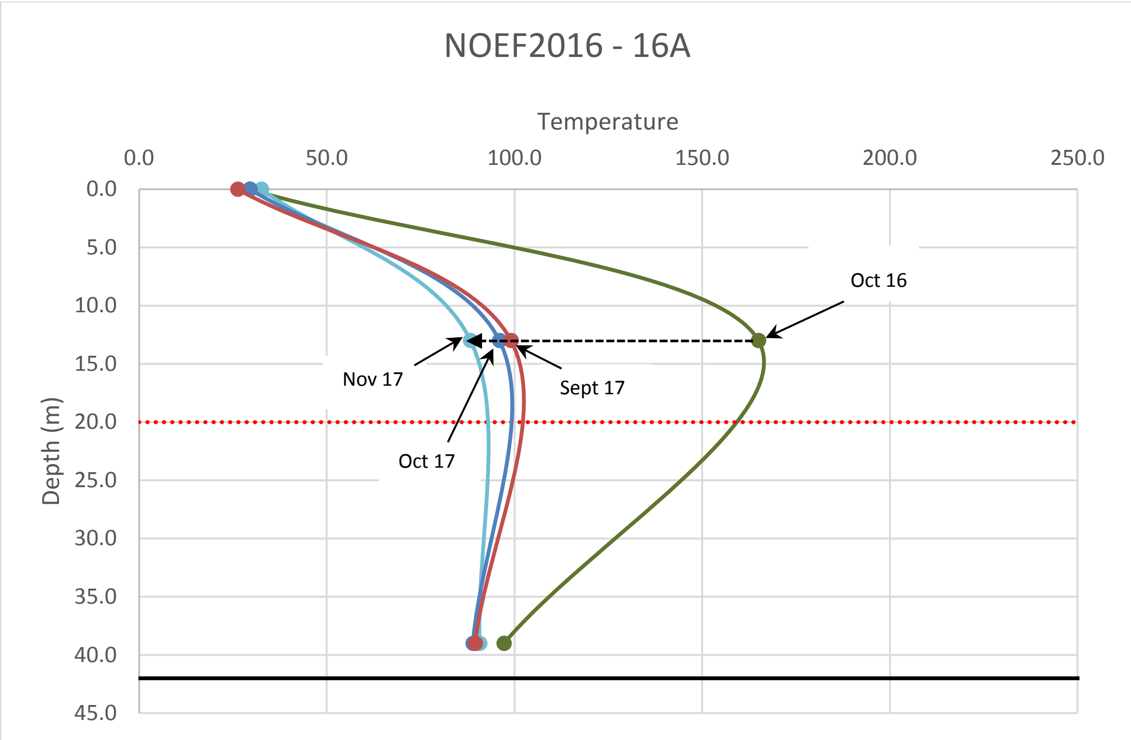


FIGURE 16: NOEF2016-16A TEMPERATURE PROFILE

NOEF2016-12A (Figure 18) shows a progressive temperature decrease at 10m from October 2016 to October 2017, with a temperature decrease from 165°C to 90°C, a cooling of 75°C in 12 months. Significantly, most of the cooling occurred in a single month between January and February 2017 (as in NOEF2016-10A). Similarly, the 19m interval has cooled from 189°C to 158°C, a 31°C cooling. Unfortunately, the 30m thermocouple ceased to function in November 2016.

Despite the significant cooling observed, NOEF2016-12A cannot be considered cool, with temperatures in the 150°C range remaining at 19m. .

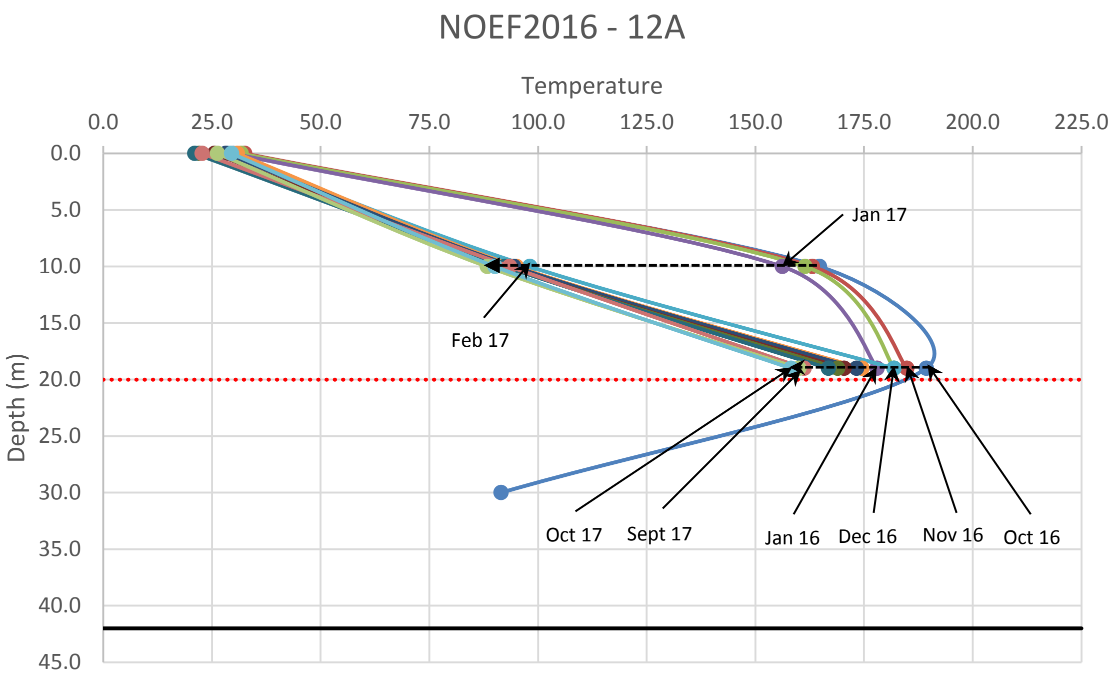


FIGURE 17: NOEF2016-12A TEMPERATURE PROFILE

5.2.3 Average NOEF temperature tends

The average monthly temperatures for 9 monitoring bores of the 2016 program are presented in Figure 17.

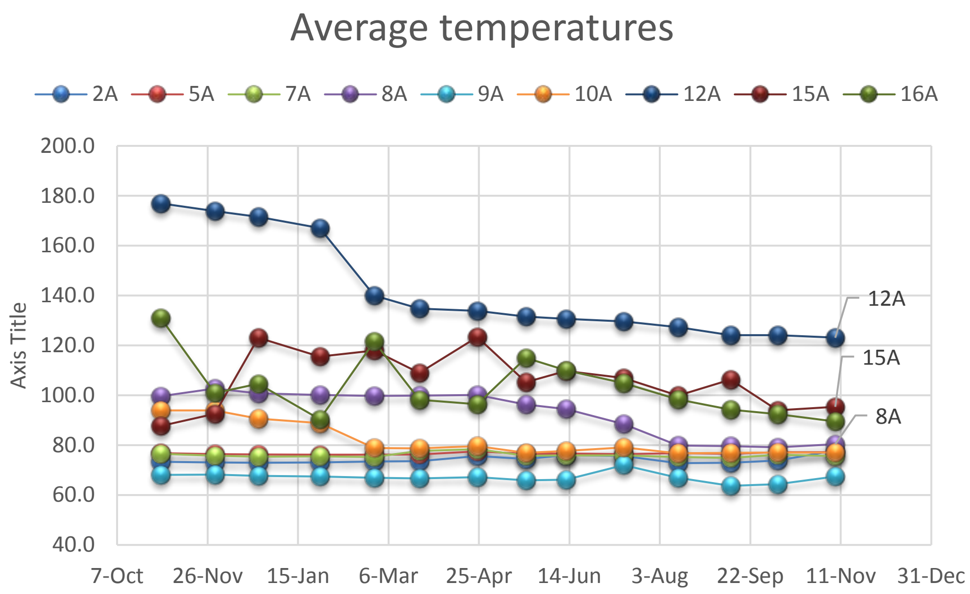


FIGURE 18: AVERAGE TEMPERATURES

While some individual variability is present, the observed overall trend is for a progressive decrease in temperature with time. The trend is predominantly present in high temperature locations: 12A, 15A, 16A, 8A and 10A show progressively decreasing average temperatures, while the cooler locations (2A, 5A, 7A and 9A) show very constant temperatures with almost no cooling.

Figure 18 shows the averages for the elevated temperature locations (12A, 15A, 16A, 8A, 10A), the background temperature locations (2A, 5A, 7A, 9A), and the averages for all the monitoring wells.

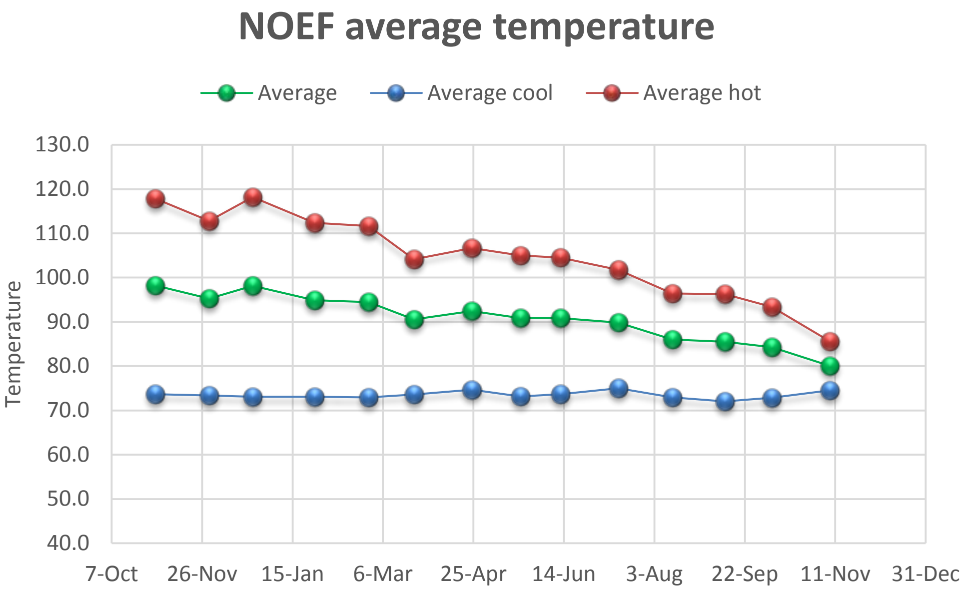


FIGURE 19: NOEF AVERAGE TEMPERATURES

The figure shows that the average temperature of the NOEF obtained from the monitoring wells has decreased from ca 98°C in October 2016 to 80°C in November 2017. The cooling trend is largely driven by decreasing temperatures in hot areas, with the average temperature decreasing from 118°C to 85°C, a decrease of 33°C. While the absolute values of the averages are relatively meaningless as they mask some clear local variability, the data clearly indicates that measured temperatures have been on a decreasing trend over the monitoring period.

5.3 Spatial Temperature Distributions

The spatial distribution of background (blue) and elevated (red) temperature locations are presented in Figure 19 and 20. Figure 19 presents the situation in December 2016, while Figure 20 presents the situation in November 2017.

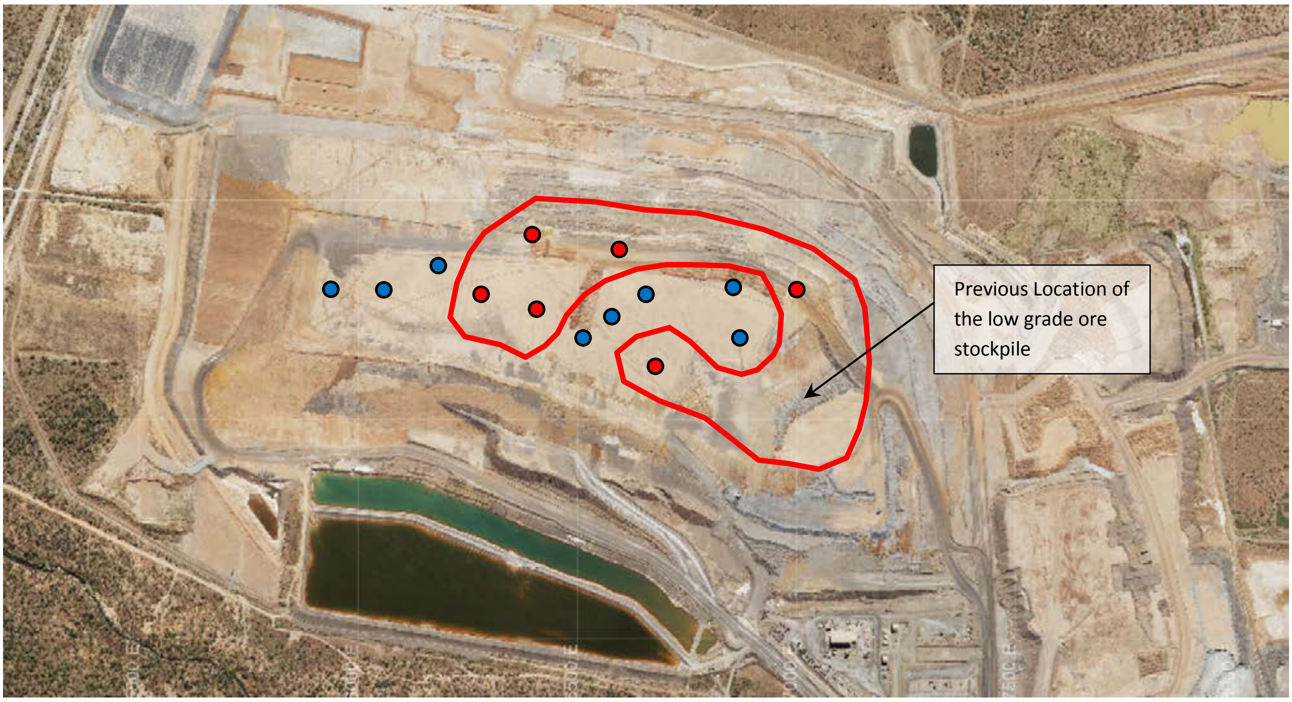


FIGURE 20: SITUATION IN DECEMBER 2016

FIGURE 21: SITUATION IN NOVEMBER 2017.

Comparison of the situation in December 2016 with November 2017 shows a significant decrease in the area of the NOEF affected by elevated temperatures:

- The rehandling and processing of the Low Grade Ore (LGO) stockpile on the south-eastern margin of the NOEF has resulted in a significant cooling of the area, with the complete removal of reacting material from the area.
- Three monitoring bores (8A, 10A and 16A) located on the plateau of the NOEF have significantly cooled and can be considered at background temperature, indicating that the bulk of the NOEF core is comparatively cool.
- The principal area where high temperatures are observed on the eastern half of the northern batter, corresponding to an area where spontaneous combustion has historically occurred. The area corresponds to the remaining area with batter and berm configuration, and is currently still undergoing remediation.

6 DISCUSSION

The background temperature of the NOEF PAF cell below 10m is on average 73°C. Although the absolute value can appear elevated compared to other published sulphidic waste rock dump values, it is only ca 40°C hotter than the temperature that can be expected from the mean air temperatures at the site. While at the higher end of the spectrum, this value is not abnormal for a high sulphide waste rock dump and indicates that oxidation rates within the core of the NOEF are not exceptionally high compared to other equivalent sites (see Lefebvre *et al*, 1994).

All the monitoring wells at background temperatures show stable temperature profiles with a complete absence of seasonal variation. The absence of seasonal variation strongly suggest that the internal temperatures in the core of the NOEF are not affected by atmospheric conditions (air temperature, moisture, wind strength and direction, etc.) and therefore that exchanges between the NOEF core and the atmosphere are limited.

The temperature profiles show a high increase in temp in the first 10 metres of waste. The high increase in temperature at shallow depth is consistent with the greatest availability of oxygen, indicating that most of the oxidation is likely to occur in the first few metres. This is consistent with oxygen measurements from the 2016 NOEF-8G well.

Figure 21 shows the O_2 concentration with depth for NOEF2016-8G together with the two temperature profiles from the adjacent NOEF2016-5A and 9A. The profiles show that the O_2 concentration goes from 20.9% at the surface to about 0.5% in the first 10 metres, and that the O_2 concentration remains at this level throughout the profile. The results suggest that oxygen is very rapidly consumed in the first metres of the NOEF.

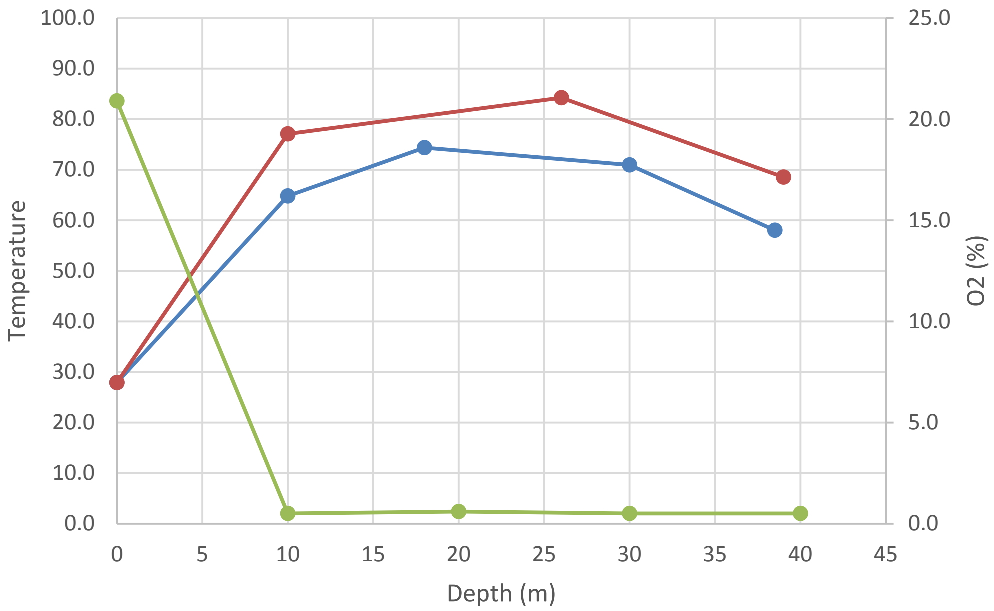
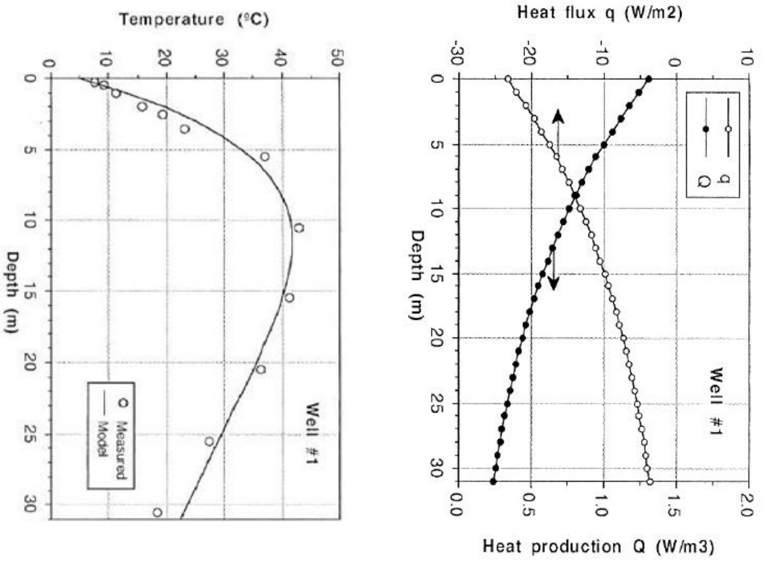


FIGURE 22: OXYGEN CONCENTRATION VERSUS DEPTH IN NOEF2016-8G

In contrast to cooler background temperature profiles, the elevated temperature profiles show much greater level of variations over time, indicating that advection of air into the stockpile and convective heat transport play a significant role in the control of temperatures at these locations. It is important to note that within a sulphidic waste rock dump, the location of the highest temperatures do not necessarily correspond to the location of highest oxidation.

As an example, the relationship between oxidation and heat flux in a sulfidic waste rock dumps in Quebec was investigated and modelled by Lefebvre *et al* (1994). The results are reproduced in Figure 22: observed and modelled temperatures within the Doyon waste rock dump, Quebec (from Lefebvre *et al*, 1994).



a b

FIGURE 23: OBSERVED AND MODELLED TEMPERATURES WITHIN THE DOYON WASTE ROCK DUMP, QUEBEC (FROM LEFEBRE ET AL, 1994)

Figure 22a shows the measured versus modelled temperatures. While the highest temperatures were measured at 10m depth, the highest heat production (and hence oxidation) occurs at the surface and decreases with depth (Figure 22b). The increase in temperature with depth is due to the vertical transport of heat by convection and the limited ability of the rocks to lose heat to the environment at depth, thereby resulting in increased temperatures towards the middle of the dump. This pattern can be clearly seen in the NOEF, such as in the NOEF2016-10A temperature profile (refer to Figure 14). The maximum temperature of 140°C at 15m likely reflects convective heat transport within the dump, and does not indicate increased oxidation or combustion at 15m in that location. This is consistent with the observed rapid temperature decrease observed at 15 m, a rate that would be unlikely if in-situ oxidation was the driving mechanism.

While the temperatures are higher in this region, oxidation rates are lower than at the margins of the NOEF which are cooler owing to more efficient heat loss. From the modelling, Lefebvre *et a*l proposed a general conceptual model of internal heat transfer within sulfidic dumps (Figure 23).

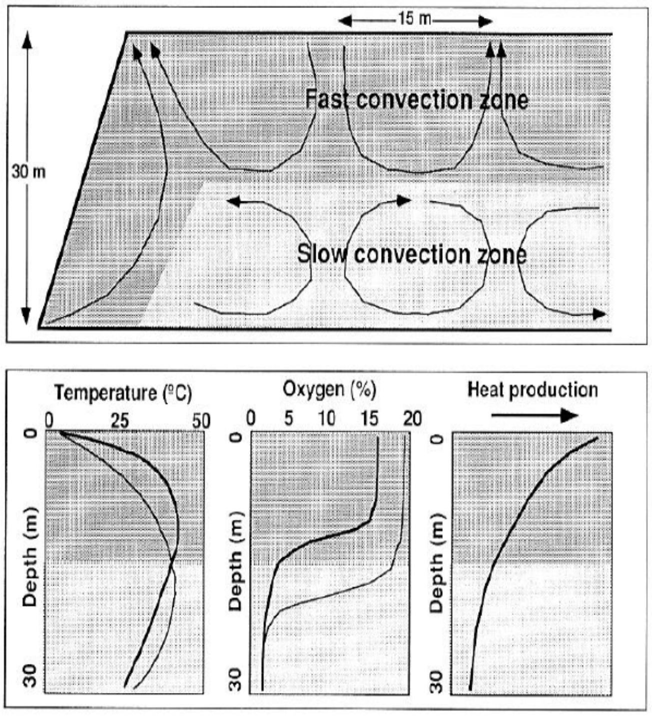


FIGURE 24: CONCEPTUAL MODEL OF A SULPHIDIC DUMP (FROM LEFEBRE ET AL, 1994)

The NOEF temperatures conform to this general conceptual model presented by Lefebvre *et al*, modified by the effects of the internal structure of the NOEF. All high temperature wells are located in close proximity to the batters, in what could be interpreted as a "fast convection zone": the highest oxidation is likely to occur closer to the batters and closer to the top surface, while the heat generated is transported down through convection and horizontally through advection.

The high vertical variability in the NOEF temperature profiles suggest that significant horizontal air transport in proximity to the batters may be occurring, in particular along the northern batter. The placement of a low air permeability layer on the NOEF to inhibit advection into the stockpile is expected to have a significant effect on the internal gas transport and therefore the residual high temperatures within the NOEF. Significant temperature decreases have already occurred in the hot areas and likely reflect the remediation efforts already conducted:

- Extinction of surface combustion across the whole NOEF.
- Battering of the NOEF to a low angle geometry, reducing the air permeability of the batter
- Placement of wet season alluvial cover to reduce net percolation of water and limit contact with oxygen of surface material.

7 CONCLUSION

Temperature monitoring at 10 locations on the NOEF from October 2016 to November 2017 indicates that significant temperature decreases have already occurred over the monitoring period:

- Three locations which had significantly elevated temperatures in late 2016 (NOEF2016-8A, 10A, and 16A) can now be considered as approaching background temperature levels.
- None of the originally cool locations have recorded an increase in temperature over the monitoring period, indicating that high temperatures are not prevalent or spreading through the core of the NOEF
- The principal remaining area of elevated temperatures is located on the eastern side of the northern batter, a zone which coincides with the last remaining batter and berm configuration and has only been remediated in September 2017.
- While high temperatures remain on the eastern half of the northern NOEF batter, significant temperature decreases of ca 65°C have already occurred locally. The average temperature of the hot locations has significantly decreased over the monitoring period from 118°C in October 2016 to 85°C in 2017.
- The placement of the low air permeability advection barrier is expected to have a significant effect on the temperatures of the northern batter. Work on the barrier has already commenced and it is expected to be in fully completed by the end of March 2018.
- The equilibrium background temperature of the NOEF core is close to 73°C. While elevated in absolute terms, it is only ca 40°C warmer than ambient temperatures at the site. This value is not exceptional for a sulfidic dump, and while indicative of ongoing oxidation, it is not indicative of exceptional conditions within the NOEF.

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