Geotechnical Engineering and Design for Warming Soil Conditions

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Effect of Warming Climate and Warming Soil Temperatures upon Adfreeze Pile Design

Case Study

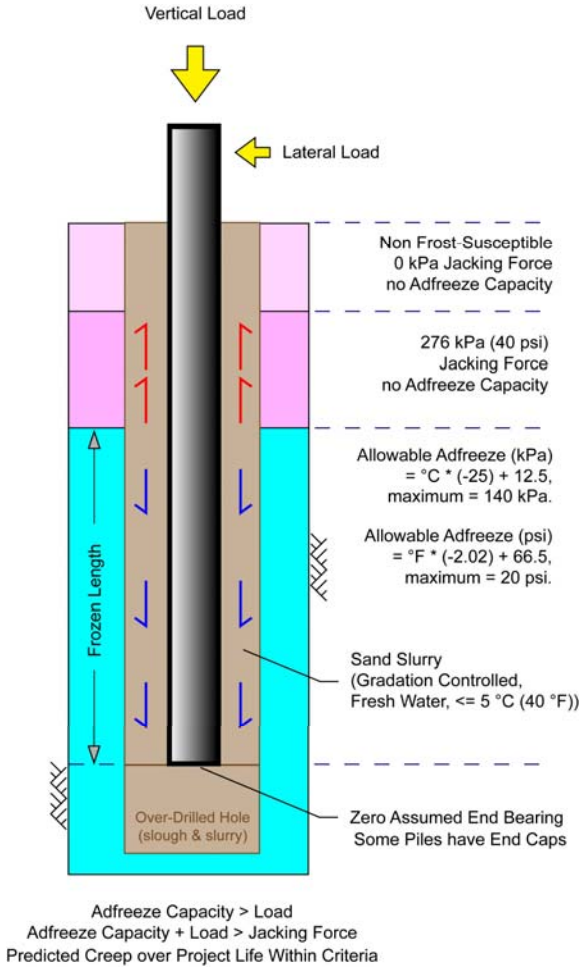
- Piperack Loading History
- Simulations to Predict Effectiveness of Slanty Thermosyphons
- Pilot Project
- Piperack Self Leveling

Summary

Adfreeze Pile Design

Use of Piles to Support Camps, Process Facilities and Pipelines

Adfreeze Pile Design Schematic

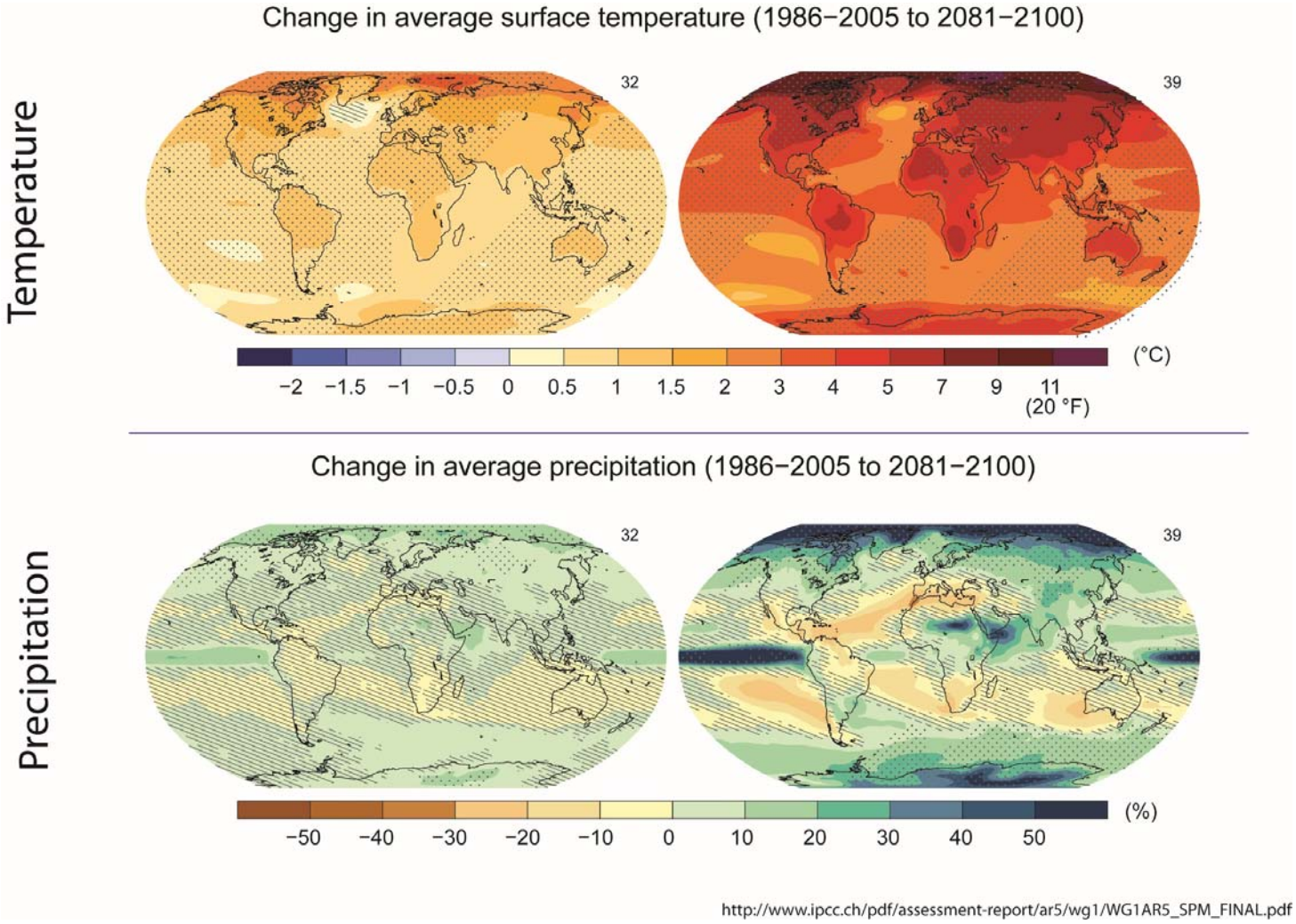


Adfreeze Capacity > Load
Adfreeze Capacity + Load > Jacking Force
Predicted Creep over Project Life Within Criteria

Camps and Process Facilities Supported on Piles with 5’ to 7’ (1.5m to 2.1m) Air Gap Between Structure and Soil Surface

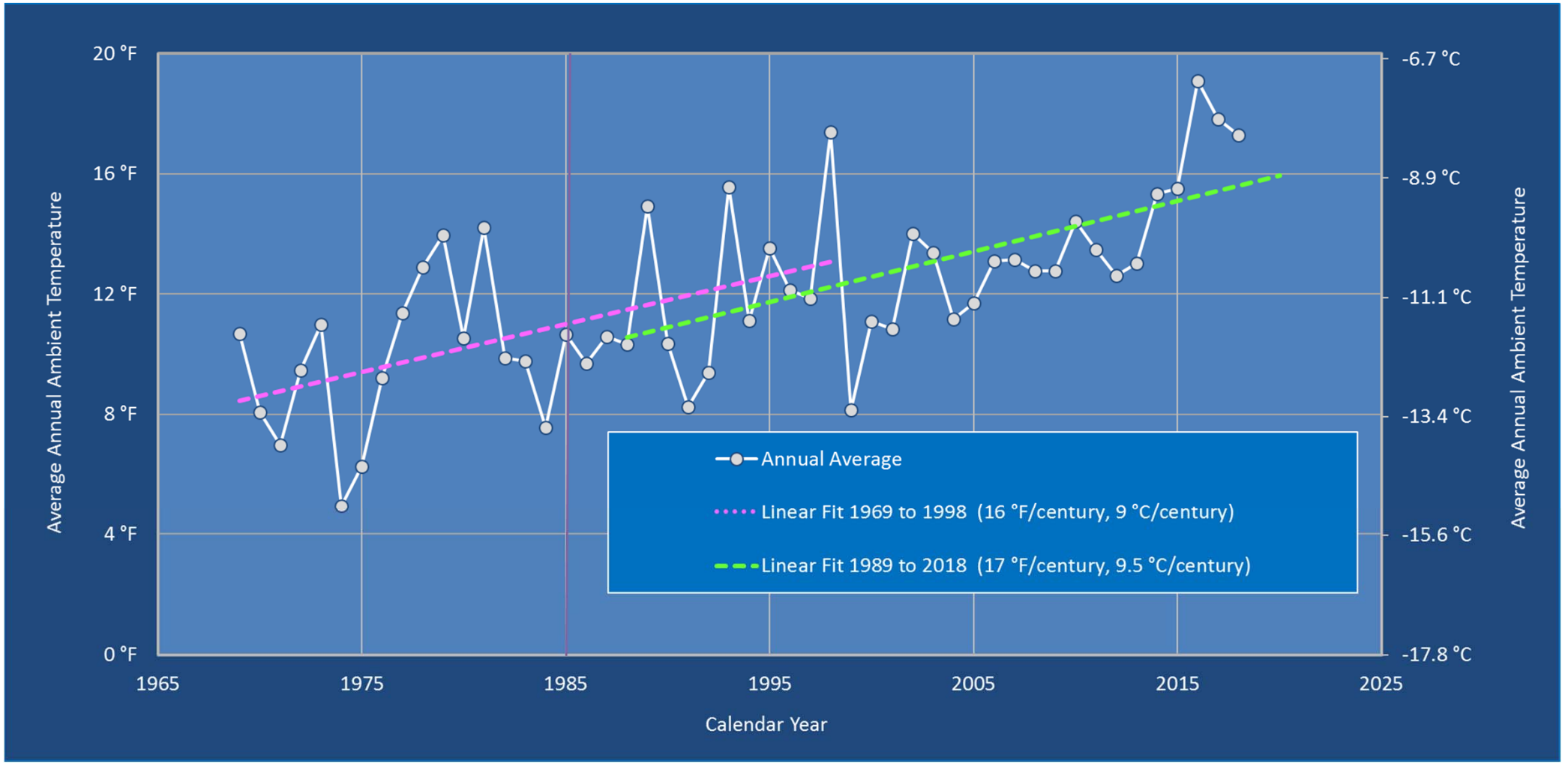
Pipes (Pipe Rack) Supported on Piles

Warming Climate

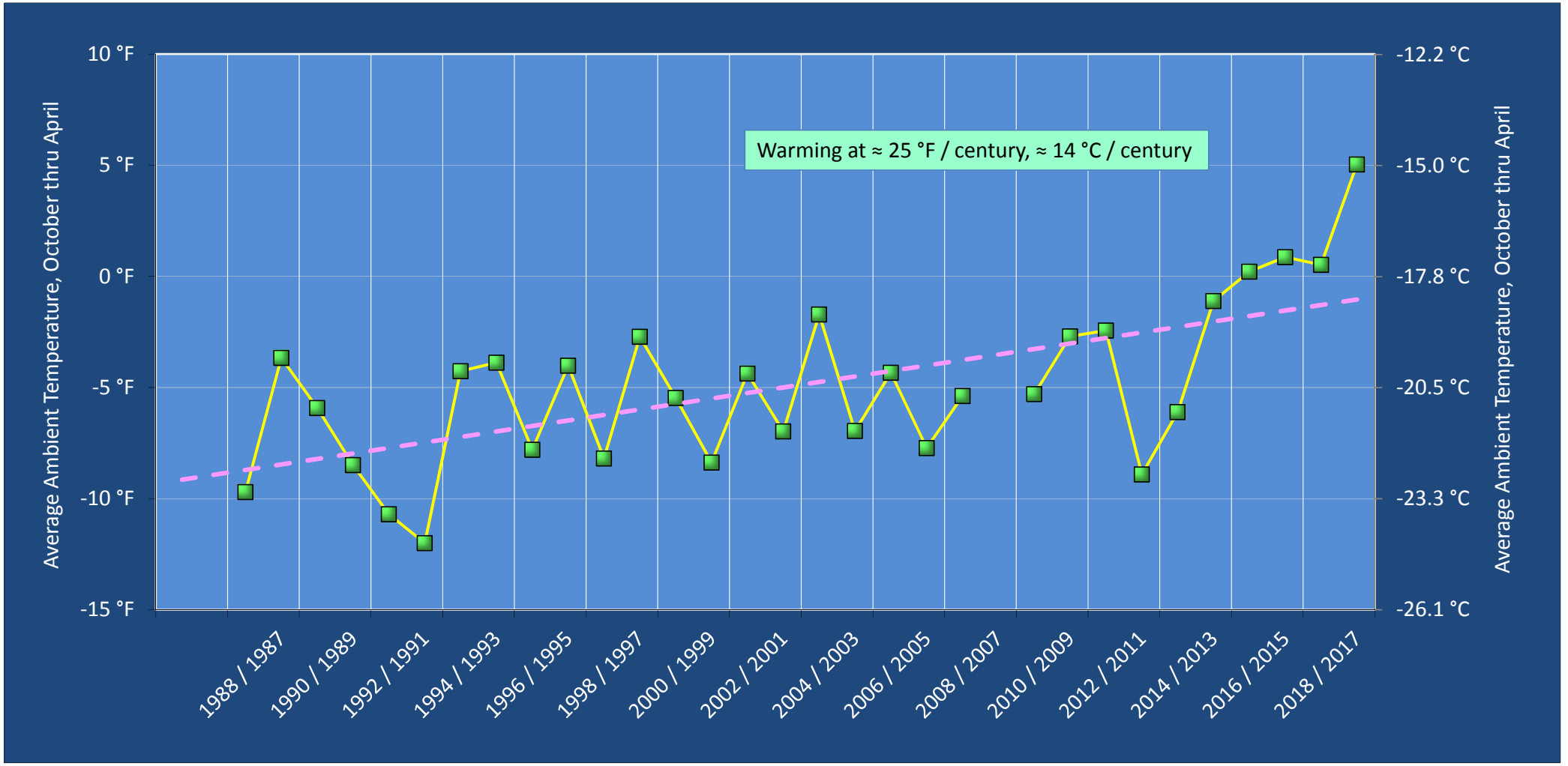


http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf

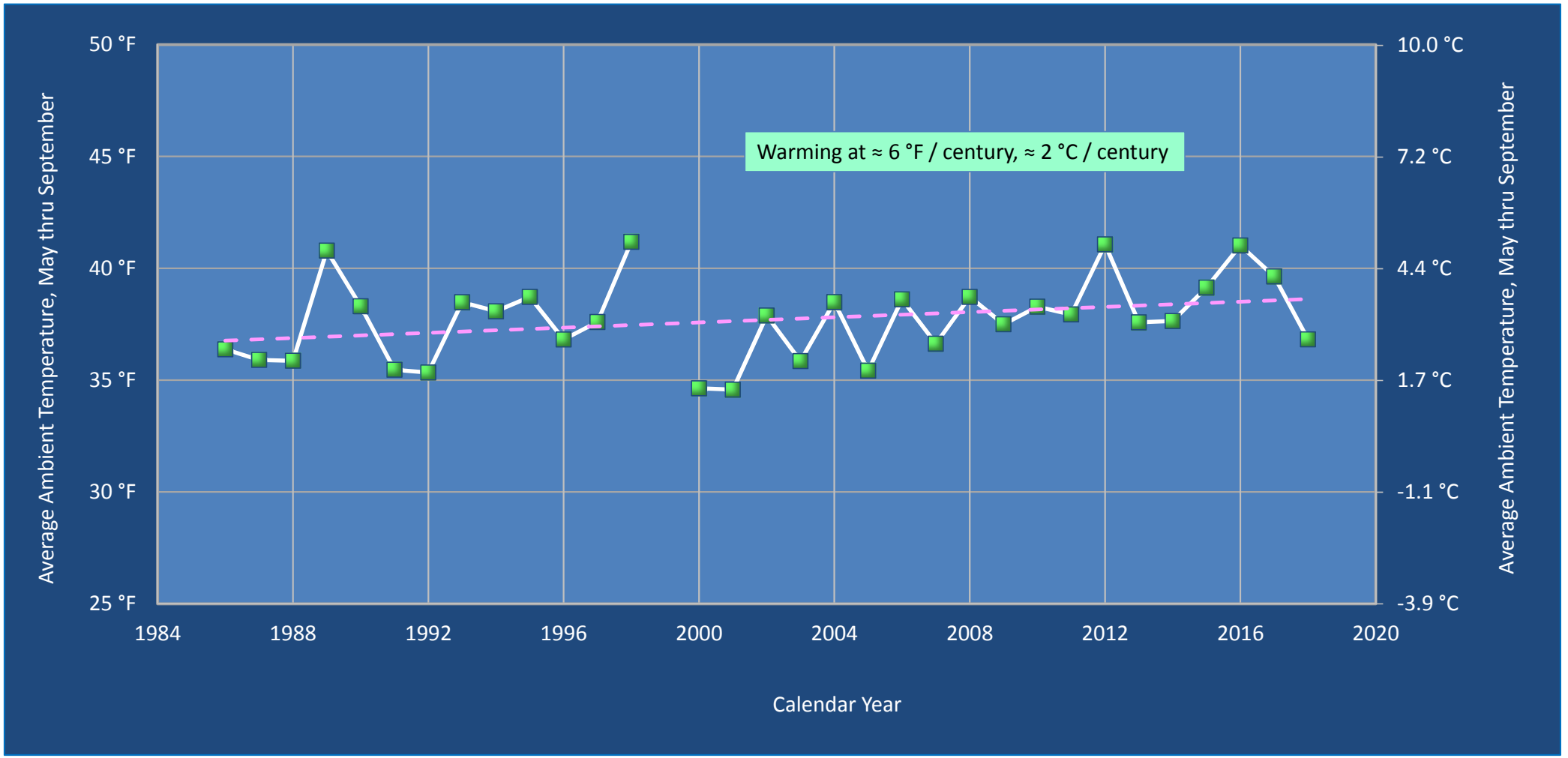
Ambient Temperature Trends, Prudhoe (ARCO and NOAA Data)



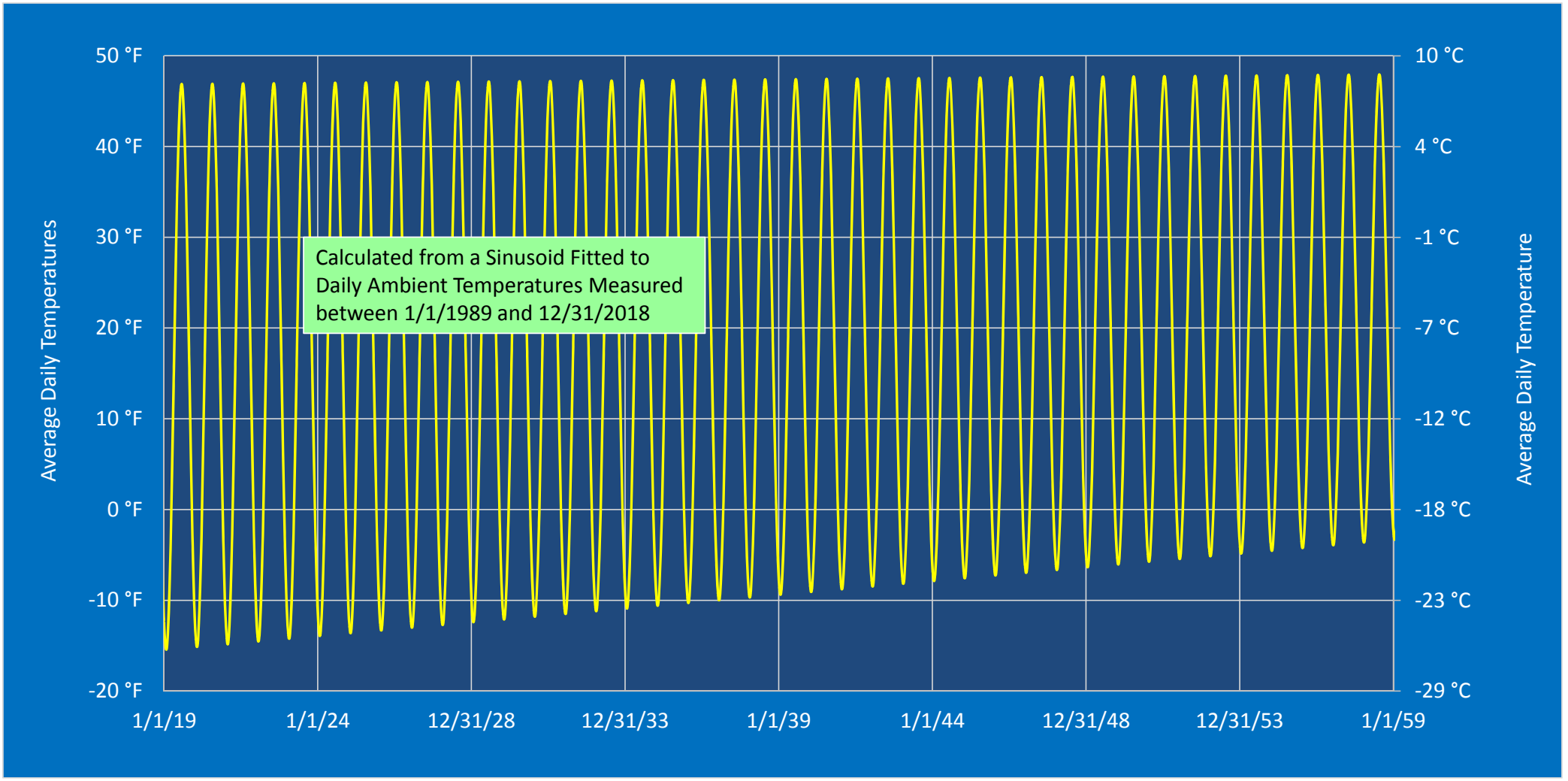
Trends in Average Annual Winter Temperatures in Prudhoe/Deadhorse, October through April



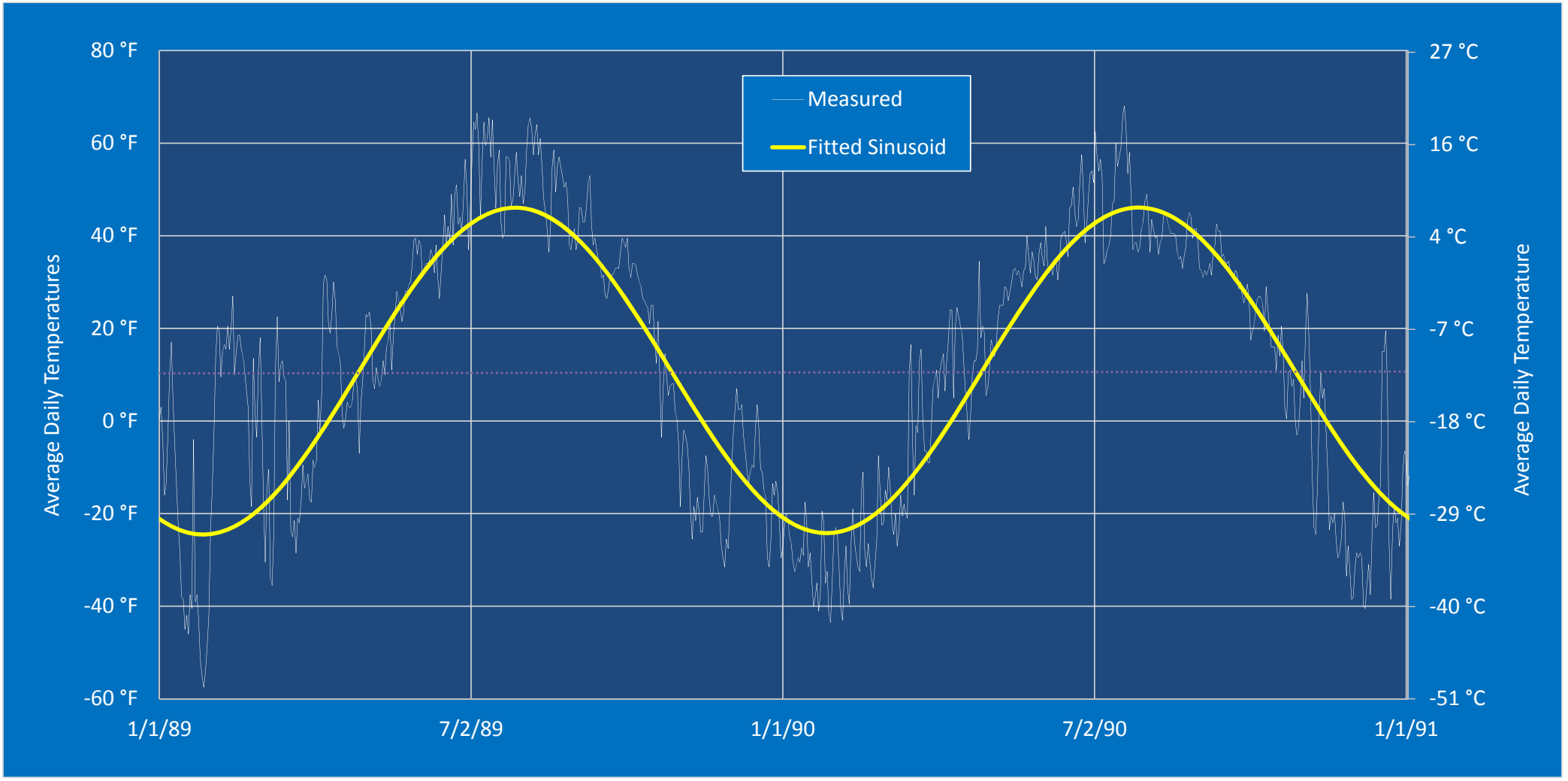
Trends in Average Annual Summer Temperatures in Prudhoe/Deadhorse, May through September



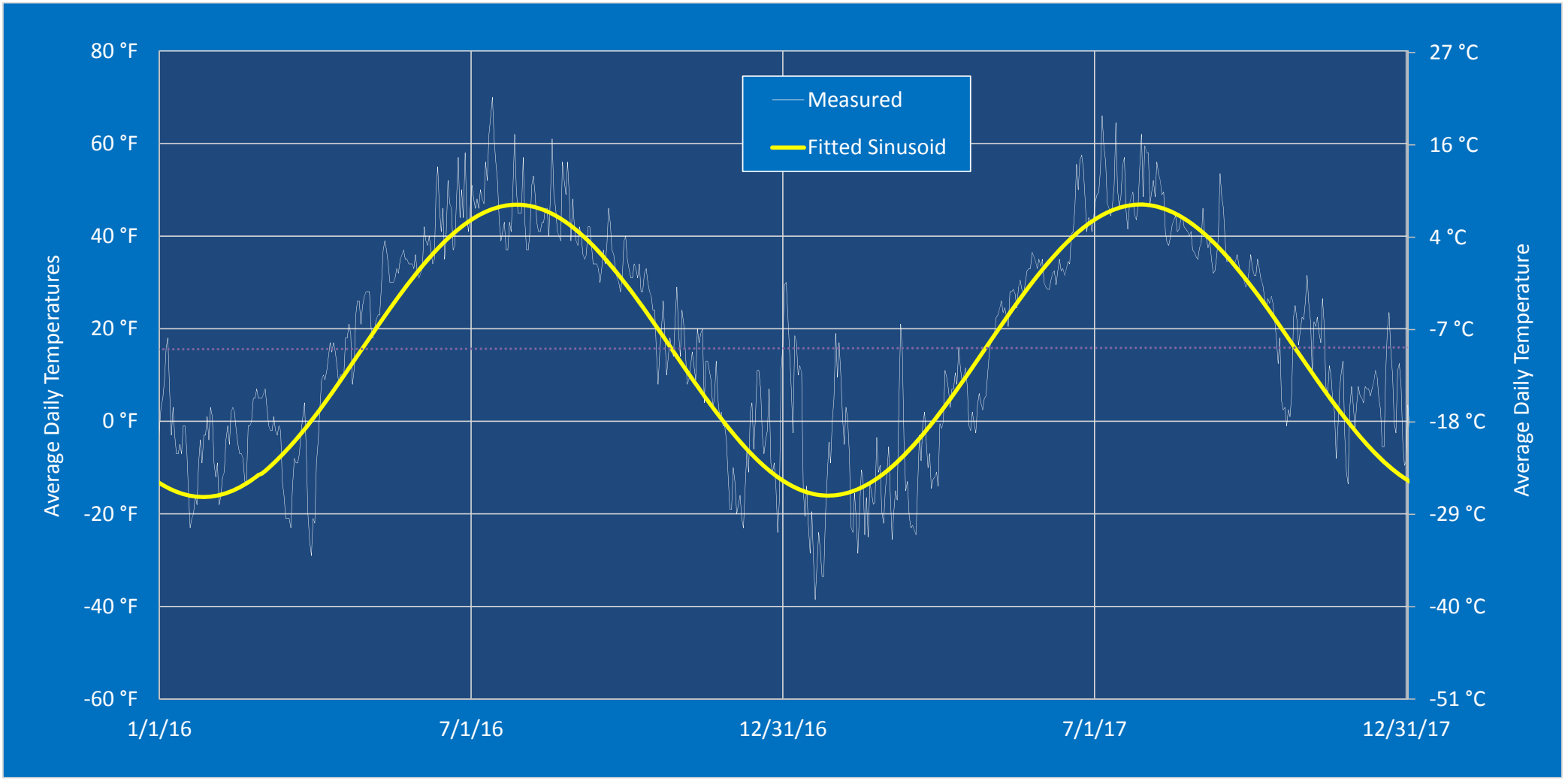
Fitted Average Daily Temperatures for Deadhorse, 2019 through 2058



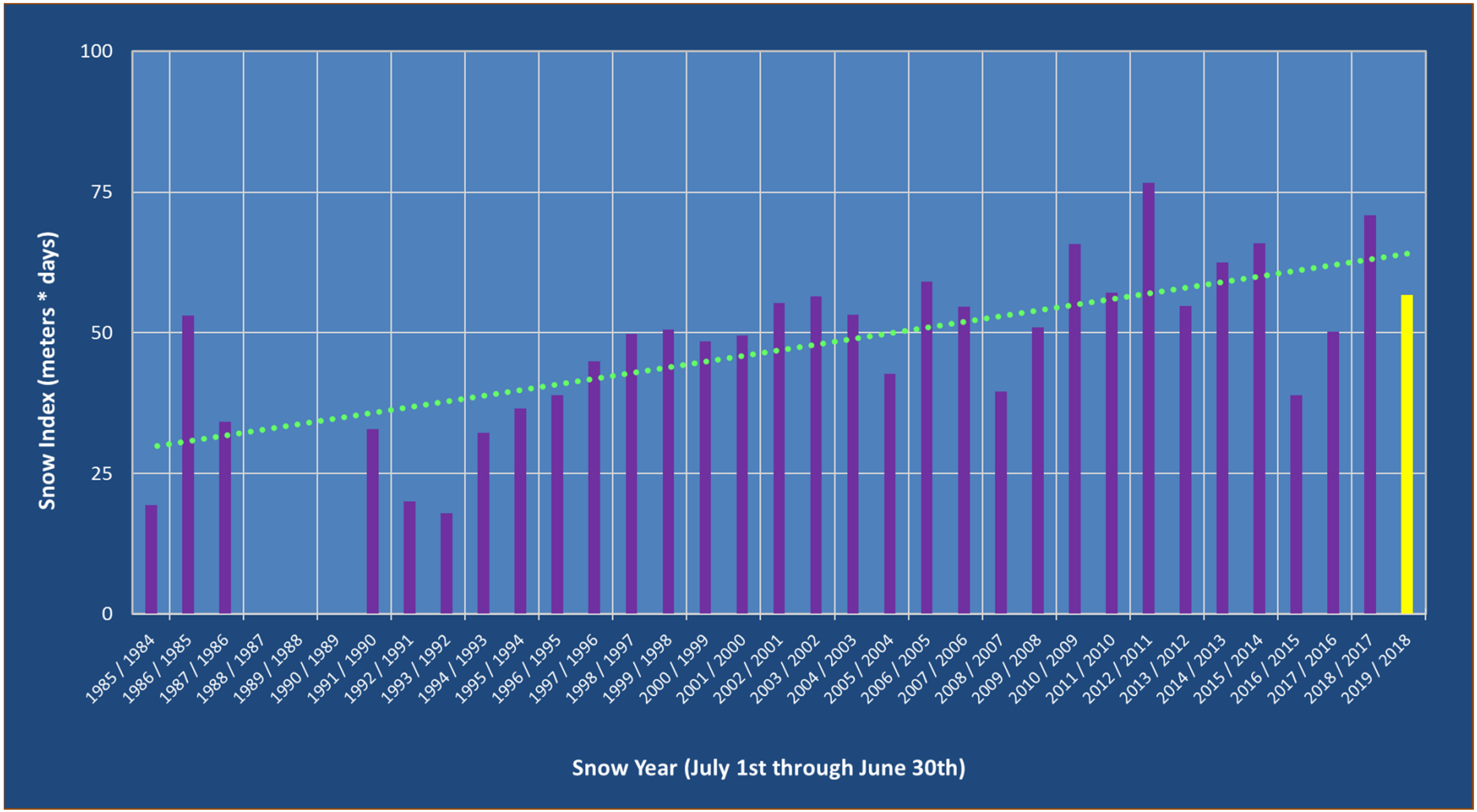
Comparison of Measured and Fitted Average Daily Temperature Measured at Deadhorse in 1989 and 1990



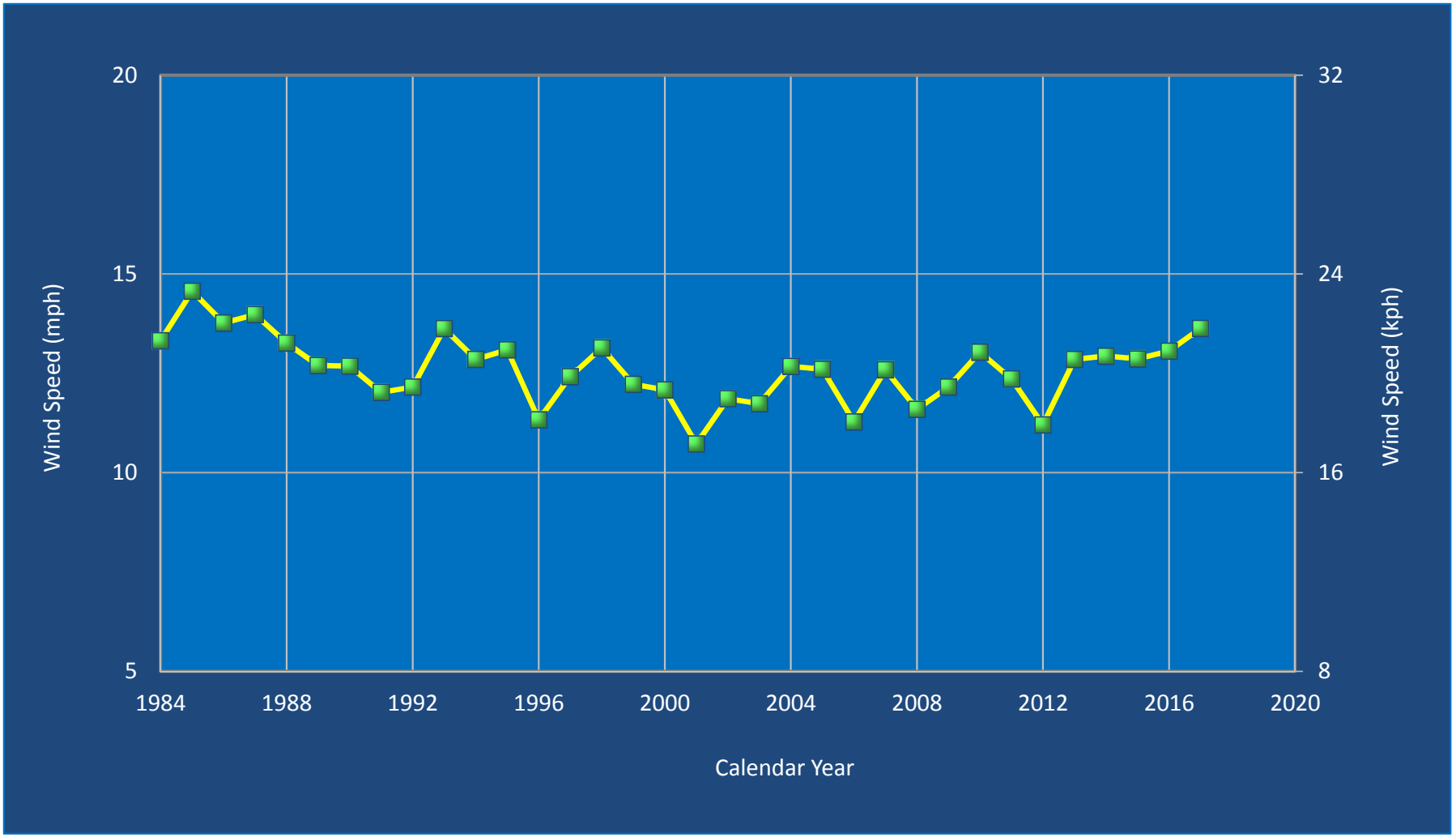
Comparison of Measured and Fitted Average Daily Temperature Measured at Deadhorse in 2016 and 2017



Snow Depth Trends, Kuparuk, Alaska, approx. 50 km (30 miles) West of Prudhoe



Wind Speed Trends, Prudhoe (NOAA Data)



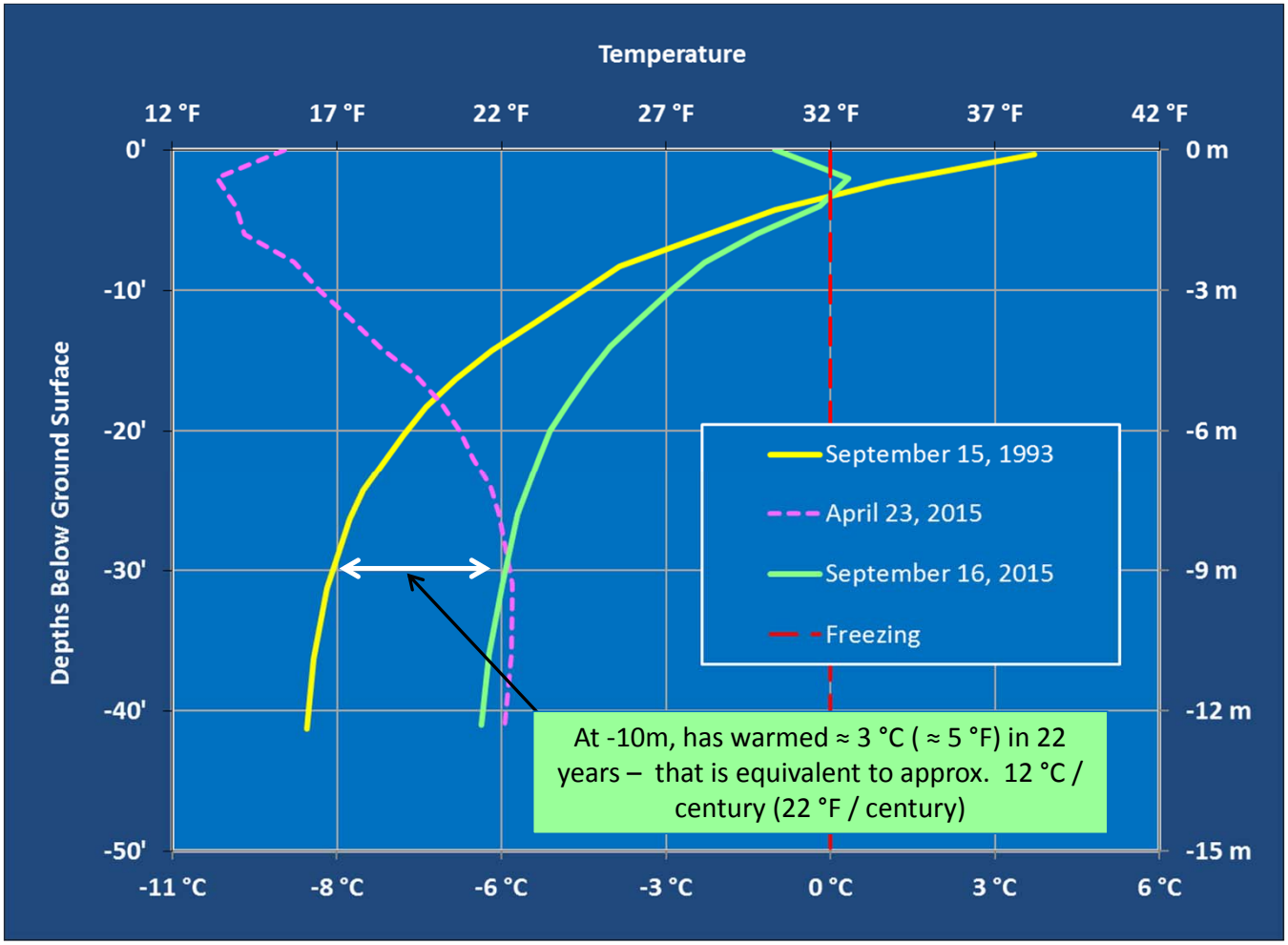
Warming Ground Temperatures

Undisturbed Tundra Soil Temperature Measurement Locations

CCP: 3 strings
AMDP: 3 strings
ESRDF: 2 strings
X-Pad: 2 strings

Deadhorse
West Dock

Temperature Profiles in Undisturbed Tundra at TE-1 near Drill Site 16



ESRDF Location (near DS16)

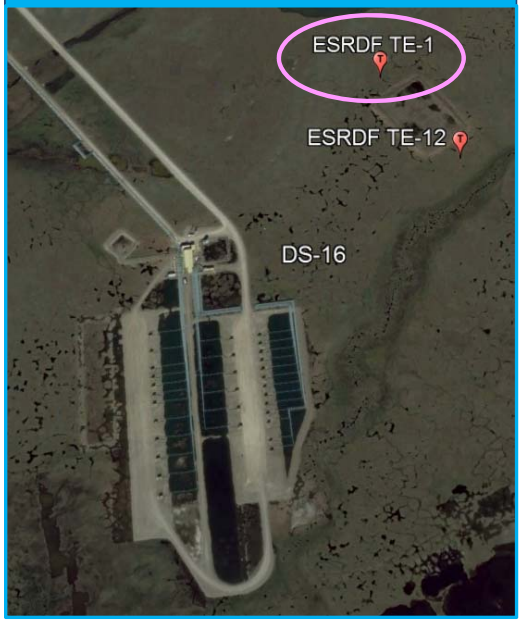
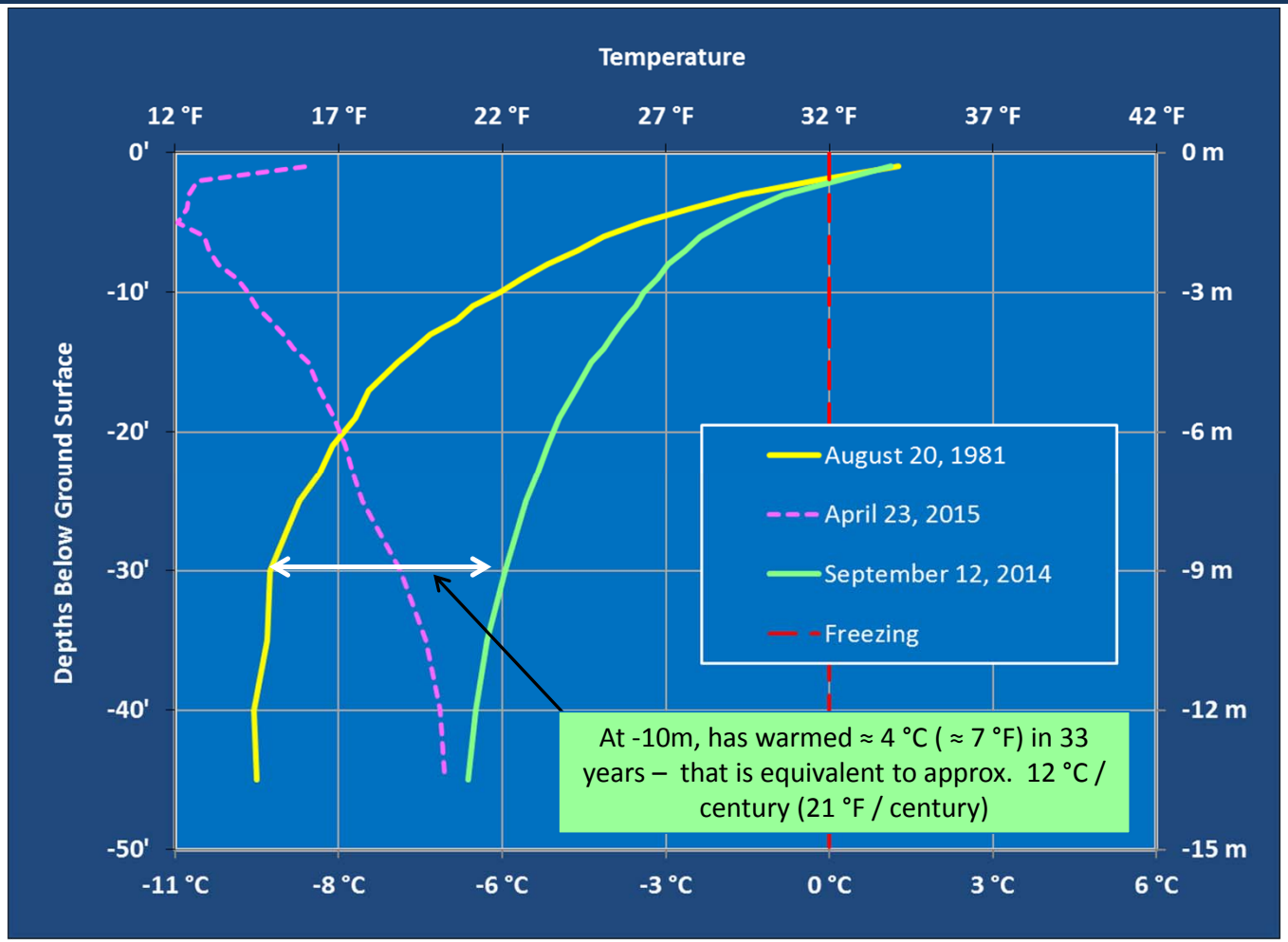


Photo of TS1, June 2013

Temperature Profiles in Undisturbed Tundra near the Central Compressor Plant



Near CCP

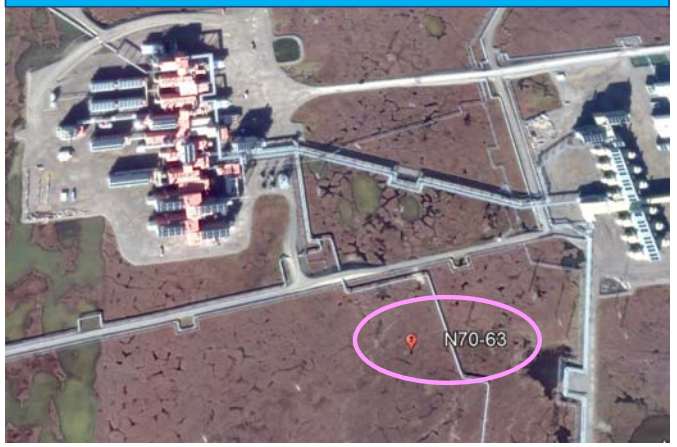


Photo of N70-63, June 2013

Undisturbed Tundra Measured Soil Temperatures, Prudhoe/Deadhorse, Alaska (Vlad Romanovsky, Tom Osterkamp)

Site Location

June 2013

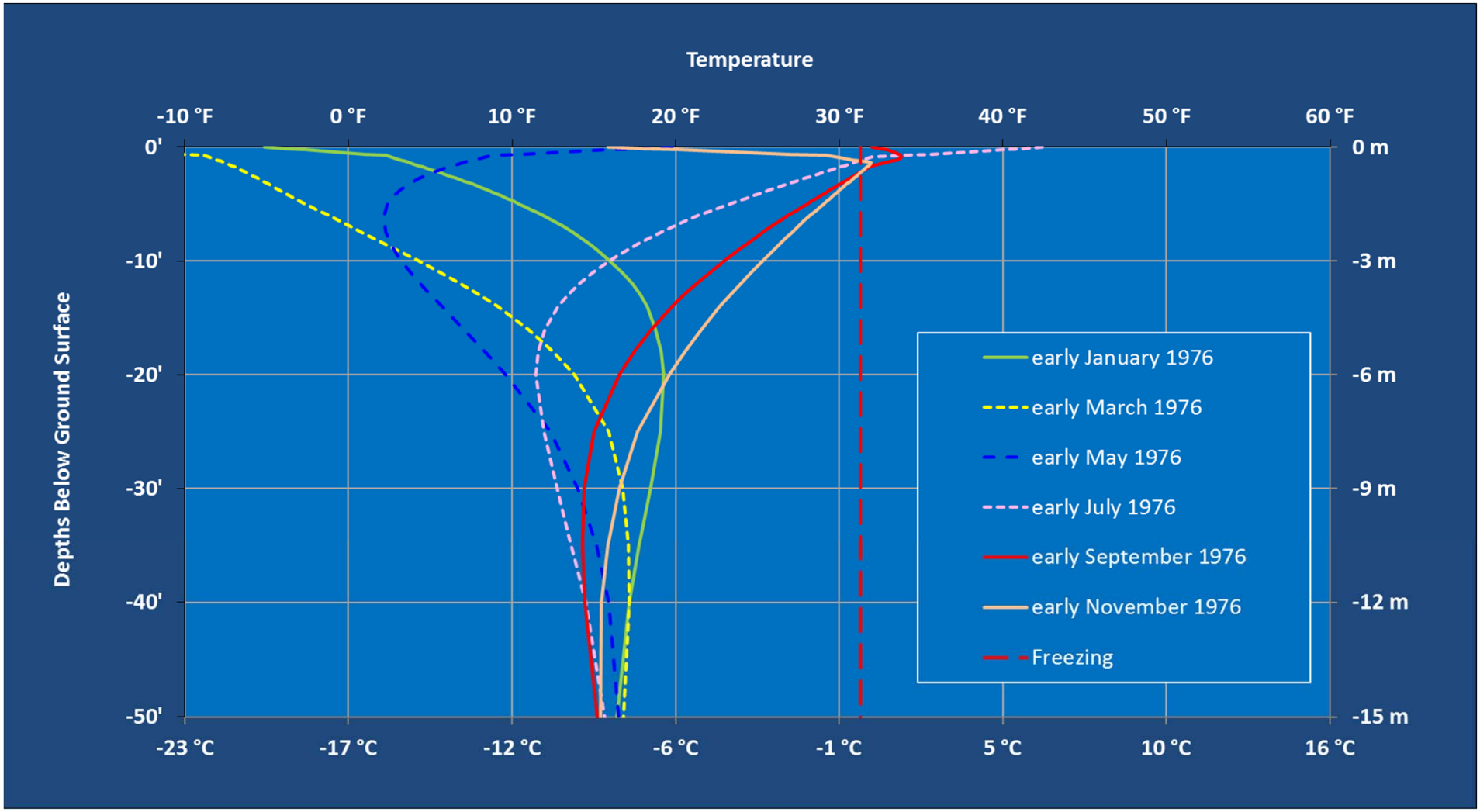
Snow Drifting (“insulation, minimizing beneficial cooling during winter”)

March 1, 2014

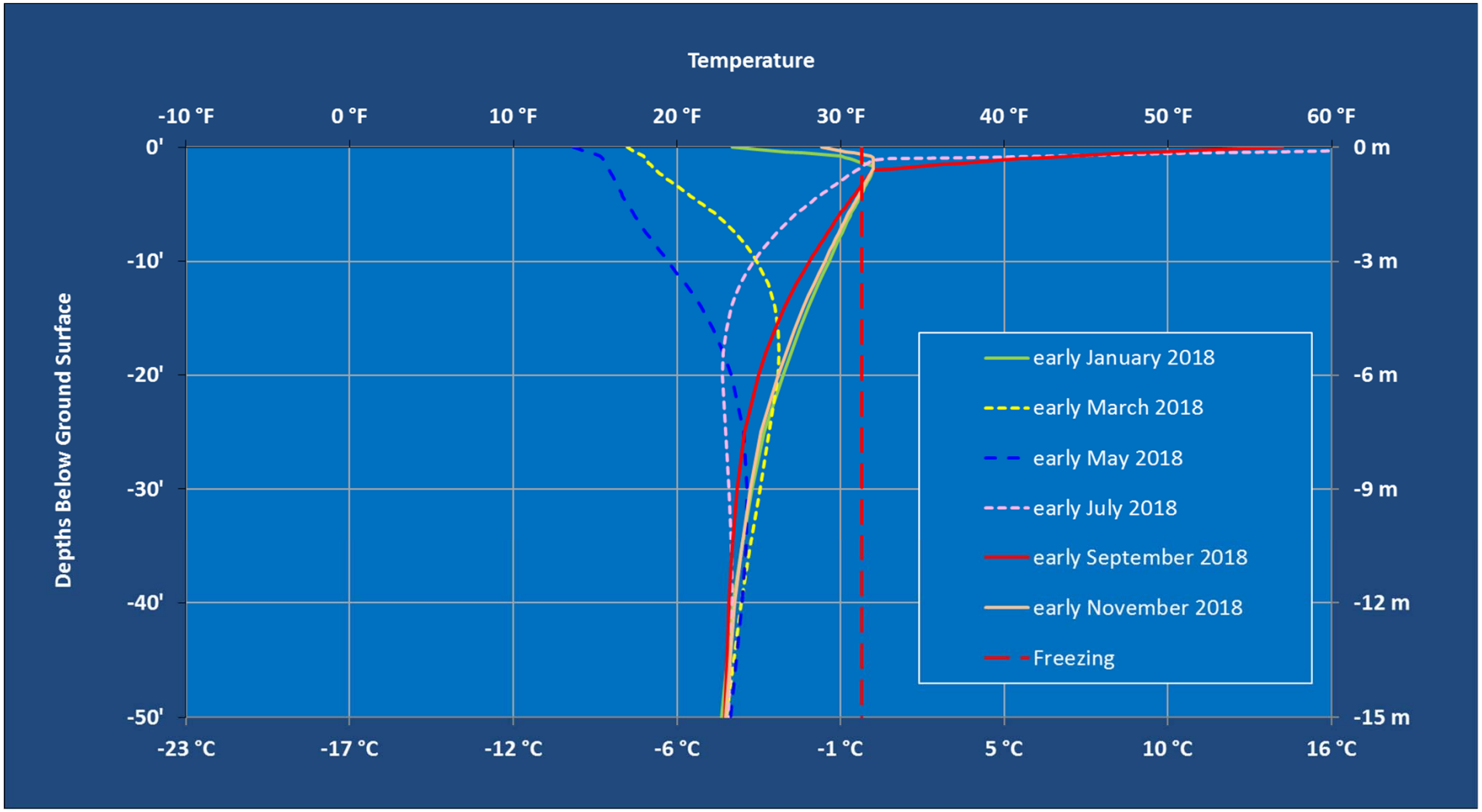
April 14, 2015

Effect of Warming Climate and Warming Soil Temperatures on Adfreeze Pile Design Lengths

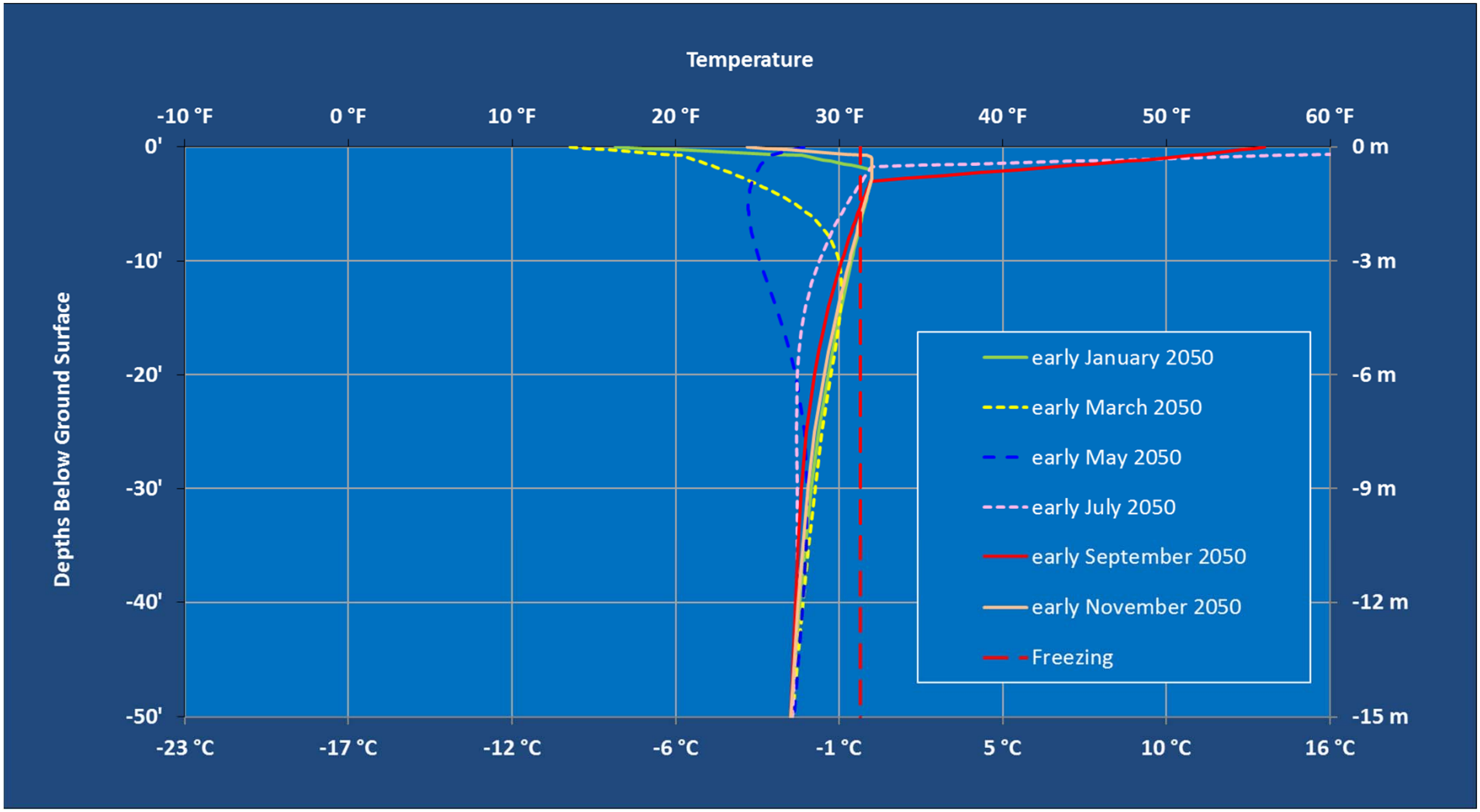
Predicted Temperature Profiles for Undisturbed Tundra, Prudhoe Bay, Alaska, 1976



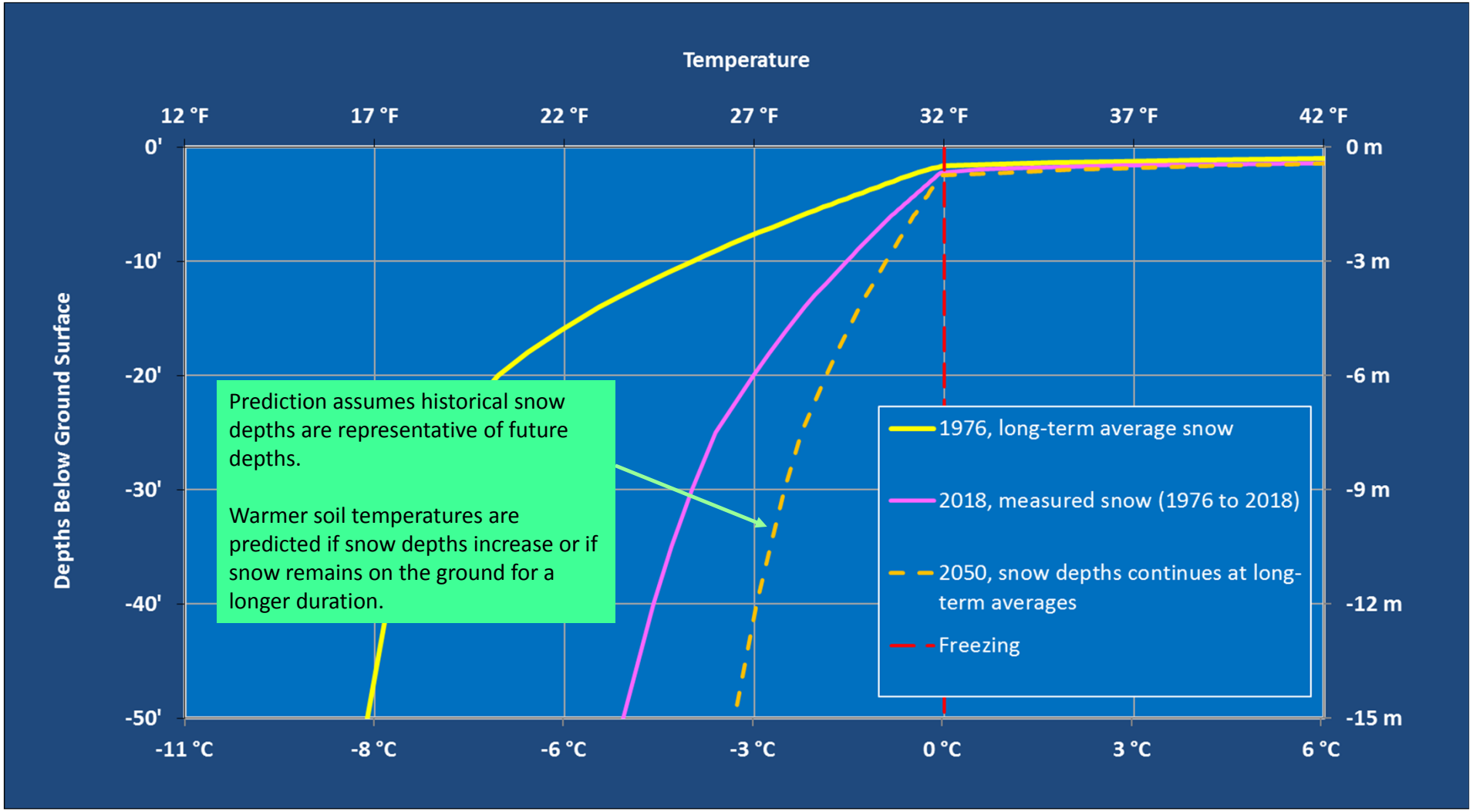
Predicted Temperature Profiles for Undisturbed Tundra, Prudhoe Bay, Alaska, 2018



Predicted Temperature Profiles for Undisturbed Tundra, Prudhoe Bay, Alaska, 2050

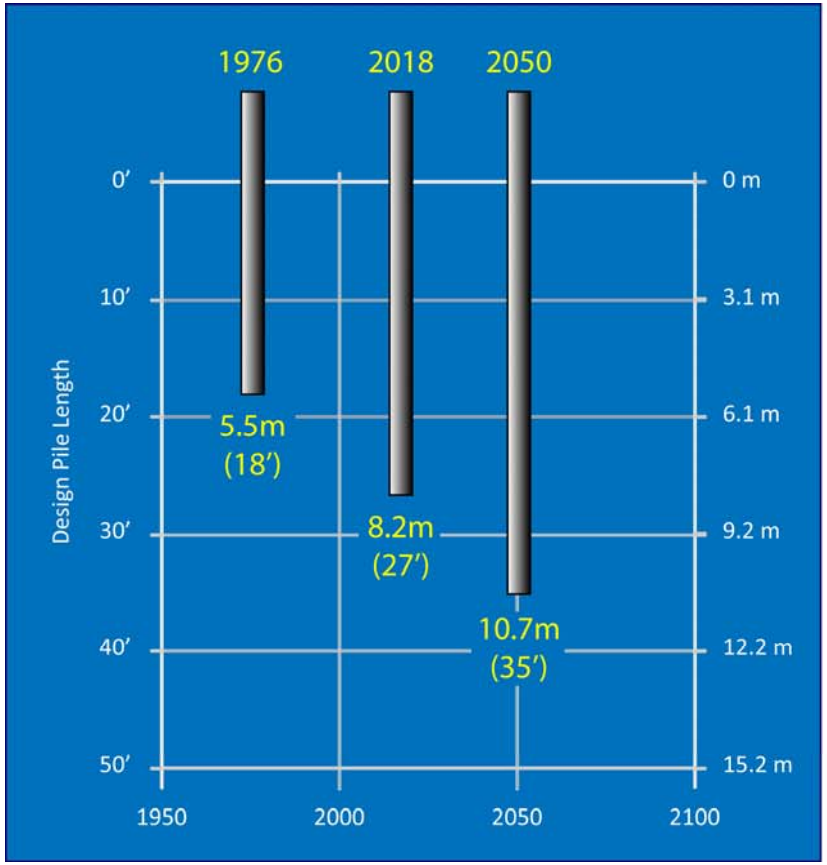


Predicted Maximum Yearly Soil Temperatures in Undisturbed Tundra

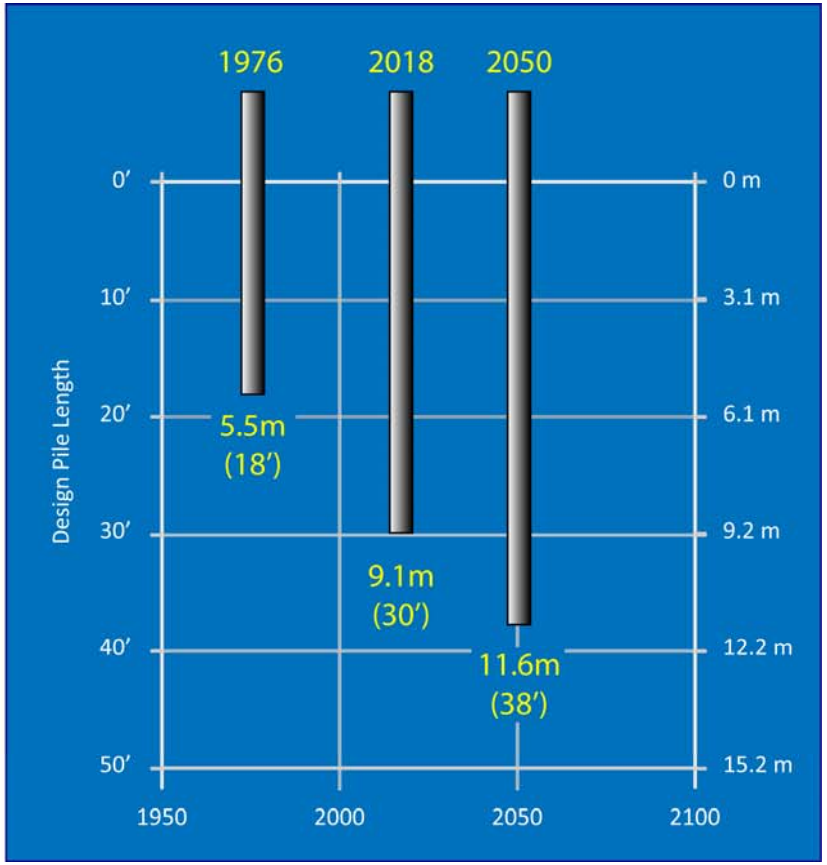


Effect of Warming Soil Temperatures upon Design Adfreeze Pile Lengths (30.5 cm dia. Pile, 445 kN design load)

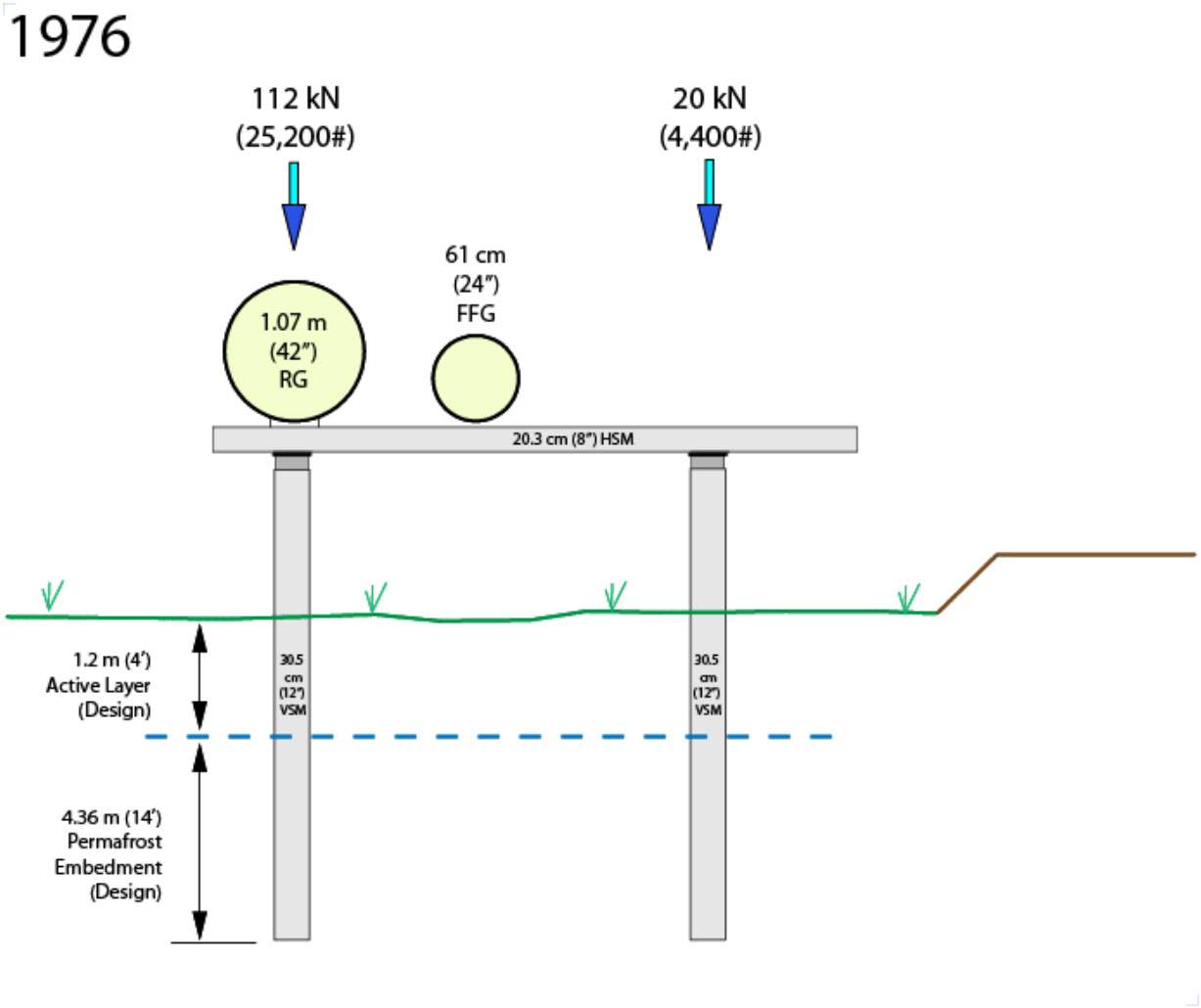
Assuming average temperature of fitted Sinusoid warms

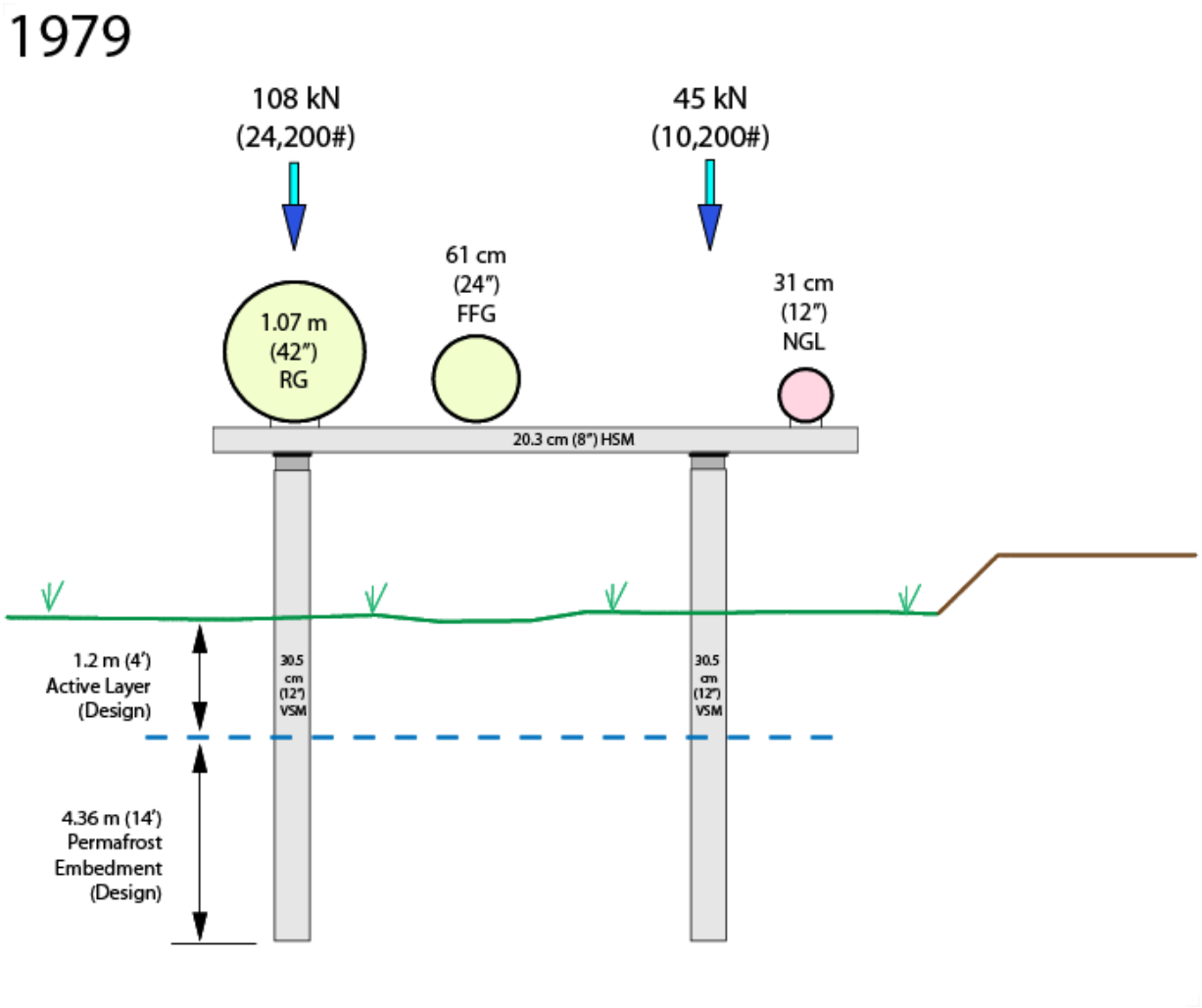


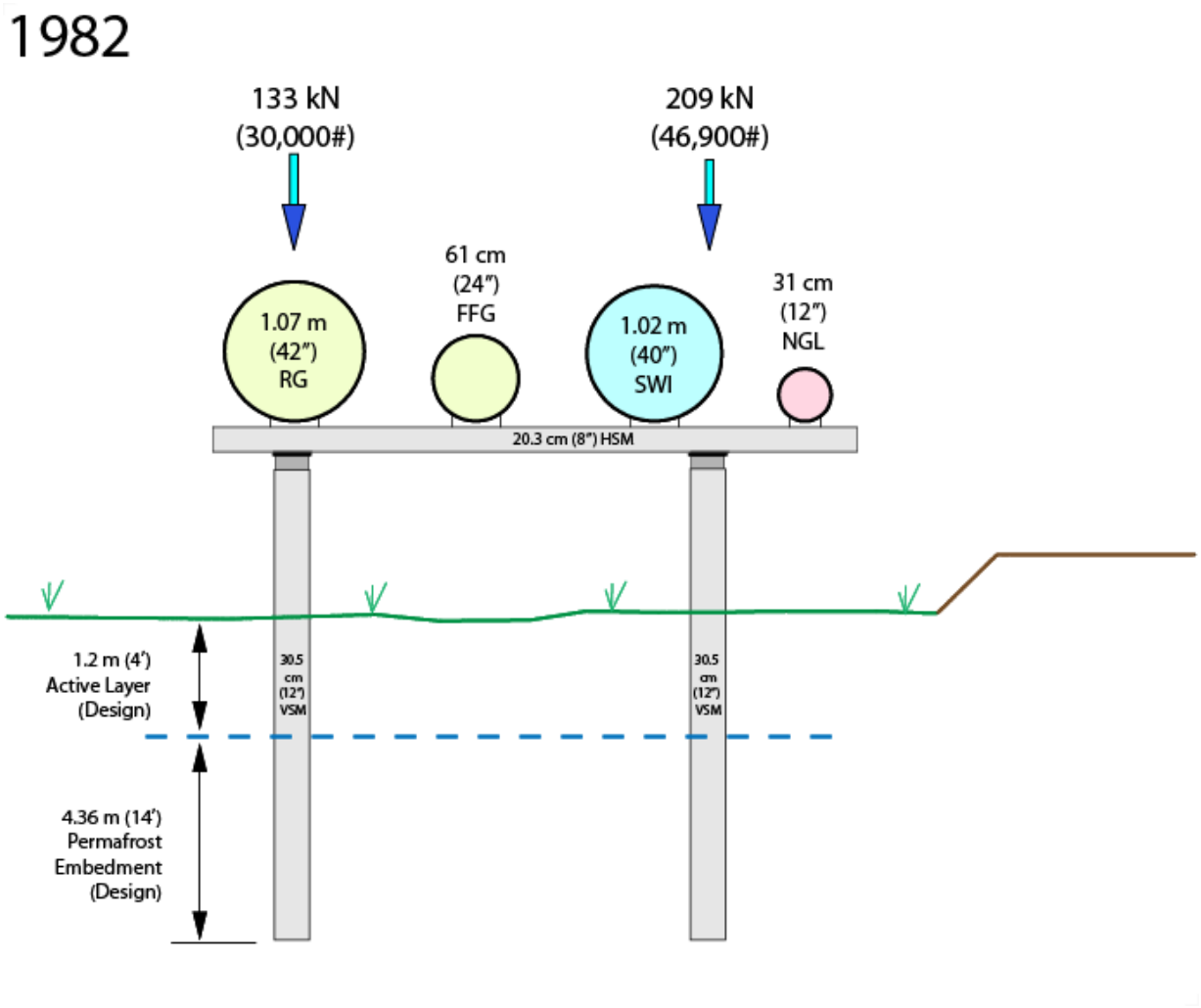
Assuming average temperature of fitted Sinusoid warms and the amplitude decreases

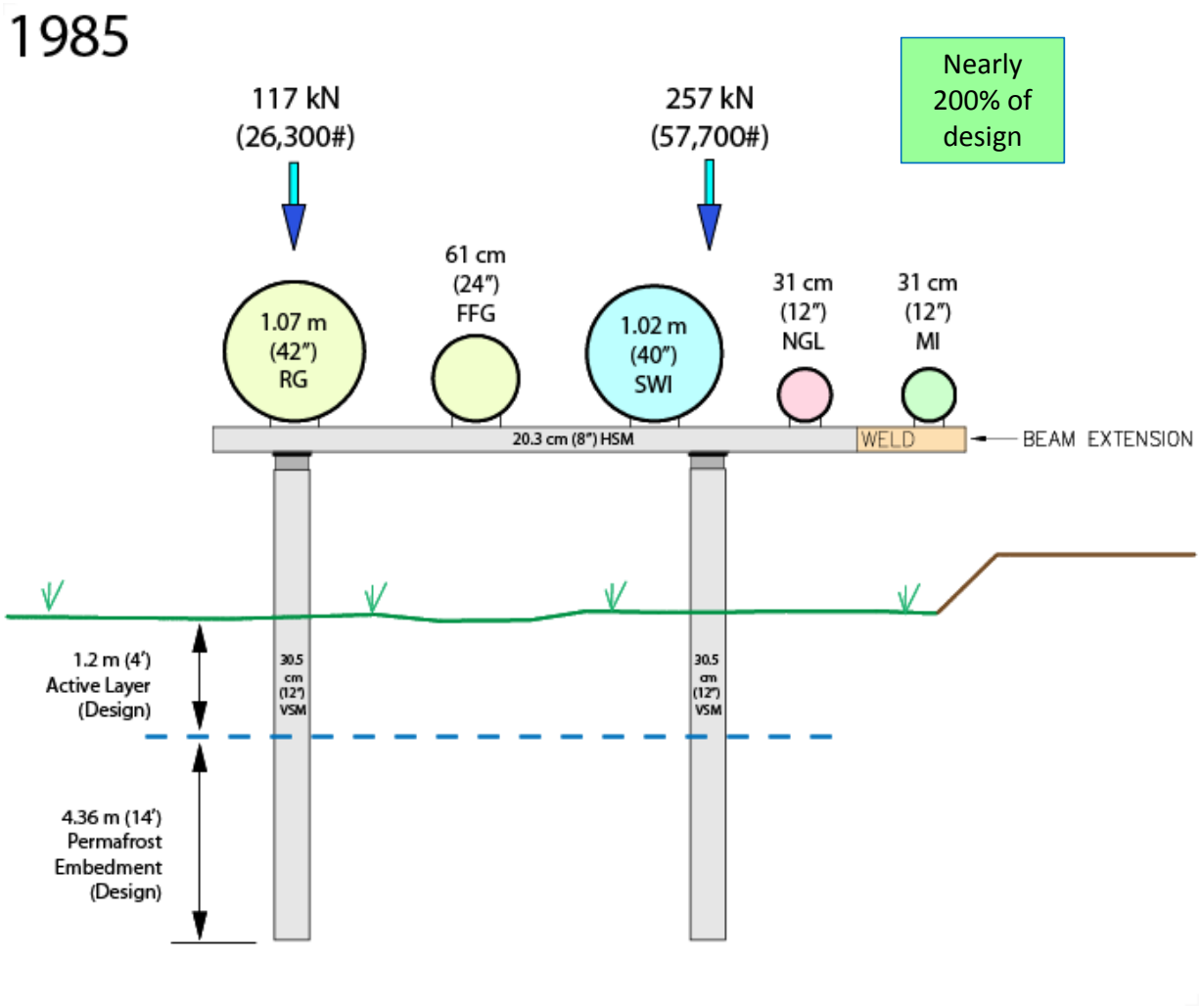


Pipe Rack Loading History


1976
112 kN
(25,200#)
20 kN
(4,400#)
61 cm
(24")
FFG
1.07 m
(42")
RG
20.3 cm (8") HSM
1.2 m (4')
Active Layer
(Design)
4.36 m (14')
Permafrost
Embedment
(Design)
30.5
cm
(12")
VSM
30.5
cm
(12")
VSM


1979
108 kN
(24,200#)
45 kN
(10,200#)
61 cm
(24")
FFG
1.07 m
(42")
RG
31 cm
(12")
NGL
20.3 cm (8") HSM
1.2 m (4')
Active Layer
(Design)
4.36 m (14')
Permafrost
Embedment
(Design)
30.5
cm
(12")
VSM
30.5
cm
(12")
VSM


1982
133 kN
(30,000#)
209 kN
(46,900#)
61 cm
(24")
FFG
31 cm
(12")
NGL
1.07 m
(42")
RG
1.02 m
(40")
SWI
20.3 cm (8") HSM
1.2 m (4')
Active Layer
(Design)
4.36 m (14')
Permafrost
Embedment
(Design)
30.5
cm
(12")
VSM
30.5
cm
(12")
VSM


1985
117 kN
(26,300#)
257 kN
(57,700#)
Nearly 200% of design
61 cm
(24")
FFG
1.07 m
(42")
RG
1.02 m
(40")
SWI
31 cm
(12")
NGL
31 cm
(12")
MI
20.3 cm (8") HSM
WELD
BEAM EXTENSION
1.2 m (4')
Active Layer
(Design)
4.36 m (14')
Permafrost
Embedment
(Design)
30.5 cm (12") VSM
30.5 cm (12") VSM

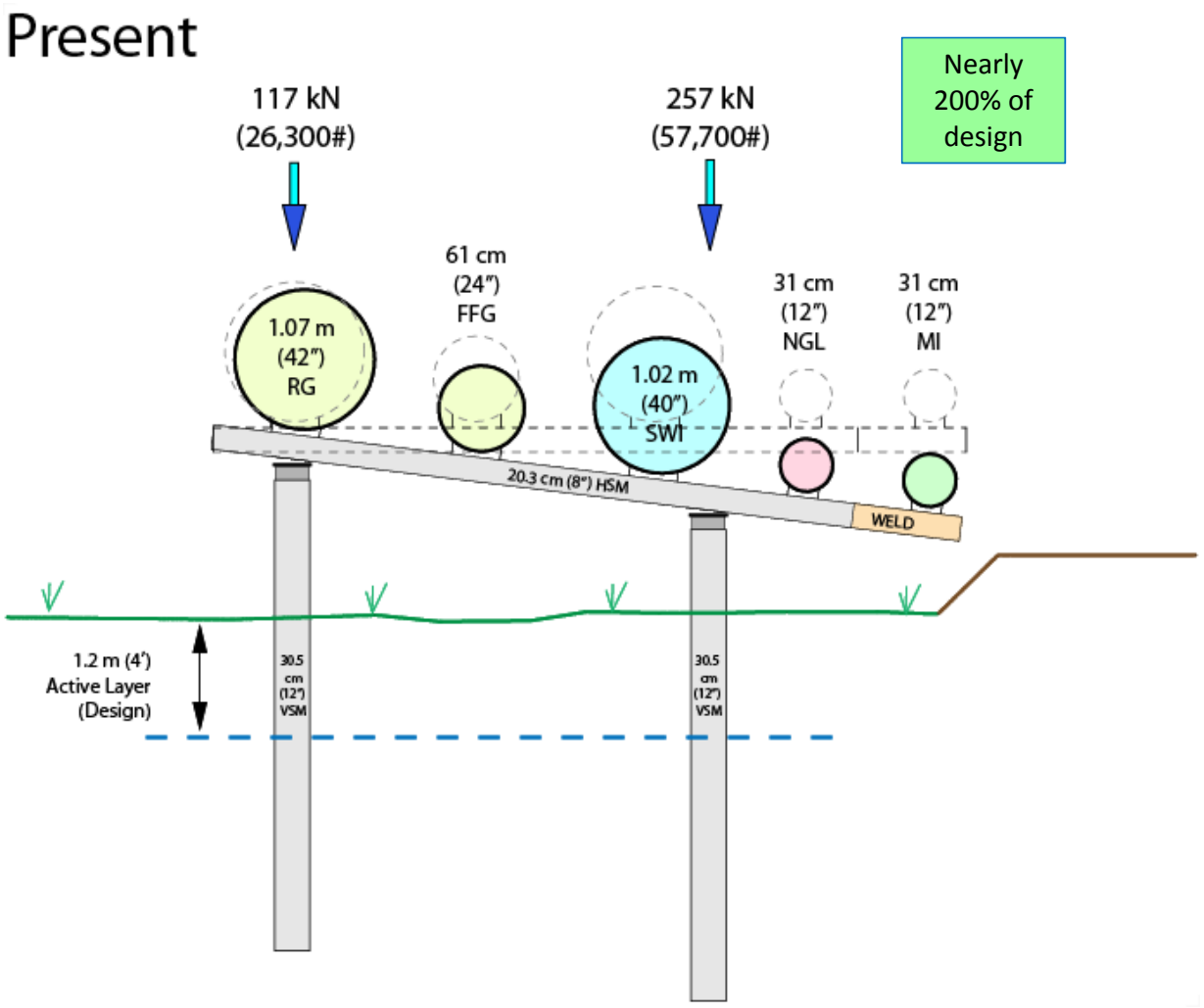
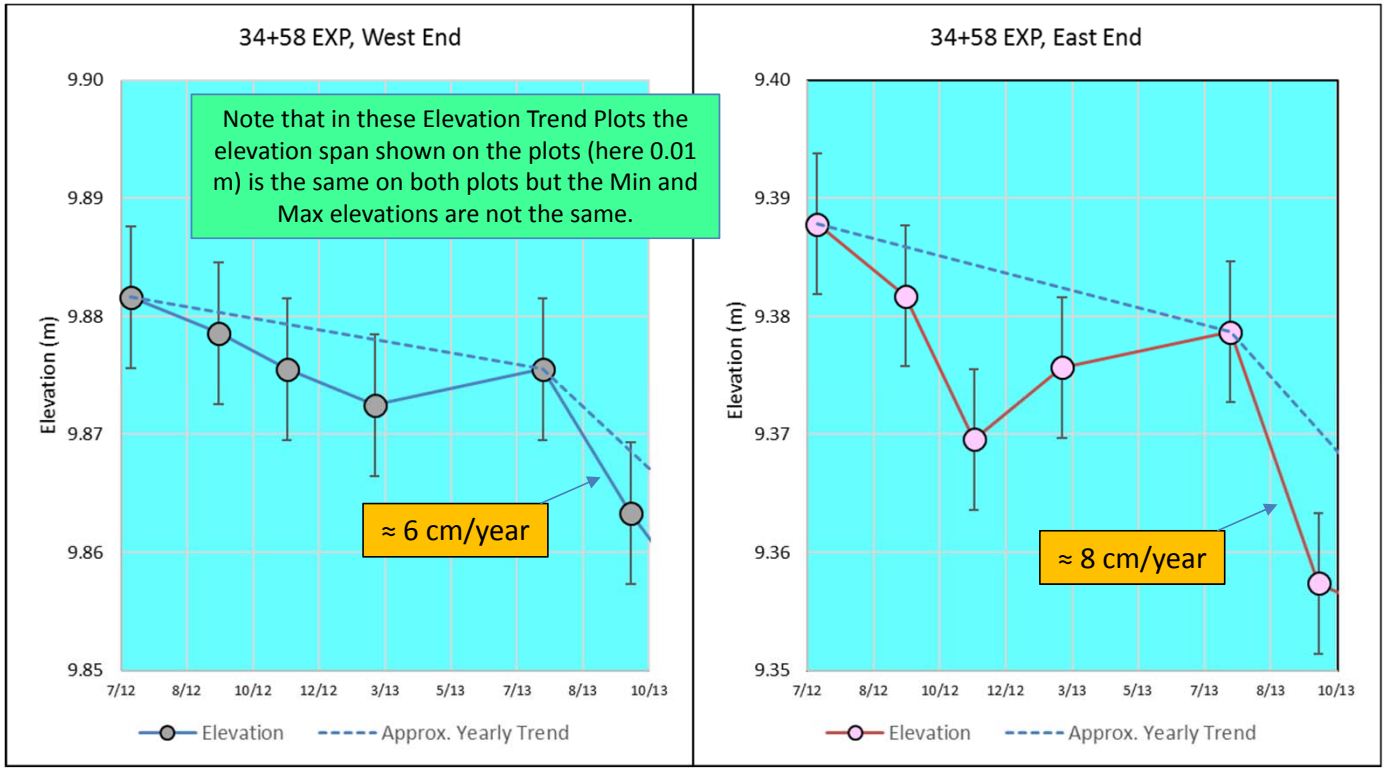

Present
117 kN
(26,300#)
257 kN
(57,700#)
Nearly 200% of design
61 cm
(24")
FFG
31 cm
(12")
NGL
31 cm
(12")
MI
1.07 m
(42")
RG
1.02 m
(40")
SWT
20.3 cm (8") HSM
WELD
1.2 m (4')
Active Layer
(Design)
30.5 cm (12") VSM
30.5 cm (12") VSM

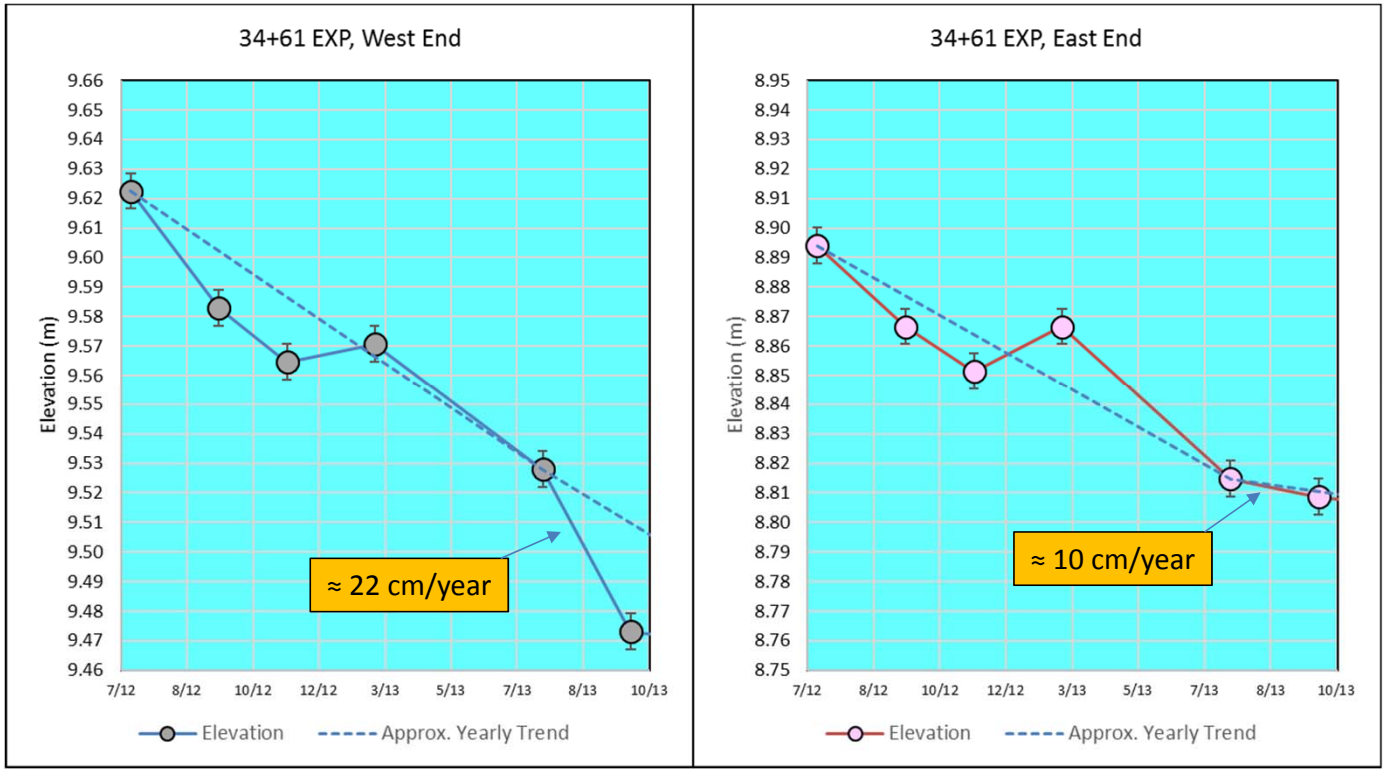
Photo of Piperack Horizontal Support Member, August 2012, Study Area

Piperack Settlement Measurements before the Pilot Project

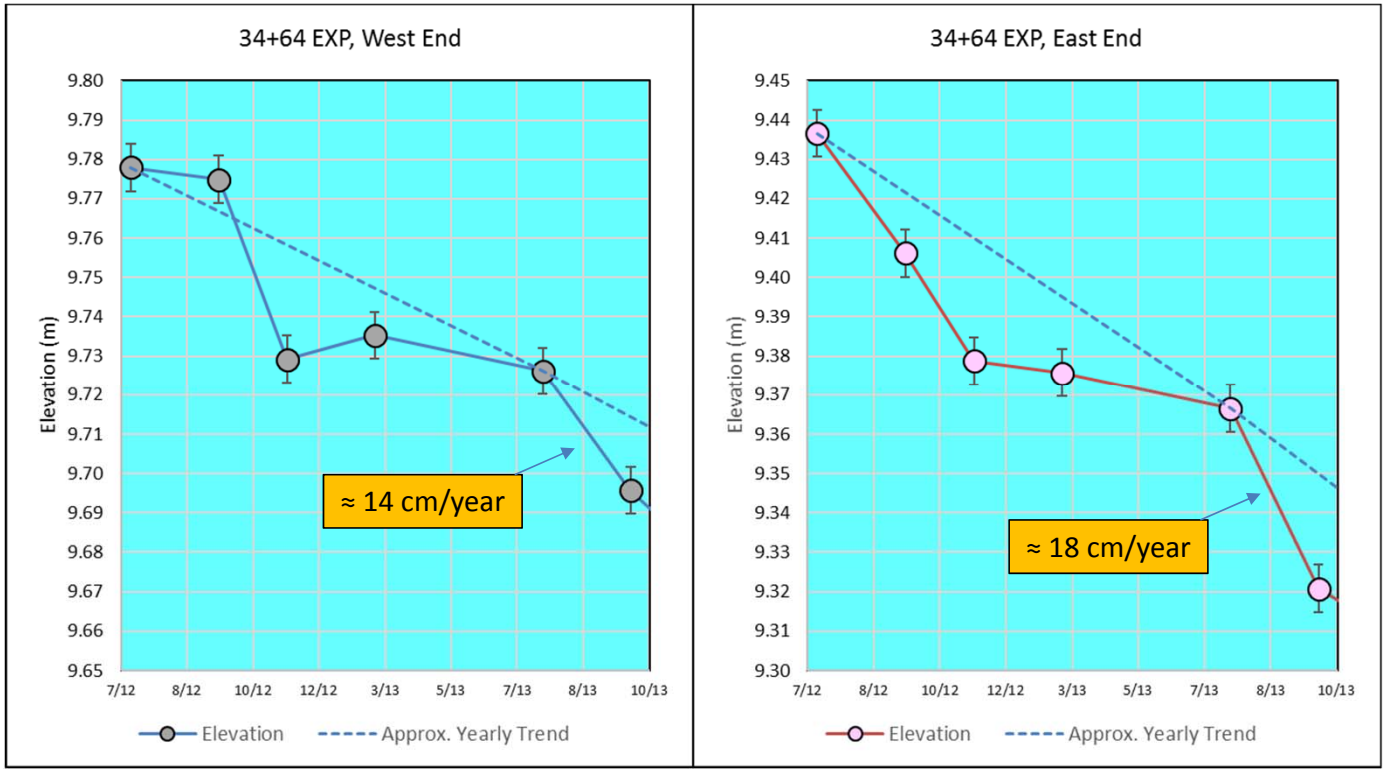
Piperack HSM Elevation Trends for the Pilot Project and Study Area, July 2012 to October 2013



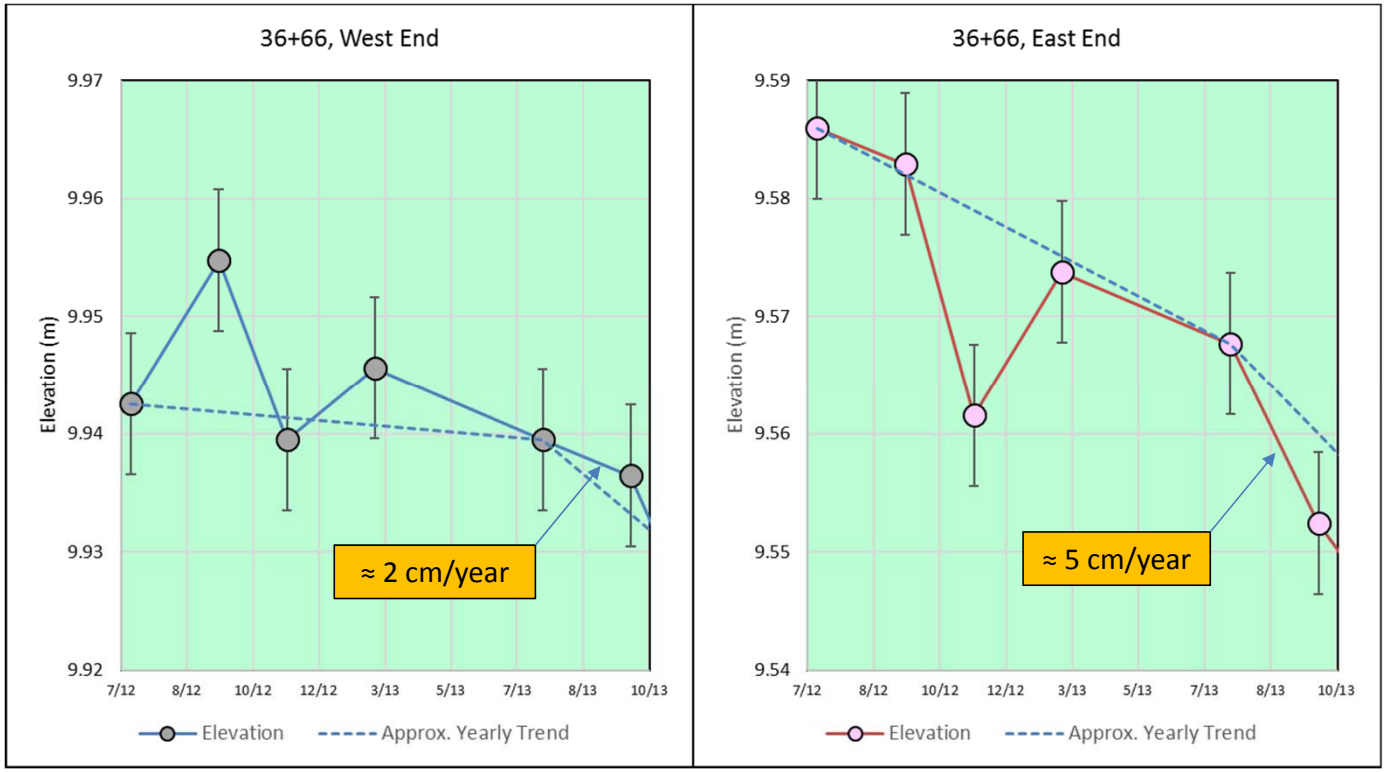
Piperack HSM Elevation Trends for the Pilot Project and Study Area, July 2012 to October 2013



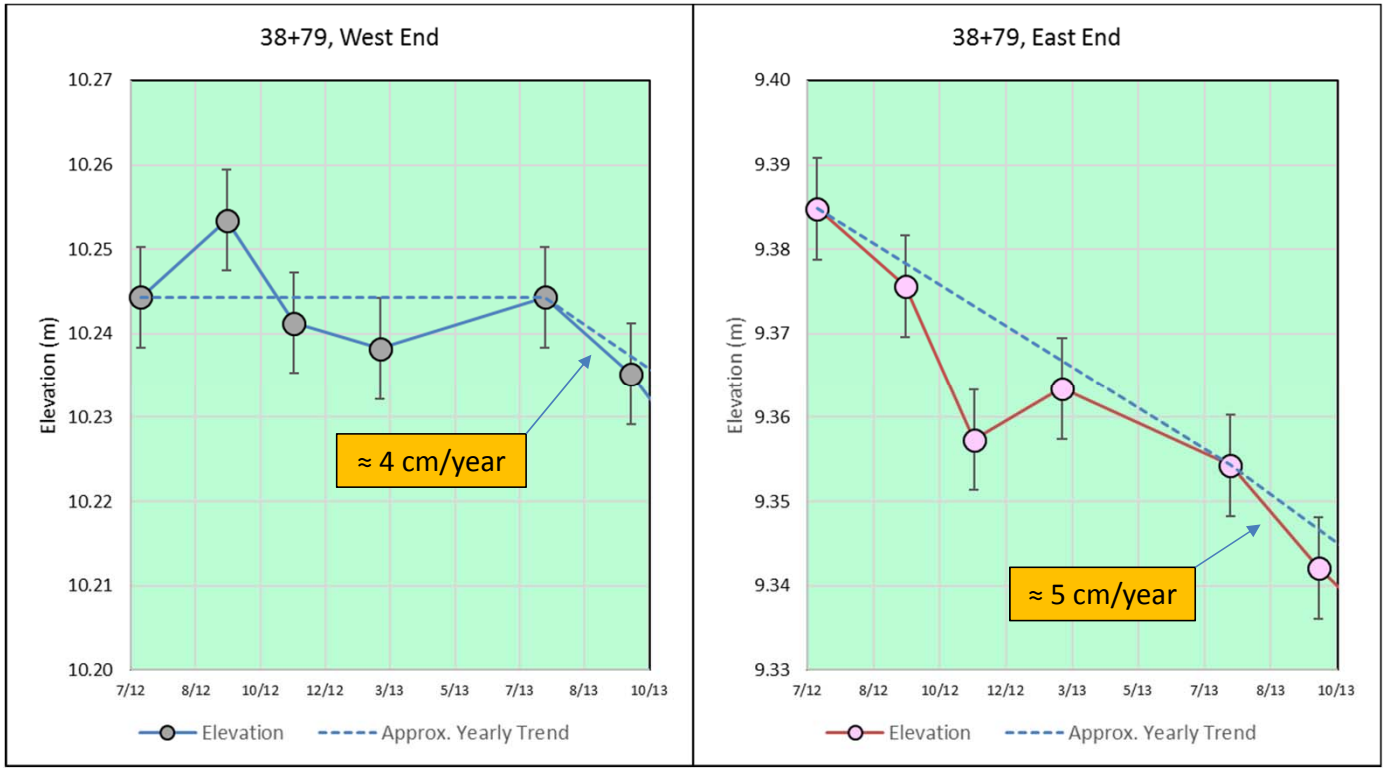
Piperack HSM Elevation Trends for the Pilot Project and Study Area, July 2012 to October 2013

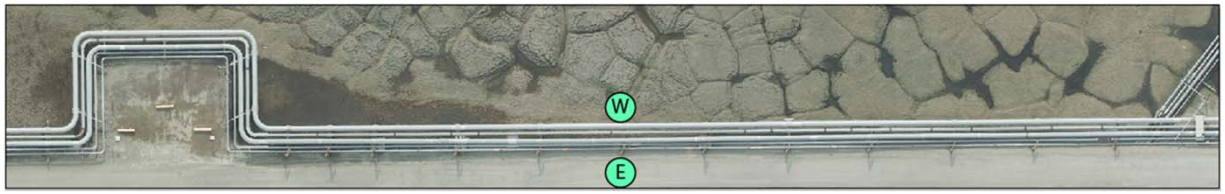


Piperack HSM Elevation Trends for the Pilot Project and Study Area, July 2012 to October 2013

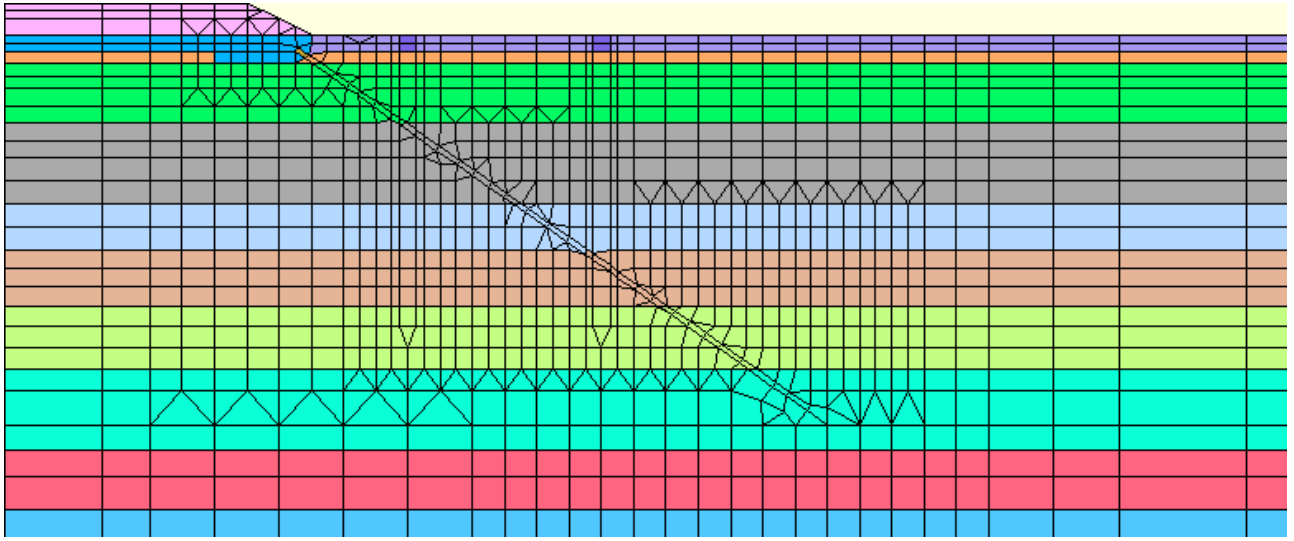


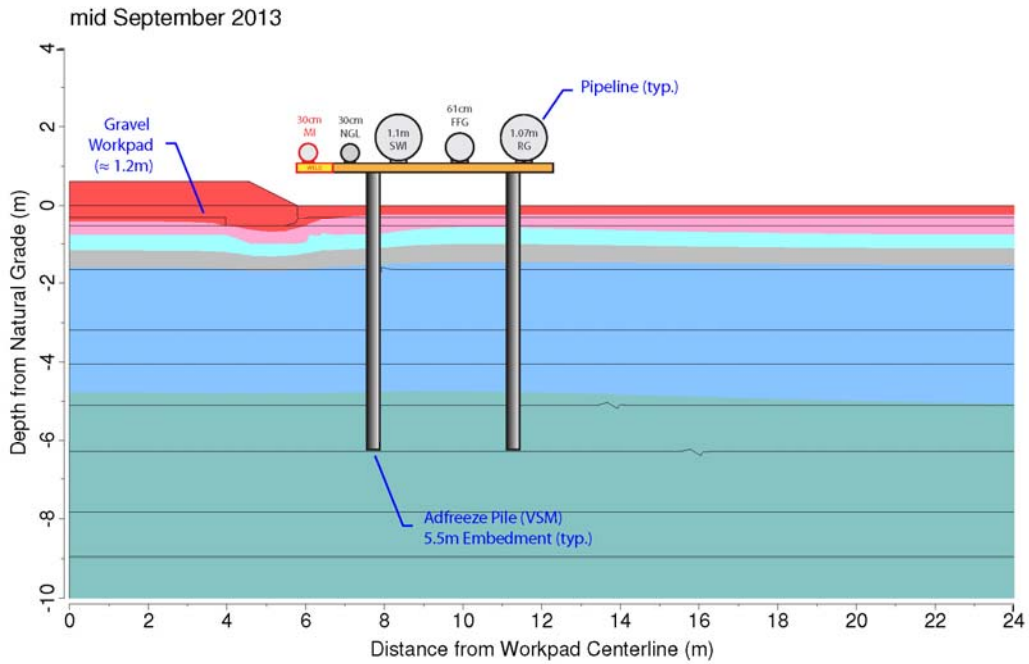
Piperack HSM Elevation Trends for the Pilot Project and Study Area, July 2012 to October 2013

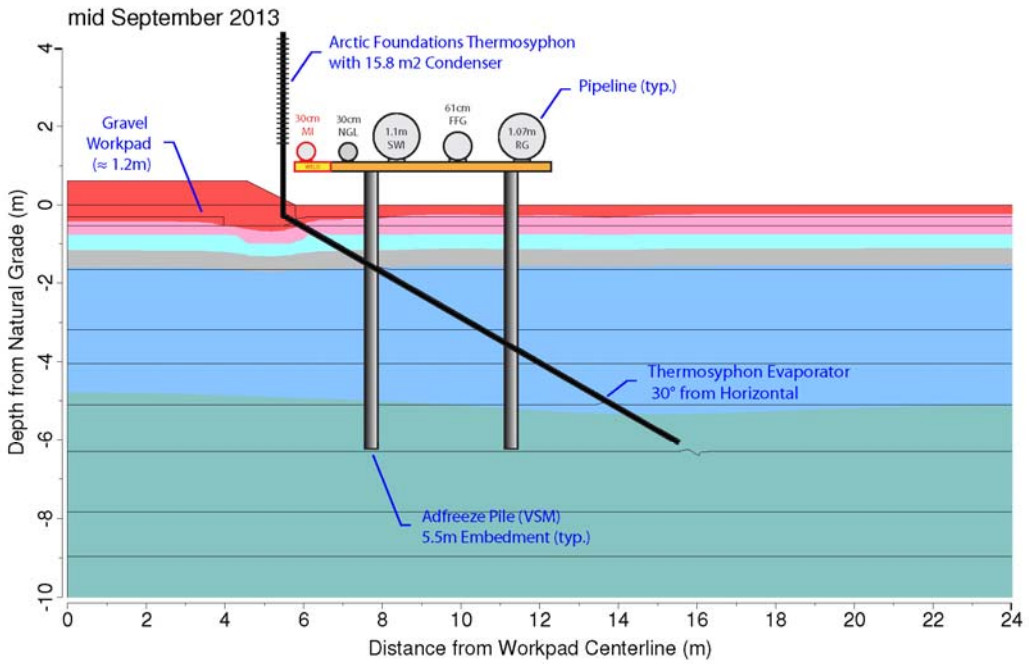




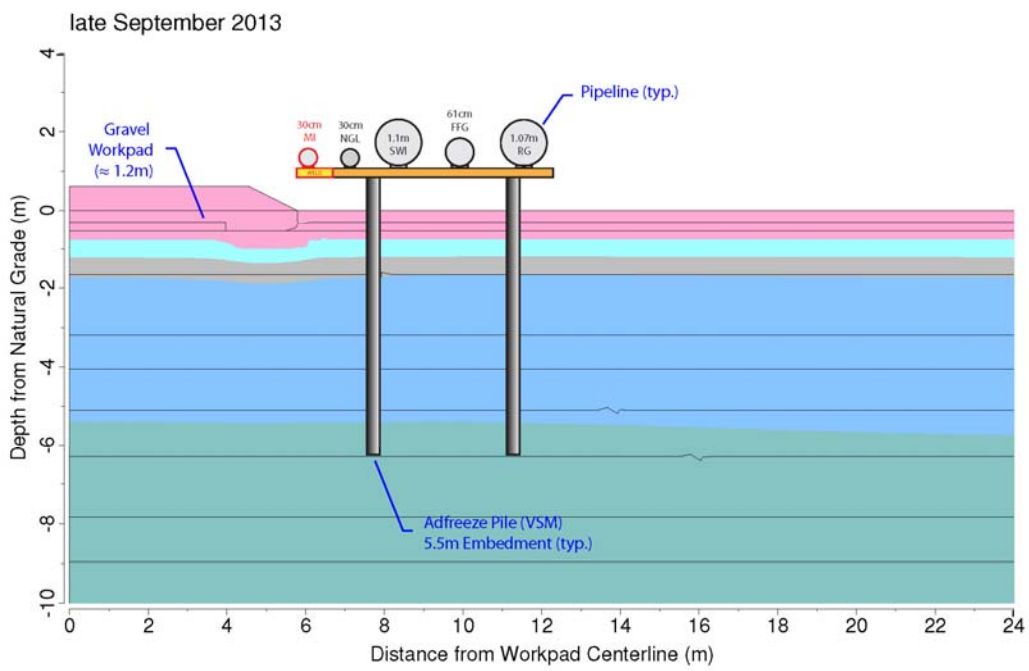
3D Geothermal Model Simulations to Predict the Effectiveness of Slanty Thermosyphons to Reduce Settlement Rate

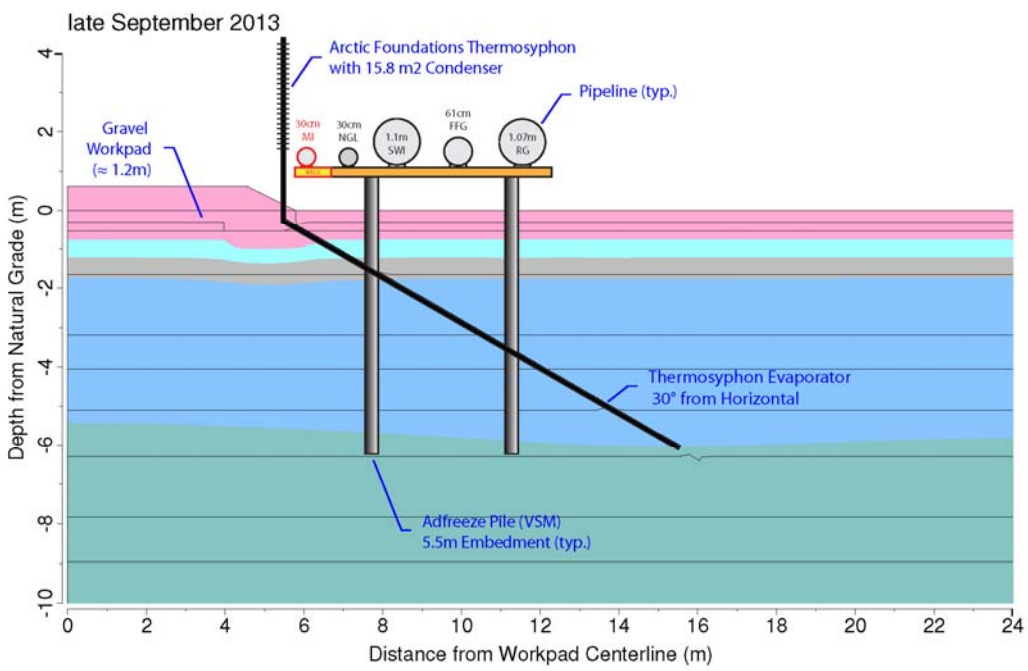




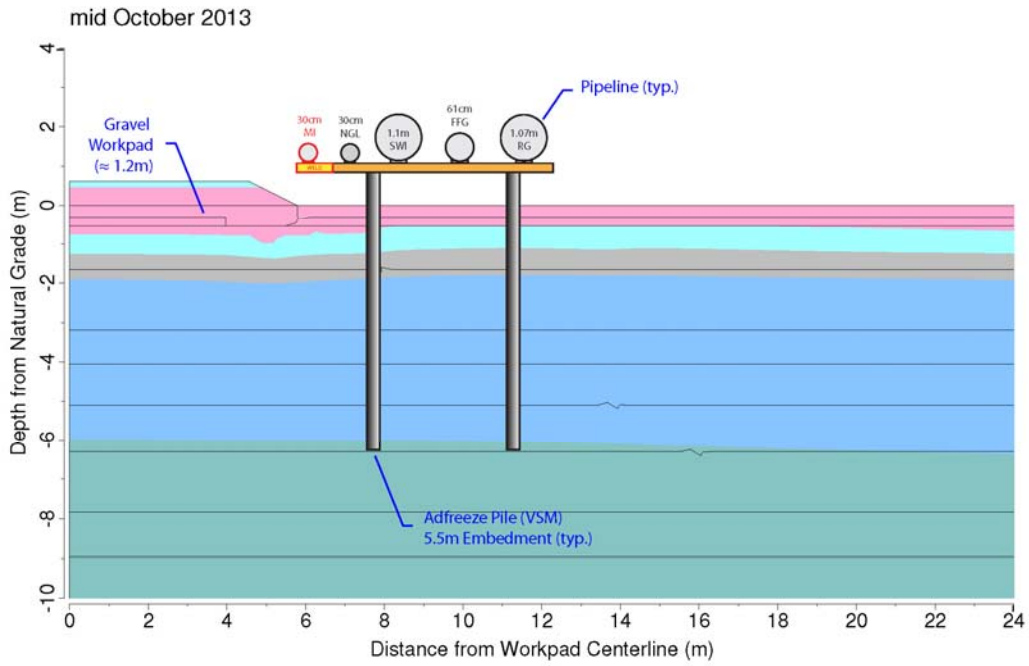


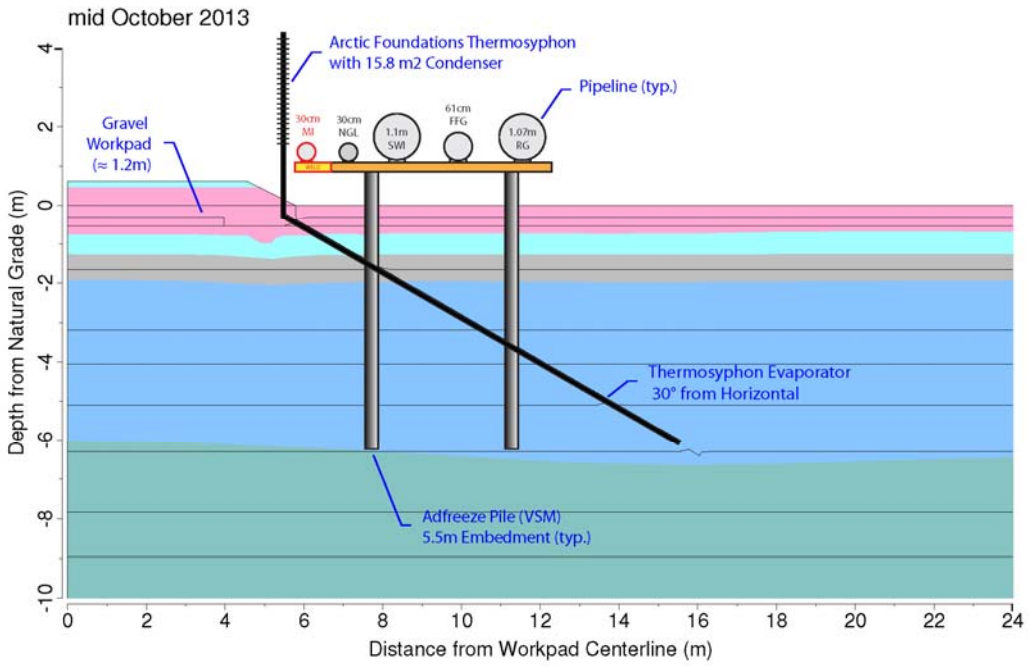
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C



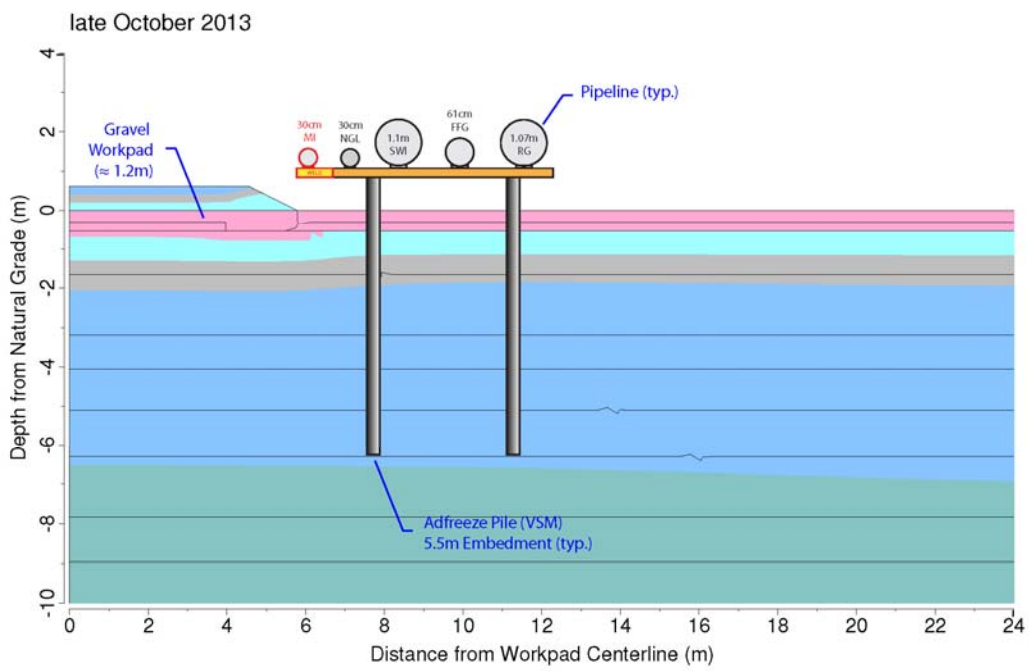


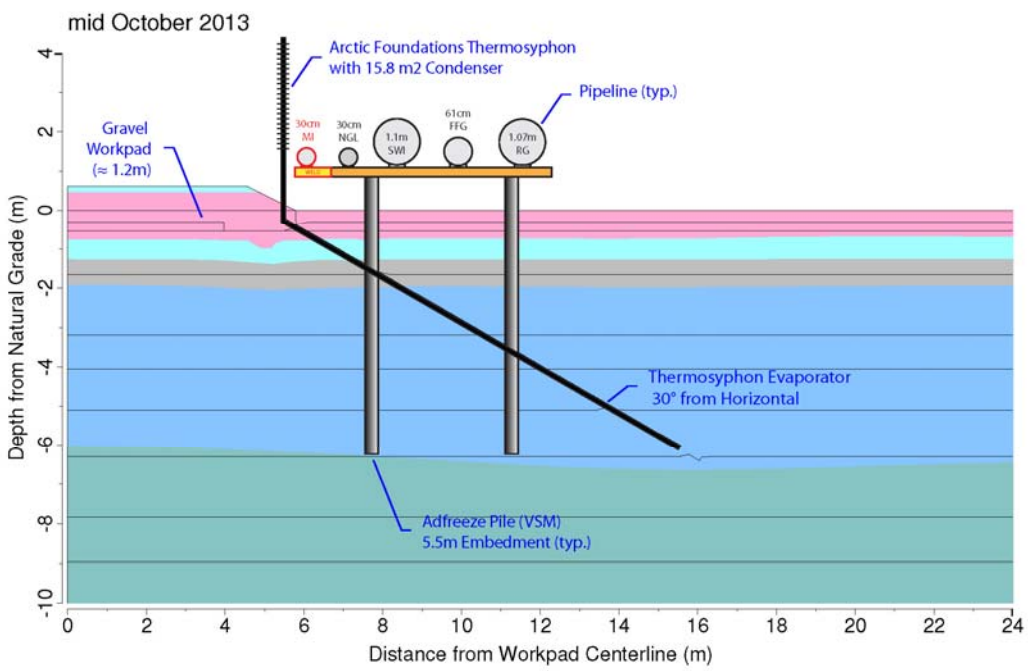
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C



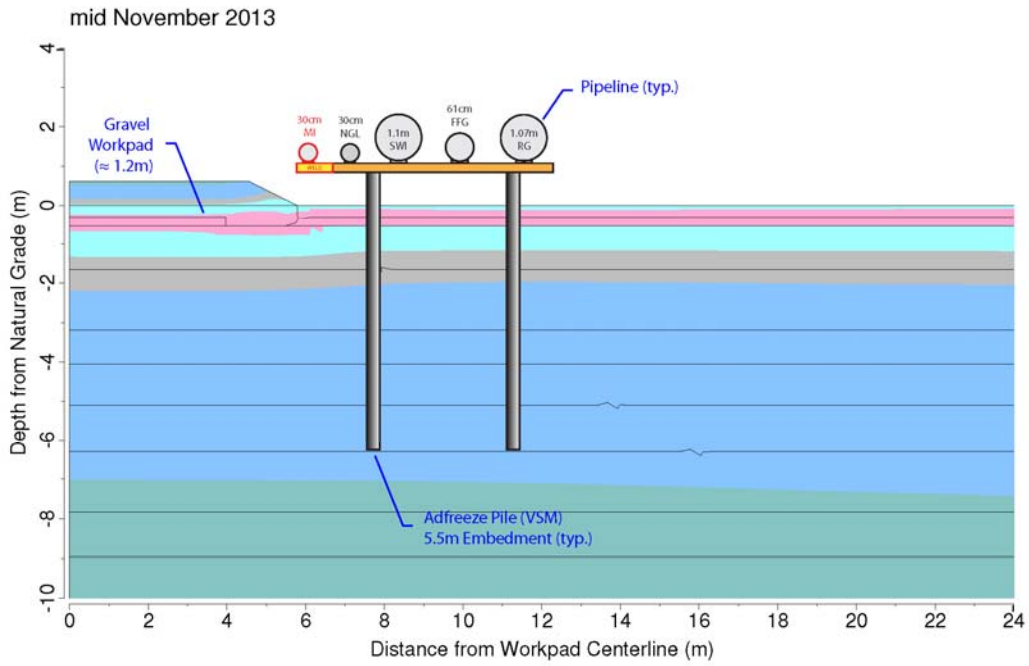


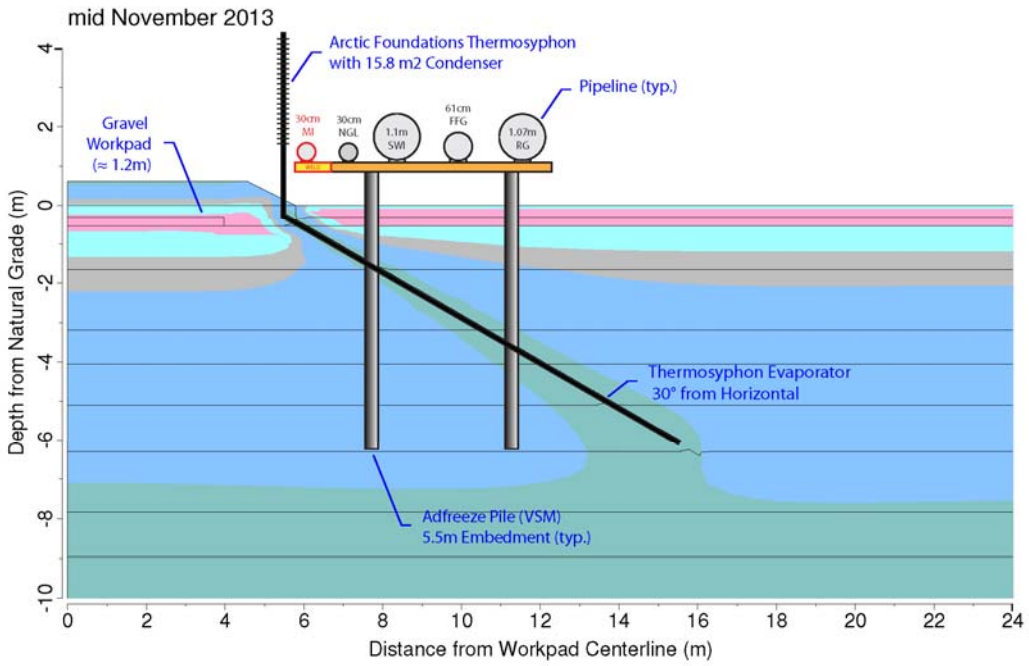
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C

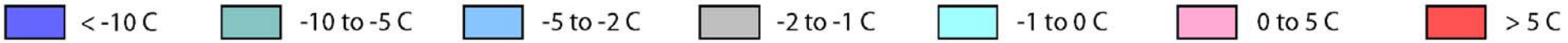


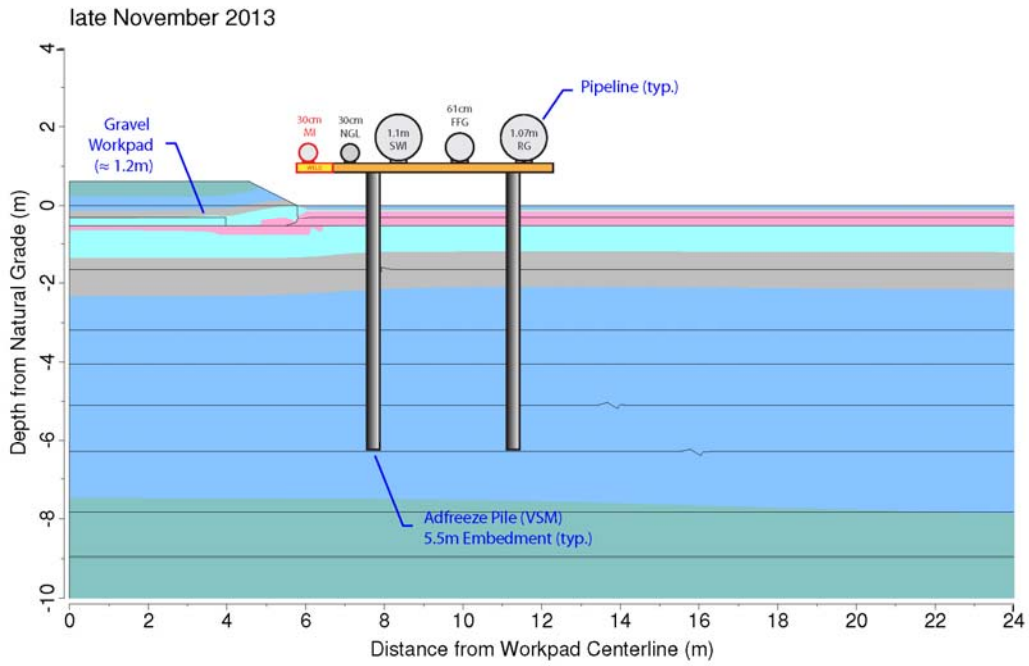


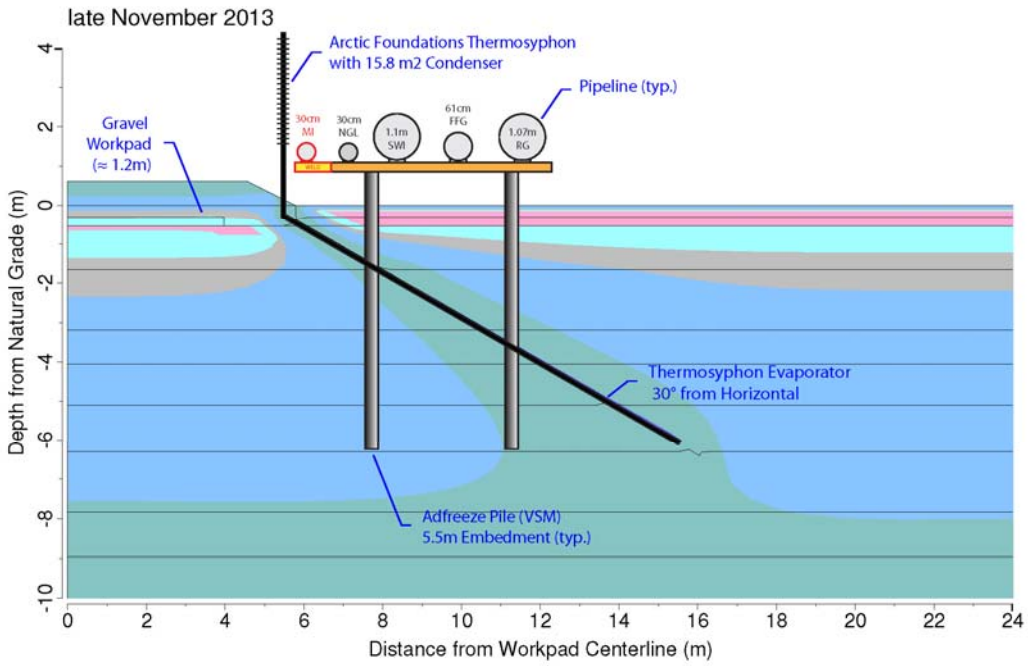
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C

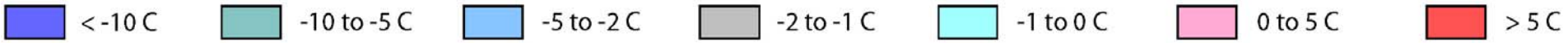

mid November 2013
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

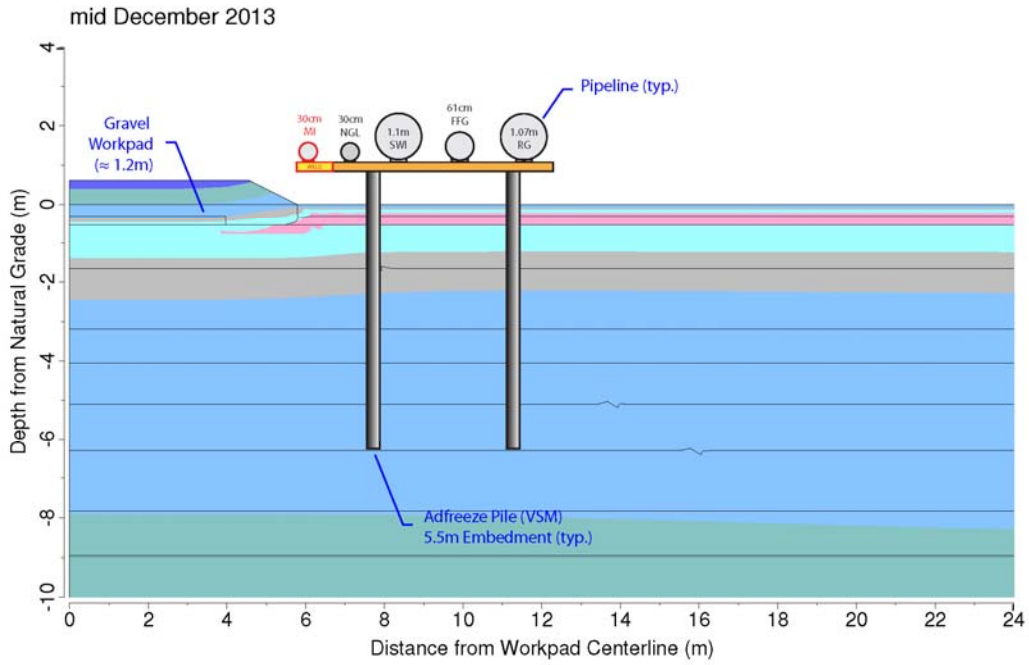

mid November 2013
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

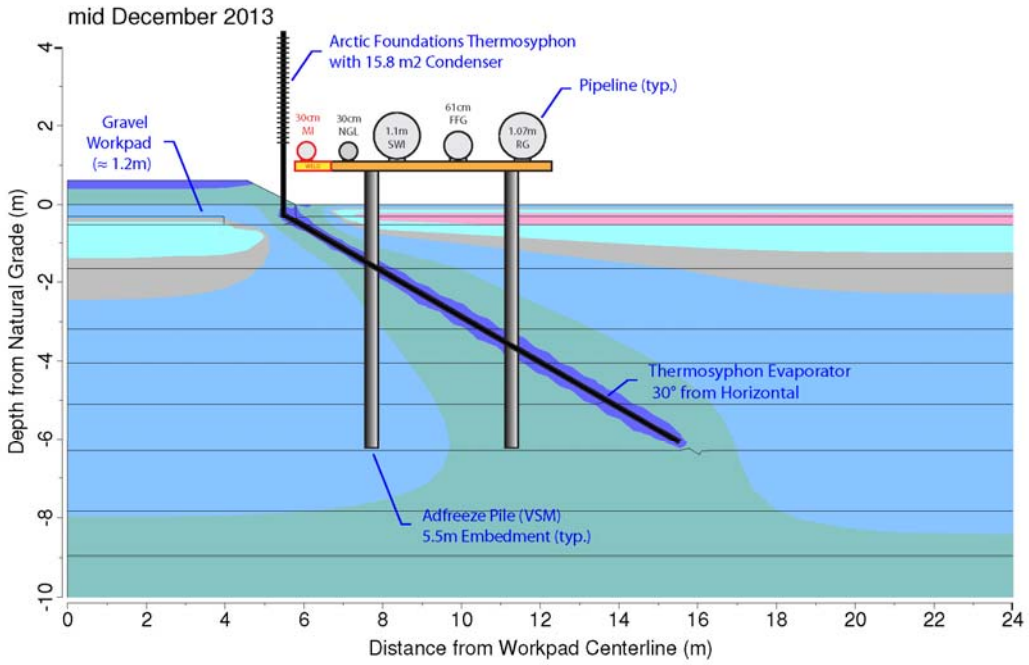

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C

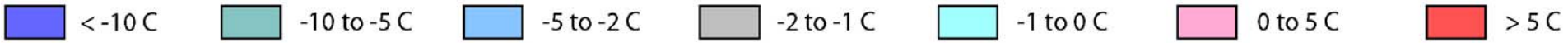

late November 2013
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


late November 2013
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C


mid December 2013
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


mid December 2013
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)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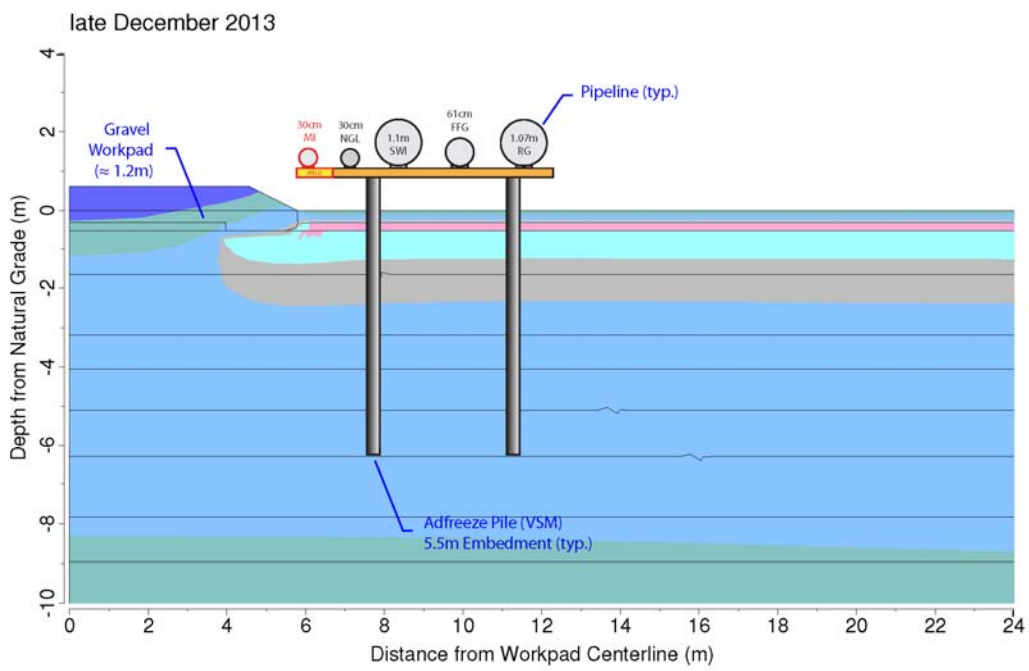
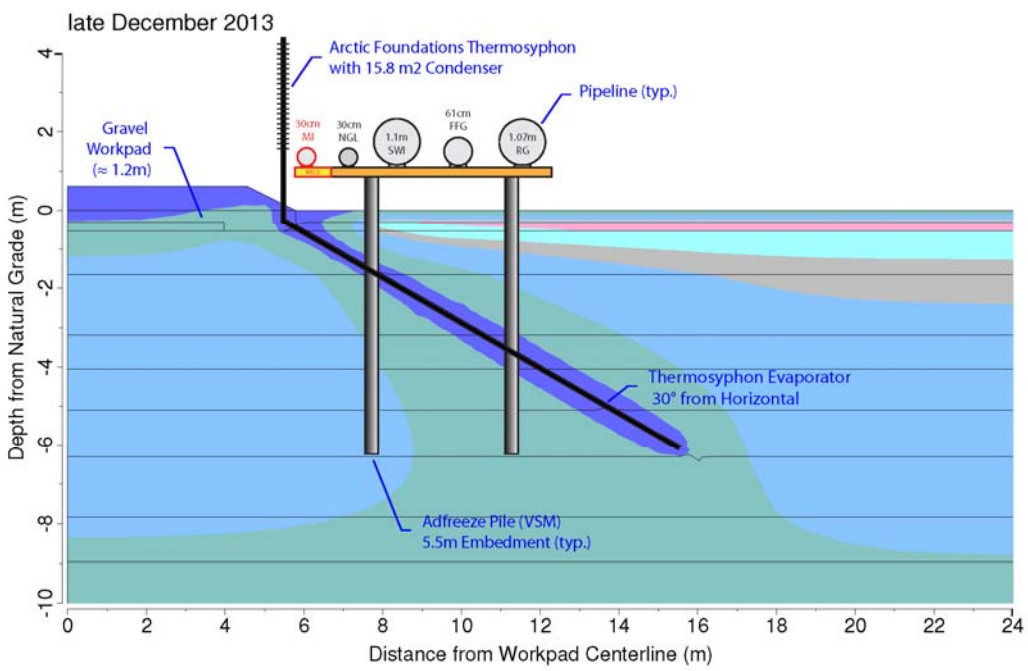
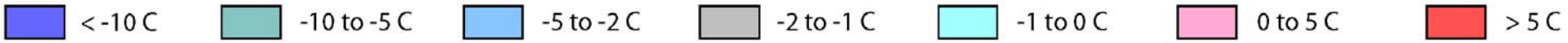
0 to 5 C
> 5 C


late December 2013
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


late December 2013
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)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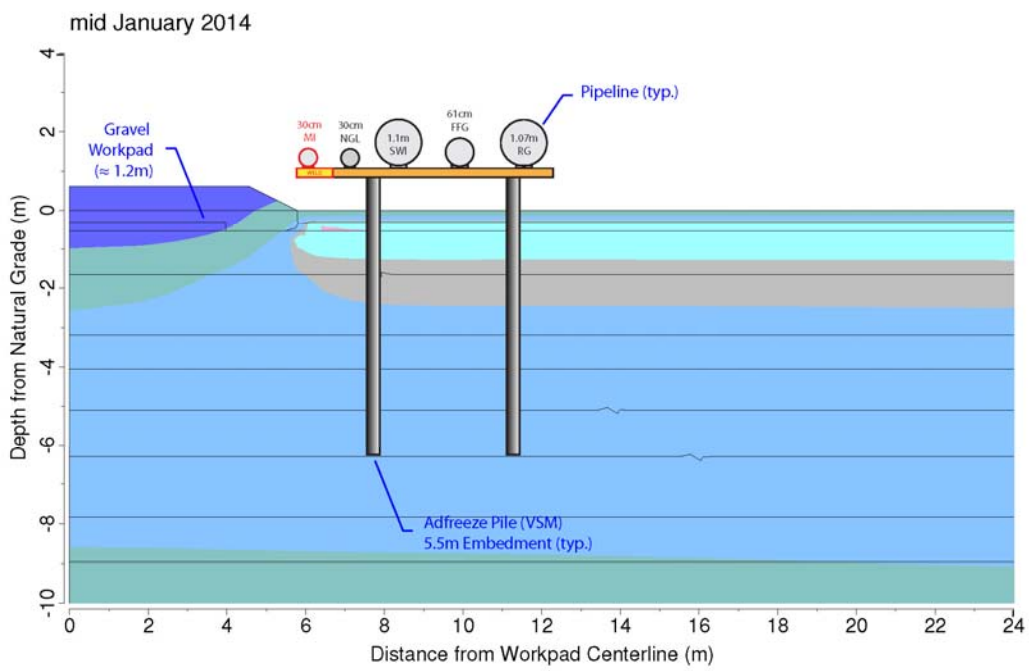
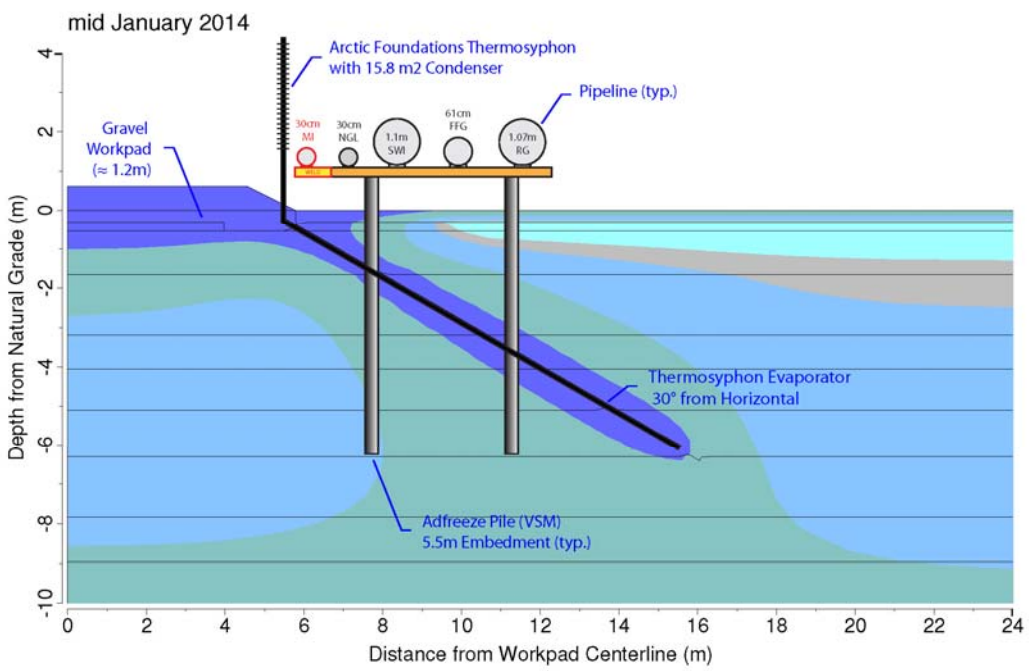
0 to 5 C
> 5 C





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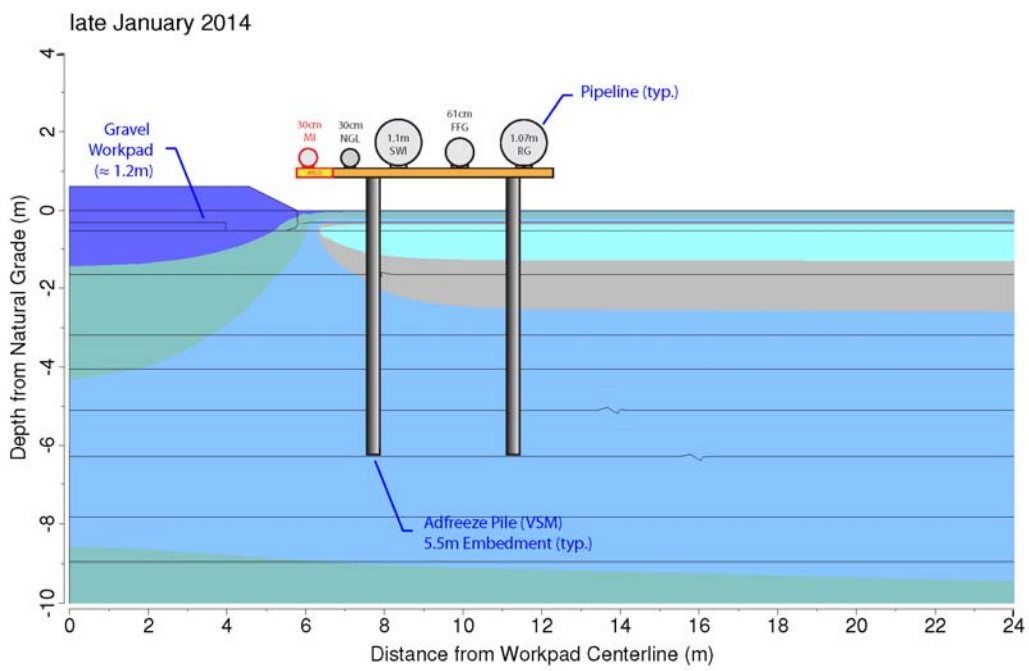
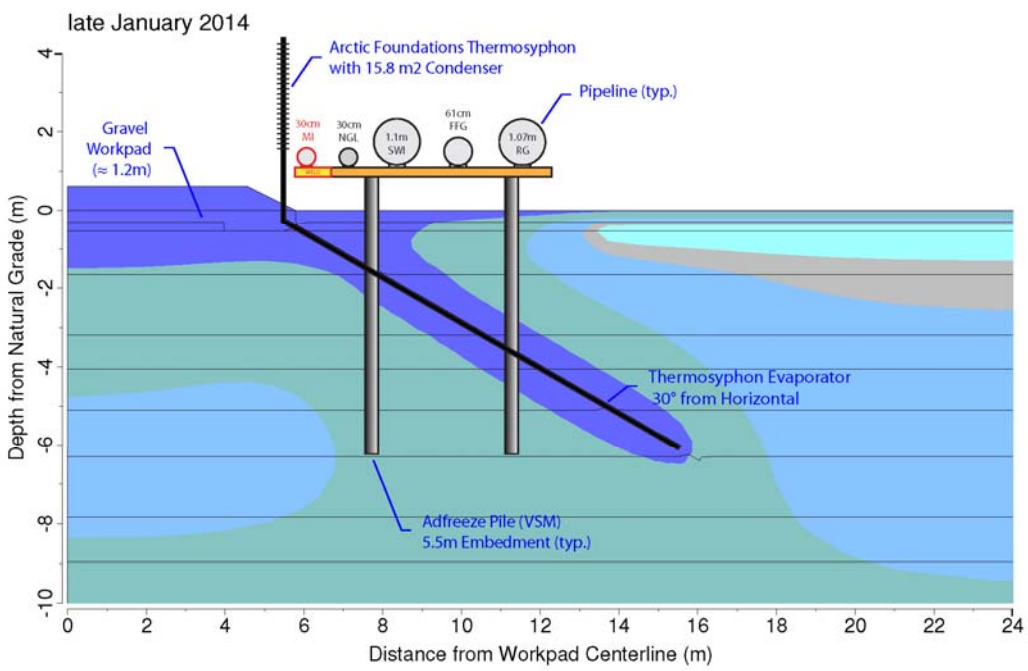
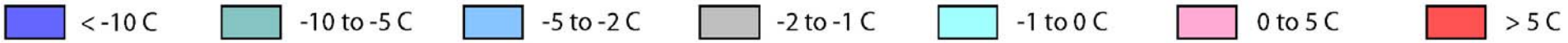
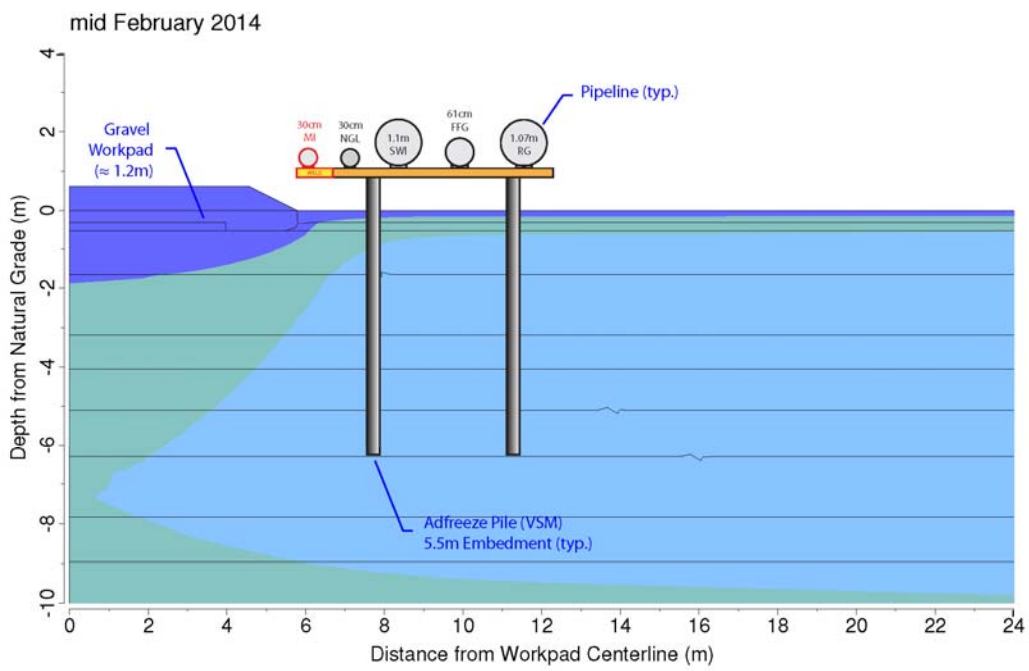
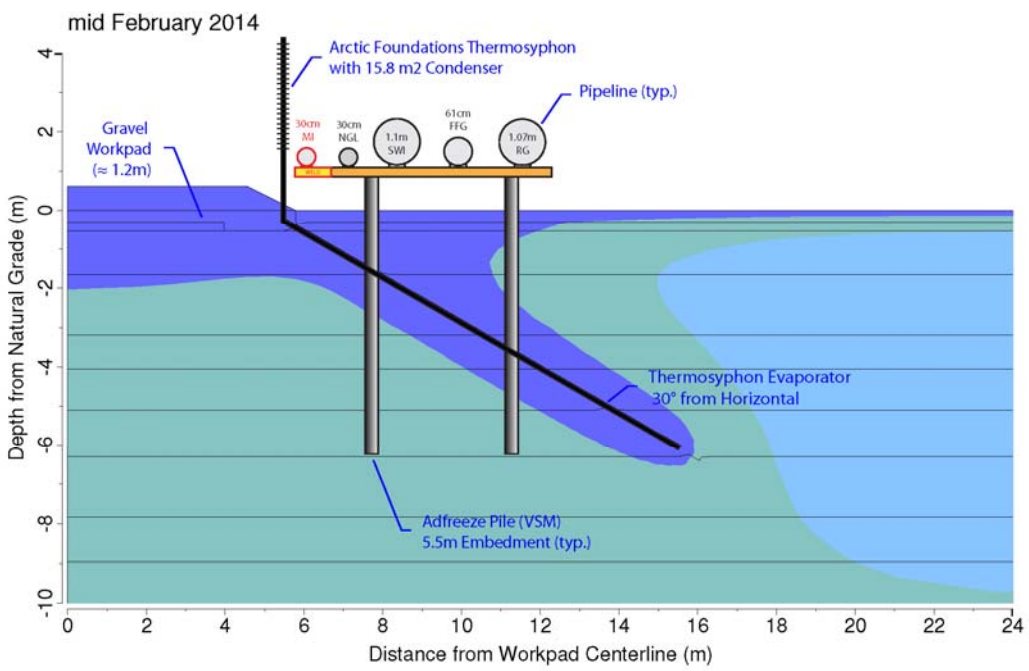
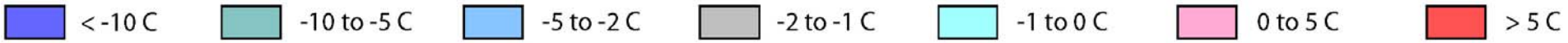

late January 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

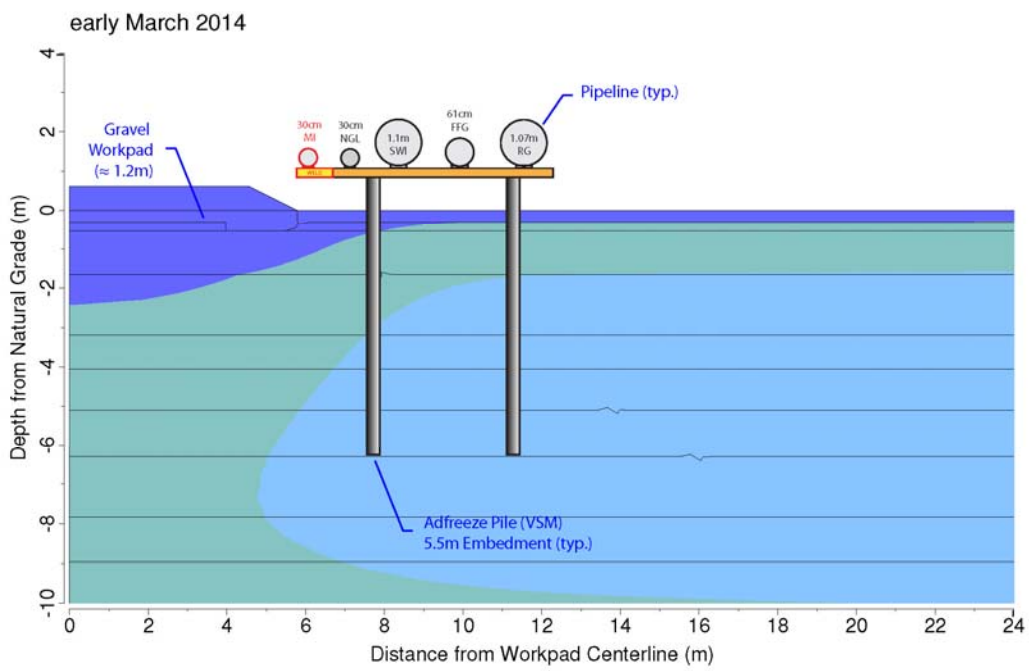

late January 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

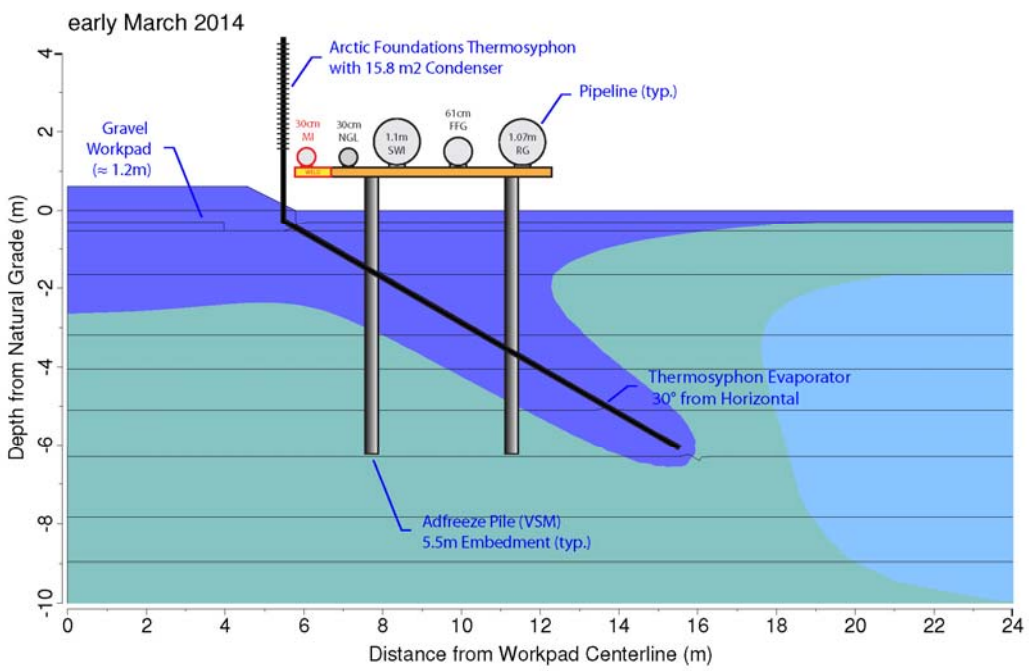

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C

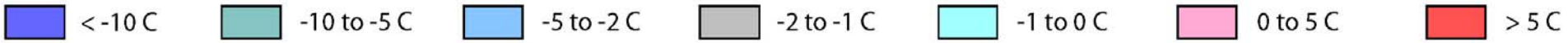

mid February 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

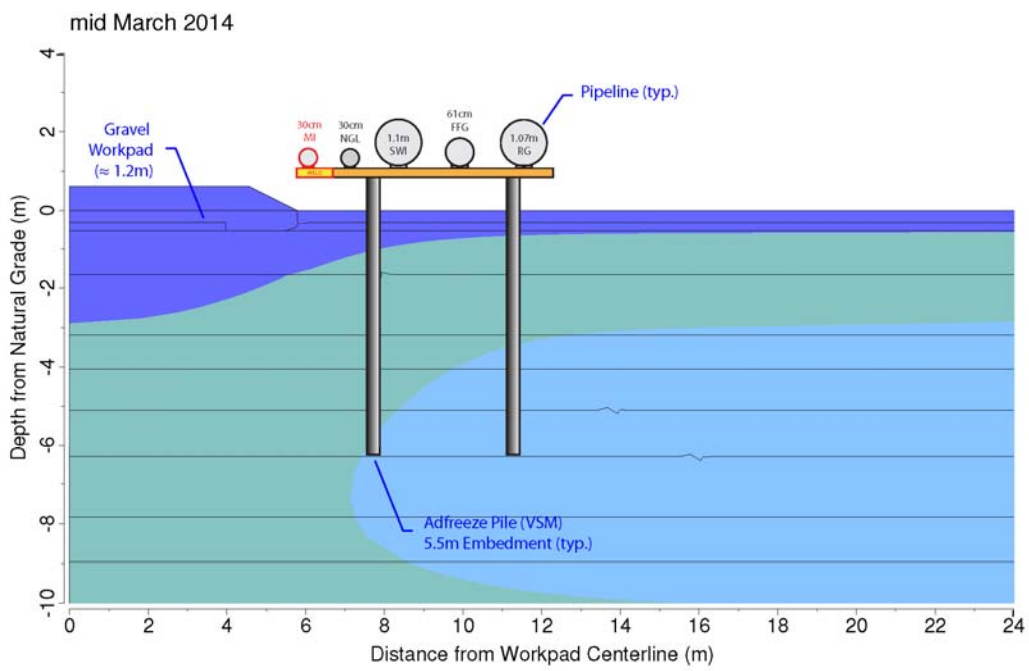

mid February 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

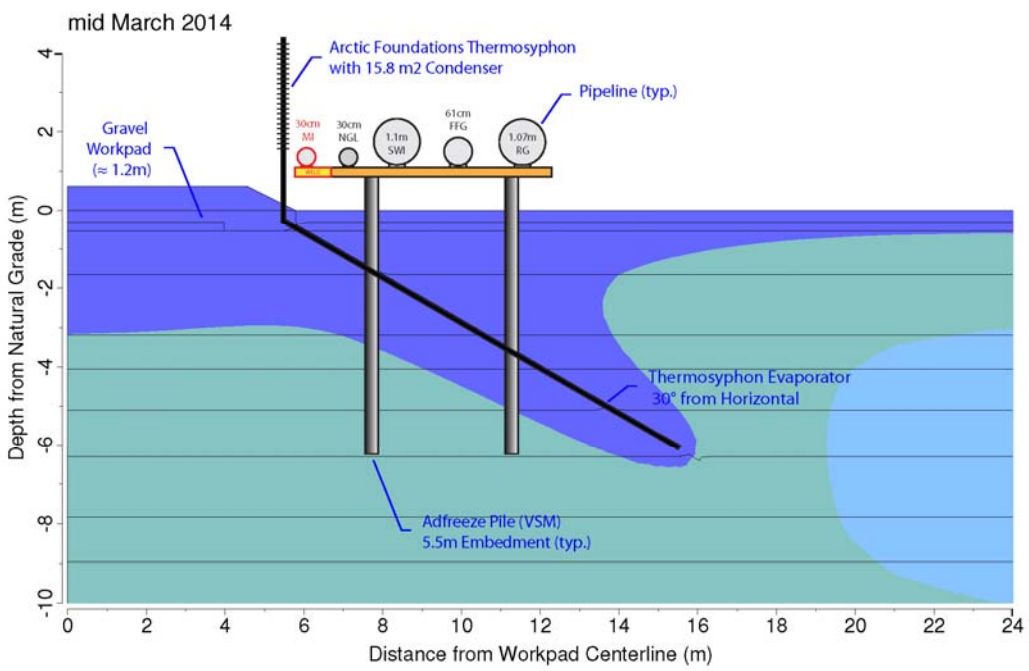

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C


early March 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

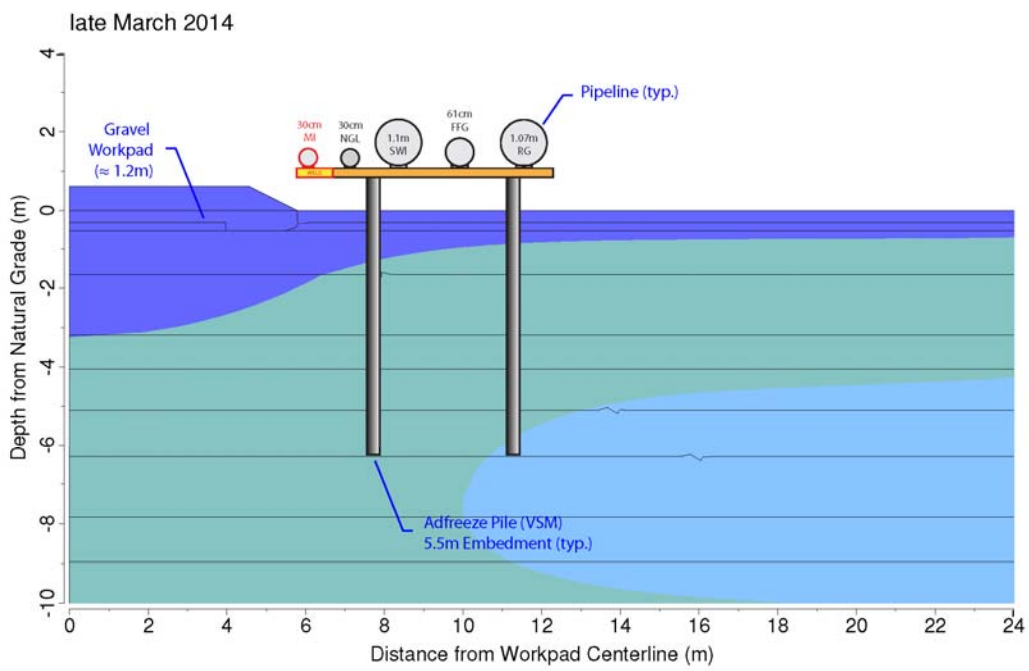

early March 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

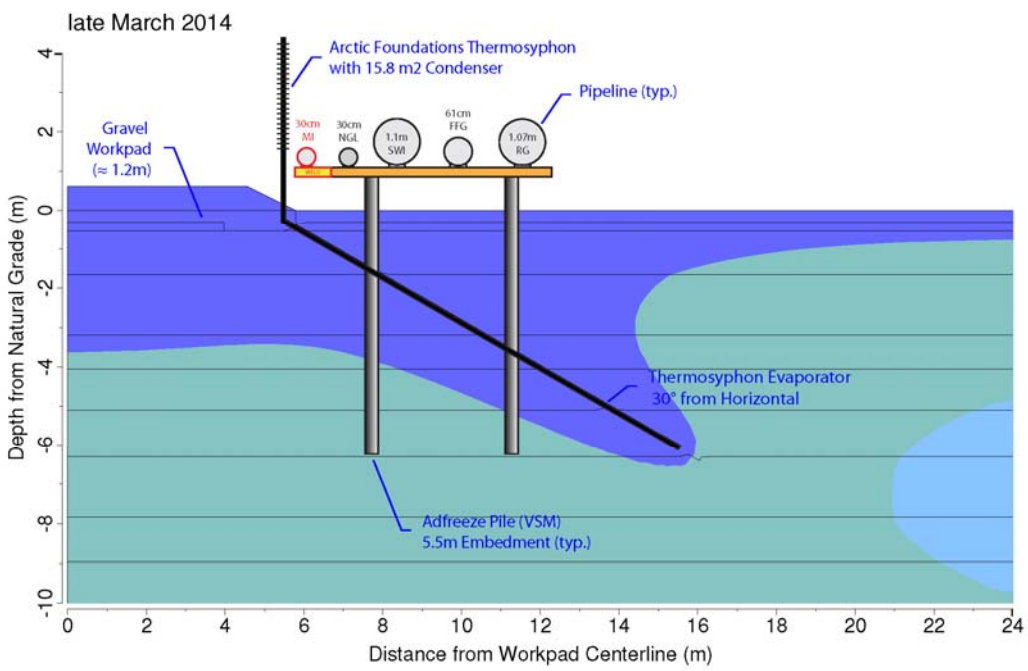

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C

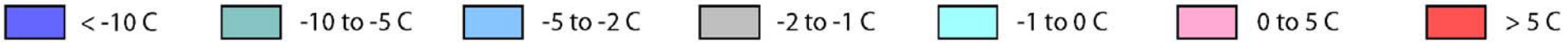


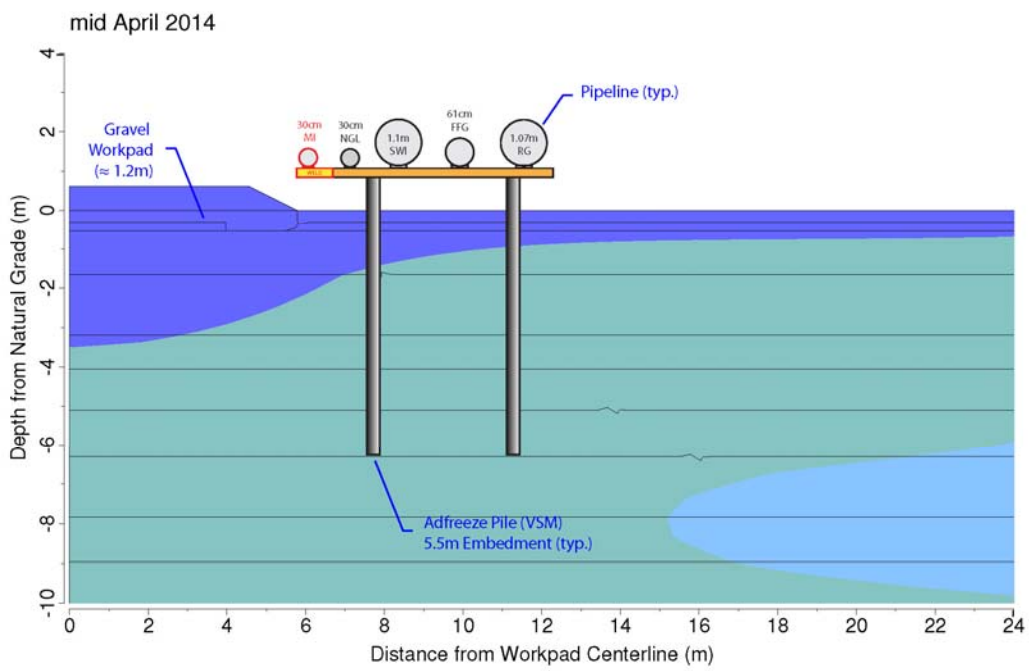


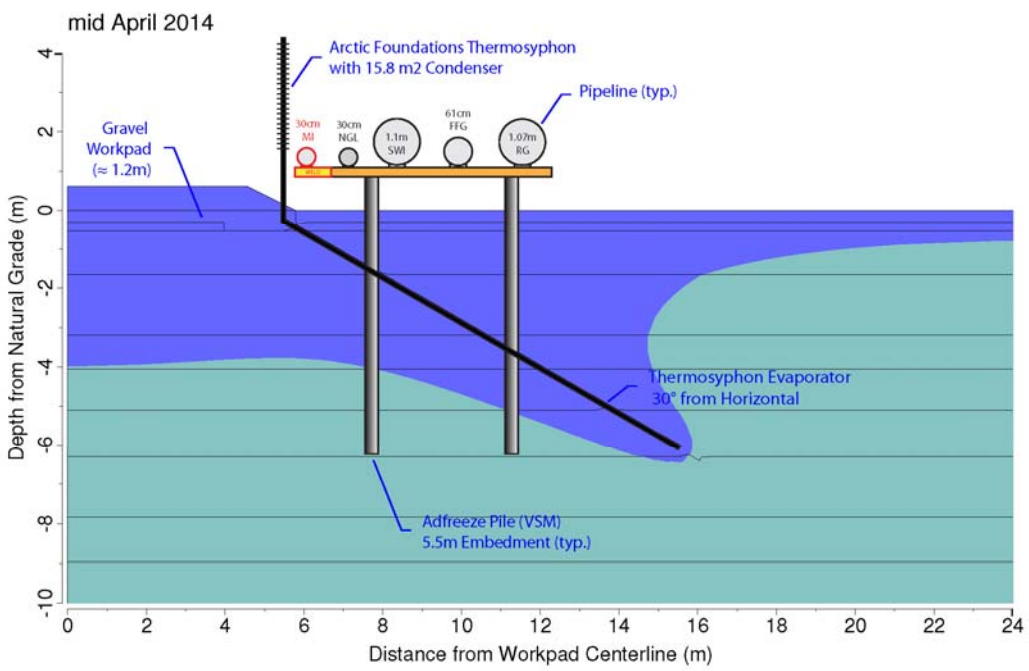
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C


late March 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

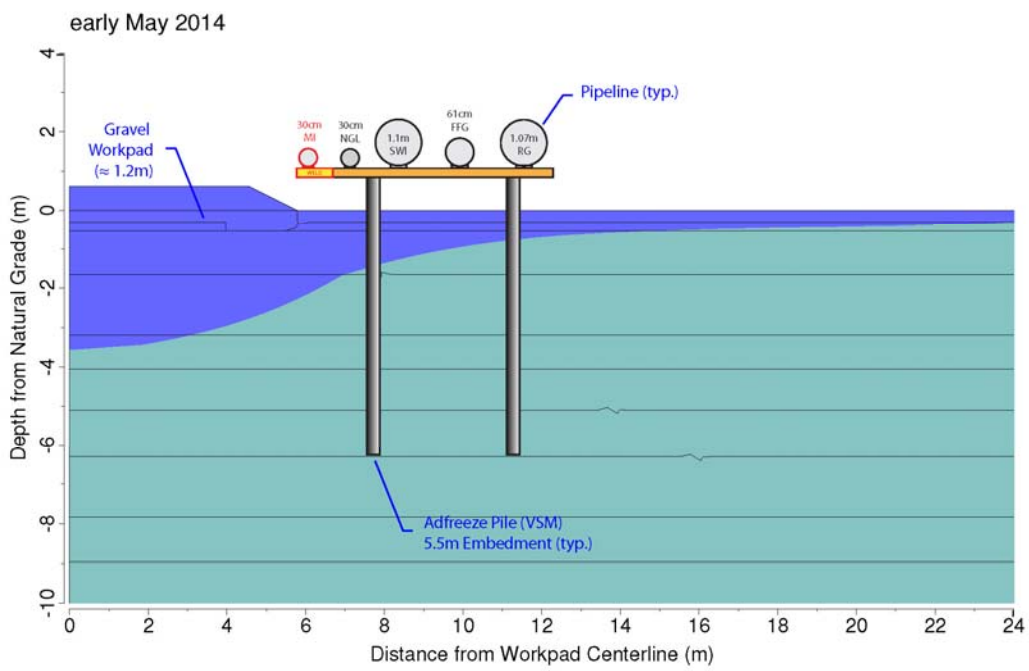

late March 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

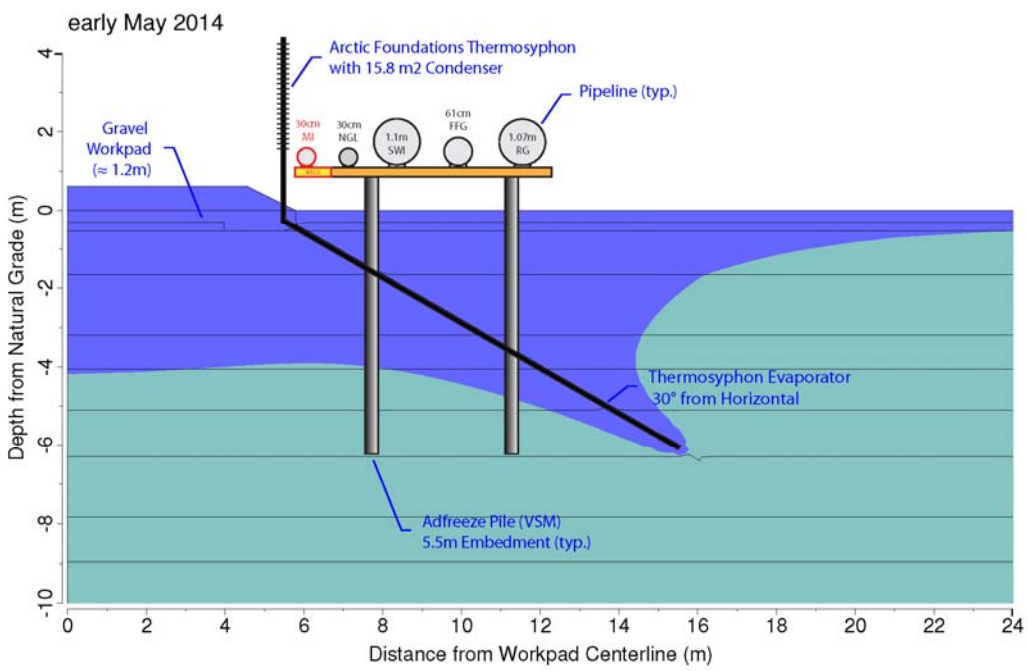

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C

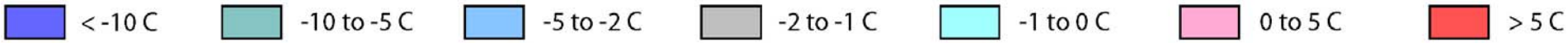


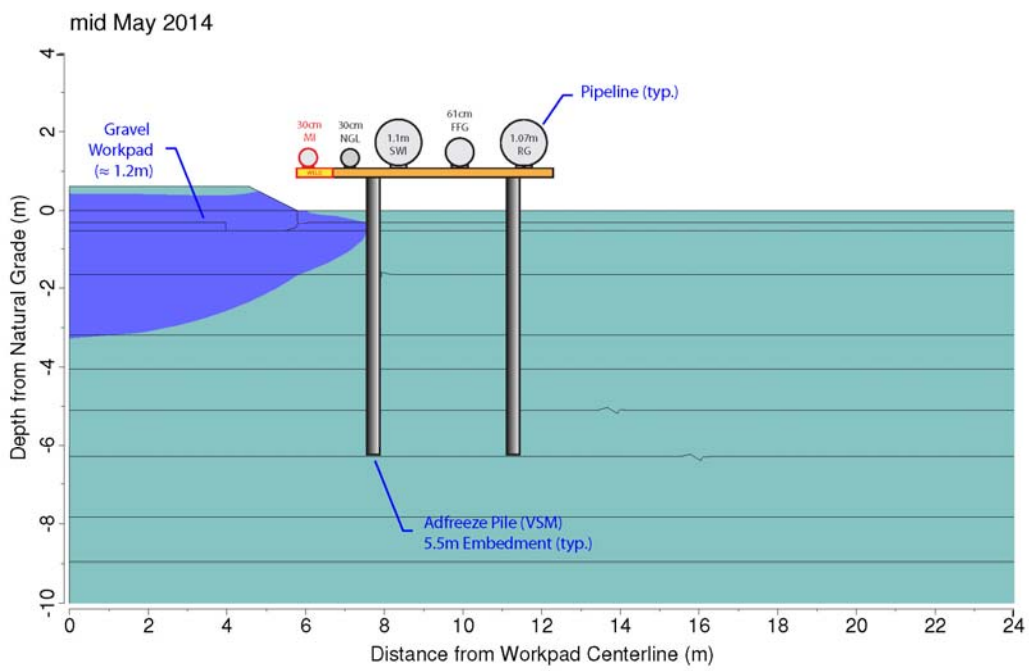


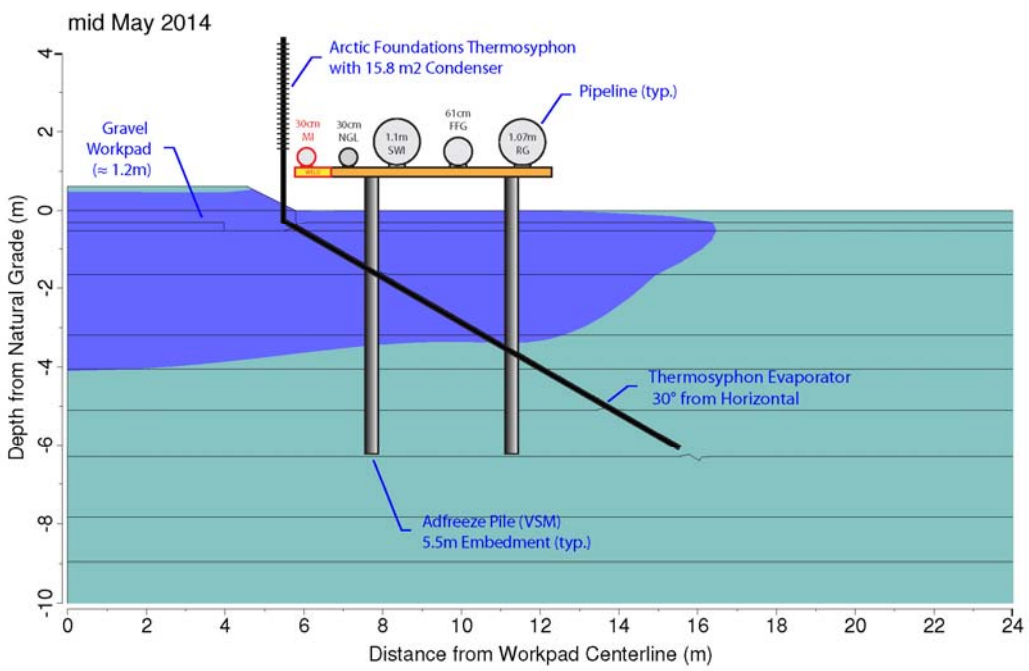
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C


early May 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

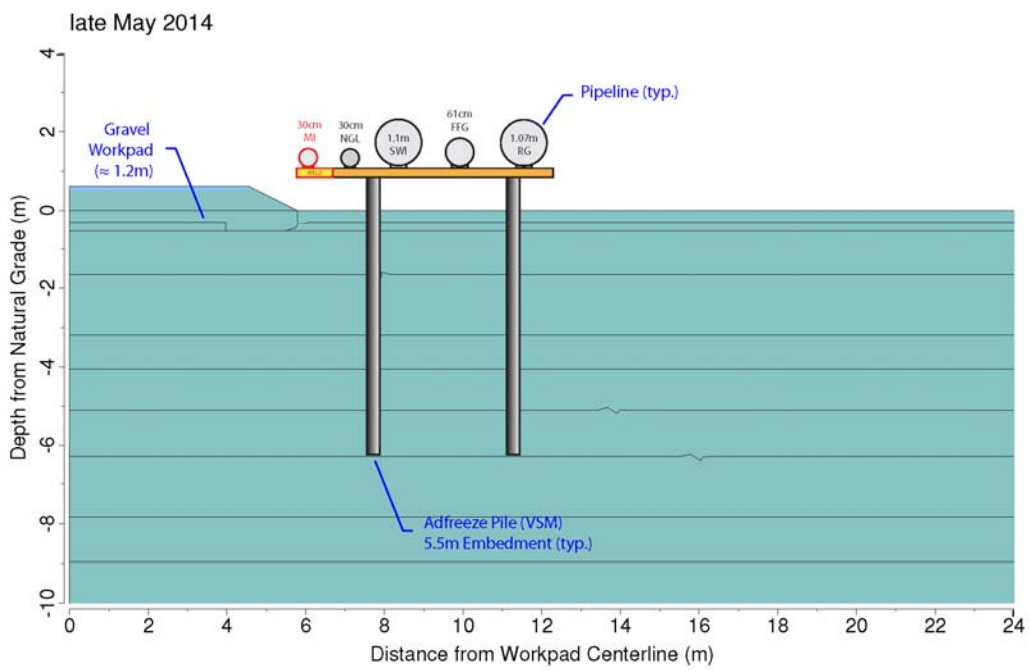

early May 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)

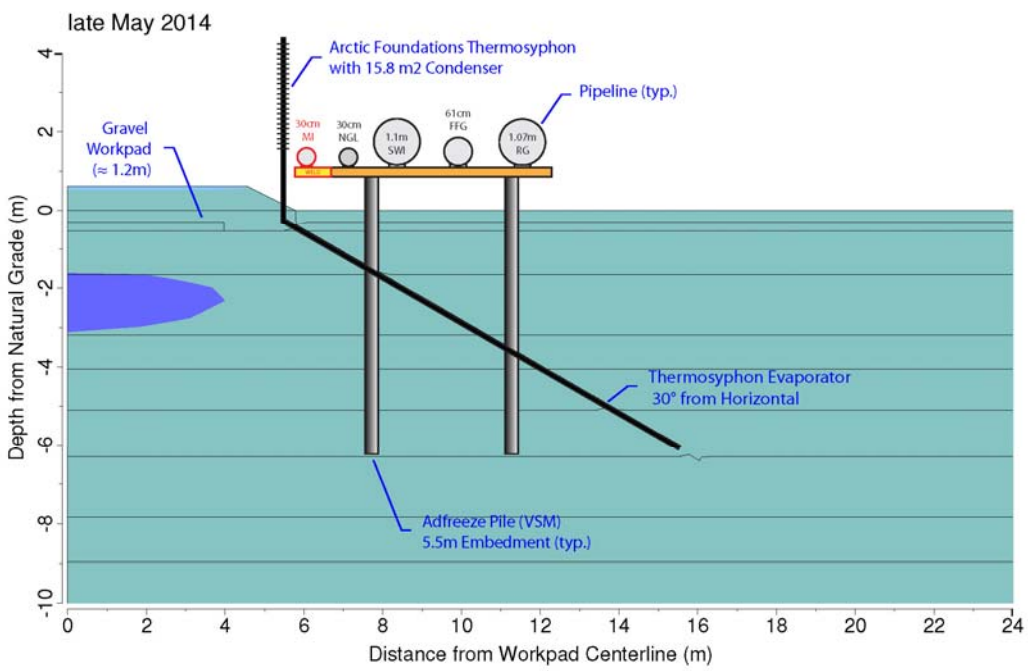

< -10 C
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C



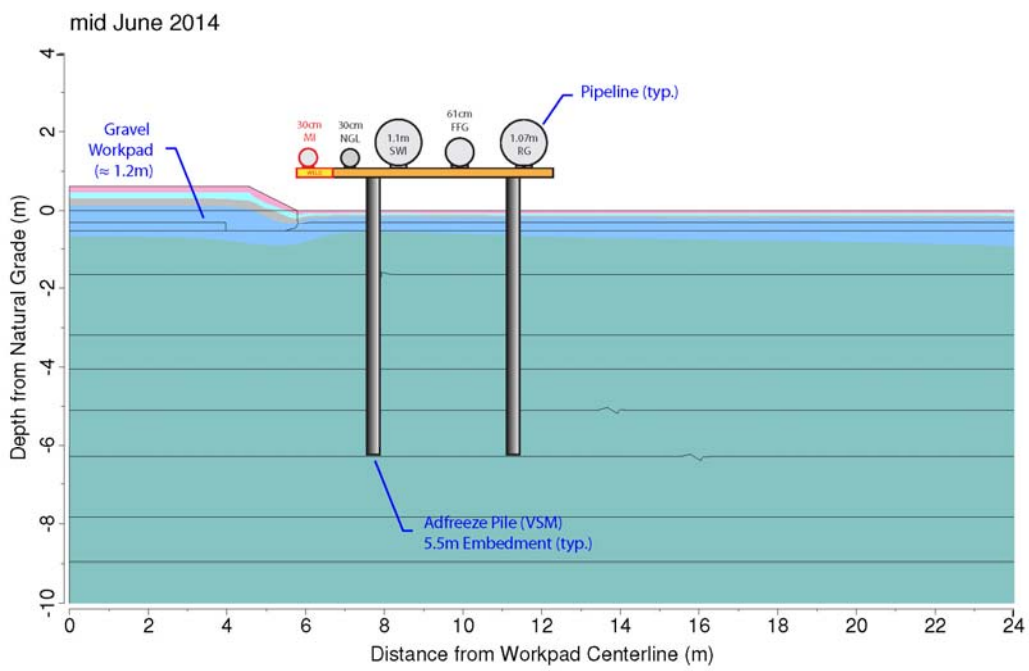


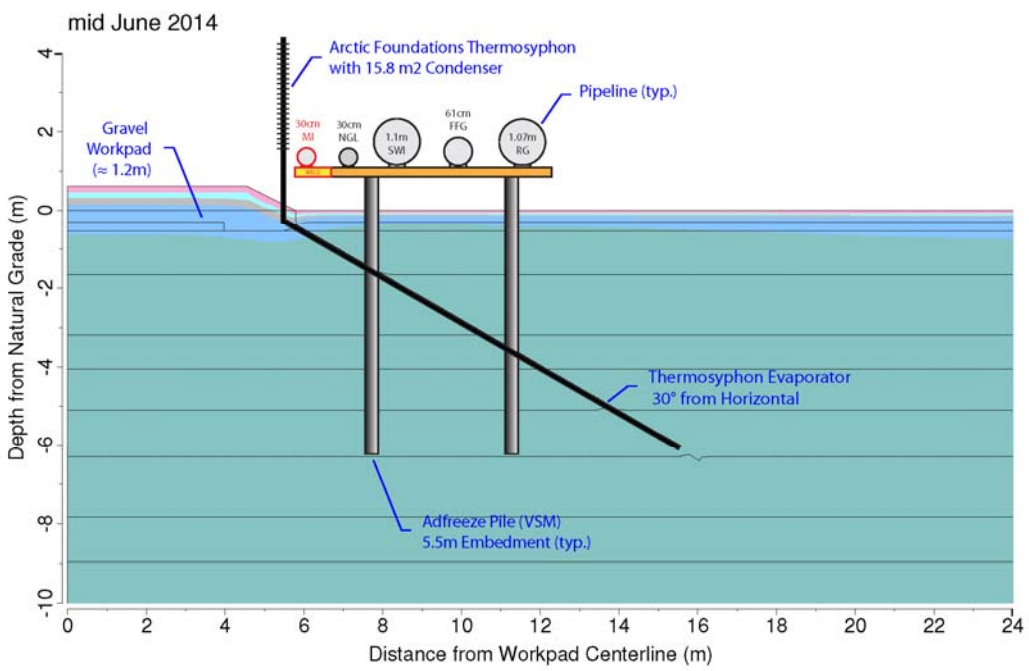
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C



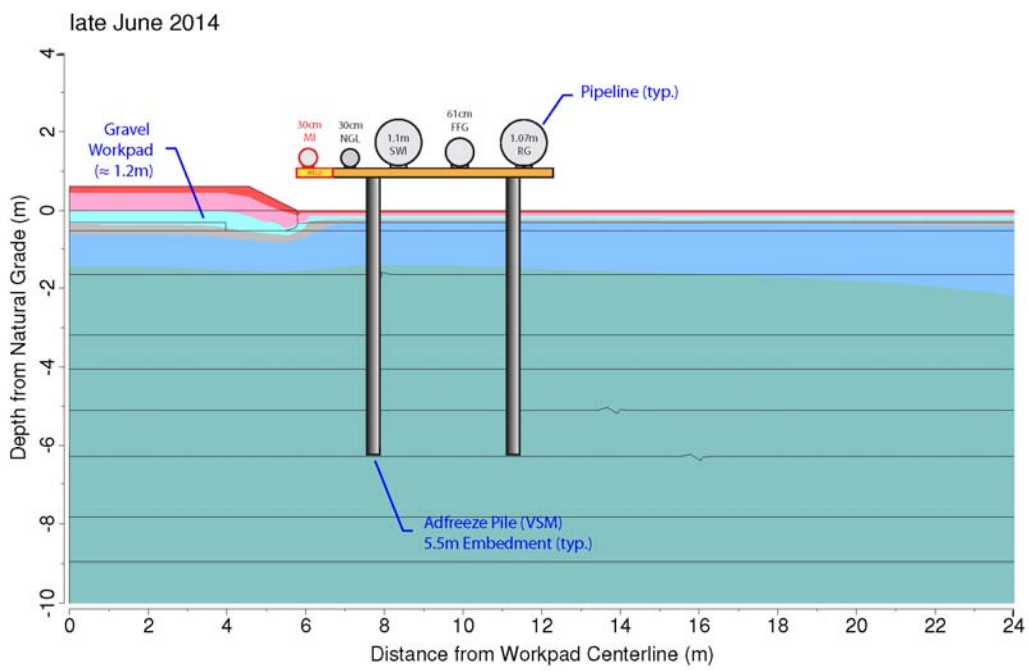


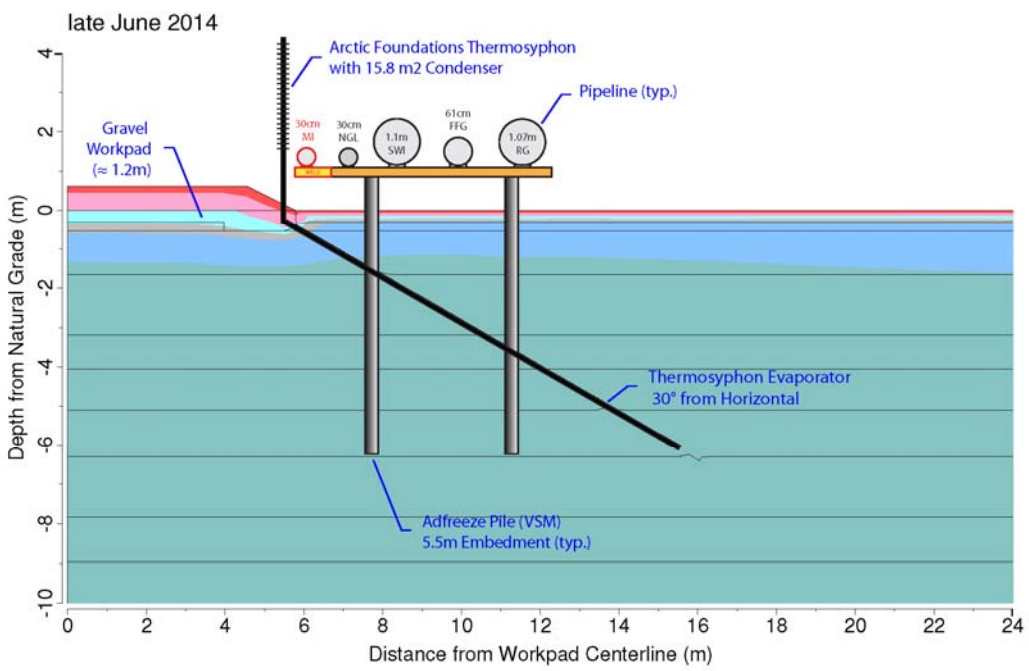
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C



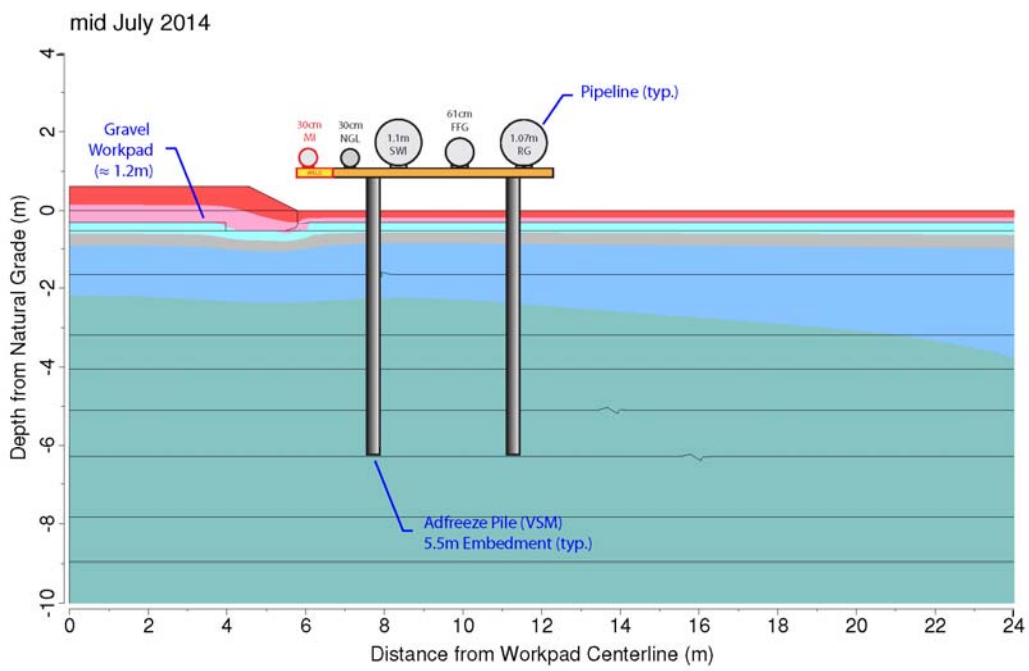


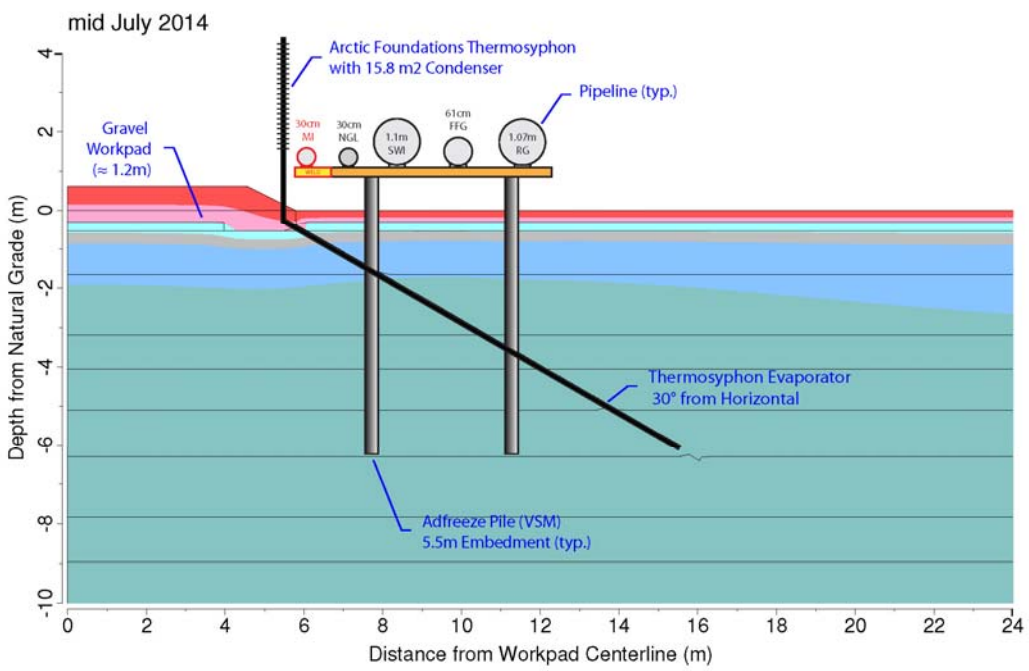
< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C

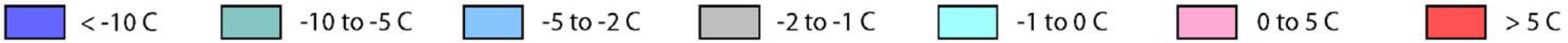




< -10 C | -10 to -5 C | -5 to -2 C | -2 to -1 C | -1 to 0 C | 0 to 5 C | > 5 C


mid July 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


mid July 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


< -10 C
-10 to -5 C
-5 to -2 C
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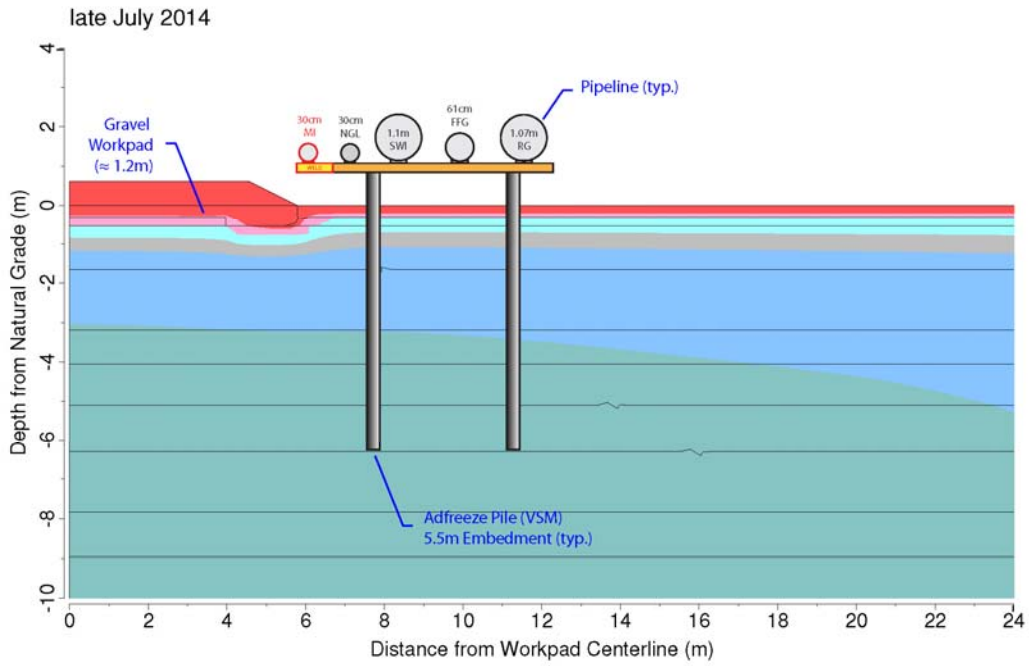
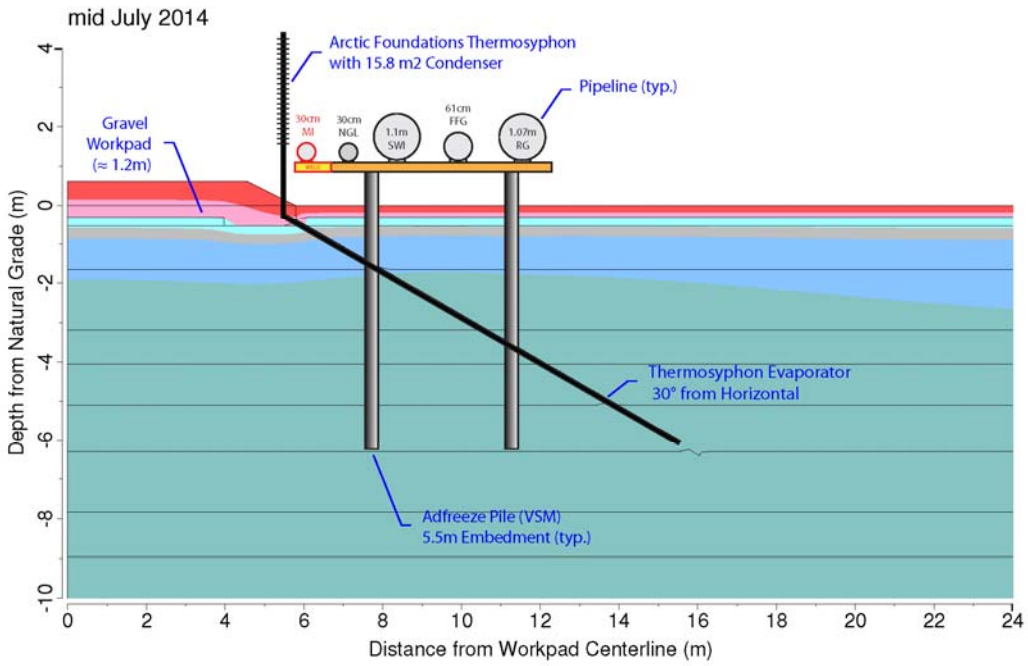
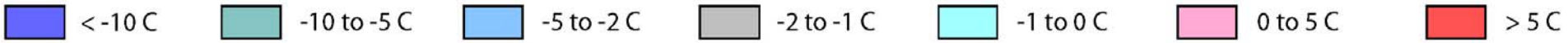
> 5 C


late July 2014
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)


mid July 2014
Arctic Foundations Thermosyphon with 15.8 m2 Condenser
Gravel Workpad (≈ 1.2m)
Pipeline (typ.)
30cm MI
30cm NGL
1.1m SWI
61cm FFG
1.07m RG
Thermosyphon Evaporator 30° from Horizontal
Adfreeze Pile (VSM) 5.5m Embedment (typ.)
Depth from Natural Grade (m)
Distance from Workpad Centerline (m)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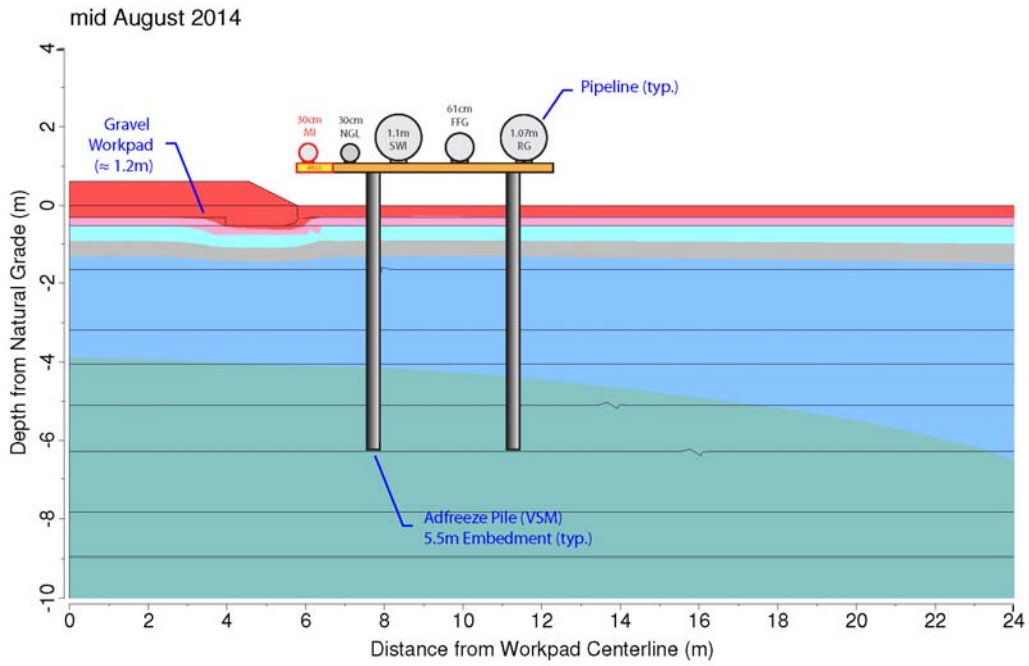
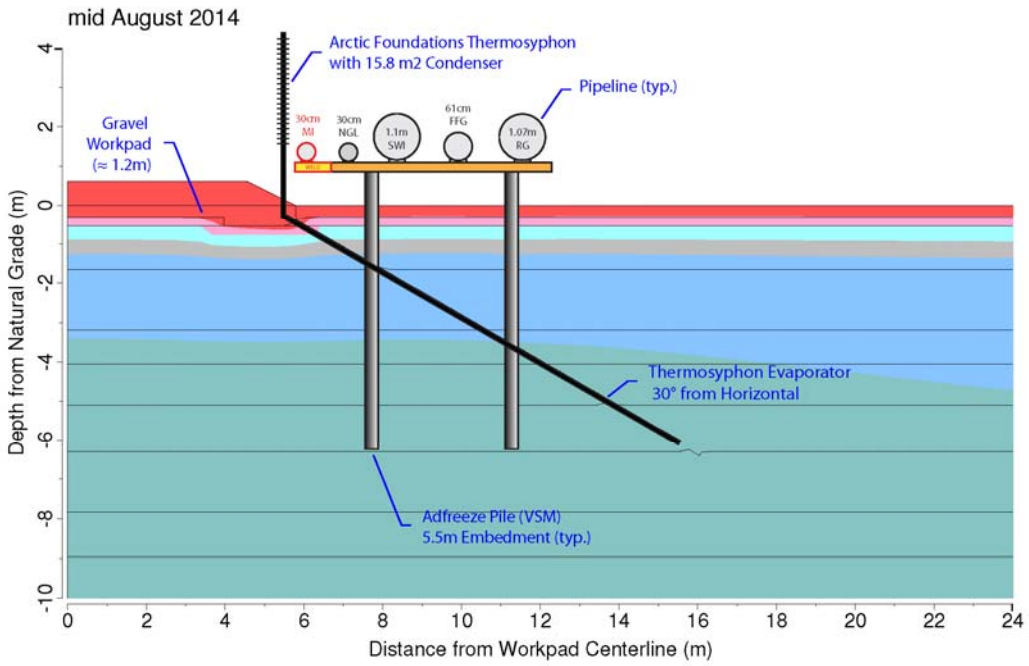
-10 to -5 C
-5 to -2 C
-2 to -1 C
-1 to 0 C
0 to 5 C
> 5 C





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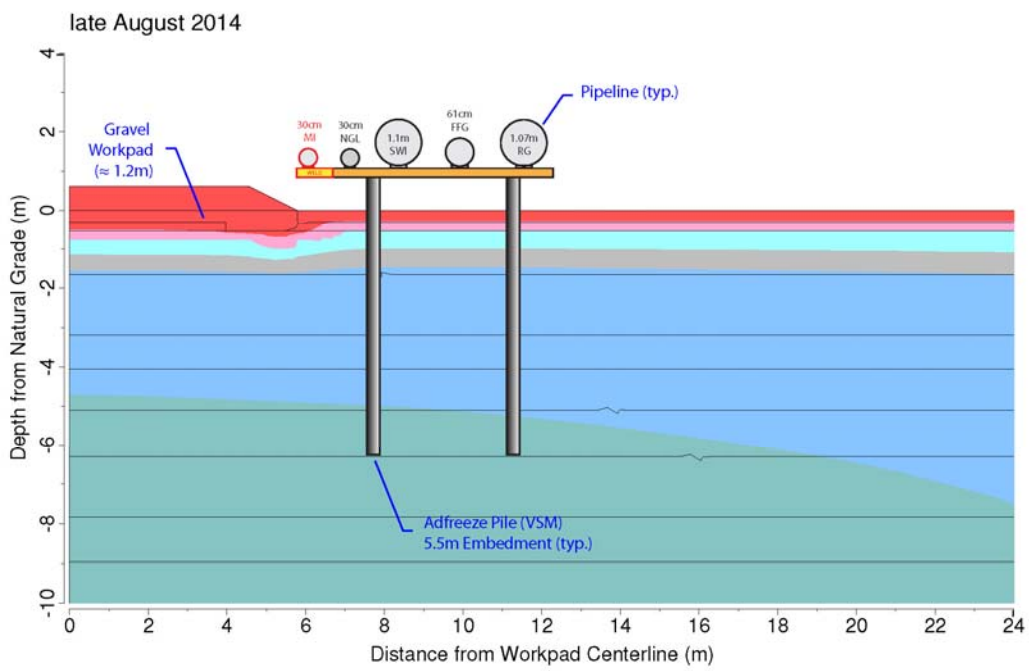

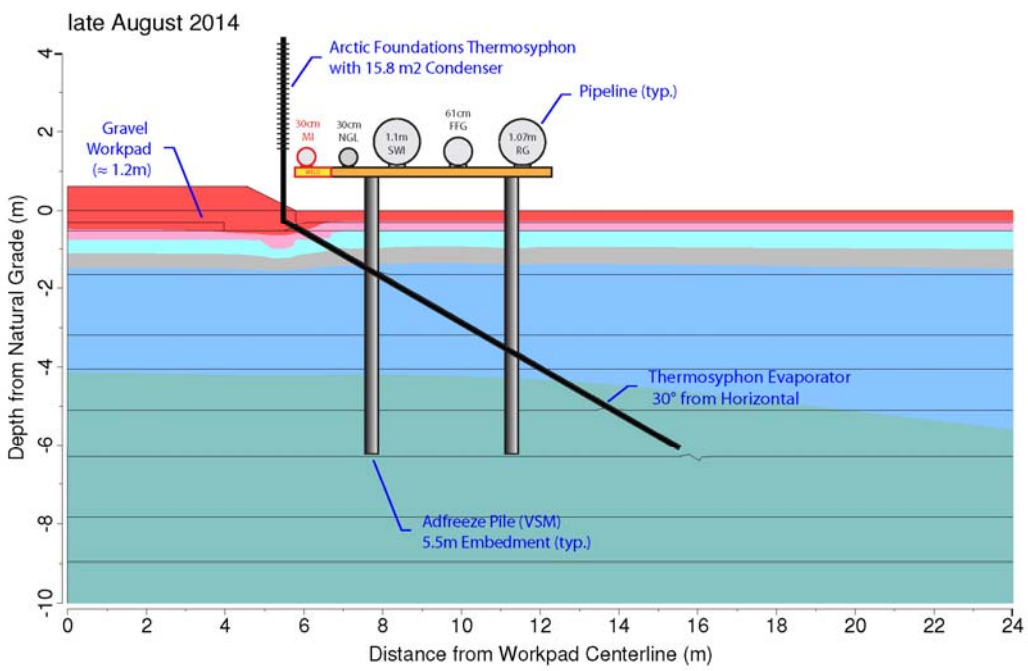

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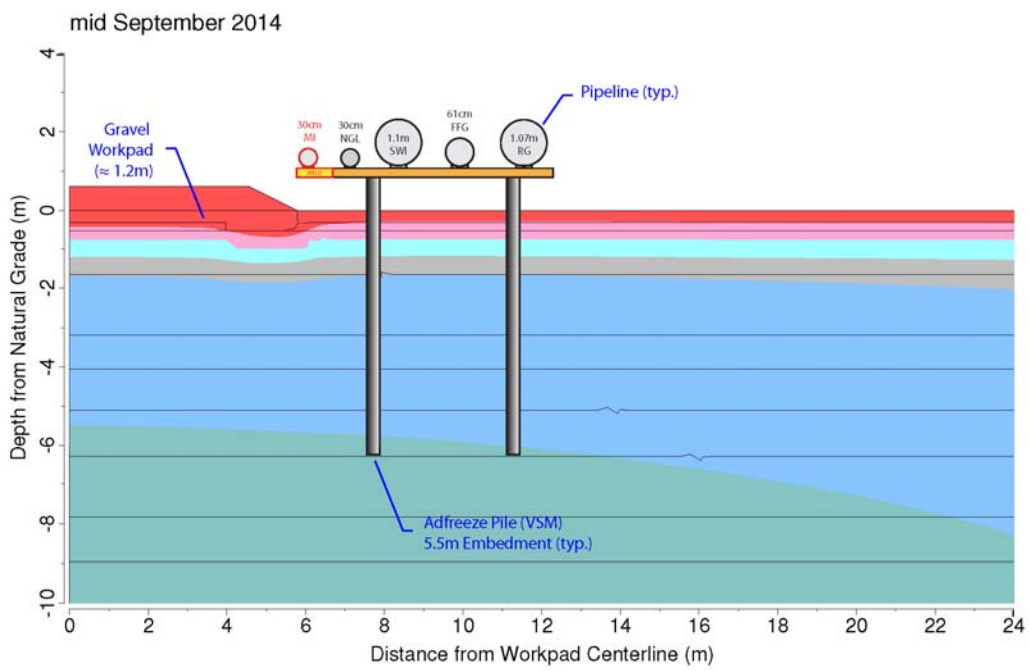
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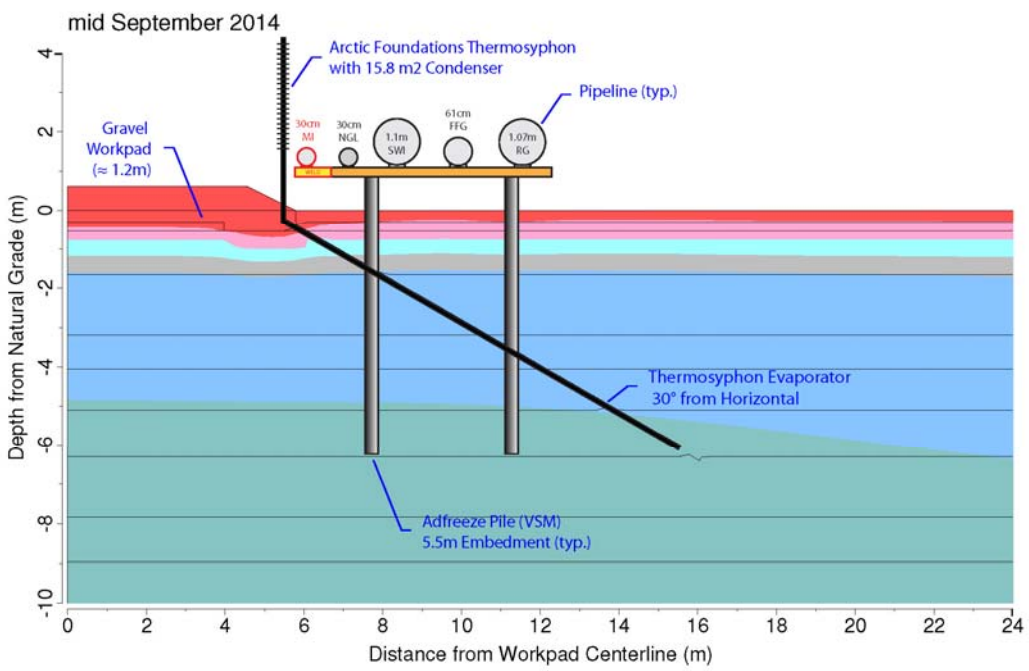
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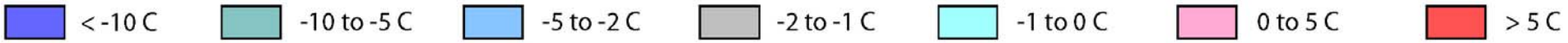
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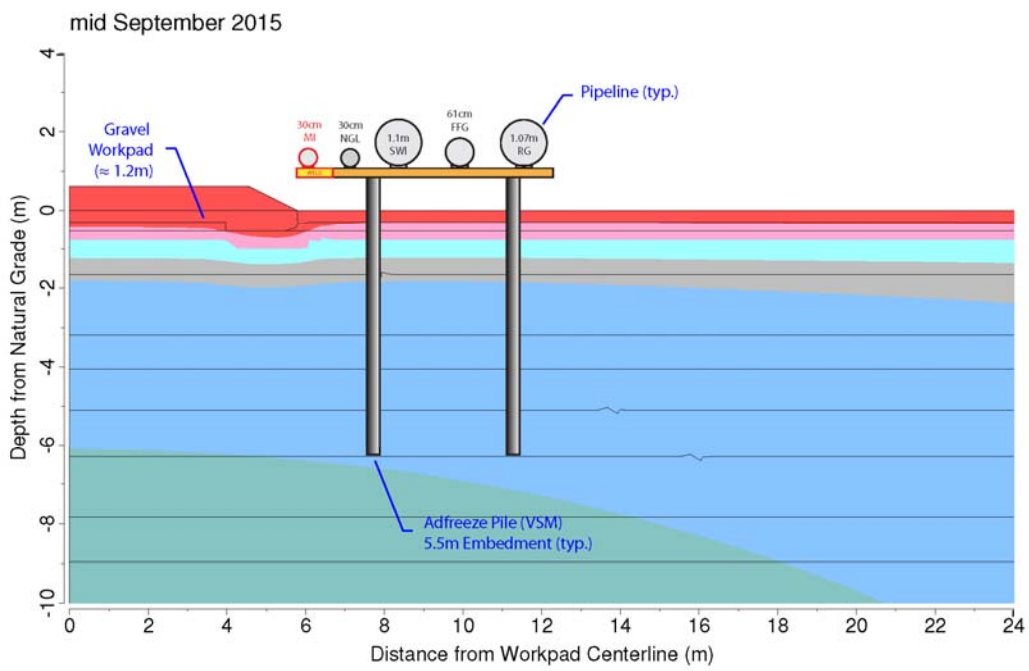

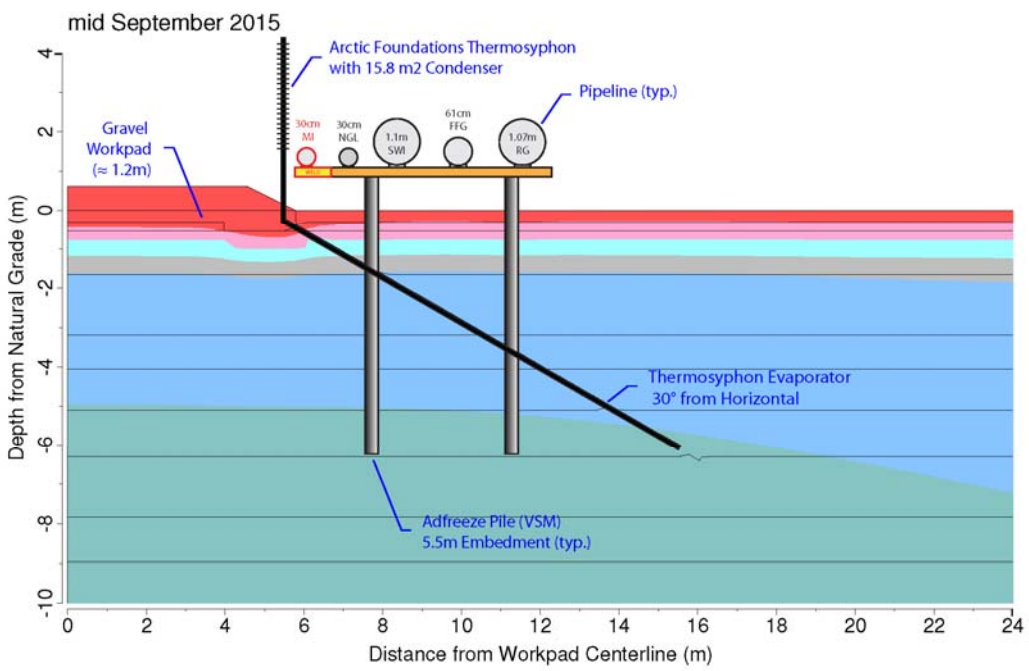

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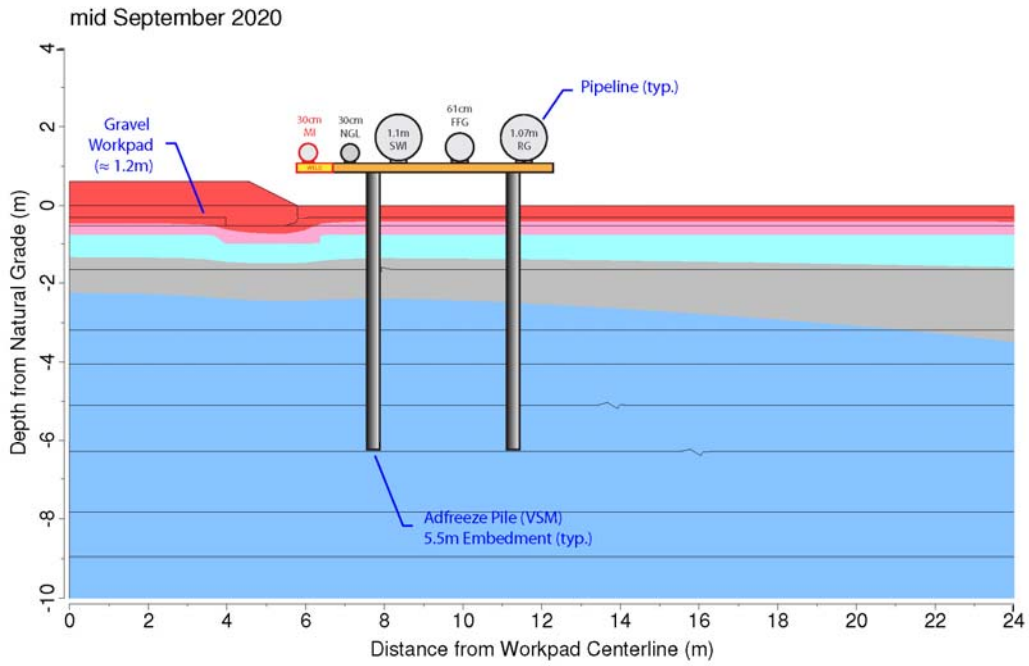

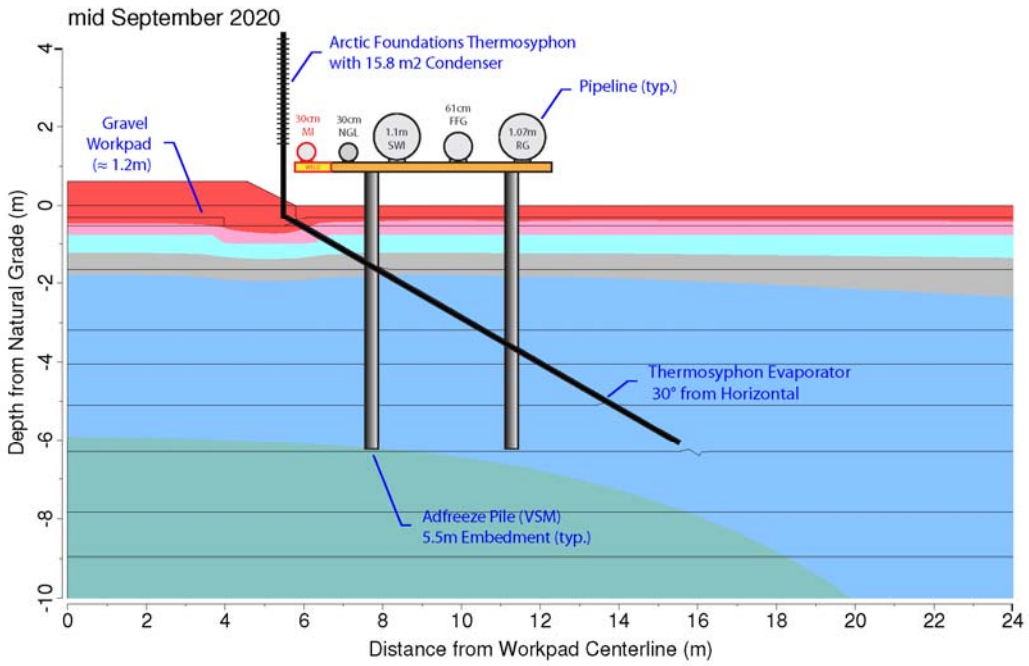

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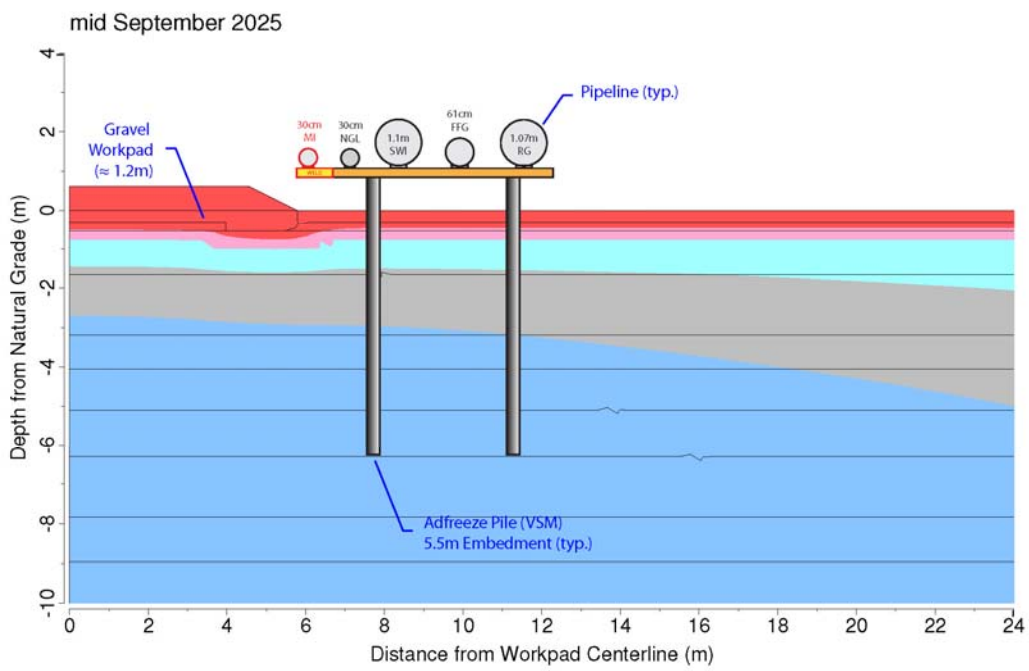

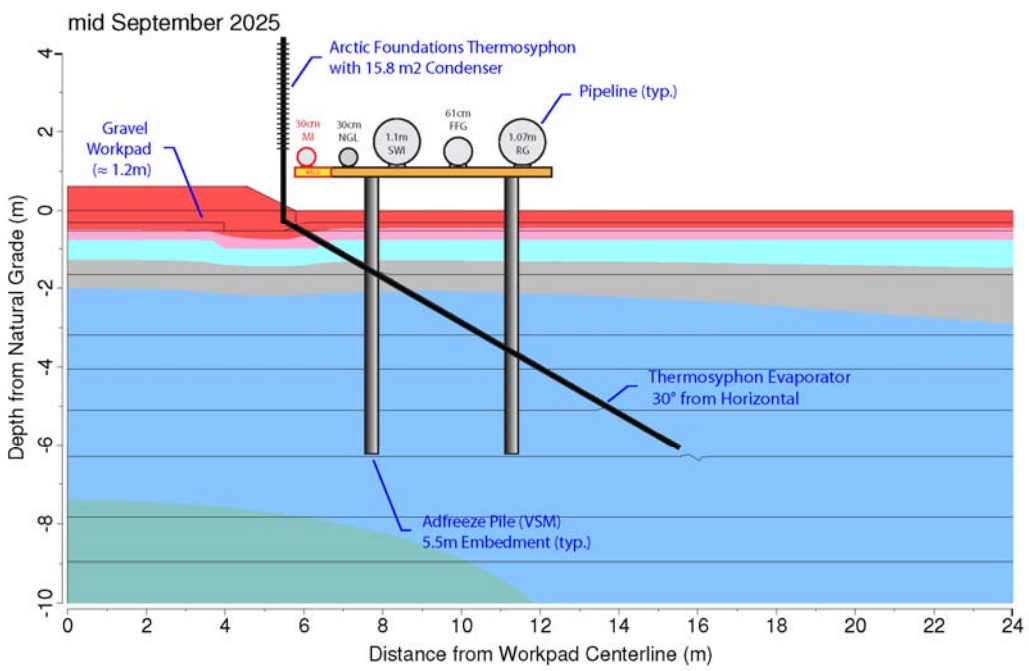

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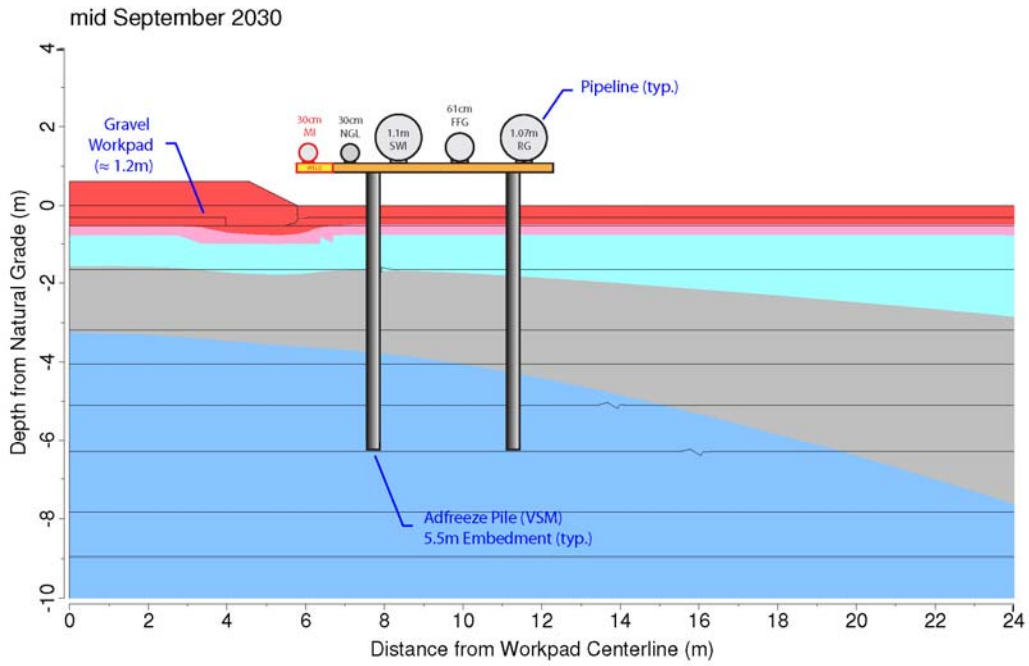

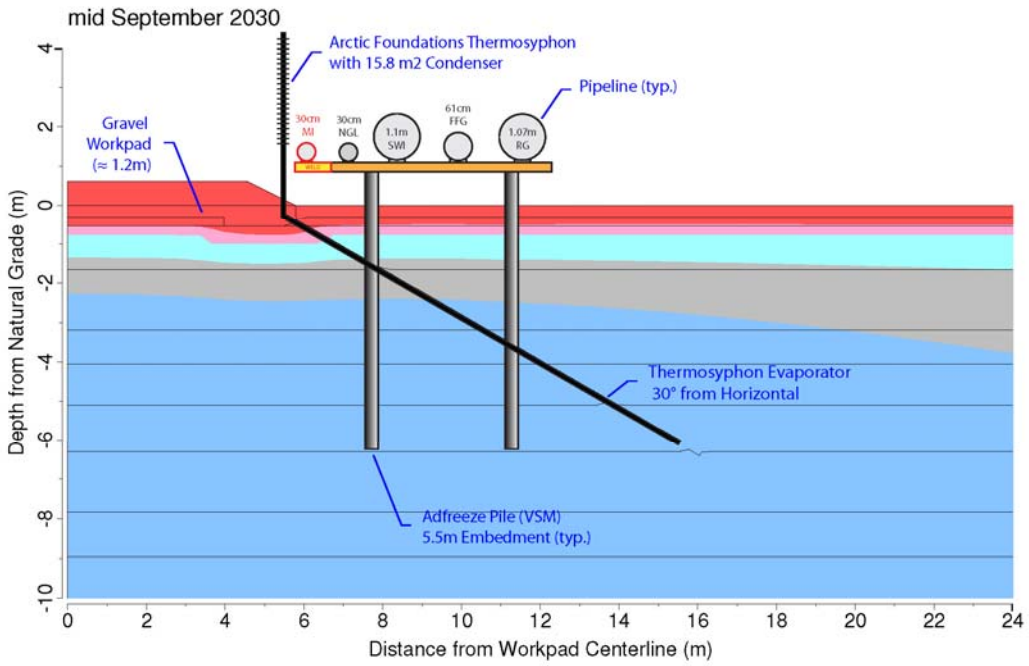

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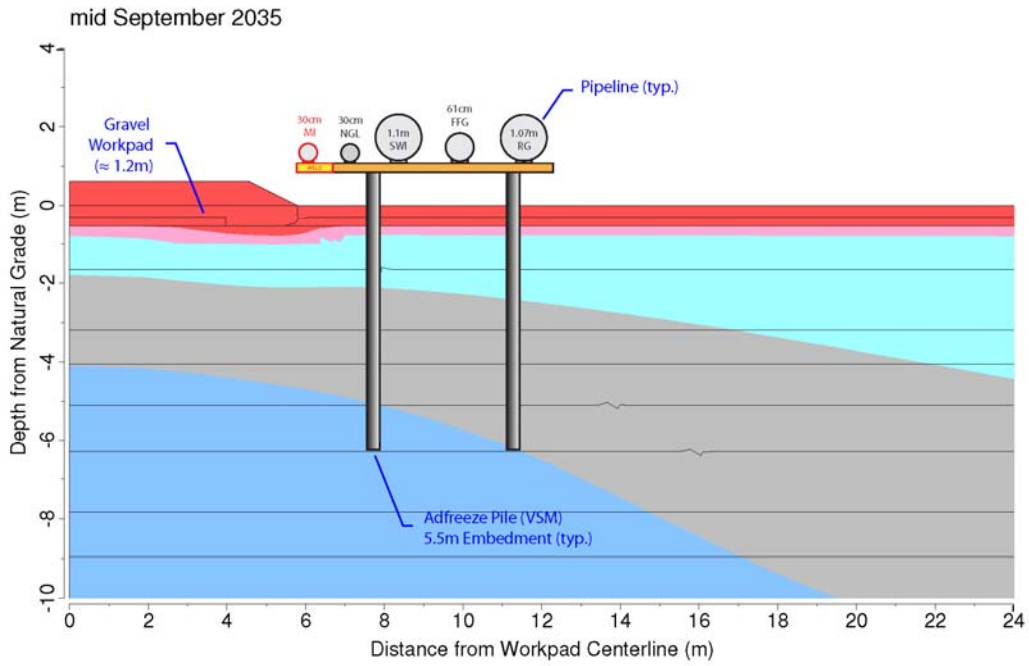

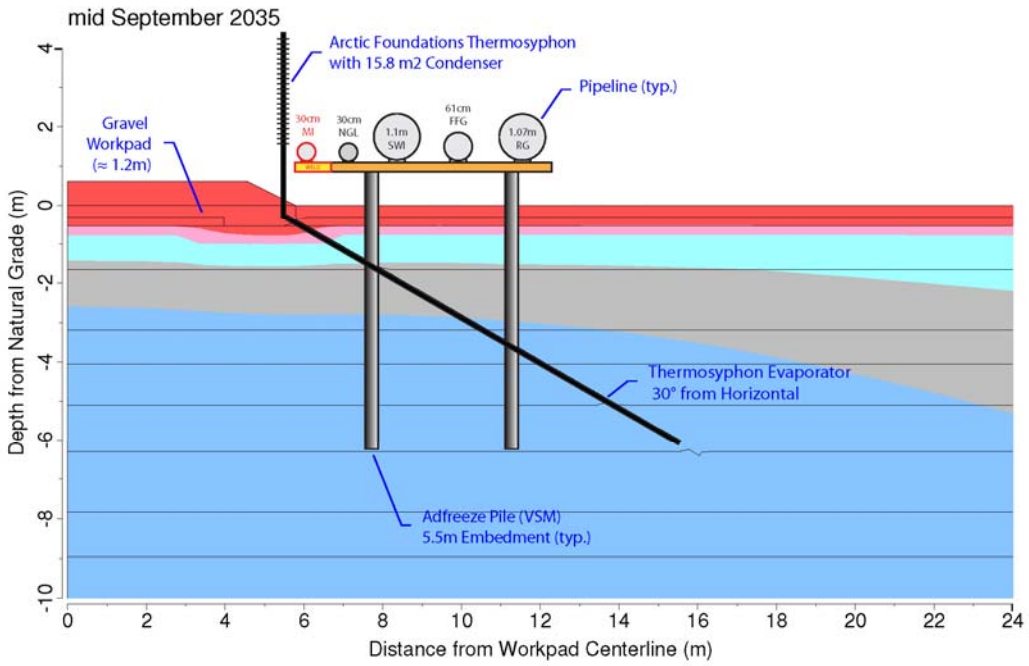

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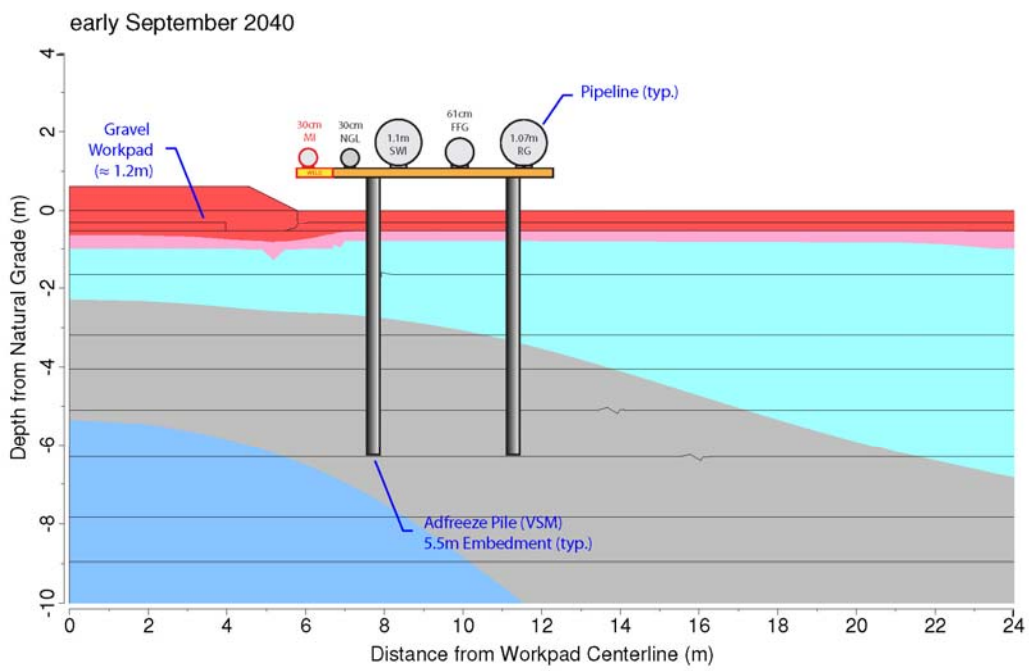

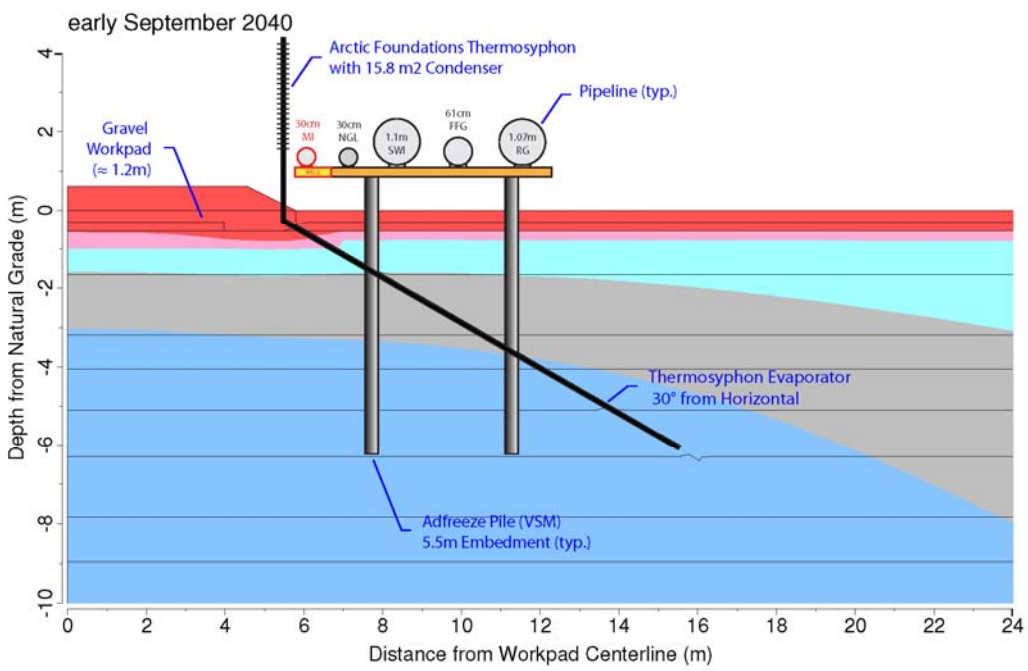

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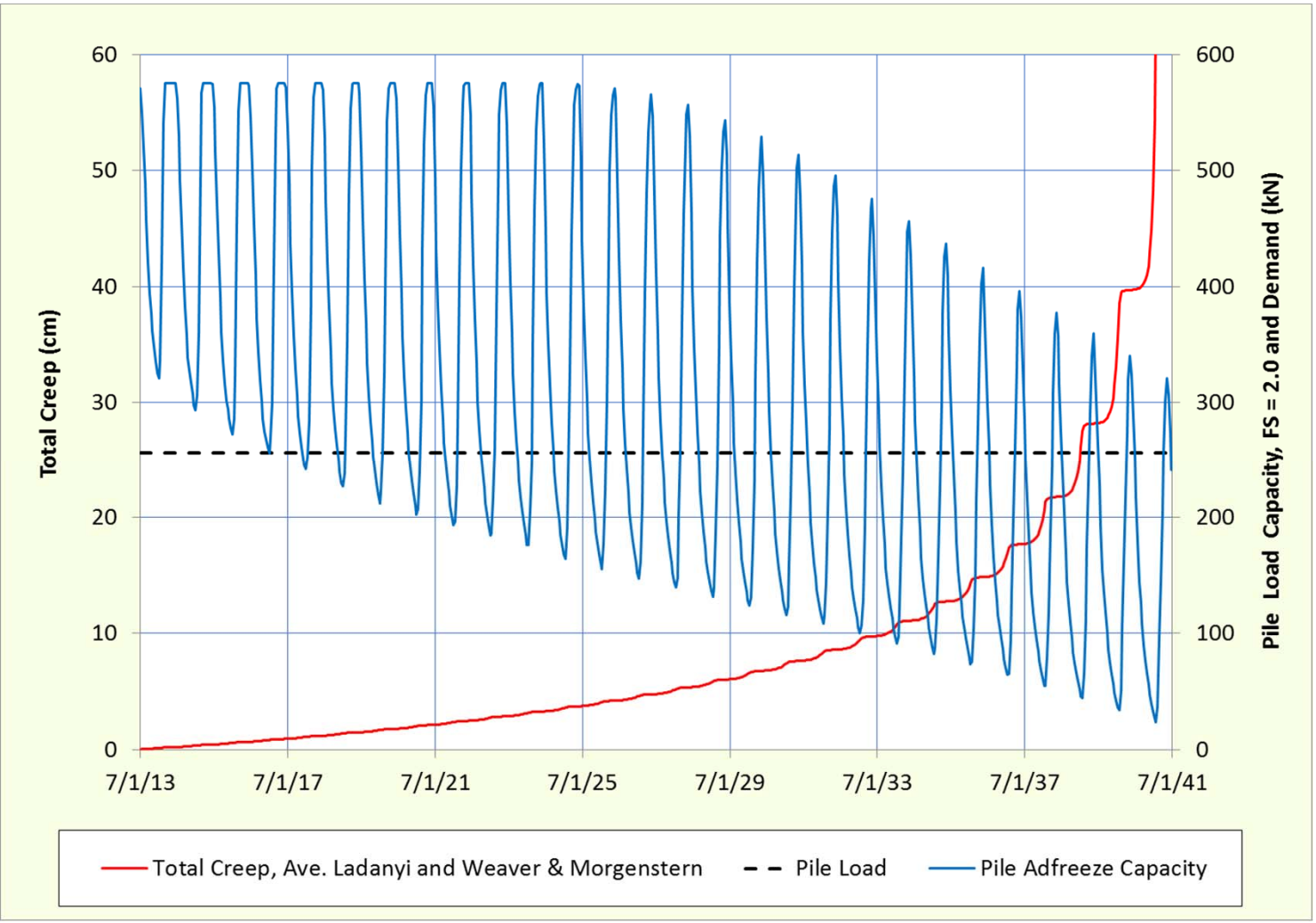
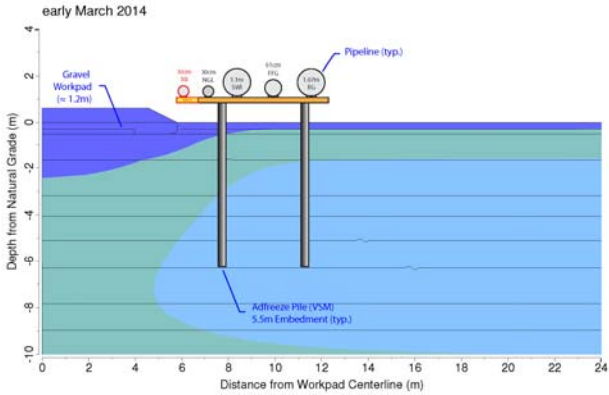
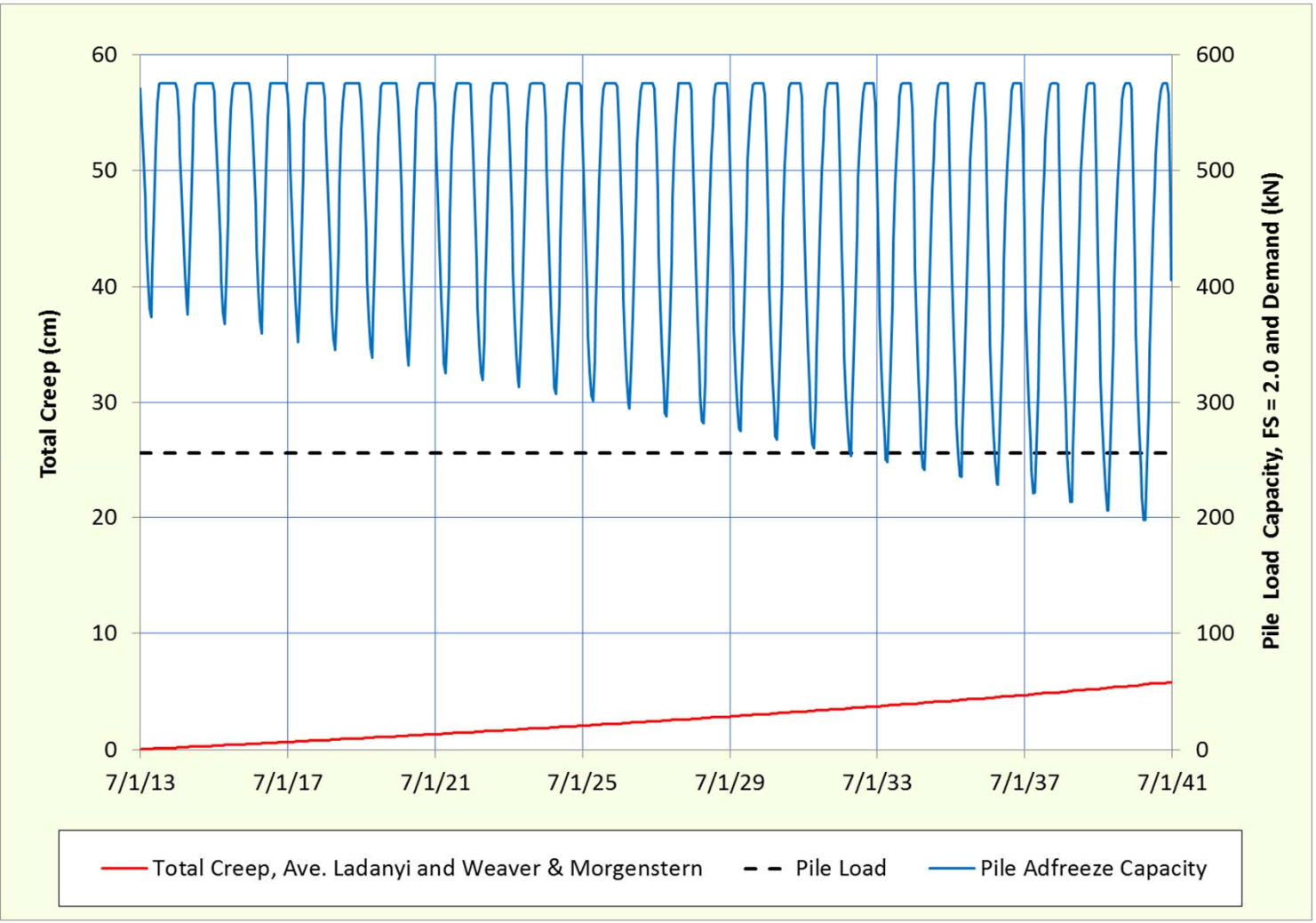
Effect of Predicted Soil Temperatures Upon Design Load Capacity and Creep

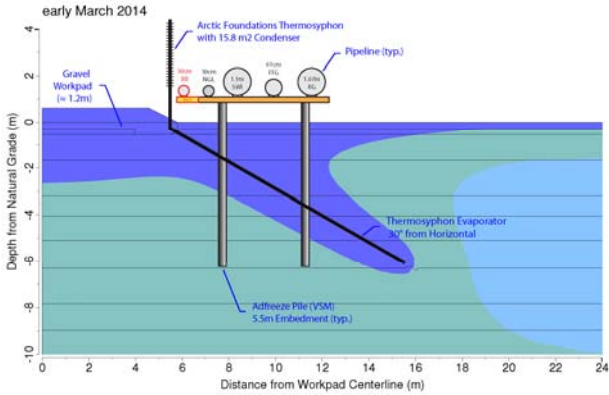
Predicted Adfreeze Capacity and Creep with NO Thermosyphon





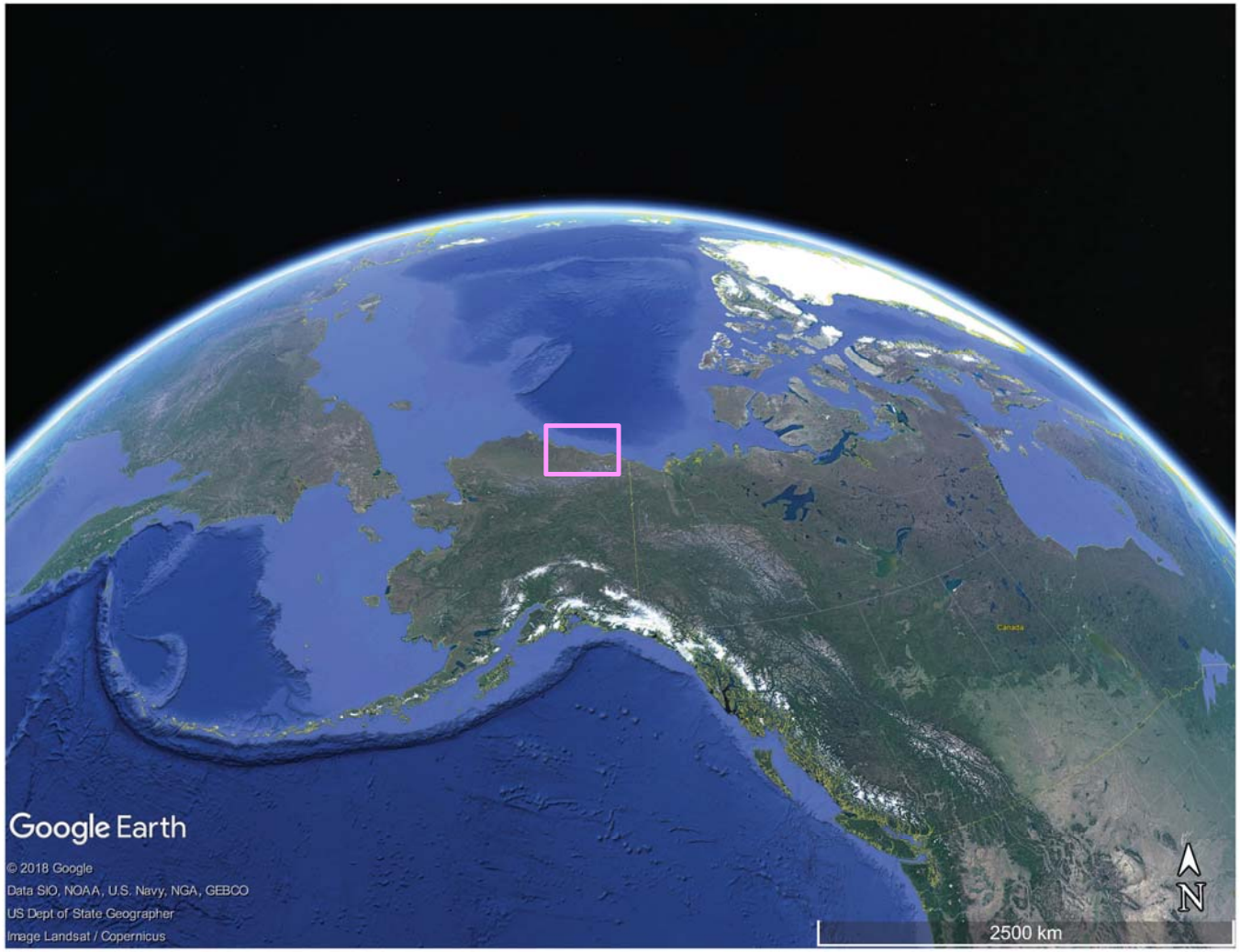
Predicted Adfreeze Capacity and Creep with Single Slanty Thermosyphon





Pilot Project: the Applied Mitigation Demonstration Project

Location of the Pilot Project



Location of the Pilot Project

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Google Earth
Image © 2019 DigitalGlobe
Image © 2019 Maxar Technologies
Image IBCAO
10 km
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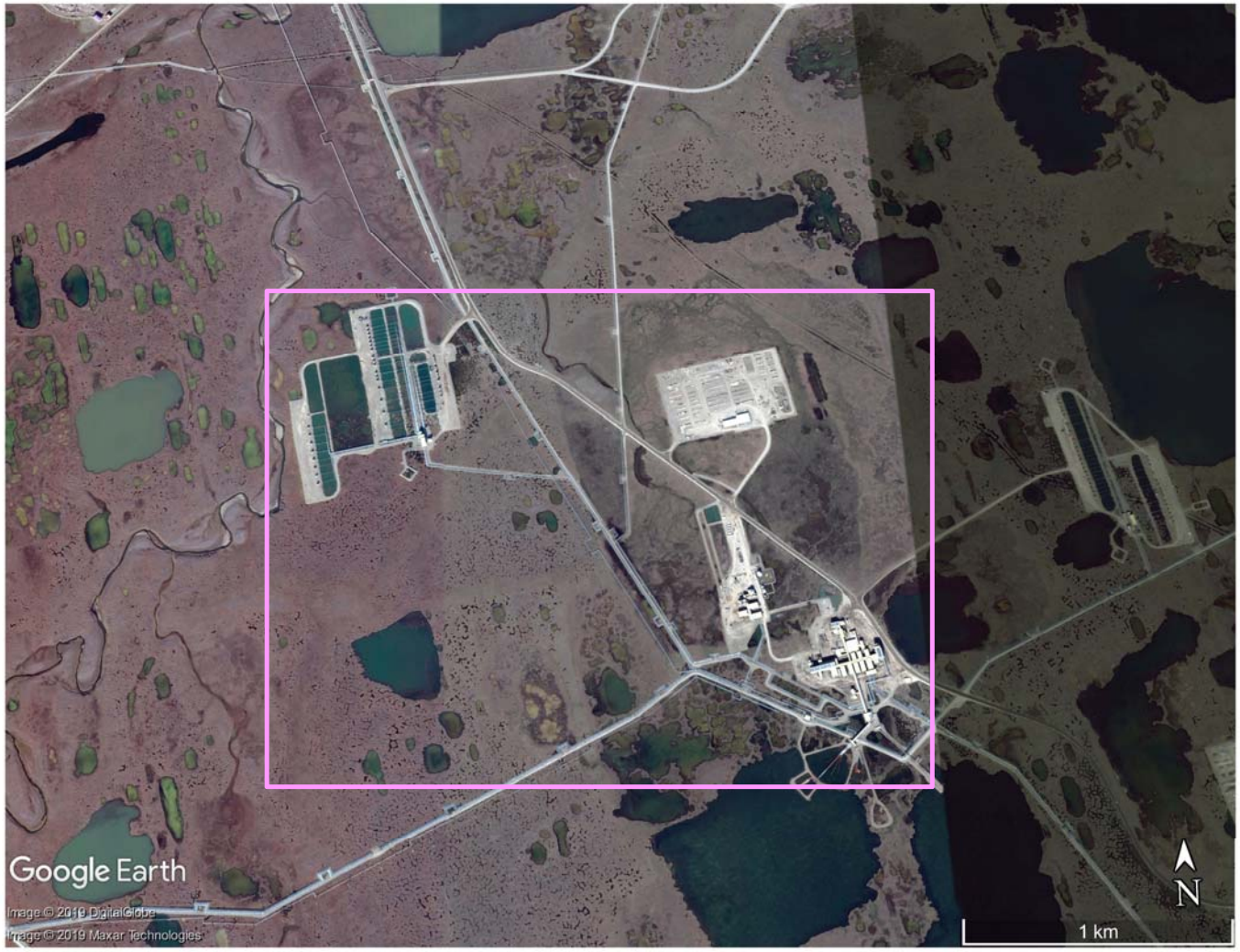
Location of the Pilot Project



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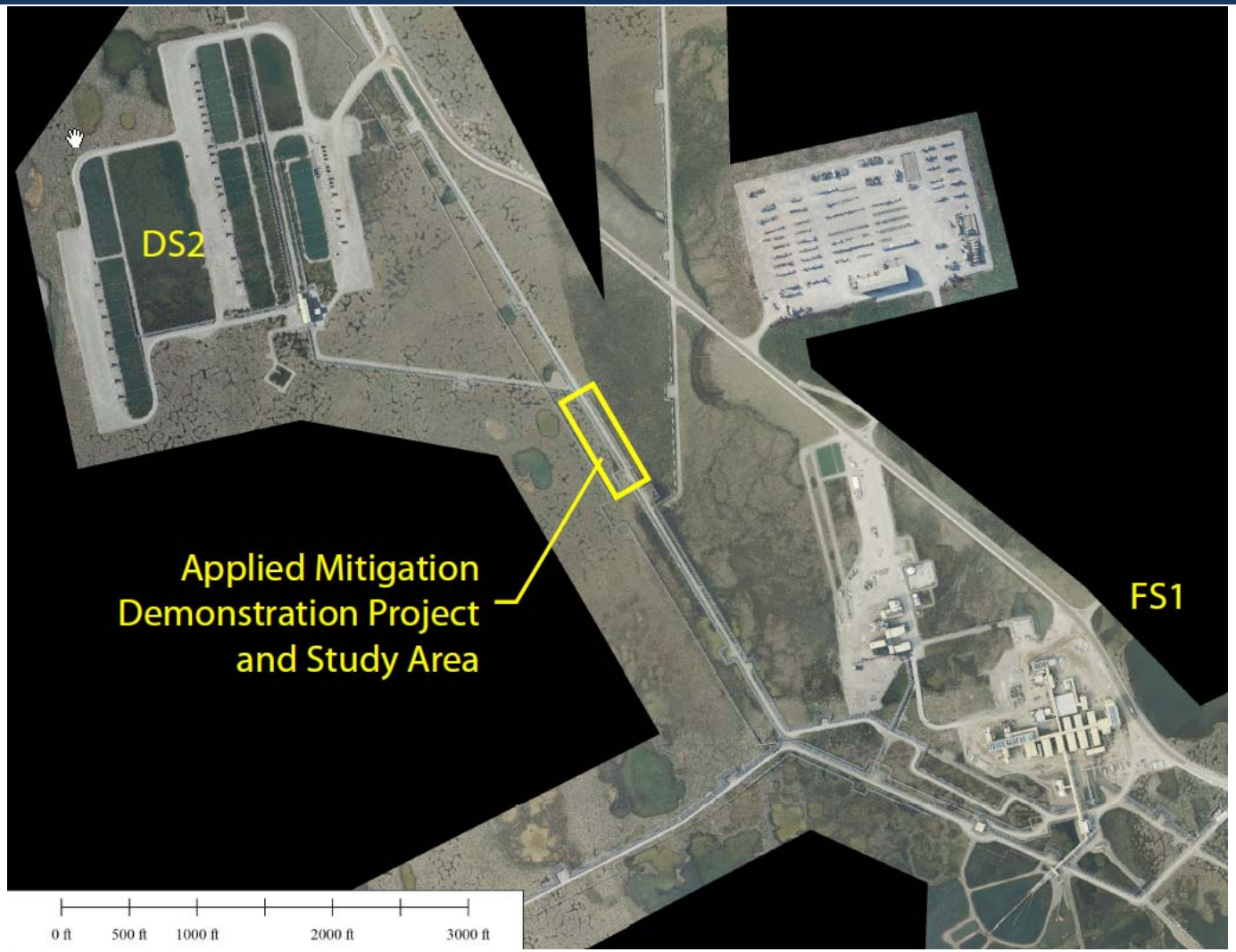
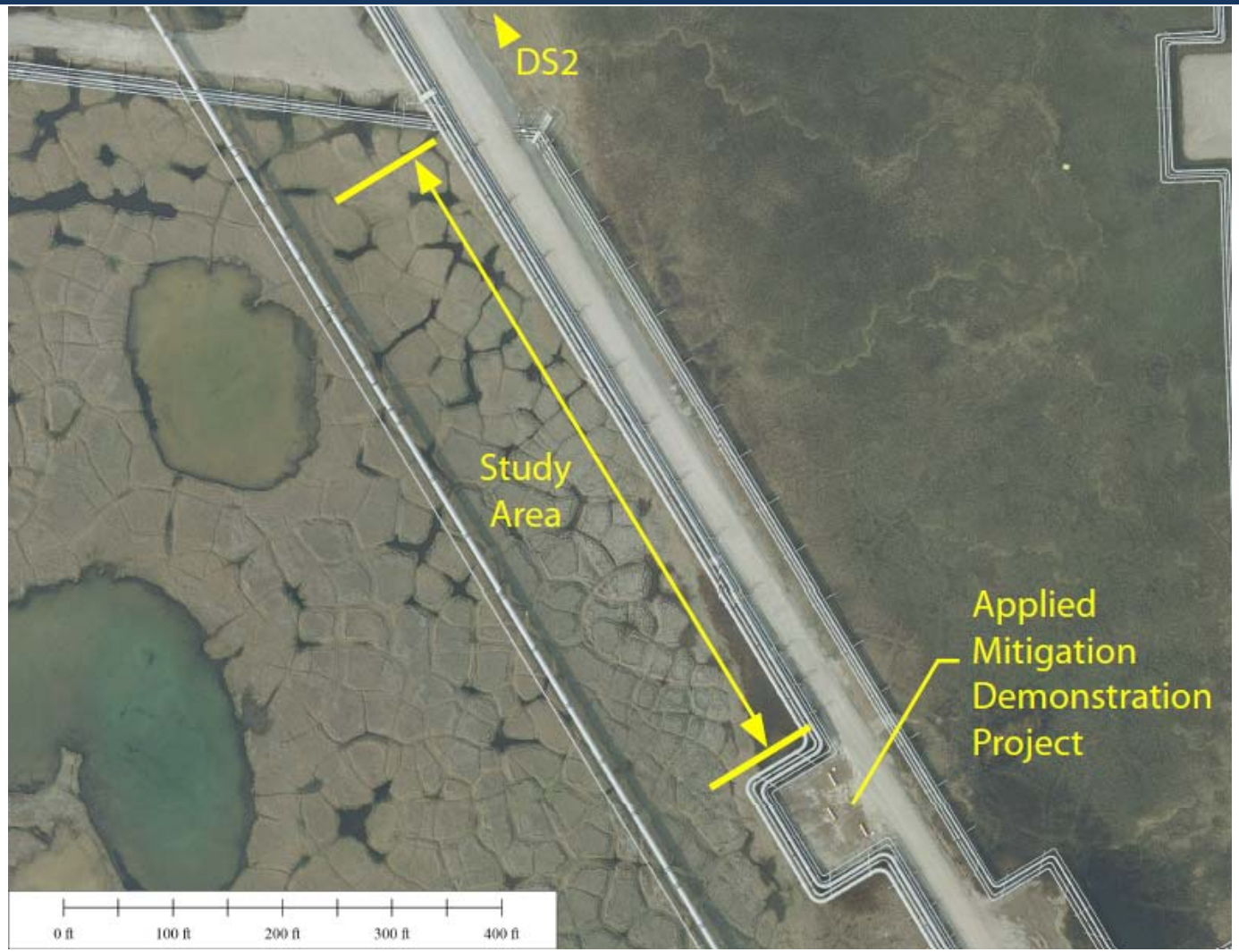
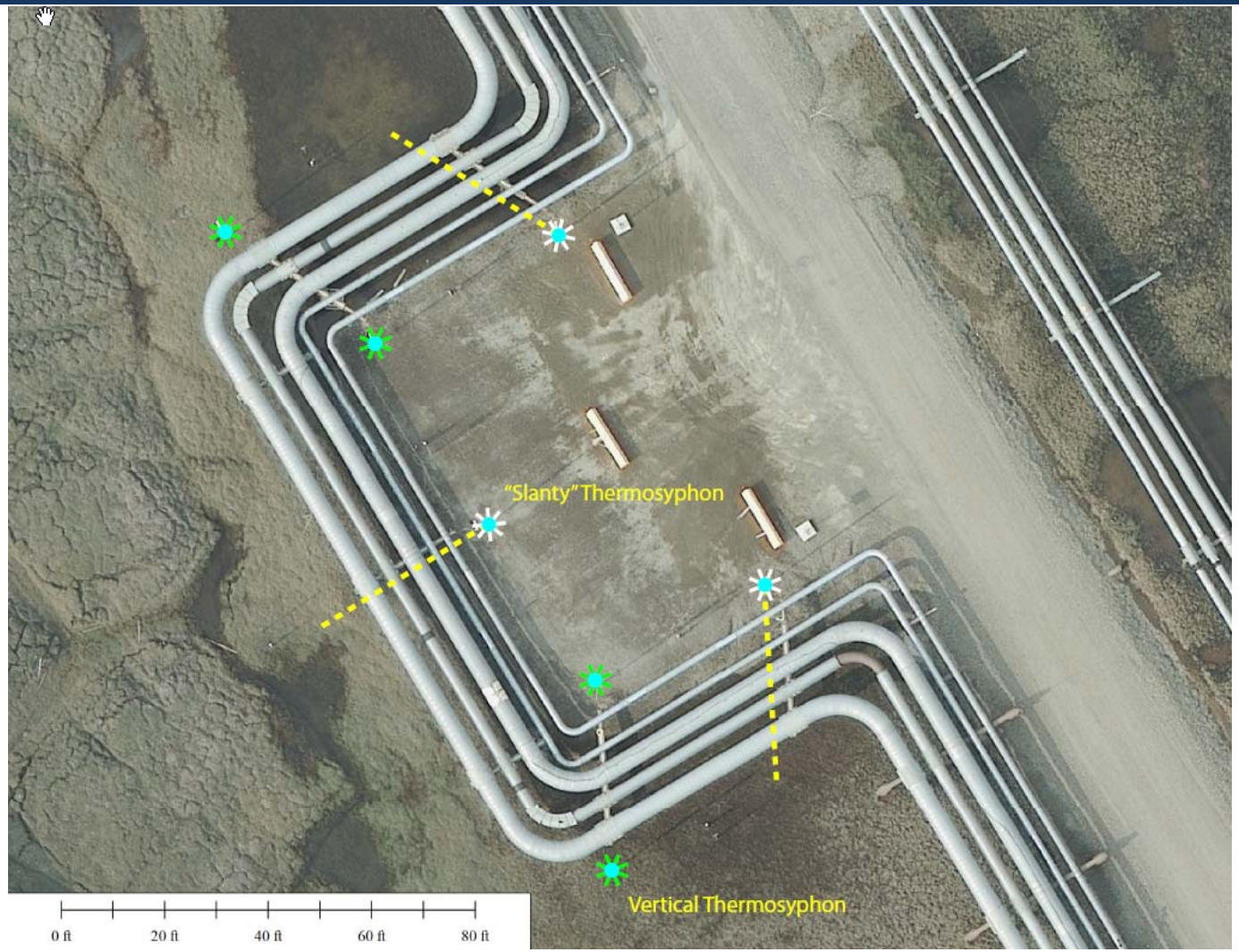


Layout of the Pilot Project and Study Area



Layout of the Pilot Project and Study Area

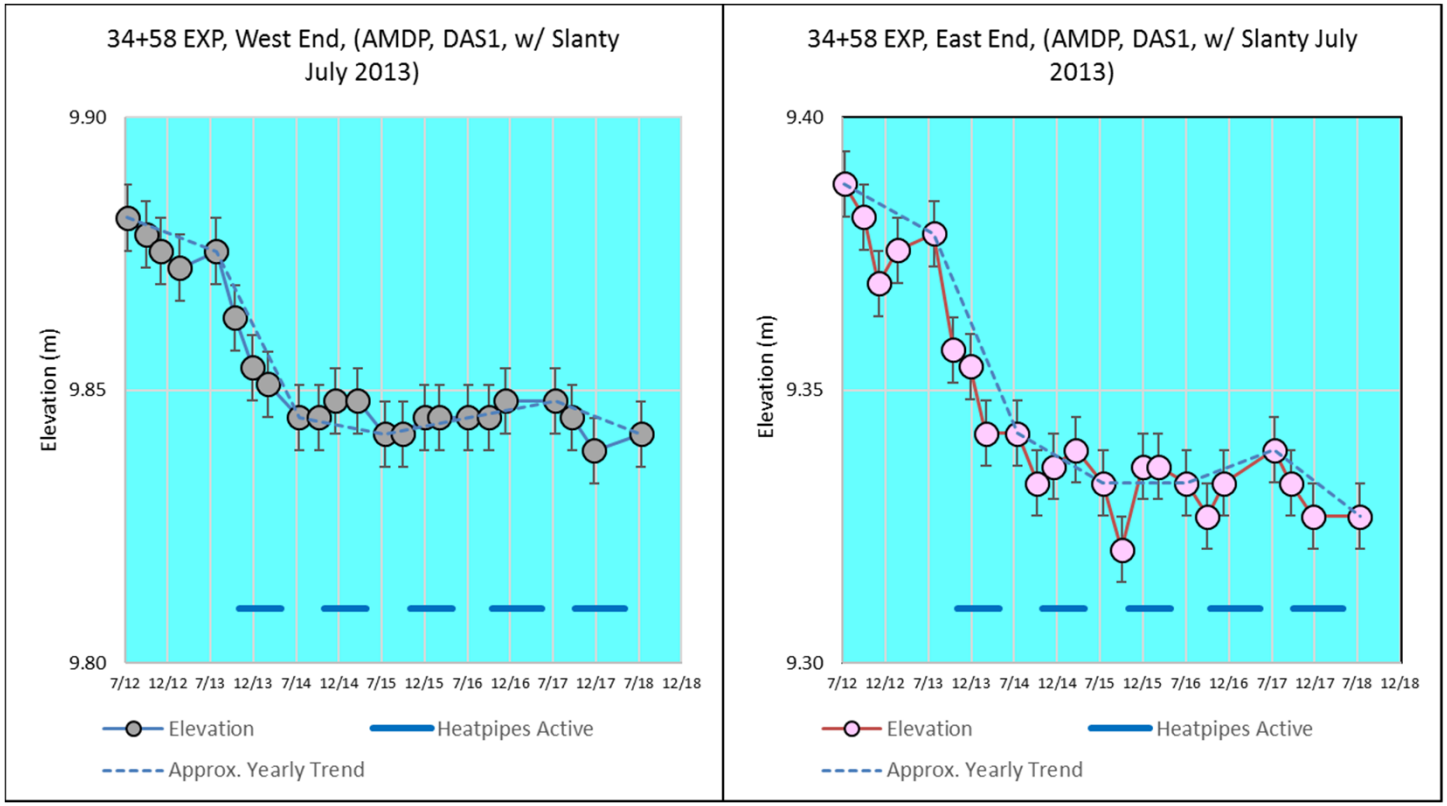


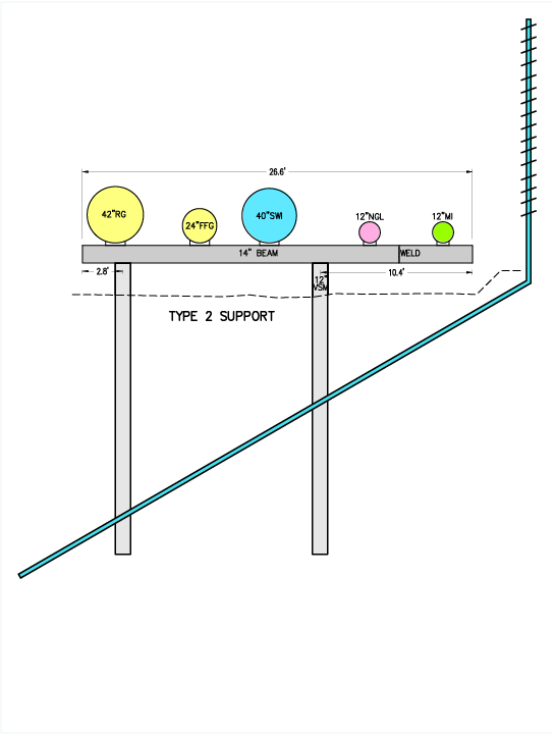
Installation of “Slanty Thermosyphons” at the Pilot Project

Photograph of the Pilot Project, August 2013

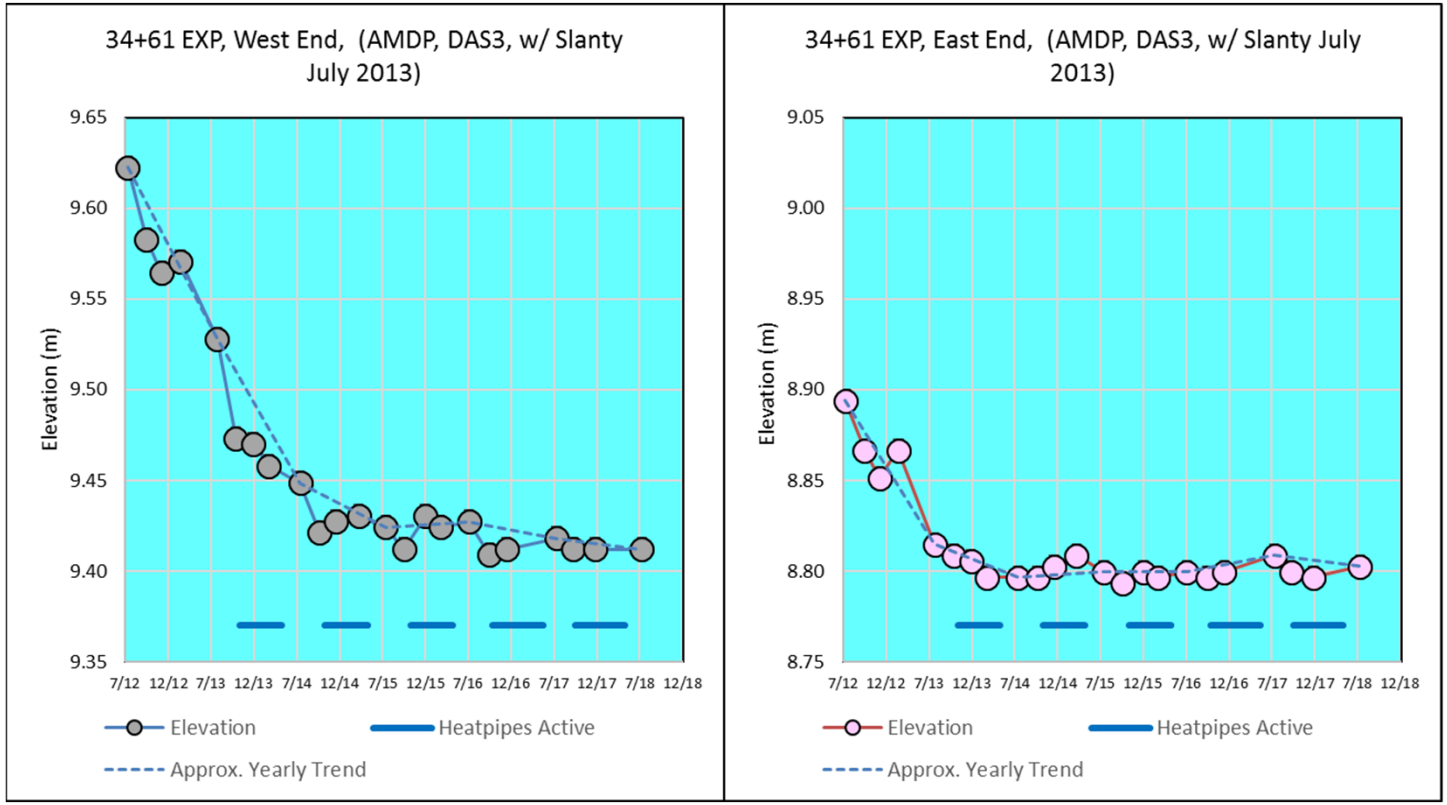
Elevation Trends since Slanty Thermosyphons were Installed

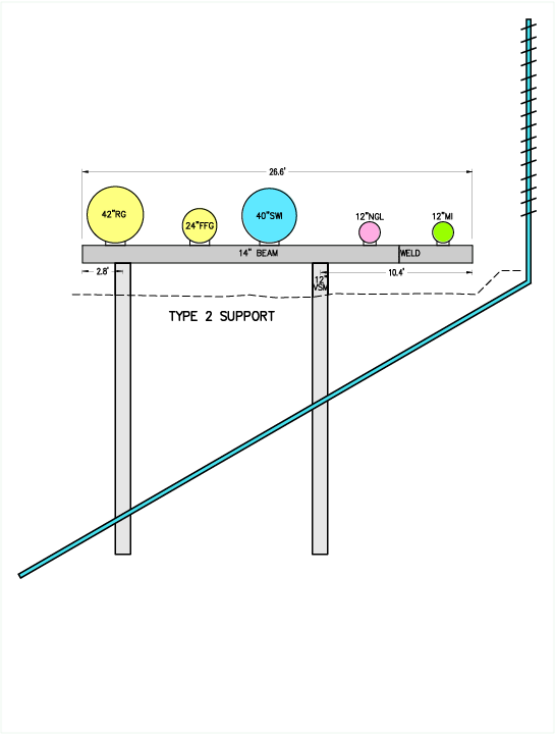
HSM Elevation Trends





HSM Elevation Trends





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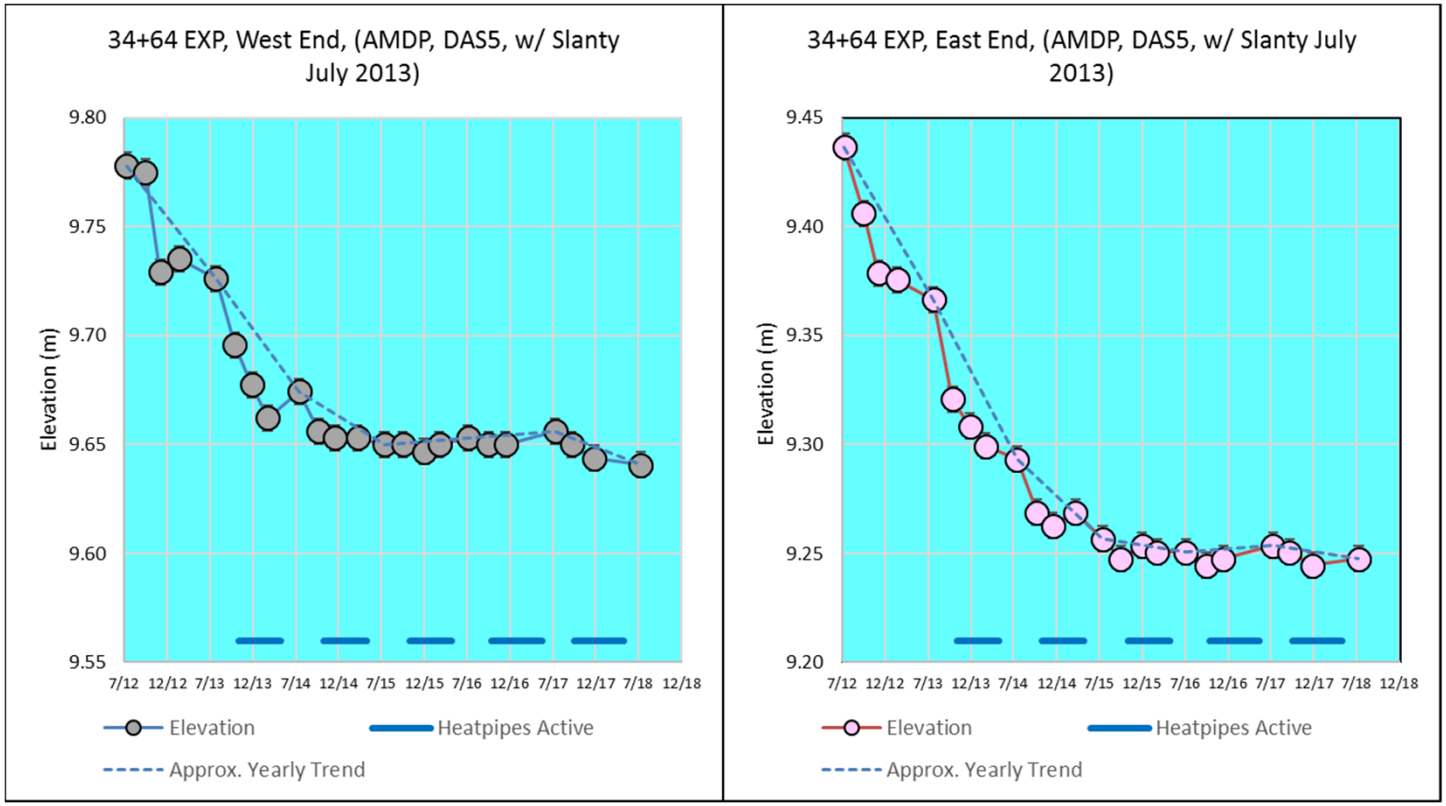
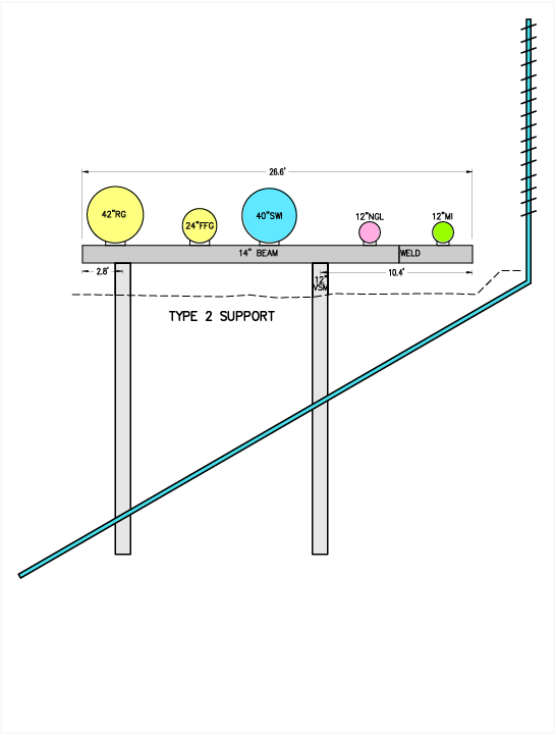
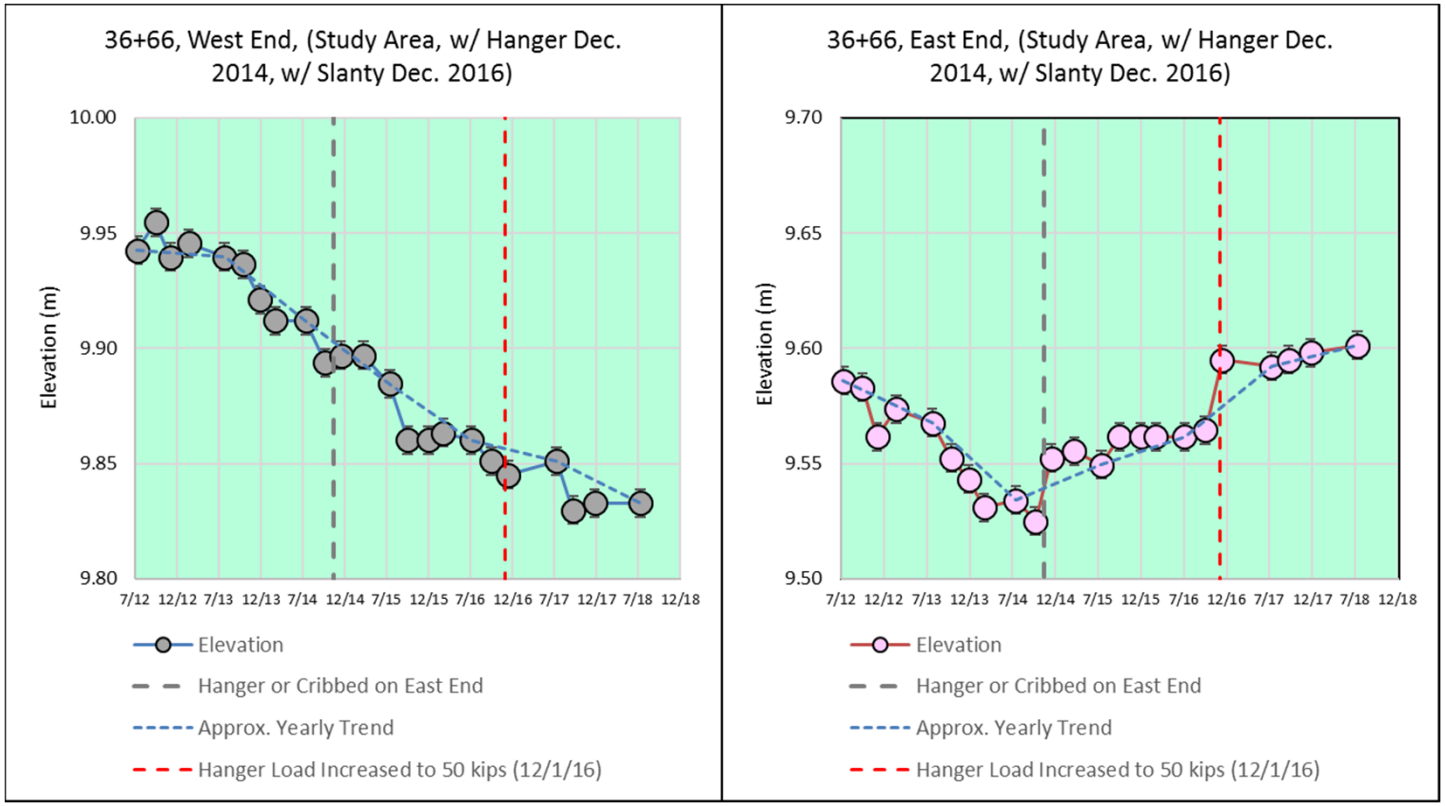


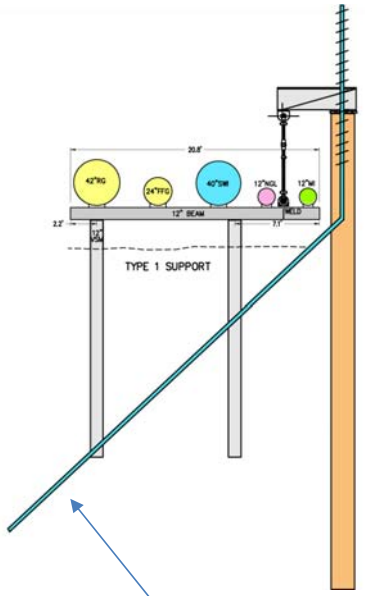


VSM Hangers used to Immediately Arrest Settlement of the Low End of the HSMs

Photograph of the Pilot Project, August 2013

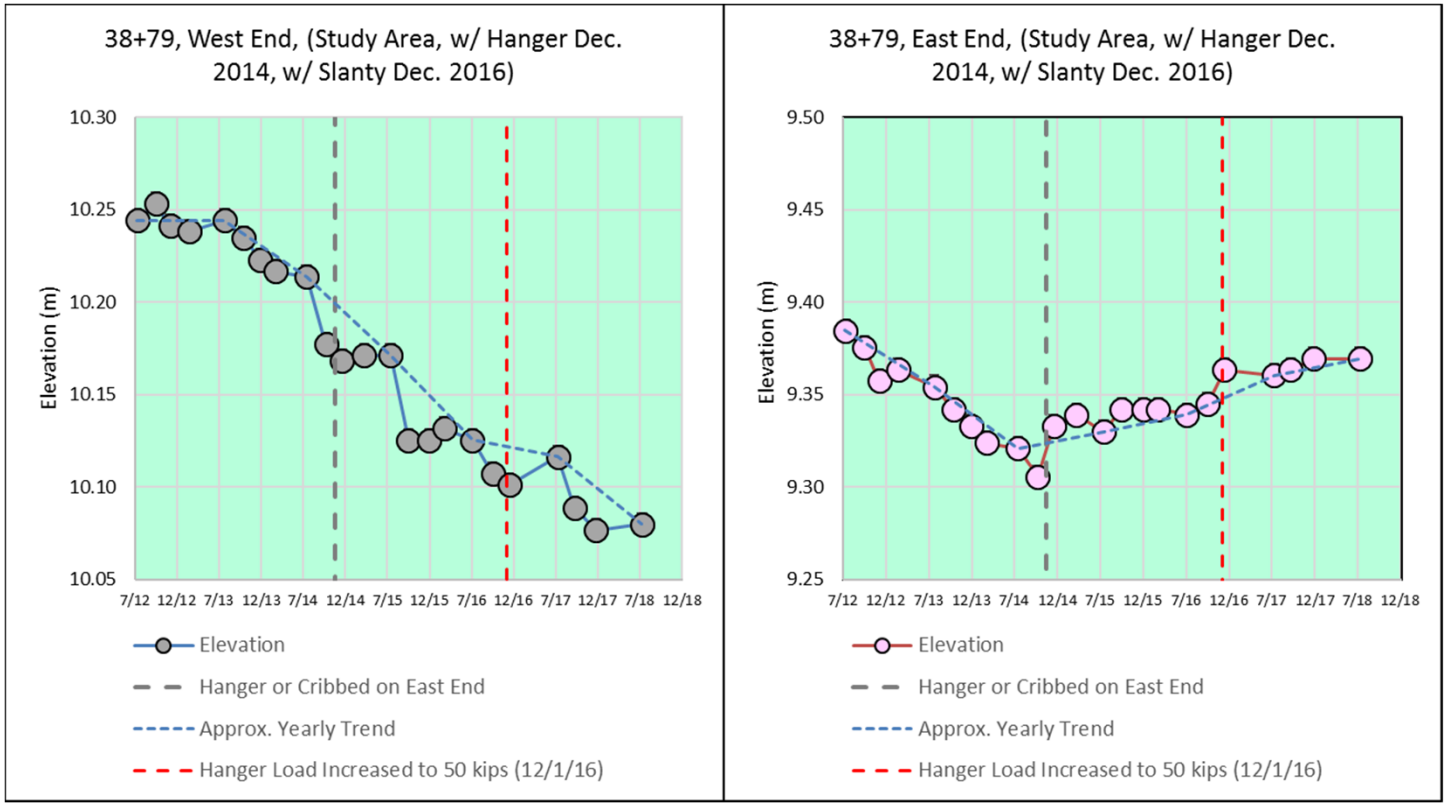
HSM Elevation Trends

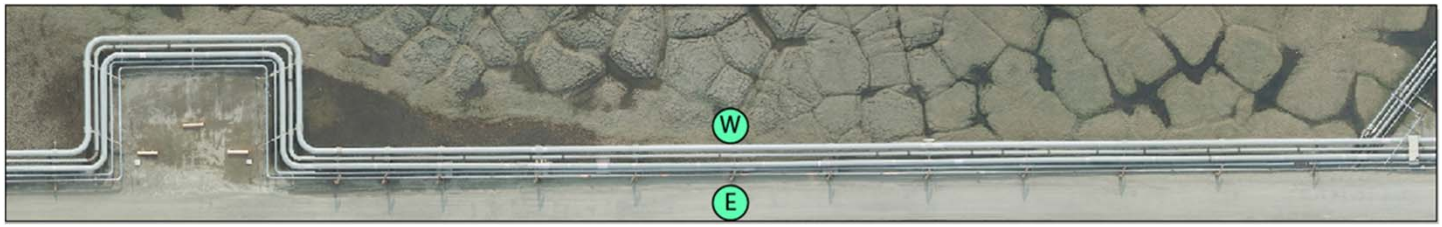


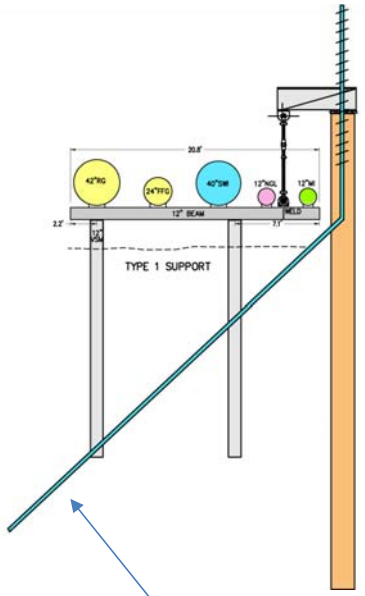


Note: Slanty is presently inactive (i.e., depressurized to 100 psig), allowing the western end of the HSM to continue to settle, resulting in self-leveling of the HSM.

HSM Elevation Trends







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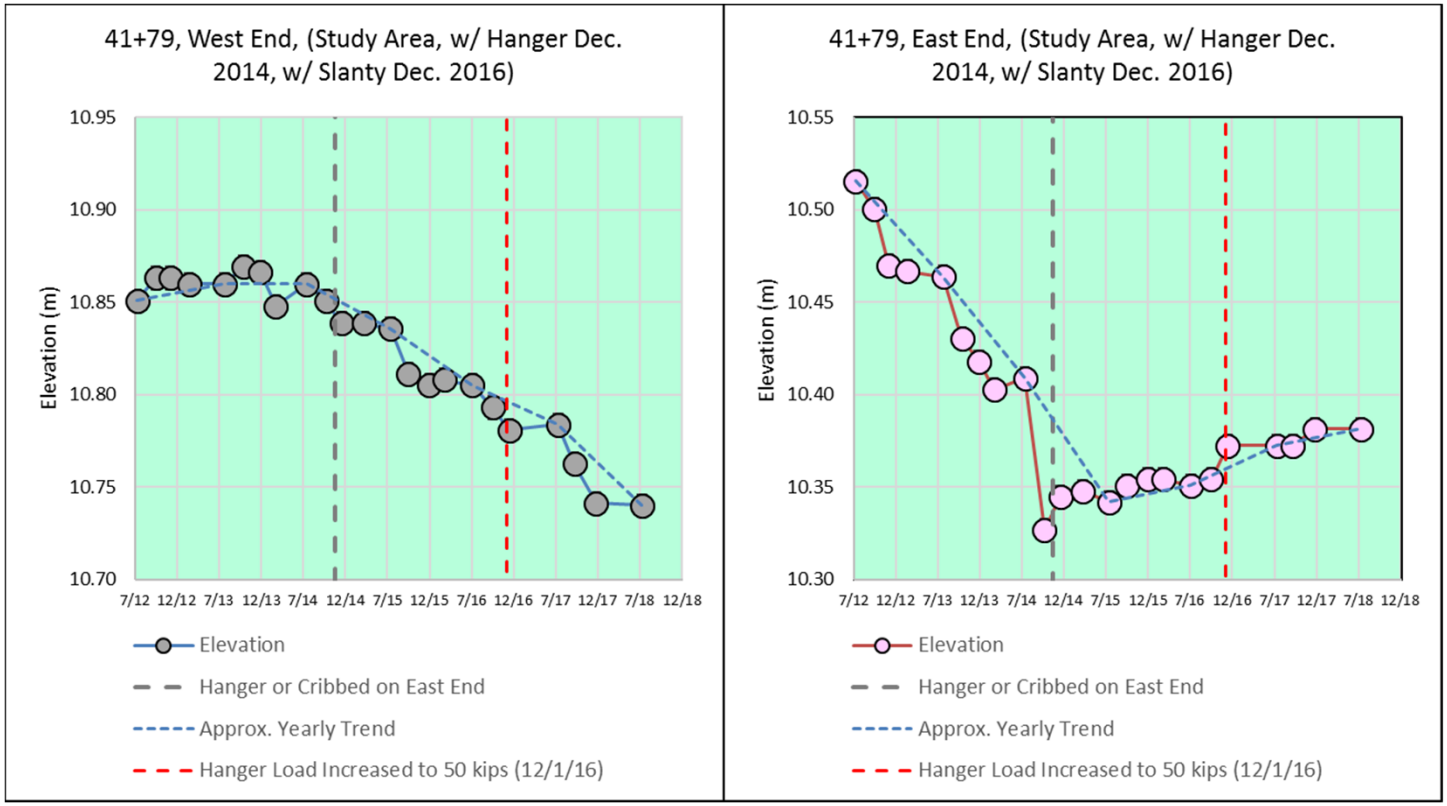
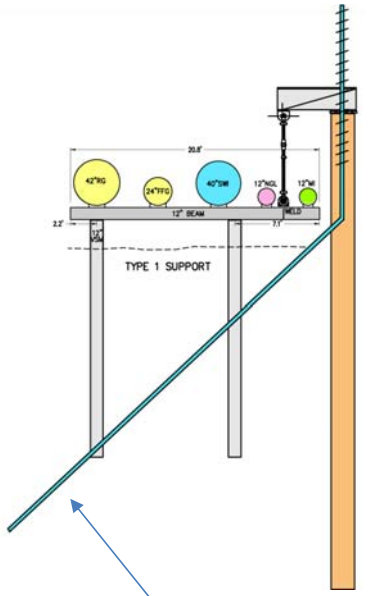
HSM Elevation Trends





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Summary

Summary

1. In the high Arctic average annual ambient temperatures are warming rapidly: in Alaska our current assumption an average increase of 9.5 °C (17 °F / century), which is nominally what is predicted by GCMs. Measured temperatures show that winters are warming about four times faster than summers -- that has an effect upon active layer depth, passive heat extraction, pile design lengths, predicted settlements and frost jacking, mitigation designs, etc. Effectively all aspects of Arctic engineering and operations.

2. Changing climate affects definition of the project design climate: should a project use a design climate predicted for the middle of a 20 year design life? The end of the design life?

3. Some GCM predictions for the Alaskan High Arctic suggest less precipitation, some predict more. Because snow is such a good insulation it has a significant affect upon soil temperatures. Currently using piece-wise linear curve to represent the historical average and assuming it reasonably represents snow depths over a 20 year project design life. We're also testing the affect of applying a factor to increase snow depths each year according to the snow-depth index.

4. The Pilot Project and subsequent slanty thermosyphon installations have demonstrated that retrofitting thermosyphons or chill pipes will significantly reduce settlement rates, even for instances where adfreeze piles have settled 45 cm (18 inches). Applications for piperacks, industrial warehouses and facilities, off-shore man-made gravel islands, etc.

5. Presently, to calculate the frost-jacking force on a pile we multiply the circumference of the pile by the assumed active layer depth then by 276 kPa (40 psi). As the active layer deepens due to warming climate does the design jacking force increase, too, or does it just apply for a longer duration?

6. Put end plates on piles so they can be refrigerated if necessary.

7. Get out into the field.

Thanks!