APPENDIX O

Effect of Climate Warming on Expected Long-Term Thaw Depths on the ASAP Right-of-Way, Alaska Stand-Alone Pipeline Project

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TECHNICAL MEMORANDUM

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RE: Effect of Climate Warming on Expected Long-Term Thaw Depths on the ASAP Right-of-Way, Alaska Stand-Alone Pipeline Project

DATE: February 17, 2017

1 INTRODUCTION

Thermal modeling was undertaken to determine the effect of climate warming on the expected long-term thaw depths in permafrost terrain on the Alaska Stand-Along Pipeline (ASAP) right-of-way (ROW).

The thermal modeling reported herein is an extension of previously reported modeling work regarding the expected long-term thaw depths in both warm and cold permafrost on the ASAP ROW, (Matrix 2016a and Matrix 2016b, respectively). The first series of these modeling analyses (Matrix 2016a) considered warm permafrost conditions with a mean annual ground temperature (MAGT) of 31.1 °F (-0.5 °C) which are representative of discontinuous permafrost terrain in the Fairbanks area. The second series of modeling analyses considered cold permafrost conditions in continuous permafrost terrain with a MAGT of 20.6 °F (-6.3 °C), representative of conditions on the Alaskan North Slope at Prudhoe Bay.

The objective of the thermal modeling including climate warming was to assess the expected effect of assumed climate warming on long-term thaw depths both on and off the ASAP pipeline ROW.

It is understood that information presented in this report will be included in a separate report for review by the US Army Corps of Engineers (USACE).

2 GEOTHERMAL MODEL SETUP

The geothermal model setup, (domain geometry, material properties, climate data, boundary conditions, and model calibration), for the climate warming modeling analyses reported herein were identical to those used in the previous modeling analyses for long-term thaw depth with the exception of the air temperature climate data which was linearly increased over time to simulate assumed constant rates of climate warming. Details regarding the geothermal model setup are provided in Matrix 2016a and Matrix 2016b.

Assumed climate warming rates for the interior of Alaska (in the discontinuous permafrost terrain zone) and the Alaska North Slope (continuous permafrost zone) were obtained from a climate report from the Alaska LNG project (AKLNG 2016). Based on that report, the climate warming rates used in the modeling reported herein were 0.08 °F/yr and 0.12 °F/yr for the discontinuous and continuous permafrost zones, respectively.

3 ROW THAW DEPTH RESULTS

Geothermal modeling results from previous modeling (Matrix 2016a and Matrix2016b) for the discontinuous and continuous permafrost zones are compared in the following sections with identical models run with climate warming applied to air temperatures.

3.1 Discontinuous Permafrost

In the absence of climate warming in discontinuous permafrost, the active layer will be on the order of 5 ft deep, and will vary depending on local conditions such as soil moisture content, terrain slope, and annual weather variations. On the pipeline ROW, ground surface heat energy imbalance caused by construction disturbance, such as tree clearing, will cause long term-progressive thaw of permafrost beneath the ROW.

Under conditions of an assumed climate warming rate, additional long-term thaw depth will occur beneath the ROW, and climate warming can cause progressive long-term permafrost thaw to develop in undisturbed terrain.

Previous geothermal modeling (without climate warming) in discontinuous terrain (Matrix 2016a) considered two cases for thaw beneath the ROW; one case with the surficial organic layer buried beneath the gravel pad on the ROW, and the other with the surficial organic layer removed before placement of the gravel pad. The thermal insulating effect of the organic layer reduces the long-term thaw beneath the gravel pad (Matrix 2016a).

To provide a consistent basis for comparison of cases with climate warming to those without, the same two cases run previously were run identically except with climate warming simulated by linearly increasing the air temperature at a rate of 0.08 F/yr. The climate warming rate was obtained from AKLNG, 2016.

Figure 1 shows a cross-section of the pipeline ROW in discontinuous permafrost terrain and the predicted 30-year thaw depth for conditions of no climate warming where the organic layer below the gravel pad has not been removed. The results shown here were previously reported in Matrix 2016a. Figure 2 shows the effect of a 0.08 F/yr climate warming rate on the 30-year thaw depths. Note that on these figures the dimensions are in meters, not feet. In the case of climate warming, progressive long-term thaw develops in the undisturbed terrain where the 30-year thaw depth reaches about 4.0 m (13 ft) deep as seen on the side boundaries of Figure 2.

Figure 3 shows the same case as in Figure 1 (no climate warming) but with the organic layer removed. In this case the 30-year thaw depth beneath the gravel pad is deeper as a result of the removed organic layer (reported in Matrix 2016a). Figure 4 shows the effects of climate warming for this case, again for a climate warming rate of 0.08 F/yr.

Figure 5 summarizes the results from the four geothermal analyses for discontinuous permafrost. As shown in Figure 5, in undisturbed terrain under the influence of climate warming (light green data series), the active layer deepens slightly each year until after 16 years the active layer is deep enough that it does not completely refreeze over the winter. In this case a permanent talik exists between the maximum seasonal frost depth from the ground surface and the top of the permafrost. After this point in time, progressive long-term thawing occurs in the undisturbed terrain. The thaw depth in undisturbed terrain reaches 14 ft after 30 years.

For cleared terrain that is allowed to revegetate after construction, Figure 5 shows the 30-year thaw depth is about 17.9 ft and 20.2 ft for the cases without and with climate warming (dark blue and light blue data series), respectively. In this case the 30-year thaw depth is increased approximately 13% as a result of climate warming.

Beneath the gravel pad the 30-year thaw depths reach 21.8 ft and 24.2 ft (dark purple and light purple data series), respectively, as shown in Figure 5. In this case climate warming increases the 30-year thaw depth by 11%.

Also noteworthy from Figure 5 is the expected change in depth of the top of permafrost under the assumed climate warming conditions. For the case of no climate warming, the top of the permafrost (which is the active layer depth in this case) is about 5 ft below ground surface. After 30 years of climate warming, long-term progressive thaw in the undisturbed terrain reaches 14 feet deep, which represents a lowering of the top of the permafrost of 9 ft. In cleared/revegetated terrain, thaw after 30 years reaches 20.2 ft, a 15.2 ft lowering of the top of the permafrost, which would be only 6.2 feet lower than the top of the permafrost in undisturbed terrain. Below the gravel pad, the top of the permafrost with climate warming would be 24.2 ft deep, a lowering of 19.2 ft compared to the case of no climate warming, and 10.2 ft below the top of permafrost in undisturbed terrain.

Figure 6 summarizes modeling results for the ROW cross-section in warm permafrost but for the case when the organic soil is not present below the gravel pad. In this case the climate warming increases the 30-year thaw depth beneath the cleared/revegetated terrain from 17.9 ft to 20.2 ft, a 13% increase. Beneath the gravel pad, 30-year thaw depth increases from 25.0 ft to 27.2 ft, a 9% increase caused by the assumed climate warming.

Based these results, it is apparent that a reasonably assumed climate warming rate increases the 30-year thaw depth beneath the disturbed ROW by a small amount (9% to 13%) relative to the thaw depth caused by ground surface disturbance on the ROW itself. Furthermore, the top of permafrost beneath the ROW under conditions of assumed climate warming would be on the order of 6 to 10 ft below the top of permafrost in undisturbed terrain.

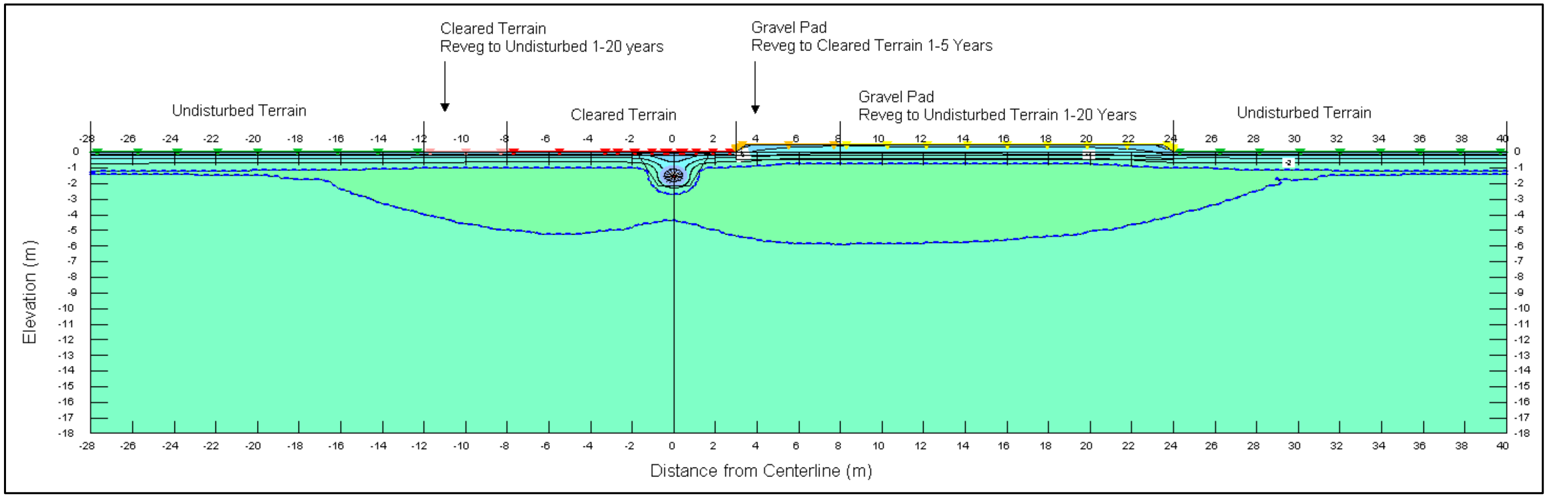

Figure 1 ROW 30-Year Thaw Depth Profile for Case with Buried Organic Layer below Gravel Pad, No Climate Warming

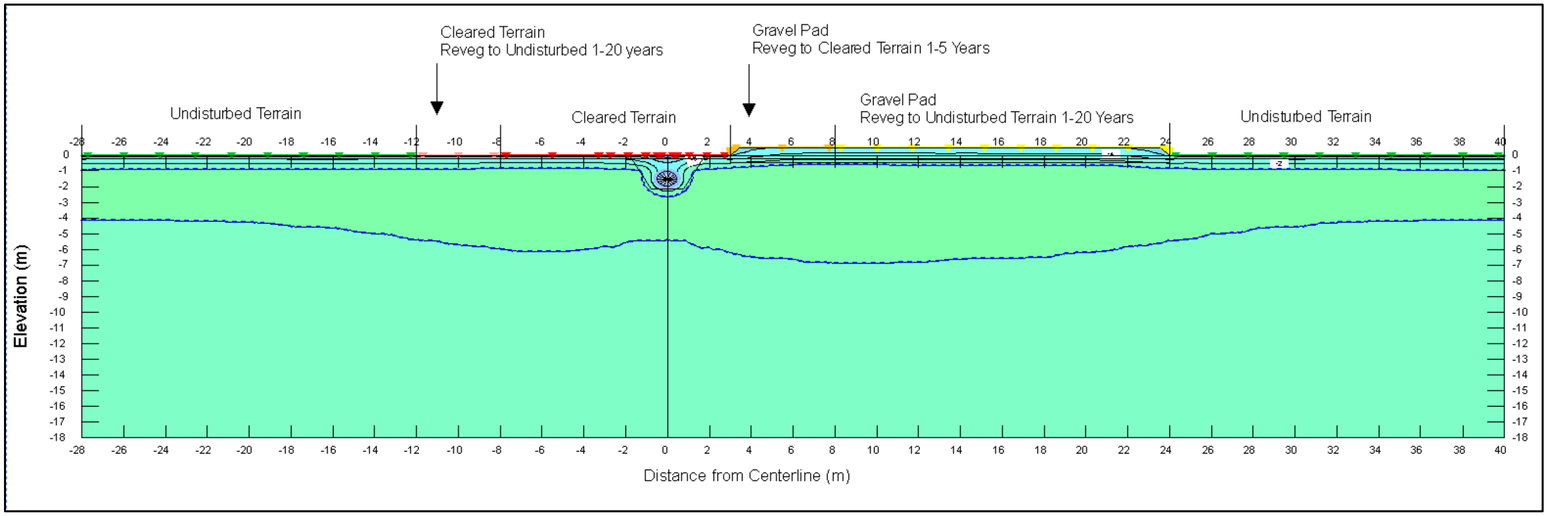

Figure 2 ROW 30-Year Thaw Depth Profile for Case with Buried Organic Layer below Gravel Pad, 0.08 °F/yr Climate Warming

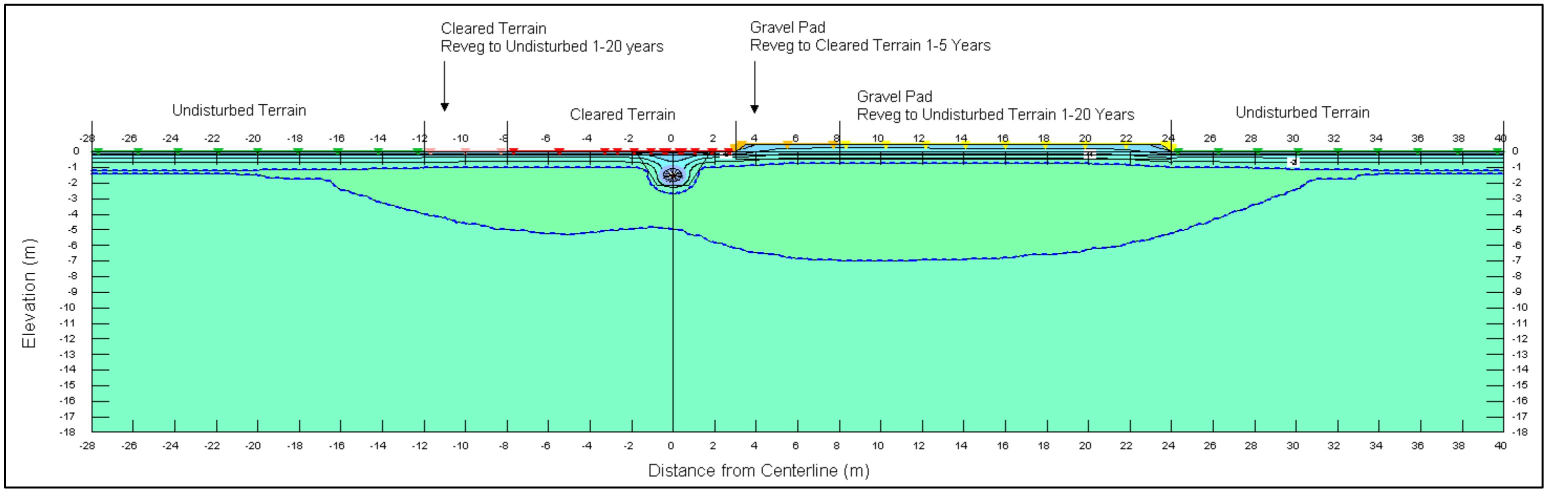

Figure 3 ROW 30-Year Thaw Depth Profile for Case without Buried Organic Layer below Gravel Pad, No Climate Warming

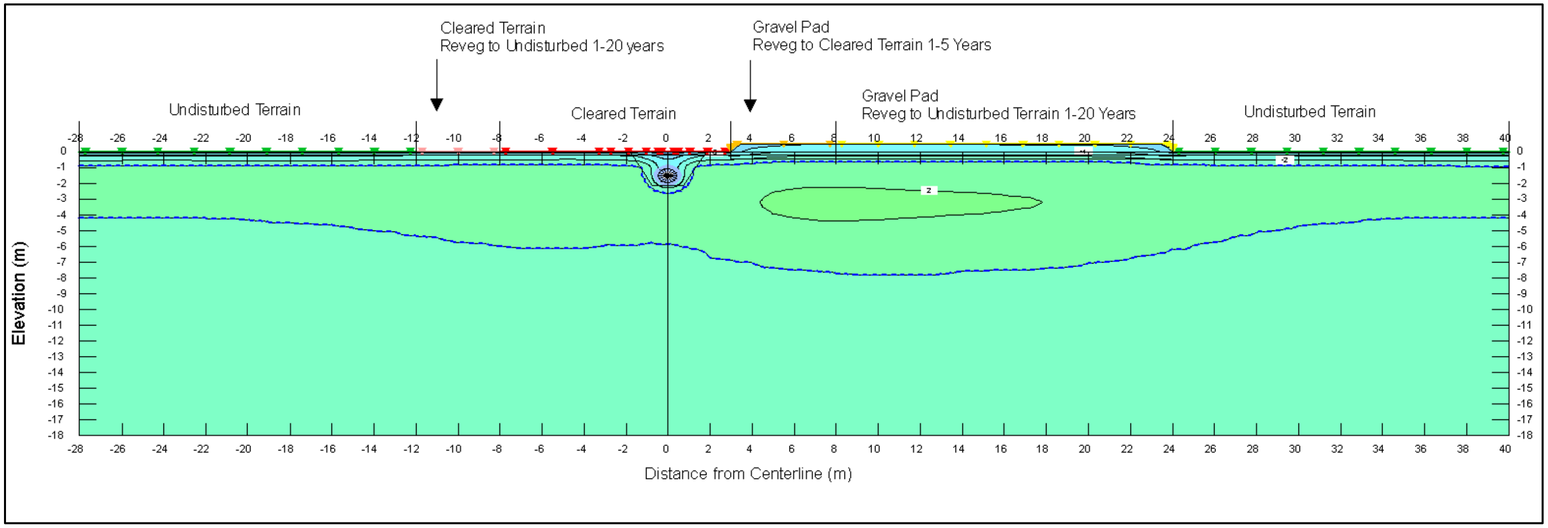

Figure 4 ROW 30-Year Thaw Depth Profile for Case without Buried Organic Layer below Gravel Pad, 0.08 °F/yr Climate Warming

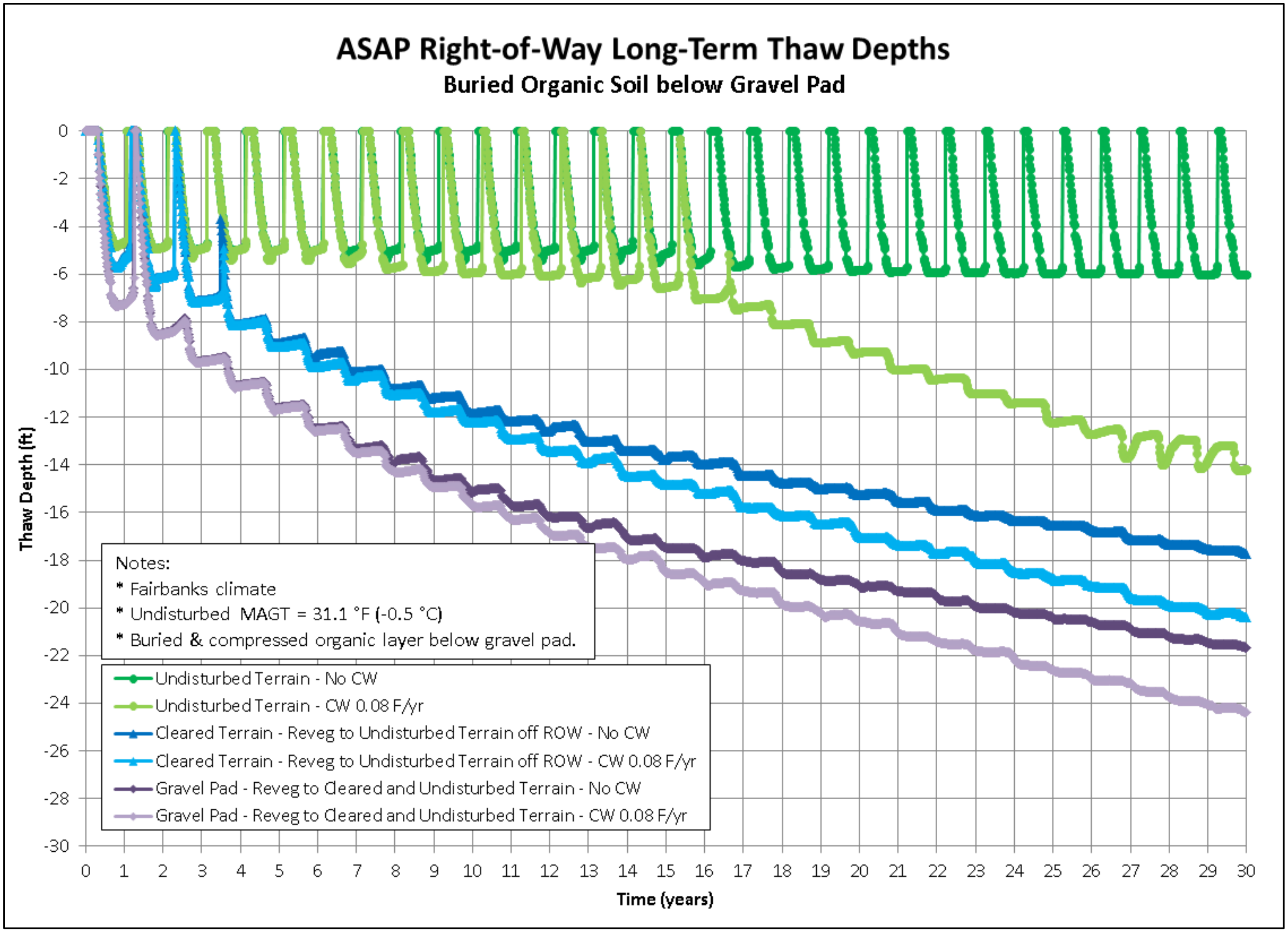

Figure 5 **ROW Thaw Depths for Case with Buried Organic Layer below Gravel Pad**

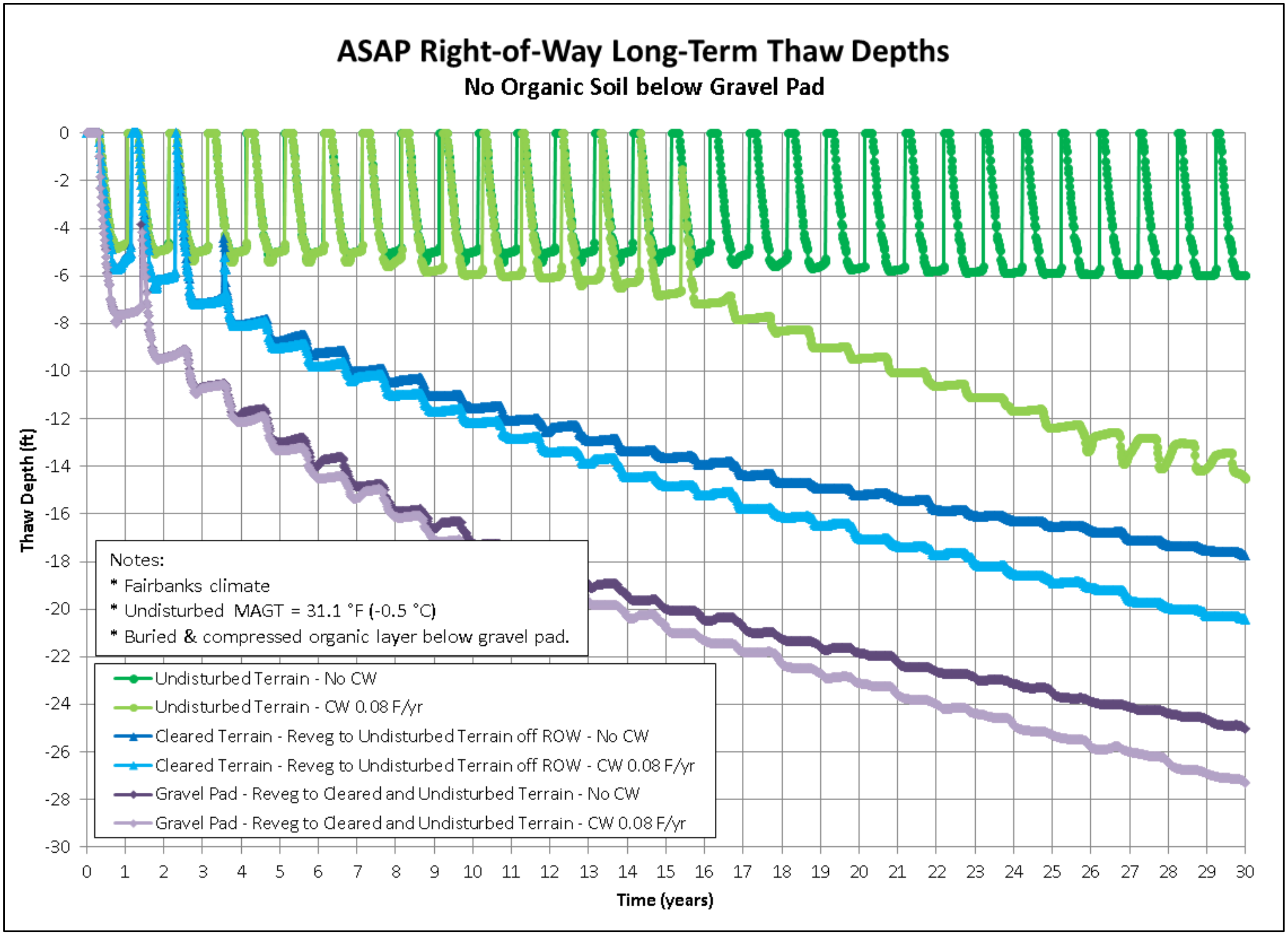

Figure 6 ROW Thaw Depths for Case without Buried Organic Layer below Gravel Pad

3.2 Continuous Permafrost

In the continuous permafrost on the Alaskan North Slope, the cold climate limits the maximum seasonal thaw depth (active layer depth) in undisturbed terrain to about 1.5 ft in the absence of climate warming (Matrix 2016b).

An assumed climate warming rate of 0.12 F/yr (AKLNG 2016) was applied to the previous geothermal modeling performed to assess the effect of a constant buried pipe temperature of 30 °F at milepost 0 (MP0) of the ASAP pipeline at Prudhoe Bay (Matrix 2016b).

Figure 7 shows the maximum annual thaw depth across the ROW near the trench under conditions of no climate warming. This figure was taken from Matrix 2016b and is reproduced here for comparison with the climate warming results. Note that as before, the dimensions shown in figures showing the model are in meters, not feet. Note that the active layer depth is observable along the right side of Figure 7 at 0.46 m (1.5 ft) deep.

Figure 8 shows the same case as Figure 7 with inclusion of the assumed climate warming rate. In this case the active layer deepens only moderately to 0.61 m (2.0 ft). Most importantly it is noted from the modeling that long-term progressive thaw is not expected after 30 years of the assumed climate warming conditions, which is a result of the very cold climate conditions and permafrost temperatures at Prudhoe Bay.

Figure 9 summarizes the two geothermal modeling cases (with and without climate warming) in continuous permafrost at Prudhoe Bay by showing the change in the active layer depth in undisturbed terrain and above the pipe over 30 years. It is noted that the active layer becomes slightly deeper each year, and no long-term progressive thaw is triggered by climate warming.

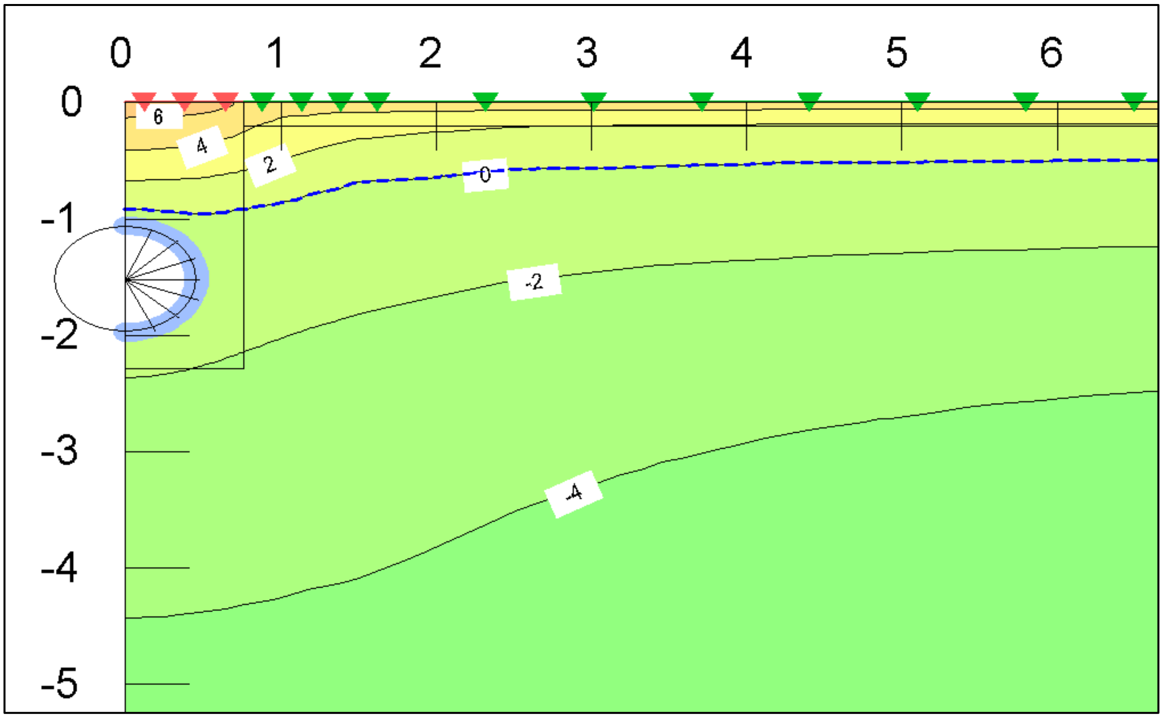

Figure 7 Maximum Annual Thaw Depth near Trench, No Climate Warming

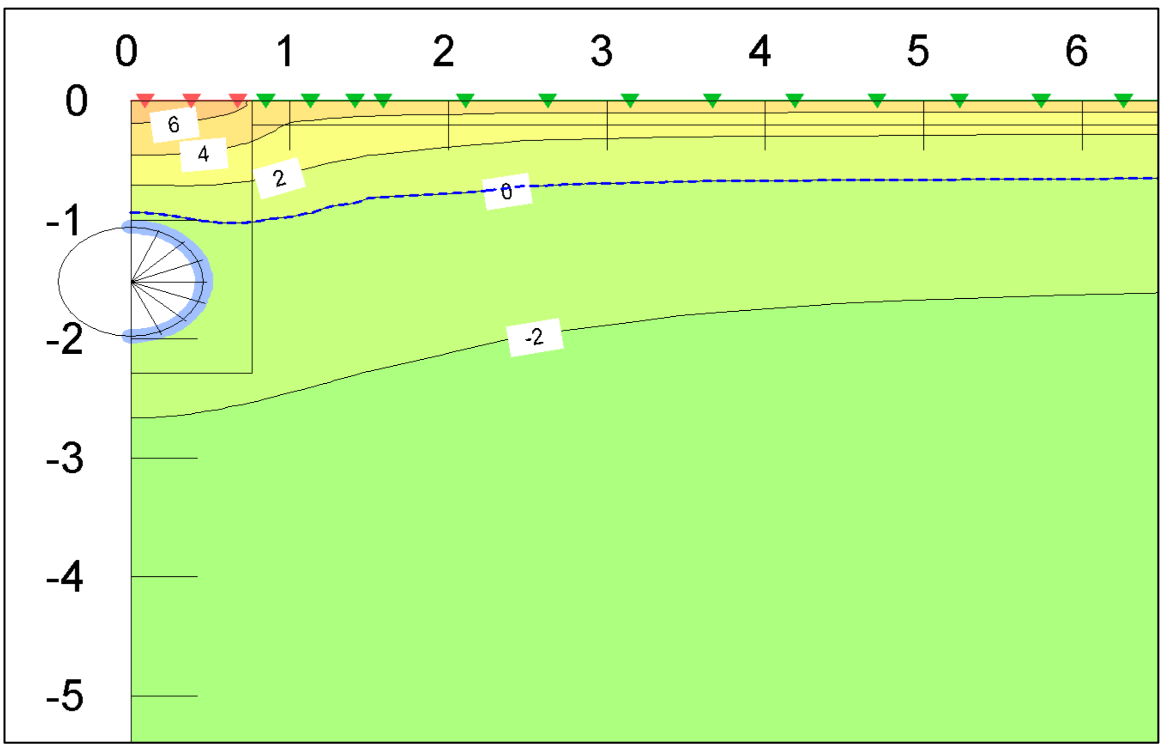

Figure 8 Year 30 Maximum Annual Thaw Depth near Trench, 0.12 F/yr Climate Warming

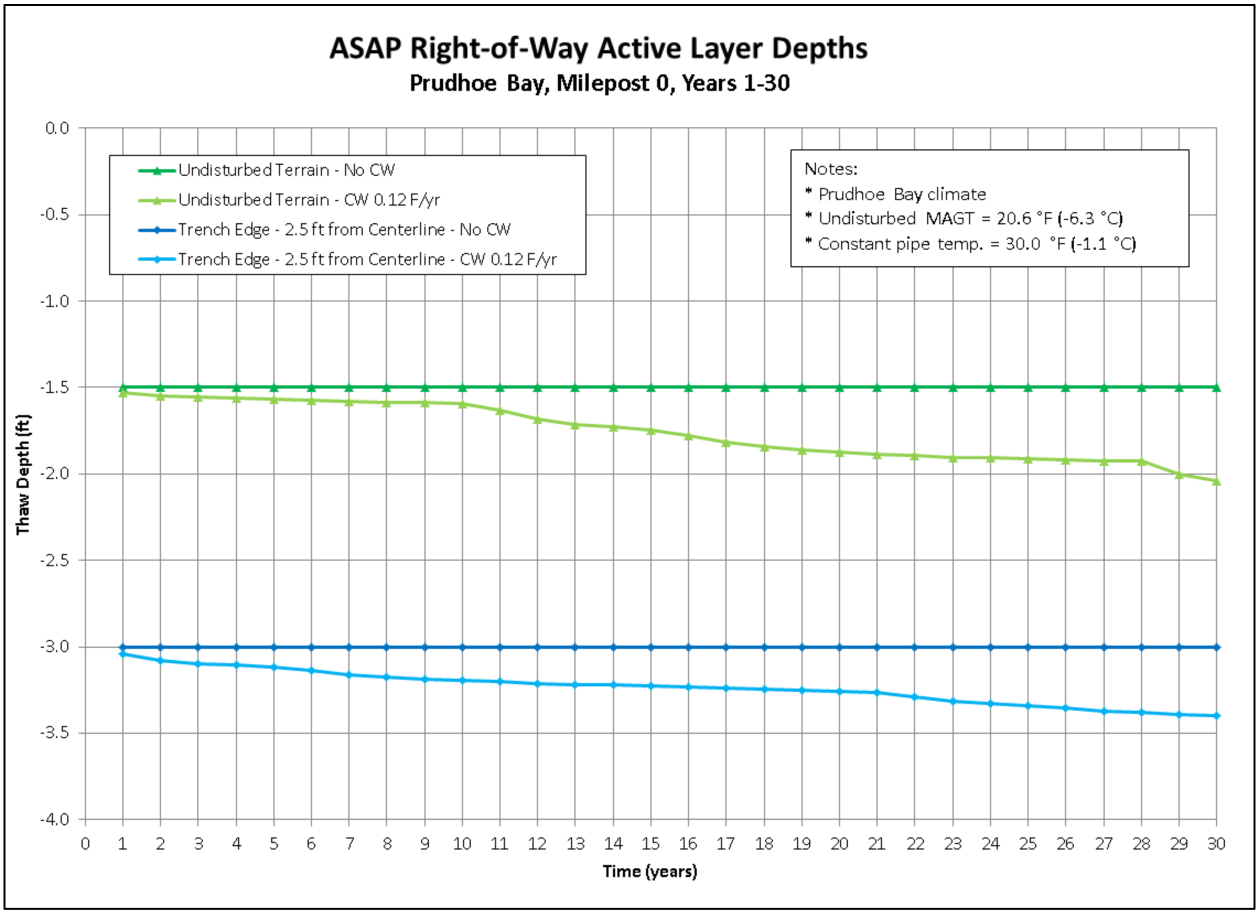

Figure 9 Comparison of ROW Active Layer Depths with and without Climate Warming

4 CONCLUSIONS

The following conclusions were drawn from the thaw depth modeling results presented herein:

- In warm permafrost, an assumed climate warming rate of 0.08 °F/yr can cause the initiation of long-term progressive permafrost thaw. The amount of time required for this to occur will depend on several factors, but for the conditions modeled herein, progressive long-term thaw began after 16 years.

- In warm permafrost, an assumed climate warming rate of 0.08 °F/yr will increase the depth of long-term progressive thaw beneath the disturbed pipeline ROW. However, only a 9% to 13% increase in the 30-year thaw depth is caused by climate warming. Accordingly, it is evident that the effect of ground surface construction disturbance on long-term thaw is significantly more than the effect of climate warming.

- In warm permafrost, the top of the permafrost table below the pipeline ROW after 30 years is expected to be 6 ft to 10 ft below the top of permafrost in the adjacent undisturbed terrain under an assumed climate warming rate of 0.08 °F/yr. This is caused by long-term progressive thaw that occurs in undisturbed terrain as a result of the assumed climate warming.

- In cold permafrost, such as that on the Alaska North Slope, climate warming is not expected to cause long-term progressive thaw. Instead, climate warming deepens the active layer depth in undisturbed terrain, increasing it from about 1.5 ft in the case of no climate warming to 2.0 ft after 30 years under an assumed climate warming rate of 0.12 F/yr.

5 CLOSURE

We trust that this technical memo suits your present requirements. If you have any questions or comments, please call the undersigned at 403-727-0260.

Yours truly,

MATRIX SOLUTIONS INC.

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Senior Geological Engineer

DISCLAIMER

We certify that this memorandum is accurate and complete and accords with the information available at the time the work was undertaken. Information provided by third parties is believed to be accurate but is not guaranteed. We have exercised reasonable skill, care and diligence in assessing the information obtained during the preparation of this memorandum.

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6 REFERENCES

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