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DATE: January 17, 2014

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THROUGH: Rick Leuser, SERAS Deputy Program Manager

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SUBJECT: TECHNICAL MEMORANDUM – BOYD’S CREEK OIL SEEP

GLASGOW, KENTUCKY,

WORK ASSIGNMENT SERAS-234

**INTRODUCTION**

The United States Environmental Protection Agency (EPA)/Environmental Response Team (ERT) requested that Scientific, Engineering, Response and Analytical Services (SERAS) personnel provide technical assistance to EPA Region 4 to locate leaking abandoned oil wells and potential migration pathways for oil and any brine associated with it.

**BACKGROUND**

The Boyd’s Creek oil field is in an agricultural area in Barren County, Kentucky, south of Glasgow (Figure 1). The area was explored for oil reserves starting in the 1860’s. Unrecorded oil production wells had been drilled and improperly abandoned by the 1930’s. In 1986, the U.S. Environmental Protection Agency (EPA) identified oil seeping from a limestone outcrop at the base of a hillside, approximately 150 feet north of the creek. This discharge followed the natural drainage into Boyd’s Creek, which is a tributary of Skaggs Creek and the Barren River Reservoir.

Approximately 15 abandoned oil wells have been plugged in the in the vicinity of this investigation, primarily between 1991 and 1993. However, oil continues to migrate toward Boyd’s Creek, and an onsite treatment facility consisting of an oil-water separator with compressors and pumps to return untreated water to the creek and collect oil in two large holding tanks located at the top of the bluff. A geophysical investigation in 2001 by Lockheed Martin under the REAC contract identified two wells in a farm field upgradient from the treatment facility.

The REAC report from 2001 (Appendix A) summarized the geology in the area. The Boyd’s Creek site is underlain by the Fort Payne Formation of the Lower Mississippian. The Fort Payne is comprised of dolomitic limestone, clastic limestone, and dolomitic siltstone. The Formation is deeply weathered to yellowish brown residual soil containing fragments and nodules of chert, quartz geodes, and silicified segments of crinoid stems. Minor amounts of oil have been produced from limestone beds in the lower part of the Fort Payne Formation. However, most oil and gas had been produced from below the Chattanooga Shale (Upper Devonian) in the Louisville Limestone, Laurel Dolomite, and Brassfield Dolomite, all Silurian.

**OBJECTIVE**

The primary objective of the geophysical survey was to map lateral variations of soil resistivity/conductivity to identify areas of low resistivity (high conductivity) that might be related to oil-associated brine emanating from improperly plugged oil wells. A second objective was to map the subsurface geology to identify natural conduits, such as fractures and dissolution features.

**METHODOLOGY**

The geophysical investigation was conducted June 10 through 12, 2014. A Geonics® EM31 MK2 (EM31), a Geonics® EM34-3 (EM34), which are both frequency-domain electromagnetic instruments, an Advanced Geosciences® Supersting Resistivity Meter, and a Geometrics®  Seismograph were used for this investigation. In addition, a WADI VLF system was used on 2 traverses to possibly identify bedrock fractures or other structure which may be controlling oil plume migration.

The EM31 is a one-person portable system with a 3.66-meter (m) long boom separating the transmitter and receiver coils that set up an electromagnetic (EM) dipole. The transmitter coil transmits an EM field inducing eddy current loops in the ground, which in turn generates a secondary field that is measured by the receiver coil. The EM field measured by the receiver is comprised of both the field generated by the transmitter and the secondary field. The measured field is broken into two components by the instrument based on phase and identified as the inphase and quadrature components.

The inphase component has the same phase as the primary field generated by the transmitter. The inphase response is sensitive to metal and is measured in parts per thousand (ppt) of the primary field intensity. It is used to locate buried metal, such as steel well casings. The quadrature component is 90 degrees out of phase with the primary field and is proportional to the conductivity of the soil. The quadrature component is internally processed in the instrument yielding the terrain conductivity as output, and is measured in millisiemens per meter (mS/m). Terrain conductivity provides information on the near surface geology and is affected by many factors including porosity, moisture content, clay content, and layer thickness.

For this survey, enhanced conductivity is suspected to indicate oil seep location and migration paths. There are two causes of increased conductivity, (1) increased ionic content of pore water within the soils due to the brine associated with the seeping oil, and (2) microbial enhanced conductivity. Microbial-enhanced conductivity has been documented in several studies (for example, Atekwana, et al., 2004[[1]](#footnote-1)), and is thought to be due to enhanced mineral weathering from microbial activity. There is a population increase of oil degrading microorganisms associated with oil in soils, and these enhanced organism populations have been linked to detectable terrain conductivity enhancements in several field-scale and laboratory studies.

The EM34 operates on the same principles as the EM31 but only outputs the terrain conductivity (internally processed from the quadrature component). The inphase component is used to maintain the coil separation. The EM34 is a two-person instrument, due to the larger coil separation, where the EM source and receiver circular coils are 63 centimeters (cm) in diameter. The coils can be separated by 10, 20 or 40 m depending on the necessary depth of investigation. The transmitter and receiver coils, connected by a cable, are manually maneuvered. Separations of 10 and 20m were used to collect vertical dipole data (Geonics literature; elsewhere this coil configuration is referred to as horizontal co-planar [HCP], or horizontal loop electromagnetics [HLEM]) in this investigation; both separations were used on Line 1, and the 20m separation was used on the subsequent 4 lines for maximum depth penetration.

The EM31 and EM34 were specifically designed to map lateral variations of soil conductivity and instrument response is a combination of soil conductivity and anomaly shape. However, data acquisition near highly conductive objects (buried metal, fences, buildings, etc.) will produce measurements related to the objects rather than the soil conductivity. Processed data is presented as contoured plan sections of each component. To streamline data processing, the responses are merged with Global Positioning System (GPS) data concurrently.

A seismic refraction survey was conducted along three parallel transects with a Geometrics seismograph connected to an array of 48 geophones spaced six feet apart. The seismic source (consisting of a sledge hammer and metal strike plate) was applied at various points along the array. The seismic waves detected by the geophones were output to a thermal chart recorder for manual analysis. Along the same transects, resistivity profiles were collected with the Supersting resistivity meter using an electrode separation of two-meters.

Very low frequency electromagnetic (VLF) data were collected along two parallel traverses across the entire field with an ABEM WADI VLF receiver. The VLF method relies on using military radio signal carrier waves from transmitters located around the world as an EM source field. The transmitter selected for the survey, located in North Dakota, is so far away that the EM field across the surveyed area is mostly a plane wave (points of equal phase are planar). This assumption is used to process field data. The method is used for detecting and mapping high-angle fractures and faults, or in the case of our survey, preferential pathways of oil migration associated with these features.

**OBSERVATIONS AND ACTIVITIES**

The geophysical investigation area was in the hay field that was also investigated in 2001 (Figures 2, 4, 5, and 6). The hay field is on a hillside that slopes southeast toward Boyd’s Creek. The primary area of investigation is the northeast portion of the field with a smaller area along the southeast edge.

Data were acquired from the EM31 in three areas; along the southeast edge of the field immediately east of the oil-water separator and tanks, the center of the field on the eastern edge in the area of anomalies identified during the 2001 investigated, and further upgradient to the north. These data positions are shown in Figure 7. Transects were nominally spaced at two m apart with a measurement taken once per second. Data were acquired from the EM34 in the northern area along five transects spaced 12m apart, as shown in Figure 13, with vertical dipole measurements taken at a six-m spacing (20m coil separation). One transect (Line 1) was also run with measurements taken at a 1.5-m spacing (with 10m coil separation).

The seismic refraction and electrical resistivity data were collected along three lines. Line 1 passed though anomalies identified in the 2001 investigation and subsequently excavated. Line 3 is at the highest elevation within the hayfield, and Line 2 is in between (Figure 11). The thermal-strip recordings from the seismograph are included in Appendix B.

Two parallel profiles of VLF data were collected across the entire field, oriented approximately North-South, at a station separation of approximately 5m, as shown in Figure 11. The station used for this survey was NML, which is in La Moure, North Dakota, operating at 25.2 kHz. Electromagnetic data propagation from this station to the survey site was approximately optimal for detecting structures oriented in a northwest-southeast direction.

**RESULTS**

EM31 Conductivity

An overall terrain conductivity map derived from the EM31 data from this survey is shown in Figure 8. Two prominent high-conductivity anomalies are identified in that figure as NEW Anomaly 1 and NEW Anomaly 2. As can be seen in the figure, these two anomalies are associated with the most significant variations in conductivity on the map. Comparing Figure 8 with Figure 6, reproduced from the 2001 geophysical report, there is a correspondence between Anomaly 1 from that report and NEW Anomaly 1 from this more recent work. Also, the area to the east of the electric fence was not entirely surveyed in 2001 due to interference, and data that was collected was contaminated by noise interference. One of the objectives of this new survey was to investigate that area, which was accomplished (Figures 7, 8, 9, and 10). The electric fence was turned off, and therefore the source of the noise was eliminated. As shown in Figures 8 and 10, NEW Anomaly 2 is interpreted from the high apparent conductivity response in that area.

Note the high conductivity trend delineated in Figure 10. Comparing the EM31 response with the Google Earth image shown in Figure 3, the high conductivity trend occurs down the access road leading to the treatment facility. In addition, hay bales are piled to the northwest of this access road to the electric fence bordering the hay field. All these cultural features decrease the confidence of the geophysical interpretation of an oil seep at NEW Anomaly 2. Vehicle parking and possible fertilizer/pesticide/(other) leaking from parked vehicles could explain the enhanced conductivity response.

EM31/EM34/Seismic Refraction

An examination of the figure from the 2001 report showing the EM31 high-conductivity responses and interpreted anomalies, shown in this report as Figure 6, led to the idea that there might be a thickening of soils above the bedrock surface toward the northwest (up the hill). This would explain a lack of anomalies where the soil thickness was thicker than the depth of exploration for the EM31, which is from 2 – 4m (6 – 12ft). For this reason, the EM34 instrument was used on a grid from the old Anomaly 4 toward the northwest up the hill, as shown in Figure 13.

The plot points for terrain conductivity using this instrument is halfway between the transmitter and receiver coils. A map of contoured apparent conductivity for the EM34 data is shown in Figure 14. As can be seen in the figure, no clear trend of high conductivity is apparent. Profile plots of these data are shown in Figure 15. Again, no specific targets can be delineated. If there is a conductivity plume (oil seep), perhaps it is not apparent due to the idea that the data have been too smoothed out by the large coil separation which was employed, which was 20m. A plot of data collected at 10 and 20m coil separations on Line 1 is shown in Figure 29, along with an apparent resistivity pseudosection of multi-electrode resistivity data along that same line (Resistivity Line 2). Also shown in that figure are the positions of Anomalies 3 and 4. Note in that figure that a trough-shaped anomaly in the 10m data corresponds with the vicinity of Anomalies 3 and 4, with the width of the trough equal to the coil separation of 10m. This is the anomaly to be expected from a conductive target of width narrower than the coil separation.[[2]](#footnote-2) Note there is no discernable anomaly in the 20m EM34 data at that position, indicating that that coil separation is in fact smoothing out the conductivity such that the known target is undetectable.

Three seismic refraction lines were positioned as shown in Figures 11, 12, and 13 to investigate the thickness of soils above the bedrock surface. The objective was to address the penetration depth question in the EM31 dataset progressing up the hill toward the northwest. All seismic data are presented in the Appendix. In this report, we concentrate on Interpretation Points A, B, C, D, and E, as shown in Figure 16.

Seismic data from Line 1 at Interpretation Point A is shown in Figure 17 and analyzed in Figure 18. First arrival picks shown in Figure 17 delineate the direct wave and the diffracted (head) wave coming from the bedrock surface.

Seismic Refraction Analysis

A simple 2-layer analysis[[3]](#footnote-3) was used to solve for the depth to consolidated bedrock. Analyzing the seismic ray paths for the simple 2-layer case, the first arrival at short source – geophone offset is the direct arrival, or direct wave (shown for data from this survey in Figure 17). The time for the energy to reach the geophone directly through the upper layer is

(1)

where *x* is the source – receiver distance, and **1 is the seismic velocity of layer 1. This is the equation of a straight line when time is plotted against distance, with a slope = 1/**1. Simply plotting first arrivals from the field data, and calculating the slope, yields the seismic velocity of layer 1.

When the seismic wave arrives at the interface between layers 1 and 2, there is a reflected wave, which returns to the surface, and a refracted wave, which penetrates into layer 2. The reflected wave, traveling through the upper layer and reflecting back from the bedrock surface (lower layer), will arrive at a time

(2)

which is the equation of a hyperbola, where *z*1 is the depth to the top of layer 2. This relation was not used in the interpretation, but the special case of the x-position where the refracted wave no longer penetrates into the underlying layer is called the crossover distance. This distance is where the head wave and the reflected wave have the same travel time back to the surface, and can be solved for using equations (1) and (2). This isn’t necessary for our purposes.

The travel time for the head wave (or refracted wave) travelling along the interface between the upper and lower layer to arrive at the geophone (shown for data from this survey in Figure 17) is

(3)

where **2 is the seismic velocity of layer 2. If time (t) is plotted against distance (x), equation (3) can be seen as a straight line of the form *y = mx + b*, where the slope, *m* = 1/**2, and *y*-intercept, *b* = can be used to solve for the depth to bedrock, *z*1. These relations were used in an Excel spreadsheet, along with picked first arrival times from the field records to determine the upper- and lower-layer seismic velocities, and the depth to bedrock. It should be noted that the bedrock surface is assumed to be parallel to the topographic surface. Also, **2 > **1 is necessary for the refracted wave to arrive back at the surface.

Figure 18 shows the resultant analysis for Line 1, Interpretation Point A. As can be seen in the figure, the upper layer is determined to have a seismic velocity of 5379ft/s, which is typical of water-saturated sediments.[[4]](#footnote-4) The lower, or bedrock, layer has a velocity of 15528ft/s, which is at the low-end of the range expected from limestone. The depth to bedrock is 15ft (4.6m), which is in general agreement with excavation results performed after the 2001 geophysical survey (G. Powell, pers. comm.).

Seismic data interpreted from Line 1, Interpretation Points B and C (Figure 16) is shown in Figure 19. Analyses of data from Points B and C are presented in Figures 20 and 21, respectively. These results show soil velocities of 2727ft/s and 2610ft/s, bedrock velocities of 14815ft/s and 12034ft/s, and bedrock depths of 13ft (4m) and 12.1ft (3.7m) for Points B and C, respectively. Again, the bedrock velocities are at the low end of that expected for limestone, and are within the range of soft limestone.4 These results indicate that the soil thickness appears to be thinning toward the southwest.

Seismic data and interpretation for Line 3 at the top of the hill, Interpretation Points D and E are shown in Figures 22, 23, 24, and 25. Saturated soil velocities were determined to be 3563ft/s and 2865ft/s for Points D and E, respectively. These values are within the standard range of water-saturated soils. Bedrock velocities were calculated to be 20877ft/s and 17575ft/s at Points D and E, respectively. These velocities are within the range for bedrock determined before, but the higher value (20877ft/s) fits in better with limestone values tabulated.4 Bedrock depth was determined to be 36.9ft (11.2m) and 29.6ft (9m) for Points D and E, respectively, again shallowing toward the southwest.

Multi-Electrode Resistivity

Resistivity data were collected in the dipole-dipole electrode configuration along 3 Lines shown in Figures 11-13. A first step in data processing and analysis is to plot apparent resistivity pseudosections[[5]](#footnote-5) for each line of data. This allows a visual inspection of data quality and can provide a format for initial interpretation. Pseudosections for resistivity Lines 1, 2, and 3 are shown in Figures 26, 28, and 30, respectively. Note that the beginning of these lines is at the northeast end of the field near the boundary fence and overhead power line. It should also be noted that “bulls-eye” type contours do not reflect geological/hydrogeological information, but rather are indicative of bad data.

The apparent resistivity pseudosection for Line 1 (Figure 26) displays the typical inverted “V” “pants leg” anomaly[[6]](#footnote-6) indicating conductive surficial regions shown in the figure as A and B. Also plotted in Figure 26 are the positions of Anomalies 5 and 6 from the 2001 geophysical report. As can be seen in the figure, these anomalies are very well detected in the resistivity dataset. Figure 27 shows the upper part of the 2D inverse resistivity model computed for data from Line 1. Targets A and B can be seen in the subsurface resistivity model, along with many other high and low-resistivity regions. Most of these regions are not real, being artifacts from the numerical modeling procedure known as Gibbs oscillations.[[7]](#footnote-7) More effort could have been used to reduce this effect using various parameters of the inverse modeling software used.[[8]](#footnote-8) Since low-resistivity anomalies can quite easily be picked from apparent resistivity pseudosections, and that 2D models seem to have numerical artifacts, both will be addressed in this report.

The co-location of Anomaly 5 with a power pole at the intersection of the two overhead power lines could be suspect, possibly being due to electrical interference noise from a ground wire. However, note in Figure 6 from the 2001 report, the anomaly was picked from a downhill (down gradient) extension of high conductivity interpreted to be a salinity plume. In summary, low-resistivity anomalies are detected from this survey at the 2001 Anomaly 5 and 6 positions, which can be interpreted to indicate either residual effects from oil seepage, or on-going seepage.

The apparent resistivity pseudosection for Line 2 is shown in Figure 28. Note in that figure that an easily distinguished low-resistivity anomaly, Target D shown, coincides exactly with the positions of Anomalies 3 and 4 as selected from the 2001 report. We definitely detect something there which may be an oil/brine plume currently, or the residual effect on the soils from a previous one. Also note in Figure 28 another anomaly was interpreted, Target C. However, this target is of very low magnitude, as can be seen in the figure, and may not represent the type of target we are looking for.

Figure 29 shows the apparent resistivity pseudosection for Line 2 lined-up with the EM34 data from EM34 Line 1. This figure was discussed previously with regard to the seemingly less-than-adequate effectiveness of the EM34 instrument for detecting oil/brine plumes.

The apparent resistivity pseudosection for Line 3 is shown in Figure 30. Anomalous low-resistivity zones have been interpreted and are shown in the figure as Targets E and F. Target E is of very low magnitude, and we interpret it as not representative of the type of target we are looking for. However, Target F is quite prominent, occurring at the farthest end of the line, which is toward the southwest. Figure 6 of this report reproduces a figure from the 2001 report in which Anomaly 1 was interpreted at the same location as Target F in Figure 30. As discussed previously, NEW Anomaly 1 was interpreted just down the hill (to the southeast) of where Target F from Figure 30 is located. It is possible that NEW Anomaly 1 corresponds to an oil/brine seep in that area, and we are also detecting that on resistivity Line 3.

Figure 31 shows the 2D models of subsurface resistivity which were derived for Lines 1, 2, and 3. As discussed previously, there are many numerical artifacts in these models, but some features can be interpreted. On Line 1, there is a very large low-resistivity region (blue in the figure) at about 30m along the traverse at depth. Referring back to Figure 26, this part of the model corresponds to the “pants leg” anomaly in the apparent resistivity pseudosection associated with Anomaly 5 from the 2001 report. The Anomaly 6 target interpreted from the pseudosection does not show up on the 2D model in Figure 31, raising some suspicion as to the validity of that model.

The Line 2 2D model shows some near-surface non-continuous high-resistivity regions (yellow-orange). These likely divide the more conductive strata above that with this more resistive strata, likely delineating the groundwater table, with the unsaturated zone over the saturated zone. The unsaturated zone may be more conductive due to leaching and clay formation in these upper soils in the same way that soil A and B horizons form. The same resistivity structure occurs in the Line 3 2D model, except that the high-resistivity regions are more continuous laterally in the Line 3 model. The upper red-dashed line in the 2D model is interpreted as the water table, which also may be separating leached soils above from re-deposited material below (such as a caliche layer in an arid environment). The seismic refraction bedrock depths are from 9-11m, which correspond to the bottom of the high-resistivity trend on the Line 3 2D model (the lower red-dashed line). Based on the modeled seismic velocities, the bedrock depth here is 9-11m.

VLF (Bedrock Structural Feature)

Figures 32 and 33 show the real (inphase) component of the VLF signal along each of Lines 1 and 2 as indexed in Figure 11. Also shown is the filtered response using the filter of Karous and Hjelt (1983).[[9]](#footnote-9) Figures 32 and 33 also show interpreted anomalies labeled as Fracture 1, Fracture 1a, Fracture 2, Fracture 3, and Fracture 4. As can be seen in Figure 32, Fracture 1a is interpreted as a small shoulder on the larger Fracture 1 in the filtered response.

As can be seen in Figure 34, interpreted Fractures 1 and 3 correspond to positions of the VLF lines where they passed underneath an overhead power line. Likewise, interpreted Fractures 2 and 4 correspond to the fence line to the north of the field (which also has an associated overhead power line). Fracture 1a does not correspond to any known cultural interference. Based on an inferred geological structure orientation NW-SE, one would expect to see that same structure on VLF Line 2. A closer examination of the data along Line 2 (Figure 33) indicates that the Fracture 3 filtered anomaly is asymmetric, with a subtle small shoulder to the north of that anomaly. The interpreted structure in Figure 34 is based upon a correlation of interpreted Fracture 1a with the northern asymmetry in Fracture 3.

**SUMMARY INCLUDING SOME FURTHER INTERPRETATION**

A geophysical investigation was conducted to locate abandoned oil wells and identify geological features that may provide conduits for oil to flow towards Boyd’s Creek. Four anomalies identified in a 2001 report on geophysical investigations of this site continue to have elevated electrical conductivity from our recent geophysical survey. These are Anomalies #1, #3-4 (these are too close together to differentiate), #5, and #6, as shown in Figure 6, which is a reproduction of a figure from the 2001 report. Excavation subsequent to the 2001 geophysical survey discovered at least one abandoned oil well coincident with one of the anomalies (#5 or #6, not clear from hearsay). The new data enhanced conductivity can be due to continued seepage of oil/brine from yet unplugged wells, or residual signature remaining in contaminated soil. A close examination of the Google Earth image (taken March 25, 2014) in Figure 3 shows color changes in the vegetation in patches to the southeast of Anomalies 1, 3, 5 and 6, which can be interpreted as resulting from downhill (down gradient) migration of fluids from these anomalies. Alternatively, some of the color change may have resulted from soil disturbance from the excavation(s) which took place following the 2001 survey.

In this geophysical survey, we discuss two anomalies: NEW Anomaly 1, and NEW Anomaly 2, as shown in Figure 8. NEW Anomaly 1 is a re-introduction of Anomaly #1 from the 2001 report, further delineated by data from this current geophysical survey. NEW Anomaly 2, near the treatment facility, may be unrelated or related to a high conductivity trend shown in Figure 10, following the access road to the treatment building. Both NEW Anomaly 1 and NEW Anomaly 2 coincide with access roads and places where vehicles are parked comparing Figure 8 with the Google Earth image, Figure 3. Spills of pesticide/fertilizer/other from parked trucks can theoretically cause enhanced conductivity as detected in this survey.

A fracture that is potentially a conduit for oil migration is interpreted to be near the southern edge of the investigation area. This fracture may intersect brine/oil at NEWAnomaly 1 and serve as a conduit for further migration. Seismic data at that location indicates bedrock depth at approximately 9m which is too deep to produce a terrain conductivity anomaly as measured by the EM31. The fact that enhanced conductivity was detected indicates that the cause of the anomaly is shallower, within the overlying soils. The location of the fracture (structure) and Anomaly 1 are summarized in Figure 34. The structure could be further delineated as a recommendation, but none of the other geophysical data collected show associated conductivity enhancements that could be due to oil migration along that path. That is unless the high conductivity from Anomaly #3-#4 and Anomaly #6 are actually along that structure (comparing Figures 34 and 6). A re-examination of delineated target D in Figure 28 shows that this enhanced conductivity is wider than a single point, and perhaps the structure (fracture) is being detected there.

**RECOMMENDATIONS**

Excavation at the inferred locations of wells at the anomalies not previously excavated (NEW Anomaly 1, Anomalies #3, #5, and #6) will confirm whether wells are the cause of the anomalies. Terrain conductivity collected on fine grids covering the two NEW Anomalies may provide a better target for excavation, particularly at Anomaly 1 where a portion of the Anomaly is most likely under the large hay bales.

The structure interpreted from the VLF data should probably be further delineated. Excavations a bit southwest of Anomalies #3-#4 could reveal whether or not it is there, and if it is containing oil/brine.

FIGURES

Boyd’s Creek Oil Seep

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Appendix A

Boyd’s Creek Oil Seep

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Appendix B

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Appendix C

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