Electric and Magnetic Field (EMF) Modeling Analysis for the National Grid 69-kV E5/F6 Line Rebuild Millbury No. 305 to Deerfield No. 4 Project

Prepared for

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Abbreviations

A	Ampere
AC	Alternating Current
ACSS	Aluminum Conductor Steel Supported
BPA	Bonneville Power Administration
DC	Direct Current
EF	Electric Field
EMF	Electric and Magnetic Field
G	Gauss
Hz	Hertz
ICNIRP	International Commission on Non-Ionizing Radiation Protection
kcmil	Kilo Circular Mil
kV	Kilovolt
kV/m	Kilovolts Per Meter
MA EFSB	Massachusetts Energy Facilities Siting Board
MF	Magnetic Field
mG	Milligauss
MRI	Magnetic Resonance Imaging
MVA	Megavolt-Ampere
MW	Megawatt
OPGW	Optical Ground Wire
RMS	Root Mean Square
ROW	Right-of-Way
T	Tesla
US	United States
WHO	World Health Organization
µT	Microtesla

1 Introduction and Summary

National Grid requested that Gradient perform an independent assessment of the electric and magnetic field (EMF) levels associated with the 69-kilovolt (kV) E5/F6 Line Rebuild Millbury No. 305 to Deerfield No. 4 Project. This Project involves reconductoring the existing 69-kV overhead E5 and F6 lines, including taps, and replacing the existing steel lattice tower structures between the Millbury No. 305 Substation in Millbury, Massachusetts, and the Deerfield No. 4 Substation in Deerfield, Massachusetts. Double circuit monopole davit arm structures will primarily be used as the new support structures. The existing shield wires will be replaced with optical ground wire (OPGW) throughout the entire line. The total Project route, including taps, is approximately 67 miles in length.

Gradient is a Boston-based environmental and risk sciences consulting firm, nationally renowned for its specialties in toxicology, epidemiology, risk assessment, forensic chemistry, EMF assessment, contaminant fate and transport modeling, risk-based remedial alternatives assessment, and the application of database management and Geographic Information Systems (GIS) tools for addressing environmental contamination. For over 25 years, Gradient scientists have prepared EMF assessments in support of permitting for proposed overhead and underground transmission line projects, electrical substation projects, electrical generation facility projects, and renewable energy projects (*e.g.*, offshore wind, solar, battery storage). Gradient has provided EMF consulting services to regulatory agencies, electric utility companies, municipal utilities, and renewable energy companies. Gradient scientists have experience testifying at regulatory hearings and presenting on EMF at meetings with regulators, stakeholders, and the general public. Gradient scientists have published book chapters and journal articles on EMF-related topics, including the 2019 book chapter "Low-Frequency Magnetic Fields: Potential Environmental Health Impacts" in the 2nd edition of the *Encyclopedia of Environmental Health* (Volume 3).

For this EMF assessment, EMF modeling was conducted at a height of 1 meter (3.28 feet) above the ground surface for 8 representative right-of-way (ROW) cross sections. We performed EMF modeling for the existing overhead circuit configuration in the ROW cross sections (referred to in the report as "pre-Project" case) and for two post-Project cases: (1) for the overhead circuit configuration after the E5 and F6 lines have been replaced and current loadings representative of the in-service year operating at 69-kV, and (2) for a second post-Project case with current loadings for the E5 and F6 lines representative of the in-service year operating at 115-kV. This second post-Project case was included because the E5 and F6 circuits are being rebuilt using 115-kV framing so as to provide the capability to increase the line voltage at a later date. For all but two of the representative cross sections, there are no other circuits within the Project ROW. For representative cross section 1 that occurs for the ROW segment entering the Deerfield No. 4 Substation, the 69-kV D4 line is present in the ROW along with the E5 and F6 lines, and this line was included in the EMF modeling for this cross section to determine the cumulative EMF levels at the ROW edges. For representative cross section 5 that occurs for a ROW segment between the Harrington Switchyard Substation and the Meadow Street Substation, the 69-kV T20 line[1] is present in the ROW along with the E5 and F6 lines, and it was included in the EMF modeling for this cross section to determine the cumulative EMF levels at the ROW edges. EMF modeling was conservatively conducted for the location of lowest conductor sag[2] for each cross section, and for both annual average and system peak load levels.

[1] The T20 circuit is typically open and was thus assumed to carry no current for both the annual average and system peak loading cases included in this EMF modeling assessment. Although it is currently a 69-kV circuit, it was assumed to be energized at 115 kV per National Grid's request.

[2] As provided by National Grid, a minimum conductor height above ground of 19.4 feet was used for pre-Project modeling of all representative cross sections and a minimum conductor height above ground of 23 feet was used for post-Project modeling of all

As discussed in more detail in Section 2 of this report, a number of national and international organizations have developed EMF exposure guidelines or limits designed to protect humans against any adverse health effects. The limit values should not be viewed as demarcation lines between "safe" and "dangerous" levels of EMFs, but rather, levels that assure safety with adequate margins to allow for uncertainties in the science. For magnetic fields (MFs), these health-based guidelines range from about 1,000 to 10,000 milligauss (mG). The International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline for allowable public exposure to 60-hertz (Hz) MFs is 2,000 mG, while the ICNIRP guideline for allowable public exposure to 60-Hz electric fields (EFs) is 4.2 kilovolts per meter (kV/m) (ICNIRP, 2010).

As discussed in Section 3 of this report, for each representative cross section, all modeled EMF levels, both within the ROW and at the ROW edges, were well below the ICNIRP health-based guidelines. Tables 1.1 and 1.2 summarize the modeled pre-Project and post-Project MF results at the ROW edges for annual average and system peak load levels, respectively, for the 8 representative cross sections. For annual average load levels, the Project will generally result in small increases to edge-of-ROW MF levels as compared to the pre-Project case that are frequently less than 1 mG and that reach a maximum of 10.06 mG. A maximum edge-of-ROW MF level of 12.18 mG was observed for the right (northeast) ROW edge for representative cross section 6 for the post-Project modeling case assuming 115-kV operation of the E5 and F6 lines, and this MF level remains only about 0.6% of the ICNIRP health-based guideline of 2,000 mG. Moreover, MF levels continue to drop off rapidly with increasing distance from the ROW edge, reaching a value of 3.26 mG 50 feet from the ROW edge.

Slightly higher post-Project edge-of ROW MF increases were observed for system peak load levels due to the higher currents typical of this line loading scenario as compared to the modeling for annual average load levels, but edge-of-ROW increases remained small in magnitude and were frequently less than 1-2 mG and <1 mG for the left and right ROW edges, respectively. The highest post-Project edge-of-ROW MF level of 19.08 mG, which was observed for the right (northeast) ROW edge for representative cross section 6 for the modeling case assuming 115-kV operation of the E5 and F6 lines, remained less than 1% of the ICNIRP health-based guideline of 2,000 mG.

Table 1.3 shows that pre-Project and post-Project modeled EF values at the ROW edges are well below the ICNIRP health-based guideline of 4.2 kV/m for all modeled cases. Because EFs are not dependent on conductor loading (*i.e.*, current), only negligible differences in EFs were obtained for annual average and system peak load levels for the post-Project 69-kV operation of the two circuits due to small differences in voltages of the E5 and F6 circuits that were provided by National Grid for the two line loading scenarios. Because EFs are dependent on voltage, higher EFs were obtained for the post-Project 115-kV operation of the two circuits as compared to the post-Project 69-kV operation. For the 69-kV modeling cases, our modeling analysis indicates that the Project will frequently result in negligible changes to EFs at the ROW edges that are less than 0.02 kV/m and a maximum edge-of-ROW increase of 0.50 kV/m. For the 115-kV modeling cases, there are some slightly larger changes in EFs at the ROW edges (ranging from -0.05 kV/m up to 0.86 kV/m), although edge-of-ROW EF levels remain low overall (all ≤0.9 kV/m).

representative cross sections based on state code clearance requirements associated with 115-kV design. Modeling at the location of lowest conductor sag is conservative because this is the location with the least clearance between the lines and the ground surface and is thus representative of the highest EMF levels that will be found beneath the lines.

Table 1.1 Summary of Modeled Pre-Project and Post-Project Edge-of-ROW Magnetic Fields for the Representative ROW Cross Sections for Annual Average Load Levels

Representative Cross Section	ROW Segment	Magnetic Field (mG) Left Edge-of-ROW			Magnetic Field (mG) Right Edge-of-ROW		
		Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)	Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	1.07	2.11	2.53	2.86	3.15	4.53
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	1.13	1.92	2.24	1.09	1.28	1.69
	From Deerfield 3 Tap to Deerfield 2	0.83	1.58	2.04	1.65	1.84	2.02
	From Deerfield 2 to Shutesbury	1.33	2.23	2.43	1.29	1.53	1.83
	From Shutesbury to Quabbin Switch Tap	1.58	2.52	2.58	0.87	1.09	1.55
	From Quabbin Switch Tap to Ware	0.56	0.64	1.16	2.16	2.33	2.26
	From Ware to Lashaway	0.75	1.38	1.78	1.94	2.14	2.09
	From Lashaway to Harrington St	1.95	2.84	2.65	1.18	1.10	0.87
	From Harrington St to Meadow St	1.76	2.61	2.52	0.97	0.93	0.97
	From Meadow St to Leicester	0.81	1.33	1.75	0.86	0.97	1.36
	From Leicester to Pondville	0.80	1.32	1.74	0.85	0.96	1.35
	From Pondville to Millbury	0.55	0.70	0.98	0.59	0.57	1.01
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	0.34	0.87	0.52	0.10	0.29	0.17
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	1.56	4.08	2.43	1.20	3.37	2.01
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	1.88	2.79	2.70	0.70	0.68	0.63
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	2.33	10.32	11.65	2.12	10.64	12.18
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	1.43	7.50	8.47	0.92	6.40	7.32
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	3.96	8.21	9.11	1.27	1.24	1.49
	From Shutesbury to Quabbin Switch Tap	4.39	8.61	9.28	0.85	0.86	1.25

Notes:
kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way; sh. = Sheet.
Left and right ROW edges are as shown on the Appendix A cross section diagrams.

Table 1.2 Summary of Modeled Pre-Project and Post-Project Edge-of-ROW Magnetic Fields for the Representative ROW Cross Sections for System Peak Load Levels

Representative Cross Section	ROW Segment	Magnetic Field (mG)					
		Left Edge-of-ROW			Right Edge-of-ROW		
		Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)	Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	1.75	3.26	3.90	4.14	4.23	2.59
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	1.81	3.00	3.53	1.49	1.78	2.49
	From Deerfield 3 Tap to Deerfield 2	1.21	2.33	3.13	2.61	2.91	3.16
	From Deerfield 2 to Shutesbury	2.18	3.63	3.89	1.95	2.31	2.81
	From Shutesbury to Quabbin Switch Tap	2.37	3.85	4.01	1.62	1.97	2.59
	From Quabbin Switch Tap to Ware	0.82	1.05	1.96	3.46	3.74	3.62
	From Ware to Lashaway	1.18	2.11	2.73	2.19	2.43	2.66
	From Lashaway to Harrington St	2.58	3.77	3.70	1.39	1.16	1.26
	From Harrington St to Meadow St	1.15	2.15	2.73	2.21	2.88	2.95
	From Meadow St to Leicester	1.00	1.74	2.50	0.98	1.20	1.91
	From Leicester to Pondville	1.00	1.73	2.49	0.97	1.19	1.90
	From Pondville to Millbury	0.69	0.88	1.34	0.57	0.61	1.45
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	0.67	1.75	1.05	0.20	0.58	0.35
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	2.25	5.89	3.52	1.73	4.87	2.91
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	1.25	2.34	2.96	1.52	2.09	2.11
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	3.80	16.32	18.36	3.21	16.62	19.08
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	2.36	11.86	13.34	1.38	9.99	11.47
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	6.43	13.17	14.46	1.91	1.87	2.29
	From Shutesbury to Quabbin Switch Tap	6.75	13.48	14.59	1.58	1.57	2.10

Notes:
kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way; sh. = Sheet.
Left and right ROW edges are as shown on the Appendix A cross section diagrams.

Table 1.3 Summary of Modeled Pre-Project and Post-Project Edge-of-ROW Electric Field Values for the Representative ROW Cross Sections

Representative Cross Section	ROW Segment	Line Loading Scenario	Electric Field (kV/m)					
			Left Edge-of-ROW			Right Edge-of-ROW		
			Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)	Pre-Project	Post-Project (69-kV)	Post-Project (115-kV)
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	Ann. Avg.	0.01	0.05	0.09	0.61	0.60	0.61
		Sys. Pk.	0.03	0.06	0.09	0.62	0.62	0.63
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Deerfield 3 Tap to Deerfield 2	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Deerfield 2 to Shutesbury	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Shutesbury to Quabbin Switch Tap	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Quabbin Switch Tap to Ware	Ann. Avg.	0.03	0.04	0.07	0.02	0.03	0.06
		Sys. Pk.	0.03	0.04	0.07	0.02	0.03	0.06
	From Ware to Lashaway	Ann. Avg.	0.02	0.04	0.08	0.02	0.04	0.06
		Sys. Pk.	0.02	0.04	0.08	0.03	0.04	0.06
	From Lashaway to Harrington St	Ann. Avg.	0.04	0.05	0.08	0.04	0.05	0.07
		Sys. Pk.	0.03	0.05	0.08	0.04	0.04	0.07
	From Harrington St to Meadow St	Ann. Avg.	0.03	0.05	0.08	0.04	0.04	0.07
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.07
	From Meadow St to Leicester	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Leicester to Pondville	Ann. Avg.	0.03	0.05	0.08	0.03	0.04	0.06
		Sys. Pk.	0.03	0.05	0.08	0.03	0.04	0.06
	From Pondville to Millbury	Ann. Avg.	0.02	0.04	0.08	0.02	0.03	0.06
		Sys. Pk.	0.02	0.04	0.07	0.02	0.03	0.06
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	Ann. Avg.	0.12	0.30	0.50	0.12	0.30	0.50
		Sys. Pk.	0.12	0.30	0.50	0.12	0.30	0.50
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	Ann. Avg.	0.17	0.08	0.13	0.33	0.27	0.44
		Sys. Pk.	0.17	0.08	0.13	0.33	0.26	0.44
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	Ann. Avg.	0.03	0.07	0.09	0.39	0.39	0.39
		Sys. Pk.	0.01	0.06	0.09	0.39	0.39	0.39
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	Ann. Avg.	0.03	0.44	0.73	0.04	0.54	0.90
		Sys. Pk.	0.03	0.44	0.73	0.04	0.53	0.89
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	Ann. Avg.	0.03	0.30	0.50	0.02	0.30	0.50
		Sys. Pk.	0.03	0.29	0.49	0.02	0.30	0.49
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	Ann. Avg.	0.07	0.36	0.61	0.03	0.03	0.05
		Sys. Pk.	0.07	0.36	0.60	0.03	0.03	0.05
	From Shutesbury to Quabbin Switch Tap	Ann. Avg.	0.07	0.36	0.61	0.03	0.03	0.05
		Sys. Pk.	0.07	0.36	0.60	0.03	0.03	0.05

Notes:
Ann. Avg. = Annual Average; kV = Kilovolt; kV/m = Kilovolts per Meter; ROW = Right-of-Way; sh. = Sheet; Sys. Pk. = System Peak.
Left and right ROW edges are as shown on the Appendix A cross section diagrams.

Section 2 of this report describes the nature of EMFs, provides values for EMF levels from common sources, and reports on EMF exposure guidelines. Section 3 outlines the EMF modeling procedures for calculating EMF strengths as a function of lateral distance from an electric transmission line (or distribution line) and provides tabular results for the modeled cross sections. Section 4 summarizes the conclusions, and the Reference list provides the references for published literature and exposure guidelines cited in this report. Appendix A provides cross section diagrams, showing both existing (pre-Project) and post-Project overhead conductor arrangements, for the representative cross sections, while Appendices B and C provide graphical MF and EF profiles, respectively, for each modeled route segment and line loading scenario. Appendix D provides a summary of the current status of scientific reports regarding potential health effects of power-frequency EMF exposures.

2 Nature of Electric and Magnetic Fields

All matter contains electrically charged particles. Most objects are electrically neutral because positive and negative charges are present in equal numbers. When the balance of electric charges is altered, we experience electrical effects. Common examples are the static electricity attraction between a comb and our hair or a static electricity spark after walking on a synthetic rug in the wintertime. Electrical effects occur both in nature and through our society's use of electric power (generation, transmission, and consumption).

2.1 Units for EMFs Are Kilovolts per Meter (kV/m) and Milligauss (mG)

The electrical tension on utility power lines is expressed in volts or kilovolts (1 kV = 1,000 V). Voltage is the "pressure" of the electricity and can be envisioned as analogous to the pressure of water in a plumbing system. The existence of a voltage difference between power lines and ground results in an EF, usually expressed in units of kV/m. The size of the EF depends on the line voltage, the separation distance between lines and ground, and other factors.

Power lines also carry an electric current that creates a MF. The units for electric current are amperes (A), which is a measure of the "flow" of electricity. Electric current is analogous to the flow of water in a plumbing system. The MF produced by an electric current is usually expressed in units of gauss (G) or mG (1 G = 1,000 mG).[3] The size of the MF depends on the electric current, the distance to the current-carrying conductor, and other factors.

2.2 There Are Many Natural and Man-Made Sources of EMFs

Everyone experiences a variety of natural and man-made EMFs. EMF levels can be steady or slowly varying (often called direct current [DC] fields), or EMF levels can vary in time (often called alternating current [AC] fields). When the time variation corresponds to that of standard North American power line currents (*i.e.*, 60 cycles per second), the fields are called 60-Hz EMFs, or power-frequency EMFs.

Man-made MFs are common in everyday life. For example, many childhood toys contain magnets. Such permanent magnets generate strong, steady (DC) MFs. Typical toy magnets (*e.g.*, refrigerator door magnets) have fields of 100,000-500,000 mG. On a larger scale, Earth's core also creates a steady DC MF that can be easily demonstrated with a compass needle. The size of the Earth's MF in the northern US is about 550 mG (less than 1% of the levels generated by typical refrigerator door magnets).

2.3 Power-Frequency EMFs Are Found Near Electric Lines and Appliances

In North America, electric power transmission lines, distribution lines, and electric wiring in buildings carry AC currents and voltages that change size and direction at a frequency of 60 Hz. These 60-Hz currents and voltages create 60-Hz EMFs nearby. The size of the MF is proportional to the line current, while the size of the EF is proportional to the line voltage. The EMFs associated with electrical wires and electrical equipment decrease rapidly with increasing distance away from the electrical wires. Specifically, EMFs

[3] Another unit for MF levels is the microtesla (µT) (1 µT = 10 mG).

from three-phased, balanced conductors decrease in proportion to the square of the distance from the conductors (*i.e.*, 1/distance^2) (IEEE, 2014).

When EMF derives from different wires or conductors that are in close proximity, or adjacent to one another, the level of the net EMF produced will be somewhere in the range between the sum of EMF from the individual sources and the difference of the EMF from the individual sources. EMF may partially add, or partially cancel but, because adjacent wires are often carrying current in opposite directions, the EMF produced tends generally to cancel. Notably, for three-phase transmission line conductors, the sum of currents going in, for example, the forward direction at any instant, are equal to the sum of currents going in the backward direction.

EMFs in the home arise from electric appliances, indoor wiring, grounding currents on pipes and ground wires, and outdoor distribution or transmission circuits. Inside residences, typical baseline 60-Hz MF levels (away from appliances) range from 0.5-5.0 mG.

Higher 60-Hz MF levels are found near operating appliances. For example, can openers, mixers, blenders, refrigerators, fluorescent lamps, electric ranges, clothes washers, toasters, portable heaters, vacuum cleaners, electric tools, and many other appliances generate MF levels in the range of 40-300 mG at distances of 1 foot (NIEHS, 2002). MF levels from personal care appliances held within half a foot (*e.g.*, shavers, hair dryers, massagers) can produce average fields of 600-700 mG. At school and in the workplace, lights, motors, copy machines, vending machines, video-display terminals, pencil sharpeners, electric tools, electric heaters, and building wiring are all sources of 60-Hz MFs.

Recognizing that magnetic resonance imaging (MRI) is a source of DC fields rather than 60-Hz fields, MRIs are a diagnostic procedure that puts humans in much larger, but steady, MF (*e.g.*, levels of 20,000,000 mG). The scanning MF superimposed on the large, steady static field (which is the source of the characteristic audio noise of MRI scans) exposes the body to time-varying MF similar to time-varying power-frequency MF.

2.4 State, National, and International Guidelines for Power-Frequency EMFs

Table 2.1 shows guidelines for 60-Hz AC EMFs from national and world health and safety organizations that are designed to be protective against any adverse health effects. The limit values should not be viewed as demarcation lines between safe and dangerous levels of EMFs, but rather, levels that assure safety with an adequate margin to allow for uncertainties in the science. Appendix D provides more information on the health-effects science underlying the available exposure guidelines, as well as a summary of EMF health-effect conclusions from international scientific, health, and safety organizations, and governmental public health agencies. As part of its International EMF Project, the World Health Organization (WHO) has conducted comprehensive reviews of EMF health-effects research and existing standards and guidelines. The WHO website for the International EMF Project (WHO, 2024) notes: "The main conclusion from the WHO reviews is that EMF exposures below the limits recommended in the ICNIRP international guidelines do not appear to have any known consequence on health."

The US has no federal standards limiting either residential or occupational exposure to 60-Hz EMFs. The Massachusetts Energy Facilities Siting Board (MA EFSB) assesses EMF levels on a case-by-case basis with a focus on practical options to reduce magnetic fields along transmission line rights-of-way. Some states, including New York and Florida, have adopted EMF guidelines that are not health-effect based and have typically been adopted to maintain the *status quo* for EMFs on and near a transmission line ROW.

Table 2.1 60-Hz AC EMF Guidelines Established by International Health and Safety Organizations

Organization	Electric Field	Magnetic Field
American Conference of Governmental and Industrial Hygienists (ACGIH) (occupational)	25 kV/m(1)	10,000 mG(1) 1,000 mG(2)
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (general public)	4.2 kV/m(3)	2,000 mG(3)
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (occupational)	8.3 kV/m(3)	10,000 mG(3)
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1™-2019 (general public)	5.0 kV/m(4)	9,040 mG(4)
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1™-2019 (occupational)	20.0 kV/m(4)	27,100 mG(4)

Notes:

AC = Alternating Current; EMF = Electric and Magnetic Field; Hz = Hertz; kV/m = Kilovolts per Meter; mG = Milligauss.

(1) The ACGIH guidelines for the general worker (ACGIH, 2024).

(2) The ACGIH guideline for workers with cardiac pacemakers (ACGIH, 2024).

(3) ICNIRP (2010).

(4) IEEE (2019); developed by the IEEE International Committee on Electromagnetic Safety (ICES).

3 EMF Modeling

3.1 Software Program Used for Modeling EMFs for Overhead Line Cross Sections

The "EMF and Corona Effects Analysis" spreadsheet-based EMF calculation program, designed by the Bonneville Power Administration (BPA) of the US Department of Energy, was used to calculate EMFs.[4] This program operates using Maxwell's equations, which accurately apply the laws of physics as related to electricity and magnetism (EPRI, 1982, 1993). Modeled fields using this program are both precise and accurate for the input data used. The results of the model have been checked against results from other software (*e.g.*, Southern California Edison's FIELDS program), confirming that the implementation of the laws of physics in this program is consistent.

3.2 Power-Line Loads

MFs produced by the three-phase overhead lines were modeled using line loadings and conductor phase angles provided by National Grid. The current per phase satisfies the relationship:

(Eq. 3.1)
$$S = \sqrt{3} \times V \times I_{phase}$$

where:

S	=	The power in kilovolt-amperes (kVA)
V	=	The line voltage in kilovolts (kV)
I_{phase}	=	The current per phase in amperes (A)

Thus, the current per phase conductor is:

(Eq. 3.2)
$$I_{phase} = \frac{S}{\sqrt{3} \times V}$$

Real power is typically expressed in megawatts (MW) (*P*), and apparent power in megavolt-amperes (MVA) (*S*).[5,6] To convert between power quoted in MW to MVA, one must divide MW by the power factor.

[4] BPA's "EMF and Corona Effects Analysis" spreadsheet-based EMF calculation program reports the root mean square (RMS) values of the real "maximum" rotating electric and magnetic fields, *i.e.*, the RMS values of the semi-major axis magnitudes of the field ellipse that are known as $B_{Maximum}$ or B_{Max} and $E_{Maximum}$ or E_{Max}. While some instruments relying on three fixed orthogonal coils (*e.g.*, fixed-coil instruments like the EMDEX II) calculate the sum of the squares of magnetic fields detected by each orthogonal coil separately and thus report a different metric (*e.g.*, $B_{Resultant}$ or B_{Res}; sometimes referred to as $B_{Product}$ or B_{prod}), B_{Res} and E_{Res} are recognized as being artefactual in nature- *i.e.*, not actual physical entities like B_{Max} and E_{Max} (IEEE, 2021).

[5] MVA is apparent power and is the vector sum of real (active) and imaginary (reactive) power. MW and MVA are not the same unless the power factor = 1.0, which, in a practical AC circuit, is generally not the case.

[6] 1 MVA = 1,000 kVA.

Both pre-Project and post-Project electric current and voltage values provided by National Grid are summarized by line loading scenario (annual average and system peak load levels) in Table 3.1 for the E5 and F6 lines, as well as the D4 line that is present with the E5 and F6 lines in representative cross section 1 for the ROW segment entering the Deerfield No. 4 Substation and the T20 line that is present with the E5 and F6 lines in representative cross section 5 that occurs for a ROW segment between the Harrington Switchyard Substation and the Meadow Street Substation. As indicated in the table, the post-Project 69-kV operation scenario and the post-Project 115-kV operation scenario generally refer to a lower and a higher power delivery, respectively.

Table 3.1 Summary of Line Load Levels for Modeled Line Loading Scenarios

Line	Line Segment	Pre-Project		Post-Project: 69-kV Operation		Post-Project: 115-kV Operation	
		Voltage (kV)	Current (A)	Voltage (kV)	Current (A)	Voltage (kV)	Current (A)
Annual Average Load Levels							
E5	From Deerfield No. 4 Substation	70.89	89.96	70.68	94.99	117.93	119.58
	From Deerfield 4 to Deerfield 3 Tap	70.89	89.94	70.68	94.99	117.93	119.52
	Deerfield 3 Tap	70.87	17.73	70.67	17.66	117.94	10.61
	From Deerfield 3 Tap to Deerfield 2	70.87	107.50	70.67	112.61	117.94	129.97
	From Deerfield 2 to Shutesbury	70.83	107.41	70.66	112.55	118.02	129.74
	From Shutesbury to Quabbin Switch Tap	70.50	92.62	70.52	97.79	118.02	120.10
	Quabbin Switch Tap	70.36	0 (open)	70.47	0 (open)	118.04	0 (open)
	From Quabbin Switch Tap to Ware	70.36	91.89	70.47	97.46	118.04	119.31
	From Ware to Lashaway	70.27	117.24	70.43	120.78	118.02	127.92
	From Lashaway to Harrington St	70.38	54.91	70.57	53.69	118.16	85.04
	From Harrington St to Meadow St	70.48	61.46	70.65	61.57	118.23	90.38
	From Meadow St to Leicester	70.53	68.75	70.70	69.43	118.27	95.23
	From Leicester to Pondville	70.75	67.94	70.90	68.69	118.42	94.45
	From Pondville to Millbury	70.95	45.63	71.06	38.00	118.53	64.69
F6	From Deerfield No. 4 Substation	70.89	95.63	70.68	101.26	117.93	122.97
	From Deerfield 4 to Deerfield 3 Tap	70.88	95.62	70.68	101.26	117.93	122.96
	Deerfield 3 Tap	70.86	0 (open)	70.66	0 (open)	117.94	0 (open)
	From Deerfield 3 Tap to Deerfield 2	70.86	95.56	70.66	101.28	117.94	122.83
	From Deerfield 2 to Shutesbury	70.81	113.73	70.65	118.96	117.99	133.46
	From Shutesbury to Quabbin Switch Tap	70.41	112.95	70.48	118.55	117.99	132.37
	Quabbin Switch Tap	70.15	71.79	70.37	71.57	117.98	42.63
	From Quabbin Switch Tap to Ware	70.15	46.90	70.37	48.70	117.98	90.16
	From Ware to Lashaway	70.27	96.20	70.43	99.00	118.02	114.83
	From Lashaway to Harrington St	70.45	95.45	70.61	98.42	118.19	113.91
	From Harrington St to Meadow St	70.50	95.24	70.66	98.22	118.23	113.66
	From Meadow St to Leicester	70.53	71.27	70.70	72.18	118.27	97.07
	From Leicester to Pondville	70.75	70.47	70.89	71.50	118.42	96.26
	From Pondville to Millbury	70.94	47.22	71.06	38.40	118.53	60.43
D4	From Deerfield No. 4 Substation	70.89	29.80	70.68	29.23	70.44	43.56
T20	From Harrington St to Meadow St	115	0 (open)	115	0 (open)	115	0 (open)

Line	Line Segment	Pre-Project		Post-Project: 69-kV Operation		Post-Project: 115-kV Operation	
		Voltage (kV)	Current (A)	Voltage (kV)	Current (A)	Voltage (kV)	Current (A)
System Peak Load Levels							
E5	From Deerfield No. 4 Substation	70.66	132.41	70.29	139.46	116.87	181.94
	From Deerfield 4 to Deerfield 3 Tap	70.65	132.42	70.29	139.46	116.87	181.90
	Deerfield 3 Tap	70.62	35.42	70.27	35.49	116.89	21.35
	From Deerfield 3 Tap to Deerfield 2	70.62	167.33	70.27	174.72	116.89	202.72
	From Deerfield 2 to Shutesbury	70.55	167.22	70.24	174.70	116.87	202.61
	From Shutesbury to Quabbin Switch Tap	70.08	155.72	69.99	163.36	116.86	195.03
	Quabbin Switch Tap	69.88	0 (open)	69.92	0 (open)	116.89	0 (open)
	From Quabbin Switch Tap to Ware	69.88	154.99	69.92	163.00	116.89	194.26
	From Ware to Lashaway	69.79	146.27	69.90	149.64	116.90	172.89
	From Lashaway to Harrington St	69.90	75.49	69.95	71.36	116.97	124.89
	From Harrington St to Meadow St	70.00	145.96	70.00	158.18	117.01	177.91
	From Meadow St to Leicester	70.04	80.89	70.08	87.53	117.07	135.01
	From Leicester to Pondville	70.20	80.23	70.26	86.98	117.22	134.36
	From Pondville to Millbury	70.34	45.29	70.41	40.67	117.35	91.03
F6	From Deerfield No. 4 Substation	70.66	146.07	70.29	154.02	116.87	190.78
	From Deerfield 4 to Deerfield 3 Tap	70.65	146.09	70.29	153.94	116.87	190.73
	Deerfield 3 Tap	70.61	0 (open)	70.27	0 (open)	116.89	0 (open)
	From Deerfield 3 Tap to Deerfield 2	70.61	145.98	70.27	153.93	116.89	190.61
	From Deerfield 2 to Shutesbury	70.55	180.93	70.25	188.95	116.90	210.84
	From Shutesbury to Quabbin Switch Tap	69.88	180.23	69.90	188.68	116.81	209.91
	Quabbin Switch Tap	69.54	103.58	69.75	103.27	116.78	61.67
	From Quabbin Switch Tap to Ware	69.54	88.13	69.75	89.59	116.78	149.88
	From Ware to Lashaway	69.79	131.68	69.90	135.01	116.90	164.30
	From Lashaway to Harrington St	69.96	130.96	70.02	134.63	117.01	163.64
	From Harrington St to Meadow St	70.01	130.78	70.06	134.44	117.05	163.44
	From Meadow St to Leicester	70.04	85.68	70.08	92.49	117.07	138.14
	From Leicester to Pondville	70.19	85.01	70.25	91.91	117.22	137.51
	From Pondville to Millbury	70.32	50.95	70.39	43.81	117.35	83.72
D4	From Deerfield No. 4 Substation	70.66	39.07	70.29	36.06	70.35	10.25
T20	From Harrington St to Meadow St	115	0 (open)	115	0 (open)	115	0 (open)

Notes:
A = Ampere; kV = Kilovolt.

3.3 Project Representative Cross Sections

Gradient modeled EMFs expected to exist 1 meter (3.28 feet) above the ground surface for 8 representative ROW cross sections. These representative cross sections reflect differences in E5 and F6 conductor arrangements/locations/heights, ROW widths, and the presence of other transmission lines within ROW segments (see Appendix A that includes the 8 representative ROW cross section drawings, as well as a plan view map of the Project route that indicates the locations of the representative cross sections). For the entire project route including the tap lines, the E5 and F6 lines will be reconductored using Drake 795 kilo circular mil (kcmil) aluminum conductor steel supported (ACSS) conductors and the existing shielding will be replaced with OPGW.

The representative ROW cross sections included the following:

- Cross section 1 is for a ROW segment leaving the Deerfield Substation No. 4 where the 69-kV D4 line is present in the ROW along with the E5 and F6 lines. The 125-foot ROW is centered on the existing double-circuit monopoles with the E5/F6 circuits, and the new double-circuit monopole davit arm structures with the reconductored E5/F6 circuits are to be offset 5 feet on the left (south) side of the ROW.
- Cross section 2 shows the most common pre-Project and post-Project conductor arrangements and ROW configuration that occur along the majority of the Project route where the existing steel lattice tower structures with the E5/F6 circuits are to be replaced with double-circuit monopole davit arm structures. There is a 5-foot offset between the existing circuit centerline and the proposed circuit centerline. The ROW width in many areas along the Project route is unknown or undefined, but is conservatively assumed to be 125 feet based on input from National Grid Real Estate.
- Cross section 3 is for the tap line into the Deerfield No. 3 Substation, where the existing single-circuit tap line structures with horizontal conductor arrangements are to be replaced with new single-circuit monopole davit arm structures. For both the annual average and system peak loading conditions, the F6 circuit is normally open and is not carrying any current. The ROW width is 125 feet.
- Cross section 4 is for the Quabbin Switch Tap, where the existing single-circuit tap line structures with horizontal conductor arrangements are to be replaced with new single-circuit monopoles with vertical conductor configurations. For both the annual average and system peak loading conditions, the E5 circuit is normally open and is not carrying any current. The ROW width is 80 feet.
- Cross section 5 is for a ROW segment between the Harrington Street Switchyard Substation and the Meadow Street Substation where the T20 overhead transmission line is also present in the ROW along with the E5 and F6 lines. The 69-kV T20 circuit is normally open and thus not carrying current; it was assumed to be energized at 115-kV per National Grid's request. Similar to cross section 2, the existing steel lattice tower structures with the E5/F6 circuits are to be replaced with double-circuit monopole davit arm structures. The ROW width is 132 feet.
- Cross section 6 is for a ROW segment between the Deerfield No. 2 Substation and the Shutesbury Substation where the existing steel lattice tower structures with the E5/F6 circuits are to be replaced with single-circuit monopole davit arm structures. Within the 100 foot ROW, the new single-circuit monopole davit arm structures with be offset 16 feet and 18 feet on either side of the ROW centerline.
- Cross section 7 is for a ROW segment between the Deerfield No. 2 Substation and the Shutesbury Substation where the existing steel lattice tower structures with the E5/F6 circuits are to be replaced with single-circuit monopole davit arm structures. Within the 130 foot ROW, the new single-circuit monopole davit arm structures with the E5 and F6 circuits are to be offset 18 feet and 23 feet on either side of the ROW centerline.
- Cross section 8 is a variant of cross section 2 where the existing steel lattice tower structures with the E5/F6 circuits are to be replaced with double-circuit monopole davit arm structures, but for a larger 10-foot offset between the existing circuit centerline and the proposed circuit centerline and a smaller ROW width of 100 feet. This representative cross section occurs intermittently between the Deerfield No. 2 Substation and the Quabbin Switch Tap (Structures 385 to 602). Although there are several other variants of cross section 8 that differ in the ROW width, the existing and proposed circuit offsets, and the distances from the circuit centerlines to the ROW edges, these

variants occur for just single span transitions and were not included in the EMF modeling analysis due to their insignificant lengths.

National Grid provided cross section reference drawings showing both existing (pre-Project) and proposed (post-Project) overhead conductor arrangements, which are attached to this report as Appendix A. Conductor phasing arrangements are shown on the cross section drawings.

EMF levels were modeled for both pre-Project and post-Project ROW conditions as a function of distance perpendicular to the direction of current flow for each route segment, assuming that the transmission lines run straight. Modeling was performed assuming the minimum ROW widths as discussed above and shown in each representative cross section drawing (Appendix A); this resulted in conservative estimates of edge-of-ROW EMF levels, as EMF levels will be lower at the ROW edges with a wider ROW. Variation in the height of the nearby grade along the ROW was not accounted for, given that the general National Grid policy is to model EMF for the most conservative location of lowest conductor sag (*i.e.*, closest to the ground surface). As provided by National Grid, a minimum conductor height above ground of 19.4 feet was used for pre-Project modeling of all representative cross sections and a minimum conductor height above ground of 23 feet was used for post-Project modeling of all representative cross sections based on state code clearance requirements associated with 115-kV design. The EMF modeling was conducted out to 50 feet beyond both ROW edges, illustrating the continued decline in EMF levels beyond the ROW edges for the assumed ROW widths.

3.4 EMF Modeling Results

3.4.1 Magnetic Field Results

Results of the MF modeling for the representative cross sections are summarized in Tables 3.2 and 3.3, as well as the figures in Appendix B. In the Appendix B figures, Panel (a) shows the pre- and post-Project modeling results for annual average load levels, and Panel (b) shows the pre- and post-Project modeling results for system peak load levels; both panels show results for the post-Project 69-kV and 115-kV operating cases for the E5 and F6 lines.

The MF modeling results show that all model-predicted MF values, including those within the ROWs, remain well below the ICNIRP health-based guideline of 2,000 mG for allowable public exposure to 60-Hz MF. Due in part to the higher post-Project load levels for both the E5 and F6 circuits, in particular for the 115-kV operation case, the Project will frequently result in increased edge-of-ROW MF levels; however, the magnitudes of the increases are small (frequently <1 mG and <1-2 mG for annual average and system peak load levels, respectively). The largest edge-of-ROW MF increases were observed for representative cross section 6, with MF increases of 7.99 mG and 8.52 mG at the left and right edges, respectively for the post-Project 69-kV operating case, and MF increases of 9.32 mG and 10.06 mG at the left and right edges, respectively for the post-Project 115-kV operating case. For system peak load levels, slightly higher maximum edge-of-ROW MF increases were observed, with MF increases of 12.52 mG and 13.40 mG at the left and right edges, respectively for the post-Project 69-kV operating case, and MF increases of 14.56 mG and 15.87 mG at the left and right edges, respectively for the post-Project 115-kV operating case. In all cases, as illustrated by Tables 3.2 and 3.3, MF values drop off rapidly with increased lateral distance from the overhead lines, such that MF levels decrease to negligible levels at short distances beyond the ROW edges.

Table 3.2 Summary of Modeled Pre-Project and Post-Project Magnetic Fields for the Representative ROW Cross Sections for Annual Average Load Levels

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	Pre-Project	0.22	1.07	18.57	2.86	0.42
		Post-Project (69-kV)	0.43	2.11	17.38	3.15	0.52
		Post-Project (115-kV)	0.52	2.53	21.22	4.53	0.73
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	Pre-Project	0.26	1.13	19.83	1.09	0.19
		Post-Project (69-kV)	0.43	1.92	17.27	1.28	0.26
		Post-Project (115-kV)	0.48	2.24	21.31	1.69	0.36
	From Deerfield 3 Tap to Deerfield 2	Pre-Project	0.13	0.83	21.85	1.65	0.37
		Post-Project (69-kV)	0.28	1.58	18.90	1.84	0.45
		Post-Project (115-kV)	0.39	2.04	22.25	2.02	0.48
	From Deerfield 2 to Shutesbury	Pre-Project	0.30	1.33	23.69	1.29	0.23
		Post-Project (69-kV)	0.49	2.23	20.37	1.53	0.32
		Post-Project (115-kV)	0.52	2.43	23.15	1.83	0.39
	From Shutesbury to Quabbin Switch Tap	Pre-Project	0.40	1.58	22.35	0.87	0.13
		Post-Project (69-kV)	0.61	2.52	19.32	1.09	0.17
		Post-Project (115-kV)	0.59	2.58	22.28	1.55	0.30
	From Quabbin Switch Tap to Ware	Pre-Project	0.28	0.56	17.28	2.16	0.61
		Post-Project (69-kV)	0.28	0.64	14.97	2.33	0.71
		Post-Project (115-kV)	0.18	1.16	19.11	2.26	0.62
	From Ware to Lashaway	Pre-Project	0.13	0.75	23.40	1.94	0.46
		Post-Project (69-kV)	0.23	1.38	19.74	2.14	0.57
		Post-Project (115-kV)	0.32	1.78	21.52	2.09	0.52
	From Lashaway to Harrington St	Pre-Project	0.58	1.95	18.02	1.18	0.38
		Post-Project (69-kV)	0.81	2.84	15.22	1.10	0.37
		Post-Project (115-kV)	0.68	2.65	18.07	0.87	0.21

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
	From Harrington St to Meadow St	Pre-Project	0.51	1.76	17.98	0.97	0.29
		Post-Project (69-kV)	0.72	2.61	15.23	0.93	0.28
		Post-Project (115-kV)	0.63	2.52	18.29	0.97	0.19
	From Meadow St to Leicester	Pre-Project	0.18	0.81	14.97	0.86	0.16
		Post-Project (69-kV)	0.29	1.33	12.44	0.97	0.20
		Post-Project (115-kV)	0.37	1.75	16.91	1.36	0.29
	From Leicester to Pondville	Pre-Project	0.18	0.80	14.80	0.85	0.16
		Post-Project (69-kV)	0.29	1.32	12.32	0.96	0.20
		Post-Project (115-kV)	0.37	1.74	16.77	1.35	0.29
	From Pondville to Millbury	Pre-Project	0.13	0.55	10.05	0.59	0.13
		Post-Project (69-kV)	0.17	0.70	6.77	0.57	0.14
		Post-Project (115-kV)	0.19	0.98	11.06	1.01	0.24
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	Pre-Project	0.08	0.34	2.25	0.10	0.04
		Post-Project (69-kV)	0.22	0.87	3.26	0.29	0.12
		Post-Project (115-kV)	0.13	0.52	1.96	0.17	0.07
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	Pre-Project	0.32	1.56	9.10	1.20	0.28
		Post-Project (69-kV)	1.12	4.08	11.59	3.37	1.00
		Post-Project (115-kV)	0.67	2.43	6.90	2.01	0.60
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	Pre-Project	0.53	1.88	17.98	0.70	0.24
		Post-Project (69-kV)	0.75	2.79	15.23	0.68	0.24
		Post-Project (115-kV)	0.66	2.70	18.29	0.63	0.15
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	Pre-Project	0.42	2.33	23.69	2.12	0.31
		Post-Project (69-kV)	2.68	10.32	25.49	10.64	2.85
		Post-Project (115-kV)	3.04	11.65	28.73	12.18	3.26
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	Pre-Project	0.31	1.43	23.69	0.92	0.18
		Post-Project (69-kV)	2.23	7.50	24.23	6.40	2.07
		Post-Project (115-kV)	2.52	8.47	27.28	7.32	2.36

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	Pre-Project	0.57	3.96	23.69	1.27	0.22
		Post-Project (69-kV)	1.10	8.21	20.38	1.24	0.27
		Post-Project (115-kV)	1.18	9.11	23.14	1.49	0.34
	From Shutesbury to Quabbin Switch Tap	Pre-Project	0.72	4.39	22.35	0.85	0.13
		Post-Project (69-kV)	1.30	8.61	19.33	0.86	0.15
		Post-Project (115-kV)	1.29	9.28	22.27	1.25	0.25

Notes:
ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way; sh. = Sheet.

Table 3.3 Summary of Modeled Pre-Project and Post-Project Magnetic Fields for the Representative ROW Cross Sections for System Peak Load Levels

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	Pre-Project	0.42	1.75	27.97	4.14	0.50
		Post-Project (69-kV)	0.73	3.26	26.02	4.23	0.52
		Post-Project (115-kV)	0.83	3.90	32.79	2.59	0.40
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	Pre-Project	0.43	1.81	29.90	1.49	0.24
		Post-Project (69-kV)	0.69	3.00	25.93	1.78	0.34
		Post-Project (115-kV)	0.77	3.53	32.82	2.49	0.52
	From Deerfield 3 Tap to Deerfield 2	Pre-Project	0.19	1.21	33.87	2.61	0.59
		Post-Project (69-kV)	0.40	2.33	29.16	2.91	0.73
		Post-Project (115-kV)	0.60	3.13	34.70	3.16	0.75
	From Deerfield 2 to Shutesbury	Pre-Project	0.50	2.18	37.30	1.95	0.33
		Post-Project (69-kV)	0.82	3.63	32.03	2.31	0.46
		Post-Project (115-kV)	0.84	3.89	36.36	2.81	0.59

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
	From Shutesbury to Quabbin Switch Tap	Pre-Project	0.58	2.37	36.22	1.62	0.23
		Post-Project (69-kV)	0.91	3.85	31.21	1.97	0.34
		Post-Project (115-kV)	0.90	4.01	35.66	2.59	0.52
	From Quabbin Switch Tap to Ware	Pre-Project	0.42	0.82	29.28	3.46	0.96
		Post-Project (69-kV)	0.38	1.05	25.12	3.74	1.13
		Post-Project (115-kV)	0.31	1.96	31.26	3.62	0.98
	From Ware to Lashaway	Pre-Project	0.21	1.18	30.04	2.19	0.48
		Post-Project (69-kV)	0.39	2.11	25.25	2.43	0.60
		Post-Project (115-kV)	0.53	2.73	29.76	2.66	0.63
	From Lashaway to Harrington St	Pre-Project	3.66	5.18	31.75	9.24	4.85
		Post-Project (69-kV)	1.07	3.77	20.76	1.16	0.40
		Post-Project (115-kV)	0.94	3.70	26.14	1.26	0.24
	From Harrington St to Meadow St	Pre-Project	0.19	1.15	29.81	2.21	0.49
		Post-Project (69-kV)	0.45	2.15	25.74	2.88	0.76
		Post-Project (115-kV)	0.54	2.73	29.87	2.95	0.73
	From Meadow St to Leicester	Pre-Project	0.23	1.00	17.82	0.98	0.17
		Post-Project (69-kV)	0.38	1.74	15.83	1.20	0.25
		Post-Project (115-kV)	0.53	2.50	24.02	1.91	0.41
	From Leicester to Pondville	Pre-Project	0.23	1.00	17.68	0.97	0.17
		Post-Project (69-kV)	0.38	1.73	15.73	1.19	0.25
		Post-Project (115-kV)	0.53	2.49	23.91	1.90	0.41
	From Pondville to Millbury	Pre-Project	0.18	0.69	10.49	0.57	0.13
		Post-Project (69-kV)	0.23	0.88	7.50	0.61	0.16
		Post-Project (115-kV)	0.25	1.34	15.46	1.45	0.35
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	Pre-Project	0.16	0.67	4.49	0.20	0.08
		Post-Project (69-kV)	0.45	1.75	6.55	0.58	0.24
		Post-Project (115-kV)	0.27	1.05	3.94	0.35	0.14

Representative Cross Section	ROW Segment	Modeling Case	Magnetic Field (mG)				
			50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	Pre-Project	0.46	2.25	13.13	1.73	0.40
		Post-Project (69-kV)	1.62	5.89	16.72	4.87	1.44
		Post-Project (115-kV)	0.97	3.52	9.98	2.91	0.86
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	Pre-Project	0.20	1.25	29.81	1.52	0.39
		Post-Project (69-kV)	0.47	2.34	25.74	2.09	0.62
		Post-Project (115-kV)	0.57	2.96	29.87	2.11	0.59
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	Pre-Project	0.70	3.80	37.31	3.21	0.45
		Post-Project (69-kV)	4.23	16.32	40.30	16.62	4.46
		Post-Project (115-kV)	4.78	18.36	45.28	19.08	5.10
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	Pre-Project	0.53	2.36	37.30	1.38	0.26
		Post-Project (69-kV)	3.51	11.86	38.34	9.99	3.24
		Post-Project (115-kV)	3.96	13.34	43.01	11.47	3.70
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	Pre-Project	0.94	6.43	37.31	1.91	0.32
		Post-Project (69-kV)	1.80	13.17	32.03	1.87	0.40
		Post-Project (115-kV)	1.90	14.46	36.36	2.29	0.52
	From Shutesbury to Quabbin Switch Tap	Pre-Project	1.06	6.75	36.23	1.58	0.23
		Post-Project (69-kV)	1.96	13.48	31.21	1.57	0.29
		Post-Project (115-kV)	1.99	14.59	35.67	2.10	0.45

Notes:
ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way; sh. = Sheet.

3.4.2 Electric Field Results

Pre- and post-Project EF modeling results for the representative cross sections are shown in Table 3.4 and the figures in Appendix C. In the Appendix C figures, Panel (a) shows the pre- and post-Project modeling results for annual average load levels, and Panel (b) shows the pre- and post-Project modeling results for system peak load levels; both panels show results for the post-Project 69-kV and 115-kV operating cases for the E5 and F6 lines. Although EFs are not dependent on conductor loading (*i.e.*, current), separate results are provided for annual average and system peak load levels due to small differences in voltages of the E5 and F6 circuits that were provided by National Grid for the two line loading scenarios. In all cases, the modeled edge-of-ROW EFs are well below the ICNIRP health-based guideline of 4.2 kV/m. For the 69-kV modeling cases, our modeling analysis indicates that the Project will frequently result in negligible changes to EFs at the ROW edges that are less than 0.02 kV/m and a maximum edge-of-ROW increase of 0.50 kV/m. For the 115-kV modeling cases, there are some slightly larger changes in EFs at the ROW edges (ranging from -0.05 kV/m up to 0.86 kV/m), although edge-of-ROW EF levels remain low overall (all ≤0.9 kV/m).

Table 3.4 Summary of Modeled Pre-Project and Post-Project Electric Fields for the Representative ROW Cross Sections

Represent-ative Cross Section	ROW Segment	Loading Scenario	Scenario	Electric Field (kV/m)				
				50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 1 (D-13148-NE sh. 1)	From Deerfield No. 4 Substation	Annual Average	Pre-Project	0.01	0.01	0.92	0.61	0.07
			Post (69-kV)	0.01	0.05	0.86	0.60	0.06
			Post (115-kV)	0.02	0.09	1.44	0.61	0.05
		System Peak	Pre-Project	0.01	0.03	0.97	0.62	0.06
			Post (69-kV)	0.02	0.06	0.92	0.62	0.07
			Post (115-kV)	0.03	0.09	1.47	0.63	0.06
Cross Section 2 (D-13148-NE sh. 2)	From Deerfield 4 to Deerfield 3 Tap	Annual Average	Pre-Project	0.01	0.03	1.00	0.03	0.01
			Post (69-kV)	0.01	0.05	0.86	0.04	0.01
			Post (115-kV)	0.02	0.08	1.43	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.84	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
	From Deerfield 3 Tap to Deerfield 2	Annual Average	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.42	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.98	0.03	0.01
			Post (69-kV)	0.01	0.05	0.84	0.04	0.01
			Post (115-kV)	0.02	0.08	1.40	0.06	0.02
	From Deerfield 2 to Shutesbury	Annual Average	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.42	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
	From Shutesbury to Quabbin Switch Tap	Annual Average	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.86	0.04	0.01
			Post (115-kV)	0.02	0.08	1.43	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
	From Quabbin Switch Tap to Ware	Annual Average	Pre-Project	0.02	0.03	0.92	0.02	0.02
			Post (69-kV)	0.01	0.04	0.81	0.03	0.01
			Post (115-kV)	0.02	0.07	1.40	0.06	0.02
		System Peak	Pre-Project	0.02	0.03	0.91	0.02	0.02
			Post (69-kV)	0.01	0.04	0.81	0.03	0.01
			Post (115-kV)	0.02	0.07	1.38	0.06	0.02

Represent-ative Cross Section	ROW Segment	Loading Scenario	Scenario	Electric Field (kV/m)				
				50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
	From Ware to Lashaway	Annual Average	Pre-Project	0.01	0.02	0.95	0.02	0.01
			Post (69-kV)	0.01	0.04	0.83	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
		System Peak	Pre-Project	0.01	0.02	0.96	0.03	0.01
			Post (69-kV)	0.01	0.04	0.83	0.04	0.01
			Post (115-kV)	0.02	0.08	1.39	0.06	0.02
	From Lashaway to Harrington St	Annual Average	Pre-Project	0.01	0.04	1.15	0.04	0.02
			Post (69-kV)	0.02	0.05	0.96	0.05	0.02
			Post (115-kV)	0.03	0.08	1.47	0.07	0.02
		System Peak	Pre-Project	0.01	0.03	1.10	0.04	0.01
			Post (69-kV)	0.02	0.05	0.89	0.04	0.01
			Post (115-kV)	0.03	0.08	1.43	0.07	0.02
	From Harrington St to Meadow St	Annual Average	Pre-Project	0.01	0.03	1.09	0.04	0.01
			Post (69-kV)	0.02	0.05	0.92	0.04	0.02
			Post (115-kV)	0.03	0.08	1.46	0.07	0.02
		System Peak	Pre-Project	0.01	0.03	0.97	0.03	0.01
			Post (69-kV)	0.02	0.05	0.89	0.04	0.01
			Post (115-kV)	0.03	0.08	1.45	0.07	0.02
	From Meadow St to Leicester	Annual Average	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.86	0.04	0.01
			Post (115-kV)	0.02	0.08	1.43	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.98	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
	From Leicester to Pondville	Annual Average	Pre-Project	0.01	0.03	0.99	0.03	0.01
			Post (69-kV)	0.01	0.05	0.86	0.04	0.01
			Post (115-kV)	0.02	0.08	1.43	0.06	0.02
		System Peak	Pre-Project	0.01	0.03	0.98	0.03	0.01
			Post (69-kV)	0.01	0.05	0.85	0.04	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
	From Pondville to Millbury	Annual Average	Pre-Project	0.01	0.02	0.95	0.02	0.01
			Post (69-kV)	0.01	0.04	0.82	0.03	0.01
			Post (115-kV)	0.02	0.08	1.41	0.06	0.02
		System Peak	Pre-Project	0.02	0.02	0.92	0.02	0.02
			Post (69-kV)	0.02	0.04	0.80	0.03	0.01
			Post (115-kV)	0.02	0.07	1.39	0.06	0.02
Cross Section 3 (D-13148-NE sh. 3)	Deerfield 3 Tap	Annual Average	Pre-Project	0.04	0.12	0.61	0.12	0.04
			Post (69-kV)	0.07	0.30	1.07	0.30	0.07
			Post (115-kV)	0.12	0.50	1.79	0.50	0.12
		System Peak	Pre-Project	0.04	0.12	0.61	0.12	0.04
			Post (69-kV)	0.07	0.30	1.06	0.30	0.07
			Post (115-kV)	0.11	0.50	1.77	0.50	0.11

Represent-ative Cross Section	ROW Segment	Loading Scenario	Scenario	Electric Field (kV/m)				
				50 ft from Left ROW Edge	Left ROW Edge	Maximum Within ROW	Right ROW Edge	50 ft from Right ROW Edge
Cross Section 4 (D-13148-NE sh. 4)	Quabbin Switch Tap	Annual Average	Pre-Project	0.04	0.17	0.80	0.33	0.06
			Post (69-kV)	0.01	0.08	0.83	0.27	0.01
			Post (115-kV)	0.02	0.13	1.39	0.44	0.02
		System Peak	Pre-Project	0.04	0.17	0.79	0.33	0.06
			Post (69-kV)	0.01	0.08	0.83	0.26	0.01
			Post (115-kV)	0.02	0.13	1.38	0.44	0.02
Cross Section 5 (D-13148-NE sh. 5)	From Harrington St to Meadow St	Annual Average	Pre-Project	0.01	0.03	1.90	0.39	0.07
			Post (69-kV)	0.01	0.07	1.91	0.39	0.07
			Post (115-kV)	0.01	0.09	1.95	0.39	0.07
		System Peak	Pre-Project	0.01	0.01	1.90	0.39	0.07
			Post (69-kV)	0.01	0.06	1.90	0.39	0.07
			Post (115-kV)	0.01	0.09	1.95	0.39	0.07
Cross Section 6 (D-13148-NE sh. 6)	From Deerfield 2 to Shutesbury	Annual Average	Pre-Project	0.01	0.03	0.96	0.04	0.01
			Post (69-kV)	0.07	0.44	1.03	0.54	0.09
			Post (115-kV)	0.12	0.73	1.72	0.90	0.15
		System Peak	Pre-Project	0.01	0.03	0.96	0.04	0.01
			Post (69-kV)	0.07	0.44	1.03	0.53	0.09
			Post (115-kV)	0.12	0.73	1.71	0.89	0.15
Cross Section 7 (D-13148-NE sh. 7)	From Deerfield 2 to Shutesbury	Annual Average	Pre-Project	0.01	0.03	0.96	0.02	0.01
			Post (69-kV)	0.06	0.30	1.02	0.30	0.06
			Post (115-kV)	0.10	0.50	1.70	0.50	0.10
		System Peak	Pre-Project	0.01	0.03	0.96	0.02	0.01
			Post (69-kV)	0.06	0.29	1.01	0.30	0.06
			Post (115-kV)	0.09	0.49	1.69	0.49	0.10
Cross Section 8 (D-13148-NE sh. 8)	From Deerfield 2 to Shutesbury	Annual Average	Pre-Project	0.03	0.07	0.98	0.03	0.00
			Post (69-kV)	0.03	0.36	0.85	0.03	0.01
			Post (115-kV)	0.04	0.61	1.42	0.05	0.02
		System Peak	Pre-Project	0.03	0.07	0.98	0.03	0.00
			Post (69-kV)	0.03	0.36	0.85	0.03	0.01
			Post (115-kV)	0.04	0.60	1.41	0.05	0.02
	From Shutesbury to Quabbin Switch Tap	Annual Average	Pre-Project	0.03	0.07	0.99	0.03	0.00
			Post (69-kV)	0.03	0.36	0.85	0.03	0.01
			Post (115-kV)	0.04	0.61	1.43	0.05	0.02
		System Peak	Pre-Project	0.03	0.07	0.98	0.03	0.00
			Post (69-kV)	0.03	0.36	0.85	0.03	0.01
			Post (115-kV)	0.04	0.60	1.41	0.05	0.02

Notes:
ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way; sh. = Sheet.

4 Conclusions

Gradient performed an independent EMF assessment for the National Grid 69-kV E5/F6 Line Rebuild Millbury No. 305 to Deerfield No. 4 Project, which involves reconductoring the existing 69-kV overhead E5 and F6 lines, including taps, and replacing the existing steel lattice tower structures between the Millbury No. 305 Substation in Millbury, Massachusetts, and the Deerfield No. 4 Substation in Deerfield, Massachusetts. The total Project route is approximately 67 miles in length (including the two tap lines to be refurbished). As discussed in this report, EMF modeling was conducted at a height of 1 meter (3.28 feet) above the ground surface for 8 representative ROW cross sections. EMF modeling was performed for a pre-Project case, as well as two post-Project cases, namely for an in-service year case assuming the E5 and F6 lines operate at 69-kV and for an in-service year case assuming the lines operate at 115-kV. For each case, EMF modeling was conducted for both annual average and system peak load levels.

As described in this report, our EMF modeling analysis demonstrated that all model-predicted, post-Project MF levels for the representative cross sections, including for both annual average and system peak load levels, are well below the ICNIRP health-based guideline for allowable public exposure to 60-Hz MF (2,000 mG; ICNIRP, 2010). Due in part to the higher post-Project load levels for both the E5 and F6 circuits, in particular for the 115-kV operation case, the Project will generally result in small increases to edge-of-ROW MF levels for the representative cross sections (frequently <1 mG and <1-2 mG for annual average and system peak load levels, respectively). The EMF modeling analysis also showed that, for the representative cross sections, all model-predicted, post-Project edge-of-ROW EF levels are well below the ICNIRP health-based guideline for allowable public exposure to 60-Hz EF (4.2 kV/m; ICNIRP, 2010). Our modeling analysis indicates that the Project will result in only small changes to EFs at the ROW edges across the modeling results (*i.e.*, all edge-of-ROW EF changes were ≤0.5 kV/m and <0.9 kV/m for the post-Project 69-kV and 115-kV operating cases, respectively).

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Appendix A

Project Route Overview Map and Representative Pre-Project and Post-Project ROW Overhead Line Cross Sections

PLAN VIEW MILLBURY TO DEERFIELD NO. 4 EMF OVERVIEW MAP

NOTES:
1. CROSS SECTION 2 IS REPRESENTATIVE OF MULTIPLE AREAS ON THE MAIN LINE. HOWEVER, SOME LOCATIONS HAVE A VARYING RIGHT OF WAY WIDTH, AS DISPLAYED ON B-13148-NE CROSS SECTION 8.
2. T20 LINE WILL BE DESIGNED TO ACCOMMODATE 115kV BUT OPERATED AT 69kV. FOR THE EMF ANALYSIS, 115kV SHOULD BE ASSUMED.

VER	DATE	VERSION DESCRIPTION	PREPARED	REVIEWED	APPROVED
1	11/03/23	ISSUED WITH EMF BID PACKAGE	PBR	ACW	LMD

VERSION 1

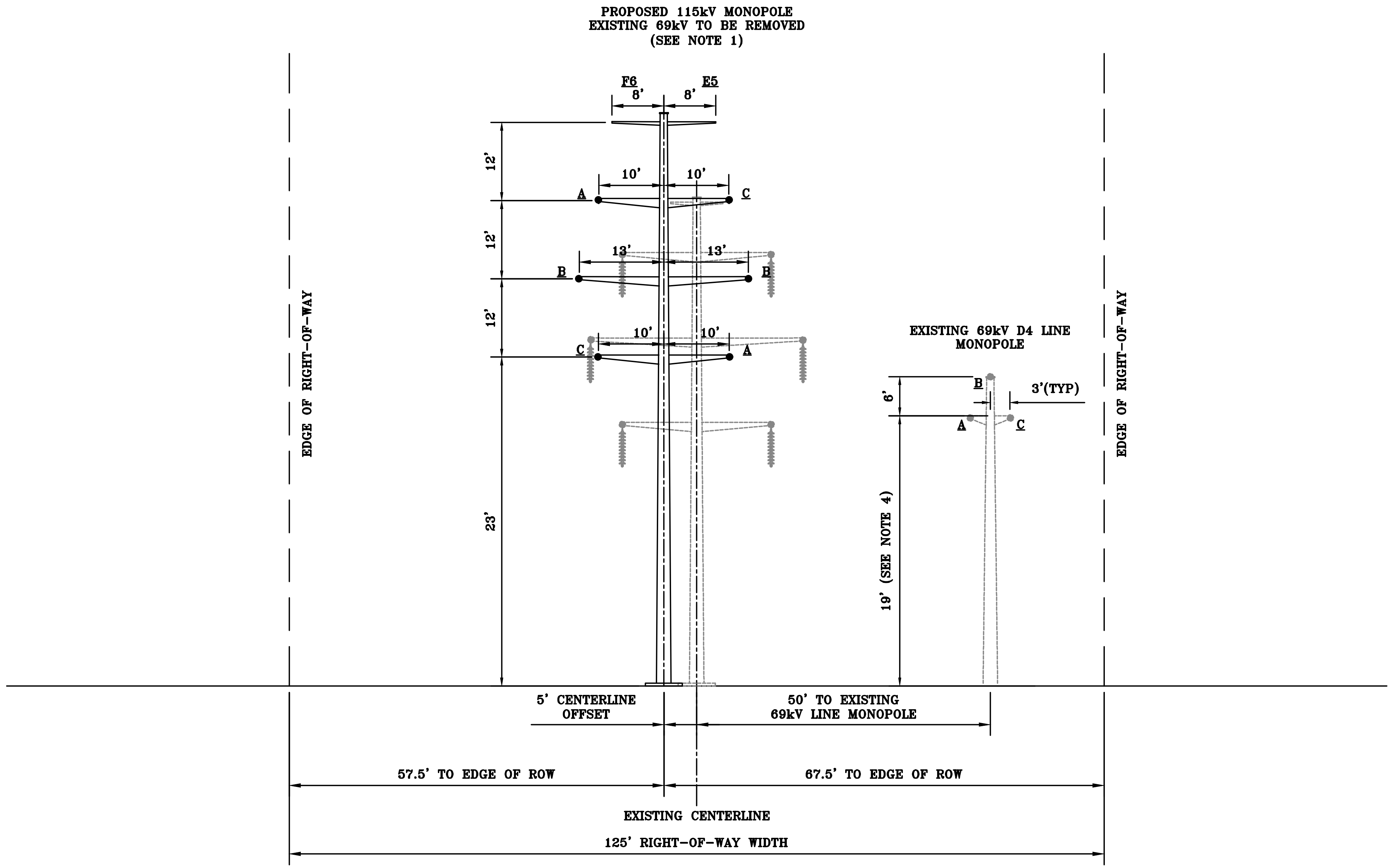
nationalgrid

PREPARED BY	PBR	11/03/23
REVIEWED BY	ACW	11/03/23
APPROVED BY	LMD	11/03/23
SCALE	NTS	
SHEET	1 OF 1	
INDEX		

E5/F6 LINE REBUILD & UPGRADE

MILLBURY TO DEERFIELD NO. 4 EMF OVERVIEW MAP

INCHES ON ORIGINAL



CROSS SECTION 1

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #4 SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.
4. THE WIRE SAG UNDER MAXIMUM OPERATING CONDITIONS FOR THE D4 LINE IS UNKNOWN, BUT IS ASSUMED AS CURRENT NESC CODE MINIMUM GROUND CLEARANCE FOR 69kV FOR LAND TRAVERSED BY VEHICLES.

NOT FOR CONSTRUCTION

nationalgrid

E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 1 OF 8 | DATE: 11/03/23

B-13148-NE

B-13148-NE

INCHES ON ORIGINAL

INCHES ON ORIGINAL

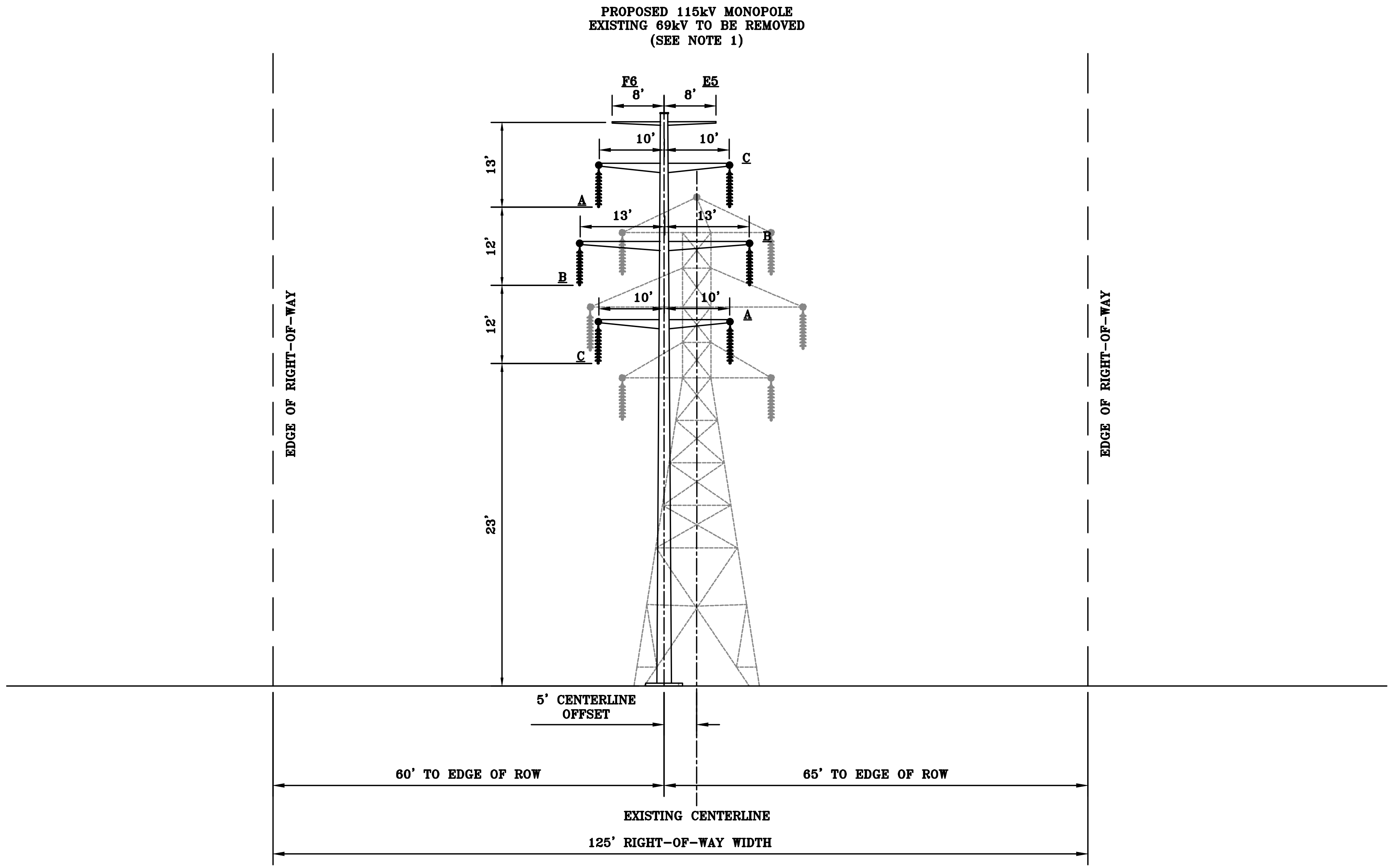
REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
1	11/03/23	ISSUED WITH EMF BID PACKAGE	AM	AW		LMD	
2							
3							
4							
5							
6							

ORIGINAL

DATE 11/03/23

DESIGNED	AM
CHECKED	AW
DRAWN	EAF
CHECKED	
REVIEWED	
APPROVED	LMD



CROSS SECTION 2

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #4 SUB

SEE EMF OVERVIEW 1 FOR STRUCTURE LOCATIONS

NOT FOR CONSTRUCTION

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.
4. DEADEND STRUCTURE LOCATIONS WILL HAVE SLIGHT VARIATION IN ARM LENGTH DUE TO LINE ANGLE.
5. DISTRIBUTION LINES ARE LOCATED ADJACENT TO SOME SPANS ON THE MAIN LINE, BUT ARE NOT INFREQUENT AND INTERMITTENT AND ARE THEREFORE NOT DEPICTED IN THE CROSS SECTION.
6. DUE TO CONSTRUCTION CONSIDERATIONS AT ANGLES, STRUCTURE PLACEMENT IN RIGHT-OF-WAY VARIES IN THESE LOCATIONS. THE CROSS SECTION SHOWN REPRESENTS MOST LOCATION ASSOCIATED WITH THIS CROSS SECTION. HOWEVER, ANGLE STRUCTURES MAY SEE LEFT EDGE OF RIGHT-OF-WAY REDUCED TO UP TO APPROXIMATELY 30 FT.
7. EXISTING RIGHT-OF-WAY WIDTH IN MANY AREAS OF THE LINE IS UNKNOWN OR UNDEFINED. THESE AREAS ARE ASSUMED TO HAVE A 125 FT WIDTH, CENTERED ON THE EXISTING LINE, BASED ON FEEDBACK FROM REAL ESTATE.

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E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS REV: 1 SHEET 2 OF 8 DATE: 11/03/23

INCHES ON ORIGINAL

INCHES ON ORIGINAL

B-13148-NE

REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
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ORIGINAL

DATE	11/03/23
DESIGNED	AM
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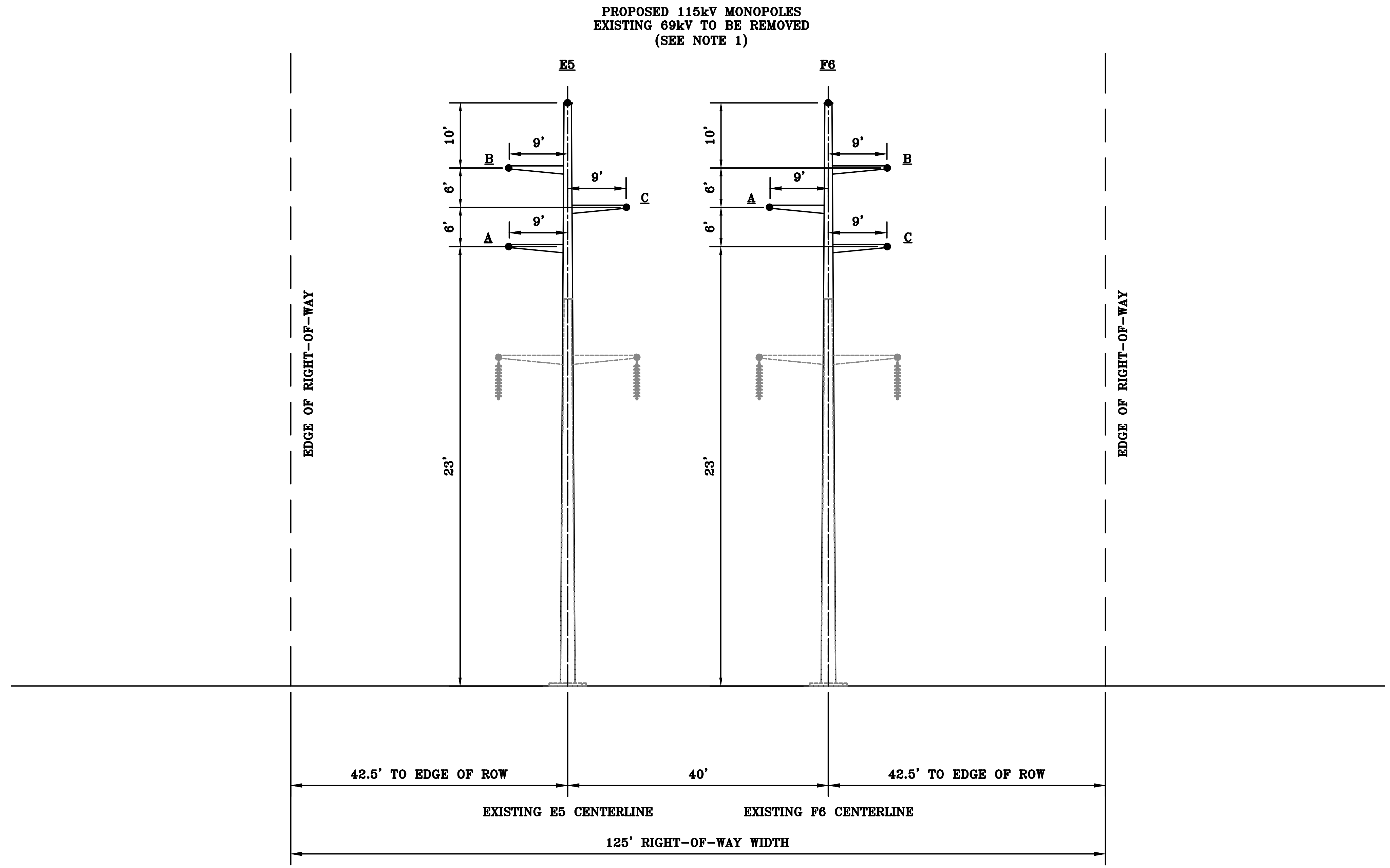
APPROVED	LMD

B-13148-NE



CROSS SECTION 3

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #3 SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69 kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.

NOT FOR CONSTRUCTION

nationalgrid

E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 3 OF 8 | DATE: 11/03/23

INCHES ON ORIGINAL

INCHES ON ORIGINAL

B-13148-NE

REVISIONS

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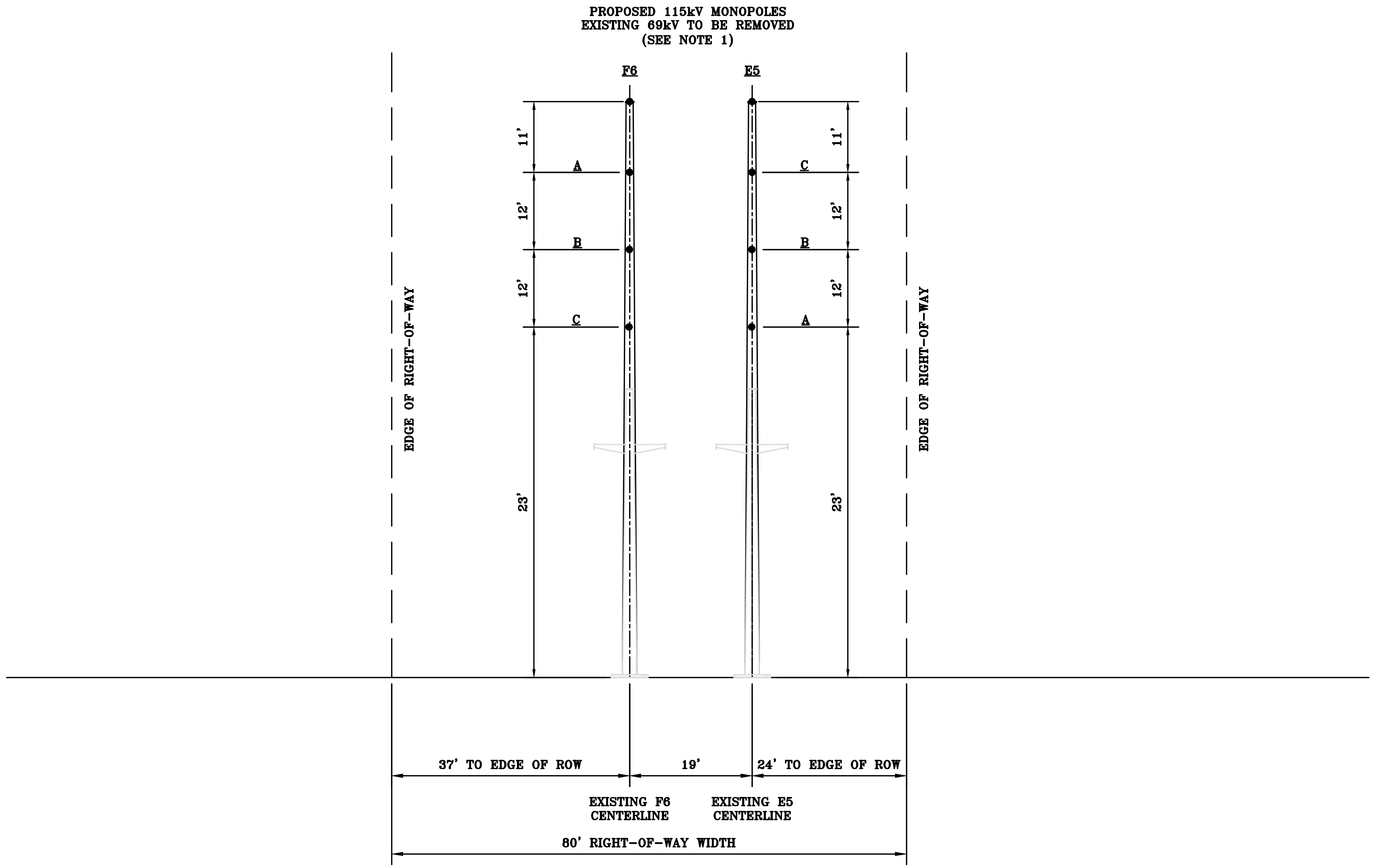

CROSS SECTION 4

LOOKING AHEAD ON LINE TOWARDS QUABBIN SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.

NOT FOR CONSTRUCTION

nationalgrid

E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 4 OF 8 | DATE: 11/03/23

B-13148-NE

INCHES ON ORIGINAL

REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
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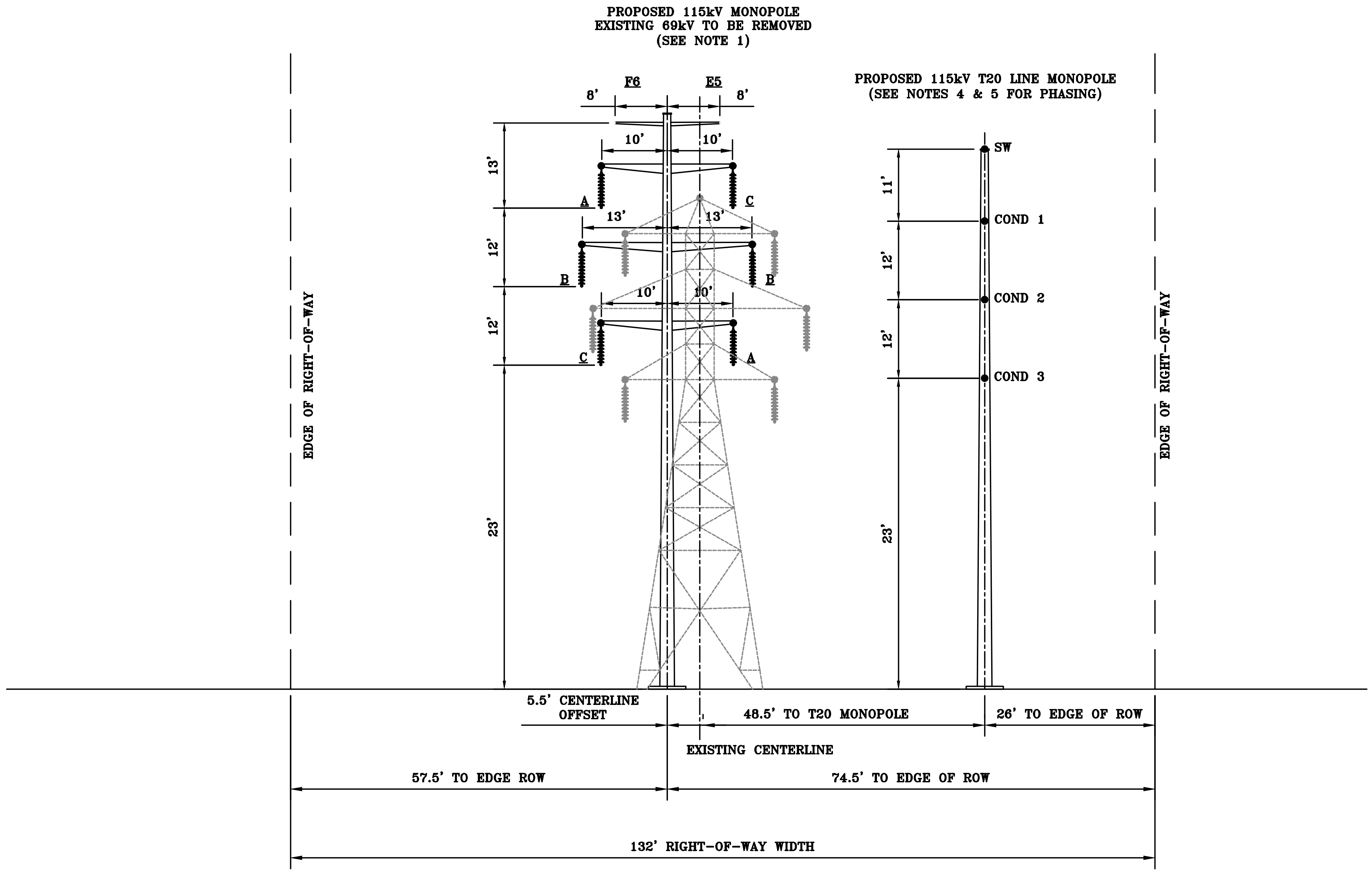
APPROVED	LMD

INCHES ON ORIGINAL



CROSS SECTION 5

LOOKING AHEAD ON LINE TOWARDS HARRINGTON SWITCHYARD

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.
4. THE T20 LINE WILL OPERATE AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS SHOULD ASSUME 115kV OPERATION. PHASING OF THIS LINE IS UNKNOWN. FOR THE PURPOSE OF THE ANALYSIS, THE PHASING CONFIGURATION WHICH GENERATES THE LARGEST EMF SHALL BE CONSIDERED,
5. T20 STRUCTURE FRAMING AND CENTERLINE DETAILS ARE PRELIMINARY.

NOT FOR CONSTRUCTION

nationalgrid

E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS REV: 1 SHEET 5 OF 8 DATE: 11/03/23

B-13148-NE

INCHES ON ORIGINAL

INCHES ON ORIGINAL

REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
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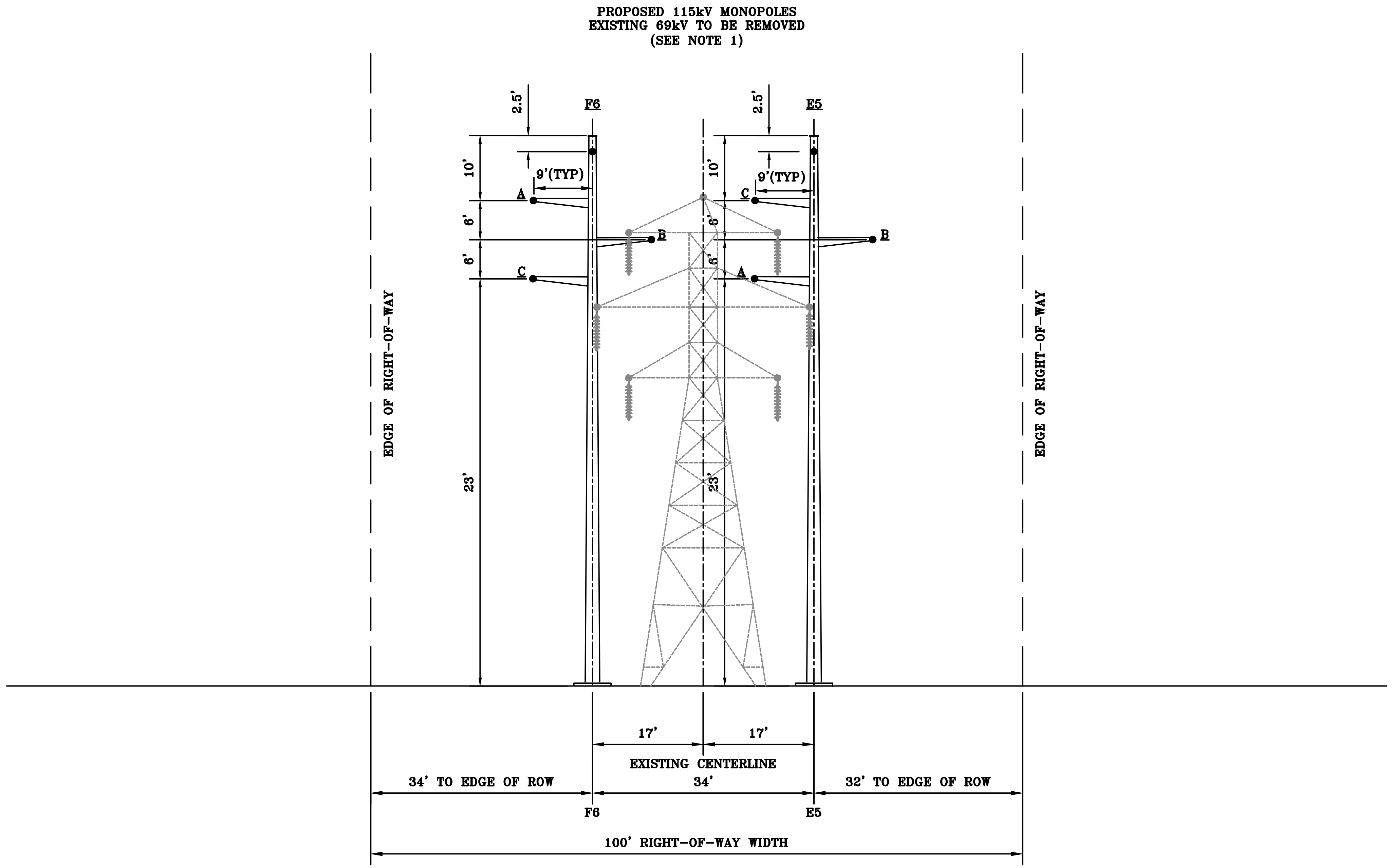

CROSS SECTION 6

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #4 SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.

NOT FOR CONSTRUCTION

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E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 6 OF 8 | DATE: 11/03/23

B-13148-NE

REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
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ORIGINAL DATE 11/03/23

DESIGNED	AM
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APPROVED	LMD

INCHES ON ORIGINAL

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REVISIONS

REV.	DATE	DESCRIPTION	MADE	CHECKED	INSPECTED	APPROVED	APPROVED
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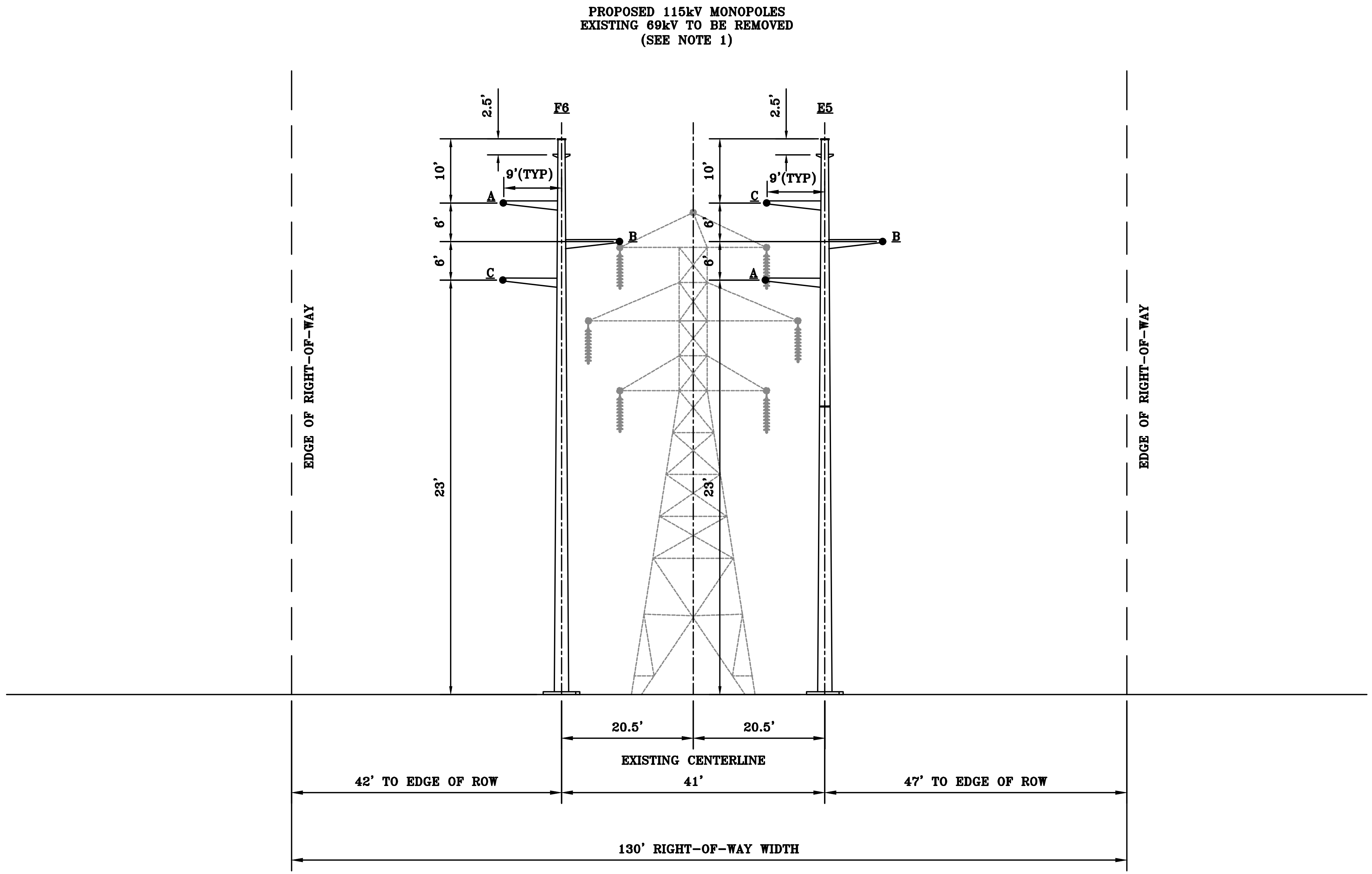
REVIEWED	
APPROVED	LMD



CROSS SECTION 7

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #4 SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.

NOT FOR CONSTRUCTION

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E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 7 OF 8 | DATE: 11/03/23

INCHES ON ORIGINAL

INCHES ON ORIGINAL

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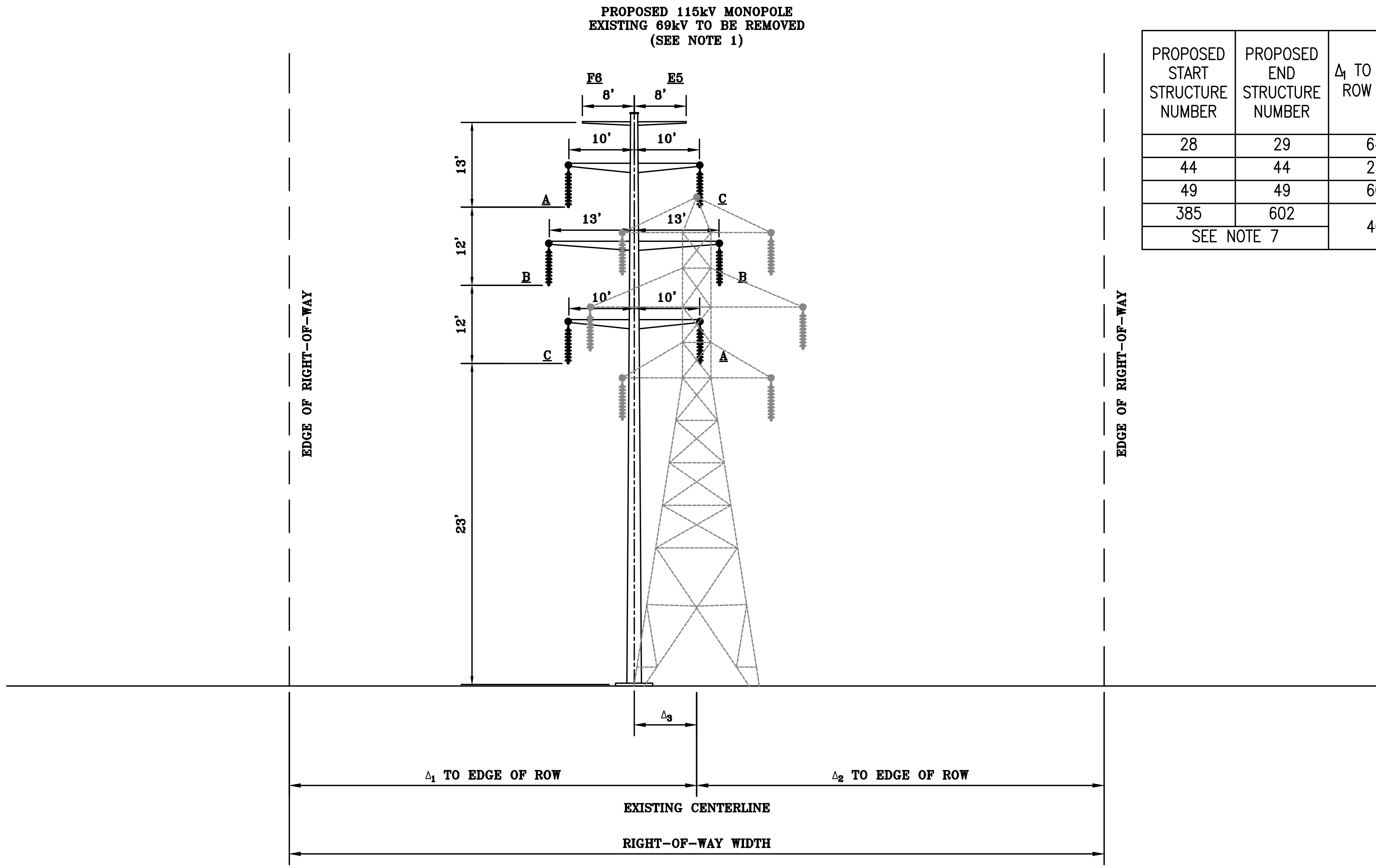
B-13148-NE



PROPOSED START STRUCTURE NUMBER	PROPOSED END STRUCTURE NUMBER	Δ_1 TO EDGE ROW (FT)	Δ_2 TO EDGE ROW (FT)	ROW WIDTH (FT)	PROPOSED STRUCTURE CENTERLINE OFFSET (Δ_3) (FT)
28	29	64	41	105	4.5
44	44	25	55	80	2
49	49	60	40	100	5
385	602	40	60	100	10
SEE NOTE 7					

CROSS SECTION 8

LOOKING AHEAD ON LINE TOWARDS DEERFIELD #4 SUB

SEE EMF OVERVIEW MAP FOR STRUCTURE LOCATIONS

NOTES:
1. PROPOSED E5/F6 LINES SHALL BE OPERATED AT 69kV BUT DESIGNED TO ACCOMMODATE 115kV. EMF ANALYSIS REQUIRED AT BOTH 69kV AND 115kV VOLTAGES.
2. SEE TABLES IN APPENDIX FOR EXISTING STRUCTURE GEOMETRY.
3. PHASE SPACING FROM CIRCUIT TO CIRCUIT MAY SLIGHTLY VARY FROM DIMENSIONS SHOWN DEPENDING ON PROPOSED POLE DIAMETERS, WHICH HAVE NOT YET BEEN DETERMINED.
4. DEADEND STRUCTURE LOCATIONS WILL HAVE SLIGHT VARIATION IN ARM LENGTH DUE TO LINE ANGLE.
5. DISTRIBUTION LINES ADJACENT TO SOME SPANS ON THE MAIN LINE, BUT ARE INFREQUENT AND INTERMITTENT AND ARE THEREFORE NOT DEPICTED IN THE CROSS SECTION.
6. LOCATIONS IN TABLE ABOVE ONLY CONSIDER UNIQUE RIGHT-OF-WAY AREAS WHERE WIDTH IS LESS THAN 125 FT. WIDER EASEMENTS ARE NOT LISTED AS THE EMF AT EDGE OF RIGHT-OF-WAY WOULD BE REDUCED COMPARED TO THE SCENARIO SHOWN IN SHEET 2. REDUCED EASEMENT WIDTH SOUTHEAST OF PONDVILLE SUSTATION NOT INCLUDED DUE TO EASEMENT ACQISITION BEING UNDERWAY.
7. 100 FT ROW OCCURS INTERMITTENTLY FROM STR.385 TO STR.602.

NOT FOR CONSTRUCTION

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E5/F6 LINE REBUILD & UPGRADE
MILLBURY SUB TO DEERFIELD #4 SUB
69kV TRANSMISSION LINE
EMF CROSS SECTION DRAWINGS

SCALE: NTS | REV: 1 | SHEET 8 OF 8 | DATE: 11/03/23

B-13148-NE

INCHES ON ORIGINAL

REVISIONS

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DATE 11/03/23

DESIGNED	CHECKED	DRAWN	CHECKED	REVIEWED	APPROVED
AM	AW	EAF			LMD

INCHES ON ORIGINAL

Appendix B

Magnetic Field Profiles for Each Representative ROW Cross Section

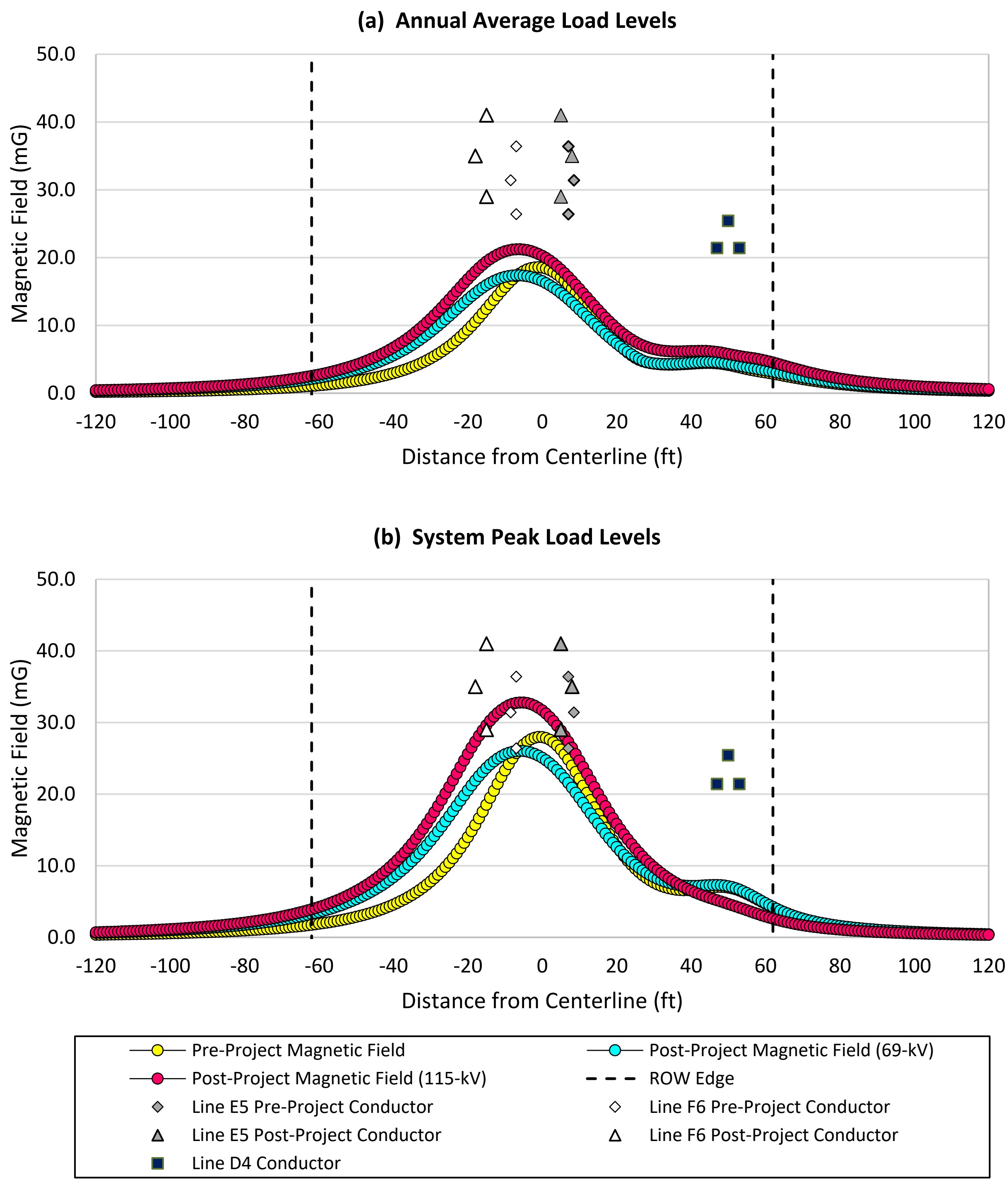

Figure B.1 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 1 (B-13148-NE Sheet 1, ROW Segment from Deerfield No. 4 Substation). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

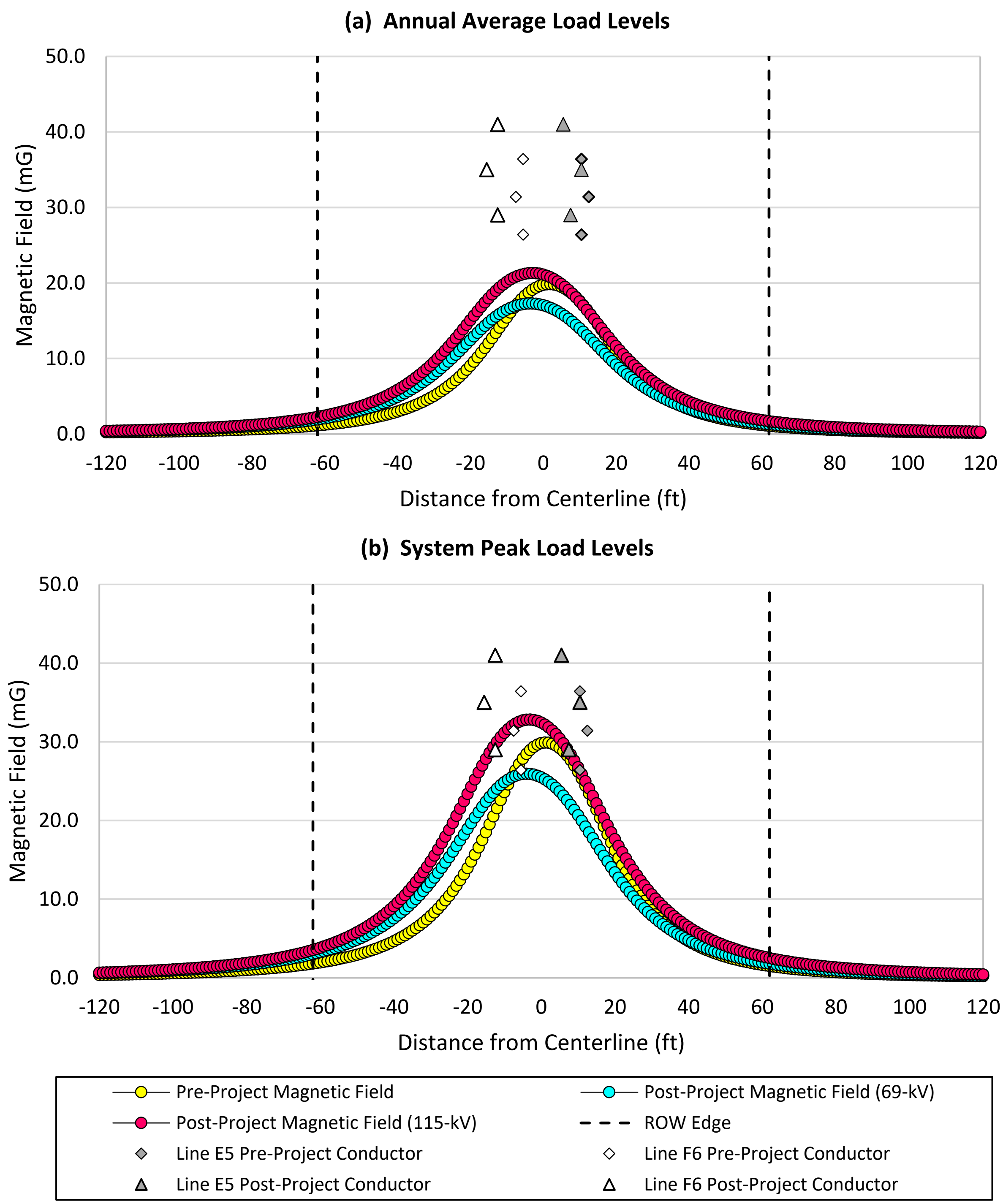

Figure B.2 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 4 to Deerfield 3 Tap). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

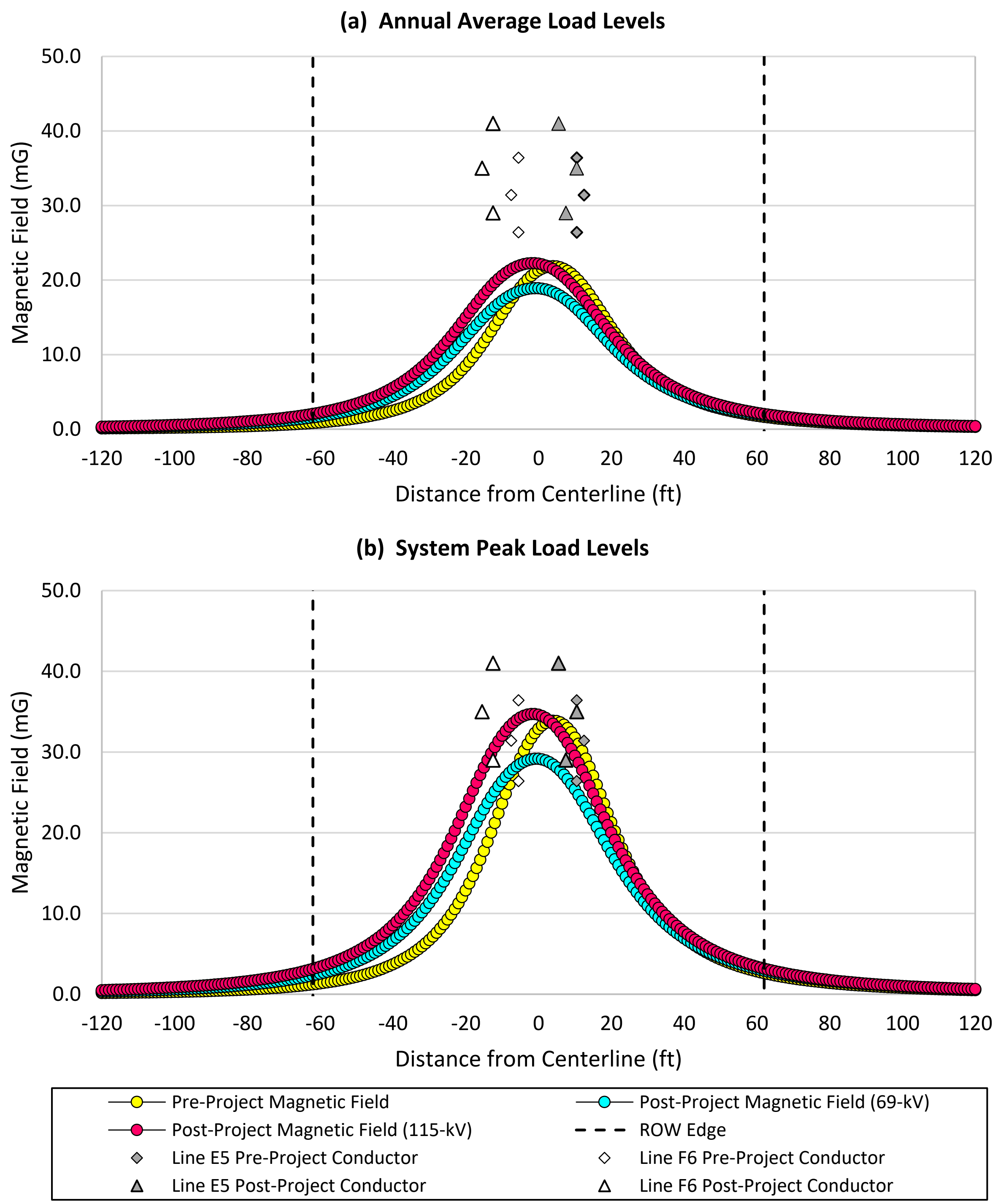

Figure B.3 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 3 Tap to Deerfield 2). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

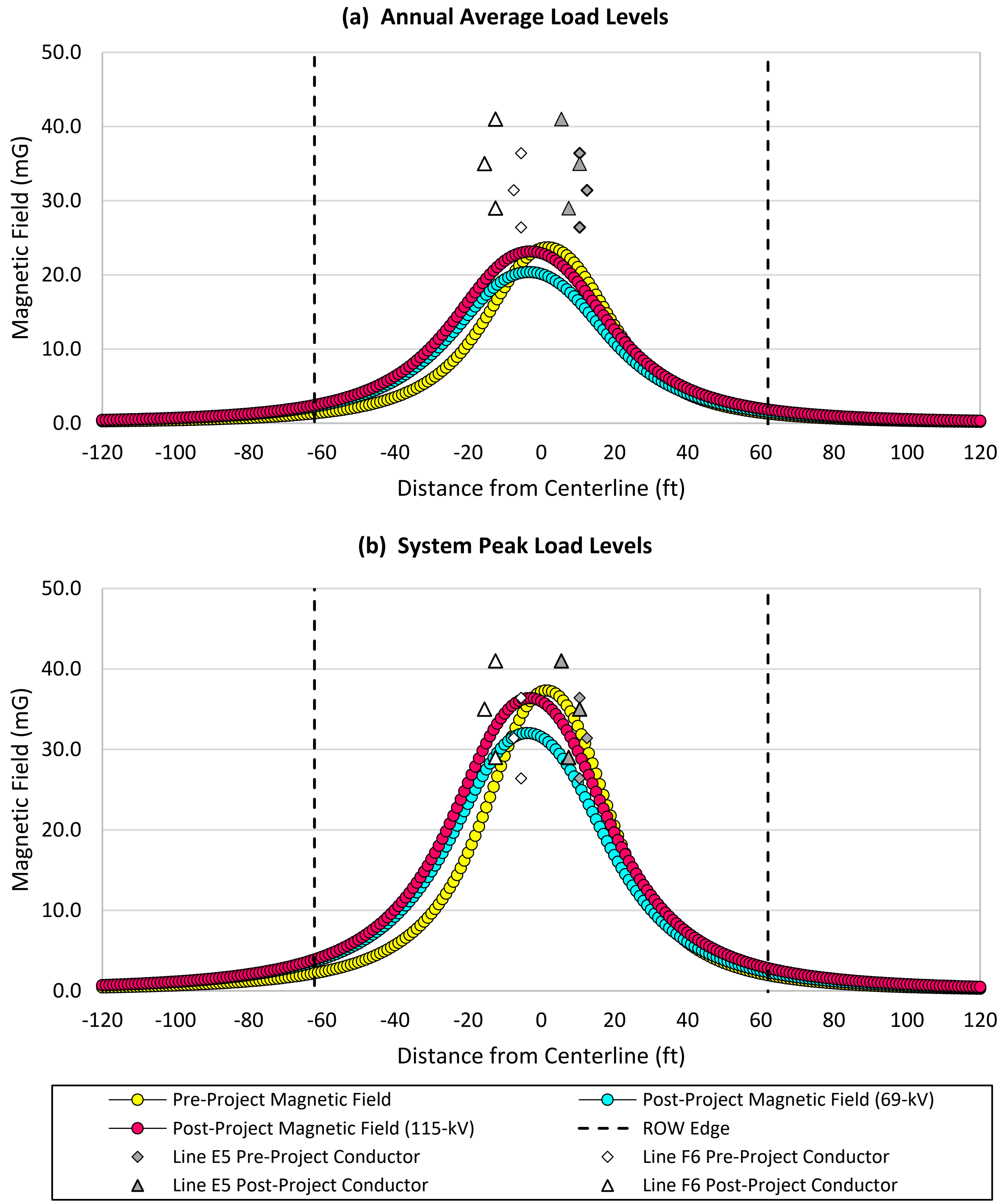

Figure B.4 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

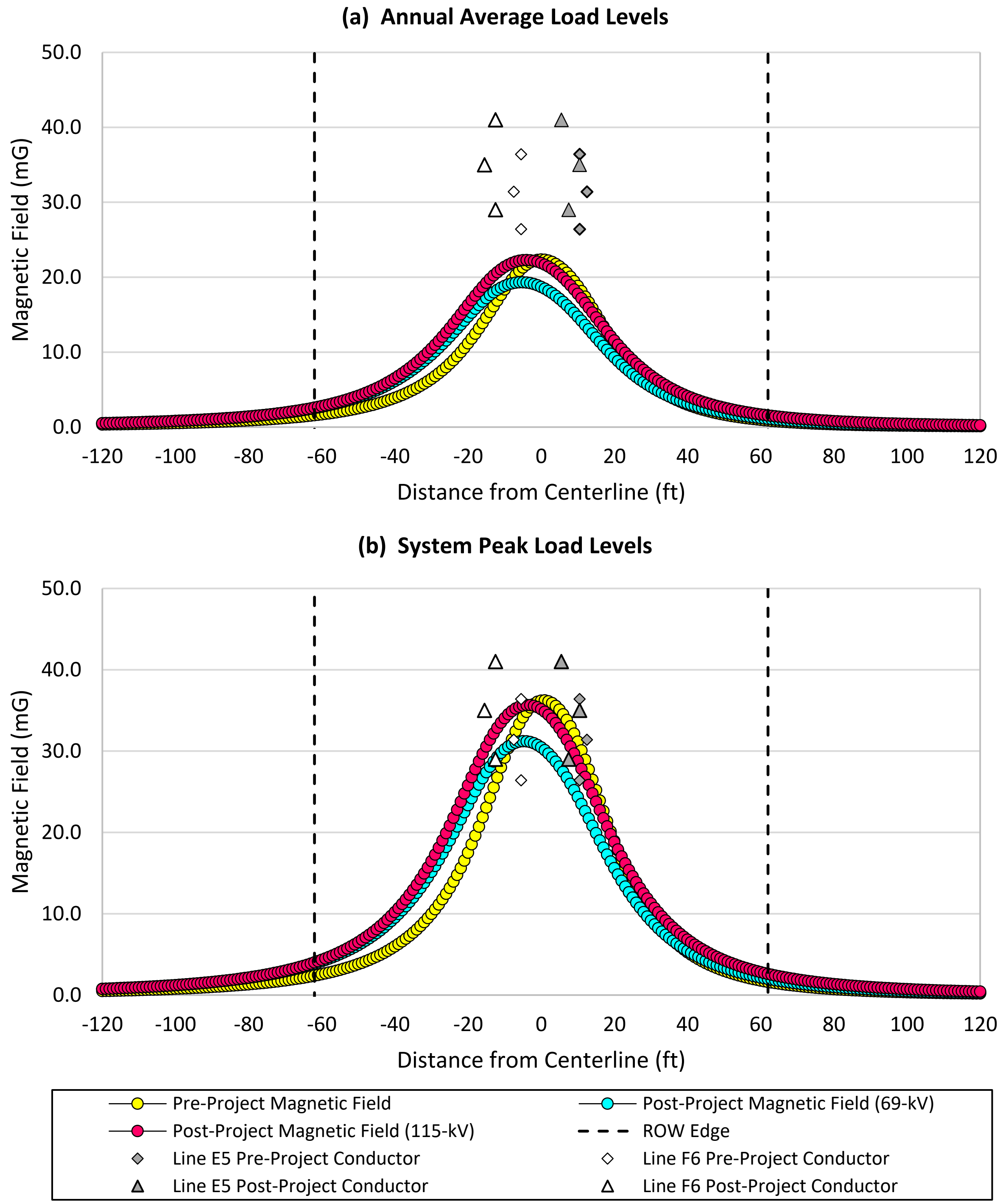

Figure B.5 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Shutesbury to Quabbin Switch Tap). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

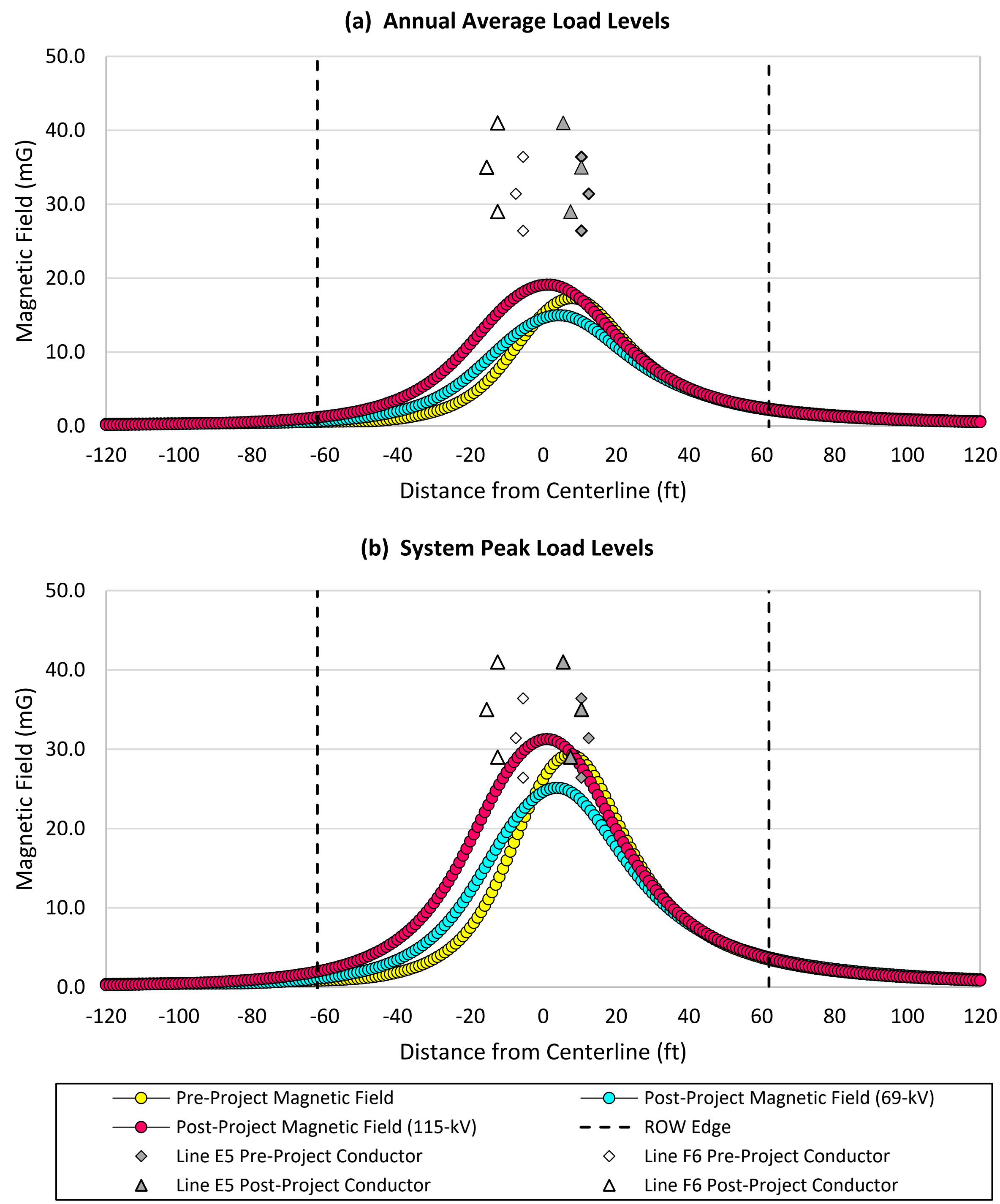

Figure B.6 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Quabbin Switch Tap to Ware). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

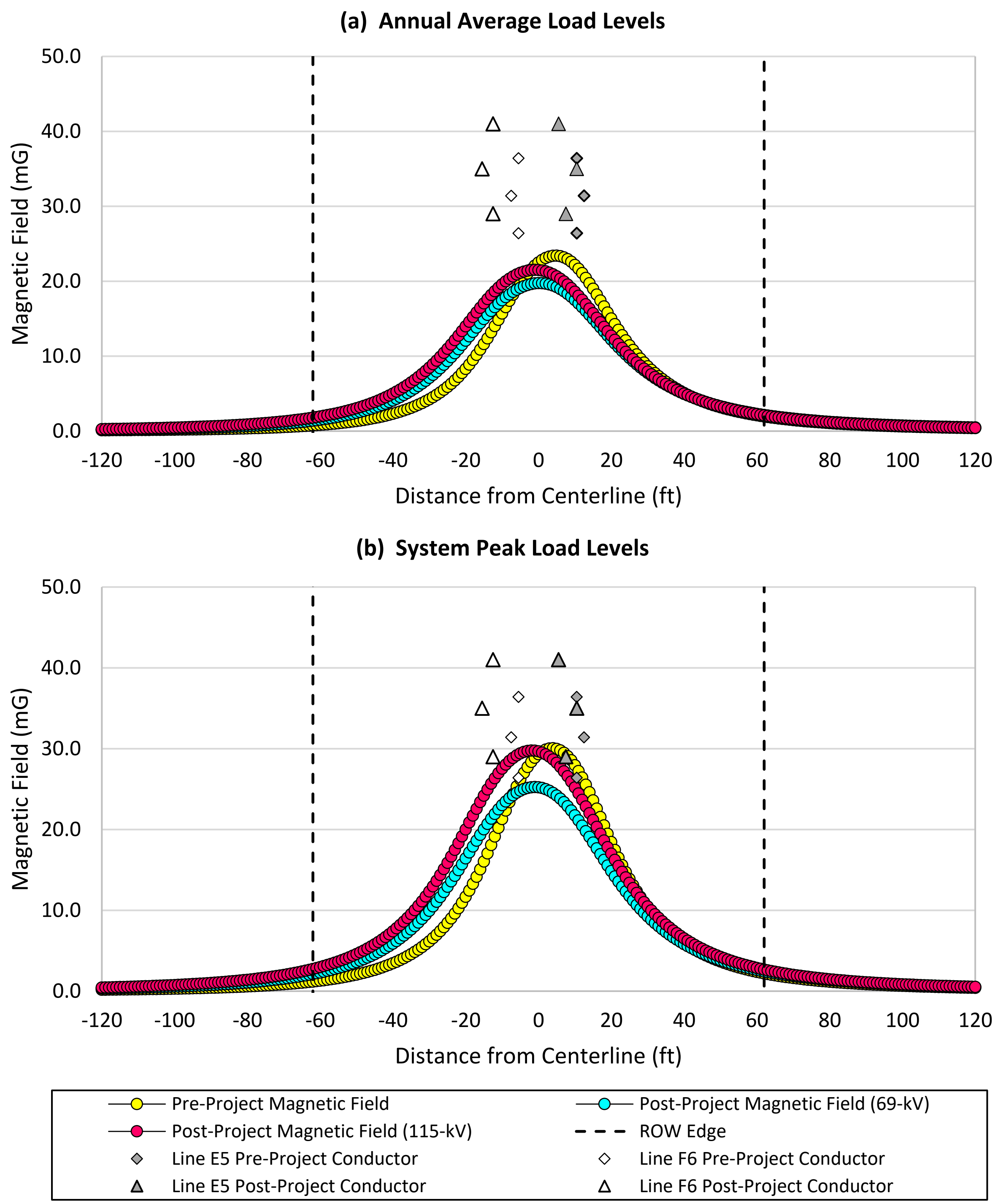

Figure B.7 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Ware to Lashaway). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

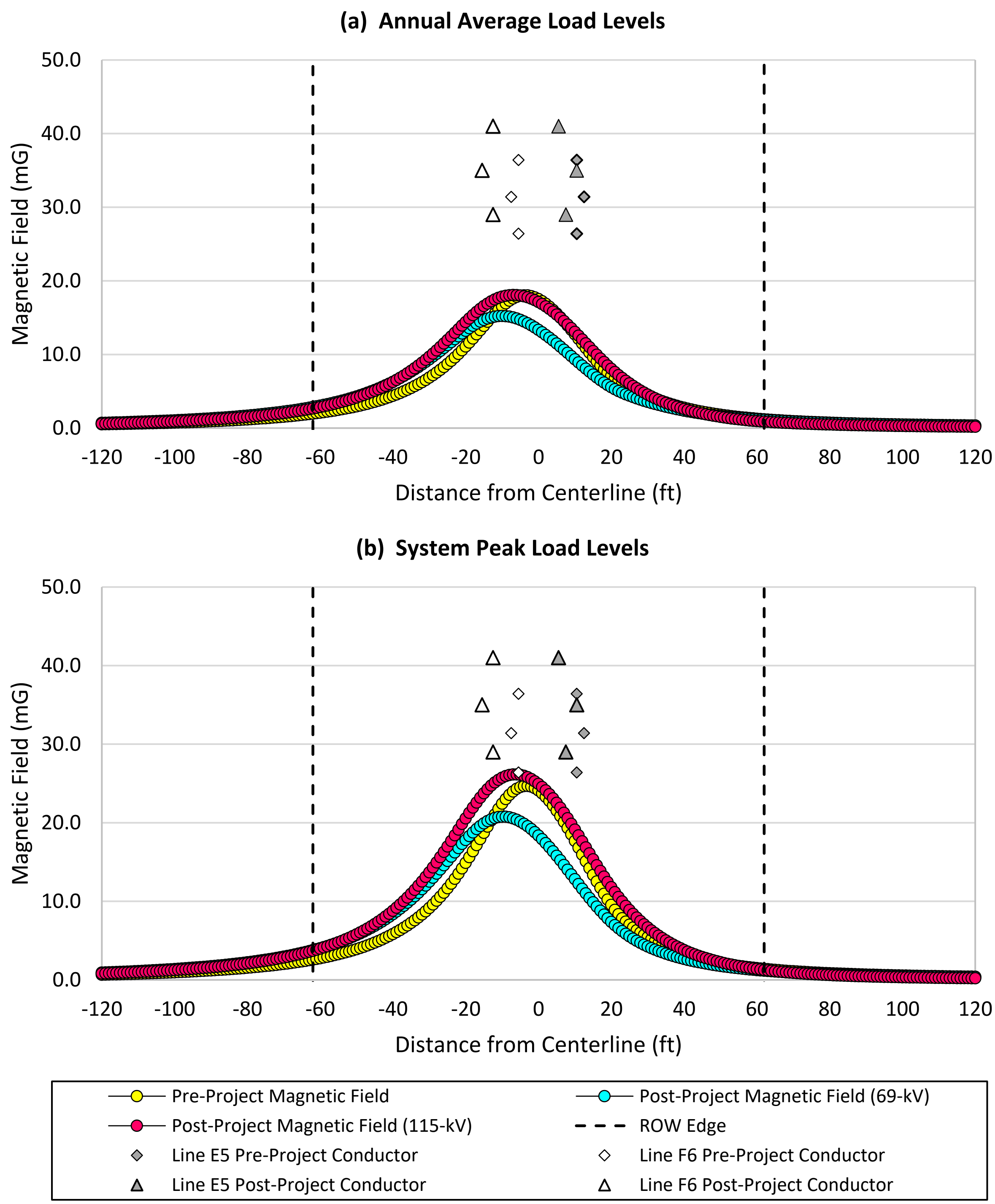

Figure B.8 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Lashaway to Harrington St). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

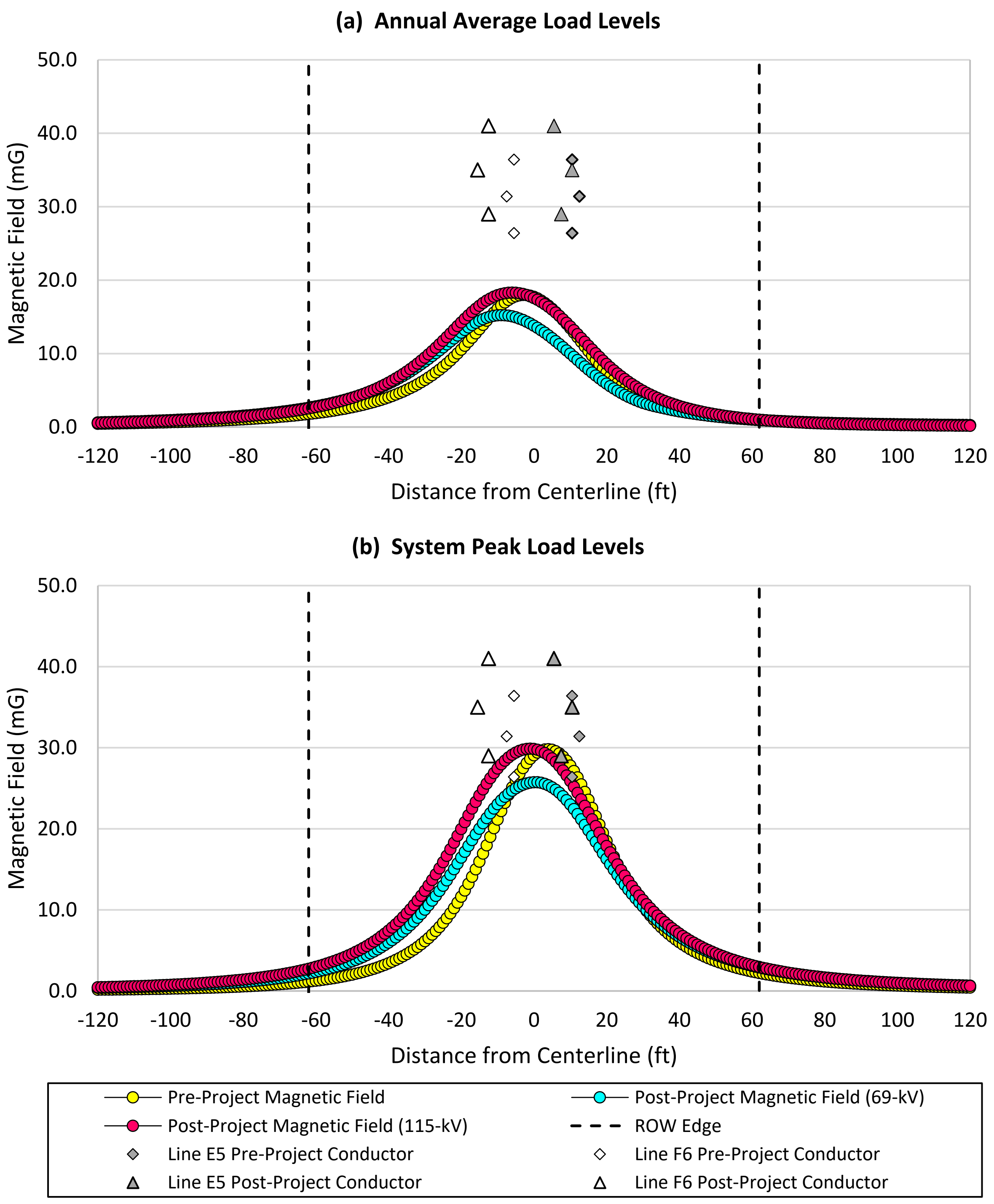

Figure B.9 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Harrington St to Meadow St). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

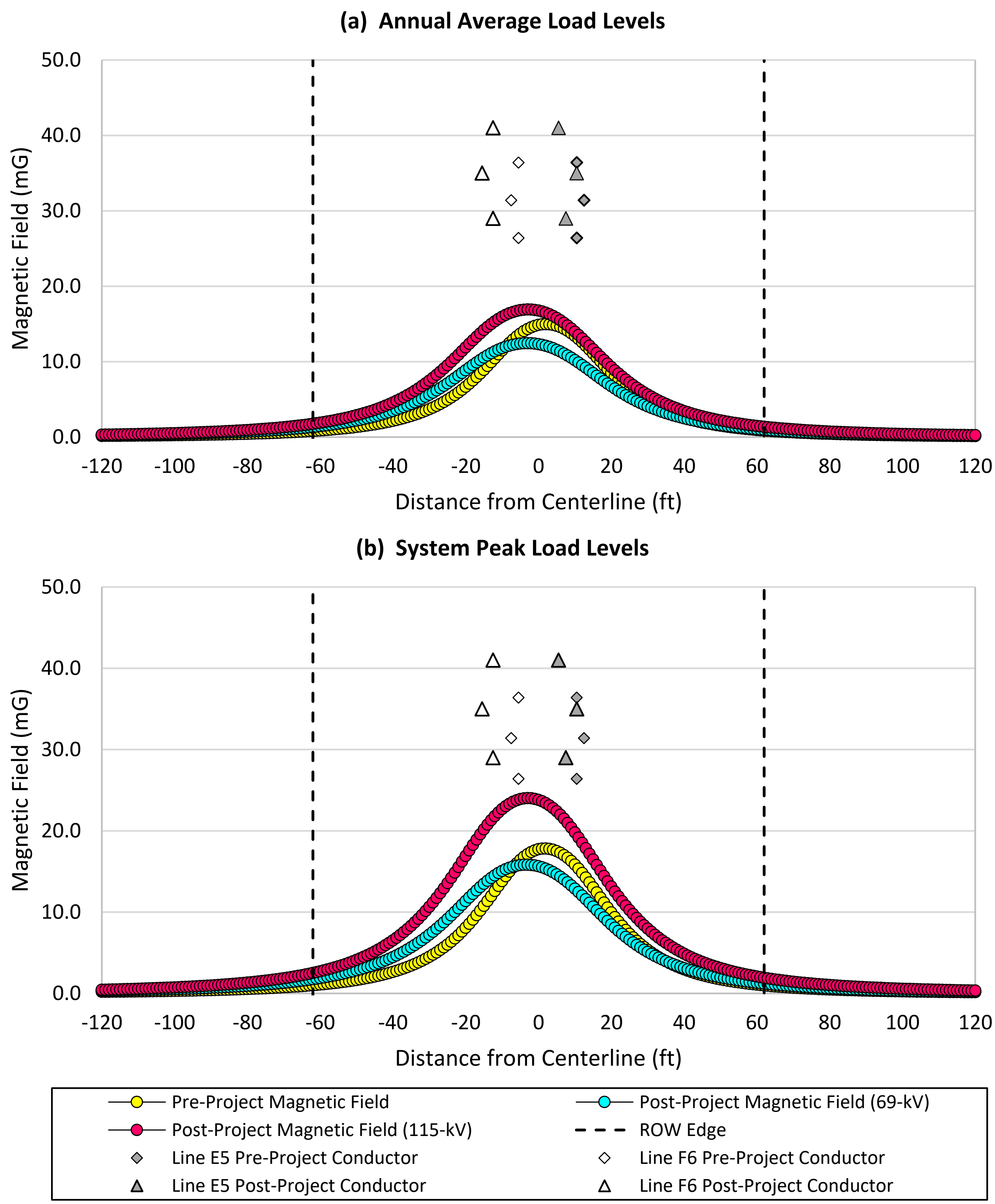

Figure B.10 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Meadow St to Leicester). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

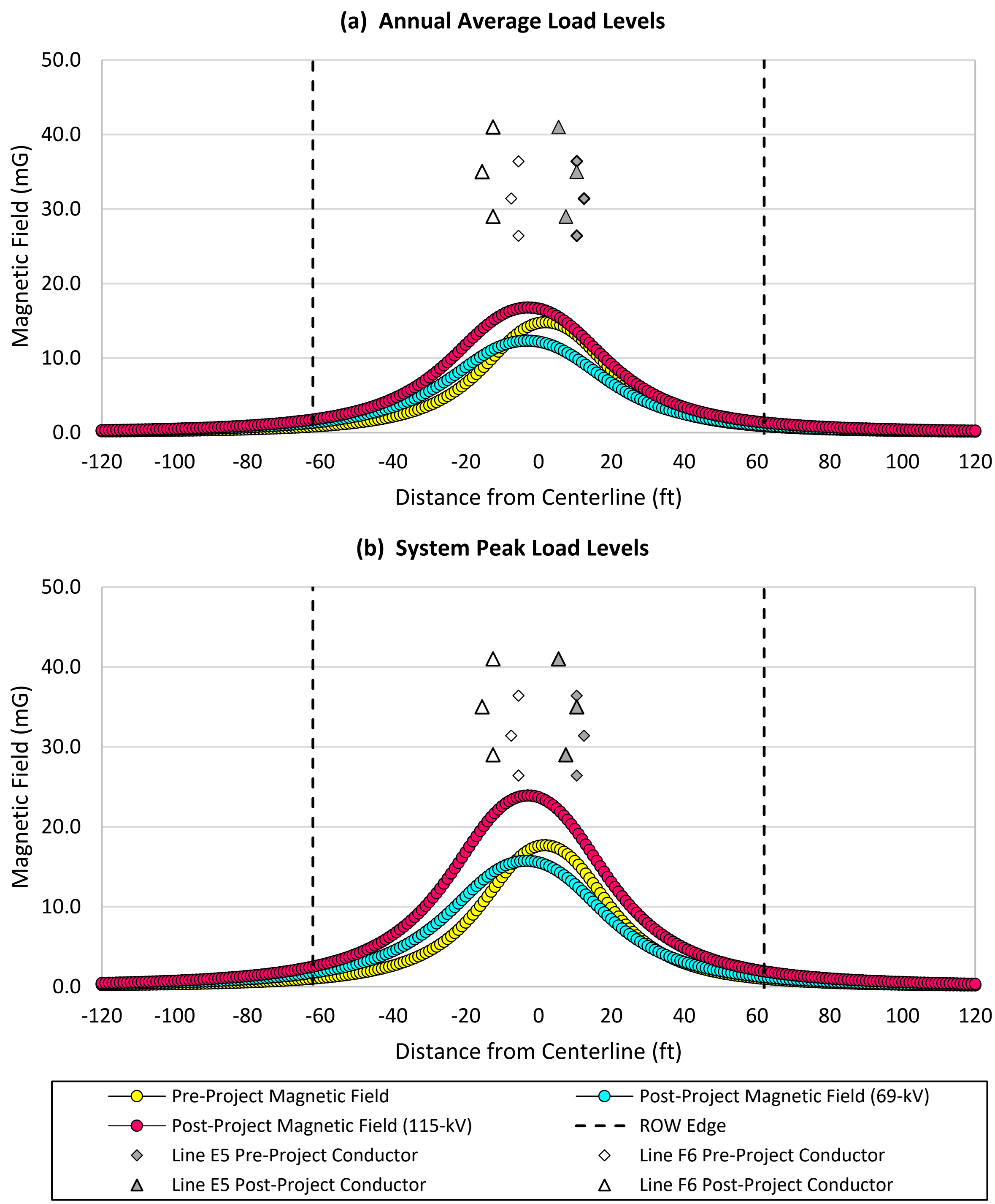

Figure B.11 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Leicester to Pondville). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

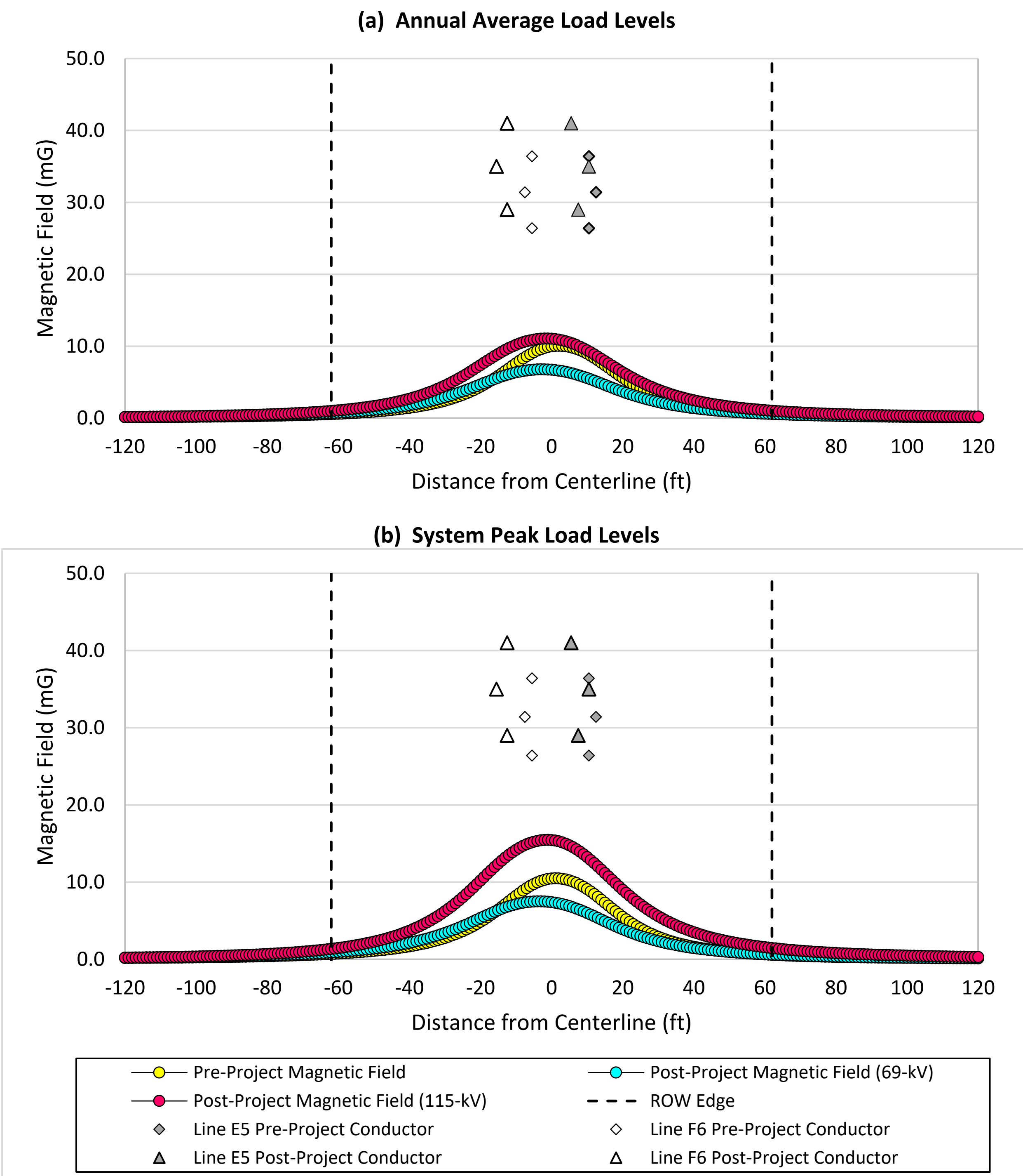

Figure B.12 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Pondville to Millbury). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

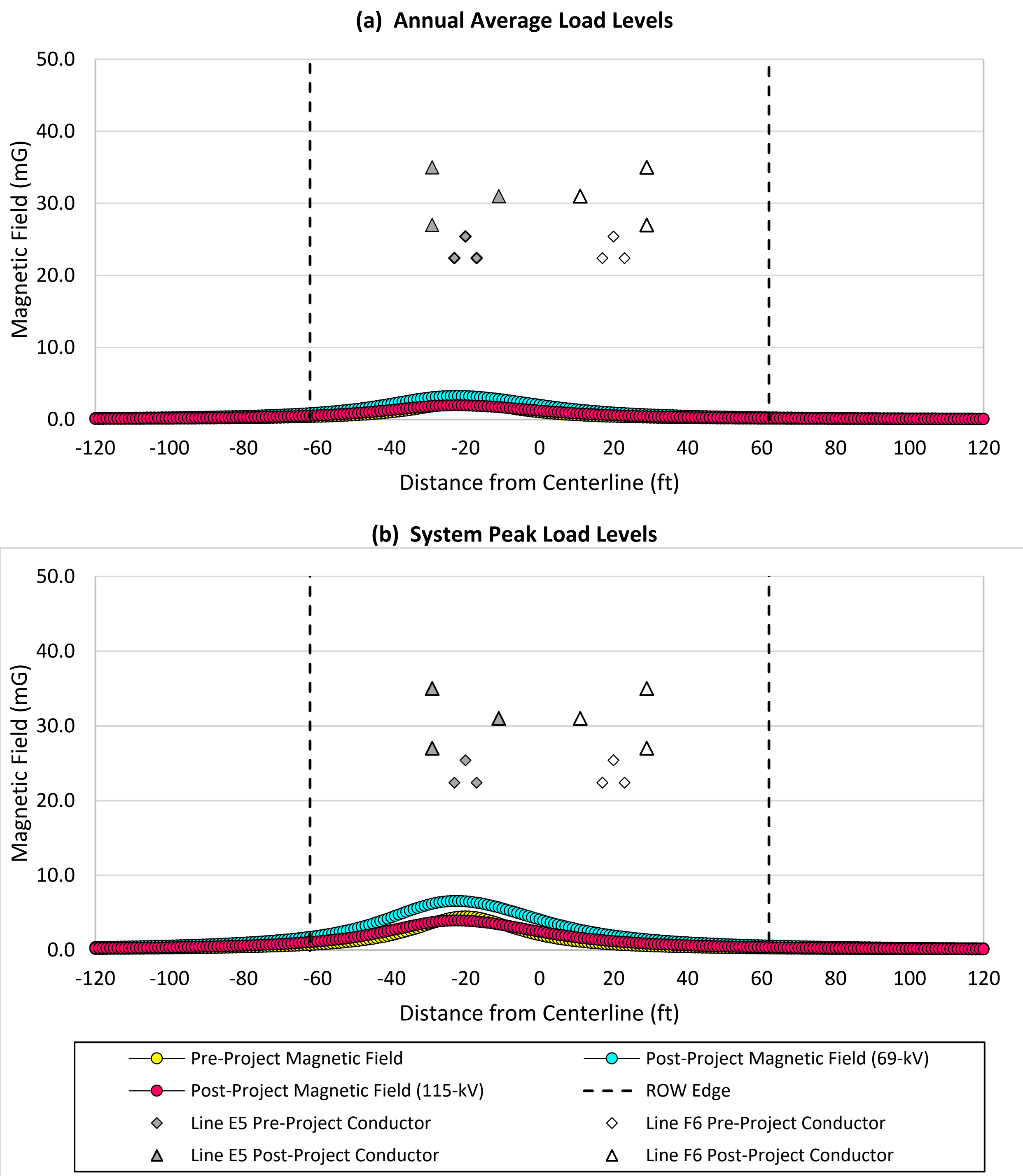

Figure B.13 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 3 (B-13148-NE Sheet 3, ROW Segment from Deerfield 3 Tap). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

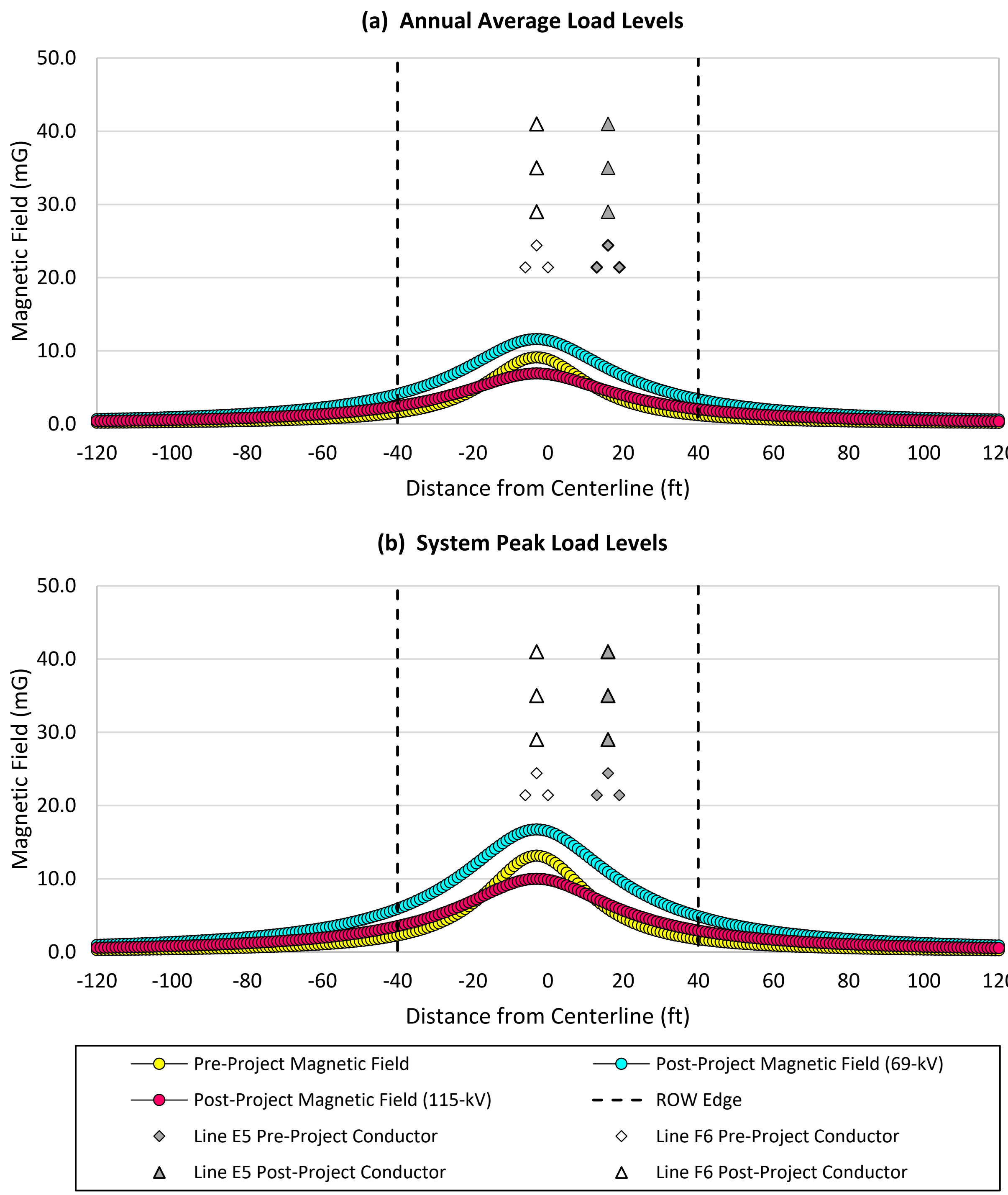

Figure B.14 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 4 (B-13148-NE Sheet 4, ROW Segment from Quabbin Switch Tap). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

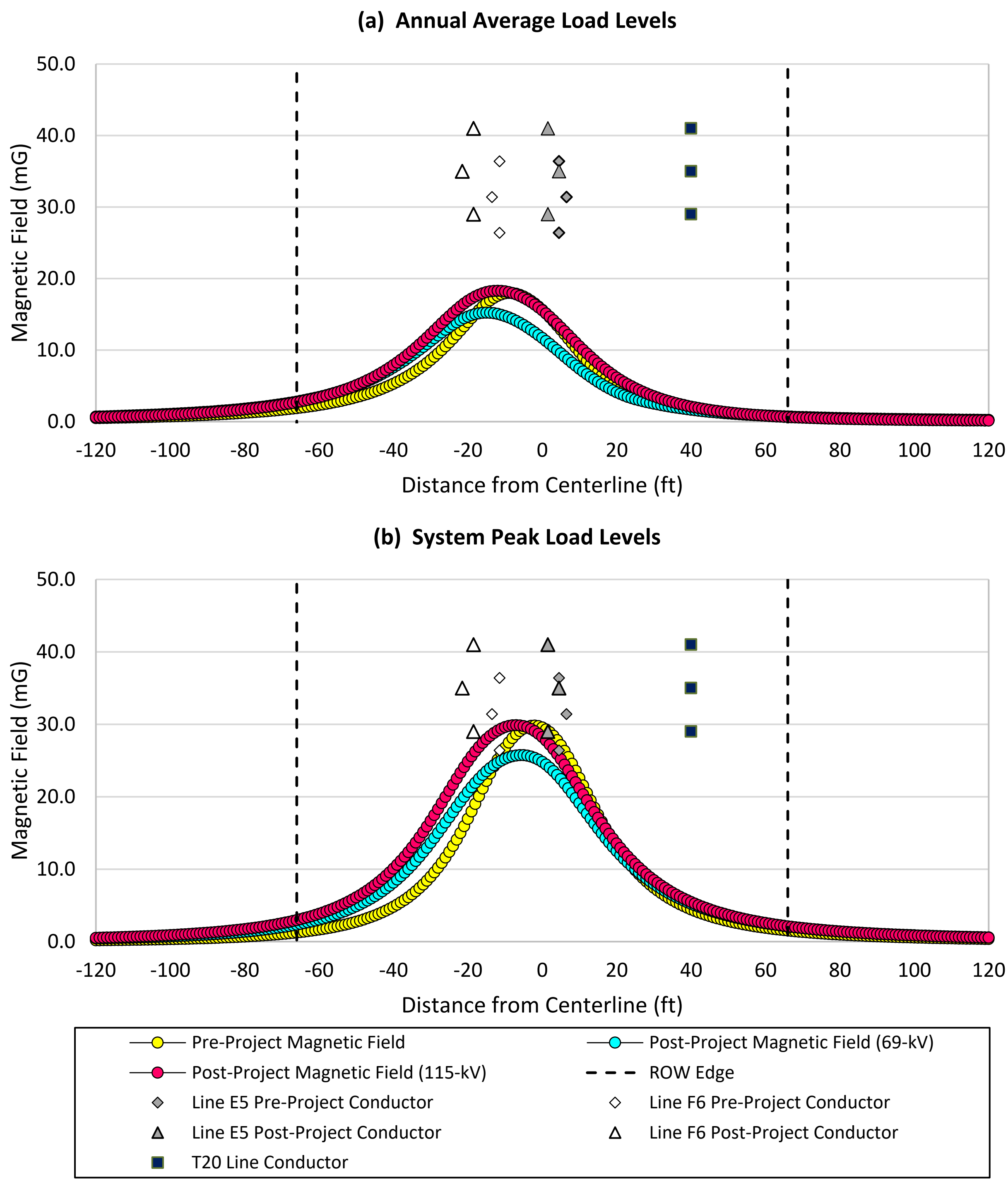

Figure B.15 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 5 (B-13148-NE Sheet 5, ROW Segment from Harrington St to Meadow St). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

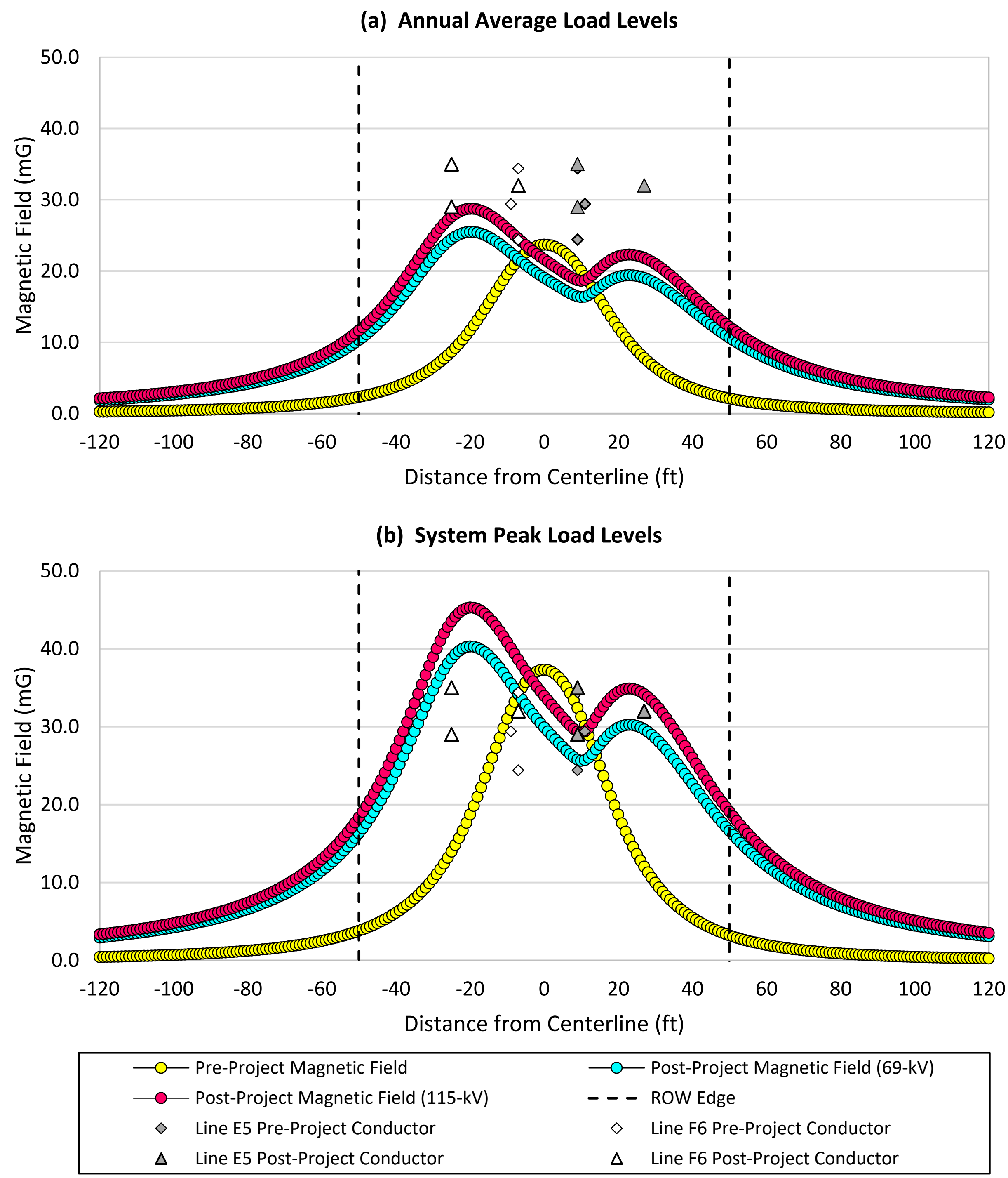

Figure B.16 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 6 (B-13148-NE Sheet 6, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

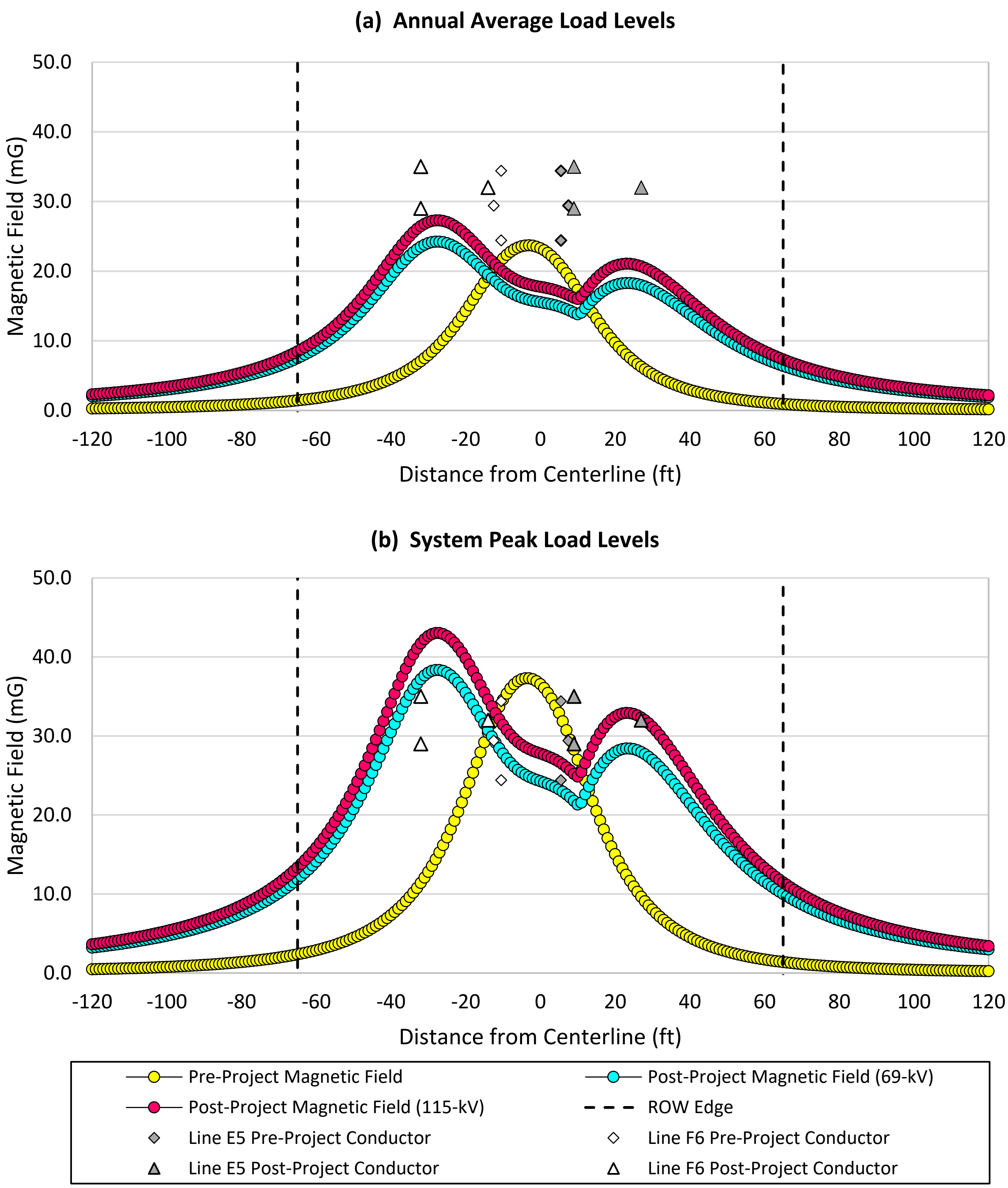

Figure B.17 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 7 (B-13148-NE Sheet 7, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

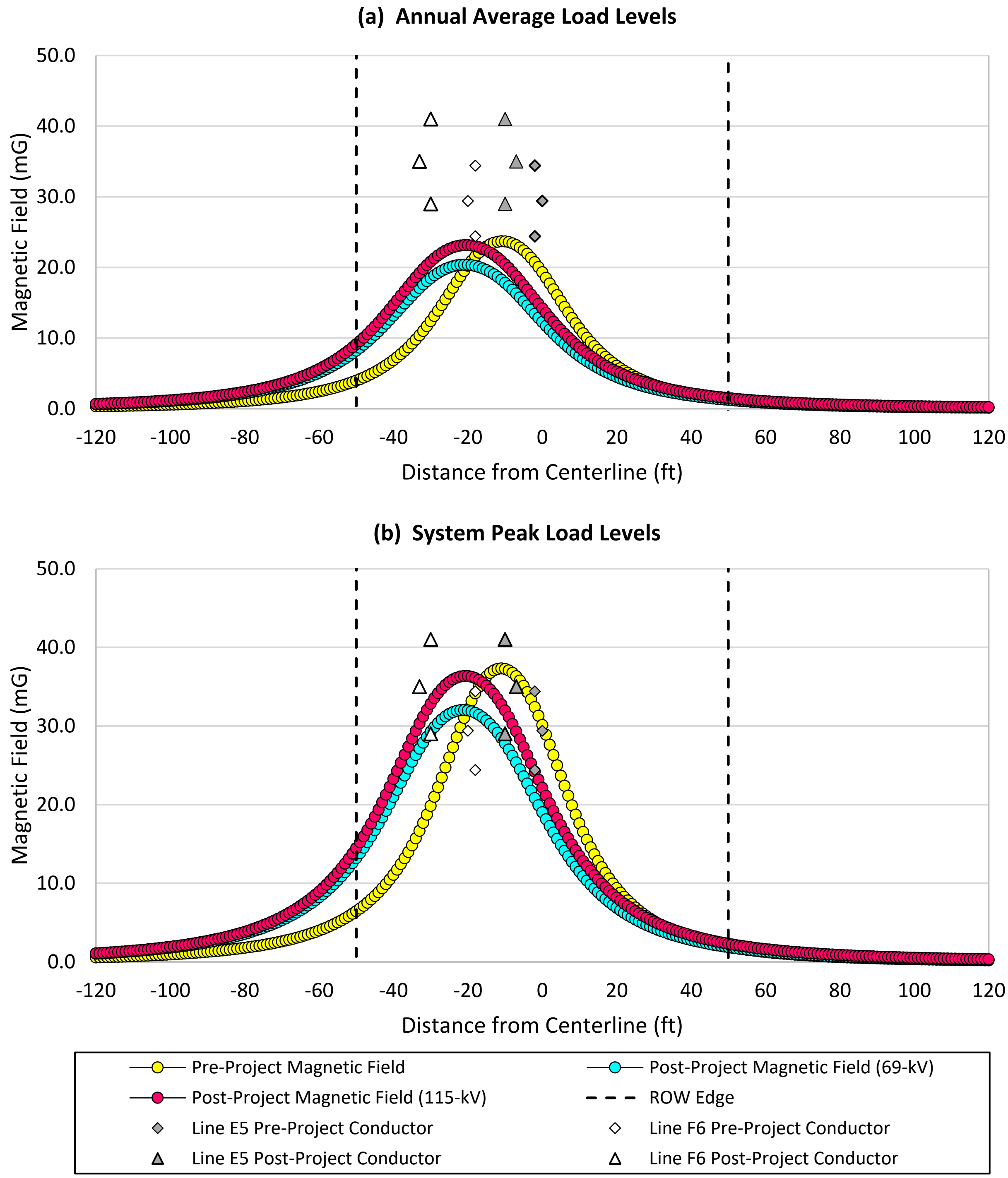

Figure B.18 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 8 (B-13148-NE Sheet 8, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

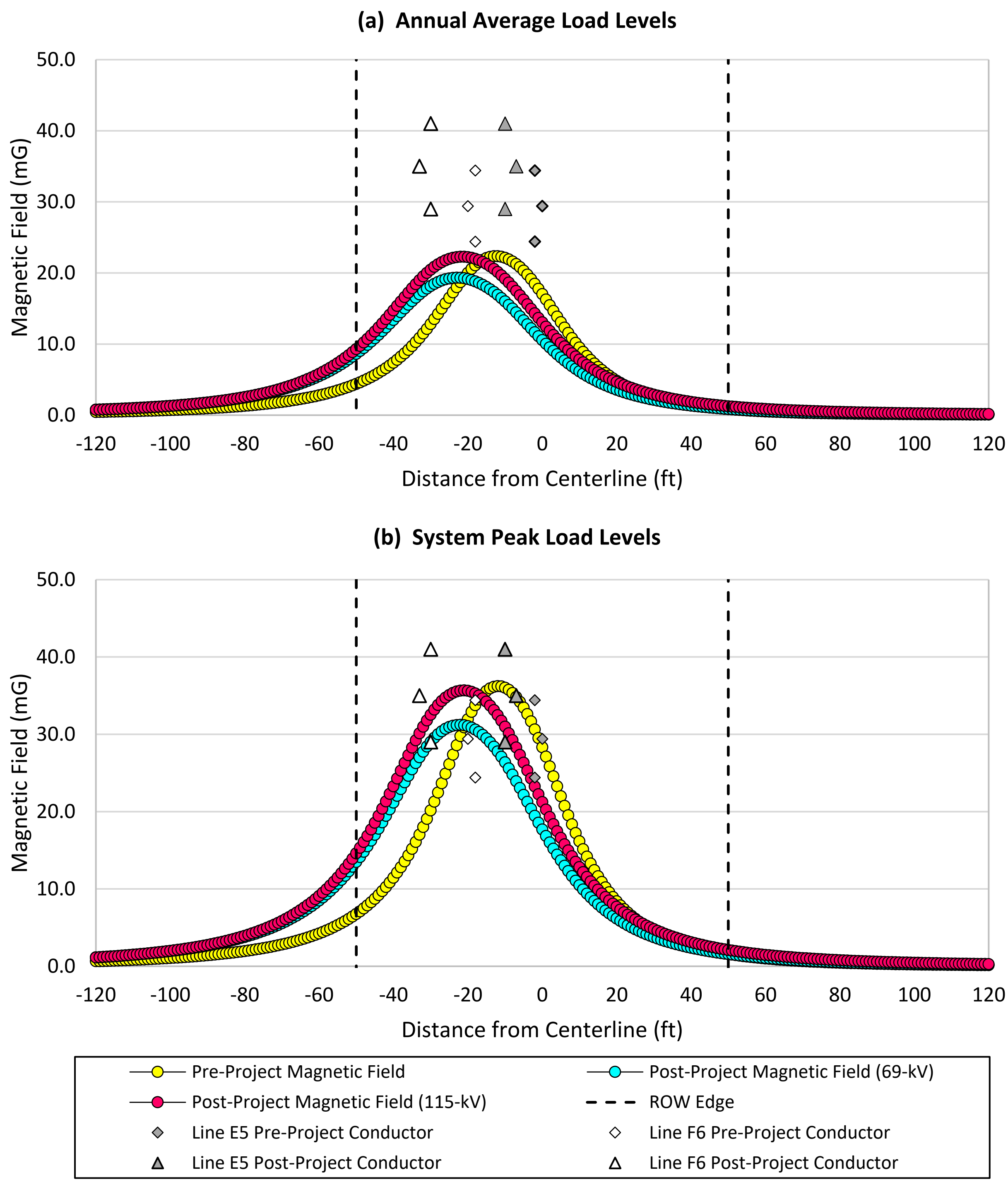

Figure B.19 Magnetic Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 8 (B-13148-NE Sheet 8, ROW Segment from Shutesbury to Quabbin Switch Tap). ft = Feet; kV = Kilovolt; mG = Milligauss; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

Appendix C

Electric Field Profiles for Each Representative ROW Cross Section

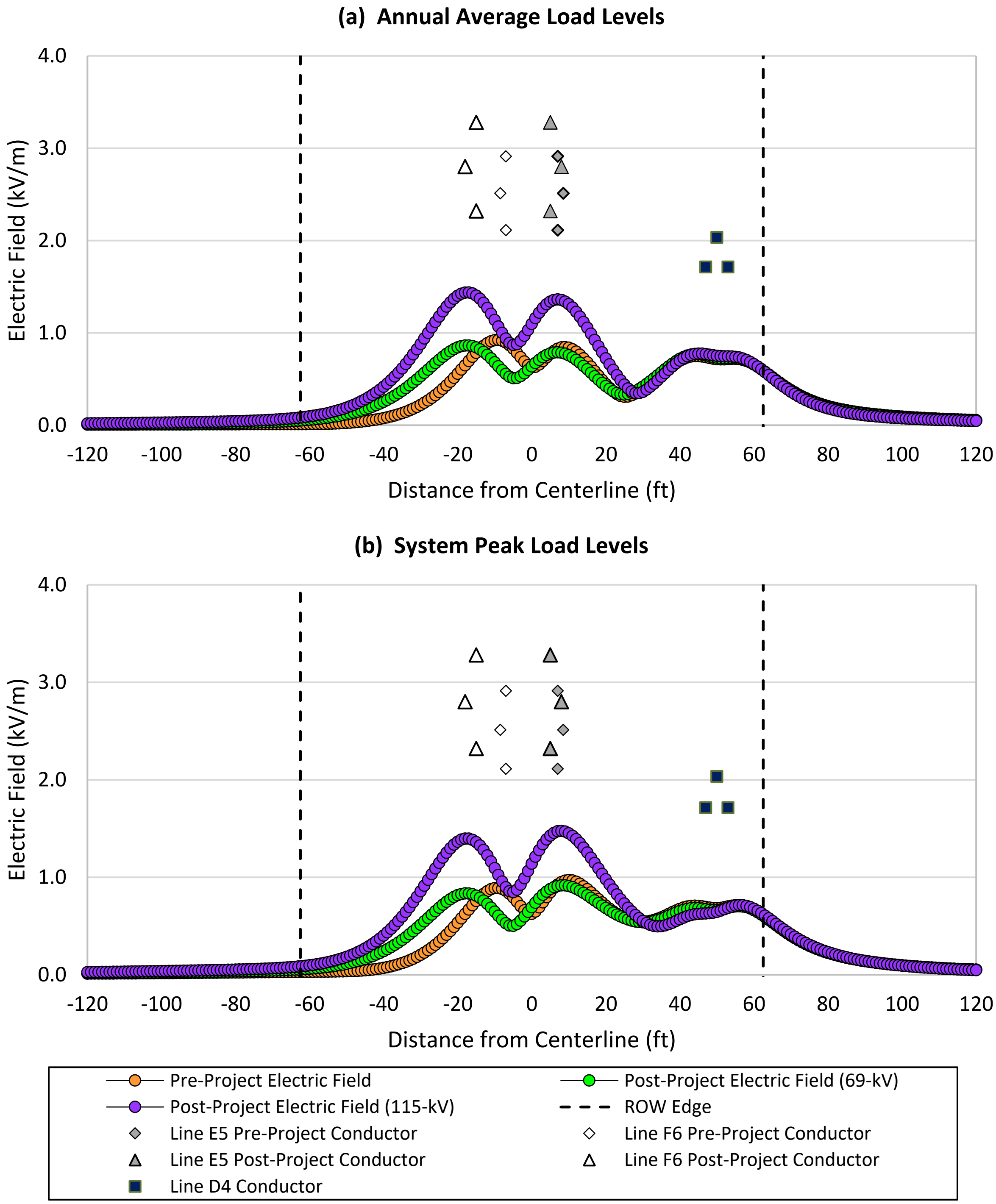

Figure C.1 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 1 (B-13148-NE Sheet 1, ROW Segment from Deerfield No. 4 Substation). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

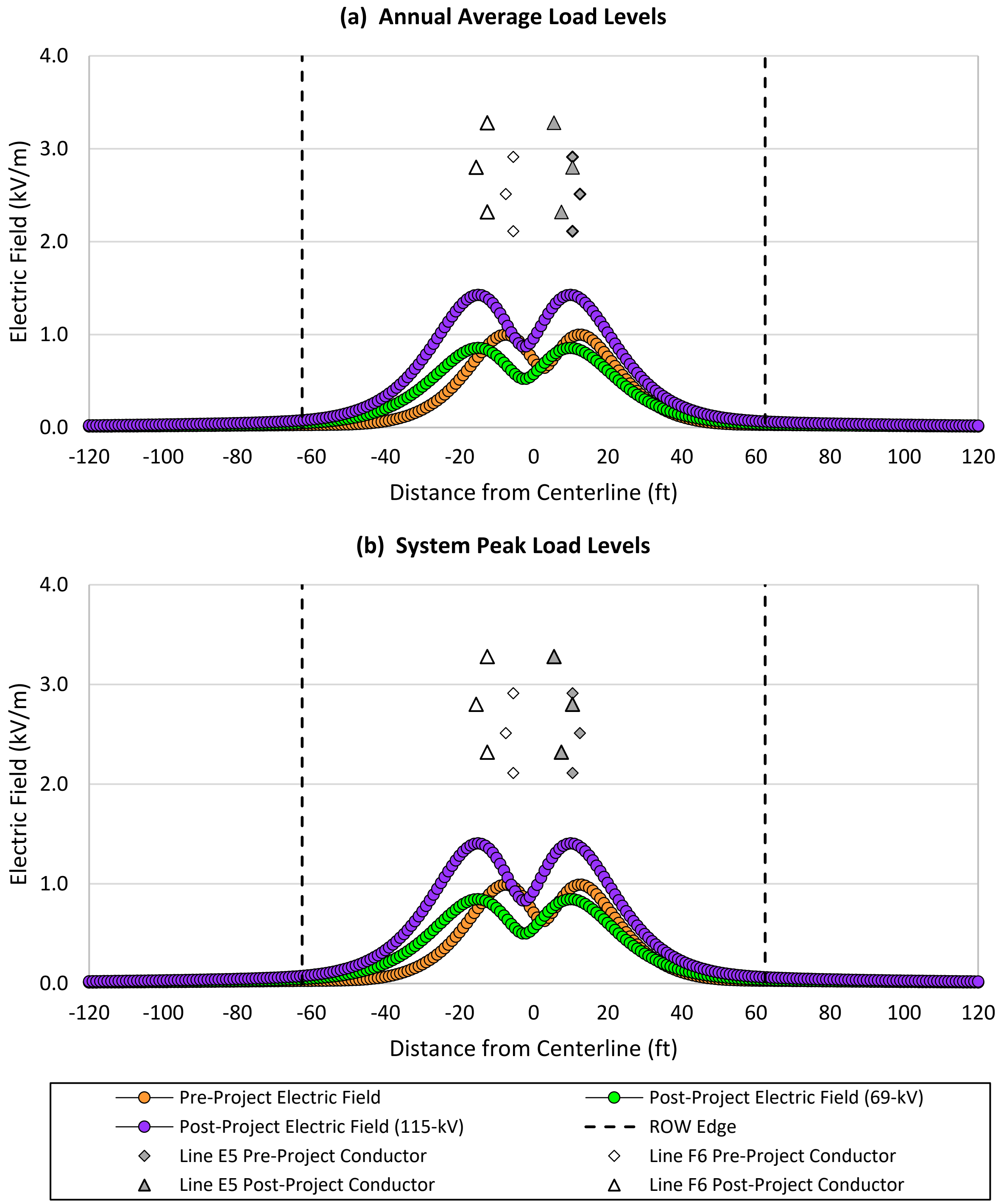

Figure C.2 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 4 to Deerfield 3 Tap). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

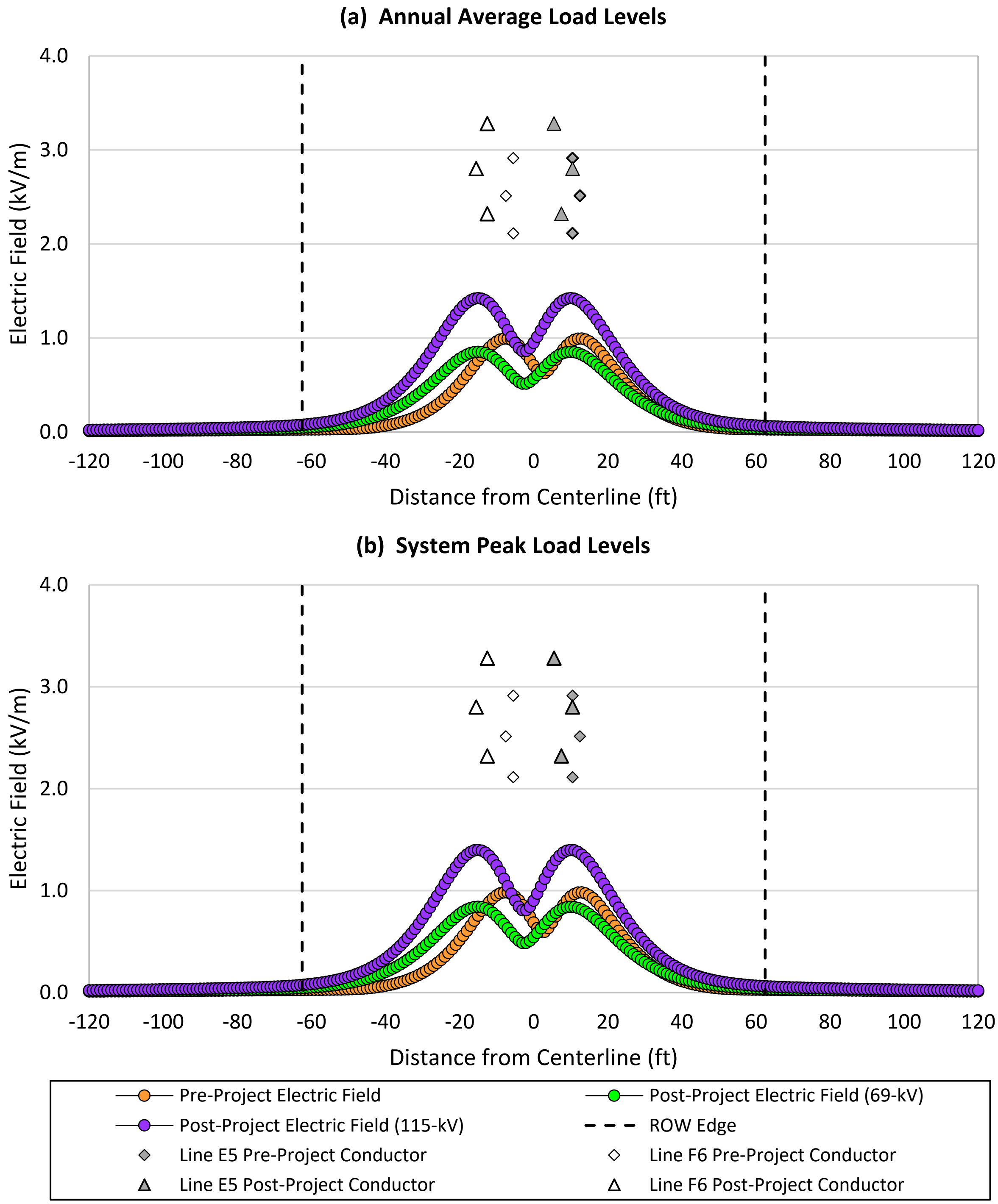

Figure C.3 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 3 Tap to Deerfield 2). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

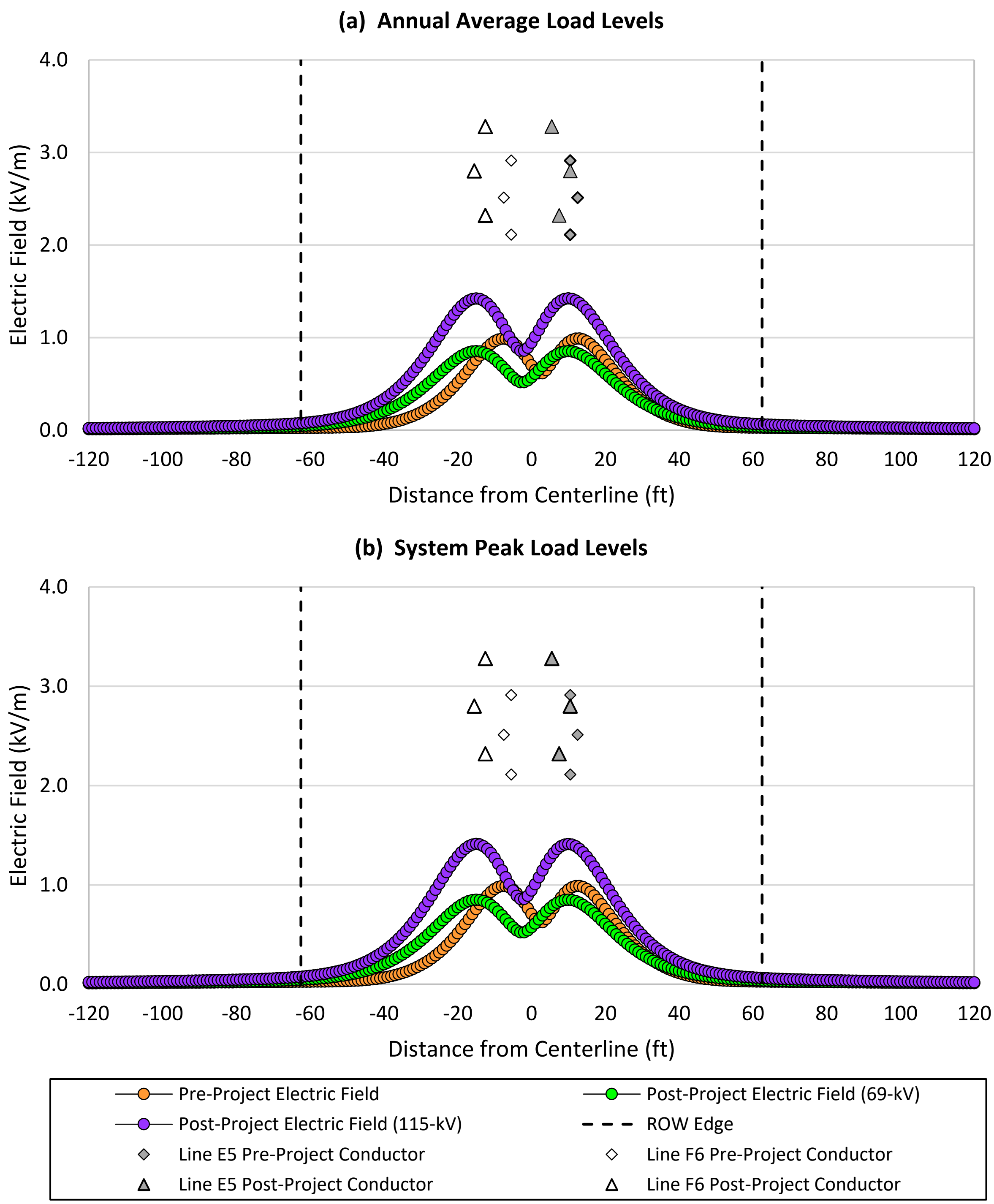

Figure C.4 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

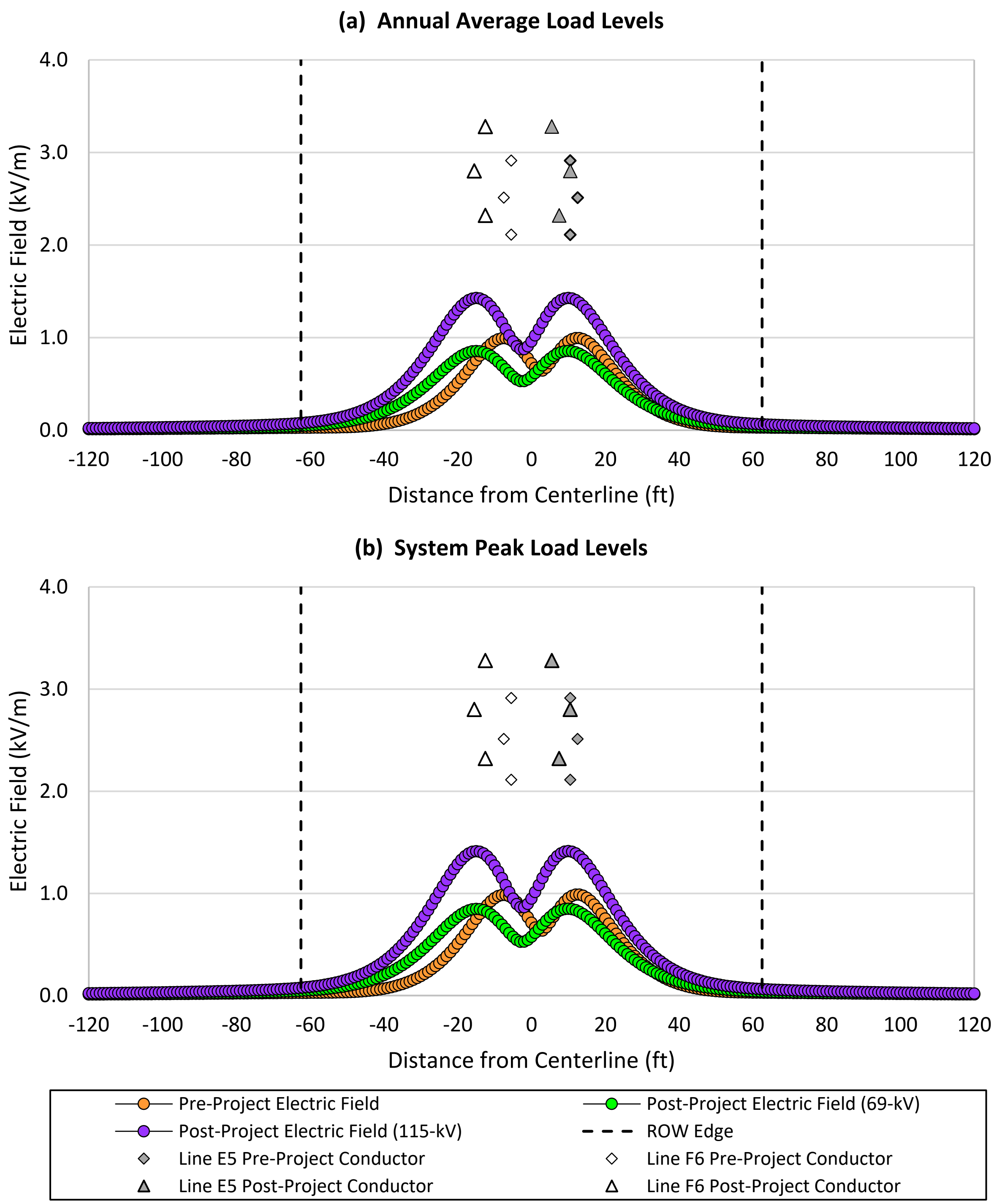

Figure C.5 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Shutesbury to Quabbin Switch Tap). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

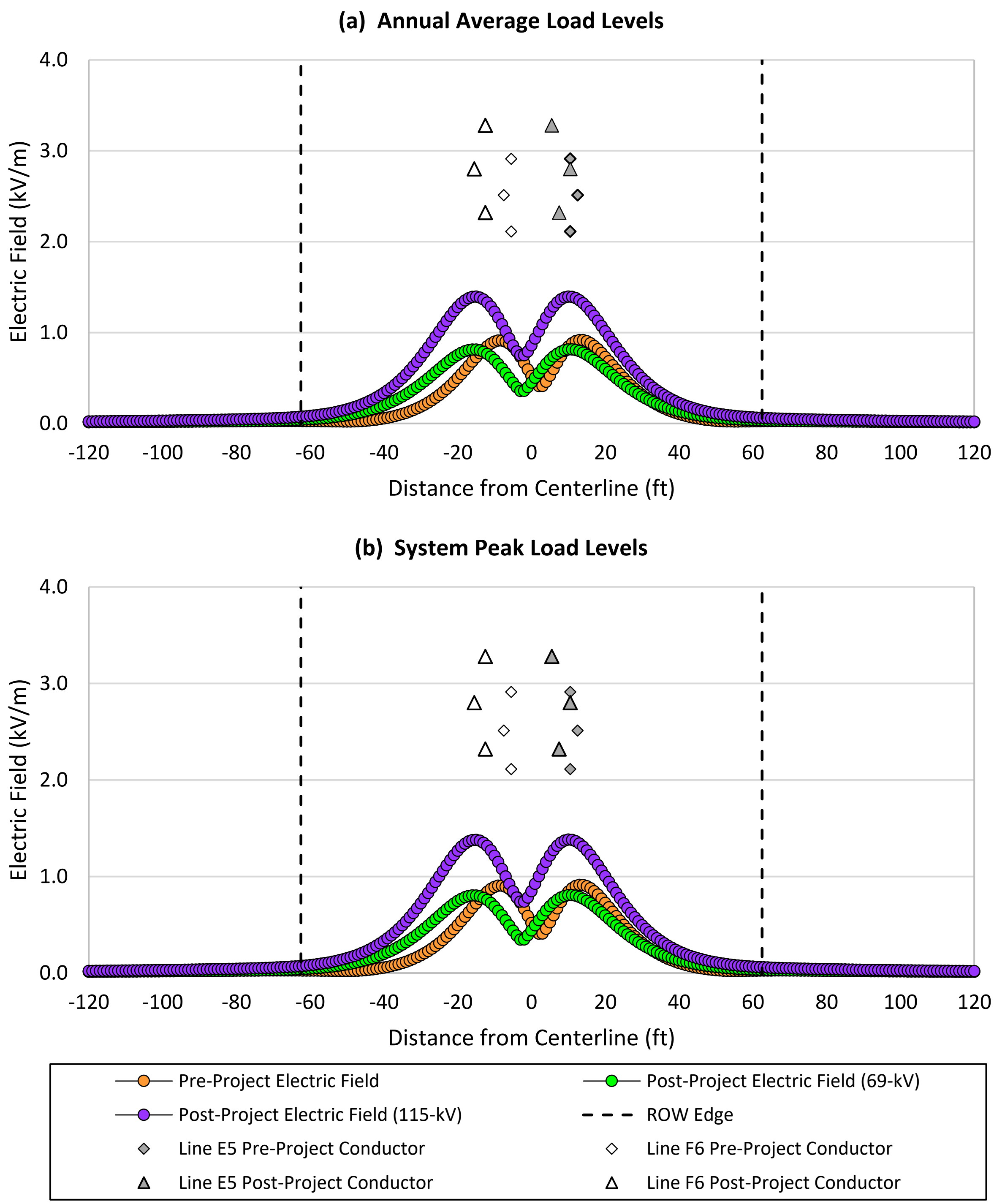

Figure C.6 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Quabbin Switch Tap to Ware). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

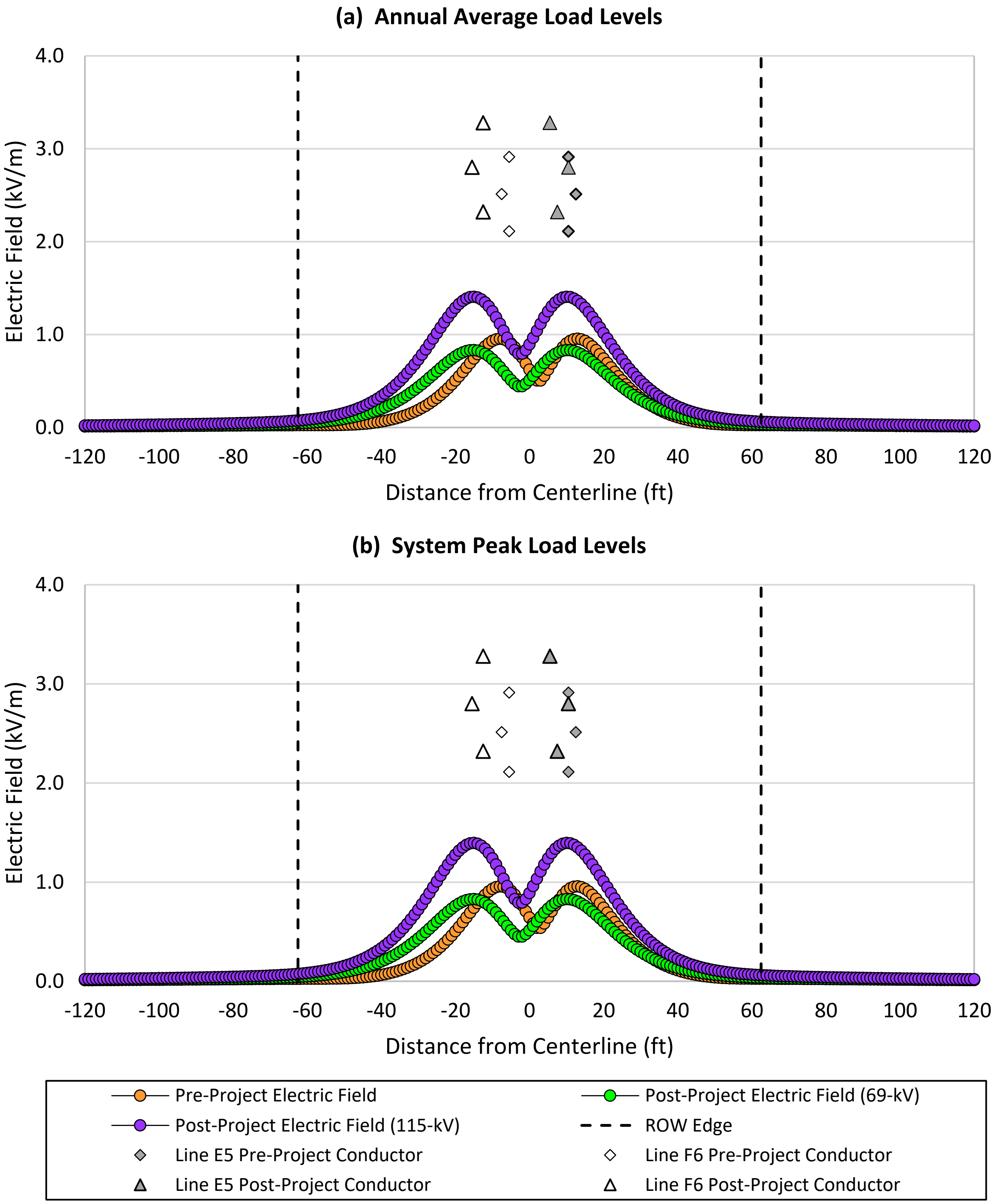

Figure C.7 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Ware to Lashaway). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

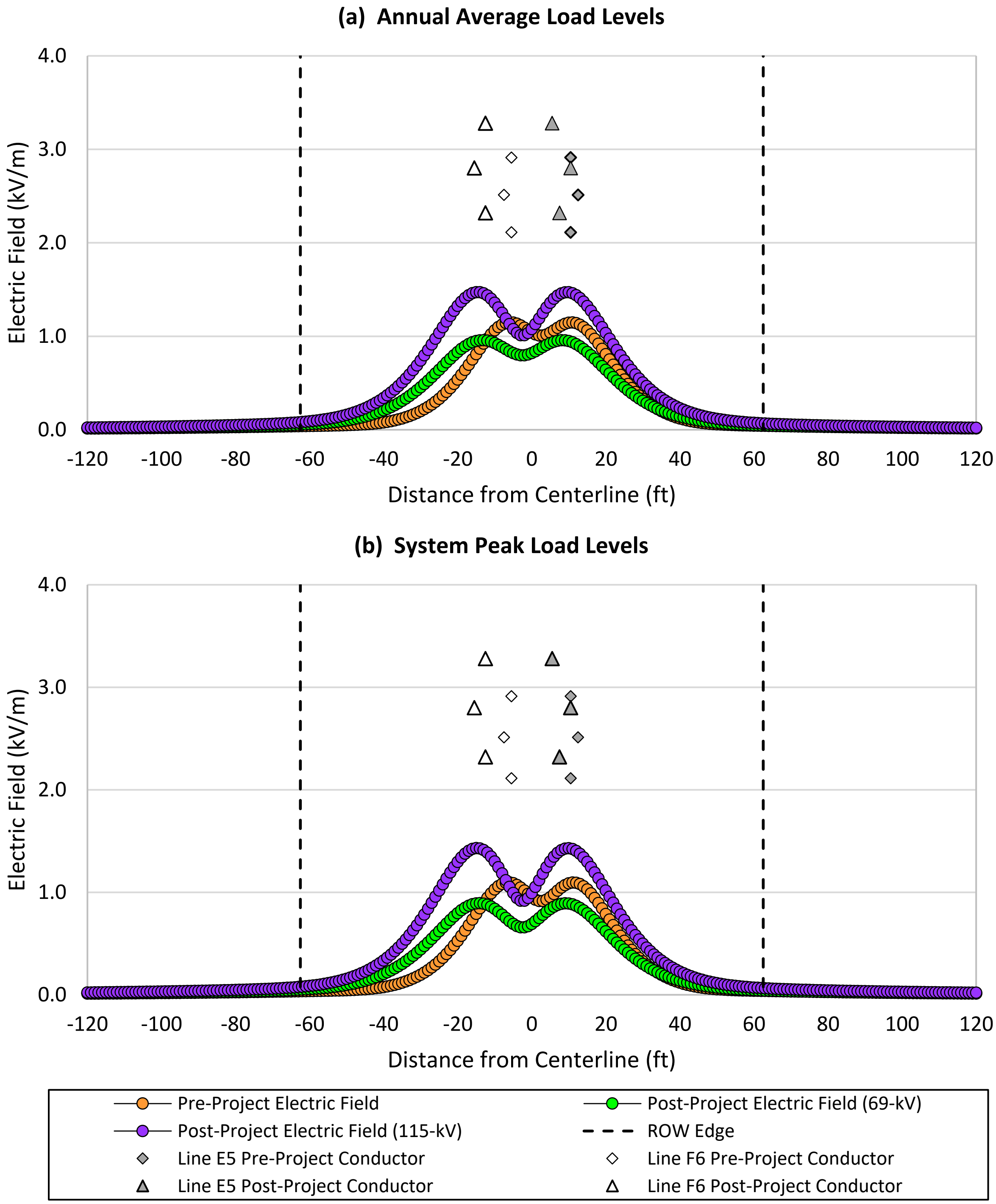

Figure C.8 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Lashaway to Harrington St). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

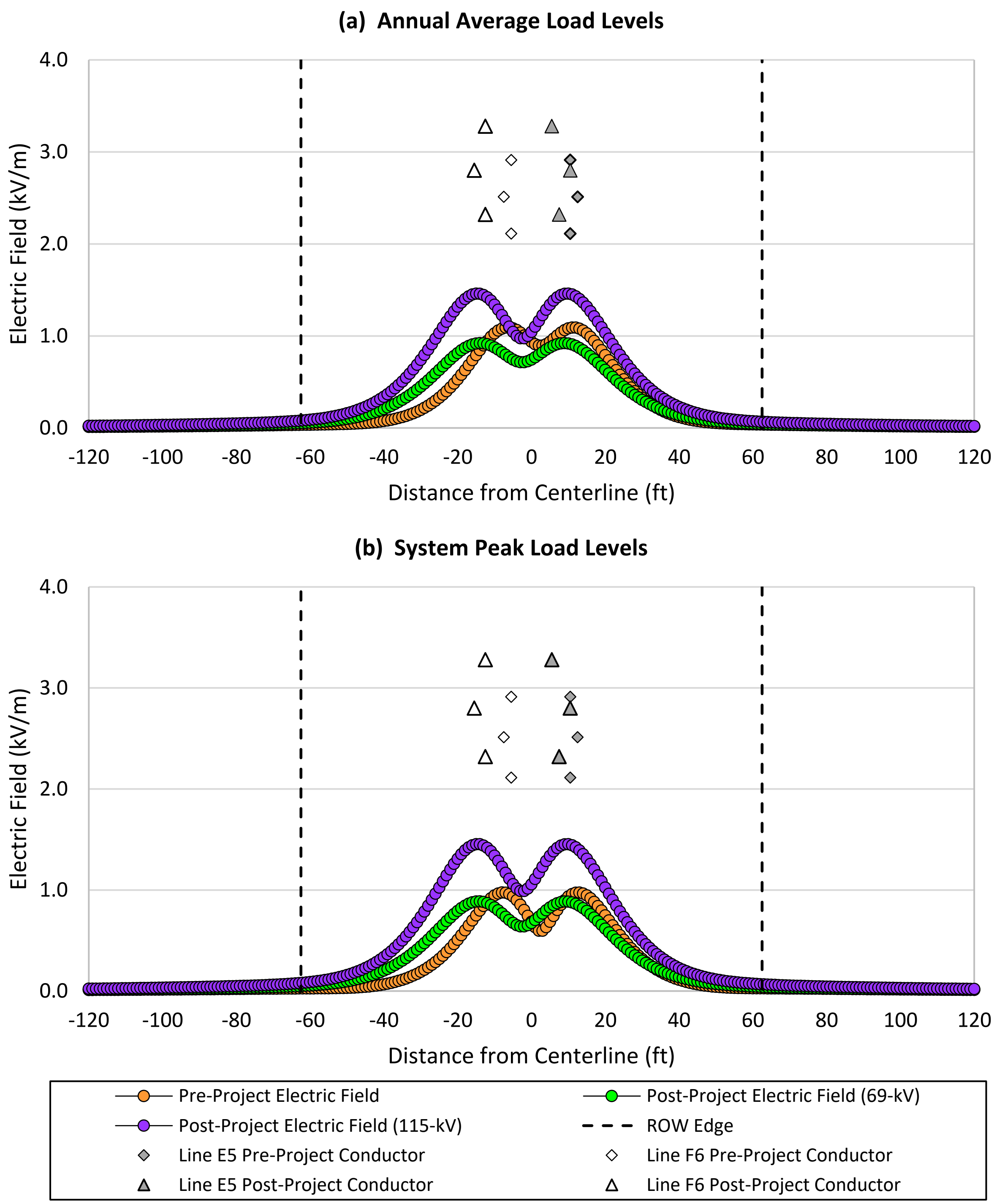

Figure C.9 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Harrington St to Meadow St). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

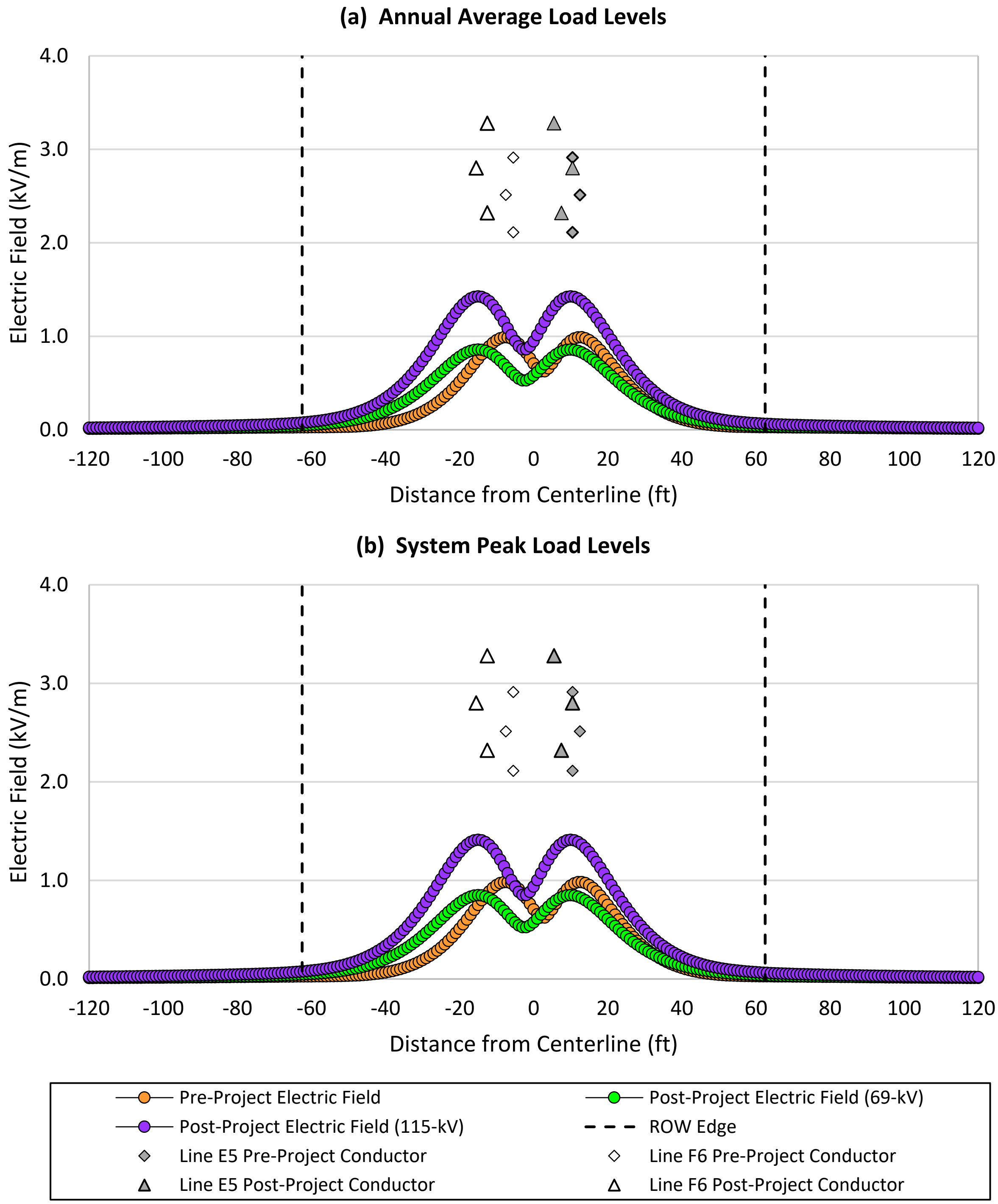

Figure C.10 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Meadow St to Leicester). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

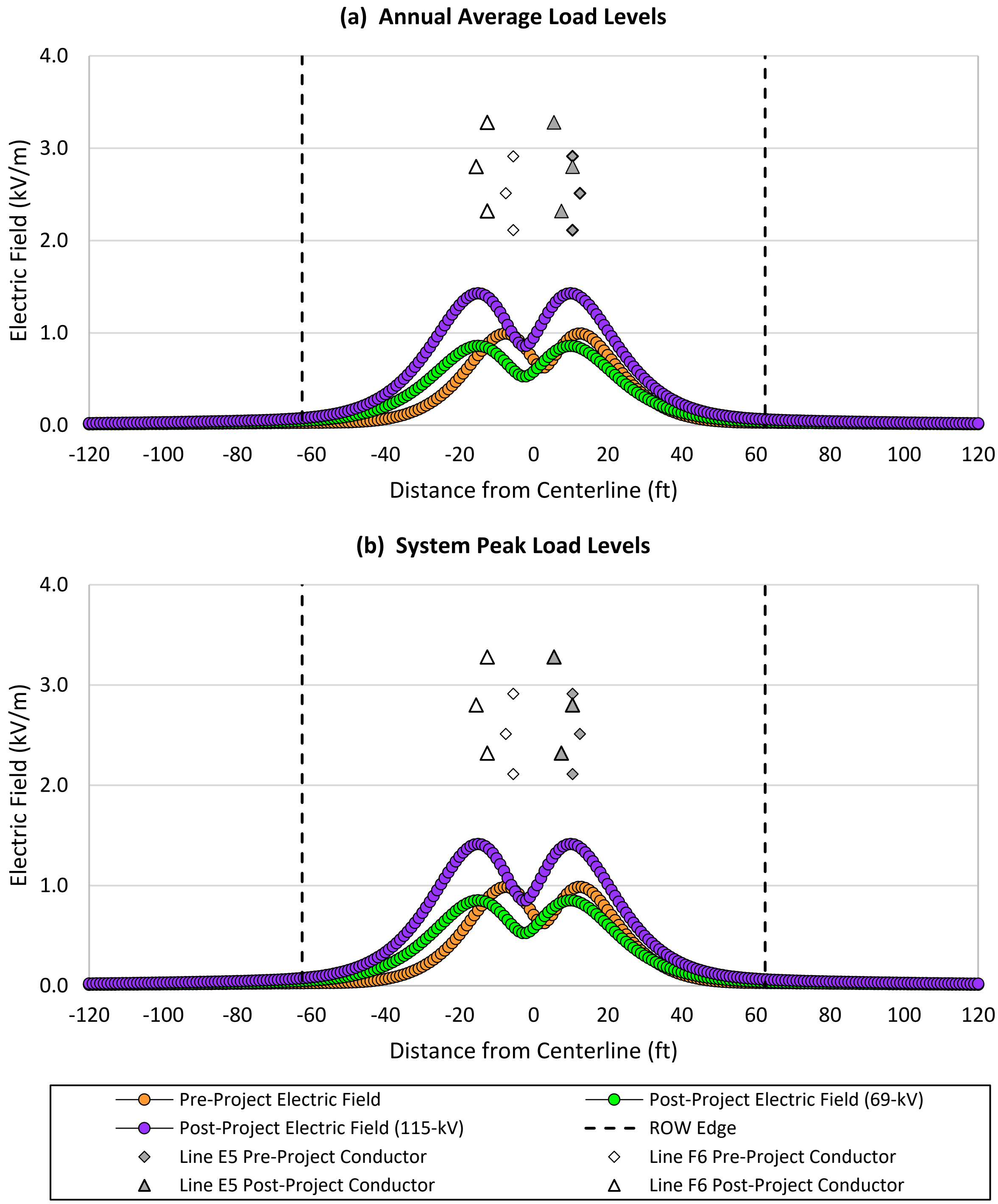

Figure C.11 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Leicester to Pondville). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

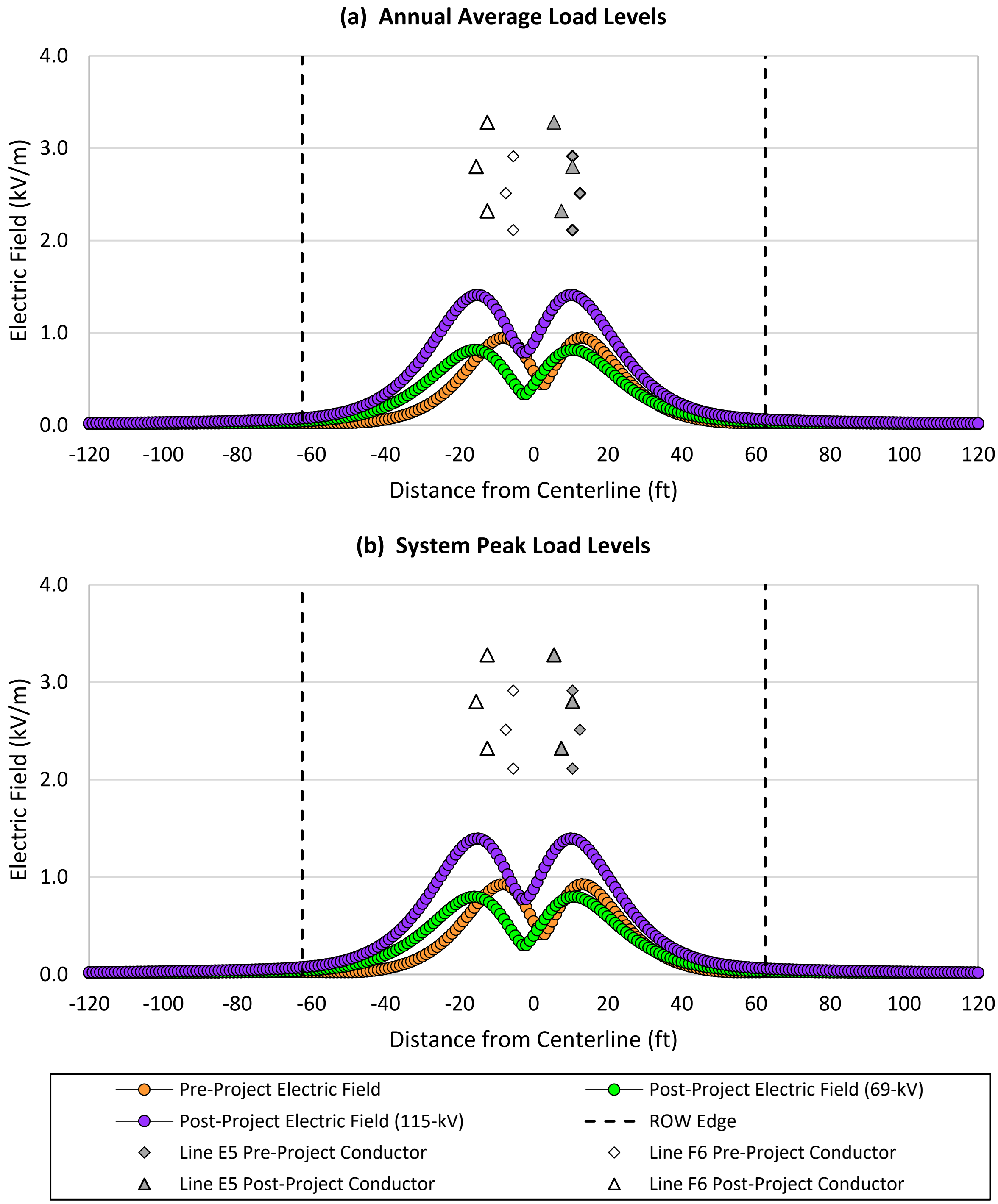

Figure C.12 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 2 (B-13148-NE Sheet 2, ROW Segment from Pondville to Millbury). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

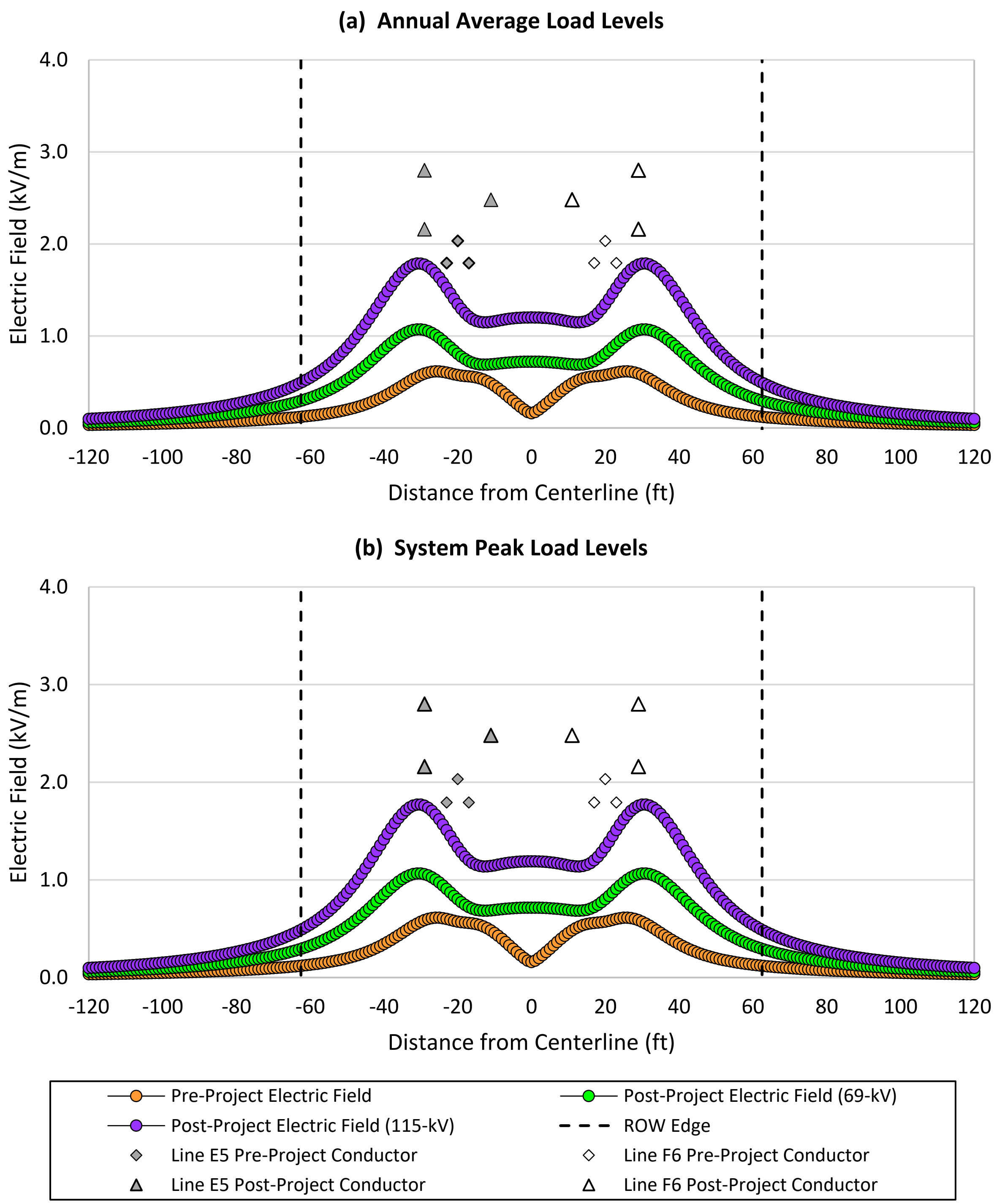

Figure C.13 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 3 (B-13148-NE Sheet 3, ROW Segment from Deerfield 3 Tap). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

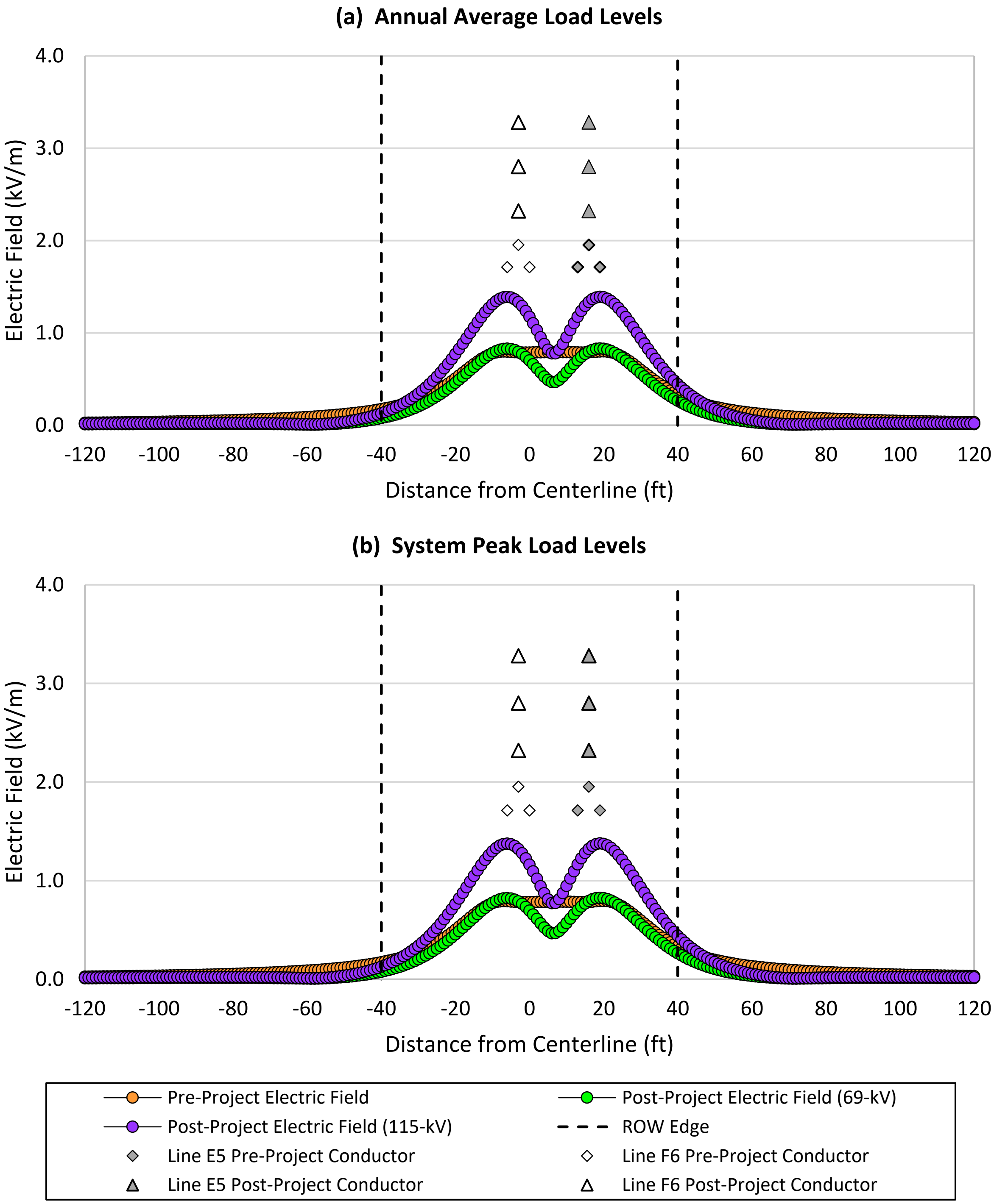

Figure C.14 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 4 (B-13148-NE Sheet 4, ROW Segment from Quabbin Switch Tap). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

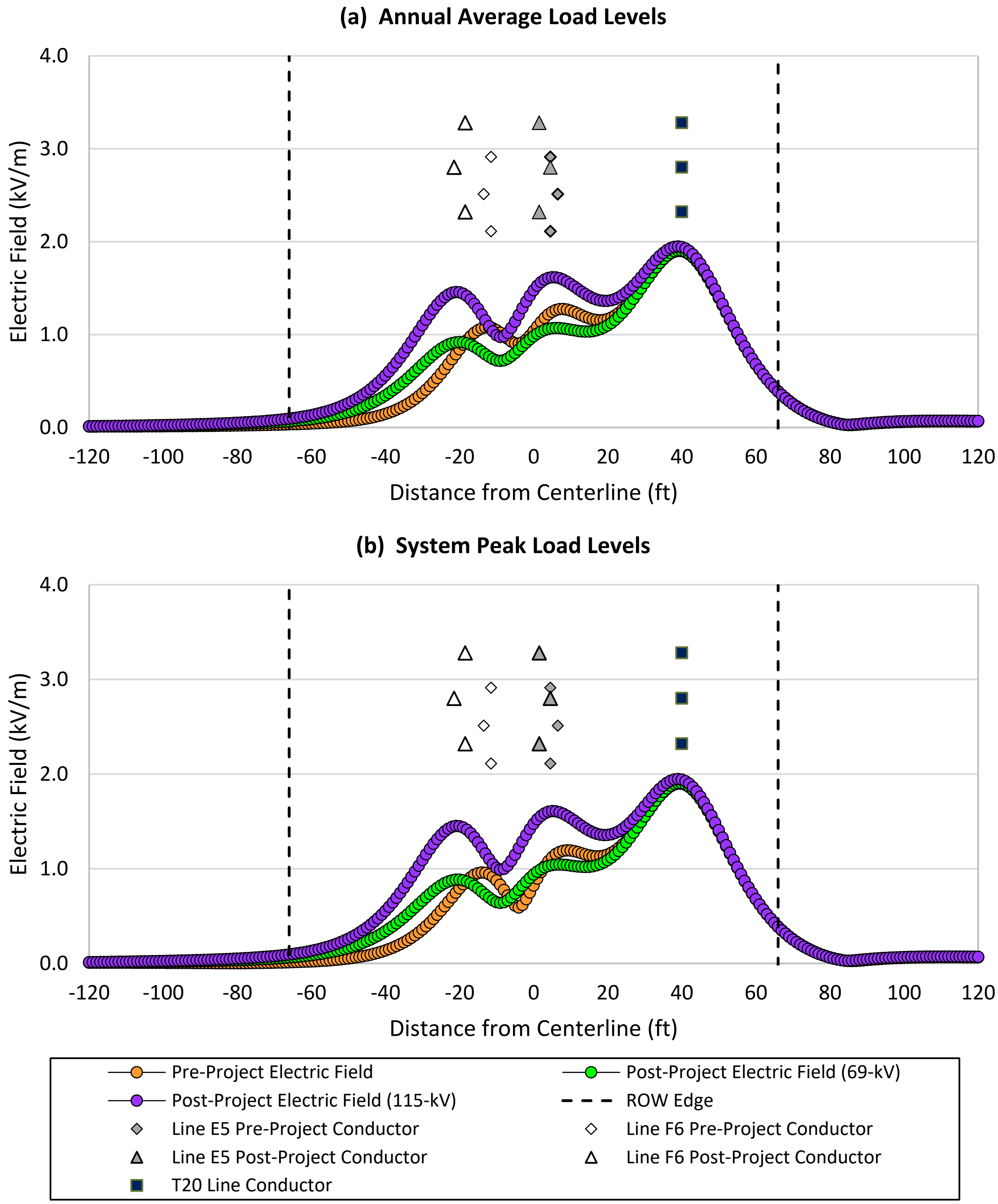

Figure C.15 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 5 (B-13148-NE Sheet 5, ROW Segment from Harrington St to Meadow St). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

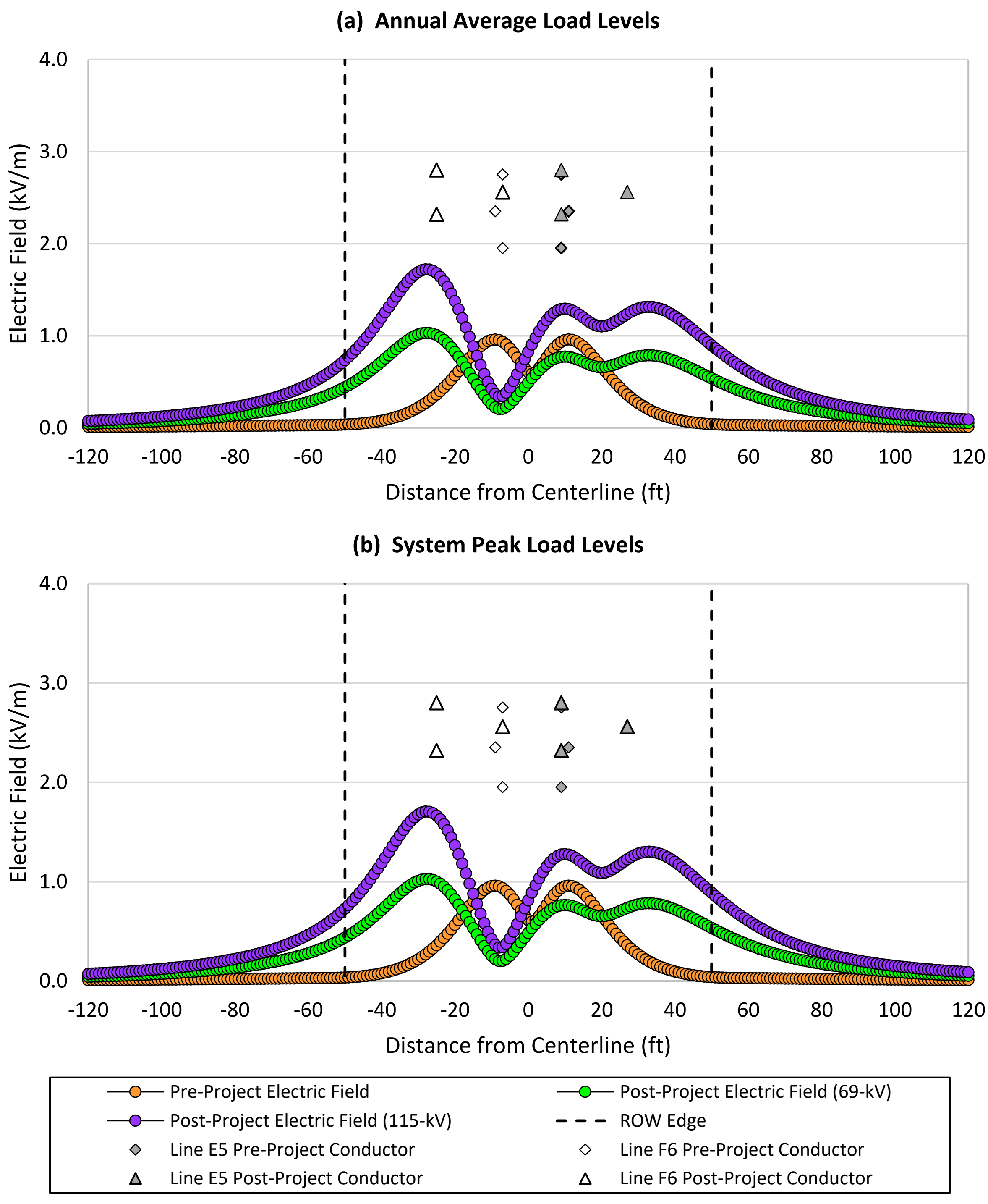

Figure C.16 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 6 (B-13148-NE Sheet 6, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

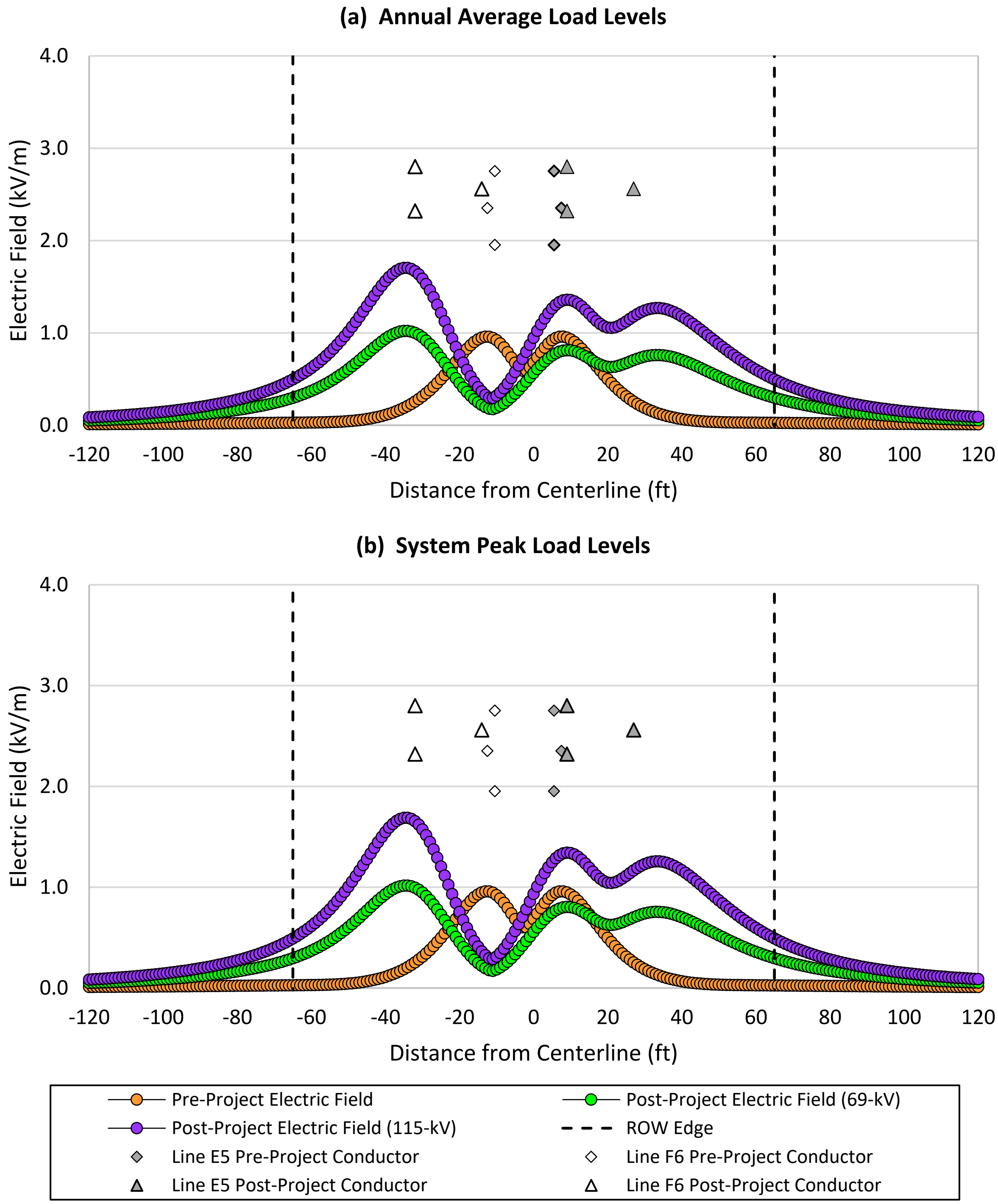

Figure C.17 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 7 (B-13148-NE Sheet 7, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

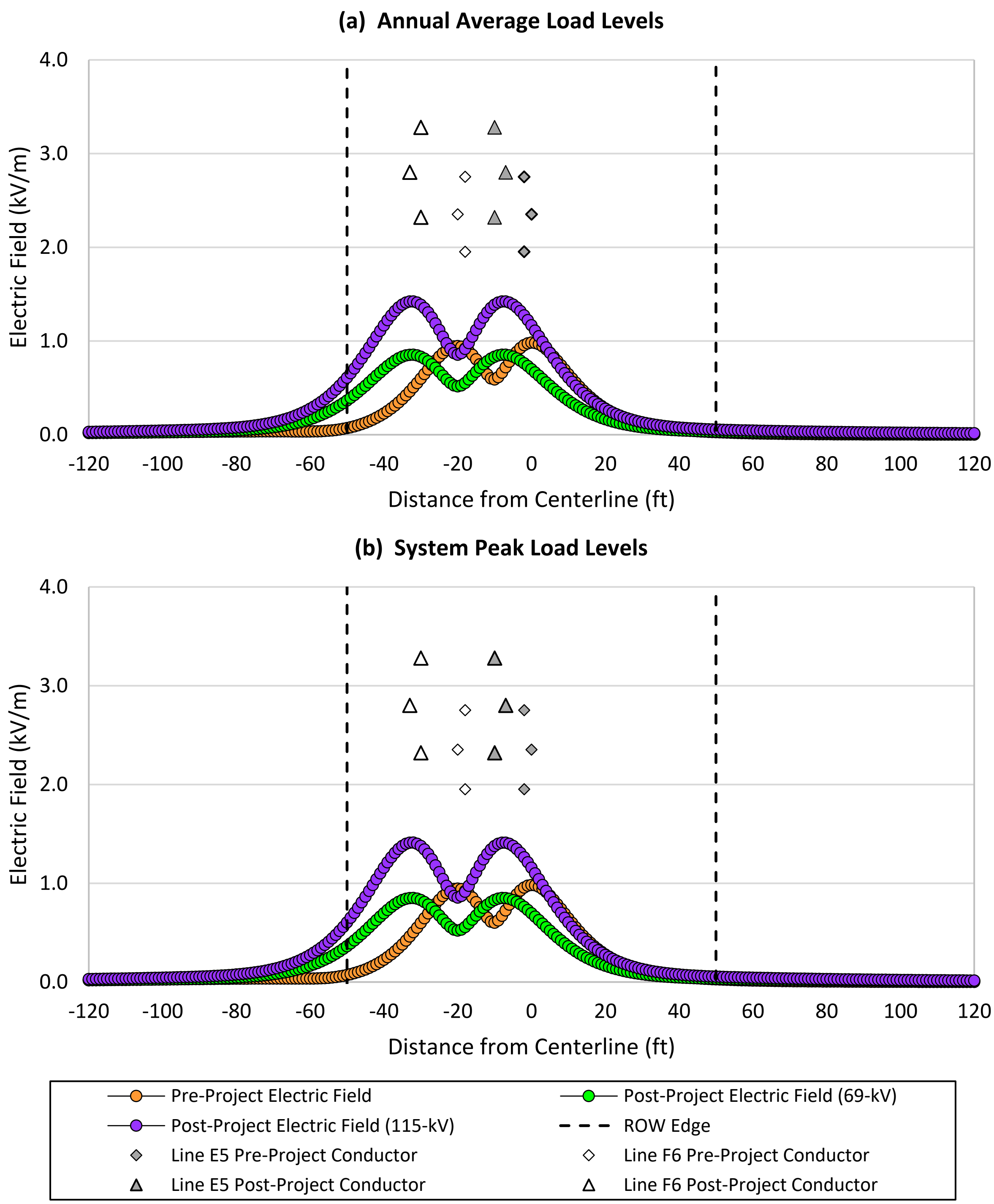

Figure C.18 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 8 (B-13148-NE Sheet 8, ROW Segment from Deerfield 2 to Shutesbury). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

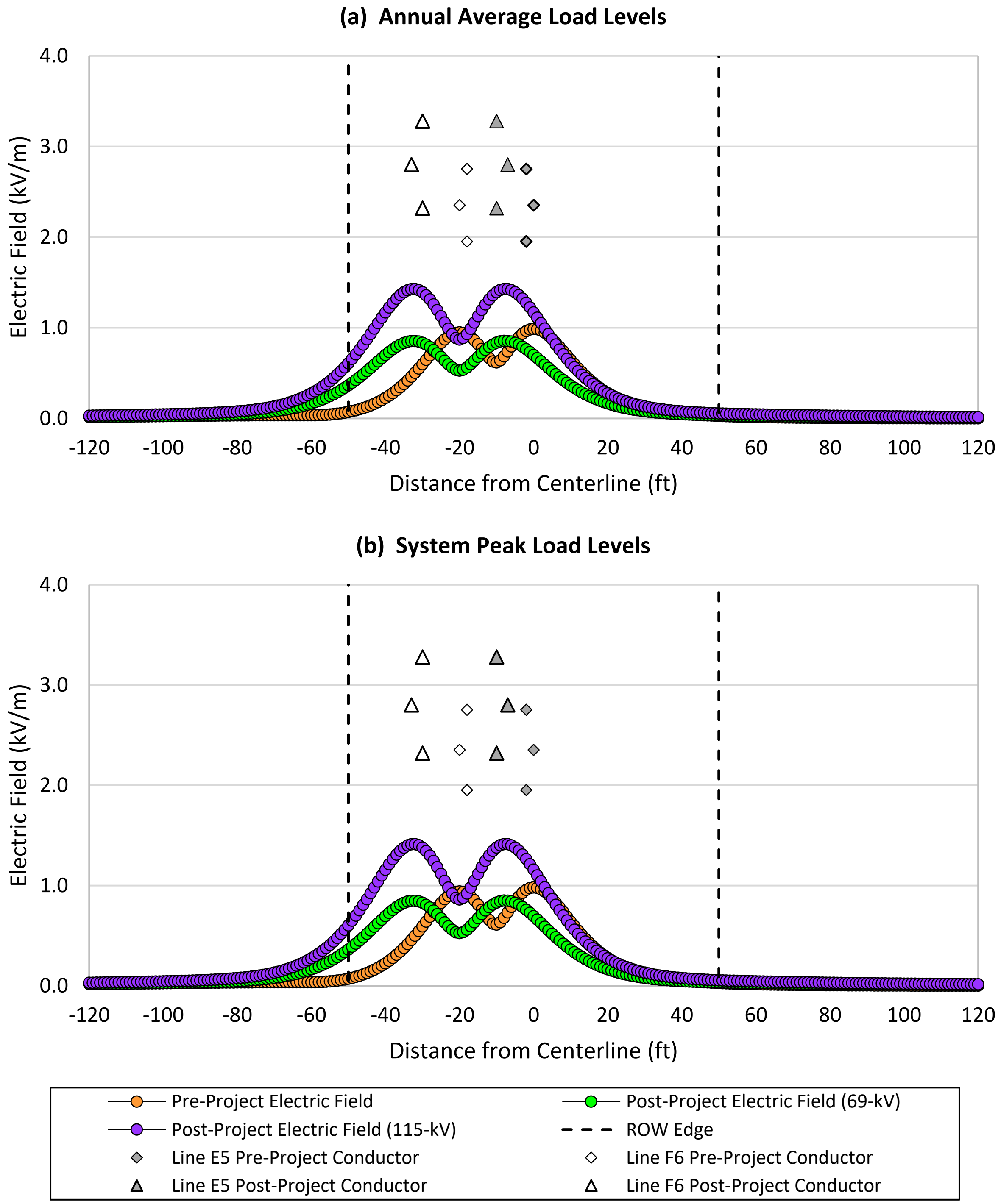

Figure C.19 Electric Field Modeling Results at 1 Meter Aboveground for Representative ROW Cross Section 8 (B-13148-NE Sheet 8, ROW Segment from Shutesbury to Quabbin Switch Tap). ft = Feet; kV = Kilovolt; kV/m = Kilovolts Per Meter; ROW = Right-of-Way. Panel (a) shows the results for annual average load levels, and Panel (b) shows the results for system peak load levels. Conductor locations on the graphs are not to scale and are provided to show relative locations.

Appendix D

Summary of Current Status of Health-Effect Conclusions for 60-Hz Alternating Current Electric and Magnetic Fields

Summary of Current Status of Health-Effect Conclusions for 60-Hz Alternating Current (AC) Electric and Magnetic Fields (EMFs)

Introduction

Electric and magnetic fields (EMFs) are invisible lines of force associated with anything that generates, transmits, or uses electricity, including high-voltage transmission lines and substations, as well as the overhead and underground distribution lines on residential streets, home wiring, and household appliances. As illustrated by Figure D.1, power-frequency (60-hertz [Hz]) alternating current (AC) EMFs are an extremely low frequency form of non-ionizing electromagnetic radiation. Electric fields (EFs) from power lines, which are usually expressed in units of kilovolts per meter (kV/m), are a product of the voltage difference between power lines and ground. Magnetic fields (MFs) are produced by the electric current carried on power lines and are usually expressed in units of gauss (G) or milligauss (mG) (1 G = 1,000 mG).[1] Unlike ionizing radiation (*e.g.*, ultraviolet rays, X-rays, gamma rays), power-frequency EMFs do not carry enough energy to break molecular bonds and damage DNA, biological cells, or tissues.

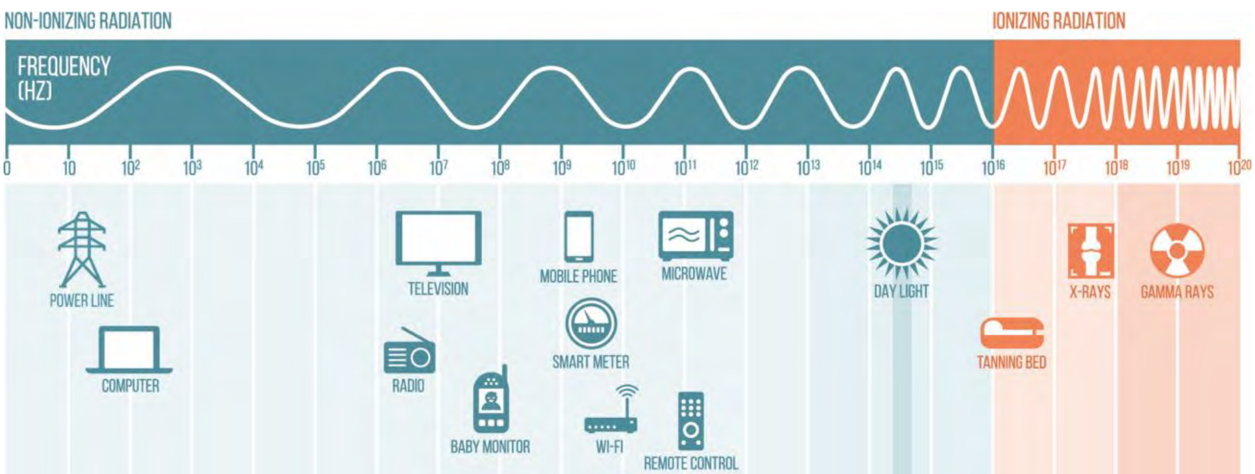

Figure D.1 The Electromagnetic Spectrum. EF = Electric Field; EMF = Electric and Magnetic Field; Hz = Hertz; MF = Magnetic Field; US = United States. As shown in the figure, the US electric power system operates at 60 Hz, and EMFs are thus frequently described as extremely low frequency (ELF) fields (*e.g.*, ELF-MFs and ELF-EFs).

Since the late 1970s when exposure to power-frequency EMFs emerged as a public health concern, following the reporting of epidemiological associations suggesting that children residing in greater proximity to overhead power lines may have a small increased risk of childhood leukemia, there has been a massive international research effort to understand whether and how power-frequency EMFs could cause childhood leukemia and other diseases (see Moulder, 2000). As described in more detail below, the three major lines of health-effects investigation for power-frequency EMFs consist of epidemiology studies of human populations, laboratory animal studies, and mechanistic studies. The biological effects of power-frequency EMFs have now been the focus of scientific research for over four decades, totaling thousands

[1] Another unit for MF levels is the microtesla (μT) (1 μT = 10 mG).

of published studies and tens of millions of dollars of research funding. More than 40 epidemiology studies alone have investigated statistical associations between residential EMF exposures or surrogates of exposure (*e.g.*, distance to transmission lines) and risk of childhood leukemia (Schmidt *et al.*, 2021), and epidemiology studies have investigated associations for risks of other health endpoints, including brain cancer, breast cancer, adult leukemia and lymphoma, reproductive and developmental effects, and neurodegenerative diseases.

With a knowledge base that now totals 40 years of scientific research and thousands of published studies, scientists have not been able to identify a plausible mechanism whereby biological processes can be adversely affected by typical levels of power-frequency EMFs. Despite advancements in study designs and larger and larger study populations, the epidemiological associations with childhood leukemia risk remains weak and inconsistent; as discussed later, more recent epidemiology studies with improved study designs and larger study populations have tended to observe weaker associations, and frequently no association at all, as compared to older studies. The scientific basis for reported statistical associations for risk of childhood leukemia remains unexplained, as many subsequent experimental and mechanistic studies have been unable to identify a biologic process whereby power-frequency EMFs can exert such an effect. Moreover, studies of carcinogenicity in animals exposed to elevated levels of EMF have been overwhelmingly negative and do not support the hypothesis that EMF exposure is a significant risk factor for carcinogenesis (NIEHS, 2002). Overall, the accumulated EMF health-effects data fail to provide a clear and coherent picture whereby the levels of power-frequency EMFs that we encounter in our daily lives present a hazard to human health.

It is the consensus opinion of a number of public health agencies and expert scientific committees, including the United States (US) National Institute for Environmental Health Sciences (NIEHS), the World Health Organization (WHO), and the US Environmental Protection Agency (US EPA), that there are no confirmed chronic (*e.g.*, long-term) human health risks from exposure to power-frequency EMFs, such as increasing the risk of developing cancer. In 1999, the NIEHS published its final report for the Electric and Magnetic Fields Research and Public Information Dissemination Program (EMF-RAPID) that was authorized and funded in 1992 by the US Congress to conduct fundamental scientific research to clarify the potential for health risks from power-frequency EMF exposure (NIEHS, 1999). An extensive range of laboratory toxicology and exposure characterization studies were conducted as part of the EMF-RAPID program, with the NIEHS concluding in its final report (NIEHS, 1999):

> The ultimate goal of any risk assessment is to estimate the probability of disease in an exposed population…The NIEHS believes that the probability that ELF-EMF exposure is truly a health hazard is currently small. The weak epidemiological associations and lack of any laboratory support for these associations provide only marginal, scientific support that exposure to this agent is causing any degree of harm.

NIEHS further addressed the body of health-effects evidence in a seminal 2002 question and answer (Q&A) booklet on power-frequency EMFs (NIEHS, 2002):

> Over the past 25 years, research has addressed the question of whether exposure to power-frequency EMF might adversely affect human health. For most health outcomes, there is no evidence that EMF exposures have adverse effects. There is some evidence from epidemiology studies that exposure to power-frequency EMF is associated with an increased risk for childhood leukemia. This association is difficult to interpret in the absence of reproducible laboratory evidence or a scientific explanation that links magnetic fields [MFs] with childhood leukemia.

Currently, on its website,[2] NIEHS (2024) states that utility "Power Lines" fall into the "non-Ionizing" radiation category, and goes on to explain, "Non-ionizing: low-level radiation…is generally perceived as harmless to humans."

In 2007, the WHO published one of the most comprehensive health risk assessments of EMF in the power-frequency range, in which the WHO critically reviewed the cumulative epidemiologic and laboratory research, taking into account the strength and quality of individual research studies (WHO, 2007a). WHO concluded overall:

> Acute biological effects have been established for exposure to ELF electric and magnetic fields [EMFs] in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field [MF] exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore, exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted. (WHO, 2007a)

As part of its International EMF Project, the WHO has continued to conduct comprehensive reviews of EMF health-effects research and existing standards and guidelines, and has not changed its conclusion that the health-effects evidence for power-line frequencies of EMF does not support a causal relationship of EMF exposure with increased childhood leukemia risk or with other adverse health effects (WHO, 2024a).

US EPA has not established any hazard levels or exposure standards for power-frequency EMFs. On its webpage focused on "Electric and Magnetic Fields [EMFs] from Power Lines," US EPA (2023) states, "Scientific studies have not clearly shown whether exposure to EMF increases cancer risk."[3]

As discussed more below, there is consistency in the conclusions from expert and governmental reviews of the full body of EMF health-effects research performed by international scientific, health, and safety organizations, and governmental public health agencies, that there are no confirmed chronic health risks for power-frequency EMF. While the possible linkage between ELF-MF exposure and risk of childhood leukemia remains a continued focus of researchers, findings from recent studies arguably only add to the uncertainties in this body of evidence. As described below, recent findings are suggestive of a decline in the association between ELF-MF exposure and risk of childhood leukemia in studies of more recent time periods (*e.g.*, post-1990s). These findings cannot be readily explained by MF exposures, and researchers continue to investigate the potential roles of confounding factors and sources of bias as alternative explanations for the observed epidemiological associations (*e.g.*, Amoon *et al*., 2022; Nguyen *et al*., 2022; Amoon *et al*., 2019).

Below, we continue our summary of the current status of power-frequency EMF health-effect conclusions with a brief discussion of the lines of scientific investigation that apply to understanding the potential human health effects of any exposure, including power-frequency EMF. We then present the status of EMF health-effect conclusions from international scientific, health, and safety organizations, and governmental public health agencies. This is followed by a discussion of recent research publications focused on the potential linkage between residential exposure to power-frequency MFs and risk of childhood leukemia, which continues to be the subject of updated epidemiological analyses and systematic reviews. Our review concludes with a summary of available health-based exposure guidelines established by international health

[2] https://www.niehs.nih.gov/health/topics/agents/emf/.
[3] https://www.epa.gov/radtown/electric-and-magnetic-fields-power-lines.

and safety organizations, which are designed to be protective against adverse health effects, as well as state guidelines for power-frequency EMFs.

Lines of Scientific Inquiry into EMF Health Effects

Epidemiology

Because of the statistical associations reported by early EMF epidemiology studies, the International Agency for Research on Cancer (IARC), which is part of WHO, classified power-line MFs as a 'possible' (Group 2B) carcinogen in 2002 (IARC, 2002).[4,5] IARC's cancer classification for power-line MFs was based on "limited" evidence from humans concerning childhood leukemia, "inadequate" evidence from humans concerning all other cancer types, and "inadequate" evidence from animals. Even though some epidemiology studies continue to provide weak suggestions of power-frequency MF health risk, the results among the studies remain inconsistent, poorly linked to actual MF exposures, and insufficient to demonstrate a causal relationship.

Epidemiology can provide statistical, correlative results between presumed exposures and disease patterns in human populations, but such associations are not able to establish causation. That is, while a laboratory scientist can precisely set exposure conditions, randomly allocate groups to be exposed or non-exposed, do careful pathology on the outcome, and can read the results blindly (*i.e.*, without knowing the exposure history), epidemiology is an observational science and cannot utilize these same rigorous scientific methods. Additional problems confound the interpretation of the power-frequency EMF epidemiology. For example, few of the epidemiology studies used actual measurements of MF exposure, and none of the exposure assessments were based on plausible mechanisms of interaction, or on validated MF metrics. Also, an epidemiologic study that reports 'statistically significant' associations is only testing that significance against the role of random chance, given the size of the populations studied. If other sources of uncertainty in epidemiologic studies were to be quantitatively included in the confidence interval (*e.g.*, confounding factors, measurement error, selection bias, misclassification), the margin of error would become wider and may well overlap a null outcome (*i.e.*, 'no association'). Reviews of MF epidemiology emphasize this point, namely that the error bars in reported results do not reflect all sources of uncertainty, and, consequently, the results are less indicative of an actual "statistically significant" link than typical confidence intervals suggest.

Laboratory Animal Studies

Hundreds of laboratory animal studies have examined the biological effects of power-frequency MF exposure in mammalian species expected to have reactions similar to humans. Support from such studies would make interpretation of power-frequency MF epidemiology less clouded and uncertain. However, these other lines of scientific evidence weigh against assigning a causal basis to the associations reported by epidemiology. Scientists have not been able to identify an established laboratory bioassay or animal

[4] Note that IARC's Group 2B possible human carcinogen classification was specific to ELF-MF. For ELF-EF, IARC concluded that there was "inadequate evidence" of carcinogenicity in humans. In general, the remaining health concerns related to power-frequency EMFs are now focused primarily on ELF-MFs rather than ELF-EFs. ELF-EFs are generally considered to be of potential lesser health concern than MFs due to consistent null findings from early research studies and because they are readily shielded by conductive objects like trees and vegetation, as well as buildings. Because they are readily shielded, power lines are generally not significant sources of long-term average EF exposure, even for populations residing nearby to utility rights-of-way (ROWs).

[5] Other agents classified as Group 2B possible human carcinogens by IARC include aloe vera, picked vegetables, and gasoline fumes. Coffee was classified as a Group 2B possible human carcinogen for about 25 years until 2016 when it was re-assessed by IARC and re-classified into Group 3 not classifiable as to its carcinogenicity to humans. Both consumption of red meat and drinking very hot beverages are classified as Group 2A probable human carcinogens by IARC.

model by which power-line MFs can be shown to consistently initiate or accelerate biological changes related to cancer risk. Lifetime exposures to high levels of 60-Hz MFs have been tested in numerous animal studies (using different species), with results failing to show that 60-Hz MFs can initiate or exacerbate any disease or pre-cancerous condition, even in genetically modified and susceptible animals. For example, research by the National Toxicology Program (NTP) extensively tested elevated, lifetime 60-Hz AC MF exposures, and the study scope and quantity of animals tested is unlikely to ever be duplicated (Moulder, 2000). The NTP study found no cancer risks, even at high MF exposure levels (1 to 2 microteslas [μT], or 10,000 to 20,000 mG). Such animal testing is the foundation (or "gold standard") for probing health effects, because it is often through such exhaustive animal studies that regulators can determine what (if any) aspect of an exposure (*e.g.*, what chemicals or what MF parameter [*e.g.*, frequency, intensity, duration, polarization]) should be regulated.

Mechanistic Studies

Studies of 'mechanisms of action' utilize well-established laws of physics, chemistry, and biology to predict and understand how MFs might alter the function of biological structures like cell membranes or genetic (DNA) molecules. Mechanistic MF research to date, representing extensive efforts by scientists worldwide, has not been able to identify plausible mechanisms or causal pathways by which typical levels of power-line MFs can cause adverse health effects. MF interactions with biological systems have been analyzed carefully in light of the biophysics of electromagnetic field interactions with matter in general and biological molecules in particular. Unlike ionizing radiation (*e.g.*, ultraviolet rays, X-rays, gamma rays), non-ionizing radiation does not carry enough energy to break molecular bonds,

The applicability of fundamental physics to all systems, and to biology in particular, permits evaluation of the interaction of MFs with ions, molecules, cells, and organisms. The conclusions are that typical power-line MFs do not create disturbances that are detectable above the many sources of disturbance (electrical, thermal agitation, and other 'noise') that are naturally present in living systems. Notably, a common medical procedure, magnetic resonance imaging (MRI), exposes patients to extremely intense static and time varying MFs *via* both the main static field and the oscillating gradient MFs that generate the MRI image. Yet, such treatments leave no biomarkers of exposure and are safer than conventional X-ray images and computerized tomography (CT) scans or nuclear medicine images. In fact, many studies have been conducted to examine the ability of human beings to detect the existence of MFs, but no convincing evidence of such a sensory ability has been found.

Consideration of different parameters of MF exposure (frequency, intensity, duration, wave shape, polarization, modulation, intermittency, *etc.*) have revealed no firm basis on which to attribute a potential for adverse biological effects to the specific values of, for example, any of the following EMF metrics: (1) electric or MF magnitudes, (2) the fundamental frequency or to harmonic frequencies, (3) continuous exposure *vs*. intermittent exposure, (4) time-averaged fields *vs*. peak fields, (5) constant-frequency MFs *vs*. variable-frequency MFs. Over the years, many hypotheses have been proposed regarding how MFs may elicit a carcinogenic response and many analyses have been performed; however, diligent attention by scientists has not yielded identified aspects, levels, or durations of MF exposure that can be traced to increased cancer risk through a chain of causal events. Without an understanding of mechanism, it remains unknown as to what, if any, aspect of MF exposure should be controlled to reduce health risks.

Integration of Lines of Health-Effects Evidence

Biological-effect evidence that may establish the existence of a health impact is often illustrated as a 'three-legged stool' (Figure D.2), where strength in each line of evidence (each leg) is required for overall strength and stability, and weakness in any one leg makes the stool unstable. That is, lack of support from all three lines of evidence restricts the conclusions that can be drawn as to the existence of a human health risk. The three legs are: (1) exposure/disease correlations in human populations (epidemiology); (2) empirical laboratory animal studies at controlled and elevated levels of exposure; and (3) *in vitro* and/or mechanistic studies of the agent's mode of action.

Figure D.2 Three-Legged Stool: Health-Effects Research Looks at Three Independent Lines of Evidence – Cellular and Molecular Studies (Mechanism of Action), Laboratory Animal Studies, and Population Studies (Epidemiology). To understand toxicity, support is required in each area.

For low-frequency MFs, evidence suggesting adverse health effects derives primarily from leg (1), but there is a profound lack of support from animal studies and mechanistic studies (legs [2] and [3]). In fact, much of the evidence from legs (2) and (3) suggests an absence of health risks from ELF-MF exposure.

Mechanistic evidence (leg 3) is crucial, as living organisms rely upon the same physical laws that govern all matter. As shown in Figure D.3 below, physics forms the basis of chemistry, which forms the basis of biology and, in turn, forms the basis of physiology and medicine. Hence, even though there is an increase in complexity as you move up in this hierarchy, each successive layer must obey the fundamental laws found to be valid for the layer below. At the most fundamental level are the laws of physics, which have been validated by experiment and internal consistency. Maxwell's laws of electromagnetism are accepted to be invariant in time and space, and their accuracy in describing the interactions between electromagnetic fields and matter underlies the functioning of virtually all technology. No exceptions have been found, despite constant challenges and tests. Likewise, physics has been found to be valid in complex systems, encompassing chemistry, biology, technology, and medicine. Simple conservation laws (*e.g.*, conservation of mass+energy, conservation of electric charge, and conservation of linear and angular momentum) apply universally, without exception.

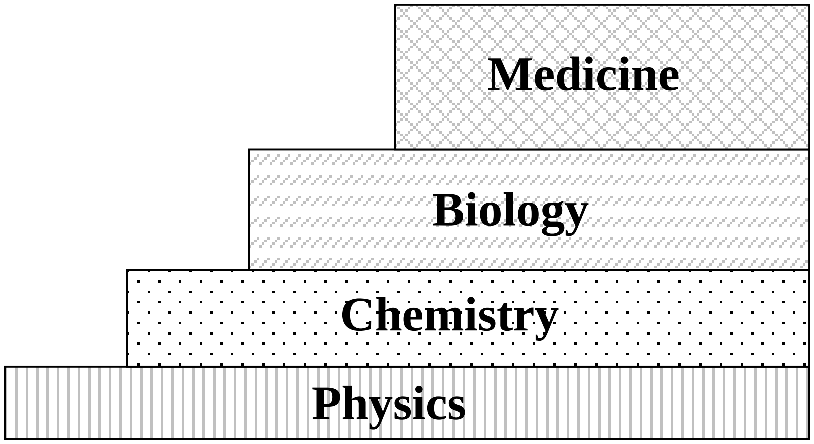

Figure D.3 Each Scientific Discipline Rests on the Underlying Laws of a More Basic Discipline

In order for MFs to cause changes within living cells, the fields must in some manner modify molecules or structures in the organism. By their very definition, MFs interact with matter only by exerting force on stationary or moving electric charges. At sufficiently high levels, these forces will add thermal energy or change the configuration of a charged biological molecule or structure. However, the magnitudes of natural forces that cells use (and are sensitive to) have been measured, and the results demonstrate that biological structures can withstand forces far larger than can be generated by typical MFs. Cells and organs function properly in spite of many internal sources of interfering thermal, chemical, electrical, and physical force effects, which exceed by a large factor the forces that can be caused by power-line MFs.

In summary, for MFs to alter physiological function, initiate dysfunction, or cause the onset of disease in humans or animals there must exist a mechanism by which magnetic forces alter molecules, chemical reactions, cell membranes, or biological structures (*i.e.*, DNA, RNA, plasma membranes, mitochondria). A MF is not a foreign molecular or chemical agent, and biological plausibility must be assessed with this in mind. The initial physical step sets off the following causal chain that must be completed in order to make any connection to disease:

Magnetic fields ⇒ matter (physics) ⇒ molecules (chemistry) ⇒ organisms (biology) ⇒ disease

A necessary condition for MFs to impact on human or ecosystem biology is that the MF-induced changes have to exceed chemical and thermal changes from natural or background influences. Changes in biological molecules are coupled to MFs through changes in forces on electrically charged structures, which in turn, must be coupled to metabolically important chemical processes (*e.g.*, reaction rates or transport rates).

Summary of EMF Health-Effect Conclusions from International Scientific, Health, and Safety Organizations, and Governmental Public Health Agencies

As summarized below, a number of international scientific, health, and safety organizations, and governmental public health agencies have reviewed the EMF health-effects literature and provided their interpretations of the EMF health-effects science. Below, we have compiled summaries that are illustrative of the current positions of a number of international scientific, health, and safety organizations, and governmental public health agencies, regarding the EMF health-effects science and the potential for human health risks arising from power-frequency EMF exposure. As discussed below, it is the consensus opinion of a number of international scientific, health, and safety organizations, and public health agencies, including the WHO, US EPA, and NIEHS, that there are no confirmed chronic human health risks for everyday exposures to power-frequency EMFs, including risk of cancers.

None of the international scientific, health, and safety organizations, and governmental public health agencies that have conducted comprehensive (*i.e.*, weight-of-evidence)[6] reviews of the EMF health-effects science have concluded that there is a sound scientific basis for causally linking long-term exposure to power-frequency EMFs with chronic health risks, and for justifying a need for health-based standards and exposure guidelines to protect against chronic health risks. As noted below and discussed more in the section on "EMF Standards and Guidelines," two international health and safety organizations (International Commission on Non-Ionizing Radiation Protection [ICNIRP] and the International Committee on Electromagnetic Safety [ICES]) have developed health-based exposure guidelines for power-frequency EMFs that are based on protection against acute or short-term effects (*e.g.*, electrostimulation). It also bears mentioning that a number of public health agencies do not even address power-frequency EMF health-effects concerns or provide recommendations on EMF exposure guidelines for power-frequency fields. This suggests that, even though the public's power-frequency EMF exposure is ubiquitous, the potential threat of a health hazard from power-line EMFs is not viewed as sufficiently established to warrant regulation. For example, the US Food and Drug Administration (US FDA), the Centers for Disease Control and Prevention (CDC), the Agency for Toxic Substances and Disease Registry (ATSDR), the Consumer Product Safety Commission (CPSC), the Office of the Surgeon General, and the NTP have not promulgated guidelines on power-frequency EMF exposure limits.

International scientific, health, and safety organizations, and governmental public health agencies, have provided the following conclusions regarding the EMF health-effects science and the potential for human health risks:

American Cancer Society (ACS) (2022):[7] "The possible link between electromagnetic fields and cancer has been a subject of controversy for several decades. It's not clear exactly how electromagnetic fields, a form of low-energy, non-ionizing radiation, could increase cancer risk. Plus, because we are all exposed to different amounts of these fields at different times, the issue has been hard to study."

US EPA (2023):[8] US EPA has not established any hazard levels or exposure standards for power-frequency EMFs, and US EPA states that "Scientific studies have not clearly shown whether exposure to EMF increases cancer risk."

European Commission, Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (2015):[9]

> In research on health effects of EMF, the lack of clearly focused working hypotheses for chosen biological endpoints is accentuated by the lack of an established biological or biophysical mechanism of action at environmental exposure levels. This does not allow researchers to conclude on the most relevant exposure parameter, and usually several alternative measures of exposure are evaluated (for instance field strength, exposure frequency, cumulative exposure, time since first exposure, *etc.*). In addition, some studies

[6] Weight-of-evidence approaches for reviewing health-effects evidence are well accepted in the public health field, and include such key elements as evaluating the entire body of relevant study findings, including from different types of studies (*e.g.*, epidemiological studies, laboratory animal studies, human clinical studies, mechanistic studies); assessing study quality and giving more weight to higher quality studies when weighing evidence; and using established, transparent, and systematic methods for integrating study evidence and reaching causal conclusions.

[7] https://www.cancer.org/cancer/risk-prevention/radiation-exposure/extremely-low-frequency-radiation.html.

[8] https://www.epa.gov/radtown/electric-and-magnetic-fields-power-lines.

[9] http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_041.pdf.

> use multiple end-points which are equally prone to false positive results, without adequate statistical corrections. Good research practice requires that all hypotheses evaluated are clearly stated and that all results pertaining to them are reported. Selective reporting, with emphasis on significant findings that were not specified in advance, can mislead the assessment by ignoring the issue of multiple testing…. The new epidemiological studies are consistent with earlier findings of an increased risk of childhood leukaemia with estimated daily average exposures above 0.3 to 0.4 µT [3 – 4 mG]. As stated in the previous [SCENIHR] Opinions, no mechanisms have been identified and no support is existing from experimental studies that could explain these findings, which, together with shortcomings of the epidemiological studies prevent a causal interpretation.

ICNIRP (2010):[10] ICNIRP (2010) conducted a comprehensive review of the body of scientific evidence related to potential adverse health effects from general public and occupational exposure to low frequency AC EMFs, concluding:

> The epidemiological and biological data concerning chronic conditions were carefully reviewed and it was concluded that there is no compelling evidence that they are causally related to low-frequency EMF exposure…. [A] causal relationship between magnetic fields [MFs] and childhood leukemia has not been established. The absence of established causality means that this effect cannot be addressed in the basic restrictions.

ICNIRP (2010) acknowledged the epidemiological evidence, suggesting that long-term exposure to 50-60 Hz MFs might be weakly associated with an increased risk of childhood leukemia, and pointed to uncertainties in this evidence, including the roles of "a combination of selection bias, some degree of confounding and chance" as explaining the epidemiological findings. In addition, ICNIRP (2010) highlighted how "no biophysical mechanism has been identified and the experimental results from the animal and cellular laboratory studies do not support the notion that exposure to 50-60 Hz magnetic fields [MFs] is a cause of childhood leukemia."

Based on basic restrictions for protection against acute health effects (*e.g.*, retinal phosphenes, nerve and muscle stimulation, shocks and burns, surface electric-charge effects such as perception), ICNIRP (2010) has established a health-based guideline for allowable general public exposure to power-frequency MF at 2,000 mG, (200 µT), and a health-based guideline for allowable general public exposure to power-frequency EF at 4.2 kV/m. Importantly, ICNIRP (2010) describes its exposure guidelines as "limiting exposure to electric and magnetic fields (EMF) that will provide protection against <u>all established adverse health effects</u>" [underline emphasis added].

The ICES within the Institute of Electrical and Electronics Engineers (IEEE) (2019)[11] conducted an updated review of the scientific and medical research literature, and retained its safety guidelines for general public exposure to 60 Hz MF and EF at 9,040 mG (904 µT) and 5.0 kV/m, respectively. IEEE (2019) specifically evaluated the evidence of possible adverse health effects for chronic low-level EMF exposure, reaching the following conclusions for exposures to electric, magnetic, and electromagnetic fields at frequencies between 0 Hz and 300 GHz:

> 1. "The weight-of-evidence provides no credible indication of adverse effects caused by chronic exposures below levels specified in this standard."

[10] International Commission for Non-Ionizing Radiation Protection (ICNIRP). 2010. "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (1 Hz to 100 kHz)." *Health Phys.* 99(6):818–836.

[11] Institute of Electrical & Electronics Engineers (IEEE). 2019. "C95.1-2019 IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic and Electromagnetic Fields 0 to 300 GHz." IEEE Standards Coordinating Committee 39, NY: IEEE, Inc.

2. "No biophysical mechanisms have been scientifically validated that would link chronic exposures below levels specified in this standard to adverse health effects."

3. "Based on the collective findings of recent reviews, the weight of the evidence continues to indicate that chronic exposure at levels specified in this standard is unlikely to cause adverse health effects."

National Cancer Institute (NCI) (2022)[12] notes on its webpage focused on "Electromagnetic Fields and Cancer" that "No mechanism by which ELF-EMFs or radio frequency radiation could cause cancer has been identified…. Studies of animals have not provided any indications that exposure to ELF-EMFs is associated with cancer." Regarding the evidence from epidemiological studies, NCI (2022) concludes:

> Most of the research has focused on leukemia and brain tumors, the two most common cancers in children. Studies have examined associations of these cancers with living near power lines, with magnetic fields [MFs] in the home, and with exposure of parents to high levels of magnetic fields [MFs] in the workplace. No consistent evidence for an association between any source of non-ionizing EMF and cancer has been found.

NIEHS (2024),[13] which funded and orchestrated a large laboratory-research program on power-frequency EMF, points out on its website that utility "Power Lines" fall into the "non-Ionizing" radiation category. On the website, NIEHS goes on to explain, "Non-ionizing: low-level radiation which is generally perceived as harmless to humans."

WHO published a lengthy monograph (WHO, 2007a) for its "Health Risk Assessment" of power-frequency EMF in 2007, as part of its International EMF Project, and came to several conclusions. WHO (2007a) concluded overall:

> Acute biological effects have been established for exposure to ELF electric and magnetic fields [EMFs] in the frequency range up to 100 kHz that may have adverse consequences on health. Therefore, exposure limits are needed. International guidelines exist that have addressed this issue. Compliance with these guidelines provides adequate protection. Consistent epidemiological evidence suggests that chronic low intensity ELF magnetic field [MF] exposure is associated with an increased risk of childhood leukaemia. However, the evidence for a causal relationship is limited, therefore exposure limits based upon epidemiological evidence are not recommended, but some precautionary measures are warranted.

Specifically, with respect to the interpretation of epidemiology associations, the summary section on p. 12 in WHO (2007a) states:

> Uncertainties in the hazard assessment include the role that control selection bias and exposure misclassification might have on the observed relationship between magnetic fields [MFs] and childhood leukaemia. In addition, virtually all of the laboratory evidence and the mechanistic evidence fail to support a relationship between low-level ELF magnetic fields [MFs] and changes in biological function or disease status. Thus, on balance, the evidence is not strong enough to be considered causal, but sufficiently strong to remain a concern.

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[12] https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/electromagnetic-fields-fact-sheet.
[13] https://www.niehs.nih.gov/health/topics/agents/emf/.

WHO released a fact sheet in June 2007 (WHO, 2007b) to accompany its full environmental health criteria monograph, and it contained similar conclusions regarding important limitations to the epidemiological evidence for childhood leukemia:

> However, the epidemiological evidence is weakened by methodological problems, such as potential selection bias. In addition, there are no accepted biophysical mechanisms that would suggest that low-level exposures are involved in cancer development. Thus, if there were any effects from exposures to these low-level fields, it would have to be through a biological mechanism that is as yet unknown. Additionally, animal studies have been largely negative. Thus, on balance, the evidence related to childhood leukaemia is not strong enough to be considered causal.

WHO (2007b) went on to discuss how the scientific evidence for other health endpoints was even weaker than that for childhood leukemia:

> A number of other adverse health effects have been studied for possible association with ELF magnetic field [MF] exposure. These include other childhood cancers, cancers in adults, depression, suicide, cardiovascular disorders, reproductive dysfunction, developmental disorders, immunological modifications, neurobehavioural effects and neurodegenerative disease. The WHO Task Group concluded that scientific evidence supporting an association between ELF magnetic field [MF] exposure and all of these health effects is much weaker than for childhood leukaemia. In some instances (*i.e.*, for cardiovascular disease or breast cancer) the evidence suggests that these fields do not cause them.

Therefore, WHO (2007b) recommended, "policies based on the adoption of arbitrary low exposure limits are not warranted."

WHO (2024b) maintains and updates a website[14] for its International EMF Project where it provides summaries of existing standards and guidelines and fact sheets, as well as scientific reviews of EMF health-effects research. On this website,[15] WHO (2024a) states, "[T]he main conclusion from the WHO reviews is that EMF exposures below the limits recommended in the ICNIRP international guidelines do not appear to have any known consequence on health." On another webpage with an EMF Q&A,[16] WHO provides the following conclusions regarding EMF health-effects research:

> Despite the feeling of some people that more research needs to be done, scientific knowledge in this area is now more extensive than for most chemicals. Based on a recent in-depth review of the scientific literature, the WHO concluded that current evidence does not confirm the existence of any health consequences from exposure to low level electromagnetic fields. However, some gaps in knowledge about biological effects exist and need further research. (WHO, 2016)

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[14] https://www.who.int/health-topics/electromagnetic-fields#tab=tab_1.
[15] https://www.who.int/teams/environment-climate-change-and-health/radiation-and-health/protection-norms.
[16] https://www.who.int/news-room/questions-and-answers/item/radiation-electromagnetic-fields.

Summary of Recent Research Publications on Childhood Leukemia

The potential linkage between residential exposure to power-frequency MFs[17] (*i.e.*, ELF-MFs) and risk of childhood leukemia continues to be the subject of updated epidemiological analyses and systematic reviews. In particular, Amoon *et al*. (2022) published an updated analysis that included pooled results from epidemiology studies published from 2010 to 2020 of MFs and childhood leukemia. Led by researchers in the Department of Epidemiology at the University of California, Los Angeles (UCLA) and the Los Angeles County Department of Public Health, this study observed no increased risk of leukemia among children exposed to greater MF levels (odds ratio [OR] = 1.01, for exposure ≥0.4 μT [4 mG] compared with exposures <0.1 μT [1 mG]). The results of the pooled analysis, which combined the primary individual-level data (24,994 cases, 30,769 controls) from either new or updated epidemiological studies conducted in California, Italy, the United Kingdom, and Denmark, are supportive of other study findings indicating a decline in reported leukemia risks from epidemiological studies using more recent (*i.e.*, post-1990s) data. Specifically, Amoon *et al*. (2022) concluded, "[O]ur results do not show the risk increase observed in previous pooled analysis and, over time, show a decrease in effect to no association between MF and childhood leukemia."

Consistent with the Amoon *et al*. (2022) findings, researchers from the WHO's IARC reported findings from the Childhood Leukaemia International Consortium (CLIC) supporting a lack of association between occupational ELF-MF exposure of parents and leukemia risk for their children (Talibov *et al*., 2019). Talibov *et al*. (2019) conducted a pooled analysis of individual-level data from 11 case-control studies (9,723 childhood leukemia cases, 17,099 controls) and reported ORs that were not statistically different from one for both paternal and maternal ELF-MF exposures and leukemia risk (including all leukemia subtypes, as well as specifically acute lymphoblastic leukemia [ALL] and acute myeloid leukemia [AML]), indicating no elevation in childhood leukemia risk with increased parental MF exposure. Based on their findings, Talibov *et al*. (2019) concluded:

> In conclusion, using a large international pool of case–control studies and a detailed quantitative JEM [job-exposure matrix], we did not find any evidence for an association between fathers' occupational ELF-MF exposures around the time of conception or mothers' occupational ELF-MF exposures during pregnancy and leukaemia in their offspring. Considering our findings and those of previous smaller less consistent studies together suggests that parental ELF-MF exposure plays no relevant role in the aetiology of childhood leukaemia.

Several meta-analysis and systematic review studies have been published in the last couple years, and despite often examining the results from a similar body of epidemiology studies, have reached different conclusions regarding the strength of the epidemiological evidence for ELF-MF exposure and risk of childhood leukemia. Seomun *et al*. (2021) reported statistically significant associations between exposure to ELF-MFs and childhood leukemia for their meta-analysis that included 27 case-control studies. Since case-control studies are subject to selection bias, as well as other methodological problems, Seomun *et al*. (2021) acknowledged their exclusive reliance on case-control studies as an important limitation to their analysis that reduces the strength of their findings. For their systematic review and meta-analysis of case-control studies and cohort studies, Brabant *et al*. (2022) reported findings indicating a statistically significant association between ELF-MF and childhood leukemia, with analyses indicating that this association was driven by results from studies performed before 2000.

[17] As mentioned previously, most of the remaining health concerns related to power-frequency EMFs are thus focused on MFs rather than EFs.

Onyije *et al*. (2022) conducted an "umbrella review" of environmental risk factors for childhood ALL that integrated findings from previously published systematic reviews or meta-analyses. For ELF-MF, Onyije *et al*. (2022) concluded that there was "some" level of evidence for an association between postnatal ELF-MF exposure and childhood ALL, in particular for the highest MF-exposed categories; in contrast, they concluded that exposure to low doses of ionizing radiation during childhood and general pesticide exposure during pregnancy were both "strongly" associated with childhood ALL. They highlighted ELF-MF as "an example where the epidemiological association was established more than 20 years ago but concerns about bias and the lack of biological plausibility of the association have precluded any conclusions on causality." The English abstract for the Herkert *et al*. (2021)[18] integrative review, which analyzed five case-control studies published between 2012 and 2020 that investigated the association between exposure to ELF-MF and risk of childhood leukemia, includes the following overall conclusion: "Due to methodological heterogeneity and confounding variables in the analyzed articles, the authors concluded that it was not possible to demonstrate the relationship between low-frequency non-ionizing radiation sources and the development of childhood leukemia." Similarly, for their recent review paper, Schmidt *et al*. (2021) emphasized how ELF-MF has yet to be "verified" as a risk factor for childhood leukemia, and they pointed to the lack of a plausible biological mechanism and the inadequate evidence from experimental animal studies: "However, how ELF-MF may cause leukemia is unknown – until today, no plausible biological mechanism has been found, and experimental *in vitro* and *in vivo* studies do not confirm the results of the epidemiological studies."

Finally, epidemiological studies continue to investigate possible alternative explanations for the observed epidemiological associations between ELF-MF exposure and risk of childhood leukemia, with postulated factors including socioeconomic status, residential mobility, residential dwelling type, viral contacts, environmental tobacco smoke, dietary agents, traffic density (as a proxy for air pollution exposure), pesticides, and corona ions (Crespi *et al*., 2019). Using the large dataset from the California Power Line Study (CAPS), several recent studies have examined potential bias and/or confounding from factors that include potential pesticide exposures associated with commercial plant nurseries located in areas underneath power lines (Nguyen *et al*., 2022), dwelling type (*e.g*., single-family homes *vs*. apartments/mobile dwellings; Amoon *et al*., 2020), and residential mobility (Amoon *et al*., 2019). While none of the investigated sources of potential bias and/or confounding have been found to explain the entirety of previously observed associations between power-frequency MFs and risk of childhood leukemia, these studies have reported some findings requiring additional investigation. For example, Nguyen *et al*. (2022) reported findings suggesting close residential proximity to nurseries as an independent risk factor for childhood leukemia, but not as an explanation for observed associations between power-frequency EMFs and childhood leukemia risk; however, they discussed how their ability to fully assess its potential confounding role was limited by the small numbers of study subjects with both high ELF-MF exposures and with close proximity to power lines and plant nurseries. Based on analyses they conducted to probe the confounding effect of residential mobility, Amoon *et al*. (2019) concluded, "We conclude that uncontrolled confounding by residential mobility had some impact on the estimated effect of EMF exposures on childhood leukemia, but that it was unlikely to be the primary explanation behind previously observed largely consistent, but unexplained associations." An additional study using the CAPS data (Crespi *et al*., 2019) conducted modeling analyses to examine the interaction between distance from high voltage lines and calculated MF levels as exposure metrics, and reported findings that "argue against magnetic fields [MFs] as a sole explanation for the association between distance and childhood leukemia and in favor of some other explanation linked to characteristics of power lines."

[18] The full paper is only available in Portuguese and has not been reviewed.

EMF Standards and Guidelines

The US has no federal standards limiting either residential or occupational exposure to 60-Hz AC EMFs. The Massachusetts Energy Facilities Siting Board (MA EFSB) assesses EMF levels on a case-by-case basis with a focus on practical options to reduce magnetic fields along transmission line rights-of-way (ROWs). Some states, including New York and Florida, have adopted EMF guidelines that are not health-effect based and have typically been adopted to maintain the *status quo* for EMFs on and near a transmission line ROW.

Table D.1 shows health-based exposure guidelines established by international health and safety organizations that are designed to be protective against adverse health effects. As mentioned earlier, these exposure guidelines are based on protection against acute or short-term effects (*e.g.*, electrostimulation) as these organizations have concluded that the health-effects evidence is too inconsistent and weak to justify a need for or to support the development of exposure guidelines for chronic health risks. ICNIRP (2010) concluded that there was not sufficient evidence to support the development of an exposure guideline specific to long-term exposure, citing both the lack of any consistent increases in any types of cancer (*e.g.*, hematopoietic, mammary, brain, skin tumors) in large-scale, long-term laboratory animal studies and the weak and inconsistent evidence from human epidemiological studies, including those addressing risk of childhood leukemia. For example, ICNIRP (2010) concluded:

> It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields [MFs] is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure.

The limit values should not be viewed as demarcation lines between safe and dangerous levels of EMFs but, rather, levels that assure safety with an adequate margin to allow for uncertainties in the science. This is because they incorporate safety factors; for example, the ICNIRP general public MF guideline of 2,000 mG incorporates a safety factor of 5. In summary, available exposure guidelines such as the ICNIRP general public exposure guidelines are generally applied for both short-term and long-term exposures, and are reasonable for use in both contexts, because there is no scientific rationale for separate guidelines focused specifically on long-term EMF exposure.

Table D.1 60-Hz AC EMF Guidelines Established by International Health and Safety Organizations

Organization	Electric Field	Magnetic Field
American Conference of Governmental and Industrial Hygienists (ACGIH) (occupational)	25 kV/m[1]	10,000 mG[1] 1,000 mG[2]
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (general public)	4.2 kV/m[3]	2,000 mG[3]
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (occupational)	8.3 kV/m[3]	10,000 mG[3]
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1™-2019 (general public)	5.0 kV/m[4]	9,040 mG[4]
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1™-2019 (occupational)	20.0 kV/m[4]	27,100 mG[4]

Notes:

AC = Alternating Current; EMF = Electric and Magnetic Field; Hz = Hertz; kV/m = Kilovolts Per Meter; mG = Milligauss.

(1) The ACGIH guidelines for the general worker (ACGIH, 2024).

(2) The ACGIH guideline for workers with cardiac pacemakers (ACGIH, 2024).

(3) ICNIRP (2010).

(4) IEEE (2019); developed by the IEEE International Committee on Electromagnetic Safety (ICES).

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