Chapter 4: Exposure Calculations

4.1 Overview

In this chapter we discuss the approach that was used for the exposure calculations in this project. In section 4.2 we begin with a brief tutorial on the approach. Section 4.3 discusses the development of the approach, both previous to and during the current project. Section 4.4 describes the computer programs used to evaluate exposure at a specific location based on the different ways of summarizing exposure and choice of mitigation strategy. Section 4.5 covers the exposure calculation results for one of the “retrofit distribution” scenarios that were modeled during the course of this project.

The concept of "effects functions" was developed at in the late 1980’s by Morgan, Nair, and Florig (Morgan and Nair, 1992) to accommodate different assumptions about how the body might react to the magnitude and timing of the changing magnetic fields over time. An "effects function" combines two concepts. The first is an exposure measure that is assumed to constitute the effective dose. The time-weighted average of the magnetic field or the percent of time an individual is exposed to fields above a threshold are examples of exposure measures. We will consider a person's particular observed value of the exposure measure, say the % of time they spent above 2mG as their "dose." The second concept is a dose-response function (e.g., a linear function of incremental risk over the relevant exposure measure). Alternative exposure measures will be discussed in this chapter. Alternative dose-response functions will be discussed in the next chapter.

Our policy models explore whether three different assumptions about exposure measures and dose-response functions lead to different recommendations. The three assumptions are:

1. Time-Weighted Average (TWA): very low exposures convey some risk and should be added in with the high readings. If this were so one should simply add up all the individual exposures during the course of the day and take the average. This average is a possible exposure measure. We then assume a dose response function such that the relative risk increases in a steady linear fashion as this average increases until some plateau of risk is reached. If this assumption were true one would want to avoid even low fields and would predict benefits from lowering extremely high fields down to very high fields.

2. Linear Threshold: our exposure measure is still an average of measurements but only of those, which exceed a specified threshold. There is no effect of the magnetic field exposure below a certain intensity ("threshold"). If this is so we should only average the fields, which exceed that threshold. Exposures below the threshold convey no risk at all and are averaged in the exposure calculations as “zero” exposures. We still assume that the higher the exposure is above the threshold the more effect it has. We then assume that the risk increases in a steady linear fashion as the average above the threshold

increases until some plateau of risk is reached. If this assumption were true, one could ignore exposures below the threshold and would achieve benefits by lowering extremely high fields down to somewhat high fields.

3. Binary Threshold: there is no risk conveyed by readings below the threshold, and risk is accumulated merely by exceeding the threshold. It doesn't matter how much the exposure exceeds the threshold. If this is so, one should use an exposure measure, which simply calculates the percent of the readings, which exceeded the threshold. We then assume (as a dose response function) that as this percent increases, the risk increases in a steady linear fashion up to some plateau of risk. If this assumption were true, one could ignore exposures below the threshold and would need to lower elevated fields to below that threshold to obtain any benefit. Lowering extremely high fields to fields above the threshold would convey no benefit at all.

Other assumptions, not investigated as part of this project, are that the relevant exposure measure is the number of rapid field changes or whether a certain field value was ever exceeded during the day.

It seemed quite possible that the choice between mitigation options or the cost effectiveness of mitigation options might be different depending on which of the three above mentioned assumptions one made about how the body responded to different patterns of exposure to power line magnetic fields. On the other hand, if mitigation options differed from the status quo only in how they changed mid-level fields, and not very low or very high fields, the ranking of options and the cost effectiveness of options might not be sensitive to biological assumptions about how the body would respond to patterns of exposure during the course of the day. One objective of our policy analysis was to see whether or not policy is sensitive to these assumptions.

4.2 Tutorial

We present this tutorial in two parts. In the first part we present how we use the concept of exposure measures and dose response functions to relate EMF exposure to plausible health endpoints. In the second, we describe how background fields are included as part of the exposure calculation.

Using exposure measures to relate EMF exposure data to plausible health endpoints

Our input is EMF exposure as a function of time, and the output is the calculated health impact. The uncertainties are that, first of all, we do not know what exposure measure if any, would be biologically active, and second we do not know what dose-response function is operating. The exposure measure could be the time weighted average of the field strength, the percentage of time a field exceeds a certain minimum threshold, or one of countless other possibilities. The dose-response might be that the effect is linearly proportional to the exposure measure, that the effect is linearly proportional up to a given maximum after which it is constant, or again countless other possibilities.

To illustrate the approach, we step through a basic example of how a calculation is carried out. The first plot, (A), represents a person's exposure for a 30 second period. In (B) the corresponding data set collected by an EMDEX meter worn by this person is shown. The EMDEX only collects measurements every few seconds and not continuously. Hence we only have certain points from the continuous tracing in "A." Using the data set represented in (B), the exposure measure is determined for the particular exposure measure of interest. In (C) the dotted line is meant to indicate that we are interested in a 15 mG threshold. If the exposure measure is "percent of time spent above 15 mG," then for this illustrative data set, 4 of 10 data points are above the threshold so that the "dose" is 40%. For the same data, if the appropriate exposure measure was time weighted average, the "dose" would be 14 mG (the average of all the summary readings in "B" or "C").

The second step is to relate the "dose" to the actual response. One typical measure of response in terms of actual health effects is the risk ratio, or RR. For a given health effect, for example, a certain type of cancer, a risk ratio of 1 indicates the base rate of that cancer, for example one chance in 5,000 per year. If for some reason the RR is increased to 2, then the chance is doubled – in this case to two chances in 5,000 per year.

In Figure 4.2 we present a simple dose-response relationship: the response is proportional to the dose. We assume, for the sake of illustration, that for each increase of 2 mG in the TWA that the RR increases by 1. Thus the change in RR per mG is here assumed to be 0.5. For example, if the TWA is 0 (zero dose) the RR is 1.0. Then if the TWA is 4 mG the incremental increase in the RR is 2 so that the RR is now 3. The arrow is used to represent the fact that there is no upper bound on the RR for this assumed dose-response curve. For example, if the TWA is 20 mG then the incremental increase in the RR is 10 (0.5 x 20). As mentioned above, if TWA is the assumed exposure measure, then the data from Figure 4.1 represents a "dose" of 14 mG. For this dose and our hypothetical dose-response function, the OR is calculated as 8, or 1 + 14 x 0.5. Both the dose and the response are marked with X's in Figure 4.2.

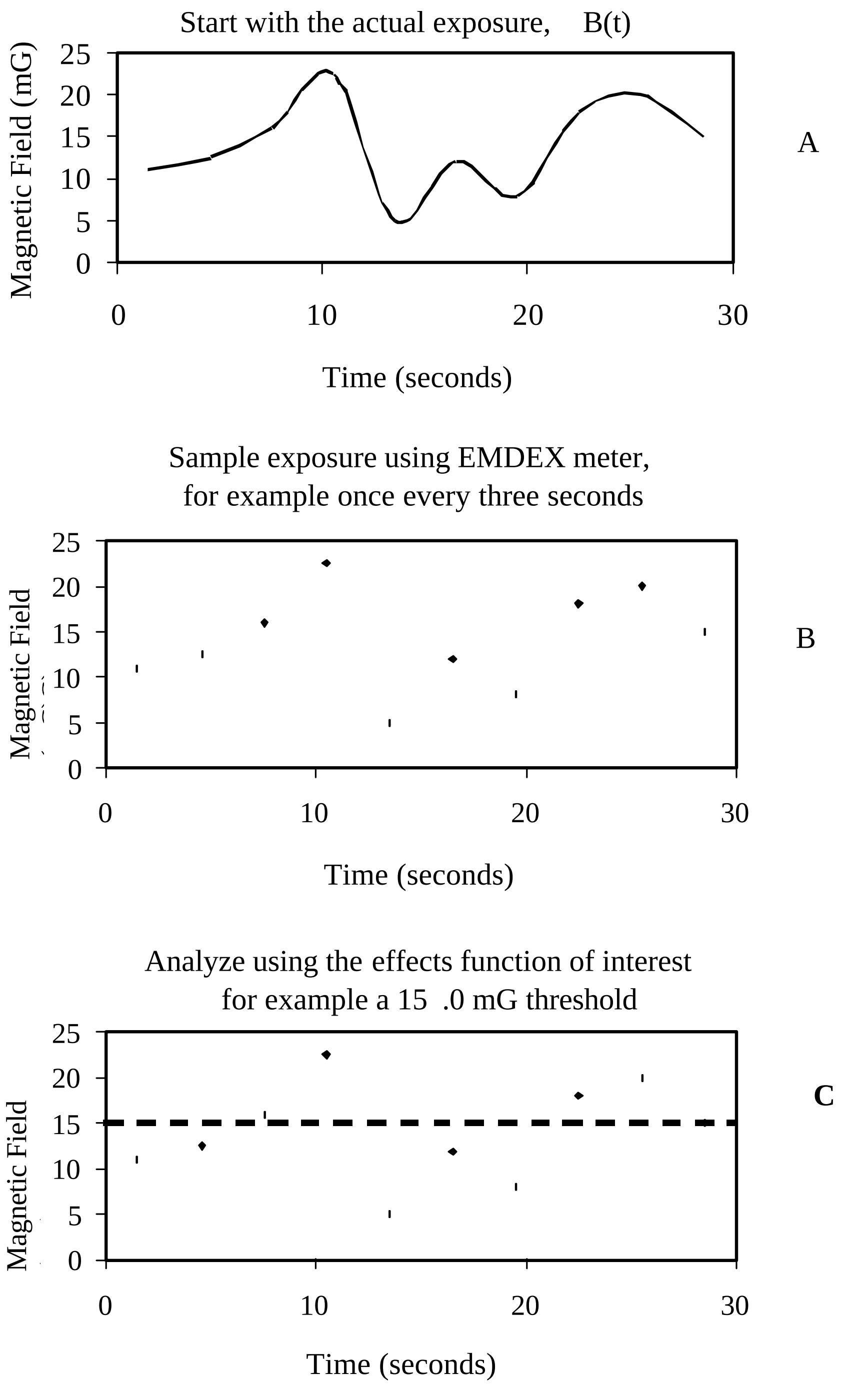


Figure 4.1: Starting with actual pattern of exposure (A), this is sampled by an EMDEX meter (B), and then processed based on chosen effects function (C).

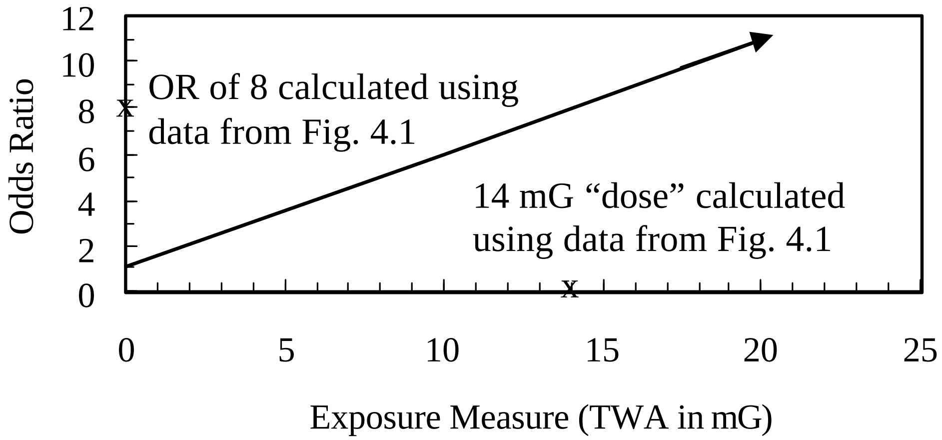


Figure 4.2: Illustrative dose-response function. The response (Odds Ratio) is assumed linearly proportional to the dose.

To summarize, we go from measured or calculated series of EMF exposures in an interval of time, to one of several possible exposure measures. From this calculated exposure measure, the response is calculated which will depend upon the dose-response curve chosen. Both the assumed exposure measure and the assumed dose-response function are quite uncertain at this time. We want to emphasize that the exposure measures, the ranges for the RRs, and the forms of the dose-response curves chosen in this section are for illustrative purposes only.

Inclusion of background fields in the analysis

People are usually exposed to a wide variety of magnetic field sources during the course of a day. If we are considering the mitigation of a particular source, it can be important to consider that source in a realistic context – meaning to take into consideration the variety of other sources present simultaneously. In this project, what is meant by "background" fields are the fields due to all sources *except* those from the source (powerlines and ground currents) being considered for mitigation.

How do we go about incorporating background fields into the calculations given in Part 1 of this tutorial? Let us step through an example, assuming that the magnetic field data in Fig. 4.1B represents exposure due to some source. We want to know what the output will be for the case where in addition there is a constant background field of 14 mG. The process is shown in Figure 4.3. First, we start with intermittent measurements from the source fields as shown in (A). We add the background fields (B) at each point in time, to obtain the new EMDEX-like time series shown in (C). This series (C) is used as the input for the exposure measure calculations, which is then used in a dose response function to produce RR.

What effect does including the background have on the calculation results? For the illustrative case given in Figure 4.3, the TWA increases from 14 mG (source only) to 20.1 mG. The calculated RR for "source only" is 2.21, while it is 2.45 when background fields are included. Thus, in this illustrative calculation, the inclusion of background fields results in an incremental increase in the RR of 0.24, or about 10%, over the case of source only. The way the fields from the powerline or ground current source and the EMDEX add is random, which is modeled in the computer program used to evaluate exposure. The specifics of how the source and background fields are added are covered in Appendix B.

The EMDEX files used to approximate typical background exposures in California were taken from California Department of Health Service's Pregnancy Outcome epidemiological study, in which a number of women primarily in the Bay Area wore EMDEX meters for an extended period of time. We used EMDEX tracings from individuals in Low Current Configuration homes, which are far from powerlines, as we want to represent the background data, meaning field sources other than power lines – appliances, household wiring, and so forth.

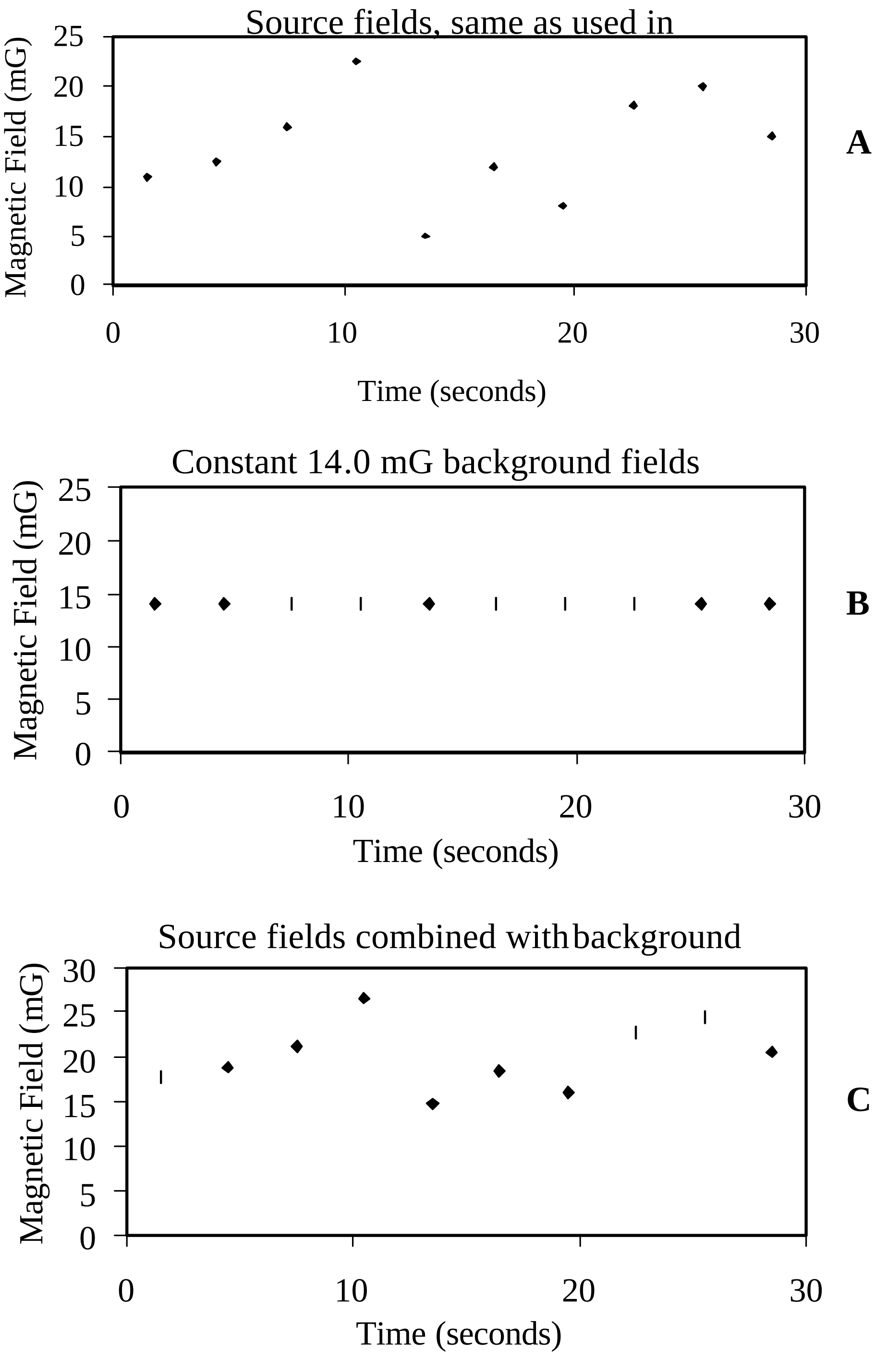


Figure 4.3 Starting with the measured exposure from the source (A) and with the background exposure (B) of 14.0 mG, the combined exposure is calculated in (C). Because of the vector nature of the fields, combining them results in lower fields than simply adding them.

4.3 Development of the Approach

Development of the approach prior to this project

During the early 90's what was called the "effects functions" approach was incorporated into policy analysis. In its first iteration, the approach was a one-dimensional approach suitable for transmission-line scenarios (Adams et al., 1995). Construction of new transmission line was among the first scenarios examined. In these scenarios a base case was considered and compared with a number of mitigation options, such as using a split-phase design or rerouting the line. Loading on the lines was assumed to be constant in time, and exposure to non-transmission sources was given by EMDEX data. At a given distance from the line, total exposure was obtained by combining the transmission-line field along with EMDEX data as described in the tutorial section. Combining exposure as a function of distance from the lines with population as a function of distance from the line, and summing over the area where exposure is significant, gives total exposure. The total exposure due to transmission and non-transmission sources combined was obtained for both mitigated and non-mitigated cases.

The advantages of this approach are that possible bioactive exposure measures and possible dose response functions are quantitatively incorporated into the analysis, the distribution of people with respect to the source is part of the analysis, and the contribution of background sources is taken into account.

During the following years two main improvements were made to approach by extending the analysis to two dimensions and by including powerline source variability. The advantage of a two-dimensional approach is that spot use of mitigation options can be modeled. For example, if a 15 mile stretch of 115 kV line is to be built to connect two substations, then most likely along the line there will be quite a bit of variability in the population distribution - the line might pass through both commercial and suburban areas, for example. If mitigation is to be carried out, then considerably greater exposure reduction might be obtained by concentrating resources where population density is greatest. Modeling population density and line configuration in two dimensions facilitates the calculation of the value of implementing spot use of mitigation strategies.

The inclusion of powerline source variability was carried out by following the method developed by Olsen (1992). Essentially, loading on transmission lines is quite variable depending both on time of day and the season of the year. Using standard Monte Carlo simulation techniques, a distribution of loading on the lines is generated which incorporates both daily and seasonal variability. Associated with the variable loading, there is now a distribution of field strengths at each position relative to the line.

As a result of including two dimensional field and population profiles, as well as including source variability in the calculation, the models became much more realistic and a much broader range of scenarios could be modeled than was the case for the one-dimensional, constant source version of this approach. In particular, combining the field distributions with EMDEX data allows for a much more realistic assessment of threshold effects than by assuming constant loading.

Creating a user-friendly program

Much of the effort early on in the project was to determine how best to dovetail the effects function and decision analysis approaches, one goal being to create as user-friendly an approach as possible. Prior to this project the computer code for the effects function approach was very much “research grade,” meaning that the input and output were highly customized and geared for use by its author. Before rewriting the effects code, better understanding of the approach was obtained by Decision Insights’ personnel, and better understanding of decision analysis approach was obtained by Jack Adams. With this understanding, it was decided to dovetail the decision analysis and effects function approaches. This was done in part by creating a user-friendly Visual Basic (VB) front-end. The approach which was developed is shown in flow-chart form in Figure 4.4. The steps numbered in the figure are described below:

1. The first job of the VB program is to query the user for information pertinent to the specific type of scenario being modeled. This will be described in detail in the next section and includes requesting information such as which type of EMF source to model, what EMDEX data to use to approximate the background sources, and where people are.

2. The next job of the VB program is to take the data from the user and create an input file to be used by the exposure program.

3. The VB program sends the input files just created to the exposure program and runs it.

4. After the exposure program has run, it creates an output file, which contains the exposure calculation results. This file is an array of exposure calculation results, storing the exposure as a function of mitigation measures, effects function, and distance from the source.

5. The user then manually imports the exposure array file into the decision analysis models programmed in ANALYTICA.

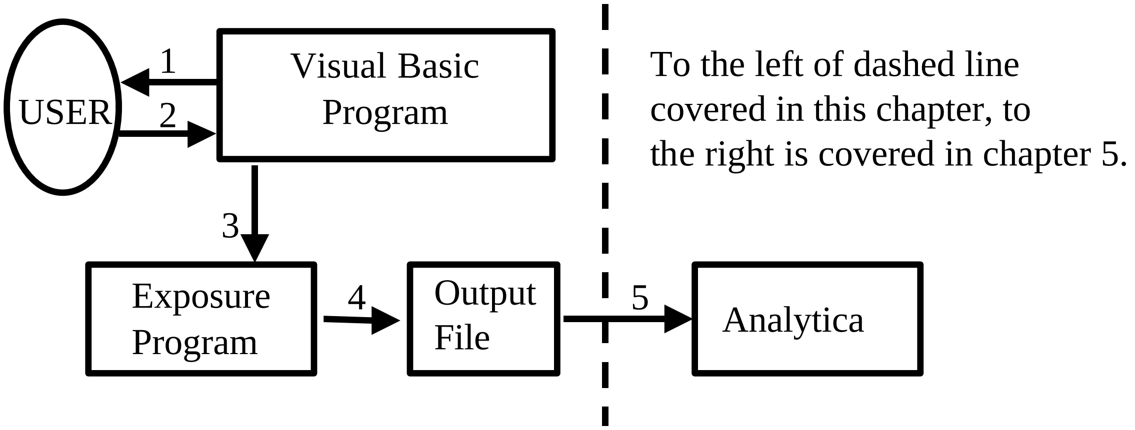


Figure 4.4 Flow Chart of Tasks in the Combined Effects Function and Decision Analysis Approaches

Other modifications of the approach during this project

The code was made more user-friendly in two more ways: first, the input-output files were made much easier to read and the exposure calculation was made to run about 20 times faster. The point of improving the input-output files was to make the interaction with the visual basic program more straightforward. The point of speeding up the exposure calculations was that prior to the project a typical calculation might take several hours, which would prohibit real time use of the program. The code was sped up dramatically by pre-calculating a distribution of the magnetic field at each location, taking into account the distribution of powerline source loading. This compares to the original approach of completely recalculating the field profile at each EMDEX time-step. The resulting reduction in calculation time was up to 95%. A calculation that took a few hours now takes a few minutes.

Another major change in the code was to extend the model to the home grounding currents scenario. The modification required took into account the three-dimensional variability in the fields created by the ground current source. This was required because the fields from ground current sources are highly variable in space, so that a one – dimensional or “quasi” two-dimensional approach is not sufficient. The fields due to currents flowing in the plumbing can vary quite a bit within a floor of a home and also between floors. Other modifications included allowing for the creation of a fairly fine set of grids within the home based on number of floors and size of the living area and allowing for various placements of the grounding conductors and the secondary drop.

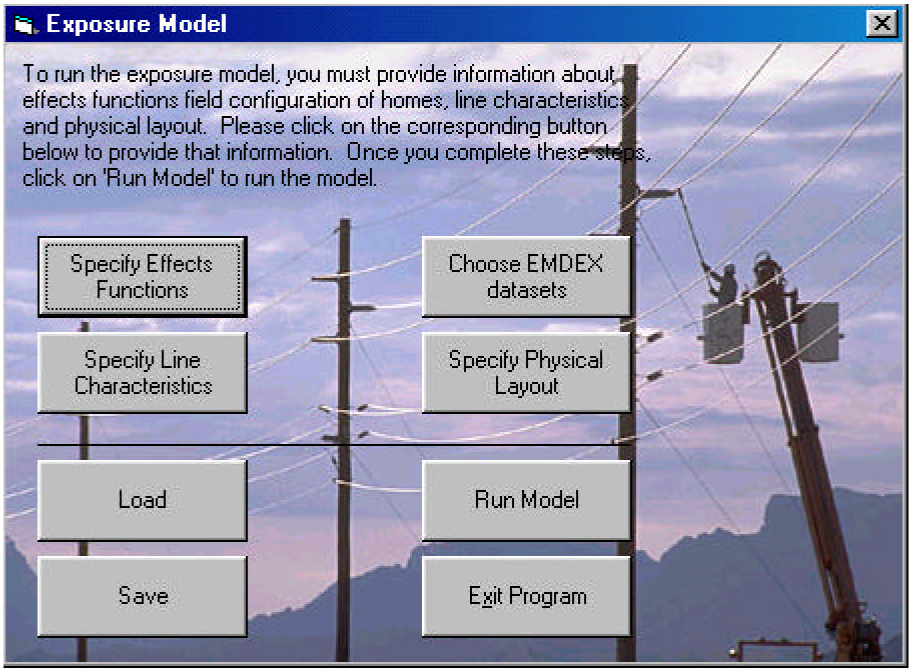
4.4 The Exposure Calculation Computer Program

The purpose of the exposure calculation program is to evaluate the per-person exposure as a function of the magnetic-field environment and of the assumed exposure measure and dose-response function. In this section we describe many of the details of this program. For the purpose of this illustration, we consider the following scenario: a double circuit, normally phased 115 kV transmission line 10 miles in length connects two substations. The entire area is rural, and the only mitigation strategy being considered is to convert the line to an optimal phase configuration. We are interested in evaluating the unmitigated base case and mitigated exposures based on three exposure measures and dose-response functions: time weighted average, 2.0 mG linear threshold, and 5.0 mG linear threshold.

First Step: Obtain Input Data from the User

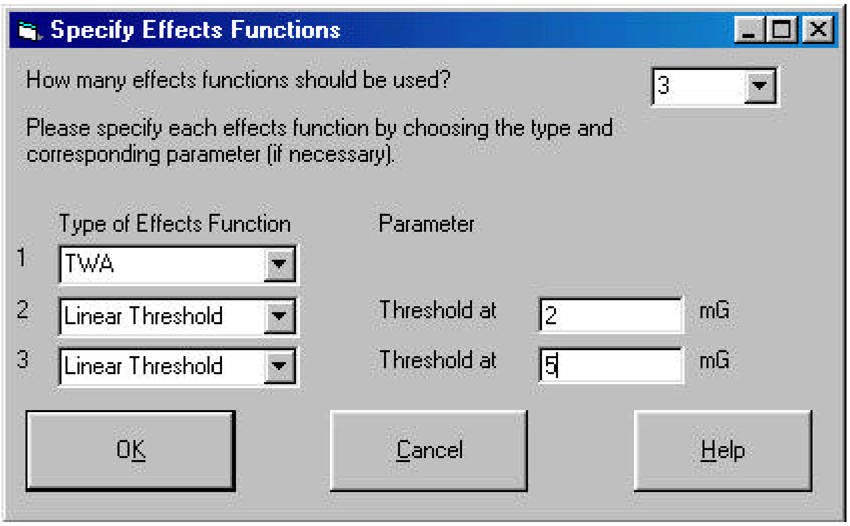
Figure 4.5 is the first screen presented to the program user when the visual basic (VB) front-end is started up. Each of the four upper buttons, when pressed, presents the user with a form to fill out to input the required data. The upper left hand button when pressed pops up the “Specify Effects Functions” screen shown in Figure 4.6. The user is allowed to specify up to 10 specific options derived from three basic options. The first, TWA, simply is the average magnetic field strength experienced at a given location. The Linear Threshold is similar to the TWA, except that any fields below the chosen threshold are averaged in as zero mG – they are considered “no exposure.” The binary threshold assumes a constant dose when the field is above the threshold, and no dose when below. For the binary threshold the dose is reported in % of time above threshold. In Figure 4.6, the user has chosen three exposure measures: TWA, linear 2.0 mG, and linear 5.0 mG.

The user next specifies the EMDEX data set to use to approximate the exposure from background sources in the scenario. To remind the reader, we defined background as fields from sources other than the ones being evaluated. These data sets are taken from the California Department of Health Services study and represent in-home time spent by pregnant women in the pregnancy outcome study. There are four choices: low current configuration, high current configuration, custom EMDEX data set, and none. The low and high current configurations correspond to the LCC and HCC designations in the Wertheimer-Leeper wire code.



To run the exposure model, you must provide information about effects functions field configuration of homes, line characteristics and physical layout. Please click on the corresponding button below to provide that information. Once you complete these steps, click on 'Run Model' to run the model.

Figure 4.5: Startup Form of the VB program



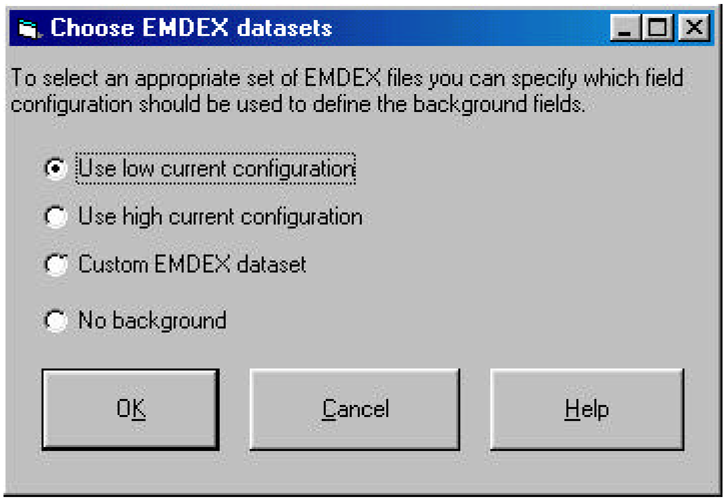
How many effects functions should be used? 3

Please specify each effects function by choosing the type and corresponding parameter (if necessary).

	Type of Effects Function	Parameter		
1	TWA			
2	Linear Threshold	Threshold at	2	mG
3	Linear Threshold	Threshold at	5	mG

Figure 4.6: Specify Effects Function Form

In general, since the user will be evaluating the impact of a power line, the EMDEX data should not include any obviously strong effect of a power line, so LCC data makes sense to use. The "Custom" choice allows the user to define a custom set EMDEX data, which could be a mix of LCC and HCC for example, or data taken in an industrial setting. The "none" choice might be made by a user to check the accuracy of the field calculations in this program, or where there is reason to believe that the background fields are negligible. The form for inputting the choice of EMDEX dataset is shown in Figure 4.7.



To select an appropriate set of EMDEX files you can specify which field configuration should be used to define the background fields.

● Use low current configuration
○ Use high current configuration
○ Custom EMDEX dataset
○ No background

Figure 4.7: The Form Used to Specify Which EMDEX Data Sets

It should be pointed out that the data sets provided with the program are for residential situations, and thus the background in industrial scenarios cannot be accurately modeled with them.

The user next inputs information pertaining to each distinct line type that will be modeled during the course of the calculations. This is done via the "Specify Line Characteristics" form shown in Figure 4.8. The user is prompted "How many line configurations should be used?" In this illustrative scenario, there are just two: a base case double circuit, and the same line except with the phases optimized for low fields. For the first configuration the values are input as shown in the figure below. The line type identification (ID) number corresponds directly with that given in the School Measurement study conducted by Enertech Consultants (1998a and b). In this case the ID is 116. The user then provides a name for this line type, which for this case is "115 kV DC, Normal Phasing."

The next step is to provide the geometrical factors that will allow the computer program to accurately model the location of the conductors. In this case D1 is the horizontal separation between the conductors, D2 is the vertical separation between the conductors, and H is the mid-span height of the lowest conductors. Other line configurations may require other geometric factors, so D3 and D4 are available for use but are not needed here. Next the user chooses the circuit type from a drop-down menu which includes the choices:

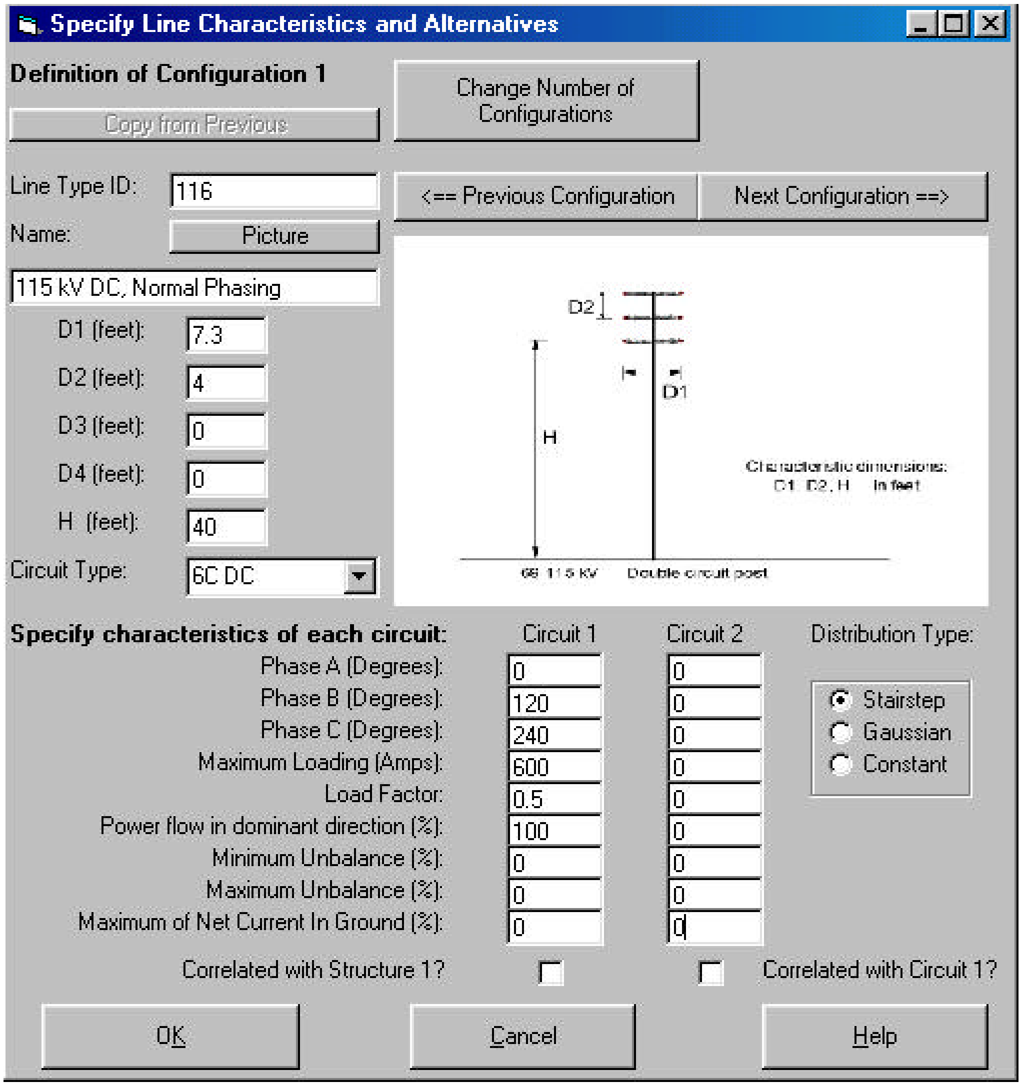
- 3C (3-conductor single circuit),
- 6C DC (6-conductor double circuit),
- 6C “SB” (this is configured like a super-bundle: in appearance it looks like a double circuit, and is configured ABC-ABC. There is only one circuit, with the each phase split between the two conductors—thus the name “super bundle,”
- “Split” (the same as the above super-bundle, except that the configuration is ABC-CBA).

The last three choices are unique to distribution:

- 3C with neutral is 4-wire distribution;
- 6C with neutral is 7-wire distribution, where two primary circuits share a neutral;
- 2C primary is either one hot with a neutral or two hot phases.

In this illustrative scenario, the user chooses the second option ”6C DC.” There are 6 conductors and two separate circuits.

For each circuit the A, B, and C phases are chosen as 0, 120, and 240 degrees respectively for both circuits. The maximum loading is chosen as 600 Amps. The load factor, a measure of how heavily loaded the circuit is typically, is chosen as 0.5. The power flow in the dominant direction is the percentage of time the power flows in the most common direction, and here is chosen to be 100%. The minimum and maximum unbalance are used to model different loading on the individual conductors. For transmission this tends to be relatively small, and the unbalance is chosen to be zero. The last box, percentage of current returning via the ground, is used for distribution only.



Definition of Configuration 1

Line Type ID: 116

Name: 115 kV DC, Normal Phasing

D1 (feet): 7.3

D2 (feet): 4

D3 (feet): 0

D4 (feet): 0

H (feet): 40

Circuit Type: 6C DC

Specify characteristics of each circuit:

	Circuit 1	Circuit 2
Phase A (Degrees):	0	0
Phase B (Degrees):	120	0
Phase C (Degrees):	240	0
Maximum Loading (Amps):	600	0
Load Factor:	0.5	0
Power flow in dominant direction (%):	100	0
Minimum Unbalance (%):	0	0
Maximum Unbalance (%):	0	0
Maximum of Net Current In Ground (%):	0	0

Correlated with Structure 1? ☐

☐ Correlated with Circuit 1?

Distribution Type:

● Stairstep
○ Gaussian
○ Constant

Figure 4.8: Form Used to Input Each Line Type

The two check-off boxes at the bottom of Figure 4.8 are used to define whether or not the loading of two circuits is correlated. By "correlated" we mean that the loading is the same percentage of the maximum loading at all times, so that if one circuit has 30% of maximum loading at a given time, so does the correlated circuit. The "correlated with structure one" box is used to indicate that the loading of a second or third structure in a right-of-way (ROW) is correlated with that of what is defined as the first structure. Since there is only one structure in the present scenario, this box does not need to be checked off. The second check-off box is for double circuits, and defines whether the loading of the second circuit is correlated with the first. Here it is left unchecked, so that although the power flow is always in the same direction for the two circuits, the magnitude of the loading is not assumed correlated.

The last “Line Characteristics” parameter that the user chooses is “distribution type,” which defines the statistics used to model the variation of the loading of the circuits. The “stair-step” model, introduced by Olson et al. (1992), incorporates both daily and seasonal variations into the overall model of the loading variations. The Gaussian model simply uses a truncated Gaussian distribution to model the loading. Based on the load factor, the maximum loading, and whether the stair-step or Gaussian option is chosen, the statistics of the loading variations on each circuit is uniquely defined. The stair-step distribution is chosen in this scenario.

Once the user has filled out the information for the first line type, he or she presses the “next configuration” button towards the top of the form. Most of the information is the same for the second line type, so the “copy from previous” button is used. The only changes are the name, this one is called “115 kV optimum phased,” and the phase of the “A” conductor is 240 degrees and the “C” conductor is 0 degrees. Besides these changes, the information is the same for the two line type.

The final information is obtained in the “Specify Physical Layout” form. To explain the use of this form, we first must introduce some terminology. In our analyses, a powerline typically connects two points, e.g., two substations. We define a “segment” of a powerline as a stretch of line, usually between a fraction of a mile and several miles long, that has similar land use, right-of-way, load, and population characteristics. Segments are used to define unique land uses or locations of a powerline. For example, a 0.5 mile segment that passes by a school is unique, because it creates exposure for a specific population of young people. As a result, one may consider special mitigation measures for this segment.

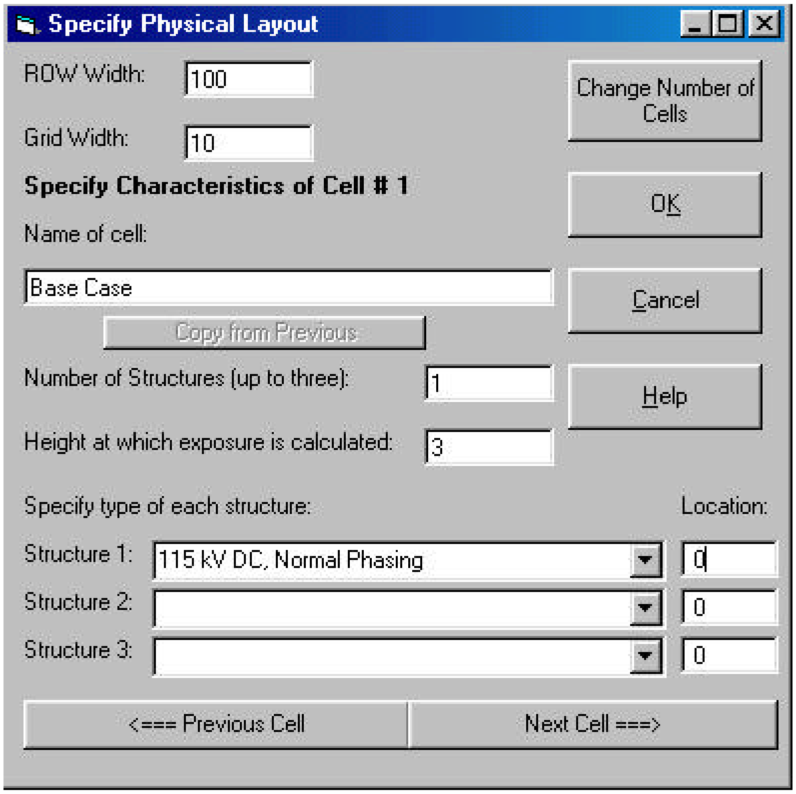
A “block” is a rectangle extending perpendicular to a segment of a powerline, usually a few hundred feet deep on each side of the line. Blocks are used for exposure calculations for different segments. “Grids” are created by subdividing a block into equal sized rectangles with the width of a segment and equal depth – usually 10-30 feet. An “exposure box” is a rectangular box with the base of one grid element and a height of a few feet. Exposure boxes are the fundamental exposure units and all exposures are assumed to be identical to the exposure of a person located in its center.

The exposure program uses the term “generic cell” or “cell” in a special, and somewhat unusual way. A generic cell combines a block (a physical area perpendicular to a segment) with a mitigation alternative (e.g., a change of the line configuration). For example, one mitigation alternative for a 0.5-mile segment of a powerline that passes by a school may be to underground that particular segment. The generic cell would then defined as the block that is 0.5 miles long and a depth of, say, 300 feet with an underground line. Each generic cell has unique exposure profile. Generic cells are used to model the effects of different mitigation strategies for different segments of the line.

The Analytica program translates the “generic cell” terminology back into “segments” and “mitigation alternatives.”

The input form that specifies these concepts for each segment is shown in Figure 4.9. In this scenario, there are only two types of line types, and only one is present at a time, so there are only two generic cells, one with a normal- phased double circuit in the ROW, and a second with an optimally phased double circuit in the ROW. In a more complicated scenario, we might have three structures in a ROW, say a double circuit line on a post, a single circuit transmission line, a distribution line, and we might consider a variety of mitigation strategies for each. Including all mitigation strategies, there might be a dozen or more distinct line types. In such a case we might have 20 or more generic cell types, each representing a unique combination of line types.

Each generic cell covers an area that is divided up by a grid. The “Distance from ROW Center” and “Grid Width” boxes define this grid. The generic cell is given a name, which is given as “base case” here. There is one structure, and so a “1” is entered in the “Number of Structures” box. The “Height at which the exposure is calculated” determines the height above ground level at which the magnetic fields are calculated - normally chosen as three feet to represent waist height for a person standing on the ground. This could be used to define a height on an upper floor in an apartment building or school. The structure boxes include a drop-down menu where the user can choose from the line types defined in the previous step. Here the “115 kV DC Normal Phasing” is chosen, and the location is “0”, which represents the center of the ROW. After completing the first generic cell the user then presses the “Next Cell” button, and goes through the same process for the second generic cell.



Specify Physical Layout

ROW Width: 100

Grid Width: 10

Specify Characteristics of Cell # 1

Name of cell: Base Case

Number of Structures (up to three): 1

Height at which exposure is calculated: 3

Specify type of each structure:

		Location:
Structure 1:	115 kV DC, Normal Phasing	0
Structure 2:		0
Structure 3:		0

Figure 4.9: The "Specify Physical Layout" Form

Second step: Calculate the per-person exposure at each location

Once the input data is obtained by the VB program it is placed into input files to be read by the exposure calculation program. The next step is to run the VB program, which in turn calls the exposure program. The exposure calculation program primarily determines the per-person exposure at the center of each exposure cell, taking into account background fields, source fields, loading variability, and exposure measure desired. In this section the calculation of the per-person exposure is illustrated through for one location and one assumed exposure measure.

Figure 4.10 shows what is meant by calculating the exposure "for one location." As discussed previously, this scenario is a 5-mile stretch of line connecting two substations. Along the length of the line, ten 0.5-mile segments are considered. Each 0.5-mile segment is the width of a block, the depth being from –300 feet to +300 feet from the center of the ROW. The total area of each block is then 600' by ½ mile. The depth of each block is divided into exposure boxes 25 feet long, so that each exposure cell is 25 feet by 0.5 mile and a few feet high. The third block from the left and one exposure box within it is marked in Figure 4.10.

There are 10 blocks, each of which contains 10 exposure boxes on each side of the ROW, for a total of 20 exposure boxes per block. The ROW itself is 100 feet wide.

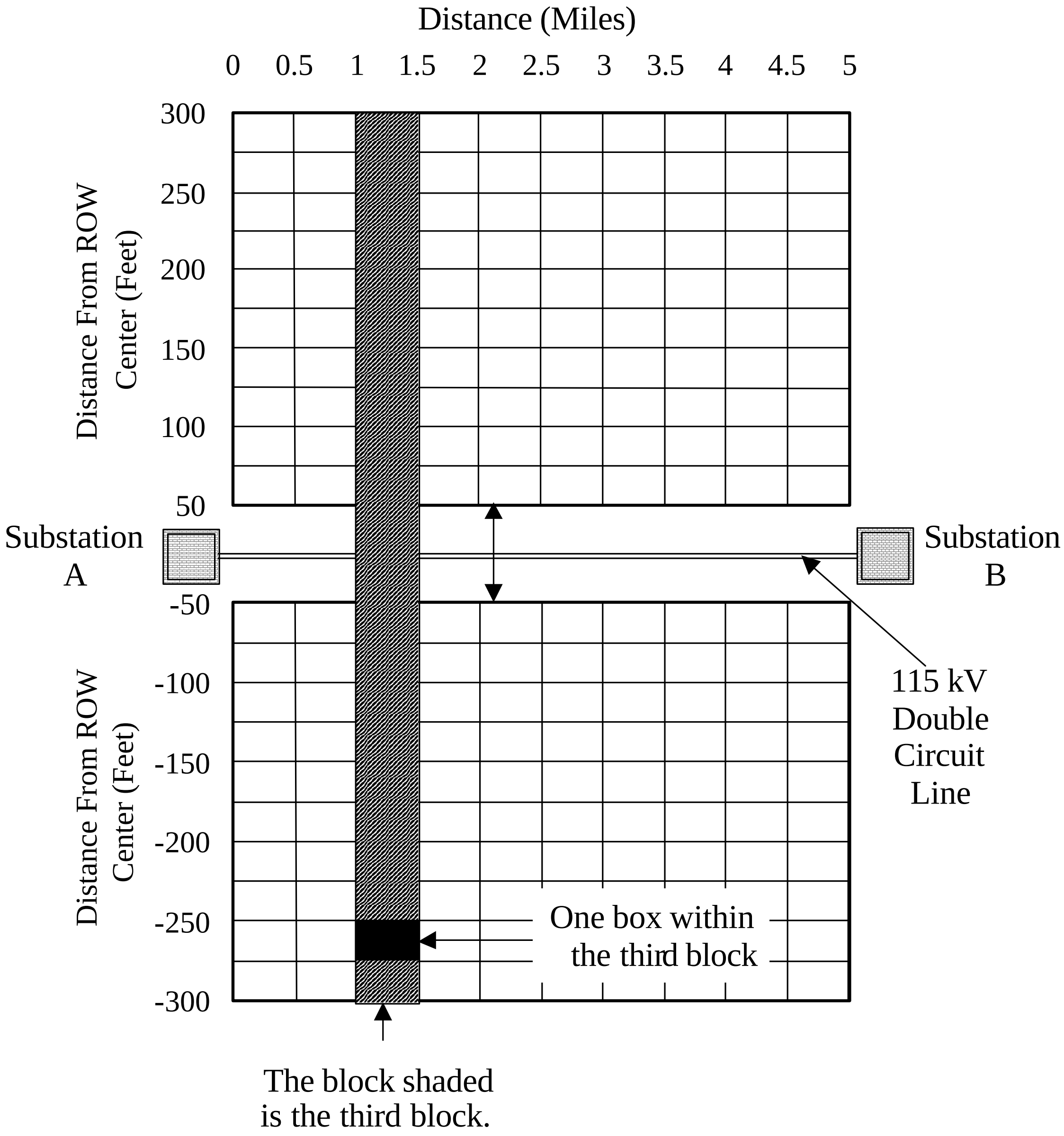


Figure 4.10: The Layout of the Illustrative Scenario of Two Substations Being Connected by a 115 kV Double Circuit Line.

Within each exposure box the exposure and population density is taken as constant. The actual location in the exposure box where the field is calculated is in the center. Thus, for the exposure box highlighted in Figure 4.10, which begins at 250 feet and ends at 275 feet, the distance from the line is estimated as 265.5 feet. The magnetic field is calculated as follows: for each circuit an instantaneous load is determined based on the loading information the user has input. Again, if there is more than one circuit, the loading between the circuits may or may not be correlated, depending on what the user specifies. Then, based on the geometric location of each conductor and the magnitude and phase of its loading, the field at 265.5 feet is calculated. This will be a separate calculation for each exposure box within each generic block type. For each exposure cell, the process of sampling the loading from the range of possible loads for all circuits and then calculating the magnetic fields at the exposure cell center is repeated 1,000 times, and an array of magnetic fields is created.

Once an array of 1,000 magnetic fields reflective of the loading variability has been created, the per-person exposure is calculated. First, the EMDEX files to be used as a surrogate for background exposure are loaded. The source and background are then combined for each EMDEX data point using a source field randomly chosen from the 1,000 element array, and the exposure measure output is obtained for that data point. For example, if the source and background combine to 1.75 mG and the exposure measure is TWA, then the value of 1.75 mG is added to a weighted total. For the same data point, if the exposure measure has a 2 mG threshold, then nothing is added to the weighted total.

An important point needs to be made here: only one set of per-person calculations needs to be made for each exposure cell in each generic block type. Thus, although we show 10 blocksin Figure 4.10, only two generic calculations need to be carried out, one for the base case and one for the mitigated case. The combining of per-person exposure with the actual number of people (which depends on land use and ROW width) is carried out within ANALYTICA and is described in detail in Chapter 8. Further details of the numerical modeling, how the source field is calculated, how the effects function is calculated, and other engineering specifications are discussed in Appendix B.

4.5 Details of the Exposure Calculations for the two Retrofit Distribution Scenarios

In this section we present in detail the “Retrofit Distribution” scenarios modeled during this project.

Scenario goals and details

The goals of these scenarios are as follows:

1. model two existing distribution systems: one 3-wire and one 4-wire configured,

2. model the decrease in loading which occurs as distance from the distribution substation is increased,

3. model the impact of a range of “retrofit” mitigation strategies, including undergrounding the lines,

4. model a mitigation strategy geared towards reducing ground currents for the case of the 4-wire system.

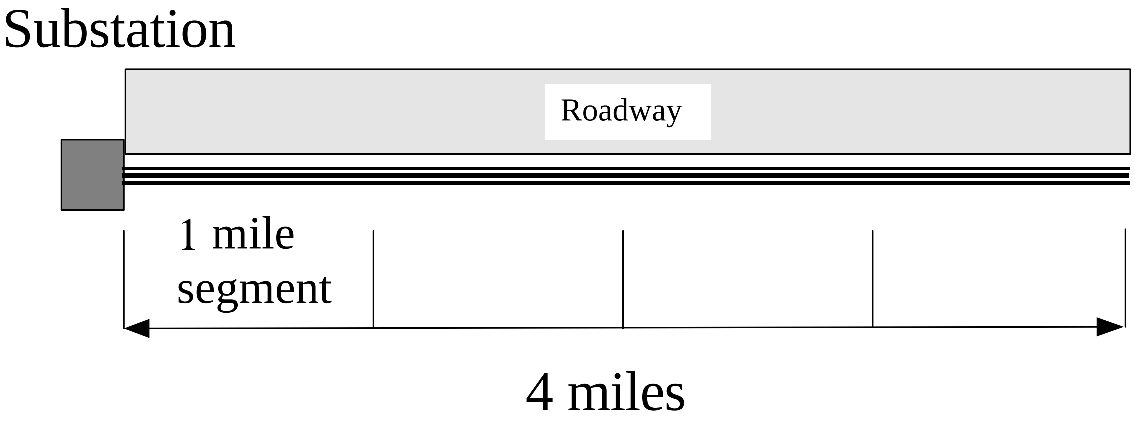


Figure 4.11: Layout for the Two “Retrofit Distribution” Scenarios

For both scenarios, a 4-mile length of primary distribution starting at the distribution substation is modeled. Primary distribution lines with 3 phases (3-wire) or 3 phases plus neutral (4-wire) are modeled. It is assumed that these radial feeders travel along a main road, and that there are taps throughout the route. Thus, the further from the substation the more lightly loaded the lines will be. As mentioned in section 4.4, the loading and the field distribution within each cell is considered constant. In order to approximate this drop-off in loading, the 4-mile length of distribution is divided up into four segments with progressively lower loading. An overview of the scenarios is shown in Figure 4.11, which is the same for both scenarios.

The loading as a function of distance is given in Table 4.1. In these scenarios, a load factor of 0.5 is assumed. For the 4-wire scenario, a certain percentage of the net current will return either by the neutral or the ground. This "earth return" current results in a net current on the primary with source fields that drop off inversely to the distance rather than the inversely to the square of the distance from balanced circuits. These net current fields can be quite important and are one reason we chose to model both 3-wire and 4-wire distribution.

The net current in a 4-wire system is determined by the unbalance between the hot phases. What percentage of the net current returns via the neutral vs. via other paths can vary dramatically, depending on factors such as condition and size of the neutral conductor, soil type, and the presence or absence of metallic conductors such as water mains which might carry part of the return current. In the 4-wire scenario, the maximum unbalance between phases is set at 50% and the maximum percentage of the return current which can return via the ground is set at 25%. We want to emphasize that these figures will vary quite a bit depending on local conditions. With these figures, the ground current is typically on the order of 10% of the per-phase current.

Table 4.1 Loads for Different Line Segments

Line Segment	Maximum Load	Typical Load
Mile 1	600	400
Mile 2	500	300
Mile 3	400	200
Mile 4	300	100

Several retrofit strategies were considered. All of these strategies are taken directly from the School Measurement study (Enertech Consultants, 1998 a and b). These include:

- raise pole height,
- switch to a compact delta configuration,
- underground using solid dielectric cables.
- For the 4-wire scenario, one additional strategy aimed specifically at reducing the earth return currents is considered: insert dielectric couplers.

The base case and compact delta configurations are shown below for both scenarios, in Figures taken directly from Enertech Consultants (1998a). In Figure 4.12, the base and compact delta are shown for the 4-wire scenario. In the base case the conductors are assumed to be equidistant. In the compact case, the three adjacent conductors are assumed to form an equilateral triangle. Based on measurement information obtained from Enertech Consultants (1998a), the distance D1 is chosen to be

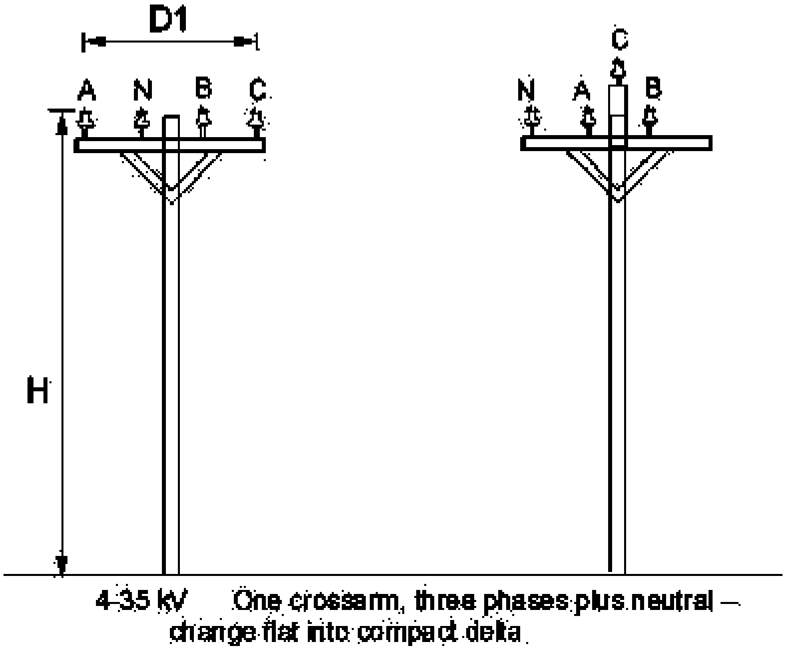


Figure 4.12: Conversion of the 4-Wire Base Case Horizontal Configuration to a Compact Delta Configuration.

(Line Types 901 and 9012 in Enertech Consultants, 1998a)

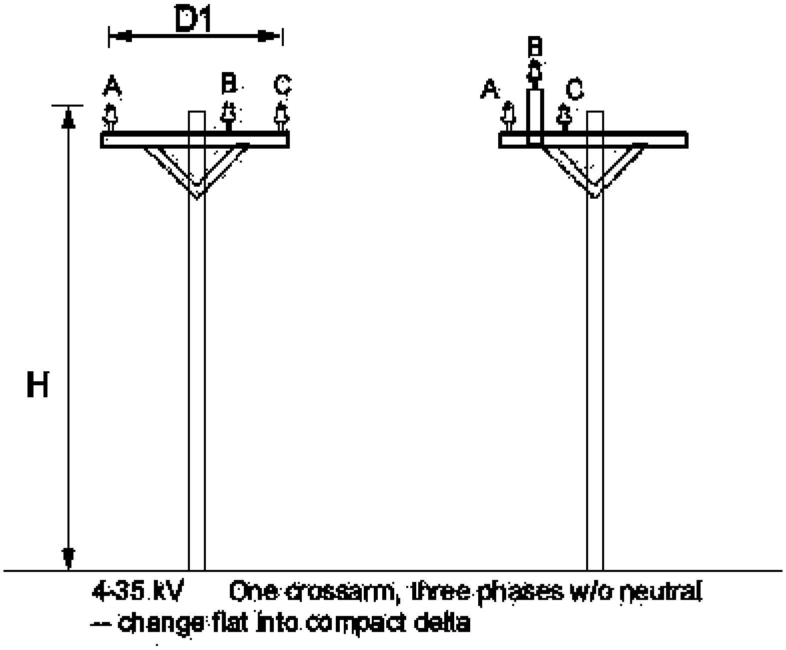


Figure 4.13: Conversion of the 3-Wire Base Case Horizontal Configuration to a Compact Delta Configuration.

(Line Types 903 and 9032 in Enertech Consultants, 1998a)

7.3 feet and the midspan height is taken as 40 feet. In Figure 4.13, the analogous line types are shown for the 3-wire scenario, and the distances used are the same as for the 4-wire configuration.

The “Raise Height” option is fairly straightforward: the existing poles are dismantled and replaced with new, higher poles. A 10 foot higher pole is assumed. For the underground option, the distance between the conductors for the underground cables was estimated at 3 inches. This estimated value comes from matching the calculated field profiles with calculation results provided by PG&E (1994). The conductors are assumed to be buried together, so that the distance between conductors is in part due to the dielectric insulation.

Exposure calculation results

In Figures 4.14 and 4.15 the per-person exposure is shown for the two scenarios under the following conditions: base case configuration, the TWA average exposure measure is assumed. The four curves are the exposure profiles for the four segments as they would be calculated at the midpoint of the 10 exposure cells on each side of the line. The curve has been smoothed out between these points.. The diminishing peak loading as the distance from the substation results in the decrease of the exposure as a function of distance from the line, which is apparent in the two figures. The peak exposure drops off by an additional factor of about 25% for each mile increase from the substation, which corresponds with the loading assumptions. Notice that the peak field is not at 0 feet from the ROW center. This is because for this case, the "ROW" is thought of as the roadway, so the location of the line is offset from the center of the ROW. If the user wishes to define the line location as the center of the ROW, he or she is free to do so. Also notice that the exposure does not drop to 0, which is because of the assumed background fields which are an integral part of the calculation. For the TWA, the background results are in per-person exposure of 0.97 mG for the EMDEX data set used in these calculations.

Comparing the exposures plotted in Figures 4.14 with those in 4.15, the exposures are very close, with the 4-wire exposures being slightly higher. The difference is due to the influence of the net current present in the 4-wire case, which as mentioned previously gives rise to fields that drop off more slowly than those due to balanced currents.

To illustrate the result of different effects function assumptions, we show the exposure calculation results for the first segment (highest loading) for three effects functions: time weighted average (Figures 4.16 and 4.17), 5.0 mG linear threshold (Figures 4.18 and 4.19) and 10.0 mG binary threshold (Figures 4.20 and 4.21). In Figure 4.17 the exposure profiles are shown for the base and mitigated cases in the 4-wire scenario, for the TWA assumption. The exposure due to the underground is deceptively high, since there are no homes directly over the line.

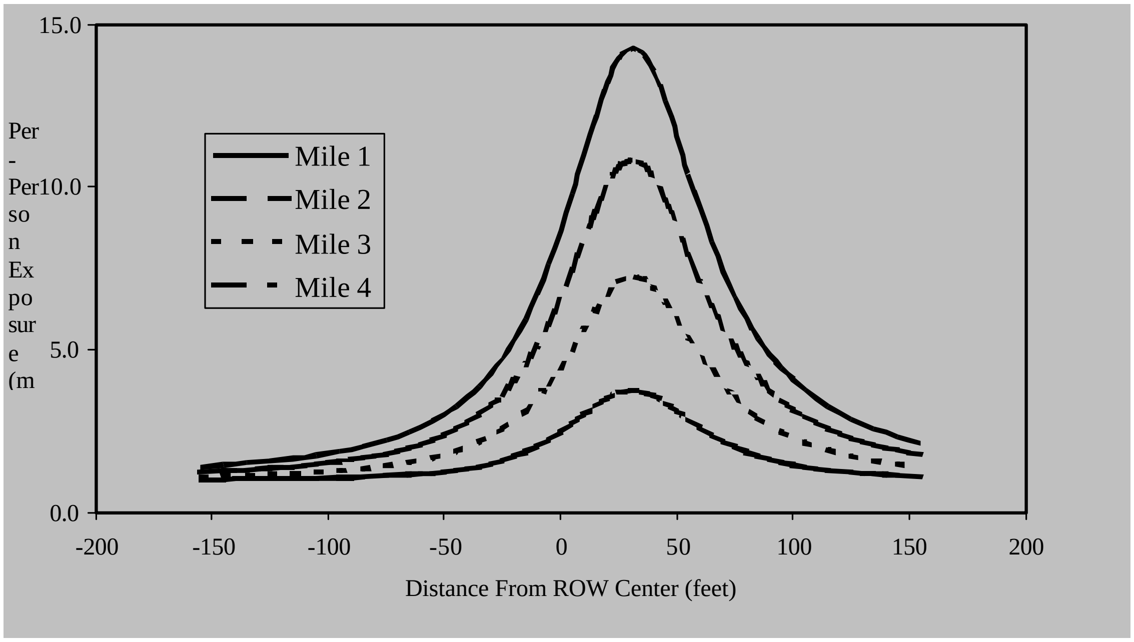


Figure 4.14: Base Case Per-Person Exposure as a Function of Distance from the Center of the ROW for the 4-Wire Configuration for One-Mile Line Segments

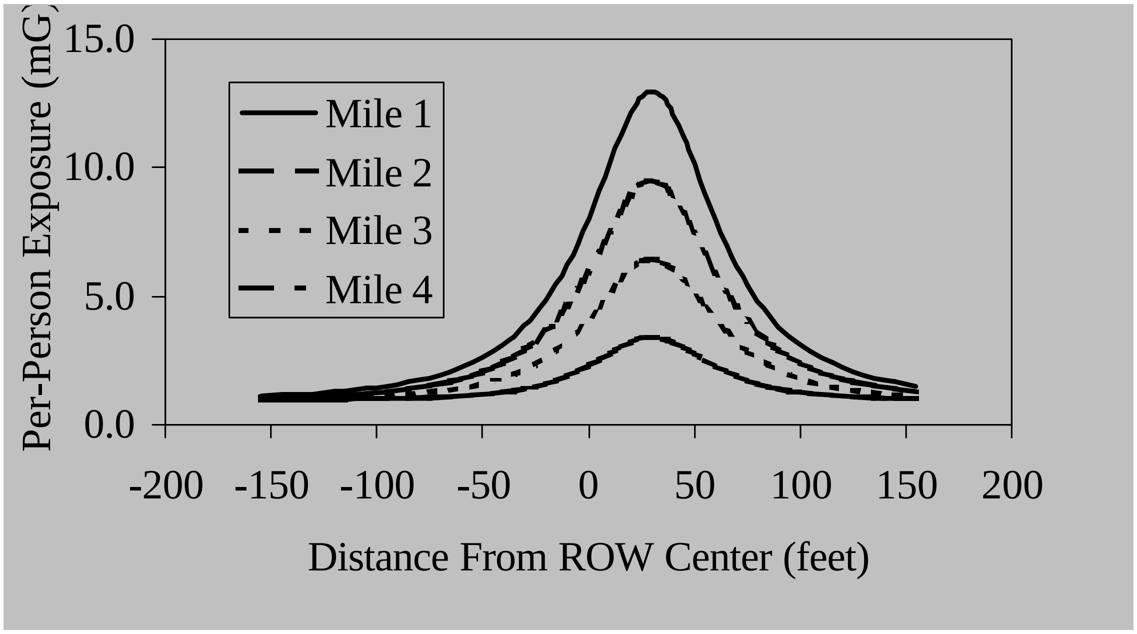


Figure 4.15: Base Case Per-Person Exposure as a Function of Distance from the Center of the ROW for the 4-Wire Configuration for Four One-Mile Line Segments

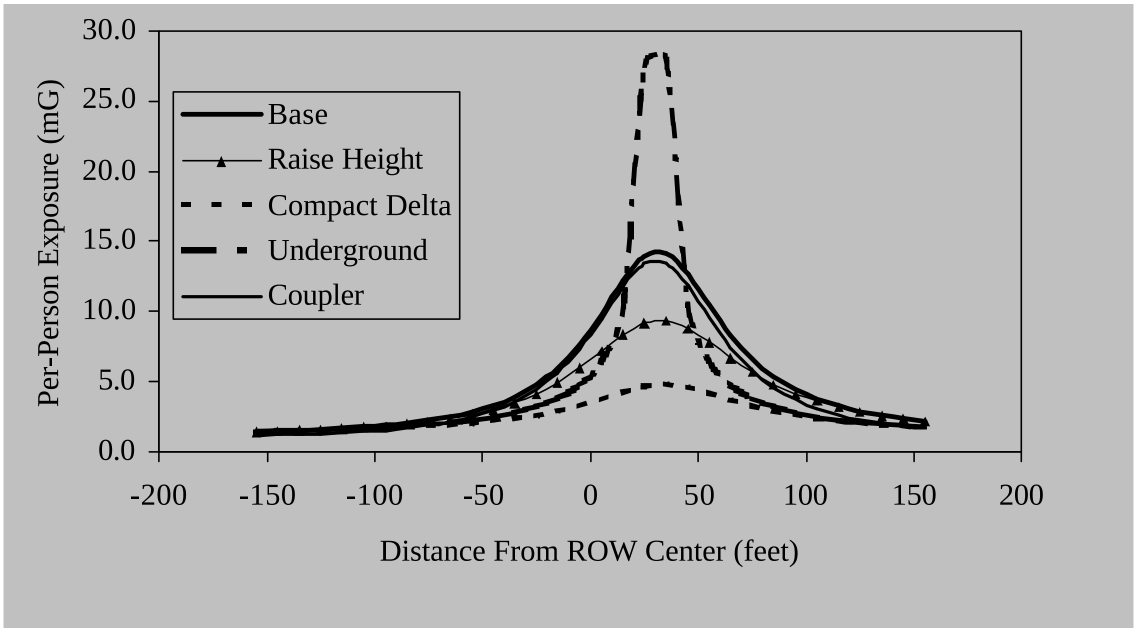


Figure 4.16: Per-Person Exposure for the TWA Effects Function, 4-Wire Configuration for Five Mitigation Alternatives

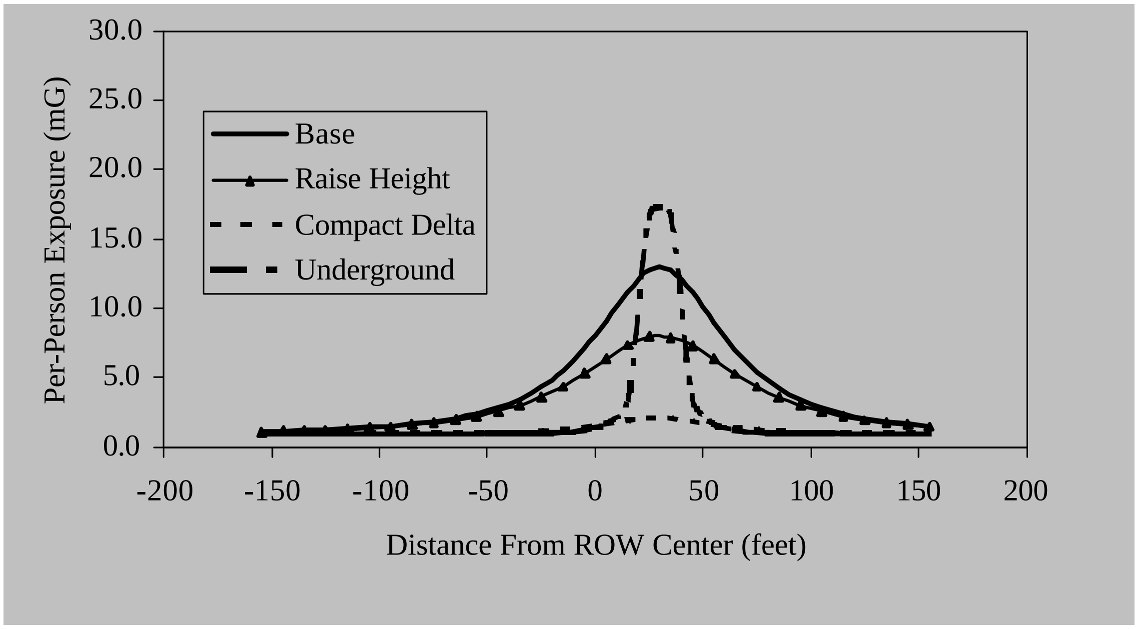


Figure 4.17: Per-Person Exposure for the TWA Effects Function, 3-Wire Configuration for Five Mitigation Alternatives

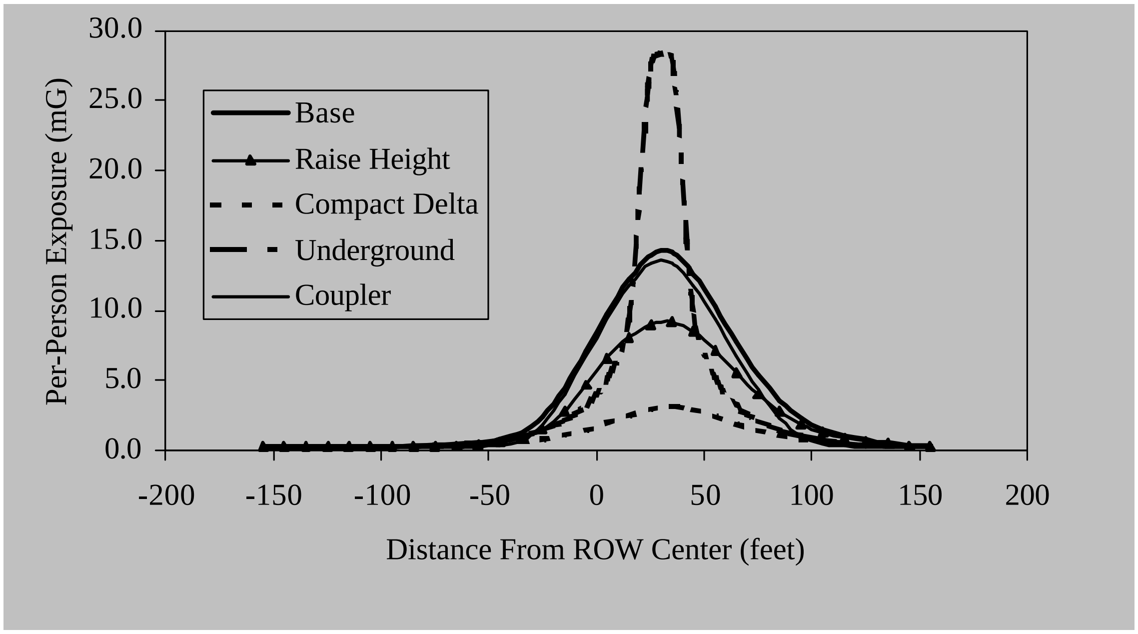


Figure 4.18: Per-Person exposure for the 5.0 mG Linear Threshold Effects Function, 4-wire Configuration for Five Mitigation Alternatives

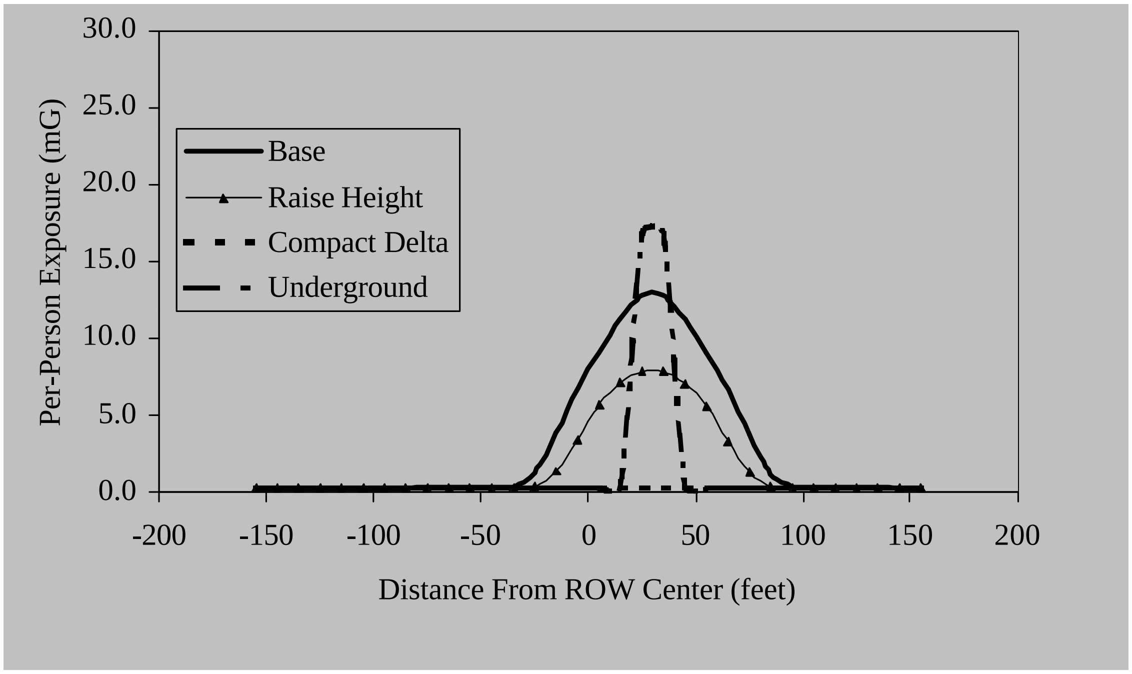


Figure 4.19: Per-Person Exposure for the 5.0 mG Linear Threshold Effects Function, 3-wire Configuration for Five Mitigation Alternatives

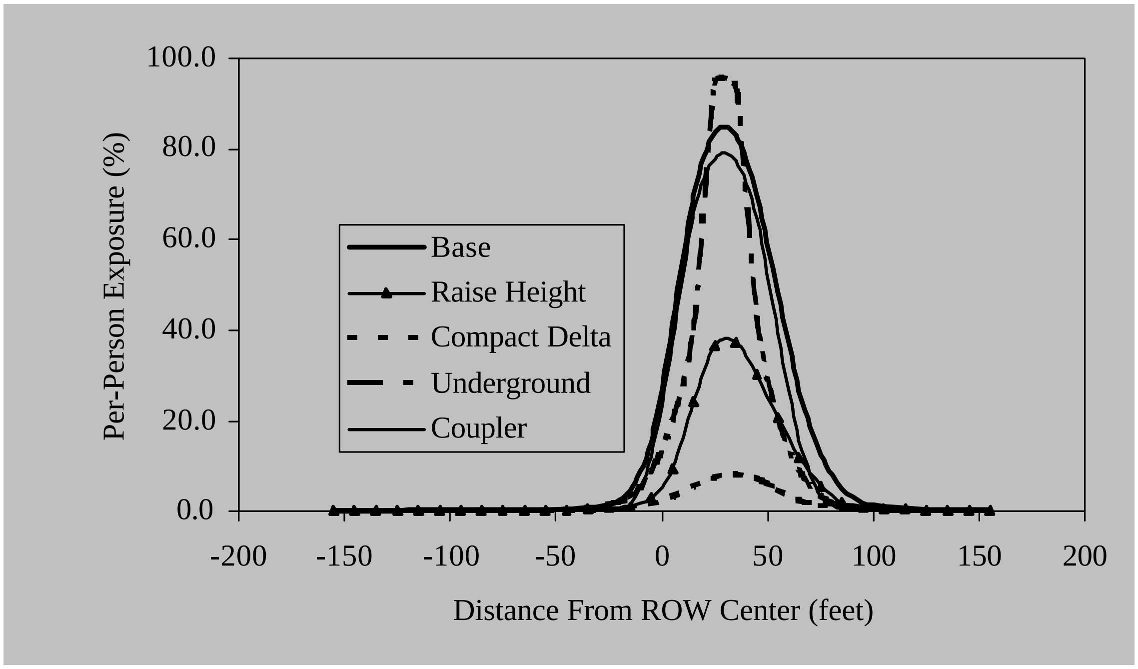


Figure 4.20: Per-Person Exposure for the 10.0 mG Binary Threshold Effects Function, 4-Wire Configuration for Five Mitigation Alternatives.

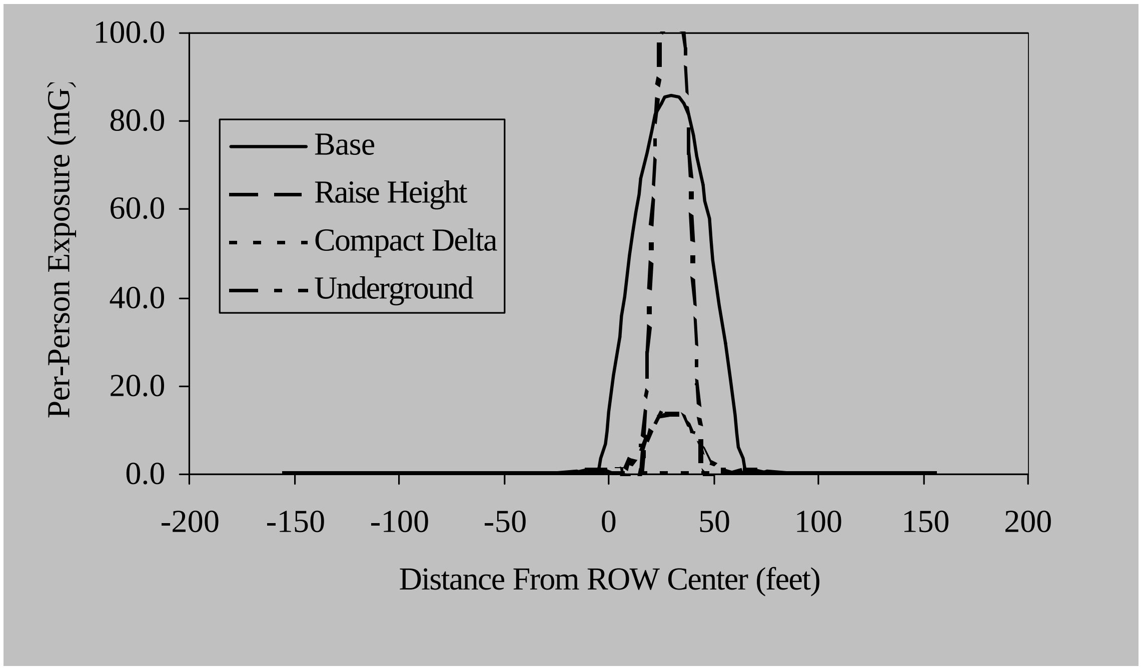


Figure 4.20: Per-Person Exposure for the 10.0 mG Binary Threshold Effects Function, 3-Wire Configuration for Five Mitigation Alternatives.