TECHNICAL MEMORANDUM

ON PARTICULAR ASPECTS RELATED 400 kV TRANSMISSION

Prepared by : Dr Pieter H Pretorius, Trans-Africa Projects

Prepared for : Mr Henry Nawa, Senior Environmental Advisor, Eskom Group Capital, PDD-Land Development (Megawatt Park)

Date : 22 July 2012 **Rev:** 0.0

---

1. BACKGROUND

During the public participation process of the EIA conducted on the Roodepoort Strengthening Project, Eskom has received specific questions related to 400 kV transmission. The project involves construction of 2 x 400 kV power lines by looping-in and out of the Apollo-Pluto 400 kV Power lines to the new Demeter Substation.

The specific questions raised by the public relate to the following topics:

- Electric and Magnetic Field (EMF) profiles for the power line and potential towers to be used. The 400 kV line is approximately 30 km in length;
- Underground versus overhead power lines along the 30 km route;
- One double circuit line versus two separate single circuit lines.

Answers to these questions are covered in this Technical Memorandum.

2. OUTLINE OF THE DOCUMENT

The answers are provided in general terms in the main body of the Technical Memorandum with support material provided in the Appendices. The main body of the Memorandum covers the following points:

- Electric and Magnetic Fields (EMF);
- Underground versus Overhead Transmission and
- Double Circuit versus Single Circuit Transmission.

3. ELECTRIC AND MAGNETIC FIELDS (EMF)

3.1 General

The request was for the following tower types to be considered 524 (Cross Rope), 515 (Self Support), 520B (Guyed V) and 529 (Cross Rope). These towers, including a 513 double circuit and 540 Multi-circuit, are illustrated in Appendix A.

3.2 Electric Fields

Power line electric fields are produced by the presence of electric charges and therefore the Voltage (V) applied to a conductor of a power line. Generally the voltage on a system is stable and therefore the electric field under the line remains relatively constant. Tower geometry and conductor height affects the electric field at ground level. Electric fields decrease with an increase in distance from the source (conductor).

Electric field levels are measured in Volts per metre (V/m). Because of the range of the levels encountered in power system environments, field levels are reported in kilovolt per metre (kV/m). (One thousand V/m = 1 kV/m).

Overhead power lines are designed to meet a maximum electric field level of 10 kV/m within the servitude and directly below the line. This level falls to lower levels and must meet the level of 5 kV/m allowed for public exposure at the servitude boundary.

3.3 Magnetic Fields

Magnetic fields are produced by the current flowing (movement of electric charge) on the conductor/s of a power line. Electric current is measured in Ampere (A). The current on a system may vary depending on the number of devices (load) supplied by the system. As the load changes, the magnetic field will change. Tower geometry and conductor height affects the magnetic field at ground level. Magnetic fields decrease with an increase in distance from the source (conductor).

Magnetic field levels are measured in Tesla (T). Because of the range of the levels encountered in typical power system environments, field levels are reported in microtesla (µT). (One millionth of a Tesla = 1 µT). Some American literature use the unit of Gauss (G) where 10 milligauss (mG) = 1 µT.

Overhead power lines are designed to meet a maximum magnetic field level of 200 µT allowed for public exposure at the servitude boundary.

3.4 Typical Field Levels

Typical Electric and Magnetic field profiles associated with the towers noted above are indicated in Appendix C based on the parameters captured in Appendix B.

4. UNDERGOUND VERSUS ABOVE GROUND TRANSMISSION

4.1 General

High-voltage underground cables can be one of three types: direct buried, trough or tunnel applications [2]. See Appendix F for details.

There are three aspect categories to consider in the comparison of overhead lines and buried cables. These are magnetic field levels, other engineering considerations and perhaps the more important aspect, cost.

4.2 Cost Comparison

Typically, overall cost will be higher by a factor 8 to 15 for the same power transfer capacity, depending on local situation and system constraints, and even higher than 15 in the case of with tunnelling [3].

Using modern cable techniques it costs approximately 12 to 17 times as much to install a typical 400 kV double circuit underground cable as it does to build an equivalent length of double circuit overhead line through normal rural / urban terrain [4].

A major element of this cost differential is accounted for by the cable itself. The underground conductor has to be bigger than its overhead counterpart to reduce its electrical resistance and hence the heat produced. The requirement to properly insulate whilst at the same time maintaining the cable’s rating means that special insulation is needed. Generally, tunnel installation costs more than direct burial, however, civil engineering costs for all methods of cable installation are considerable compared to that of an overhead line [4].

4.3 Magnetic Field Comparison

Underground cables, whether directly buried or in a tunnel, produce no external electric field due to the shielding effect of the ground / covering above and to the sides of the cable.

Because of the smaller distance to the buried cable, cables can have a much higher maximum magnetic field levels directly above the cable, compared to overhead power lines. The magnetic field of the cable is also more localised compared to that of an overhead power line. These aspects can be observed in Figure 1 below [2].

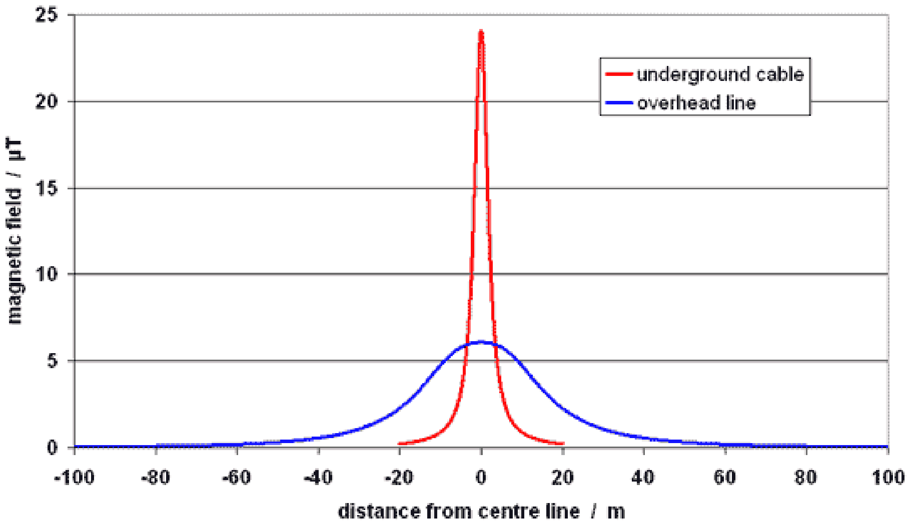

Figure 1: Typical magnetic field of a buried cable compared to that of an overhead line [2].

In some cases, instead of being buried directly in the ground, an underground cable is placed in a tunnel which can be ten or more metres below ground [2]. In this instance, the conductors cannot be approached closely by members of the public, and the magnetic field at the surface is much reduced and may be lower than an equivalent overhead line and often lower than background fields from other sources [2].

4.4 Engineering Considerations - Possible Drawbacks of Cable Systems

Particular engineering considerations of buried high voltage cables that requires evaluation in the decision to apply an overhead line or a buried cable include [3]:

- 400 kV cables present inherently huge capacitances; the capacitive charging current imposes a constraint on the effective application of cables in AC transmission systems [3].
- The strong capacitive behaviour causes voltage deviations, especially in unloaded situations (when switching for example), which limits manageable application to relatively short distances [3].
- The integration of these characteristics in the existing electricity network may lead to transient overvoltages and resonance effects, jeopardising system reliability [3].
- Routing: Tunnelling may be necessary, particularly near urban areas [3].
- Operation and Maintenance:
  - Even though the fault rate may be lower for underground cable systems compared to overhead lines, cable fault location is more challenging [3].

- Repair time for underground cables is longer (more than 20 times) compared to overhead lines [3]. This causes longer outage periods, an aspect not easily available for the Eskom system these days.

- Decommissioning of underground cables systems is more challenging and expensive.

400 kV AC underground cables is a valuable but costly solution. For technical reasons, its use is limited to particular situations and those most cost effectively considered as providing the “missing link” (where overhead transmission is not possible) in optimum overhead route planning with maximum lengths up to 40 km (depending on local system conditions and constraints, this maximum length may have to be lowered) [3].

For longer distances and loads exceeding 400 - 500 MW, HVDC is the remaining underground option. The latter is more applicable to specific cases like sea crossings and large off-shore non synchronous grids if justified by economic benefit vs impact on environmental and visual amenity or as a last resort for improving security of supply [3].

5. DOUBLE CIRCUIT VERSUS SINGLE CIRCUIT TRANSMISSION

5.1 General

Transmission lines that carry three phase power are usually configured as either single circuit or double circuit. A single circuit configuration has three sets of conductors for the three phases whilst a double circuit configuration has six sets of conductors (three phases for each circuit).

5.2 Power Transfer

Because Double Circuit towers support two circuits on a single tower, double circuit lines enable the transfer of more power along a single servitude compared to two single circuit lines. Double circuit transmission may in some cases be less costly (where towers other than cross-rope towers are selected; cross-rope towers are preferred because of lower cost), requires less land and is considered ideal from an ecological point of view.

5.3 Electromagnetic Coupling

Running two circuits in close proximity to each other, as in the case of a double circuit line, will introduce inductive coupling between the conductors of the two circuits. This needs to be considered when calculating fault levels and when designing the protection schemes.

5.4 Visual Impact

The vertical circuits typically associated with a double circuit tower usually means that the double circuit tower is higher (about 36 m) compared to the single circuit cross rope tower (just over 28 m). The higher tower is perceived to have a higher visual impact.

5.5 Maintenance

5.5.1 Servitude Maintenance

In the case of two single circuit lines, effectively 2 x servitudes need to be cleared and maintained as opposed to the single servitude of a double circuit line.

5.5.2 Live Line Maintenance

Considering the fact that live line workers will be dropped from the air by means of a helicopter onto the line, such a drop for live line maintenance is easier in the case of the horizontal circuits of the 2 x single circuit lines compared to the vertical circuit of the double circuit lines. In addition, the risk of bridging a clearance is higher in the case of the double circuit line, with circuits on top of each other as opposed to next to each other as in the case of the two single circuit lines.

5.6 Electric and Magnetic Fields

If required, the phases of double circuit lines can be configured to reduce electric and magnetic fields at ground level, providing that the field gradient on the conductors meet the required levels in the case of the electric field

5.7 Costs

With the preference to cross-rope towers, because of lower steel usage and therefore lower cost, double circuit lines are in general more costly compared to single circuit lines. Details are presented in Appendix D.

5.8 Common Cause Failures

Veld fires present the most significant risk to double circuit lines in terms of common cause failures (CCF). However, veld fires can be managed through proper servitude maintenance. The following causes are assessed from a common cause failure (CCF) point of view and are covered in Appendix E:

- Birds
- Lightning
- Veld Fires
- Tornado’s
- Flooding
- Aeroplanes
- Mist / Fog
- Theft of tower members

5.9 Summary of the Disadvantages of Single and Double Circuit Transmission Lines

The Table below presents a summary of the disadvantages of 1 x double circuit 400 kV line versus 2 x single circuit 400 kV lines. Where a disadvantage is noted for a specific technology, an advantage is expected for the opposite technology. The details are presented above and within the Appendices noted.

Summary of Disadvantages of Single Circuit Lines Comapred with Double Circuit Lines

1 x Double Circuit 400 kV Line - Disadvantages	
Aspect	**Remarks**
Cost	Double circuit lines are in general more costly compared to single circuit lines constructed from cross-rope towers.
Common cause failures (CCF)	Veld fires present the highest risk in terms of a common cause failure to double circuit lines.
Electromagnetic coupling	Special attention has to be given to electromagnetic coupling between circuits.
Higher visual impact	Taller double circuit towers compared to two single circuit towers. (Some may consider two single circuit towers to have a higher visual impact). The 529 Cross-Rope tower can be considered as having the least visual impact.
Live line maintenance	Live line worker landings more difficult and live work more risky compared to single circuits.

2 x Single Circuit 400 kV Lines - Disadvantages	
Aspect	**Remarks**
Electric and Magnetic Field Levels	Firm fields based on tower configuration and design and cannot be reduced through changes in phase configuration with the same tower (Field effects are generally not an issue as the line is designed to meet specific limits).
Land Use / Servitude constraints	More servitude required compared to a double circuit line.
Power transfer	Less power transferred along a single servitude compared to a double circuit line.
Servitude maintenance	2 x servitudes have to be maintained compared to 1 x servitude in the case of a double circuit line.

6. CONCLUDING REMARKS

Specific questions raised during the EIA process of the Roodepoort Strengthening Project, relating to the following topics were addressed in the Technical Memorandum:

- Electric and Magnetic Field (EMF) profiles for the power line and potential towers to be used.
- Underground versus overhead power lines along the line route;
- One double circuit line versus two separate single circuit lines.

It has been shown that electric and magnetic field levels of the towers proposed for the line meet the required levels for public exposure.

The main considerations with under-grounding of 400 kV transmission lines include cost, magnetic field considerations and specific engineering aspects in relation to above ground or cabled transmission.

The main consideration in the decision of applying two single circuits versus a single double circuit line is cost, justifying two single circuit applications (using cross rope towers) as a cost effective means of transferring power. A double circuit line can be 48 % more costly compared to 2 x single circuit lines constructed with cross rope towers.

The main consideration in the decision of applying overhead transmission as opposed to cabled transmission is cost, justifying the application of overhead transmission. With the cost of under-grounding a 400 kV double circuit line being 12 to 17 times more costly, effectively means an undergrounding cost of 18 to 25 times higher than the 2 x single circuit cross-rope towers.

In South Africa, Eskom is a public utility answerable to the Public Finance Act in which all costs need to be declared and justified. Additional costs for undergrounding or for double circuit line application are subject to the same scrutiny under the Act. These costs will have to be recovered in some way and it is likely to be either by a general increase in tariffs or by direct contributions from those requiring underground cables and / or double circuit transmission.

7. REFERENCES

[1] Personal correspondence with Mr Henry Nawa, Senior Environmental Advisor, Eskom Group Capital, PDD-Land Development, 19 June 2012.

[2] National Grid, http://www.emfs.info/Sources+of+EMFs/Underground/, Last accessed 22 Jul 2012.

[3] F Van Den Berghe, Electricity Infrastructure Workshop, Is 380 kV Underground Cable an Option?, Brussels, 13 February 2007.

[4] UK National Grid, Undergrounding High Voltage Electrical Transmission - The Technical Issues, Issue No 2, Aug 2009.

[5] Personal e-mail correspondence with Mr Viven Naidoo, Chief Line Designer, Eskom Line Engineering Services, 12 July 2012.

8. ACKNOWLEDGEMENT

This work was made possible through funding and opportunity provided by Eskom Holding SOC Ltd, in particular the Transmission Line Engineering Services (LES) of Eskom.

The following persons are acknowledged and thanked for the valuable technical discussions in the context of this Technical Memorandum:

Mr Arthur A Burger, Chief Line Design Engineer, Line Engineering Services, Eskom, and Mr Viven Naidoo, Chief Line Design Engineer, Line Engineering Services, Eskom.

9. APPENDIX A - TOWER TYPES CONSIDERED

9.1 General

The following Figures illustrates examples of typical 400 kV single circuit and double circuit towers.

9.2 Tower Type 524 (Cross-Rope)

The 524 Cross-Rope tower is an older design and preceded the 529 Cross Rope tower which is a preferred Cross-Rope for 400 kV application. Maximum tower heights can reach 32 m depending on the conductor bundle applied. For a 3 x Tern conductor, typical attachments heights are 28 m.

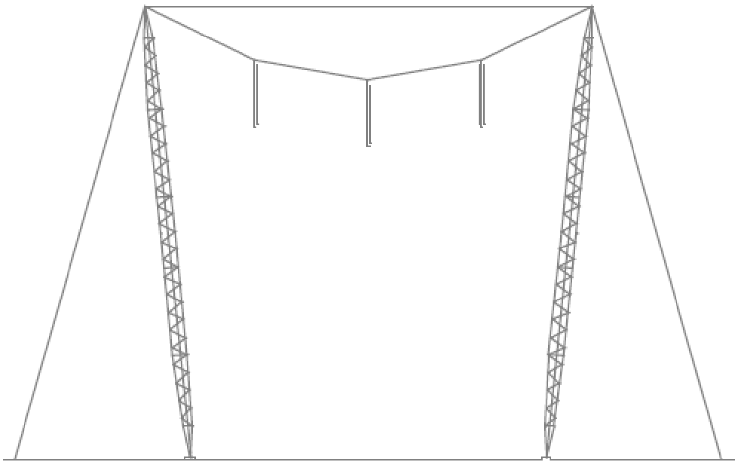

Figure A-1: Tower Type 524 (Cross Rope).

Figure A-2: Tower Type 524 (Cross Rope).

9.3 Tower Type 515 (Self Support)

The 515 self-support tower is illustrated in Figure A-3 with a photograph of this tower illustrated in the background of Figure A-2. Tower heights range from 27,5 m to 39,3 m with leg extensions.

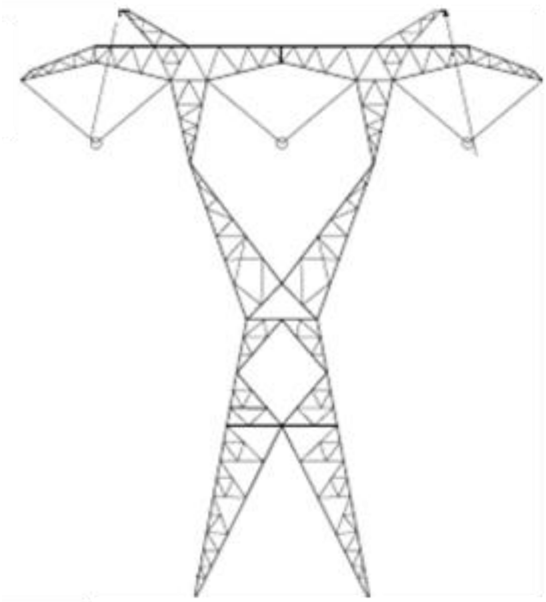

Figure A-3: Tower Type 515 (Self Support).

9.4 Tower Type 520B (Guyed V)

The 520B Guyed-V tower is illustrated in Figures A-4 and A-5 and with a maximum tower height of 39,9 m depending on conductor bundle application.

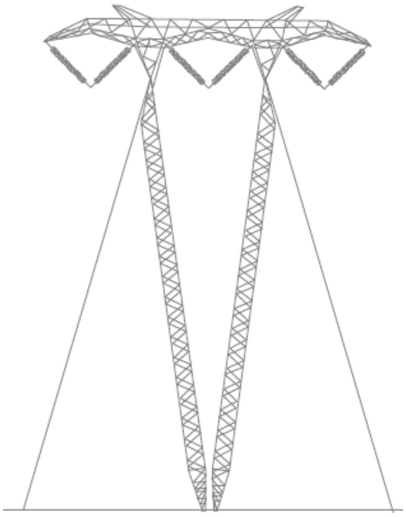

Figure A-4: Tower Type 520B (Guyed V).

Figure A-5: Tower Type 520B (Guyed V).

9.5 Tower Type 529 (Cross Rope)

Due to its stronger design, compared to the 524 Cross Rope tower, the 529 Cross-Rope tower is the preferred tower for 400 kV applications. Because it carries less steel compared to a self-support tower, the cross rope tower presents a significant saving in manufacturing and construction costs. With a 3 x Tern conductor bundle the attachment height is typically 28 m. The 529 Cross-Rope tower is similar in appearance to the 524 Cross-Rope tower.

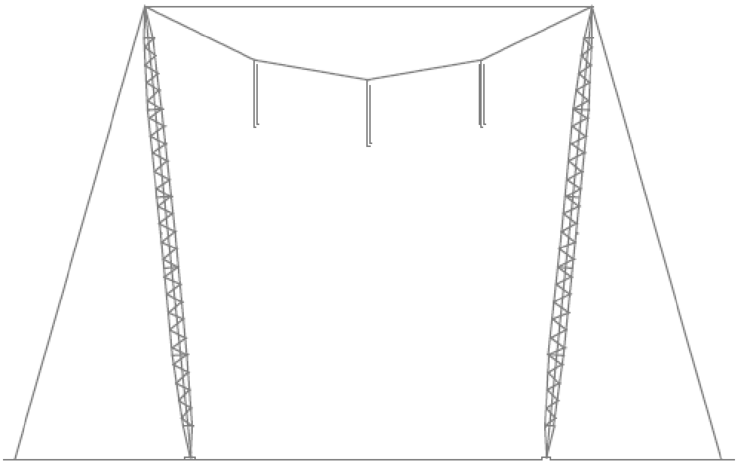

Figure A-6: Tower Type 529 (Cross-Rope).

Figure A-7: Tower Type 529 (Cross-Rope).

9.6 Tower Type 513 (Double Circuit Self Support)

Figure A-8 and A-9 illustrate the 513 tower with typical maximum heights up to 35,9 m.

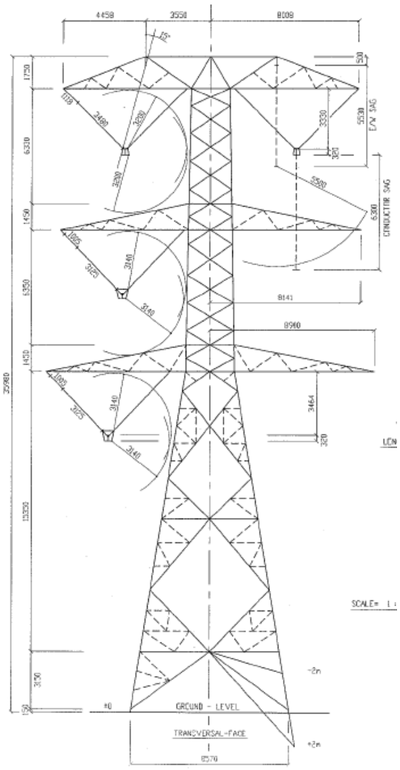

Figure A-8: Tower Type 513 (Double Circuit Self Support).

Figure A-9: Tower Type 513 (Double Circuit Self Support).

9.7 Tower Type 540 (Multi-circuit)

The 540 multi-circuit tower is illustrated in Figure A-10 and is a new tower designed by Eskom. The maximum tower height is 61,1 m with the configuration as per that shown in Figure A-10. This tower can be applied as a double circuit tower with similar configuration to that illustrated in Figure A-8 and a maximum tower height approaching that of the tower indicated in Figure A-8.

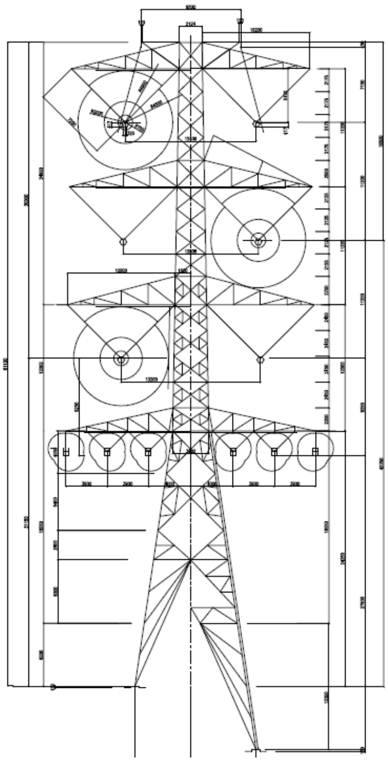

Figure A-10: Tower Type 540 (Multi-circuit).

10. APPENDIX B - PARAMETERS CONSIDERED FOR THE FIELD CALCULATIONS

The following Table summarises the parameters used for the electric and magnetic field calculations, irrespective of the tower applied.

Tower Type	- as specified in Appendix C
Conductor Type	- Tern ACSR conductor
Number of Conductors per Bundle	- 3
Conductor Diameter	- 27 mm
Sub-conductor Spacing	- 450 mm
Ground Wire Conductor Type	- 19 / 2,7
Ground Wire Diameter	- 13,48 mm
Umax	- 420 kV
Phase to Ground Clearance (mid-span)	- 10 m
Power Rating	- 600 MVA (0,95 Power Factor)

It should be noted that conductor height may vary based on load and climatic conditions (solar radiation, wind and temperature). For the cases considered, the mid-span phase to ground clearance was fixed at 10 m.

Typical 400 kV lines have servitudes that are 55 m wide.

11. APPENDIX C - ELECTRIC AND MAGNETIC FIELD PROFILES

11.1 General

The following images illustrate the electric and magnetic field profiles for the different lines considered:

11.2 Tower Type 524 (Cross Rope)

11.2.1 Electric Field

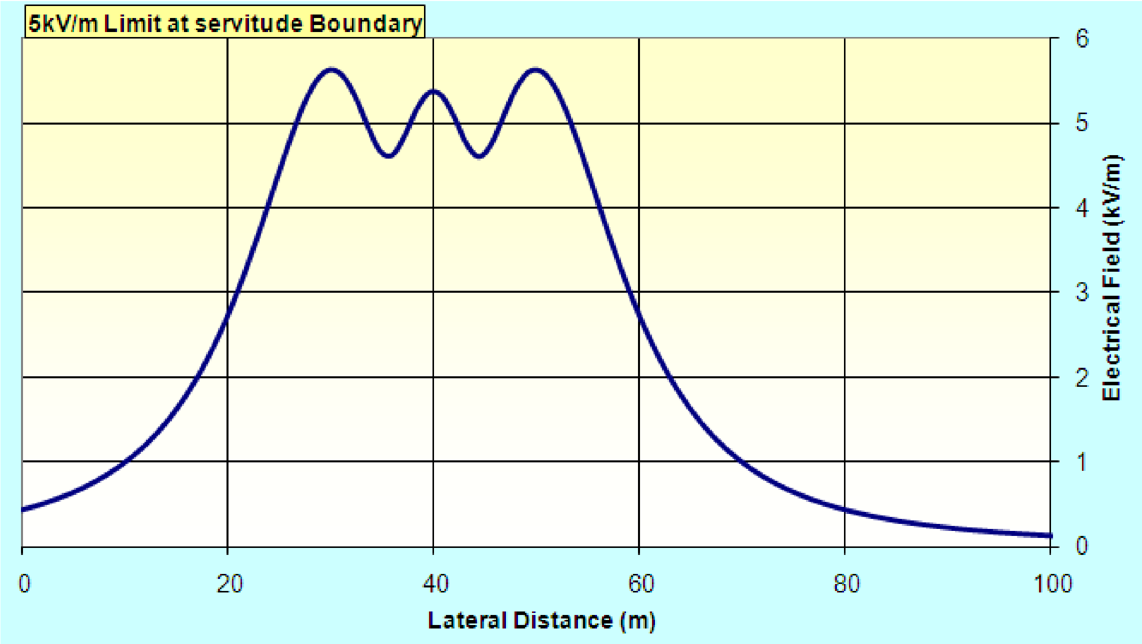

Figure C-1: Electric Field.

11.2.2 Magnetic Field

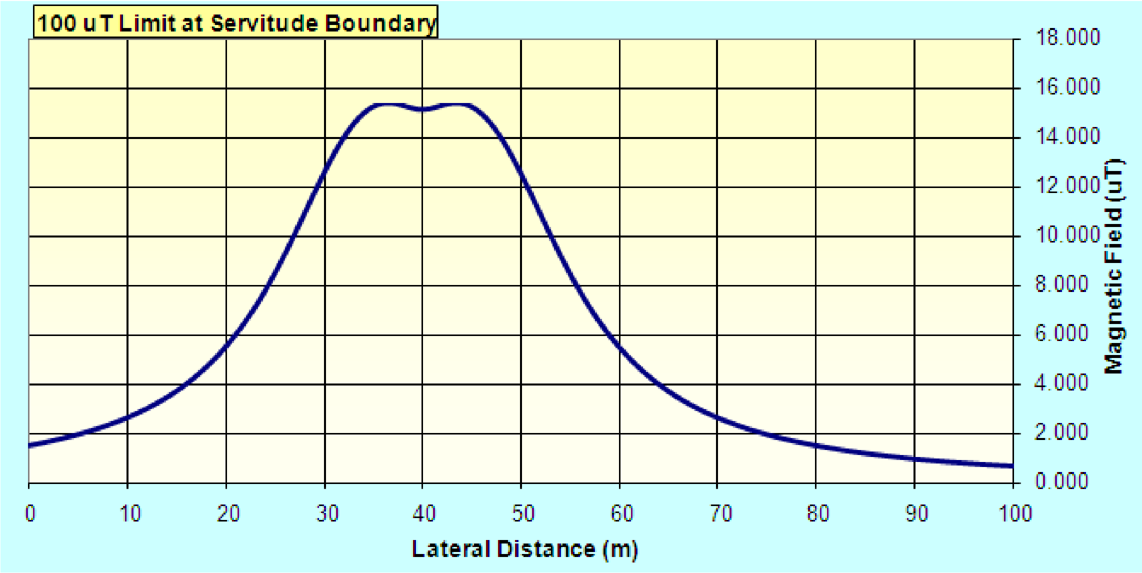

Figure C-2: Magnetic Field.

11.3 Tower Type 515 (Self Support)

11.3.1 Electric Field

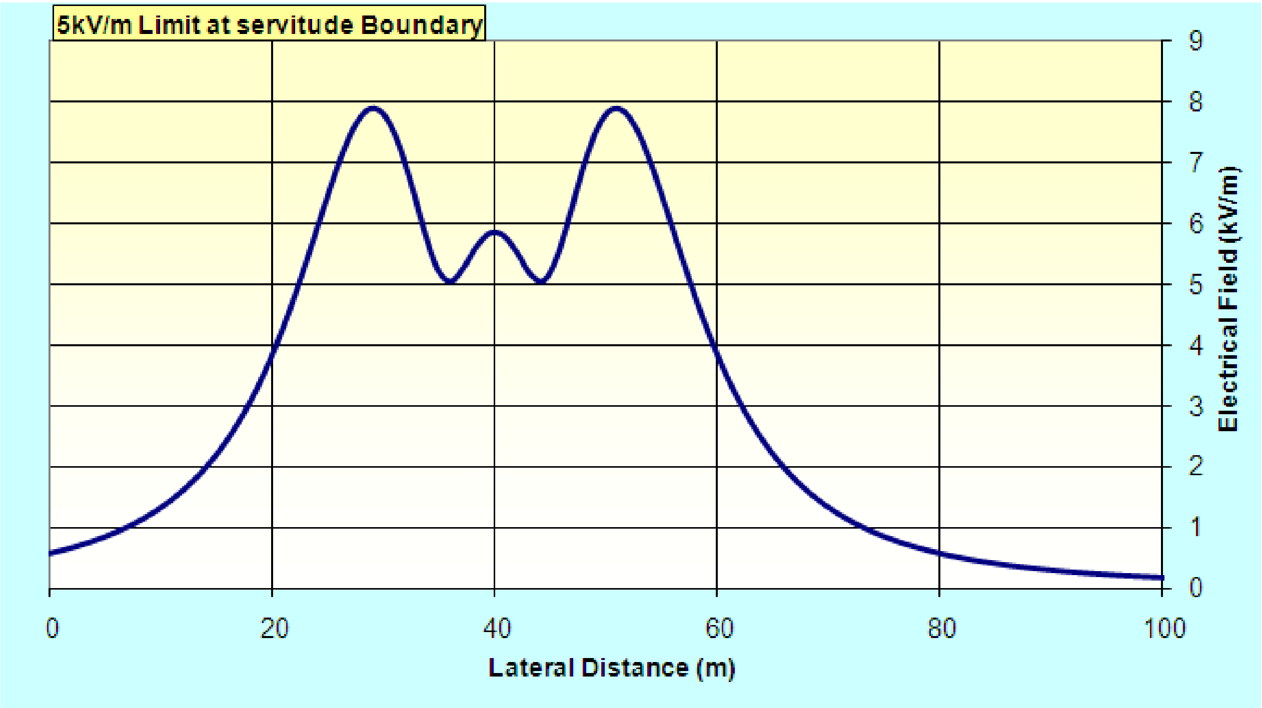

Figure C-3: Electric Field.

11.3.2 Magnetic Field

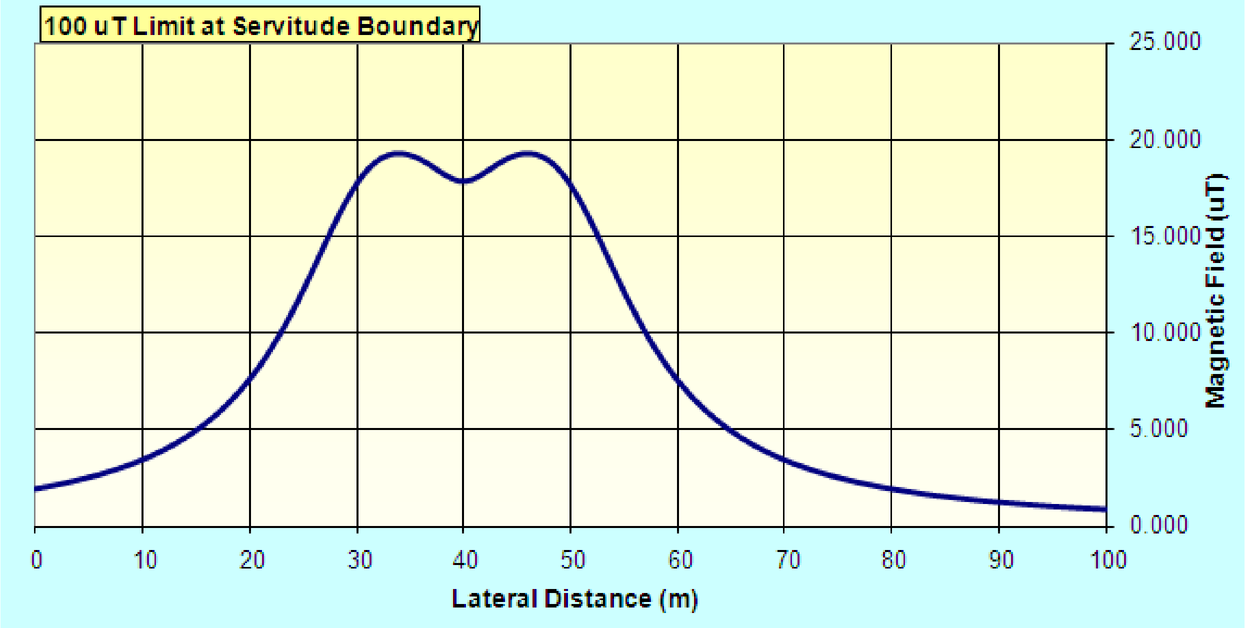

Figure C-4: Magnetic Field.

11.4 Tower Type 520B (Guyed V)

11.4.1 Electric Field

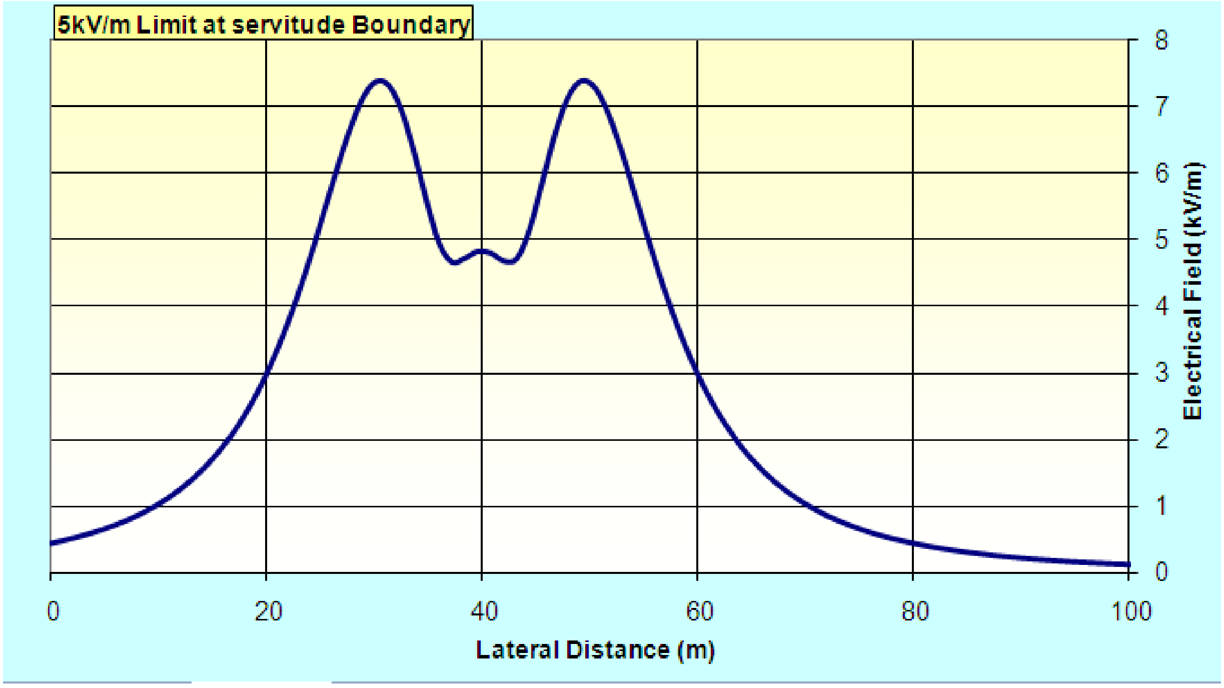

Figure C-5: Electric Field.

11.4.2 Magnetic Field

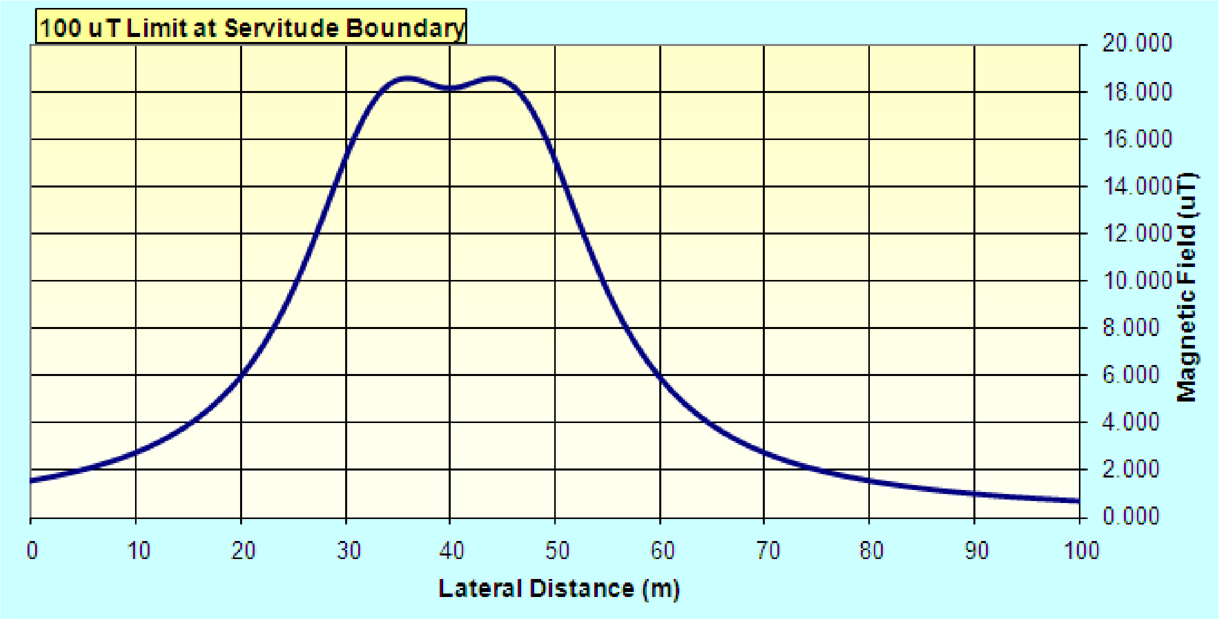

Figure C-6: Magnetic Field.

11.5 Tower Type 529 (Cross Rope)

11.5.1 Electric Field

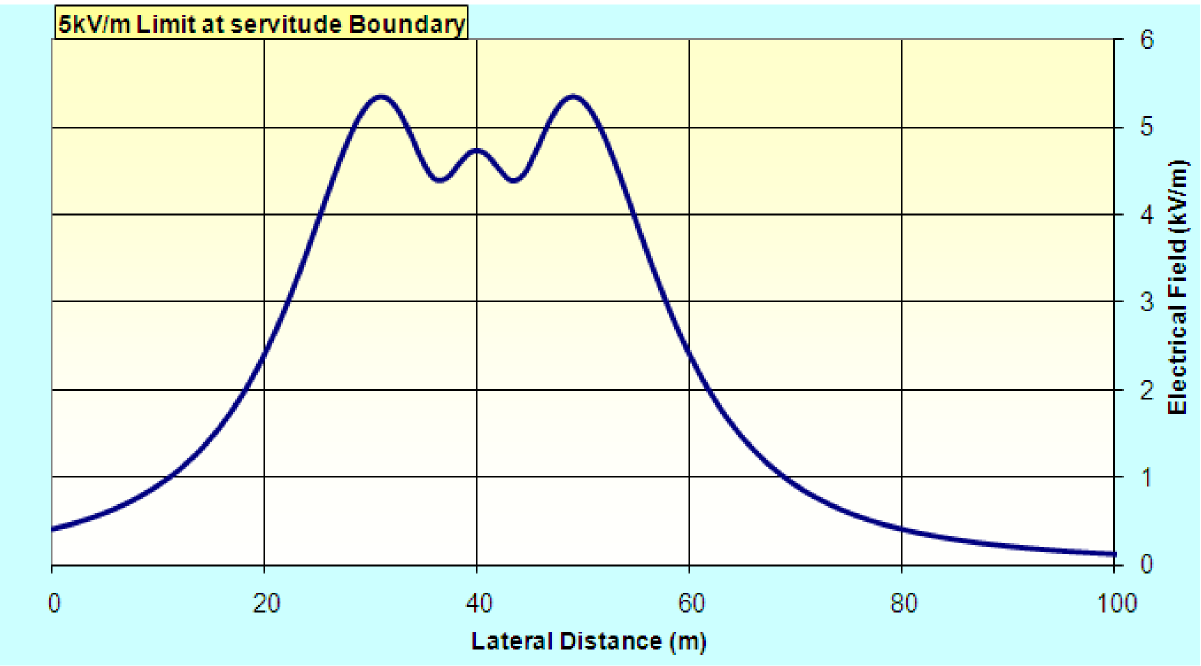

Figure C-7: Electric Field.

11.5.2 Magnetic Field

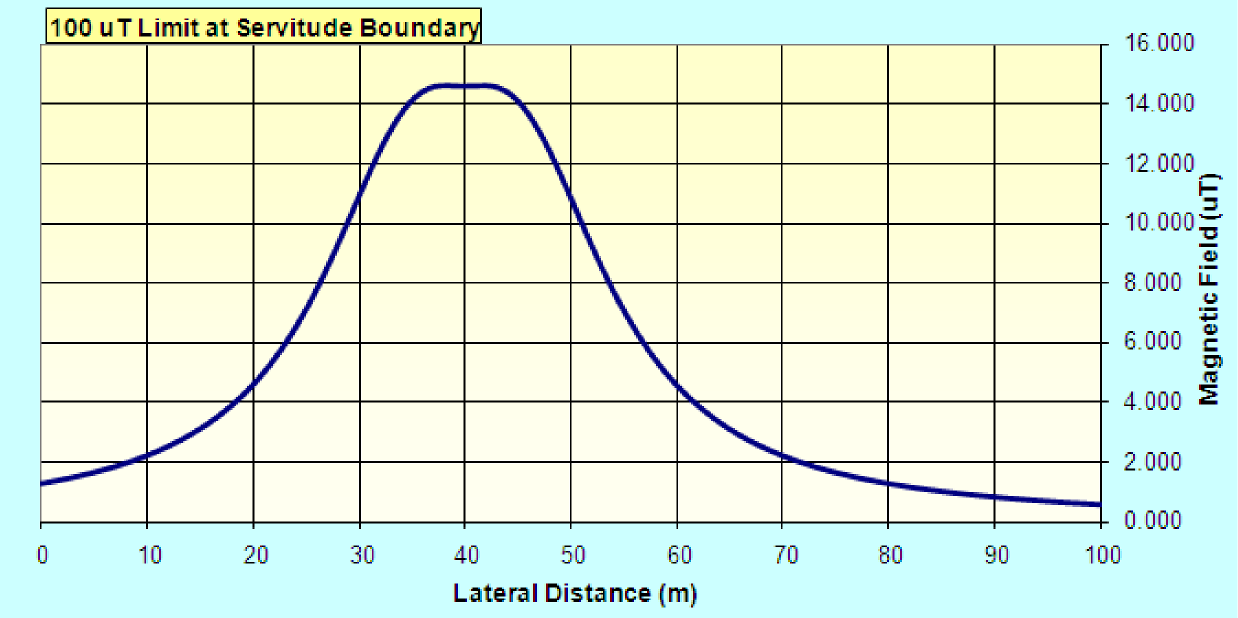

Figure C-8: Magnetic Field.

11.6 Tower Type 513 (Double Circuit Self Support)

11.6.1 Electric Field

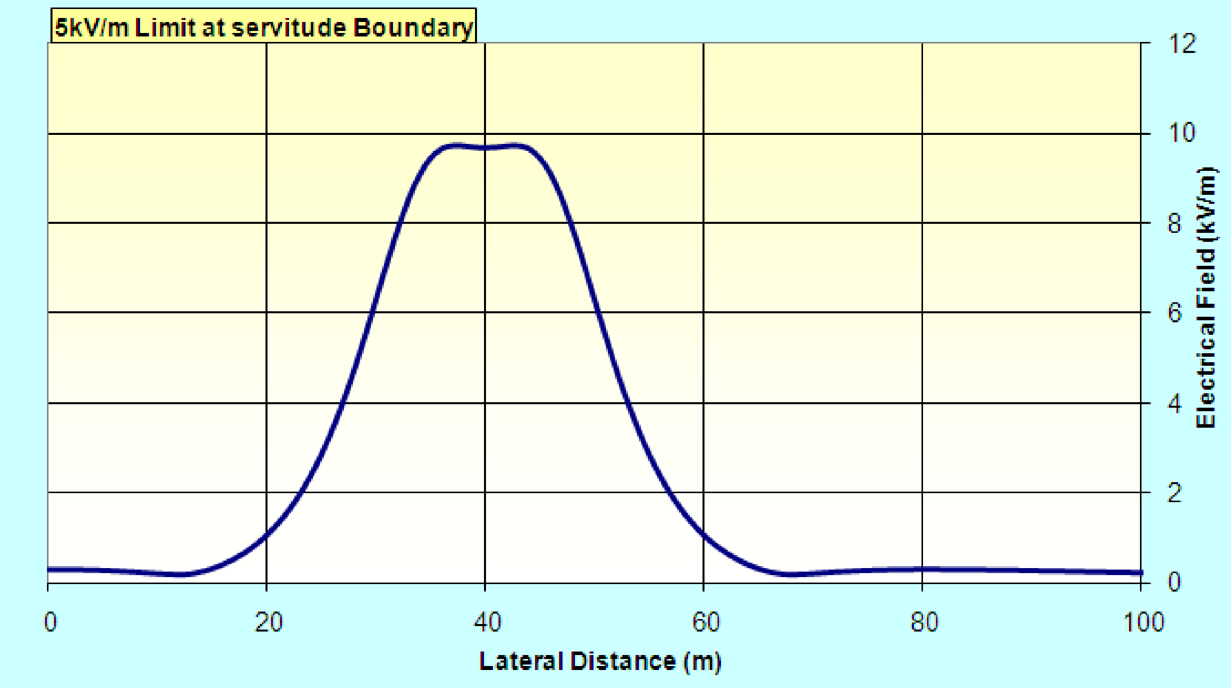

Figure C-9: Electric Field.

11.6.2 Magnetic Field

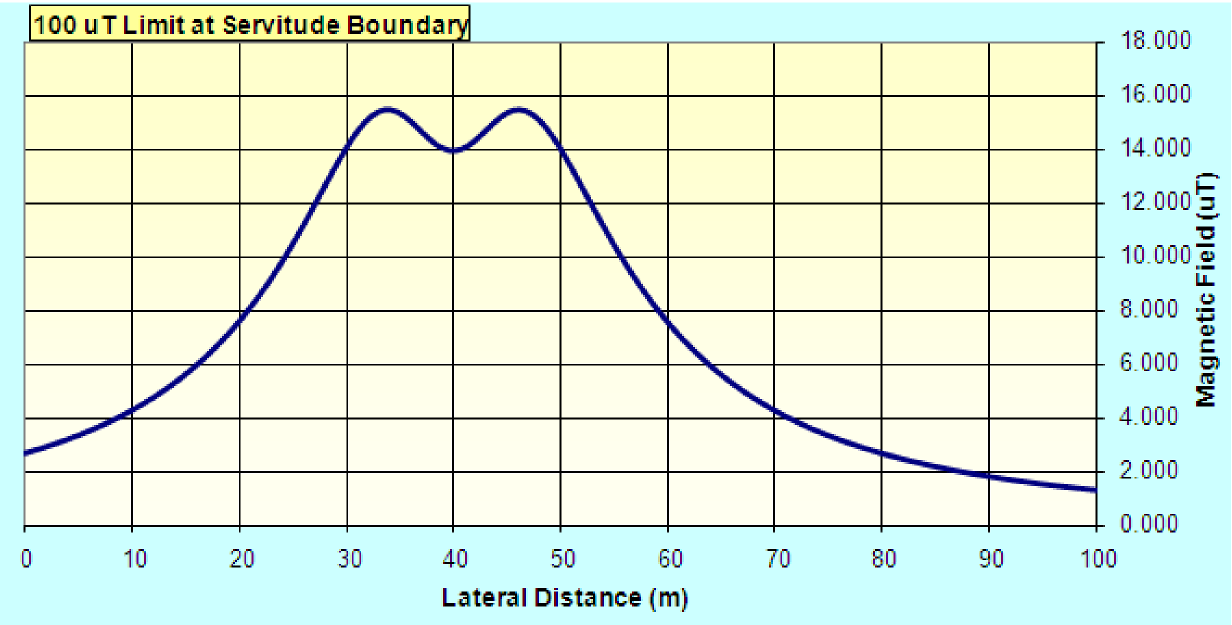

Figure C-10: Magnetic Field.

12. APPENDIX D - COSTS ASSOCIATED WITH SINGLE / DOUBLE CIRCUIT LINES

The estimated capital costs associated with a 3 x Tern conductor on a 529 A tower and a 523 A (equivalent to 513) double circuit tower are as follows [5]:

Single circuit tower (529A) : R 80,52 million x 2 = R 161,04 million

Double circuit tower (523A) : R 237,59 million

Compared to 2 x single circuit lines constructed with cross-rope towers, a single double circuit line constructed with double circuit towers is anticipated to be about 47,6 % more costly.

13. APPENDIX E - COMMON CAUSE FAILURES

13.1 Birds

As a possible cause of failure, bird streamer faults can be eliminated by ensuring the applicable clearances are such that bird streamers of typical lengths are unlikely to bridge the bridge critical gaps associated with the 400 kV line. Larger clearances on the tower and accommodated in the design will effectively eliminate bird faults.

13.2 Lightning

Based on the performance of existing 765 kV and 400 kV lines, lightning is the more important cause to be considered in electrical failures. Based on earlier studies done on the 765 kV double circuit, self-support tower structure, it has been shown that for lightning, a performance of 0,44 faults / 100 km / annum can be met. The 400 kV double circuit can be designed to meet the lightning performance required as per the User Requirement Specification (URS).

13.3 Veld Fires

Veld fires are the second most important consideration in view of the electrical performance of existing 400 kV and 765 kV lines. The minimum mid-span clearance for existing 765 kV lines is 15 m with 8,1 m for 400 kV lines. Eskom has indicated that a preferred increase of 2 m of the mid-span clearance would greatly improve veld fire performance of 765 kV lines. Raising the conductor height of a 400 kV tower will equally improve the performance in terms of veld fires. In addition, the field levels at ground level, will be lowered.

13.4 Tornados

Because of its low probability of occurrence, line designs (in South Africa) do not allow for mechanical and electrical failure that may result from tornados. Further, because a CCF is likely to result also in the case of 2 x single circuits, little benefit will be derived from implementing separate circuit lines as opposed to a double circuit line in the case of tornados.

13.5 Flooding

The effect of a CCF as a result of flooding can be incorporated in the design and operation of the line through proper selection of topography. No additional benefit will be derived from implementing separate circuits as opposed to a double circuit line in the case of flooding.

13.6 Aeroplanes

Because of its low probability of occurrence, line designs do not allow for mechanical and electrical failure that may result from aeroplanes that are flown into the line.

13.7 Mist / Fog

The effect of a CCF as a result of mist / fog on separate circuit lines, in adjacent servitudes, will be the same as for a double circuit line. No additional benefit will be derived from implementing separate circuit lines as opposed to a double circuit line in the case of mist / fog.

13.8 Theft of Tower Members

More recent tower designs incorporate measures against theft of tower members. It is realised that theft of tower members may result in a worst case in the cascaded collapsing of towers.

14. APPENDIX F - TYPICAL HIGH VOLTAGE CABLE INSTALLATIONS

14.1 Direct Buried Cable

The three conductors are buried in a trench in the ground, sometimes with cooling pipes as well. The picture on the left shows a typical direct buried cable installation [2]. Once work is completed, the soil is backfilled and there is no visible sign of the cable along most of its length. The diagram on the right shows typical dimensions [2].

Figure F-1: Direct buried cable being installed [2].

14.2 Troughed Cable

In this case, the three conductors are closer together and contained in a concrete trough flush with the ground surface [2]. The picture on the left shows the trough covers of a trough installation and the diagram on the right gives typical dimensions [2].

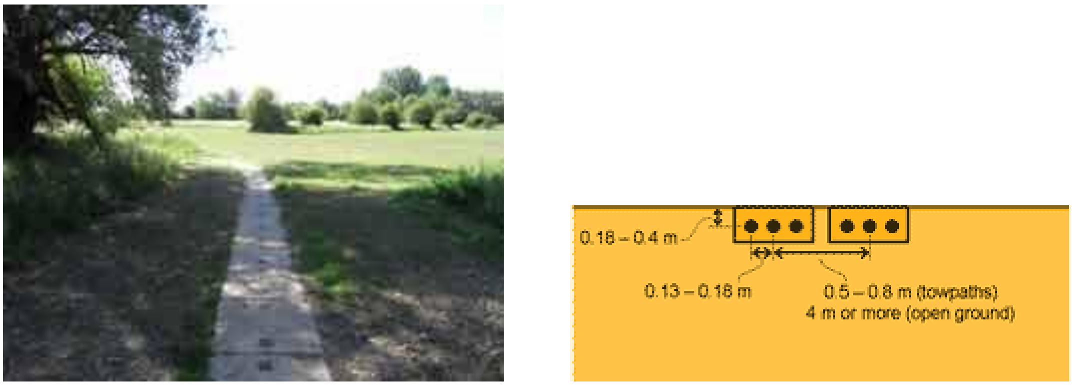

Figure F-2: Trough buried cable [2].

14.3 Tunnelled Cable

Cables can be placed in a tunnel bored deep (about 10 m) beneath the ground. This is typically applied were the cable needs to cross under a river or in urban areas [2]. Various designs are available with the conductors often bundled together [2]. The image below shows the arrangement typically used for new tunnels [2].

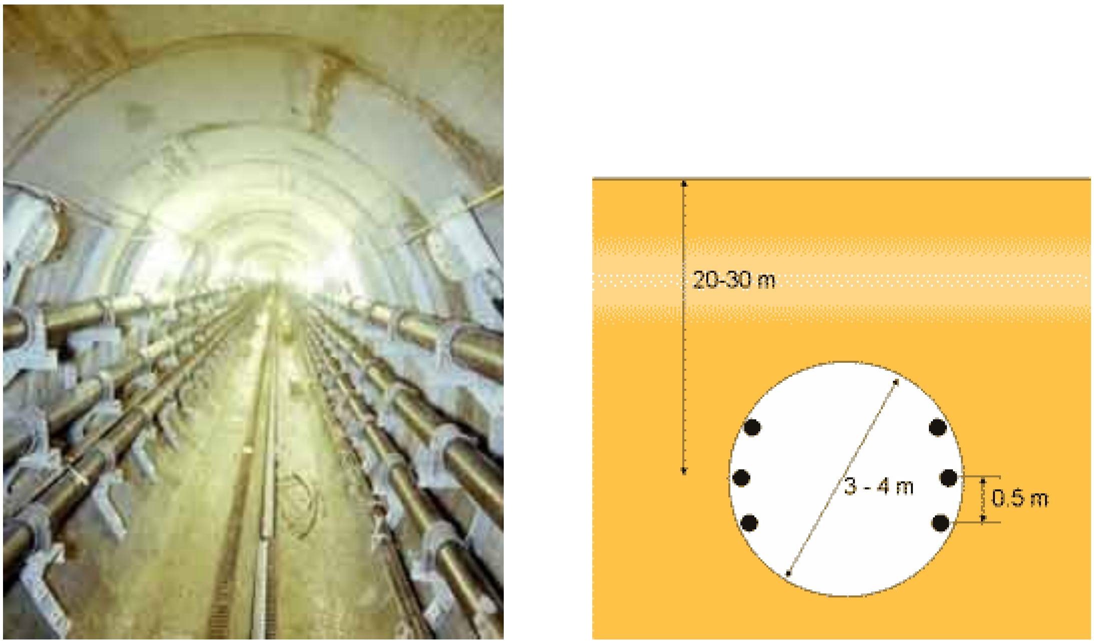

Figure F-3: Tunnel buried cable [2].