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Electrical Transmission on the Lunar Surface

Part I—DC Transmission

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March 2001

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ABSTRACT

The study of high power transmission lines for use on the lunar surface can be divided into ac, dc, and power beaming techniques. This report includes a comprehensive study and modeling of dc electrical transmission lines. A brief discussion of important environmental characteristics is provided since electrical transmission line design will be heavily influenced by the environmental requirements. An overview of the initial lunar base power requirements is followed by some basic characteristics of dc electrical power transmission. A careful look at the design parameters of a transmission line is given. This includes considerations for the conductor materials, the insulating methods, power conversion, geometry design, and deployment. These design parameters are presented with consideration for the lunar environment. Detailed analysis techniques for two geometries (two-wire parallel and coaxial) are given for two deployment configurations (above and below the lunar surface). An extensive parameter study is provided for the following parameters:

• specific transmission line application (power and length)	5 choices
• geometry	2 choices
• deployment location	2 choices
• conductor material	2 choices
• insulation	1 choice per line type
• time of day	2 choices
• % power loss	3 choices
• depth for below surface lines	3 choices

Six different line characteristics are modeled as a function of operating voltage:

• line radius	(r	vs	V)
• total line mass	(M	vs	V)
• material temperature	(T	vs	V)
• conductor resistance	(R	vs	V)
• specific mass	(m	vs	V)
• per cent power loss.	(% PL	vs	V)

The models include calculations for conductor sizes, masses, cable resistances as a function of temperature and material, and the flow of thermal energy (including conduction and radiation).

This report is meant as an objective look at dc transmission and does not intend to promote dc over other techniques. A similar report on models of ac transmission is forthcoming. The summary and conclusion does include observations of a general nature, which, along with the extensive collection of parameter studies, can be used as design guidelines for lunar base power studies. The models can be adapted to other geometries and deployment configurations.

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SYMBOLS

A	area (m^2)
C_P	specific heat at constant pressure
F_{ws}	view factor from line to space
I	current (A)
k_c	thermal conductivity of conductor material (W/m-K)
k_d	thermal conductivity of dielectric material (W/m-K)
k_m	thermal conductivity of lunar soil (W/m-K)
L	length (m)
m	mass (kg)
P_{lost}	percent power loss (%)
P_S	source power
P_{TL}	power loss on transmission line (W)
q_r	total thermal energy that must be dissipated from line (W)
R	resistance (Ω)
R_c	thermal resistance due to conduction for the conductor (K/W)
R_d	thermal resistance due to conduction for the dielectric (K/W)
R_r	thermal resistance due to radiation (K/W)
R_t	thermal resistance due to conduction (K/W)
r	radius (m)
r_m	depth of buried transmission line (m)
T_m	average temp. of the surroundings for a specified depth below lunar surface (K)
T_o	outer surface temperature of coaxial line (K)
T_{sur}	temperature of the surroundings (K)
T_w	operating temperature of the line (K)
V	voltage (V)
ε	emissivity
η	efficiency (%)
ν	density (kg/m^3)
ρ	resistivity (Ω-m)
ρ_c	resistivity of the conductor (Ω-m)
σ	Stefan - Boltzmann constant = 5.67E-08 (W/m^2-K^4)

I. INTRODUCTION

Previous uses of electric power in space have been limited to relatively low levels. For example, Pioneer derived its power from a set of radioisotope thermoelectric generators which delivered approximately 150 watts of electrical power [1]. Apollo's average net power plant output was 0.9 kW which was derived from a fuel cell and reactant cryogenic storage system. The shuttle uses a similar system with an average net power of 7 kW [2]. As larger and more complex systems are placed in orbit and on other planetary surfaces the need for power increases. For instance, the space station will initially be capable of generating 75 kW from a photovoltaic system, and will eventually expand to approximately 300 kW with the addition of a set of solar dynamic generators [1]. The initial lunar base will require 100 kW, and will later utilize over 1 MW. The classical utility power technologies in use on the earth will not provide the highly specialized, very reliable systems needed to operate in the unique space environment. This increase in the need for more power in space has resulted in a renewed emphasis on research and development on electrical power generation, distribution, and utilization in the space environment.

An important component of a high power electrical systems will be the power distribution system. Once the power is generated from solar, fuel cell, or nuclear sources it will need to be transmitted to the loads. Previous electrical power distribution systems, for instance on the Apollo or Space Shuttle, typically used classical transmission cables, primarily because the transmission distances were very short and, for the most part, were located in, and therefore protected by, the spacecraft. Typically,however, this technology is not applicable for high power transmission, long distances, or through space vacuum. Current plans for the initial lunar base includes the transmission of 100 kW over distances of about 5 km. This will result in significant exposure of the transmission lines to the space environment. Special problems with such a transmission system will be cost, deployment, reliability, safety, efficiency, maintainability, and environmental effects.

This report is part of a research project at the Space Power Institute at Auburn University to study the transmission of electrical and thermal power between components on the lunar surface. Initially the work focuses on electrical power distribution techniques. This report specifically summarizes the investigations into the transmission of dc electrical power on the lunar surface. Later reports will present ac power transmission techniques, and the effects of power conversion on design, deployment, and cost of both ac and dc transmission designs.

II. THE LUNAR ENVIRONMENT

Spacecraft in orbit around the earth have to operate in a unique environment. Compared to classical earthbound systems several new problems are present, generated both by the "floating" aspect of being suspended in orbit, and by the space environmental conditions. Several problems, such as structural support, motional instabilities, microgravity, the lack of an electrical ground reference, etc., are created by the orbital location. Environmental stresses include solar radiation, wide thermal swings, micrometeorites, and the upper atmosphere space plasma. Many of these problems are not present for a lunar base. There is "solid" ground for structural support, and there is negligible plasma. On the other hand, since the moon has negligible atmosphere it has many environmental characteristics in common with those found in earth orbit. The environment at the surface of the moon is a vacuum, experiences the same strong radiation fluxes as in earth orbit, is subject to micrometeoric impact, and undergoes a wide range of temperature variation. Although the gravity at the moon's surface is not zero it is much less than that on the earth.

Most of these environmental conditions are not found anywhere on the earth, and will have a very strong influence on the design and operation of any system on the lunar surface. Thus, it is important to include a few details on the lunar environment and how these environmental characteristics might effect different aspects of a power system.

A. Vacuum

The moon has very little atmosphere, the pressure ranges from about 10^{-12} torr ($2x10^5$ molecules/cm^3) at night to 10^{-8} torr during the day [3-6]. The sources of what little atmosphere there is include (1) diffusive and/or sputter release of implanted solar wind noble gases and possibly some molecular gases formed by reduction of lunar minerals by solar wind hydrogen; (2) radioactive decay of K, U, and Th within the interior, producing ^{40}Ar, ^{222}Ra, and He; (3) meteorite and comet impact vaporization, providing water and CO_2; (4) possibly some small contributions by degassing from impact events or gas venting; and (5) contamination by the spacecraft in the vicinity [3,7,8].

Uncontaminated vacuum is an excellent electrical insulator [9,10] and might be used to successfully separate high voltage conductors without the need for bulky and massive solid dielectrics. This will be discussed further in the section on insulation. Also, since there is no atmosphere, there are generally no contaminants to chemically degrade materials.

On the other hand, the lack of an atmosphere also causes special problems. Since there is no atmosphere on the moon there is no modulation of the solar and cosmic radiation, or of micrometeorites, all of which are greatly reduced by the earth's atmosphere before reaching the earth's surface. In addition to being an excellent electrical insulator vacuum is also a very good thermal insulator. This will lead to special problems getting rid of system heat.

B. Radiation

The spectral distribution of sunlight is approximately blackbody at 5760 K [3]. Energy flux at the moon from the sun is 1.97 cal/(cm^2min) or 1371± 5 W m^{-2} [3]. Since there is no atmosphere the intensity of the sun is the same at the lunar surface as it would anywhere in the earth/lunar orbit. Since the moon has negligible magnetic field the charged particles from the solar wind, solar cosmic rays, and galactic cosmic rays also reach the surface unimpeded [3,11,12,13]. Solar radiation (especially the UV) can result in severe degradation of dielectric materials.

C. Micrometeoroids

The moon is bombarded with meteoroids and micrometeoroids ranging from 10^{-12} g to greater than 100's of kg at velocities from 2.4 to 72 km/s [3,14,15,16]. Although the majority are very small and occur infrequently it will be important to account for a few impacts during the lifetime of a power system. Ideally a micrometeoroid impact will not result in total system failure.

D. Thermal

Surface temperatures are extreme, ranging from 100 K during the lunar night to over 350 K during the day [3,4]. These temperature variations will result in severe material and system design problems. The high temperatures combined with the vacuum create system cooling problems. Normally cooling can be achieved through one of three modes of heat transfer: conduction, convection, and radiation [17]. Conduction, which is the transfer of energy from more energetic molecules to less energetic molecules of a substance, requires direct contact with another material. The only natural sink for the conduction of system heat would be the lunar soil, which has a very high temperature (380 K) during the lunar day. Convective heat transfer occurs by the transfer of energy due to molecular motion and fluid motion. Convective cooling is also unavailable on the lunar surface since there is no atmosphere or water available. Thus, in the lunar vacuum, radiation, or the emission of energy from matter in the form of electromagnetic waves, is the only method to remove system heat. Of the three methods of heat transfer, radiative heat transfer is the least efficient method of cooling (at least at typical system temperatures) and therefore, high efficiency for lunar power systems is important to avoid the need to radiate large amounts of heat.

E. Gravity

The gravity at the surface of the moon is 162.3 cm/s^2 or roughly 1/6 of that at the surface of the earth [4,18]. This will facilitate the movement of massive objects. For instance, in the low lunar gravity a power transmission line could be suspended with much fewer support structures than on the earth, since the sag and conductor stresses are less. On the other hand, in the low gravitational field, mass is not as effective at holding objects stationary on the surface of the moon, and the effects of system generated forces (such as magnetic forces in conductors) need to be considered.

F. Soil

The moon is composed of two major region types, the maria and the highlands [19]. The highlands (also known as terrae) are the rugged, densely cratered portions of the moon which appear as bright regions. They are typically older surfaces and at a higher elevation than the maria. The maria are found predominantly on the near side of the moon in topographical basins, and are composed of basaltic lava flows. Visually the maria appear as the smooth, dark areas of the moon. The maria are covered by a layer of brecciated rocks and debris called regolith, which varies from three to sixteen meters in depth. A few rocks can be found in the regolith, but typically the particle size is less than 1 mm in diameter with a consistency that varies from silt to fine sand [3].

There are two basic types of rock found on the moon. Igneous rocks, which are formed through processes of crystallization of minerals from a silicate melt, and breccias, rocks created as a result of meteoric impacts [20]. The elemental composition of the lunar surface is summarized in Table 1, and the chemical composition is shown in Table 2.

Element	Average Lunar Surface Percent of Atoms	Comments
O	61.0	
Na	0.4	
Mg	4.3	
Al	9.5	more Al in Terrae than in Maria
Si	16.3	
Ca + K	6.0	
Ti	0.3	very little Ti in Terrae
Fe	2.3	3 times as much Fe in Maria as in Terrae

Table 1. Elemental composition of lunar soil [3].

	Highland Rocks		Mare Basalts	
	Anorthositic Gabbro	Gabbroic Anorthosite	Olivine Basalt	Green Glass
SiO_2	44.5	44.5	45.0	45.6
TiO_2	0.39	0.35	2.90	0.29
Al_2O_3	26.0	31.0	8.59	7.64
FeO	5.77	3.46	21.0	19.7
MnO	--	--	0.28	0.21
MgO	8.05	3.38	11.6	16.6
CaO	14.9	17.3	9.42	8.72
Na_2O	0.25	0.12	0.23	0.12
K_2O	--	--	0.064	0.02
P_2O_5	--	--	0.07	--
Cr_2O_3	0.06	0.04	0.55	0.41
Total	99.9	100.2	99.77	99.4

Table 2. Chemical composition of lunar soil [3].

The soil properties of interest for the design of lunar transmission lines are mainly the electrical and thermal properties. Particle size, however, may be important due to the possibility of electrostatic charging of lunar dust which might contribute to electrical breakdown. For the case of dc transmission, the primary electric properties of concern are the dc conductivity and the dielectric strength. Both of these will be important for considering the feasibility and optimal design of an underground transmission system. The uppermost lunar surface layers typically have dc conductivity values of 10^{-13} to 10^{-16} mhos/m [21]. Values for the dielectric strength could not be found, but we can make an approximation to the probable value by assuming that it will be similar to the dielectric strength of similar materials found on earth. If ac transmission is used the dielectric constant and loss tangent values will also be needed. These have been measured, over various frequencies, at the Apollo 15 and 16 sites [21,22].

The thermal properties of interest include the thermal conductivity, and subsurface temperature profile of the soil. The surface temperature of the soil throughout the lunar day/night cycle as measured during the Apollo 17 mission is shown in Fig. 1. Sunrise occurs at 0 degrees. The total temperature swing from 384 (± 6) K at noon (90 degrees) to 102 (± 2) K just before sunrise (350 degrees) is about 262 K with a mean surface temperature of 216 (± 5) K. This swing drops rapidly a few centimeters into the soil (Fig. 2a), so that the temperature swing at 5 cm is about 90 K, at 10 cm about 30 K, at 30 cm about 3 K, and at 1 m it is essentially constant.

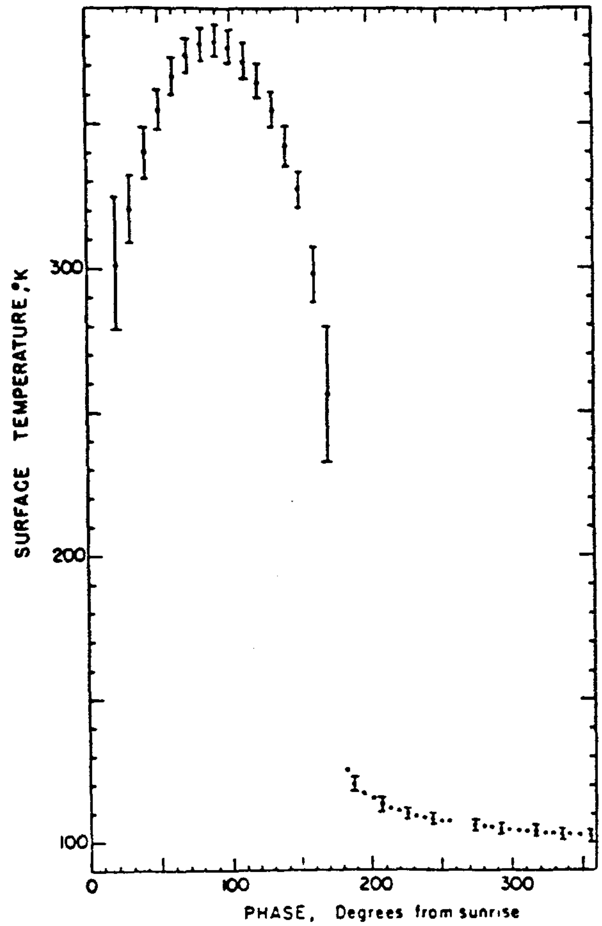
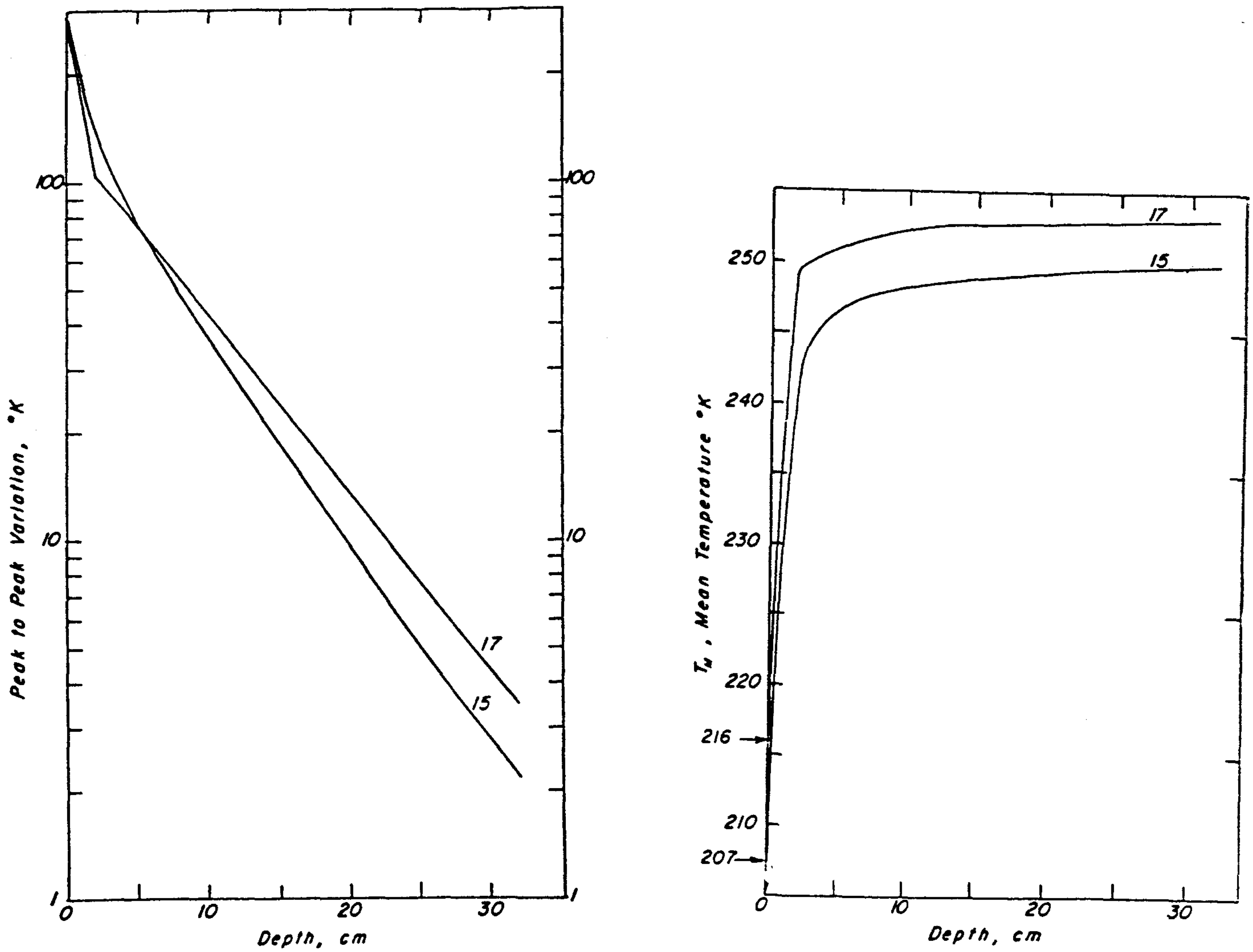


Fig. 1. Soil surface temperature over a lunar cycle [24].

The mean subsurface temperature (below 50 cm) is approximately 250 K, which is 35 K above the mean surface temperature of 216 K [23]. Figure 2 shows results from the thermal models developed as a result of the Apollo 15 and 17 thermal measurements [24]. Figure 2b shows the increase in mean temperature as a function of depth. At about 30 cm in depth the temperature has stabilized at the mean subsurface temperature of 250 K. The difference in mean temperatures from the surface to subsurface is a result of an increase in thermal conductivity with increasing depth. The thermal conductivity of the soil at a depth of 2 cm or less is approximately $1.5x10^{-5}$ W/cm-K, and increases from 2 cm to 15 cm to a value of $1.5x10^{-4}$ W/cm-K. The slope of the temperature change at sunrise and sunset is controlled almost entirely by the thermal properties of the upper 2 cm of soil. Because the upper 2 cm consist of porous, low conductivity material, radiative heat transfer to/from space dominates over conductive heat transfer to the surrounding soil. At the Apollo 15 and 17 sites the ratio of radiative to conductive heat transfer, at the maximum temperature of the lunar day, was found to be 2.5 - 3 and 1.7 - 2.2 respectively [24]. Therefore, during the day when the soil temperature is high heat flows more readily due to radiative processes than conductive processes. This results in the steep slope of the temperature at sunrise and sunset [25]. As the temperature drops the subsurface heat must slowly be released throughout the lunar night by conduction from the subsurface soil (with a higher conductivity) through the surface layer. This results in the flat plateau seen during the lunar night. Thus, the temperature gradient, occurring mostly over the top 2 cm of soil is a result of the change in heat flow processes from night to day.



(a) Peak-to-peak temperature variations vs depth. (b) Mean temperature vs depth.

Fig. 2. Soil temperature as a function of depth [24].

III. POWER TRANSMISSION ON THE LUNAR SURFACE

The designs for the initial lunar base configurations are currently being formulated. Figure 3 illustrates the conceptual layout for the first several phases of lunar base establishment with the power sources, transmission lines, and loads. The function of the electrical power transmission system is to transport power from the sources (SP-100/Thermoelectric Generator, Photovoltaic/Regenerative Fuel Cell, or Nuclear Power Plant) to the loads (habitat/laboratories, the launch/landing site, and the manufacturing site). The transmission lines will need to carry different amounts of power over various distances, depending upon the source characteristics and the load requirements. The transmission lines must be reliable, efficient, easy to deploy, and safe. Unlike terrestrial systems, power outages can have disastrous consequences. Lunar power systems must be very reliable, with redundancy built-in to provide backup. Efficiency is much more important than for terrestrial systems because the input power is limited, and because waste energy in the form of heat is very difficult to dispose of. Lunar power systems may very likely work at higher temperatures than terrestrial counterparts to aid in the rejection of waste heat. The transmission line must be easy to deploy due to the constraints imposed by the necessity of working in a space suit. Because of the absence of medical facilities, or quick access to them, it is very important that all systems be very safe. Many of these special requirements, plus the remoteness of the moon will significantly increase the cost of a lunar power system over conventional power systems.

The first phase of the lunar base most likely will include an SP-100 power source with an electric output of about 100 kW growing to later include a larger reactor suppling up to 1 MW of electrical power. The first transmission line will most likely be the 100 kW, 5 km line from the SP-100/thermoelectric generator to the habitat. Later the 100 kW, 200 m line will be added to the PV/RFC, followed by the 120 kW, 5 km line to the launch/landing facility. Finally, with the addition of a large power source such as the 1 MW nuclear power plant a 800 kW, 1 km line will be needed to supply the resources mining facility.

There are several potential methods of transmitting power from one site to another at a lunar base. Electrical energy might be transported through transmission lines and might use ac, dc, or rf waveforms. In addition it may be possible in future technologies to transport power in some form of electromagnetic beam, such as using microwave or laser beams. Later technologies may use cryogenic conductors to decrease the losses and thus the operating temperatures.

The purpose of this report is to present the initial results of a study to investigate these various methods of transporting power on the lunar surface. This first study focuses only on dc transmission , and a follow-up report will deal with ac transmission. The transmission line used for most of the studies is the 100 kW, 5 km line shown in Fig. 3 going from the SP-100 power source to the habitat. In order to keep the study simple, so that the key design parameters can be compared, certain aspects of the electrical transmission system are not considered in this initial report. These include, multiple parallel lines, forced cooling (with pumped liquid or gas), and the requirements of the loads and sources.

IV. DC TRANSMISSION OVERVIEW

The transmission of power using a high-voltage dc waveform is the most efficient method of electric power distribution, in that it has fewer line losses. For years this benefit has been overshadowed by the difficulty in stepping up dc voltage for distribution. Thus, ac voltage transformation has been relatively cheap and simple and has dominated the utility power industry. It is only recently that dc power converters and inverters have been developed which not only produce the desired voltage as effectively as ac transformers, but also do so with less mass and volume. The only obstacle remaining is that the cost of this new technology is considerably more than it's ac counterpart. As more and more dc transmission lines are utilized terrestrially, and as more research is conducted for their use in space, the costs should decrease. Historically, ac distribution has been a good, reliable method of power transmission. With new dc power conversion technology, dc may soon be considered as an equal, or in some instances a superior alternative.

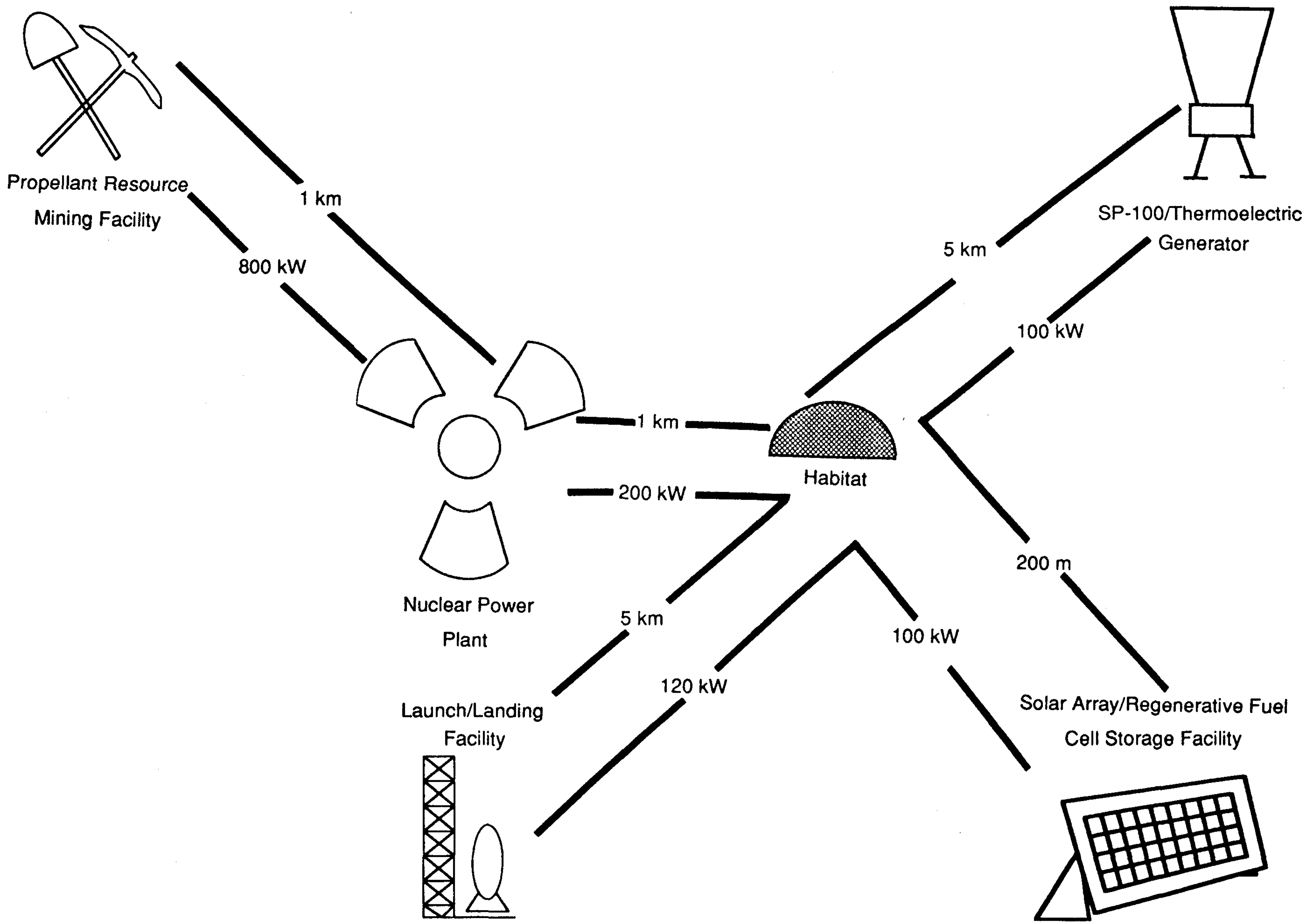


Fig. 3. Lunar base layout.

V. FACTORS EFFECTING TRANSMISSION LINE DESIGN

Probably the most important, or at least the most talked about, parameter for design for space systems is the cost. Of course, operational requirements must be met; safety, environmental, and reliability issues satisfied; and, technically achievable designs developed. But ultimately, the system or program becomes reality only if the cost can be met within the political and socioeconomic structure responsible for the program. Thus, in the early planning and design stages of a program it is often important to study the cost of the system as a function of design. The cost of lunar transmission systems will be a complex function of many parameters. These include mass, volume, materials, deployment requirements, reliability, safety issues, manufacturing requirements, etc. In this report many of these parameters that will effect cost are investigated as a function of some of the system design parameters. Such system design parameters include voltage, efficiency, lifetime, current waveform, materials, etc. In this section some of these design parameters are discussed. The analysis to demonstrate their interdependence is presented later, in section VII - Parameter Studies.

It is important to point out that transmission line design can not ultimately be considered independently of other system components, such as the power sources, power convertors, and loads. All power components are synergistic. For example, an inexpensive transmission line design may necessitate an expensive power conversion, may be inefficient, or may require undesirable limitations on load management. This report considers design options for conventional cable-type transmission lines and the effects of these design options on transmission line mass (and thus cost). It does not consider the effects of power conditioning, sources, or loads, nor does it consider new technological concepts such as power beaming or superconducting lines.

A. Design Guidelines for Material Selection

A dc transmission line typically consists of a two metal conductors, an insulator, and/or some sort of support or shielding structures. The conductor materials are invariably metal, while the dielectric materials which insulate the two conductors from each other and from the rest of the world are composed of solid, liquid, gaseous, and/or vacuum insulation. The selection of the optimum conducting and dielectric materials for a given application depends on the mechanical, physical, and chemical properties of the materials and on the design specifications of the transmission line. Important factors influenced by the choice of materials include power loss, mass, and reliability in the operating environment.

Typical mechanical properties important in the lunar environment are flexibility, strength, flow, and abrasion resistance. The cable must be flexible and strong so that it can be easily deployed without being damaged. Under the extreme temperature ranges the flow (or gradual deformation) of the material is important, especially for the dielectric materials. Abrasion, vibration, and shock resistance will not be as critical to lunar design as it is to terrestrial design because of the absence of weather on the moon. However, they may need to be considered if the method of installation/deployment is to lay the lines across the lunar surface or to bury them at a shallow depth. All of the mechanical properties of the transmission line are subject to degradation over time due to exposure to the harsh environment. Since the materials are exposed to an extreme temperature range (much larger than any encountered on earth over the same period of time) careful attention must be paid to the response of the materials to temperature. Also, there can be degradation due to the solar radiation, micrometeoric impact, or prolonged exposure to vacuum. Almost without exception dielectric materials are much more sensitive to these environmental stresses than are the metallic conductor materials [26,27,28]. The cost of transport and the difficulties of maintenance necessitates a long operating life, therefore, material degradation and system reliability will be an important factor. As described above the mechanical properties of the candidate materials will primarily affect the usability of the material. The other factors (mass and energy loss) will be determined primarily by the physical and chemical requirements of the materials.

The physical properties are divided into two sections, electrical and thermal characteristics. Electrical and thermal characteristics will be considered for both the conductor and the dielectric material. The primary electrical property of the conductor is the resistivity. Important dielectric material electrical properties include the electric field breakdown strength, conductivity, and later, for ac applications, the dielectric constant and loss factor. The important thermal properties for both types of materials include thermal conductivity, thermal expansion and contraction, heat capacity, melting point, and any temperature dependant damage mechanisms. The most obvious short-term effect of the environment on conductor materials is an increase in resistivity of a conductor as a function of temperature [29]. Otherwise most environment effects on conductors are more long-term degradation, such as annealing, embrittlement, loss of strength, etc. The dielectric material, on the other hand, is very susceptible to environmental stresses. The selection of the insulator must take into account the influence of temperature, radiation, micrometeoric impact, and exposure to the vacuum on adhesion, deformation, tensile strength, outgassing, charge carrier densities, dielectric constant, loss factor, and breakdown [26,27,28].

It would appear that it would be difficult to provide a more chemically benign environment than would be found in a vacuum, which is without any air, water, acid rain, oxygen, or Los Angeles smog. There are two reasons, however, for potential chemical degradation of materials on the lunar surface. The first is chemical changes or interactions between materials stimulated by the environmental stresses, such as the wide temperature range, various types of radiation, and vacuum. For instance, some dielectric materials will change their composition or begin to evaporate upon prolonged exposure to a vacuum. The second is that despite the apparently chemically pristine environment on the lunar surface there will be contaminants, most of them generated by human presence on the surface. These might come from rocket-fuel by-product fallout, material outgassing, or effluents from the habitation or manufacturing modules. The chemical compositions of dielectrics must be suitable for use in this potentially contaminated lunar environment. For example, rocket fuel fallout from the launch and landing site can chemically alter or degrade some insulators [27].

B. Conductor Material

There are a number of different conductor materials used on earth. However, if we limit our discussion to those best suited for power transmission and those that are easily and economically manufactured we can quickly narrow our discussion to copper and aluminum. While both forms of metal are available in various alloyed forms, for simplicity a useful comparison can be made by considering only the pure forms of the metals. Significant differences achieved by the use of certain alloys will be pointed out.

(a) Copper

Copper has been established as a universal conductor because of its low resistivity, chemical stability, reasonable cost, and good ductility [27]. It is available in three forms, annealed, medium-hard drawn, and hard-drawn. The characteristics of annealed and hard-drawn copper are shown in Table 3.

Annealed copper is copper which has been heated and then allowed to cool for the purpose of increasing its ductility. The process softens the metal and decreases its tensile strength (resistance of a material to a force tending to tear it apart). Annealed copper should not be considered for suspended power transmission on the moon because of the increased tension on the conductors. However, the process of annealing is important when discussing lunar transmission line operation. The large temperature swing from day to night may result in inadvertent annealment of the conductor material thus increasing the chance of mechanical failure, and decreasing the operating life of the line. In order to prevent the conductor from becoming softened or brittle the operating temperature of the line should change as little as possible over the lunar day. Constant temperature control might be accomplished through voltage (and thus current) control (see voltage section). Annealed copper could be considered as an alternative for surface or below ground installation because of the decreased strain on the line for these deployment configurations.

However, because the operating temperature of annealed copper is lower than the other forms of copper, the poor thermal conductivity of the lunar soil will probably eliminate it as an option.

Medium-hard drawn copper wire is annealed wire which has been drawn to a slightly smaller diameter, resulting in slightly increased strength and hardness over that of annealed copper. In contrast, hard-drawn wire has been repeatedly drawn without intermediate annealing producing a wire with a tensile strength and maximum operating temperature considerably greater than that of annealed copper [1]. Because of its superior characteristics, the hard-drawn copper conductor was the only one included in the analyses.

PROPERTY	Al (61% conductivity)	Cu (97% conductivity)		ACSR
		annealed	hard-drawn	
Max. operating temp. (C)	300	500	600	--
Density, g/cm^3	2.7	8.89	8.92	6.95
Tensile strength, lb/in^2	35,000	35,000	45,000	--
Melting point, C	660	1083		--
Coefficient of expansion, per C	23.0×10^{-6}	16.92×10^{-6}		13×10^{-6}
Modulus of elasticity, (lb/in^2),(kg/mm^2)	10×10^6 , 7030	17×10^6, 11950		23×10^6,1.6×10^5
Resistivity at 20 C, Ωm	2.9×10^{-8}	1.7×10^{-8}		--
Thermal conductivity(W/m-K, at 300 K)	237	401		

Table 3. Properties of three conductor materials [27,31,36].

(b) Aluminum

Aluminum (Al) is a good candidate for overhead power transmission on the moon because of its low mass, low cost, and relatively good thermal and electrical properties. While the conductivity is approximately two-thirds that of copper, its savings in mass is significant. For wires of equal conductivity the Al wire must be 66% larger than the Cu wire. The savings in mass, however, will be approximately 50% with only a decrease of 25% in the tensile strength as compared to that of the copper conductor. Aluminum's major drawbacks are its softness and difficulties in making connections. Both of these drawbacks could affect an aluminum transmission line's reliability and operating life. Because of these poorer physical characteristics aluminum conductors with steel reinforcement (ACSR) are typical used instead of solid aluminum for suspended transmission lines on earth [30]. They have increased strength and less sag than standard aluminum, allowing longer spans, and shorter and fewer supporting structures. Because the physical characteristics of solid Al and ACSR are similar, only the solid aluminum was included in the parametric study in section VII. The characteristics of both are shown in Table 3.

(c) Stranded Cables

Stranded cables use a group of wires in a single cable. Cables sized No. 0 AWG and larger are typically stranded for increased flexibility and ease in handling. Stranding causes a slight increase in mass and electrical resistance as a result of the increased length of the line taken up by the twisting of the wires. The parametric study in section VII will not include stranded cable because of the large number of stranded configurations available, but it is recommended that the larger diameter lines be stranded for the improved flexibility, and to avoid damage which may occur when large solid cables are bent. Also, it is very likely that stranded cables will radiate heat more effectively, since their surface area to volume ratio is larger than solid cables. There are tables available from which, given the solid diameter, it is possible to calculate the equivalent stranded diameter for any stranded cable configuration. This would allow calculation of the required cable diameters for given current requirements. Also, the increase in mass and resistance can be calculated [31,32]. The thermal analysis for a stranded cable would be more complex than the simple cylindrical conductor and is not discussed in this report.

(d) Conductor Size

The size of the conductor is dependent on thermal properties of the conductor and insulator, line voltage, power transmitted, mechanical strength, voltage drop, length of the line, and length of the span. Most of these factors are variables which can be optimized for a given design criteria. A minimum diameter can be set with regard to the mechanical strength of the conductor. The conductor should be able to withstand a minimum of two times the sum of all the stresses on the line. The causes of tension for a transmission line on the moon is limited to the mass of the conductor and the shortening of the conductor due to temperature decreases. Keep in mind that in the moon's lower gravitational field larger masses can be suspended over longer distances than on the earth. Although mechanical strength will be an important parameter for actual deployment, the focus for this report will be the radius of the conductor as determined by the electrical requirements, such as current, efficiency, etc. When the diameter of a line is unreasonably small in a parameter study it will be noted.

C. Dielectric Material

The selection of the proper dielectric material will be more complicated than the conductor selection. Whether the dielectric used is vacuum or a solid the possibilities of failure are increased greatly for the dielectric material over the conductor material. In particular, the effect of the lunar environment must be carefully analyzed. This includes radiation, meteoroid, thermal, and vacuum effects. The difficulty in doing this is compounded by the fact that the environmental parameters cannot be considered separately, but must be synergistically examined along with the transmission line characteristics such as the voltage and current contributions to the stress on the dielectric. Although many properties have been measured for many dielectrics there is still a void of understanding in the effects of multistresses on dielectric materials. For example, temperature ratings are typically based on tests performed on the material alone and in a controlled setting. The actual operating temperatures of the material could be either higher or lower in the presence of other materials, or a different environment [33]. Very little work has been done to simulate the lunar environment and determine the synergistic effects of several environmental effects on materials [34]. Therefore, the final choice of dielectric can not be made until dielectric reliability experiments have been conducted with more accurate simulation of the lunar environment . Nevertheless, preliminary solid dielectrics have been suggested as potential candidates based on their mechanical, physical, and chemical properties. For example, all those initially considered must operate efficiently at a controlled temperature in spite of the large temperature variation which occurs over the lunar day. There are basically four different classes of insulation material for power systems: solid, liquid, gaseous, and vacuum. Although liquid and gaseous insulants are not strong candidates they will be considered briefly.

(a) Liquid and Gas

The use of liquids and gases as insulants has found widespread use in earthbound technology. Basically, gases and liquids have similar characteristics and in a general sense can be discussed together. For simplicity gases and liquids will be grouped together and referred to as fluids. Fluids generally have lower breakdown strengths than good solid dielectrics. However, fluids have some unique characteristics that make them very useful. The fluids can flow and fill odd shaped and small regions between conductors. Dielectric oil and high pressure gases are heavily used by the power utility industry to fill transformers, capacitors, and closely spaced buswork structures and insulate adjacent conductors from one another. Fluids can also transfer heat much more efficiently than solid dielectrics, and maintain safe operating temperatures in compact regions by quickly removing waste heat. This is due to the excellent thermal conductivity of fluids or by convective heat removal by flowing gases or liquids. Finally, fluids have the unique characteristic of being "self-healing" dielectrics. This means that in many cases of an electrical breakdown of the fluid material under high field stresses the material recombines, and retains most of its former breakdown strength following cessation of the breakdown current. This characteristic is most evident in the exclusive use of liquids and gases (and sometimes vacuum) for all high power utility switches.

Applications of the use of gases and liquids surround us everywhere. Air is the most common dielectric. It is used to insulate practically all above ground transmission lines, substation buswork and connections, and many exposed conductors in the household (such as the prongs on an electrical cord). In higher field stress regions high pressure air or SF_6 is used as a gas insulate. In even higher field regions liquid insulates such as mineral or petroleum based oils are used.

Despite the many applications of fluids on the earth there is one key problem that reduces their applicability to the space environment. With any minute leak of the containment structure a fluid will leak into the space vacuum and be irretrievably gone, and any such loss must be continuously replenished. Liquid dielectrics are almost as massive as solid dielectrics and provide less holdoff strength. Any gas insulant must be contained in a structure capable of withstanding the stresses of atmospheric pressure (or greater) against vacuum.

Thus, it seems much more promising to focus on solid-dielectric or vacuum-insulated transmission lines, especially over long distances where the probability of the development of leaks is very high. Perhaps later, leak resistant containment structures can be developed, or gases can be produced in such quantities at a lunar manufacturing facility to reduce the cost of gas replacement.

(b) Solid

For the power levels being considered (which are low by earth standards), a solid dielectric would be the likely candidate if the proposed power system were to operate on the surface of the earth. In addition, the choice of materials, for a terrestrially based system, could be quickly narrowed down from previous experiences to one of five classes of chemical compounds: rubbers, vinyls, polyolefins, fluorocarbons, and nylons [27]. The terrestrial properties for each of these are well documented and can be found in Tables 4 and 5. However, the proposed system is not terrestrially based, and the validity of these properties must be questioned for operation in the multistress lunar environment. The ideal solution would be to present equivalent tables derived from actual dielectric performances in the lunar environment, or even in an earth orbit environment. Needless to say, little (if any) data is available on insulator operation in the lunar environment. More information is available for earth orbit operation; however, this data is scarce when compared to available terrestrial data. The lack of information can be attributed to our limited access to space, and because, unlike earth systems, which regularly expose transmission lines to the environment, spacecraft (in order to avoid failures and extend operating life) have been designed to contain materials, such as insulation, that could be damaged by exposure to the space environment. The exception to this practice is the long duration exposure facility (LDEF) experiment recently retrieved [35]. LDEF will supply an enormous amount of much needed information on the effect that long term space missions have on various materials. However, few of the materials used in the experiment can be considered typical solid electrical insulators. Most of the experiments focused on thermal coatings and on materials to be used for the actual space structure [36]. As a result, the usefulness of the information will be limited for this particular application. The next best solution would be to utilize information obtained through simulation of the lunar environment. As mentioned earlier, synergistic lunar environment simulation has not been done adequately as of this date, but is highly recommended as a necessary step in the lunar base design. Until, these experiments have been performed, the best course of action is to combine the available information to obtain as accurate a picture as possible of the solid dielectric options for lunar base operation. This information includes data obtained from terrestrial operation, data obtained by simulating the space environment, and data obtained directly from space use.

	Rubbers						Fluorocarbons			Polyolefins		
	Silicon	Neoprene	Butyl	Fluorocarbon rubber	Polyurethene	Vinyl (PVC)	TFE	FEP	CTFE	Polyethylene	Polypropyline	Nylon
Mechanical Properties:												
tensile strength	low	high	medium	medium	very high	high	high	medium	high	low	high	very high
elongation	fair/good	excellent	goood/excelt	fair	good/excellent	fair/good	fair/gd	good	fair	excellent	good/excellent	good
flexibility (low temp)	excellent	fair	fair	fair	good/excellent	poor/fair	good			poor/fair	very poor	good
abrasion resistance	poor/fair	good/excelt	good	good	excellent	good	fair/gd			fair/good		excellent
Physical Properties:												
resistivity(Ω-cm)		10^{11}	10^{17}	10^{12}		10^{15}	10^{18}	$2x10^{18}$	10^{18}	10^{16}	10^{16}	10^{14}
melting temp. (C)	>375					200	330	290		130	200	
cont. op temp.(C)	-55/200	-55/90	-55/90	220	-40/120	-65/95	-65/260	<200	-65/200	100	120	120
thermal conductivity (W/m-K)	.167-.335				.167-.209	.167-.209	.251	.251	.222	.335-.502	.117	.243
Dielectric Properties:												
dielectric strgth(V/mil)	400	500	750	500			430	500	550	600/700	650	280

Table 4. Solid dielectric characteristics.[1,5,6]

INSULATOR	DENSITY gm/cm^3
TFE fluorocarbon	2.19-2.16
FEP fluorocarbon	2.14-2.16
Polyvinyl chloride	1.16-1.65
Irradiated modified polyolefins	1.10-1.20

Table 5. Densities of dielectric materials [27].

Of the rubbers, only synthetic forms were considered because of their superior physical and mechanical properties which make them better suited for extreme environmental requirements. Synthetic rubbers include: silicon, neoprene, butyl, and polyurethane. Silicon is characterized by high corrosion resistance, good temperature response, and flexibility. Neoprene has excellent abrasion resistance and flexibility, but its electric properties limit it to low voltage and low frequency applications. Butyl is commonly used as primary insulation for high power, low frequency power cable. It also has excellent resistance to rocket fuels and is therefore used at missile launch sites [27]. Lastly, polyurethane has outstanding mechanical properties but its electrical properties are marginal for use as a primary insulator.

Polyvinylchloride (PVC) is not used as an insulator in its pure form. Compounding ingredients are added to create the desired properties. The major additives are stabilizers (to inhibit breakdown at high temperatures), plasticizers (to add flexibility), and fillers (to decrease flammability). The addition of the plasticizers will also have significant effect on the electrical, mechanical and chemical properties of the material. A large number of these compounds are available with many different characteristics. It is therefore a good assumption that a form of PVC can be fabricated to give optimum operation in the lunar environment. However, if its melting temperature cannot be raised significantly its use will be limited, especially if considering high power underground transmission.

Of the polyolefins, polyethylene has the better mechanical properties, but its low melting temperature (400 K) will probably eliminate it as a potential dielectric for lunar applications.

All of the fluorocarbons have outstanding electrical characteristics. TFE has superior operating characteristics over a wide range of operating temperatures, but is not as strong mechanically as FEP and CTFE.

Finally, nylon can be characterized generally as a dielectric with good electrical and mechanical properties and excellent abrasion and cut-through resistance. However, its operating temperature is borderline for the lunar temperature fluctuation.

Most of the characteristics of the compounds discussed above reflect normal operating conditions on earth. While some of these, such as melting temperature, will not change; others, such as recommended operating temperature, and dielectric strength may be altered significantly in the lunar environment. In an attempt to predict how the properties of the dielectric may change, the major components of the lunar environment, their independent effects, and some combinational effects on dielectrics resulting from simulation experiments will be discussed. Finally, results from actual space exposed materials will be presented.

The combined effects of vacuum, thermal heating, and radiation are expected to be the predominant cause of degradation for dielectrics in lunar applications. There is a significant amount of literature available on both the combined and independent effects of thermal heating, vacuum and radiation on insulators [37-45] Much of this research was done for the nuclear power industry and therefore reflects operation at atmospheric pressures; however, this information still gives valuable insight into the complexity of multiple stresses on solid dielectrics.

Examined independently, vacuum, thermal heating, and radiation all result in dielectric degradation which could result in dielectric failure. As the temperature increases most dielectrics experience an increase in electrical conductivity and a decrease in thermal conductivity [39]. In a transmission line this will result in a decrease in efficiency and an increased possibility of thermal breakdown in the dielectric. It has been proposed that the decrease in dielectric strength with increasing temperature is the result of a corresponding decrease in density. As the molecular structure of the dielectric loosens, small voids are created which may act as stress points for breakdown to originate, or at least increase the ability of the charge carriers to travel through the dielectric, thereby increasing the insulator's electrical conductivity [37].

Exposure to radiation can effect both the electrical, mechanical, and chemical properties of an insulator. The type and severity of damage for a given dosage is dependent on the chemical structure of the material, and as a result, varies for different classes of insulators. A summary of typical radiation effects in solids is given in Table 6 [34]. Table 7 lists common insulating materials according to their resistance to radiation [34]. A common effect of radiation on a solid dielectric coaxial cable is the inducement of a current due to kinetically moved charge and a conductivity [42,44]. For some materials, such as polymers, this effect on the electrical properties is minimal, and it is the mechanical properties that suffer the most damage [40]. All damage is, of course, a function of the level and energy of the radiation to which the material is exposed.

Evaporation and outgassing are the two processes of concern when referring to the effect a vacuum has on dielectrics. Evaporation of the dielectric material itself can occur when the vapor pressure or temperature of the material is too high [34]. The resulting loss in mass could degrade the properties of the material, contaminate the local environment, and generally decrease the reliability of the power system. Outgassing or, the evolution of atomic or molecular species from material surfaces, of gases that were entrapped during manufacturing processes, or adsorbed while exposed to the atmosphere will have similar effects on the insulation and on the transmission line's reliability. However, because the outgassing rate will continue to decline with increased exposure to the vacuum environment there will be some set time after which the effects of outgassing will be negligible. The time required will depend upon the amount of gasses adsorbed in the material, and the amount of material that is exposed to the vacuum.

Mechanical	Electronic	Chemical
Crystal structure	Optical absorption	Diffusion
Density	Photoconductivity	Ionic conductivity
Hardness	Dielectric loss	Reactivity
Thermal conductivity	Electrical conductivity	Stability
Tensile strength	Resonant frequency	
Fatigue strength	Damping factor (Q^{-1})	
Ductility	Opacity	
Viscosity	Flashover field	
Microcracking	Thermal conductivity	
	Dielectric strength	

Table 6. Typical radiation effects in solids

Material	Approximate Damage Dose Rads (Si)	Material Sensitivity
Photographic film	1	Most sensitive to radiation damage
Biological organisms	10^2	
Semiconductor devices (ionization effects)	10^3	
Optical material devices	10^4	
Gyro-fluids		
Fluorocarbon(Teflon, in air)	$2 \times 10^4 - 10^5$	
Lubricants (organic)	10^7	
Fluorocarbon (Teflon, in vacuum)		
Semiconductor devices (bulk)		
Elastomers, polyurethane		
Pyrotechnics	10^7	
Polyamide (Nylon)		
Polyethylene	10^8	
Polyester (Mylar)		
Magnetic materials		
Epoxies, silicones	10^9	
Phenolics, polyimides		
Fiberglass-epoxy circuit boards		
Carbon and alloy steels		
Polystyrene, polymide		
Ceramics	10^{11}	Least sensitive to radiation damage
Aluminum alloys		
Stainless Steel		

Table 7. General sensitivity of materials to radiation

In actual practice a dielectric will be exposed to more than one component of the space environment at a time,i.e., the radiation, thermal, and vacuum stresses will all occur simultaneously. The general multistress response is an overall enhancement in the degrading effects. However, simply linearly combining the previously discussed effects of thermal heating, radiation, and vacuum, is not accurate because of the synergistic qualities of these stress stimuli [34]. As an example of the complexity of examining these factors together, it has been shown that, for polymeric insulators, the combination of radiation and thermal heating not only increases the induced conductivity in the dielectric (as opposed to the conductivity induced if the dielectric were exposed to only one of these stimuli), but also that the order of applying the stimuli is critical to the degree of damage [38]. The experiments show that a higher conductivity and increased damage to mechanical properties are evident in dielectrics irradiated before thermal stressing than in dielectrics irradiated after thermal stressing. On the other hand, the combination of radiation and vacuum appears, at least in some aspects, to be beneficial [43]. Because of the additional charge generated by air ionization in the voids that occur between the insulation and the conductors,the induced charge in coaxial cables irradiated in a vacuum is less than in cables irradiated in air. These findings support the conclusion that in order to provide reliable information, experiments detailing the exact nature of the lunar environment must be performed. In summary, apparently no work has been done to study the combined effects of all of the important environmental stresses that will be found on the lunar surface.

In addition to insulation covering or separating adjacent conductors, other forms of insulation may be necessary. If vacuum-insulated, suspended transmission lines are selected they will require solid dielectric insulation from the supporting structure (assuming that the supporting structures are metallic). These insulators vary in size and shape according to the desired line configuration and the operating voltage of the line. They are typically made from porcelain, glass, or fiberglass. At the voltages under consideration internal support insulator breakdown is unlikely. In vacuum, however, surface flashover is more likely than in atmospheric applications on the earth. Thus, support insulators for bare conductors will have to be designed to minimize the possibilities of surface flashover. Important criteria include insulator material, triple points, polarity, insulator angle, and conductor material.

Transmission lines distributed on or below the surface may need to be shielded to provide protection, but the soil itself may serve as an adequate electrical insulator. While the range of resistivities defining an electrical insulator depends on the application and applied voltage, it is typically between 10^6 and 10^{20} ohm-cm [30]. The resistivity of lunar rock varies from 10^6 to 10^{10} ohm-cm depending on temperature [46]. Most likely the resistivity of the lunar soil will be similar. Also, most materials that exhibit low thermal conductivity also have low electrical conductivity (high electrical resistivity). Therefore, it is very likely that the lunar soil can be used as an electrical insulator.

(c) Vacuum

Vacuum is used as high voltage insulation for many earth applications, such as in x-ray tubes, electron microscopes, power vacuum switches, and particle accelerators [47-49]. Compared to dielectric materials vacuum has a very high breakdown strength. A 1 cm plane parallel gap has a breakdown strength of about 100 kV, and only a few cm are needed to hold off 1 MV. A combination of vacuum and magnetic insulation is used in particle accelerators to hold off several MV over a few centimeters.

Breakdown mechanisms in a small vacuum gap (less than a few mm) are dominated by electrode processes, such as field emission from minute electrode projections and electron emission enhancement from electrode contaminants [50]. Breakdown mechanisms in larger vacuum gaps (greater than a few mm) are strongly influenced by any inter-electrode contamination, including particulate and gaseous contaminants. Other parameters that influence vacuum breakdown include electrode separation, polarity, temperature, material, and surface preparation; and, externally applied radiation.

Vacuum could be a convenient, reliable, and low cost form of electrical insulation in the space environment. It takes only a few mm of spacing between conductors to provide 10 kV or more of insulation. However, the use of vacuum insulation in earth applications almost invariably occurs in a clean, controlled, well characterized vacuum environment. In the space environment there are several stresses that might influence a vacuum insulated region and lead to electrical breakdown. These stresses of importance include electrode and inter-electrode contamination, (including gaseous and particulate matter), electrode temperatures, incident radiation, impact by high velocity microparticles, space plasma, and magnetic fields.

If there should be a significant increase in the pressure near the conductors of a vacuum-insulated transmission line low pressure gas breakdown can occur [51]. Gas contamination might be due to an external source or might come from the electrodes or adjacent solid dielectrics. If vacuum insulation is used, contamination sources (material outgassing or effluents from spacecraft and manufacturing operations) must be characterized and controlled.

Particulate contamination could influence a vacuum insulated region in three possible methods [52, 53]. Particulate contamination on electrode surfaces can significantly alter the electron emission characteristics of the electrodes. Small particles in the high field region of a vacuum gap can be accelerated to sufficient velocities to impact an electrode liberating charge carriers. And finally, larger contaminate particles can become polarized and join together to form long semiconducting chains reducing the electrode spacing. It will be very important to characterize and understand the influence of natural and manmade contaminant particles. On the lunar surface the fine dust present in the upper layers of soil could pose a problem for vacuum insulated transmission lines.

Vacuum breakdown potentials are influenced by the electrode temperatures [54-56]. It will be important to take the temperature extremes of the space environment into account for any space application of vacuum insulation.

Also, vacuum surface flashover across dielectric surfaces can significantly lower the operating potential of a vacuum insulated system . All electrodes in a vacuum insulated system must somewhere be supported by solid dielectric insulators. If there is a high field stress across these solid dielectric components vacuum surface flashover must be considered. Important parameters for surface flashover include the dielectric material, its temperature, and condition; gas absorbed and adsorbed by and onto the solid dielectric; the electrode geometry near the solid dielectric; and, incident radiation.

D. Primary Transmission Line Parameters

The parameters that have the greatest effect on the mass and volume of a transmission line are its operating voltage and temperature. For a given power and efficiency increasing the voltage correspondingly decreases the current, thereby, decreasing the required size of the conductors and decreasing the mass of the transmission line. The decrease in the size of the conductor will increase the resistance of the line, but since the current decreased the resistive power per unit length is the same (assuming a fixed value of efficiency). A conductor with a smaller radius will have a lower surface area to volume ratio. Since the dissipation of the resistive power will mostly occur by radiation the smaller, higher voltage lines will run hotter. There will be limitations on the maximum operating voltage of the line set by the power conversion methods, the transmission line insulation methods, and possibly even safety issues. The size of the wire should not be decreased to the point of mechanical failure, and neither should the temperature rise above the material recommended operating temperature.

Raising the operating temperature of the line, just as in increasing the voltage, decreases the cost by decreasing the required mass. However, increasing the temperature typically results in a lower operating life, and a decrease in efficiency. Until materials that can operate at high temperatures with minimal negative effects are developed, the preferred method of decreasing the mass is by raising the operating voltage.

The only other method of decreasing the mass of the line is by selecting materials with low densities. Rather than placing a great amount of importance on the material's density, we will stress the fact that the mass can be optimized through proper voltage and temperature settings.

E. Power Conversion

Power conversion is an integral component of the transmission distribution system. Converters will provide the proper voltage for distribution from the power source and will convert the transmission distribution power to the desired voltage required at the load. The power sources currently being considered for the lunar base all have output voltages less than 200 volts [57-59]. For efficient transmission, it will be necessary to step up the voltage before distribution and step it back down once is has reached its destination. Otherwise the size of the conductor required to transmit the power at such low voltages will be prohibitively massive. The photovoltaic arrays, and SP-100 thermoelectric generator are both dc sources, while the Stirling engine is an ac energy conversion device. The loads can be either dc or ac and will probably be a mixture of both. As a result, dc/dc, ac/dc, and dc/ac converters will be needed. Important design factors for these devices are high efficiency, low mass and volume, constant output voltage and frequency (dc/ac), low EMI, and simple circuitry [59-60]. Figure 4 illustrates a typical power conversion scheme.

Bottrill and Tanju [59] investigated a number of power conversion techniques for use in the space environment. Their findings showed that using present technology there are methods of power conversion techniques that satisfy the requirements for advanced high power space applications. Table 8 was constructed using their findings.

The devices discussed above are proof that the main limitation to dc transmission (the difficulty in stepping up voltage) no longer exists. And while the cost is greater than the ac transformer's cost, the potential savings due to the decreased mass of the transmission line make it an attractive option. In addition, as dc converters become more established their design and manufacturing costs will drop. The effects of the power conversion methods on mass, etc., are not included in this current report, but will be discussed in a later report.

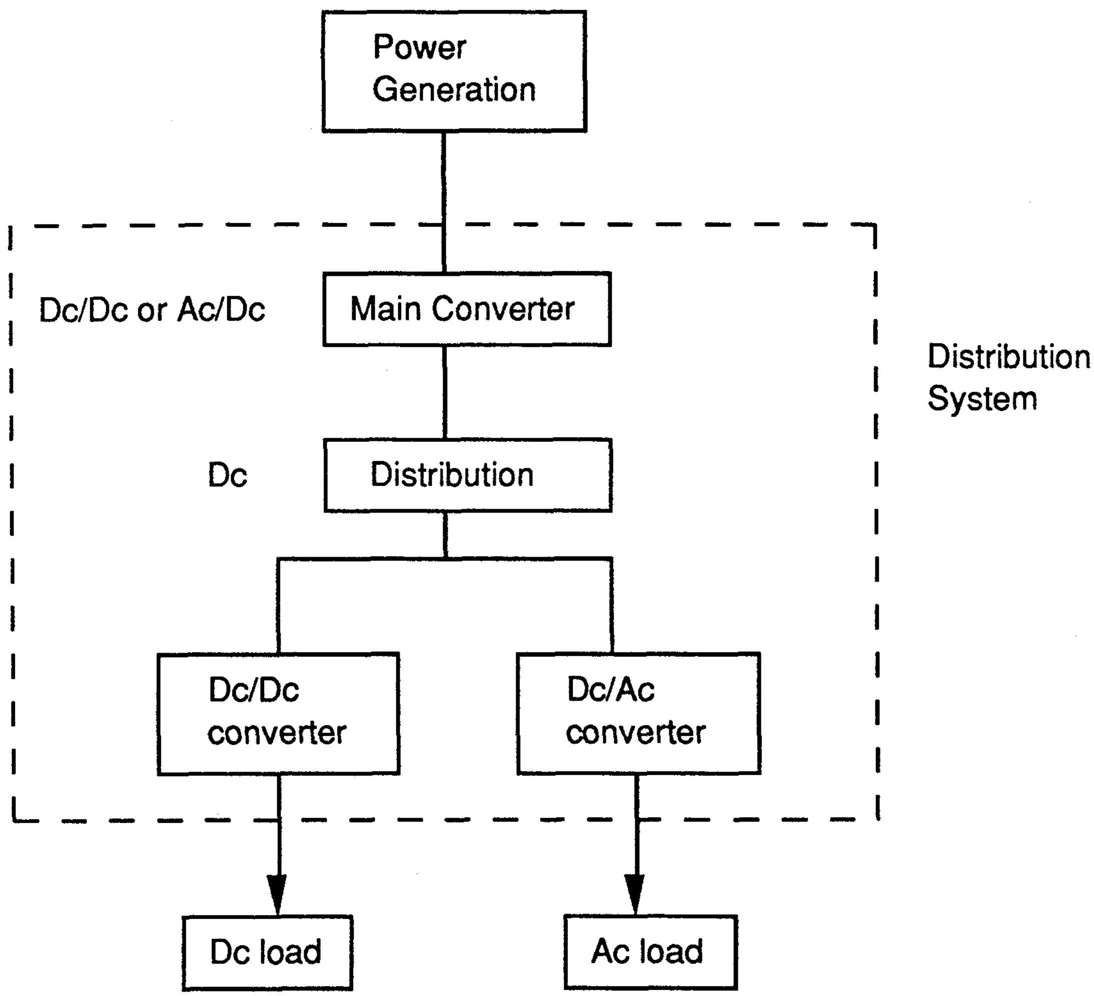


Fig. 4. Power system diagram showing conversion stages for a dc distribution system.

CONVERSION	RECOMMENDED TECHNIQUE	COMMENTS
dc/ac	pulse width modulated MOS controlled thyristor resonant inverter	recommended over phase shift control in high power or high frequency applications
dc/dc	resonant mode bridge; 3 types: series, parallel, series-parallel	the series resonant converter has the best operating characteristics except for low voltage, high current outputs where the series-parallel converter is preferred
ac/dc	conventional approaches link ac/dc converters switched mode rectifier controlled rectifier new class of ac/dc converters type 1 type 2	the new class of ac/dc converter was developed to meet the design factors of space power conversion systems; the type 2 new class converter is best suited for high power ratings

Table 8. Power conversion methods [59].

F. Deployment Geometry

In the design of the lunar transmission line it is important to consider the geometry of the conductors and insulators, and their placement (referred to as location). The general characteristics and merits of the several geometries and line locations will be considered here.

There are a number of possible geometries or transmission line types that could be considered. Complex lines might consist of cable bundles, multiple coax, multilayer parallel plates, etc. The analysis of these lines would be unnecessarily complex. The most simple and distinct geometries were chosen for analysis, since many of the more complex geometries are combinations of the simple ones. Study of the simplest geometries will provide the needed insight into mass, radius, and temperature variations with line voltage. The simplest three transmission line geometries include:

- two-wire parallel transmission line
- two-cylinder, concentric, coaxial transmission line (the inner conductor solid or hollow)
- two parallel plate transmission line

For dc study two transmission line types will be evaluated: the two-wire transmission line and the coaxial transmission line. The two-wire transmission line is the simplest in construction, transportation and deployment, but has the disadvantage of external electric fields. This would increase safety hazards and the possibility of interaction of the electric fields with the space environment might lead to electric breakdown. The two wire transmission line is similar to high voltage overhead transmission lines in earth transmission systems, or low voltage distribution in buildings and houses. The coaxial transmission line is more complex. Its advantages, however, include some shielding of the insulator from space radiation, and the containment of the electric fields. Thus, the coaxial cable is safer (assuming there is such a thing as a system ground on the outer conductor), and the external fields will not interact with the environment.

As discussed in the dielectric section two options will be considered for insulation, vacuum and solid. (Liquid and gaseous dielectrics are not considered because of mass and containment considerations.) Most likely a two-wire transmission line would use vacuum insulation and a coaxial transmission line would use vacuum insulation or solid dielectrics. Vacuum insulation is attractive because of its low mass and high breakdown strength. Its electric breakdown strength is a function of the distance separating the transmission lines and contamination of the vacuum environment. Unless the conductors are widely spaced and laying on the surface or below the surface some form of support insulators will be needed (concentric spacers for the coaxial line). Solid dielectrics are considered for use with the coaxial transmission line.

There are three possible transmission line deployment configurations (or locations) with respect to the lunar surface: (1) above the surface, (2) on the surface, or (3) below the surface. The above-the-surface method requires that the transmission line conductors be suspended on some sort of support structures such as poles. This geometry will have the best thermal characteristics because the entire conductor is exposed and can radiate waste heat. The distance from the lunar surface to the line should be large enough to allow free thermal radiation, and to allow vehicular or personnel travel safely beneath them. However, it should be noted that there may be some difficulty repairing the lines in "space suits" so the support poles should be designed with this in mind. The supporting poles are additional masses not required for on-the-surface or below-the-surface distribution and their masses are not taken into account in this initial report. Below-the-surface deployment is the safest and most convenient, but the poor thermal conductivity of the soil will probably limit subsurface transmission as an option for high power transmission lines [58]. If the lines are laying on the surface insulating "clamps" may be needed to prevent the movement of the lines due to Lorentz forces between them, or the lines will need to be placed far enough apart such that the forces are not strong enough to move them. Care will also need to be taken to prevent damage to the lines by vehicles and to prevent injury to astronauts. Perhaps the ideal deployment would be a combination of on-the-surface and below-the-surface. The cables could be covered in areas where there is a large amount of traffic or activity, and exposed in other areas to allow for radiative cooling. The analysis section only considers the above surface and below surface options. From these results the usefulness of the other methods can be estimated. A summary of the methods of deployment are shown in Table 9.
Figure 5 shows a two-wire transmission line for the three deployment configurations, and Fig. 6 shows a similar coaxial transmission line for the three deployment configurations. The important dimensions of the cross section of each geometry are shown in the suspended case. The only parameters with respect to the lunar surface are the thermal characteristics of the soil (temperature, thermal conductivity, etc.) and the depth of the below-the-surface case.

Method Of Deployment	Advantages	Disadvantages
Suspended	best thermal characteristics	requires towers or poles; requires additional insulation for supports
Below surface	minimizes hazard and inconvenience of lines	difficult to cool; additional work to bury; difficult to repair
On surface	easy deployment	Lorentz forces; limits mobility; in the way

Table 9. Methods of lunar transmission line deployment.

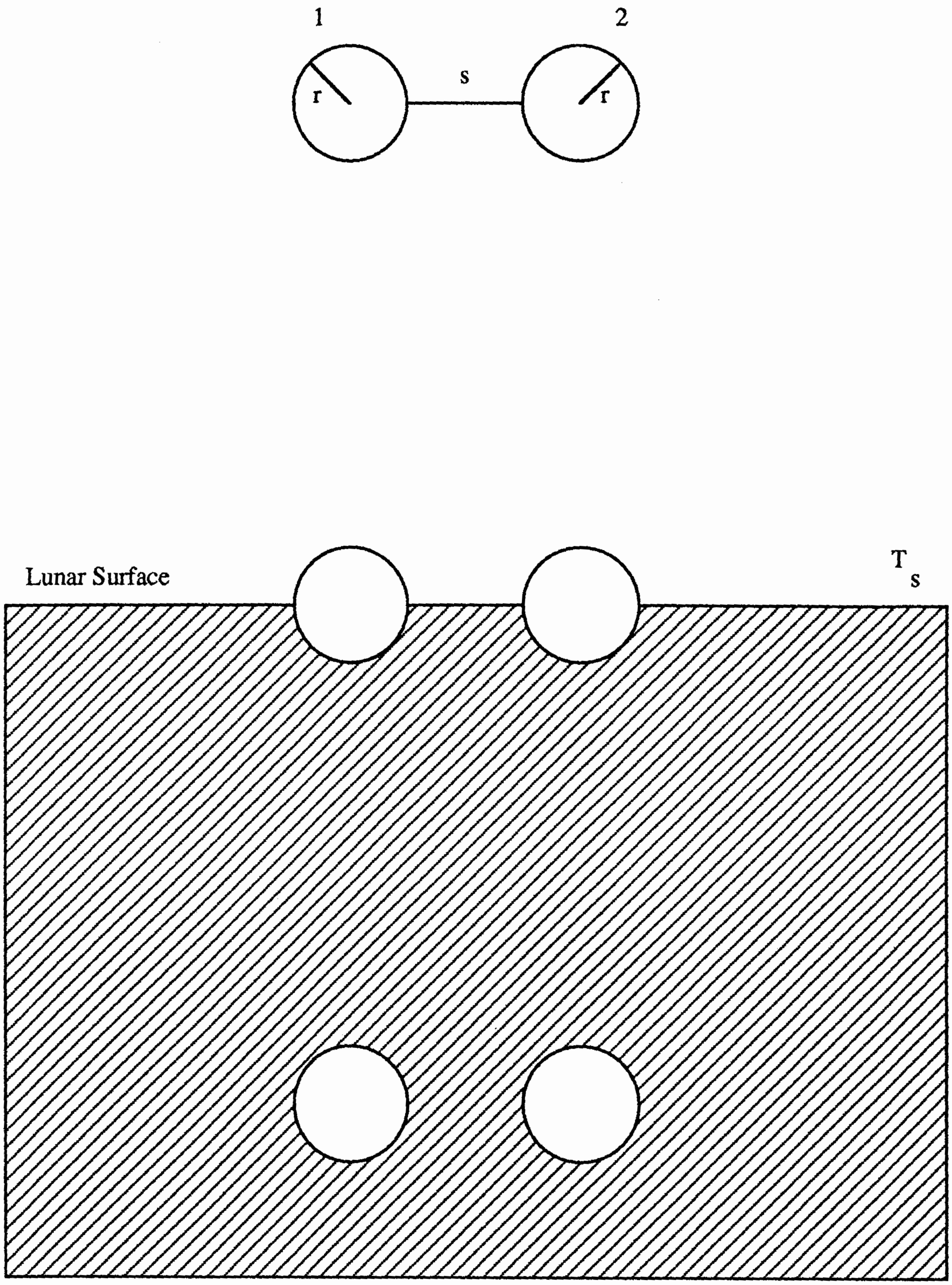


Fig. 5. Two wire transmission line above, on, and below the surface.

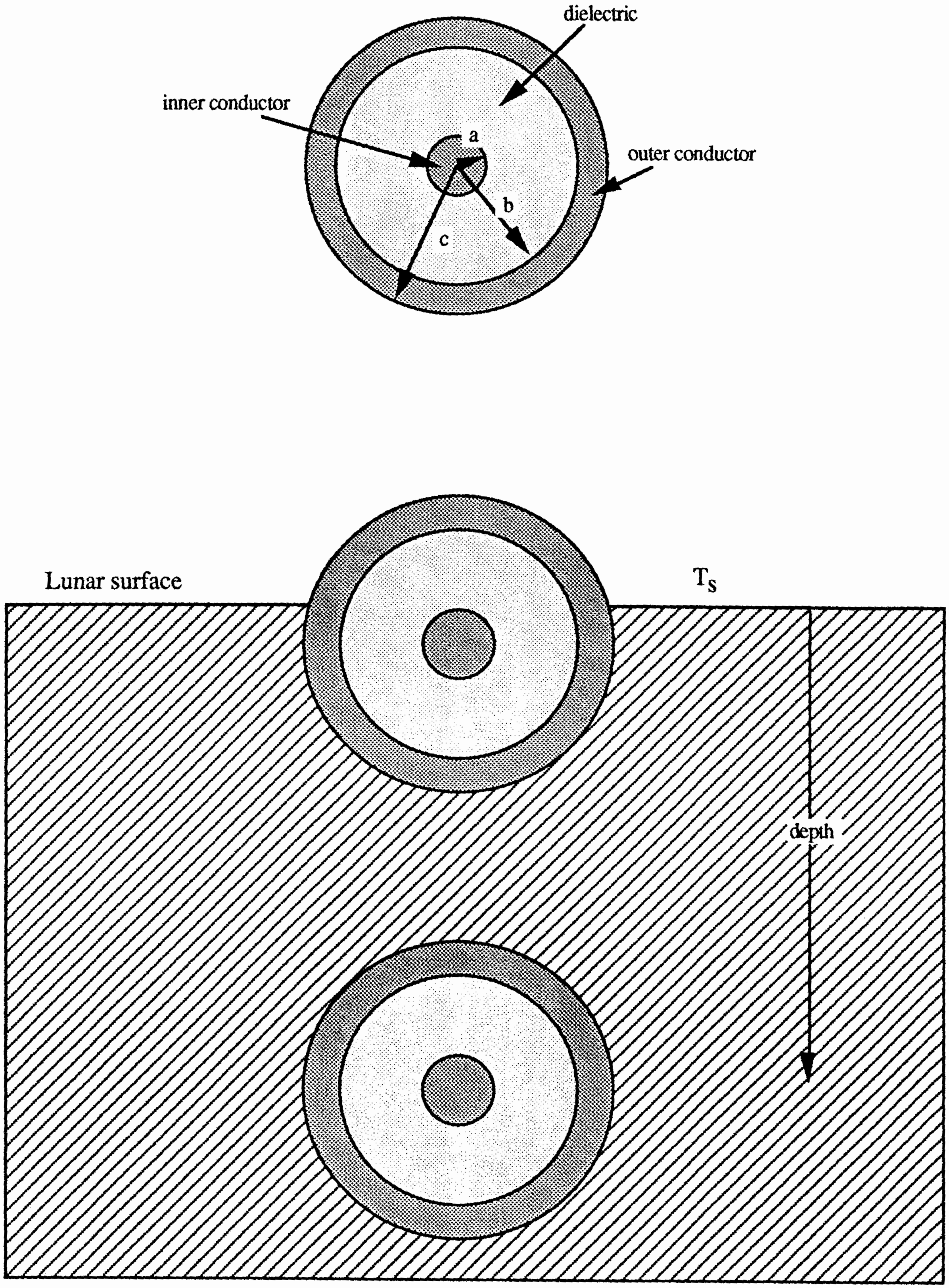


Fig. 6. Coaxial transmission line above, on, and below the surface.

VI. ANALYSIS TECHNIQUES

In this section the methods of analysis are presented. Since there are some fundamental differences between the four design cases studied, analysis methods are discussed for each case. Assumptions and approximations are given. All calculations are done in the standard SI system of units. The units used are listed in the list of symbols on page 10.

A. Vacuum-Insulated, Two-wire, Suspended Transmission Line

Expressions for a vacuum-insulated, two-wire, suspended dc transmission line operating in the lunar environment are developed for the wire radius, mass, and operating temperature in terms of the line voltage, source power, length, and percent power loss.

In the analysis of the power transfer on a transmission line the following approach is used. The resistance of a circular cross-section wire with radius r and length L is given by

$$R = \frac{\rho L}{\pi r^2} \qquad \Omega \tag{1}$$

The power lost in a length L of a transmission line (composed of two wires each of length L) is

$$P_{TL} = 2\, I^2 R = \frac{2 P_S^2 R}{V^2} \qquad W \tag{2}$$

where P_S is the power output of the source, V is the transmission voltage at the source end, and I is the current that results from the input of the source power into the transmission line at the source line voltage V.

Combining (1) and (2)

$$P_{TL} = \frac{2 P_S^2 \rho L}{V^2 r^2 \pi} \qquad W \tag{3}$$

The percentage of power lost in the transmission line is

$$P_{lost} = \left(\frac{P_{TL}}{P_S}\right) \times 100 \qquad \% \tag{4}$$

and the efficiency of the line is given by

$$\eta = \left(\frac{P_S - P_{TL}}{P_S}\right) \times 100 \qquad \% \tag{5}$$

The above order of analysis (given the voltage and resistance find the current, power, and efficiency) is typical of the analysis of power calculations for a transmission line given the physical line characteristics (such as conductor material and radius). For the lunar transmission line problem presented here, however, we need to solve in the reverse order, as you would in designing a transmission line based on desired specifications. In other words, given the power input, line voltage, and desired efficiency, what is the power loss, line resistance, and resultant radius of the wire to provide this power loss and efficiency. In this case we have a fixed value for the power output of the source, P_S from the PV/RF or the SP-100. Given the input power and efficiency (or power loss) as fixed design parameters, the voltage is taken as a variable design parameter. For each voltage studied the current to be driven down the line is found by

$$I = \frac{P_s}{V} \qquad A \tag{6}$$

If a certain minimum efficiency η is desired (in this study 5 % is used) then the maximum power loss, P_{TL}, is also determined

$$P_{TL} = P_S\left(1 - \frac{\eta}{100}\right) \qquad W \tag{7}$$

The radius of the one wire of the transmission line is then found by first solving for the resistance

$$R = \frac{1}{2}\frac{P_{TL}}{I^2} \qquad \Omega \tag{8}$$

Then using Eq. (1)

$$r = \sqrt{\frac{\rho L}{\pi R}} \qquad m \tag{9}$$

Using (9) the mass of one wire is easily found

$$m = \pi r^2 \nu L \qquad kg \tag{10}$$

where ν is the mass density of the conductor material.

Finding the operating temperature of the line requires a thermal analysis of the conductors. Because of the poor thermal conductivity of the lunar soil, (see section II.F. Lunar Soil) the surface of the moon was approximated as a reradiating surface. Therefore, it was possible to assume zero net radiation transfer between the transmission lines and the lunar surface.

When calculating the heat transfer from two adjacent bodies it is important to include a configuration factor. The configuration factor is basically the influence that each wire has on the other wire as far as its ability to radiate heat. Obviously the closer the wires the less heat can effectively radiate away from each wire, because essentially they are absorbing some of each others heat. The configuration factor for a two-wire transmission line [61] as shown in Fig. 7 (two parallel cylindrical conductors) is

$$F_{1,2} = \frac{1}{2\pi}\left[\pi + \sqrt{\frac{s}{r}\left(4 + \frac{s}{r}\right)} - \left(2 + \frac{s}{r}\right) - 2\cos^{-1}\left(\frac{2}{2 + \frac{s}{r}}\right)\right] \tag{11}$$

where s is the distance between the surface of the two conductors 1 and 2, each with a radius of r. This configuration factor $F_{1,2}$ x 100 gives the percentage of energy radiated by wire 1 that is intercepted by wire 2.

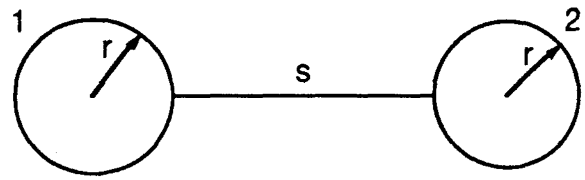


Fig. 7. Two-wire transmission line.

The worst case would be for zero separation distance between the two cables (s/r = 0). The value of $F_{1,2}$ for this case is .182, or 18.2 % of the energy from wire 1 is intercepted by wire 2. Thus, 81.8 % of the energy from a wire in a two wire transmission line radiates out into space compared to 100 % for a single wire radiator; therefore, the corresponding configuration factor to space for a wire is .818. In the analysis a s/r ratio of 1 was arbitrarily used, resulting in a view factor of .89 (89 % of the waste heat from the transmission line will radiate into space). A plot of the configuration factor for values of s/r varying from 0 to 5 is shown in Fig. 8.

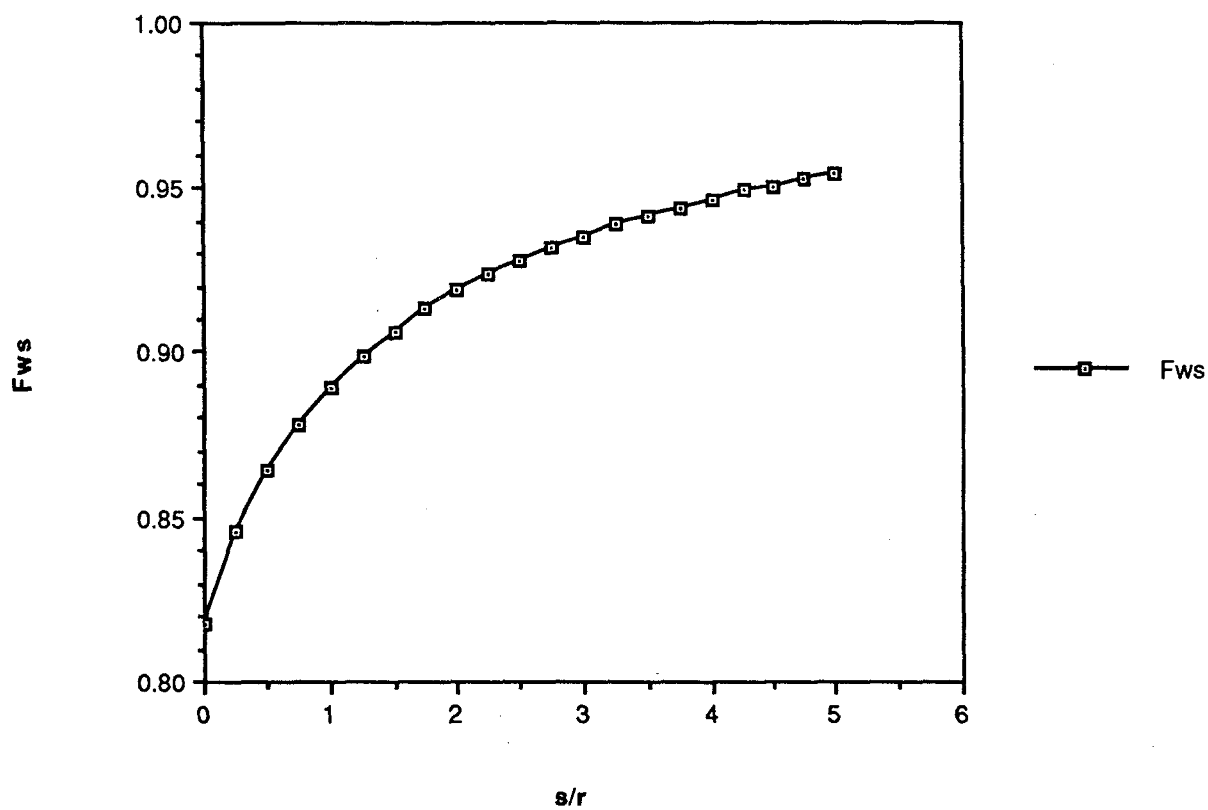


Fig. 8. Configuration factor for a two-wire transmission line.

The only significant power losses for a vacuum-insulated dc line are resistive losses. The only method of dissipating this waste energy in a vacuum is through radiation. Half of the cable will be radiating to space (0 K), and the other half will radiate to the lunar surface which varies from 100 K to 380 K over the lunar day.

In addition to the heat input from the resistive losses in the wire there is also the energy flux from the sun that impinges upon the wire. This solar energy absorbed is obviously zero at night when the wire receives no flux from the sun, but in the lunar day it is significant. In the earth/lunar orbit the solar constant, or the energy flux from the sun is 1371 ± 5 W m^{-2}. Figure 9 illustrates the solar radiation incident upon a wire. This occurs anytime during the day, when the sun is above the horizon. On the earth the intensity of the solar radiation at the surface is a strong function of the time of day and thus position of the sun in the sky because of the effects of the atmosphere. On the lunar surface, however, the lack of an atmosphere allows the same solar flux to be incident upon the wire throughout the complete day, even though it comes from a different angle. From Fig. 9 the width of the wire that intersects the solar flux is 2r = d, the diameter. Thus, for a single wire of length L the total power intercepted is given by 2rL x 1372 W. The reflectance coefficient for aluminum is about 0.9, or the absorptivity coefficient is about 0.1. Thus, only 10 % of the energy incident upon an aluminum cable will be absorbed. The solar power incident upon the wire is then

$$q_s = 0.1 \times 2rL \times 1372 = 274.4\, r\, L \quad \text{W} \qquad (12)$$

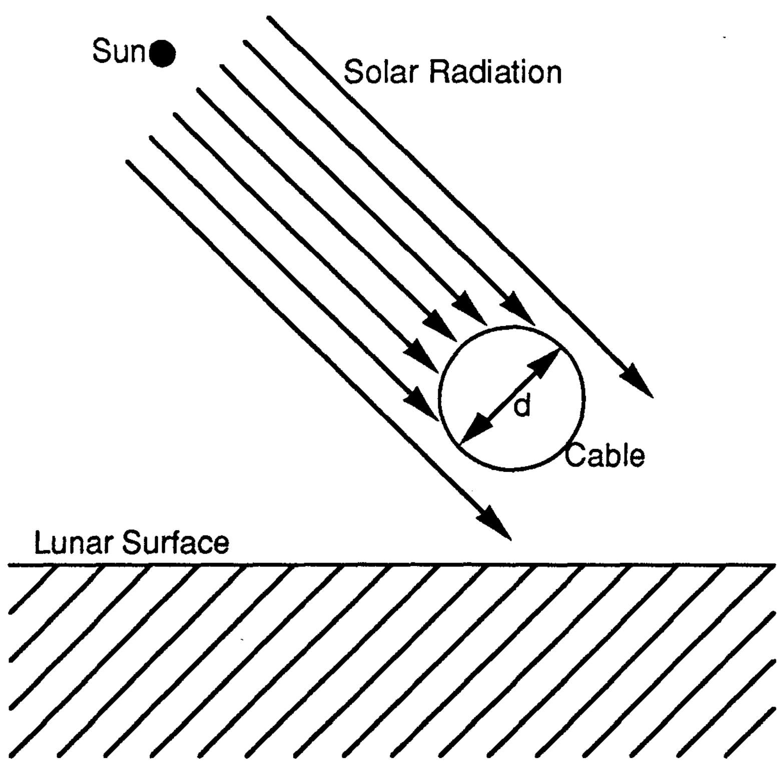


Fig. 9. Solar radiation incident upon a wire.

In equilibrium the total power in the wire, the sum of the resistive power (q_I) and the absorbed solar power (q_s), must be dissipated by radiation (q_R). Thus,

$$q_I + q_s = q_R \qquad W \qquad (13)$$

The problem of the radiation of a wire on the lunar surface can be treated by considering the wire as a small object radiating to a distance large object at a fixed temperature. If the wire at a temperature T^4 is completely surrounded by such an object at a temperature T, then the power radiating from the wire is given by

$$q_R = \sigma \varepsilon A(T_w^4 - T^4) \qquad W \qquad (14)$$

However, as illustrated in Fig. 10 the upper half of the wire radiates to a large distant object (deep space) which is at the temperature $T_0 = 0$ K, and the lower half of the wire radiates to another large object (the lunar surface) which is at T_{sur}. When the sum of the two radiating terms are added together, and the configuration factor is added to account for the nearby presence of the other wire, the
heat transfer rate q is given by Eq. 15.

$$q = I^2 R + 274.4 rL = \sigma \varepsilon F_{ws} \frac{A}{2}\left[\left(T_w^4 - T_o^4\right) + \left(T_w^4 - T_{sur}^4\right)\right] \qquad (15)$$

where

	$T_0 = 0$ K	is the temperature away from the moon,
	T_{sur}	is the temperature of the lunar surface,
	T_w	is the temperature of the wire,
	σ	is the Stefan-Boltzman constant,
	ε	is the emissivity of the wire surface,
	A	is the surface area of the wire, and
	F_{ws}	is the configuration factor due to the other wire

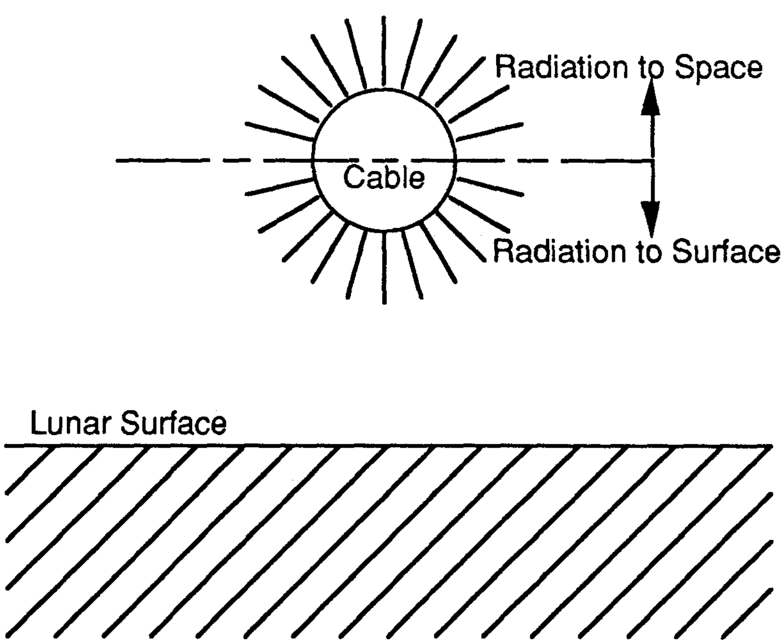


Fig. 10. Radiation of a wire to space and to the lunar surface.

For space away from the lunar surface $T_0 = 0$ K and the emissivity (ε) was arbitrarily chosen to be 0.9 for typical metallic materials. (The emissivity will vary according to the conductor material and the operating temperature, but these variations should be small.)

Substituting for $A = 2\pi rL$, and collecting the r terms

$$I^2R = \sigma\varepsilon F_{ws} 2\pi rL\left[T_w{}^4 - \frac{1}{2}T_{sur}{}^4\right] - 274.4rL \tag{16}$$

Now solving for the radius of the wire

$$r = \frac{I^2 R}{\sigma\varepsilon 2\pi L F_{ws}\left(T_w{}^4 - \frac{1}{2}T_{sur}{}^4\right) - 274.4L} \quad \text{m} \tag{17}$$

From Eq. (2) and (3) we get

$$I^2R = \frac{P_s{}^2 \rho L}{V^2 r^2 \pi} \quad \text{W} \tag{18}$$

Substituting Eq. (18) into Eq. (17) we can solve for r in terms of material parameters, P_S, V, and the wire temperature

$$r = \left(\frac{P_s{}^2 \rho}{2V^2\pi^2\sigma\varepsilon F_{ws}\left(T_w{}^4 - \frac{1}{2}T_{sur}{}^4\right) - 274.4\pi V^2}\right)^{\frac{1}{3}} \quad \text{m} \tag{19}$$

Now to simplify the expression let

$$x = \frac{1}{2\pi^2\sigma\varepsilon F_{ws}\left(T_w{}^4 - \frac{1}{2}T_{sur}{}^4\right) - 274.4\pi} \tag{20}$$

so that

$$r = \left(\frac{P_s{}^2 \rho x}{V^2}\right)^{\frac{1}{3}} \tag{21}$$

Eq. 21 and Eq. 3 can be used to find a new expression for the power losses.

$$P_{TL} = \frac{L}{\pi}\left(\frac{P_s{}^2 \rho}{V^2 x^2}\right)^{\frac{1}{3}} \tag{22}$$

or Eq. 21 and Eq. 4 give

$$P_{lost} = \frac{100L}{\pi}\left(\frac{\rho}{P_s V^2 x^2}\right)^{\frac{1}{3}} \quad \% \tag{23}$$

Solving this expression for x and then using Eq. 20, T_W can be found.

$$T_w = \left[\frac{\left(\frac{\pi P_{lost}}{100L}\right)^{\frac{3}{2}}\left(\frac{P_s V^2}{\rho}\right)^{\frac{1}{2}} + \frac{1}{2}\left(2\pi^2\sigma\varepsilon F_{ws} T_{sur}^{\ 4}\right) + 274.4\pi}{2\pi^2\sigma\varepsilon F_{ws}}\right]^{\frac{1}{4}} \quad K \tag{24}$$

In the above expression the resistivity (ρ) of the conductor material is given by Eq. 25 below. The resistivity is a function of the temperature of the material and a new value must be found for each temperature value. The relationship of resistivity to temperature is approximately linear over the range experienced by the wire, although it becomes somewhat inaccurate at the higher wire temperatures.

So, approximately

$$\rho_c = \rho_1\left[\frac{T_c + T_o}{T_1 + T_o}\right] \tag{25}$$

where ρ_c is the resistivity of the material @ T_c
T_c is the new wire temperature
T_o = - 45 K for Al
T_o = - 32 K for Cu
T_1 = 293 K
$\rho_1 = 2.38 \times 10^{-8}$ Ωm for Al @ T = 293 K
$\rho_1 = 1.77 \times 10^{-8}$ Ωm for Cu @ T = 293

The value of T_C was updated each iteration to approximate the increase in resistivity which will occur because of the increasing voltage's effect on the temperature. Increasing the voltage decreases the transmission line current since the input power is fixed. In order to maintain the same efficiency it is necessary to decrease the radius of the wire. As the radius of the wire decreases for an increasing voltage the mass of the transmission line goes down. However, since there is less wire surface area with which to radiate away heat, the temperature of the line will also increase.

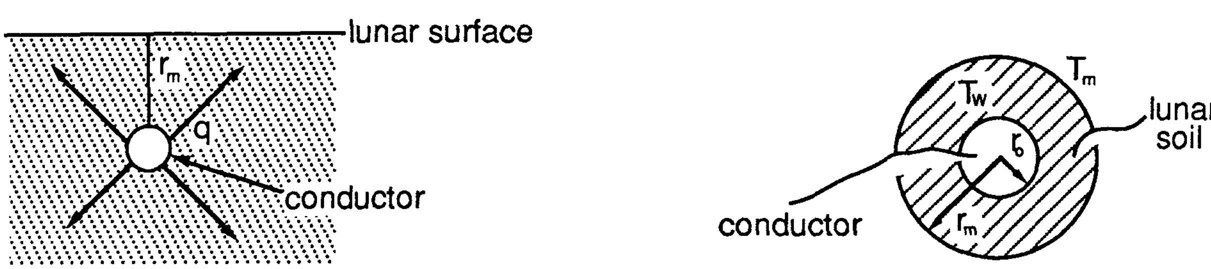
B. Vacuum-Insulated, Two-Wire, Buried Transmission Lines

Expressions for a vacuum-insulated, two-wire, buried transmission line operating below the lunar surface are again used to obtain the wire radius, mass, and operating temperature as functions of the operating voltage, source power, line length, depth in the soil, and percent power loss.

The same equations used to find the wire radius and mass for the suspended case apply for the buried case. As in the suspended case the resistivity was iteratively updated to improve it's accuracy as the temperature of the line increases with increasing depth and voltage. However, a new equation had to be developed for the operating temperature of the line, since heat flow must now occur by conduction through the lunar soil instead of by radiation.

While the surface temperature of the moon varies by 280 K over the lunar day the low thermal conductivity of the regolith keeps the temperature below the lunar surface rather constant. In the experiments performed by Apollo 15 [46] it was found that at a depth of half a meter there was less than 10 K temperature change.

Because of these findings, and in order to simplify the calculation of the temperature of the conductor it was assumed that instead of the wire being some depth below a planar surface (see Fig. 11a) that the wire was surrounded by some thickness of soil (see Fig. 11b) where the temperature of the outside is an approximate average of the sum of all the temperatures found along that radius. This is reasonably accurate if the cable is not too close to the surface.



(a) Cable beneath surface

(b) Cable with shell of lunar soil

Fig. 11. Thermal flow modeling for underground cable.

This average temperature will change according to depth and time of day. (During the day the average temperature will be higher, and during the night the average temperature will be lower.) However, as discussed earlier, this change will be minimal, and since the analysis was performed for depths of 1 meter and less (it was considered that burying the cable at a depth over 1 meter would be too costly and difficult) a T_{AV} = 250 K was assumed for all cases.

As previously mentioned the thermal conductivity of the lunar soil is low. The Apollo 15 experiments found varying values at different locations depths [23]. Using this information a value of k=.008 W/m-K was selected for use in all cases as an approximation. (The thermal conductivity was found to be as high as .017 W/m-K at a depth of a meter in some locations, but because the previous approximation made in finding T_{AV} will result in cooler temperatures a lower thermal conductivity was selected to counterbalance this effect). Using this approximation q was found using thermal resistance theory.

The thermal resistance seen by the wire is given by Eq. 26, where r_m is the depth of the wire, and is measured from the center of the wire to the lunar surface, r_0 is the radius of the wire, L is the length of the transmission line, and k_m is the thermal conductivity of the lunar soil.

$$R_t = \frac{\ln\left(\frac{r_m}{r_o}\right)}{2\pi k_m L} \qquad (26)$$

The heat transfer rate is then given by

$$q = \frac{T_w - T_m}{R_t} = \frac{T_w - T_m}{\ln\left(\frac{r_m}{r_o}\right)}(2\pi k_m L) \qquad (27)$$

where T_m is the average temperature of the soil and T_w is the operating temperature of the wire. There is now no longer a heat input component from incident solar flux, so the only heat input is from resistive heating, thus $q = I^2R$ and

$$T_w = \frac{I^2 R \ln\left(\frac{r_m}{r_o}\right)}{2\pi k_m L} + T_m \quad \text{K} \qquad (28)$$

C. Solid-dielectric Insulated, Coaxial, Suspended Transmission Line

A solid-dielectric insulated, coaxial, suspended transmission line is composed of an inner, cylindrical wire, an insulating dielectric layer, and an outer conducting layer, which is the return path for the transmission line. The radius of the inner conductor is determined exactly as it was for the two-wire transmission line. For a given conductor material the size of the inner conductor is determined by the voltage, the power to be transmitted, and by the desired efficiency of the line.

The thickness of the dielectric will be determined by the rated breakdown strength of the dielectric material chosen, and by the desired "safety factor" for the insulation. For example, if a specific dielectric is rated at 10 kV/mil then on the average a 10 mil thick piece of the dielectric will fail at 10 kV. Obviously one can not operate at the rated breakdown voltage so an operating voltage is chosen that is considerably less. An example is the wiring found in the walls of a home to supply electricity to the outlets and the lights. Typically the insulation is rated at 600 V breakdown strength, but it is operated at 110 V. Typically a dielectric might be operated at a voltage 0.1 to 0.2 of its breakdown strength. Thus, the dielectric with a breakdown strength of 10 kV/mil should be operated at a voltage of 1 to 2 kV/mil.

Because of the severity of the multistress environment on the moon, any dielectric chosen should be conservatively underrated. The degree of underrating will be a complex function of the type of dielectric, its partial discharge inception level, how it degrades in the lunar environment, the desired reliability and safety factor, and the value of the voltage. Any design will have to be thoroughly tested and evaluated under simulated lunar conditions before use.

For this analysis a voltage operating value of 0.1 of the rated breakdown strength was chosen. Thus,

$$E_o = 0.1 \times E_b \qquad (29)$$

where E_o is the operating field strength of the dielectric and E_b is the breakdown field strength of the dielectric. The required thickness of dielectric is then given by

$$t = \frac{V_t}{E_o} \qquad (30)$$

where t is the dielectric thickness and V_t is the operating voltage of the transmission line.

Once the radius (a) of the inner conductor and the thickness (t) of the dielectric are known , the inner (b) and outer (c) radii of the outer conductor can be determined by Eq. 31 and 32.

$$b = t + a \qquad (31)$$

$$c = \sqrt{a^2 + b^2} \qquad (32)$$

A cross section of a coaxial cable showing the dimensions is shown in Fig. 5.

For dc the total required conductor mass for a given set of operating parameters will be the same for the coaxial transmission geometry as for two-wire transmission. Therefore, the overall mass will increase for coaxial cables due to the addition of the dielectric material.

For the total transmission line (inner conductor, outer conductor, and dielectric) the mass is given by

$$m_T = m_C + m_D = L\pi v_c (a^2 + (c^2 - b^2)) + L\pi v_d (b^2 - a^2) \qquad (33)$$

where m_T , m_C , and m_D are the total mass, the mass of the two conductors, and the mass of the dielectric; and, ν_c and ν_d are the mass densities of the conductor and dielectric materials, respectively, and L is the length of the line.

The thermal analyses of the coaxial cable is solved using thermal resistance theory. First the sources of heat and the heat paths will be discussed.

The are three sources of heat energy input into the coaxial cable:

q_{I1} = the heat generated due to the resistive loss in the inner conductor,
q_{I2} = the heat generated due to the resistive loss in the outer conductor, and
q_s = the heat due to the absorption of solar energy.

For the suspended coaxial cable the sum of these three heats must be radiated into space.

$$q_R = q_{I1} + q_{I2} + q_s \qquad (34)$$

Both q_{I2} and q_s are generated in the outer conductor and can be radiated directly into space similar to the heat in the single conductor of the two-wire transmission line. On the other hand, q_{I1} is generated in the core of the cable and must pass through the dielectric layer and the outer conductor to be radiated into space. In equilibrium there is only one direction for heat energy to flow. All heat must flow outward to the outer surface and be radiated into space. Figure 12 shows these four heats and the various temperatures used in the thermal analysis for the coaxial cable.

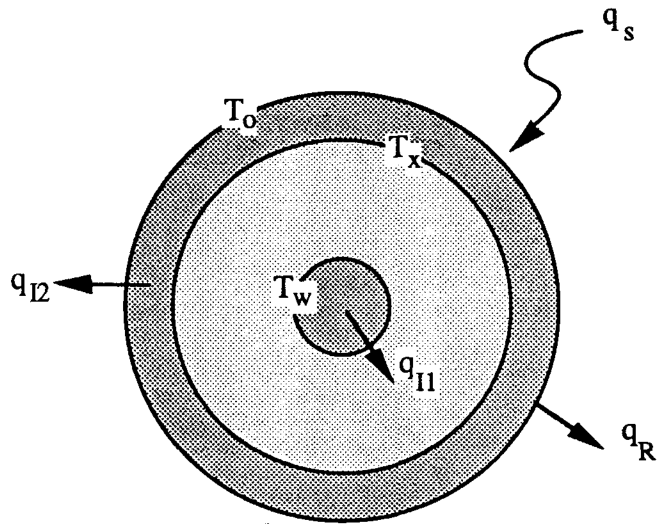


Fig. 12. Cross section showing temperatures and heat flows.

The temperature to be found ,T_W, is the temperature between the dielectric and the inner conductor. T_X is the temperature between the outer conductor and the dielectric. T_W was chosen as the limiting temperature because of the restriction of a lower operating temperature on the dielectric, and because T_W will be greater than T_X .

First, the heat transfer rate q_{I2} for the outer conductor is found as a function of the transmission line's radius. Next, the temperature of the outer conductor is found as a function of the radiation characteristics of the cable and the temperature of the environment. These two equations are then solved simultaneously to find T_X. Then T_W is found as a function of the conduction characteristics of the dielectric.

To find q_{I2} it must be recognized that the heat transfer rate within an electrical conductor is not a constant, but is dependent on the depth into the conductor. For example, referring to Fig. 6, at radius r = b, the resistive losses for the outer conductor are at a minimum, and at r = c, the resistive losses are at a maximum. Because the heat transfer rate is not constant, the thermal resistance concepts, and related heat rate equations, previously used can not be used to find q_{I2} (this is only true if we want find q_{I2} as a function of T_X and T_O). Instead, the heat equation for cylindrical coordinates is used to find T as a function of r, and then Fourier's Law is applied to find q_{I2} as a function of r [62].

The heat equation for cylindrical coordinates is given by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(k_c r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k_c\frac{\partial T}{\partial \phi}\right)+\frac{\partial}{\partial z}\left(k_c\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c_p\frac{\partial T}{\partial t} \tag{35}$$

Assuming 1 dimensional in the radial direction, steady state, with uniform heat generation in the cylinder (35) reduces to

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)+\frac{\dot{q}}{k_c}=0 \tag{36}$$

where

kc = thermal conductivity of the conductor and

$\dot{q}$ = the volumetric generation rate of one conductor is given by

$$\dot{q}=\frac{I^2R}{2V}=\frac{I^2R}{2\pi r^2L} \qquad \frac{W}{m^3} \tag{37}$$

By integrating twice with respect to r, T(r) is found as a function of two integration constants C_1, and C_2.

$$T(r)=\frac{-\dot{q}r^2}{4k_c}+C_1\ln r+C_2 \tag{38}$$

To find C_1 and C_2 we introduce the following boundary conditions.

$$T(b)=T_X \qquad \text{and } T(c)=T_O$$

Applying these conditions to (38) we obtain

$$T_x=\frac{-\dot{q}b^2}{4k_c}+C_1\ln b+C_2 \tag{39}$$

and

$$T_o=\frac{-\dot{q}c^2}{4k_c}+C_1\ln c+C_2 \tag{40}$$

Solving for C_1 and C_2 and substituting back into (37), we get the following

$$T(r) = \frac{\dot{q}}{4k_c}\left(b^2 - r^2\right) + \left[T_o - T_x + \frac{\dot{q}}{4k_c}(c^2 - b^2)\right]\left[\frac{\ln r - \ln b}{\ln c - \ln b}\right] + T_x \qquad (41)$$

By applying Fourier's law, (the rate equation for heat conduction),

$$q_r = -k_c(2\pi rL)\frac{dT}{dr} \qquad (42)$$

we can find an expression for the heat transfer rate as a function of r.

$$q(r) = -k_c(2\pi rL)\left[\frac{-\dot{q}r}{2k_c} + \frac{1}{r\ln\frac{c}{b}}\left(T_o - T_x + \frac{\dot{q}(c^2 - b^2)}{4k_c}\right)\right] \qquad (43)$$

If we evaluate q(r) at r = c this will give q_{I2} which is also equal to 1/2 the thermal loss of the line.

$$q(c) = q_{I2} = -2\pi k_c cL\left[\frac{-\dot{q}c}{2k_c} + \frac{1}{c\ln\frac{c}{b}}\left(T_o - T_x + \frac{\dot{q}(c^2 - b^2)}{4k_c}\right)\right] = \frac{1}{2}I^2R \qquad (44)$$

Solving for T_X gives

$$T_x = \left(\frac{I^2R}{4\pi k_c cL} - \frac{\dot{q}c}{2k_c}\right)c\ln\frac{c}{b} + \frac{\dot{q}(c^2 - b^2)}{4k_c} + T_o \qquad (45)$$

Now the temperature of the outer conductor can be found as a function of the radiation characteristics of the cable and the temperature of the environment:

The heat flow equation from the outer conductor to space is

$$q_R = q_{I1} + q_{I2} + q_s = \frac{T_0 - T_{sur}}{R_{rad}} = I^2R + .2srL \qquad (46)$$

Note that we are using thermal resistance theory again, we are able to do so because over the temperature change T_O to T_{sur} the heat transfer rate is a constant.

In Fig. 12 the thermal resistance of radiation is given by R_{trad}. Similar to before T_w and T_o are the temperatures of the inner conductor and the outer surface, respectively, and T_X is the temperature at the interface of the dielectric and the outer conductor.

$$R_{trad} = \frac{1}{\sigma A\left(T_o^2 + T_{sur}^2\right)(T_o + T_{sur})} \quad \text{for the case of the coaxial} \qquad (47)$$

Using (46) and (47) to solve for T_O we get

$$T_o = \left[\frac{I^2R + 54.9Lc}{2\pi\sigma cL} + T_{sur}^4\right]^{\frac{1}{4}} \qquad (48)$$

in order to account for half the cable radiating to space (0K) and half radiating to the lunar surface Tsur should be set to half temperature of the lunar surface.

T_x can now be found from (45) by substituting (48) in for T_o

Now that we have T_x we can find T_w by using resistive theory techniques at the boundaries of the dielectric.

q_{I1} is given below

$$q_{I1} = \frac{T_w - T_x}{R_d} \qquad (49)$$

where

$$R_d = \frac{\ln\frac{b}{a}}{2\pi k_d L} \qquad (50)$$

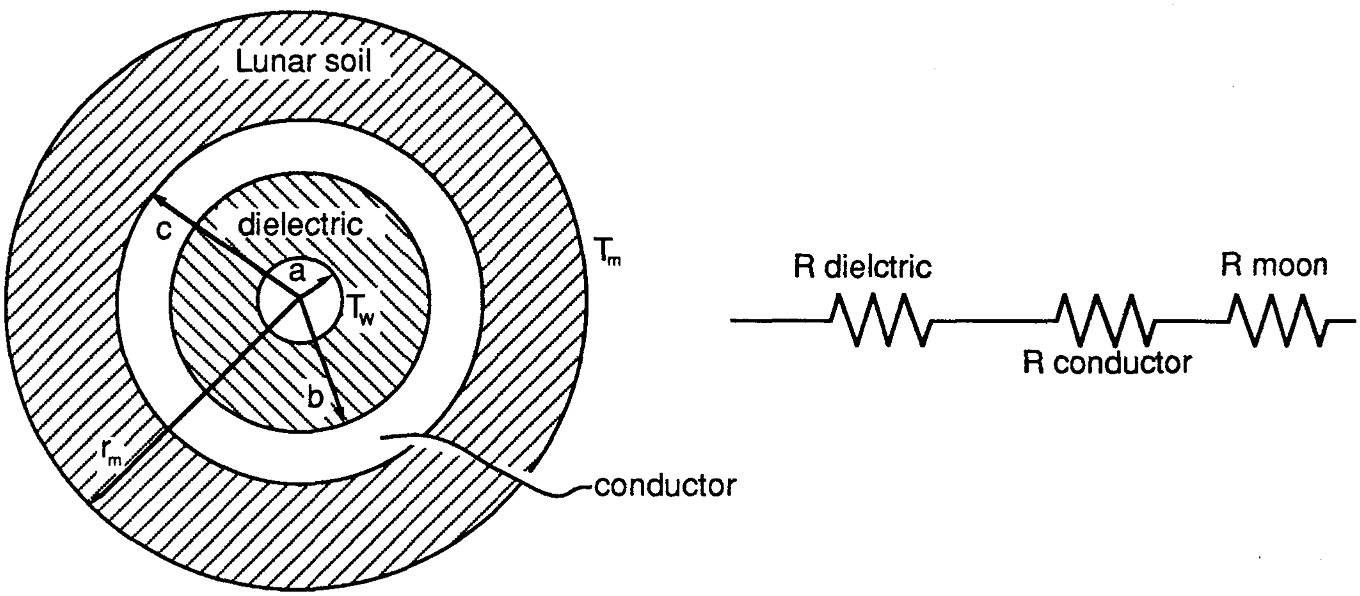
and k_d = thermal conductivity of the dielectric.

T_w is then

$$T_w = \frac{1}{2} I^2R \left(\frac{\ln\frac{b}{a}}{2\pi k_d L}\right) + T_x \qquad (51)$$

D. Solid-dielectric Insulated, Coaxial, Buried Transmission Line

The mass equation (Eq. 33) developed for case C (the coaxial suspended transmission line) is also valid for the coaxial buried case, and will therefore not be repeated in this section. In addition, the assumptions used in case B (the buried solid cylindrical transmission line) will also be applied to this case. Figure 13(a) shows a cross section of a coaxial transmission line beneath the lunar surface. In addition to the three components of the cable (inner conductor, dielectric, and outer conductor) a spherical shell of lunar soil of radius r_m is assumed. The equivalent thermal resistance circuit is shown in Fig. 13(b).



(a) Cross section of below-the-surface cable. (b) Thermal resistance circuit model.

Fig. 13. Below the surface thermal model for coaxial transmission line.

The development of the equation for T_W is very similar to that followed in section C. First, the heat transfer rate q_{I2} for the outer conductor is found as a function of the transmission line's radius. This relationship has not changed and is again represented by (44). Solving for T_X will give (45). Next, the temperature of the outer conductor is found, not as a function of the radiation characteristics of the cable and the temperature of the environment as in section C, but as a function of the conduction characteristics of the cable and the average temperature of the surrounding soil.

The equation for the heat flow from the outer conductor to the lunar soil is

$$q_R = q_{I1} + q_{I2} = \frac{T_0 - T_m}{R_m} = I^2R \qquad (52)$$

where R_m is the thermal resistivity of the lunar soil given by

$$R_m = \frac{\ln\frac{r_m}{c}}{2\pi k_m L} \tag{53}$$

and k_m is the thermal conductivity of the lunar soil.

From (52) T_o is then

$$T_o = I^2 R R_m + T_m \tag{54}$$

Substituting (54) in for T_o in equation (45) T_x is found. From T_x we can find T_w by following the same steps in section C. Refer to equations 49, 50, and 51.

VII. PARAMETER STUDIES

In order to examine the interaction of the many parameters of a lunar power transmission line the following study varies several parameters while holding others constant. As with any system study with many parameters the total number of combinations can be enormous, and it is impractical to cover all possible cases. Also, many would not be instructive, would be redundant, or would be impractical combinations. The following combinations of parameters were initially chosen to hopefully provide an optimum cross section for understanding the key lunar power transmission design issues. After the following parameter study was completed and as it continues to be analyzed it will become obvious that there are other combinations that should be tried, or there are better methods to display the data. The parameters and their possible states are:

Transmission line application-

The five possible transmission lines for the initial lunar base design discussed in section III are used. The different lines are defined by their power transmitted and their length. The 100 kW, 5 km and the *120 kW, 5 km* are very similar and give almost identical results. Thus, there are really four classes of transmission lines studied:

- *100 kW, 200 m* - a relatively low power, short line
- *100 kW, 5 km* - a low power, long line
- *200 kW, 1 km* - a medium power, medium length line
- *800 kW, 1 km* - a high power, medium length line

Geometry-

Two geometries were considered for this parameter study: the *two-wire* transmission line, and the *coaxial* transmission line. These are described in section V-F, Deployment Geometry, and are shown in Figs. 5 and 6.

Location-

Two possible locations are considered for each of the above two geometries: *above the lunar surface* - this would be similar to an earth transmission line, suspended some distance above the surface of the planet, and *below the surface* - or buried in the soil.

Conductor material-

Two conductor materials (*copper and aluminum*) are occasionally compared.

Insulation-

For this study the two-wire transmission line always uses vacuum (or the soil) as an insulation, and the coaxial transmission line uses a solid dielectric (in this case TFE).

Day/Night-

Most of the calculations are done for the *day*time conditions, since this represents the most stressful environment. A few calculations are done for *night* to point out some of the differences that the thermal environment can make.

Efficiency-

For most of the calculations the line efficiency is fixed at 95 %. This means that the line must transmit 95 % of its electrical energy and dissipate (in the form of heat) 5 % of its electrical energy. It turns out that forcing the efficiency, as a driving parameter, to be 5 % was not the optimum approach for some of the studies. This will be discussed further in the conclusions. A few studies vary the efficiency from 95 % to 99 % for comparison. They are useful for comparison.

Depth-

Most below ground studies are for 25 cm deep. A few plots vary the depth from 3 to 50 cm.

These parameters and their values are shown for the 28 cases studied in Table 10. Generally each parameter has 1 value, which is shown as the red square. In addition, a family of curves is usually generated by letting one of the parameters take on several values. In this case the values are shown in blue. At the lower portion of the table is listed the plots that are included for each case. The plots are presented in increasing order in this section starting on page 54. To find the page number of a specific case use the List of Data Plots found on page 7.

Table 10. Parameters for Case Studies

The red denotes the single value for the given parameter that applies to all curves on the plot.
The blue denotes the range of values for the given parameter that gives the multiple curves on the plots, i.e., the blue denotes the third variable on the family of curves of a plot.

blue ■ red ▨

Case #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Application	100 kW, 200m											blue	blue	blue	blue												blue						
	100 kW, 5 km	red	red	red	red	red	red	red	red			blue	blue	blue	blue	red	red	red	red					red		red	blue						
	120 kW, 5 km											blue	blue	blue	blue												blue						
	200 kW, 1 km											blue	blue	blue	blue												blue						
	800 kW, 1 km									red	red	blue	blue	blue	blue					red	red	red	red		red		blue						
Geometry	Two-wire	red	red	red				blue	blue	blue	blue	red	red			red	red			red	red			red	red	red	red	red					
	Coax				red	red	red	blue	blue	blue	blue			red	red			red	red			red	red						red				
Location	Above Surface	red		blue	red		blue	red		red		red		red		red		red		red		red		red	red	red	red						
	Below Surface		red	blue		red	blue		red		red		red		red		red		red		red		red					red	red				
Conductor Material	Al	blue	blue	red	blue	blue	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	red	blue	red	red	red				
	Cu	blue	blue		blue	blue																				blue							
Insulation	Vacuum	red	red	red				red	red	red	red	red	red			red	red			red	red			red	red	red	red	red					
	Solid (TFE)				red	red	red	red	red	red	red			red	red			red	red			red	red						red				
Day/Night	Day	red		red	red		red	red		red		red		red		red		red		red		red		blue	blue								
	Night																							blue	blue	red	red						
Efficiency	1 %															blue	blue	blue	blue	blue	blue	blue	blue										
	3 %															blue	blue	blue	blue	blue	blue	blue	blue										
	5 %	red	red	red	red	red	red	red	red	red	red	red	red	red	red	blue	blue	blue	blue	blue	blue	blue	blue	red	red	red	red	red	red				
Depth for Below Surface	3 cm																											blue	blue				
	25 cm		red	red		red	red		red		red		red		red		red		red		red		red					blue	blue				
	50 cm																											blue	blue				
	1 m																																
Plots included in this report	A - r vs V	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓				
	B - M vs V	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓						
	C - T vs V	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
	D - R vs V	✓	✓					✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓						
	E - m vs V	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓				
	F - %PL vs V																							✓	✓	✓	✓						

r = radius of a single wire of two-wire line, or radius of coaxial line
M = total mass of line
T = maximum temperature in the transmission line
R = resistance of one conductor of either line
m = specific mass (mass per unit length) of transmission line
%PL = percent power loss in the transmission line (i.e., compared to the power transmitted)
V = operating voltage of the transmission line

The following material constants were used in the calculations:

$\rho_{AL\ initial} = 2.83 \times 10^{-8}\ \Omega\text{-m}$	the initial (at 295 K) resistivity of aluminum
$\rho_{CU\ initial} = 1.77 \times 10^{-8}\ \Omega\text{-m}$	the initial (at 295 K) resistivity of copper
$\nu_{AL} = 2700\ \text{kg/m}^3$	density of aluminum
$\nu_{CU} = 8920\ \text{kg/m}^3$	density of copper
$\nu_{TFE} = 2175\ \text{kg/m}^3$	density of TFE (the solid dielectric in the coaxial line)
$F_{ws} = .89$	the view factor used for the two-wire above ground
$\varepsilon = 0.9$	emissivity of the conductors
$T_{sur\ day} = 380$ K	lunar surface temperature during the day
$T_{sur\ night} = 100$ K	lunar surface temperature during the night
$T_m = 250$ K	soil temperature below about 30 cm
$k_m = .008$ W/m-K	thermal conductivity of the lunar soil
$k_{al} = 237$ W/m-K	thermal conductivity of aluminum
$k_{cu} = 401$ W/m-K	thermal conductivity of copper
$k_{TFE} = .251$ W/m-K	thermal conductivity of TFE
$E_B = 430$ V/mil	dielectric breakdown strength of TFE

For a given transmission line the power level and efficiency are fixed. For various voltages the current that must flow in the line to transfer the power is determined. Knowing the current flow and the required power loss the line resistance is calculated, and the conductor radius necessary to give this resistance. Knowing the line geometry and the heat produced by the resistive losses the thermal model predicts the heat flow and the material temperatures. Since the material temperatures effect the conductivities the resistance calculation is redone to determine a more accurate resistance. This process is continued iteratively until the line temperature and resistance is accurately determined. The results are presented in six different plots:

Five different plots are used to display the interaction of the parameters:

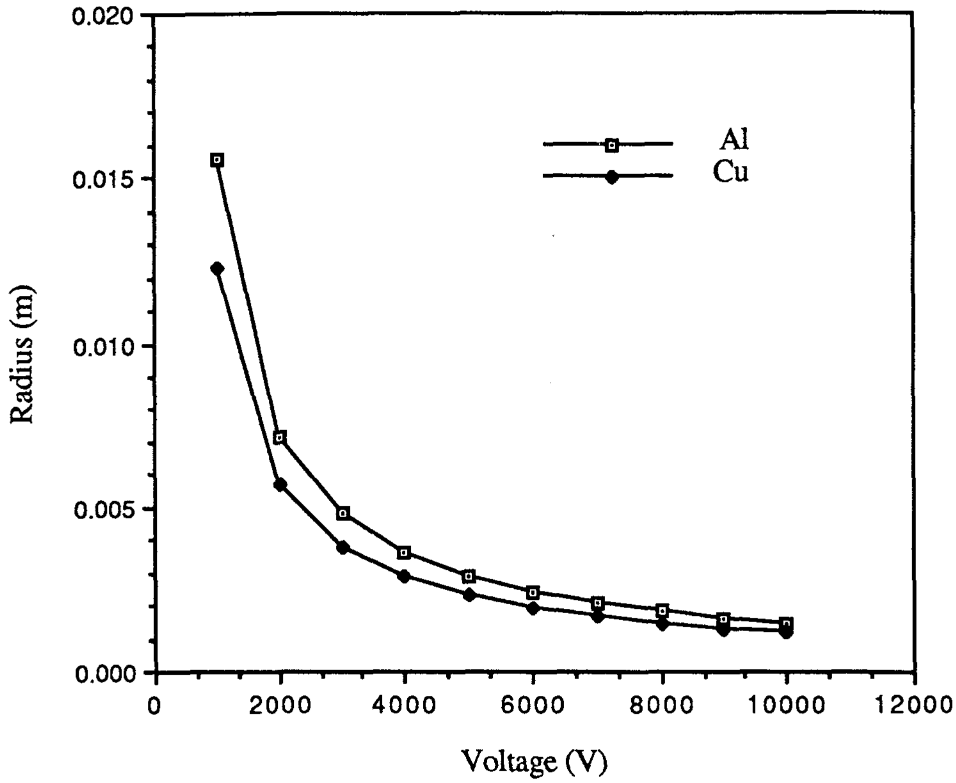
- line radius vs voltage
- total line mass vs voltage
- line temperature vs voltage
- conductor resistance vs voltage
- specific mass vs voltage
- % power loss vs voltage

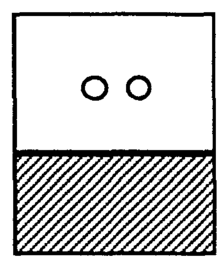
The voltage is varied between 1 and 10 kV in 1 kV increments, so that there are 10 data points for each plot. The points are connected together in a piece-wise approximation. Occasionally, when a parameter is changing rapidly the curve is not very smooth, but for most plots the 10 data points and the piece-wise connection results in smooth curves.

For the two-wire transmission line the radius, temperature, and resistance are found for one wire, while the total mass and specific mass are found for both wires of the transmission line.

For the coaxial transmission line, the resistance is found for one conductor while the radius, temperature, total mass and specific mass are found for both conductors and the dielectric. The radius of the inner conductor is equal to the radius of one wire of a 2-wire line under identical operating conditions. The dielectric for all coaxial cases was chosen to be TFE.

Case 1.A





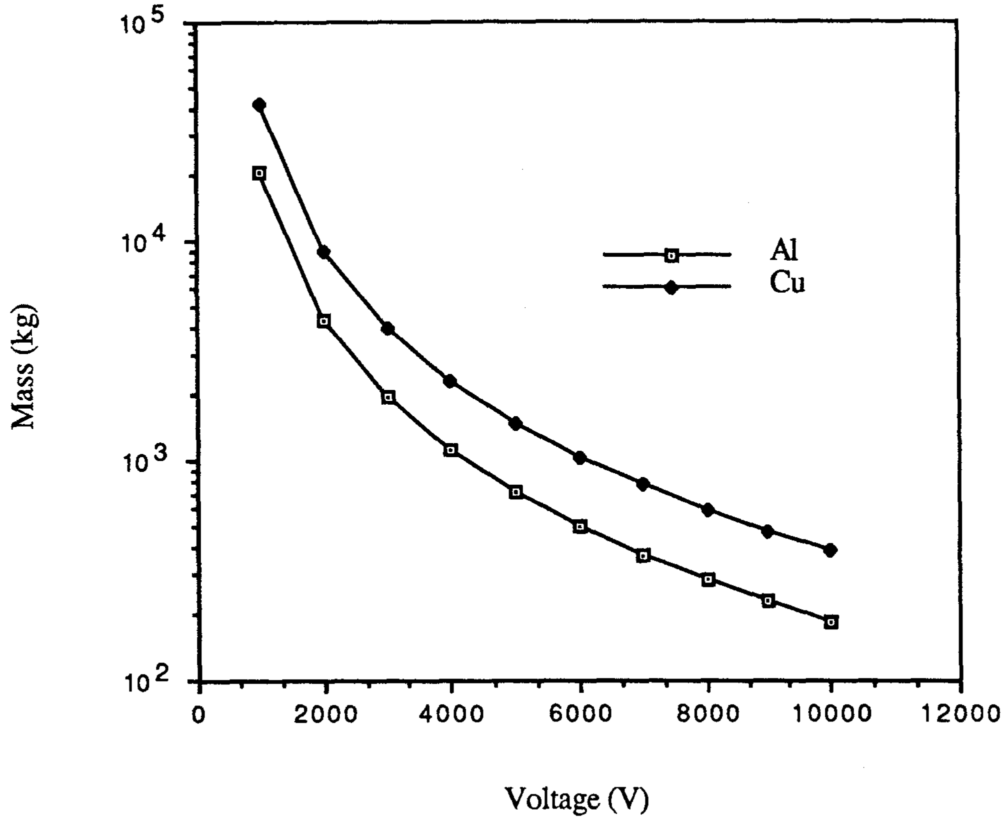
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

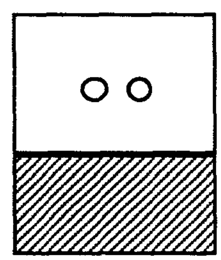
1) Copper transmission lines have a smaller radius than aluminum due to its higher conductivity.
2) For a constant power an increasing voltage results in a lower current and thus a smaller radius line can be used for the same power loss.
3) As the voltage increases above 8 to 10 kV the decrease in radius is not as great.

Case 1.B



Transmission Line Parameters

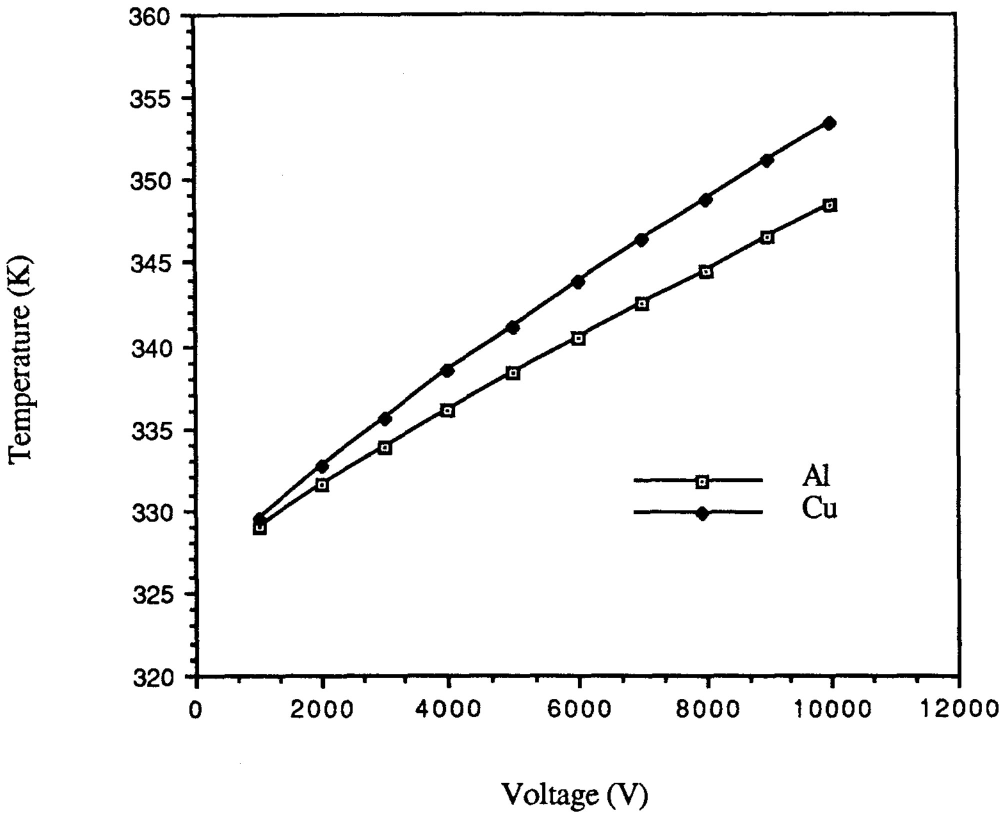
Application 100 kW, 5 km
Geometry two-wire
Location above
Conductor *aluminum, copper*
Insulator vacuum
Day/Night day
Power loss 5 %

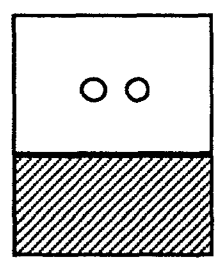


Comments

1) Aluminum lines are lighter than copper (even though thicker) due to its lower density.
2) Total mass of line decreases with increasing voltage due to decreasing radius (see Case 1.A).
3) Note the rapid decrease in total mass (log scale) with voltage.

Case 1.C





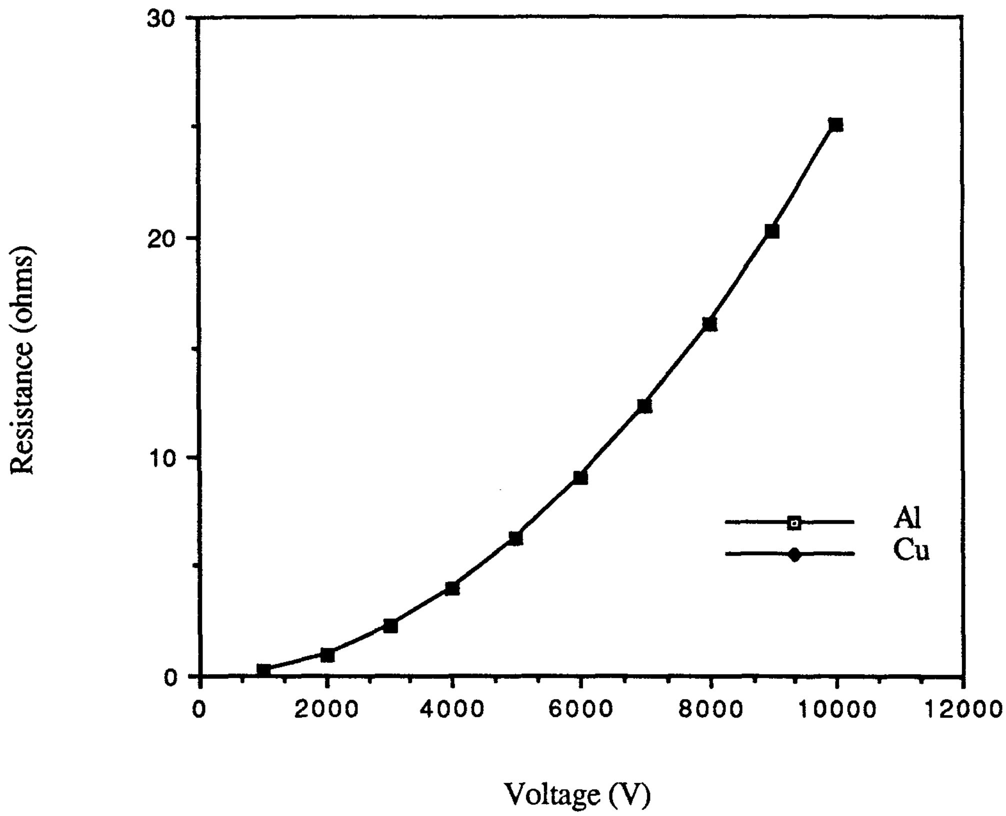
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

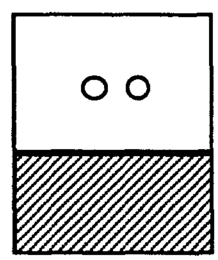
1) Copper lines run hotter because at the same power, voltage, and power loss the copper line is smaller in diameter, resulting in lower surface area to volume ratio for radiation (see Case 1.A).
2) The temperature increases with voltage (keeping a 5 % efficient line) because the surface area for radiation is decreasing and yet the energy dissipated is the same (i.e., 5 % of the total line power must still be dissipated, regardless of the voltage).

Case 1.D



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum, copper
Insulator	vacuum
Day/Night	day
Power loss	5 %

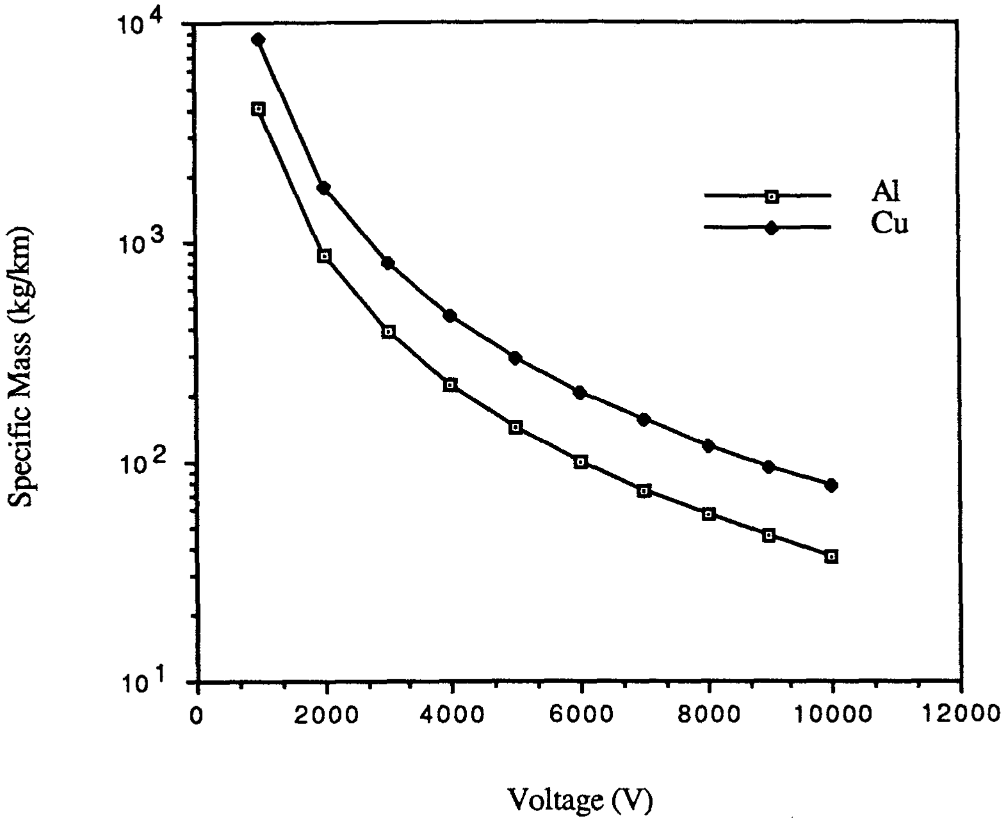


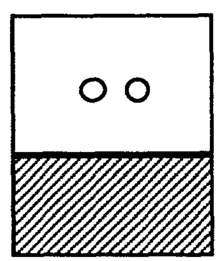
Comments

1) Copper and aluminum lines will have identical resistances because the assumed power and power loss determines the resistance for a given voltage regardless of the conductor material.

2) Resistance increases with increasing voltage, because the conductor radius is decreasing. The resistance increases inversely as the current decreases, keeping the resistive power loss at the constant 5 %.

Case 1.E





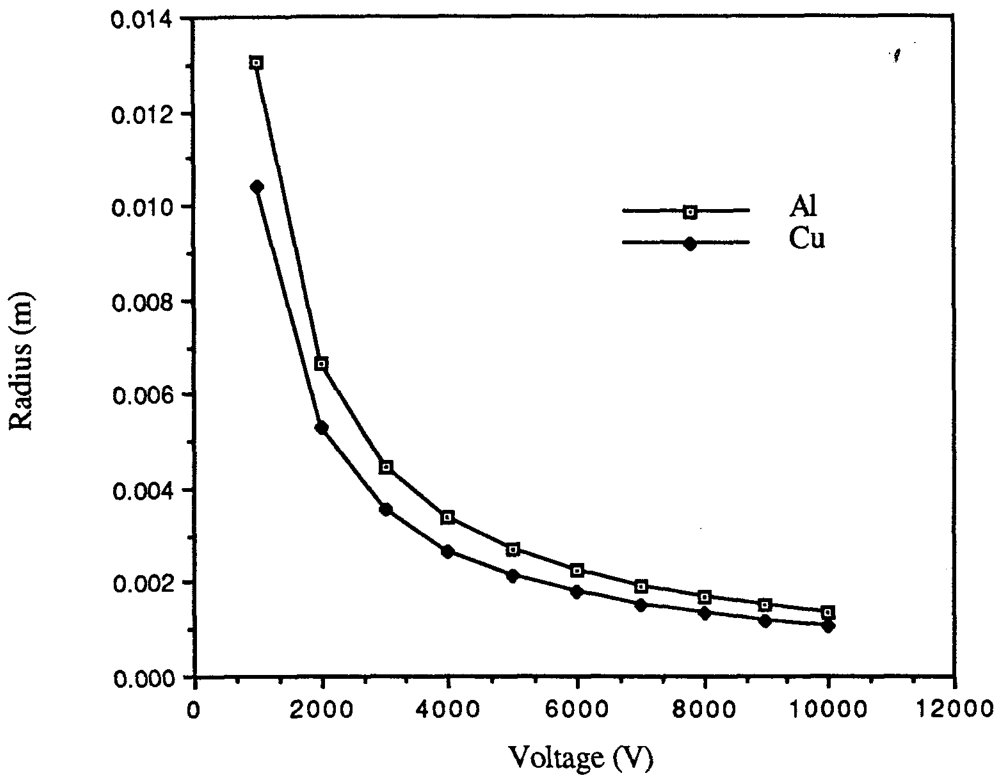
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

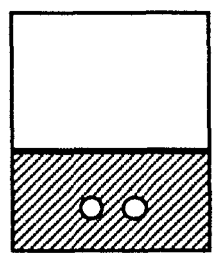
same comments as for 1.B

Case 2.A



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	below
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	
Power loss	5 %

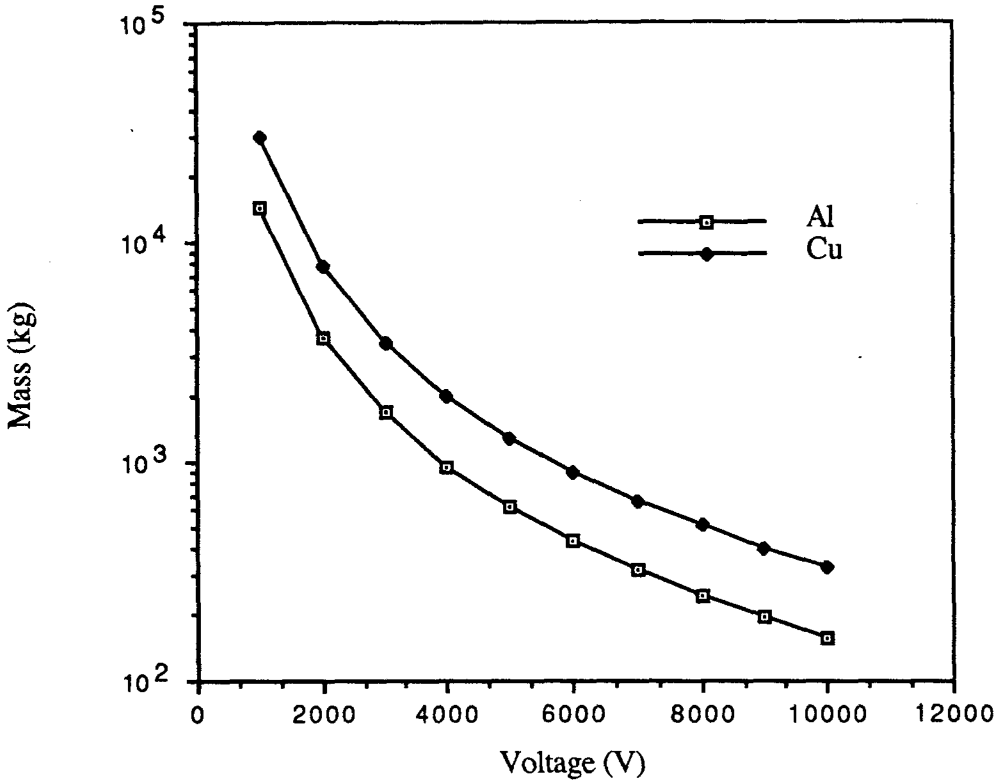


depth 25 cm

Comments

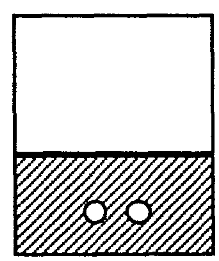
1) Copper transmission lines have a smaller radius than aluminum due to its higher conductivity.
2) For a constant power an increasing voltage results in a lower current and thus a smaller radius line can be used for the same power loss.
3) As the voltage increases above 8 to 10 kV the decrease in radius is not as great.

Case 2.B



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	below
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	
Power loss	5 %

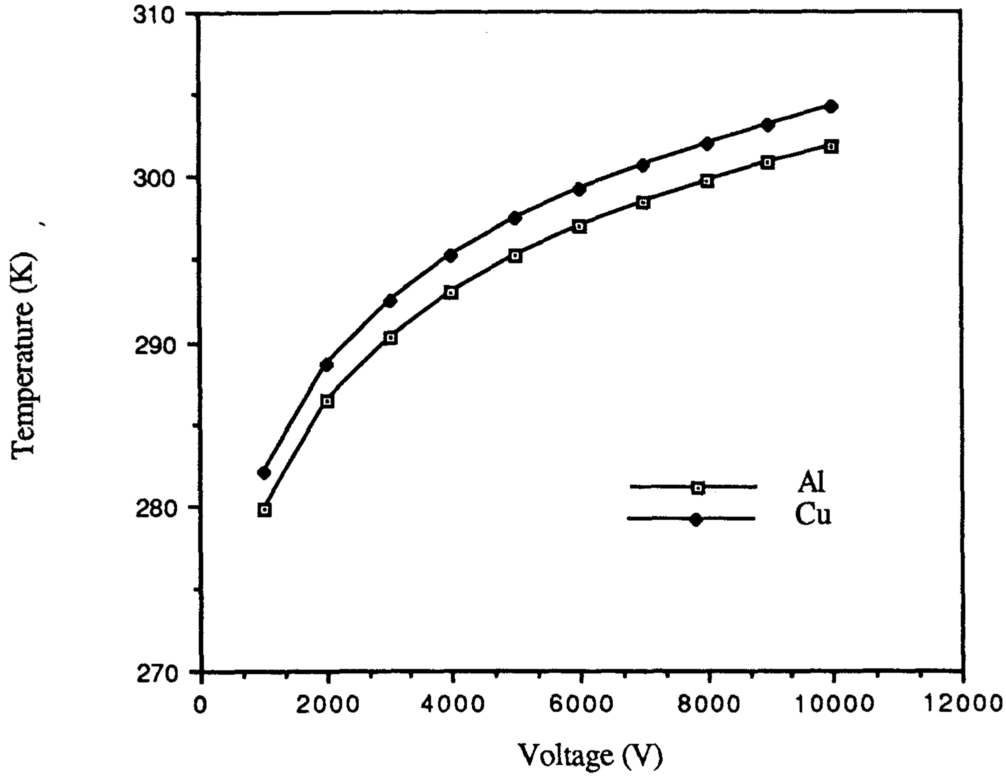


depth 25 cm

Comments

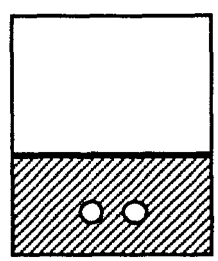
1) Aluminum lines are lighter than copper (even though thicker) due to its lower density.
2) Total mass of line decreases with increasing voltage due to decreasing radius (see Case 1.A).
3) Note the rapid decrease in total mass (log scale) with voltage.

Case 2.C



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	below
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	
Power loss	5 %

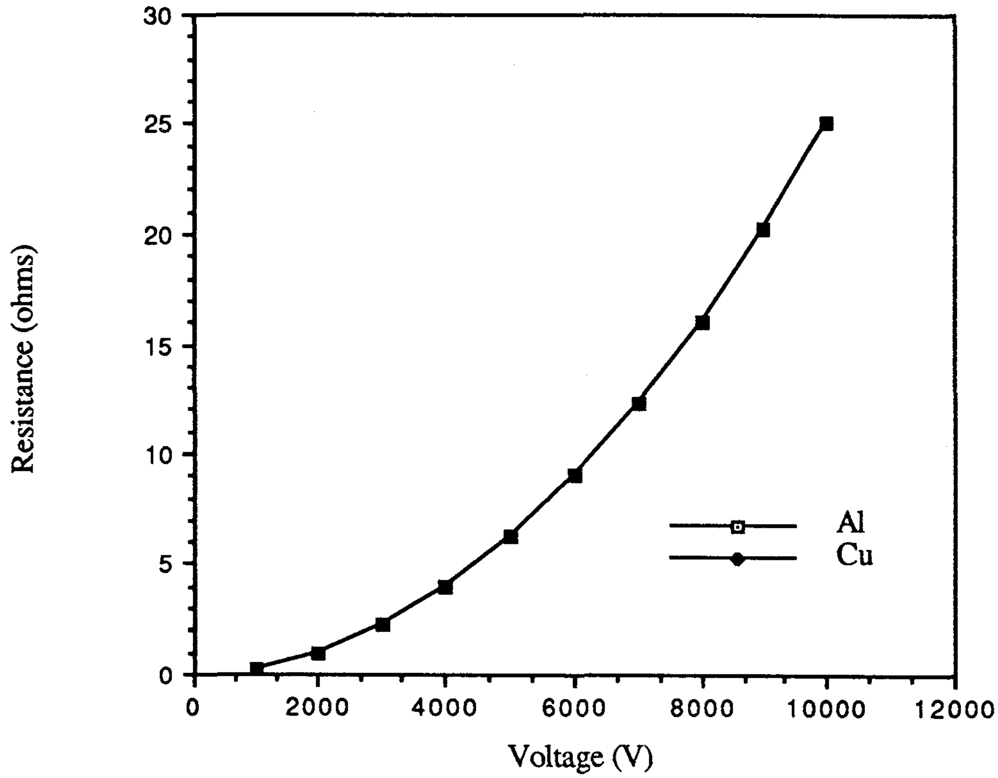


depth 25 cm

Comments

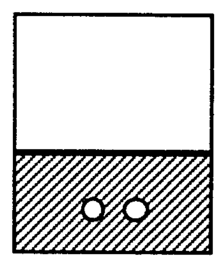
1) Similar to the two-wire above ground (Case 1.C) the copper transmission line is hotter since it has a smaller radius. In this case it has less surface area contact with the soil for heat conduction.
2) Also as before an increase in the voltage results in a hotter temperature since the smaller radius has greater difficulty in conducting away the waste heat.
3) The heat flow mechanism for the below ground is different from the above ground (conduction as compared to radiation), thus the shape of the temperature vs voltage is different.

Case 2.D



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	below
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	
Power loss	5 %

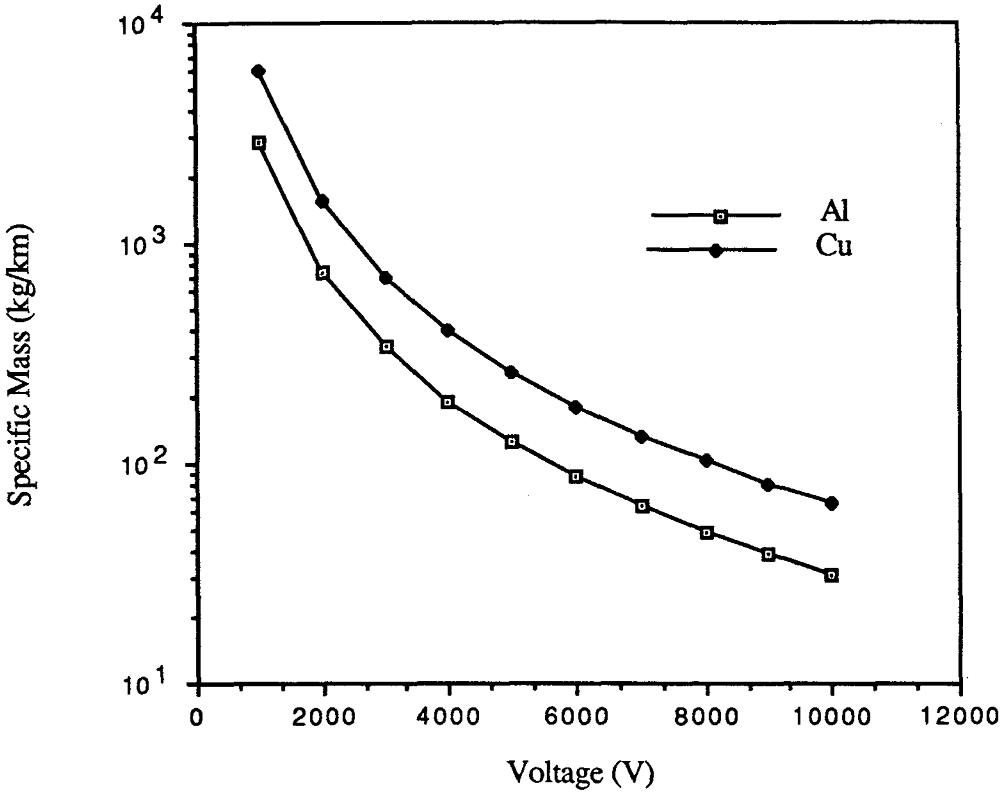


depth 25 cm

Comments

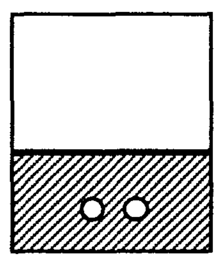
1) Same resistance as above ground case (1.D).
2) No difference in line resistance between Al and Cu (see comment Case 1.D).

Case 2.E



Transmission Line Parameters

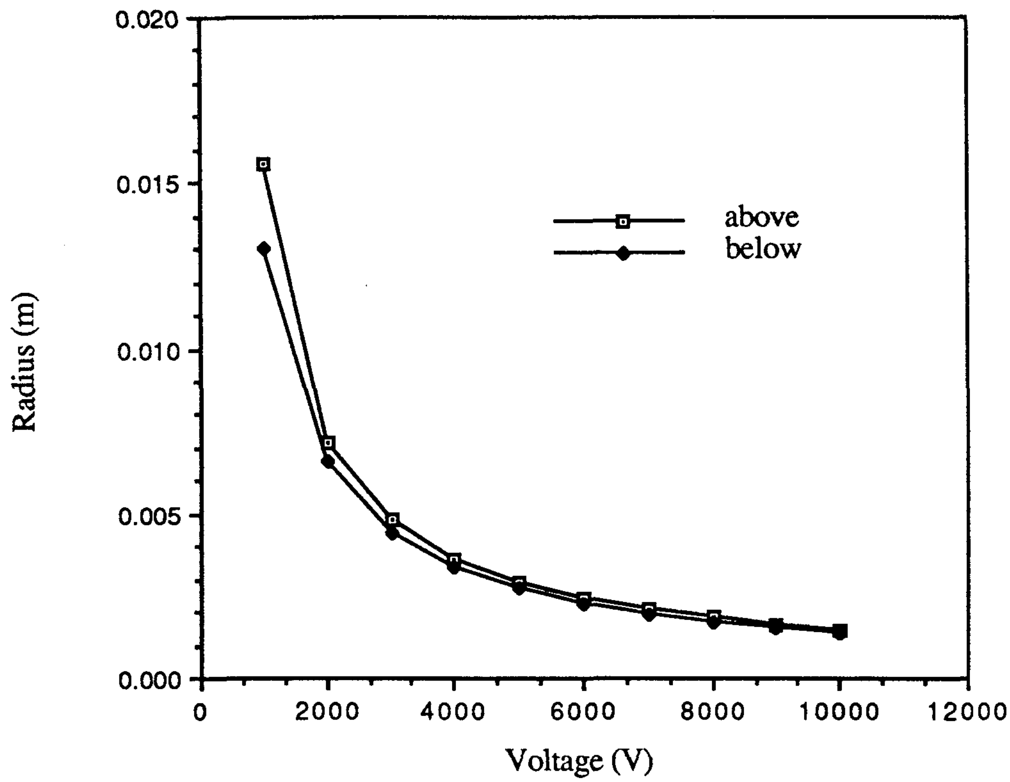
Application	100 kW, 5 km
Geometry	two-wire
Location	below
Conductor	*aluminum, copper*
Insulator	vacuum
Day/Night	
Power loss	5 %



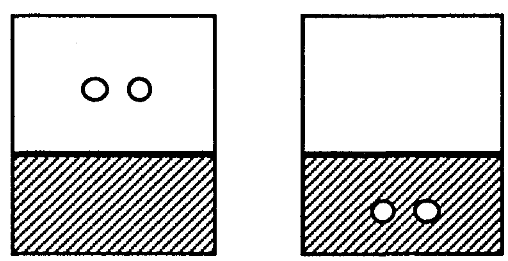
depth 25 cm

Comments

Case 3.A



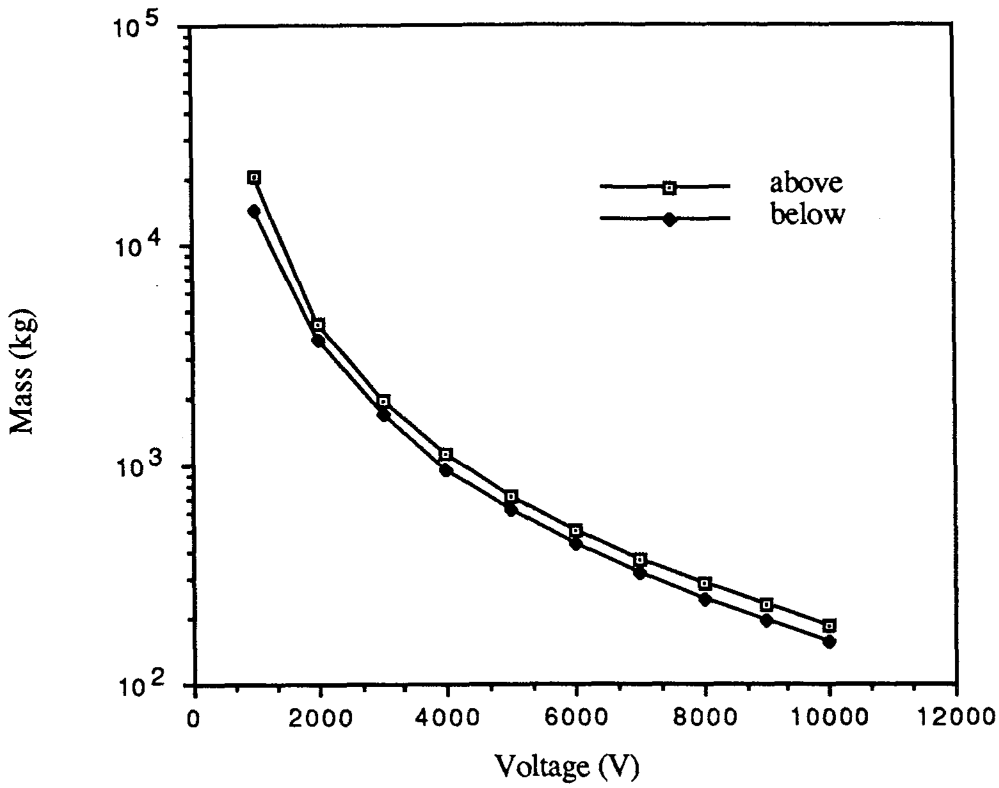
Transmission Line Parameters	
Application	100 kW, 5 km
Geometry	two-wire
Location	*above, below*
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %



Comments

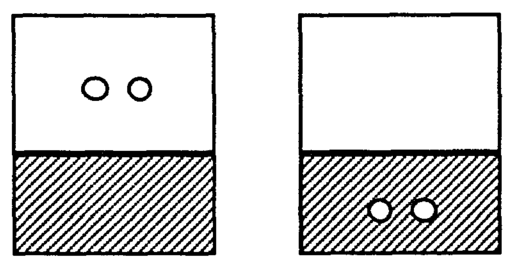
1) The above ground transmission line is slightly larger than the below ground line, because the above line runs hotter, resulting in a lower conductivity , than the below ground line, i.e., for the same power and power loss the above ground line must be larger in order to have the same total line resistance as the below ground line.
2) This effect becomes insignificant at higher voltages.

Case 3.B



Transmission Line Parameters

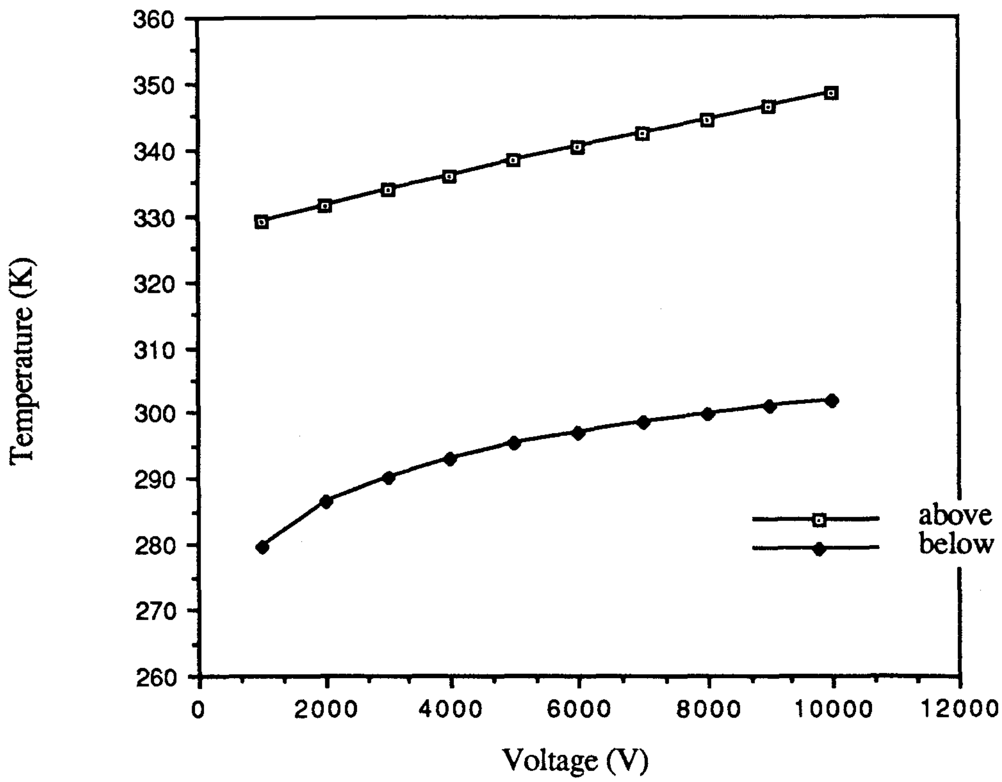
Application	100 kW, 5 km
Geometry	two-wire
Location	*above, below*
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %



Comments

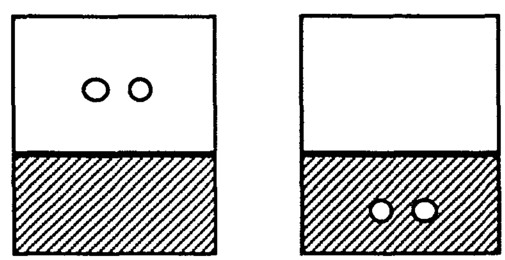
1) The mass curve form follows the radius curve form.
2) Note, however, that the mass plot is log, so that small variations in a difference in radius between above ground and below ground are not as obvious on the total mass plot. This is because the mass is proportional to the square of the radius.
3) A below ground line will be slightly lower in mass than an above ground line. This actually applies only to this transmission line which has a very low power loss per unit length. The below ground line for this case runs a little cooler than the above ground line.

Case 3.C



Transmission Line Parameters

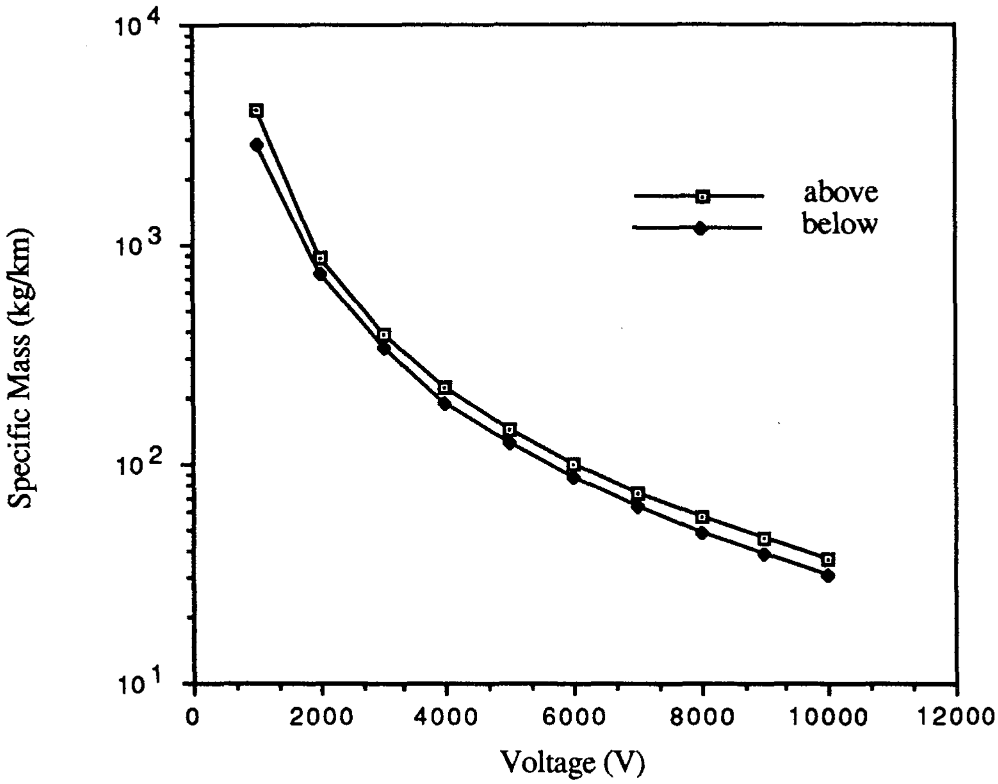
Application	100 kW, 5 km
Geometry	two-wire
Location	*above, below*
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

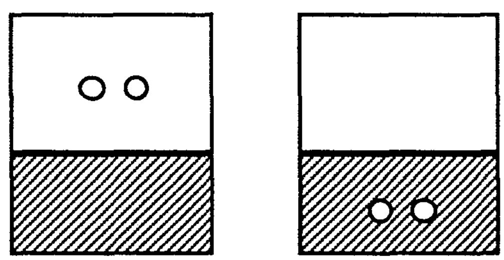


Comments

1) The below ground line runs cooler than the above ground line because at low power loss per unit length levels conduction to surrounding soil is more efficient than radiation into space.

Case 3.E





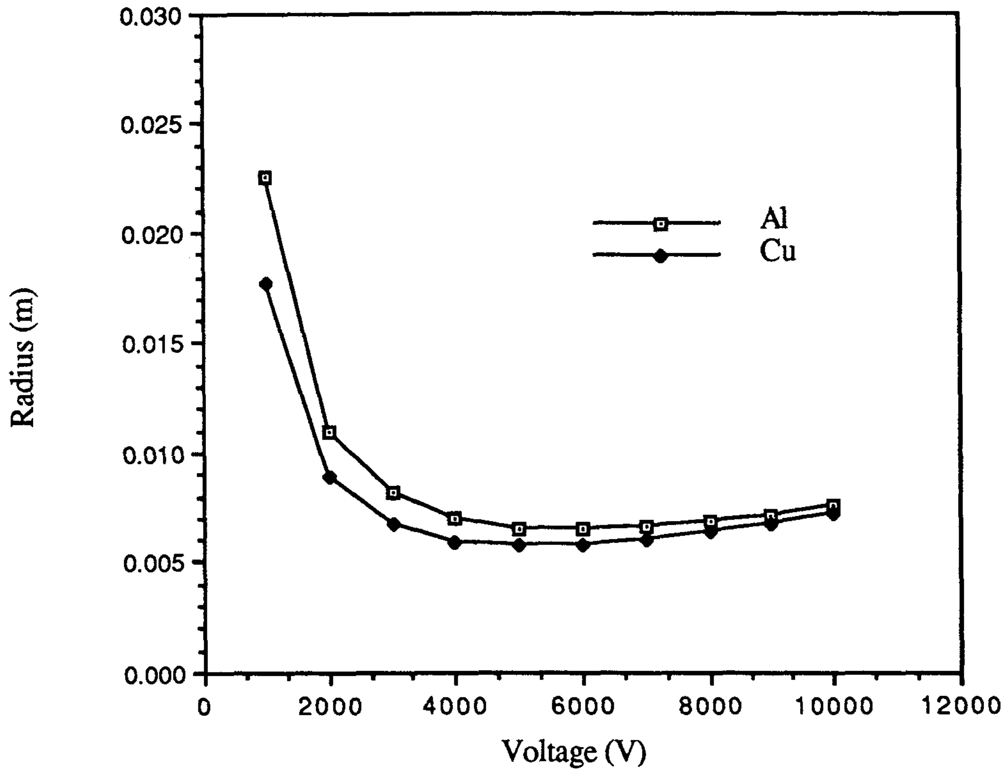
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	*above, below*
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

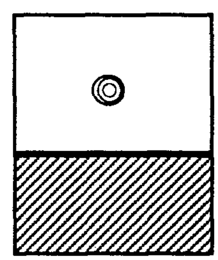
1) Same comments as total mass plot (Case 3.B).

Case 4.A



<u>**Transmission Line Parameters**</u>

Application	100 kW, 5 km
Geometry	coax
Location	above
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

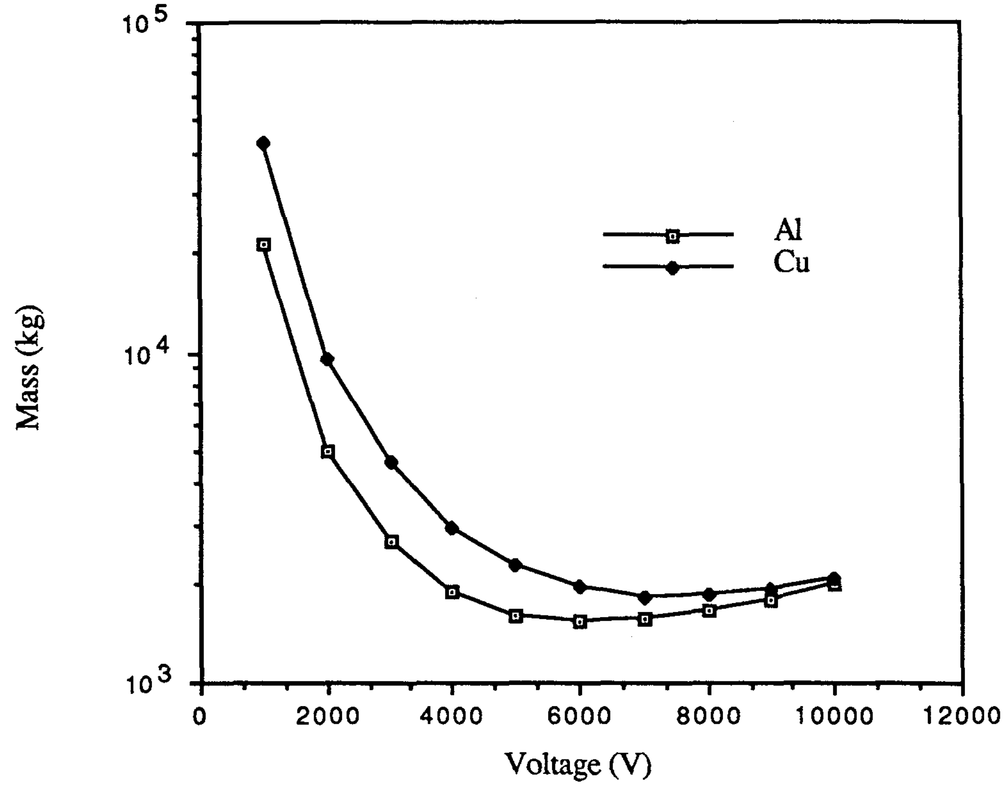


<u>**Comments**</u>

1) The inner conductor of a coaxial line is essentially the same as one conductor of a two-wire line The total radius of a coaxial, however, includes the inner conductor, the dielectric, and the outer conductor, so that the radius of a coaxial line will certainly be larger than the radius of a single conductor of a two-wire line. (At 1 kV one conductor of an Al two-wire line is about 16 mm in diameter, while the coaxial line is about 23 mm in diameter).

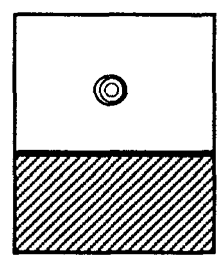
2) For the coaxial design an increase in the voltage decreases the size of the conductors, exactly as it did for the two-wire line (Case 1.A). However, as the voltage increases the insulation thickness must increase. At low voltages (from 1 to 4 kV) the decreasing size of the conductors dominates the overall radius of the line. Above 4 kV, however, the increasing size of the dielectric soon dominates over the conductor to keep the overall size of the line constant or even increasing as the voltage increases.

Case 4.B



Transmission Line Parameters

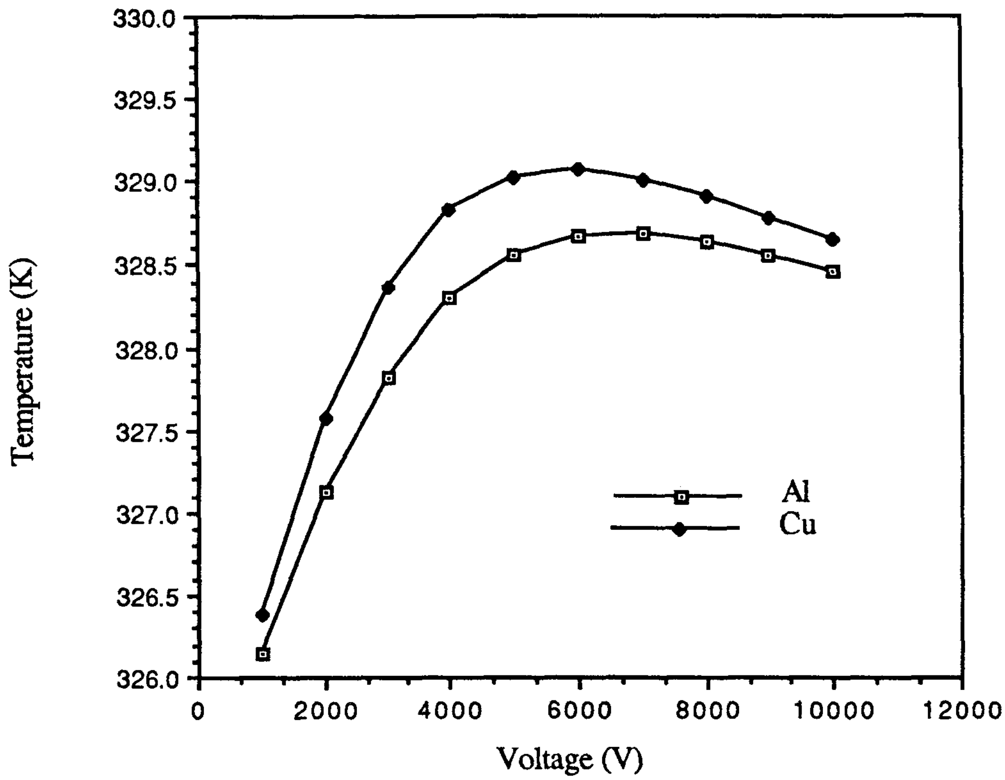
Application	100 kW, 5 km
Geometry	coax
Location	above
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

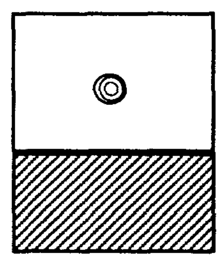


Comments

1) The mass difference between aluminum and copper becomes insignificant at higher voltages because the line mass is being dominated by the mass of the solid dielectric.

Case 4.C





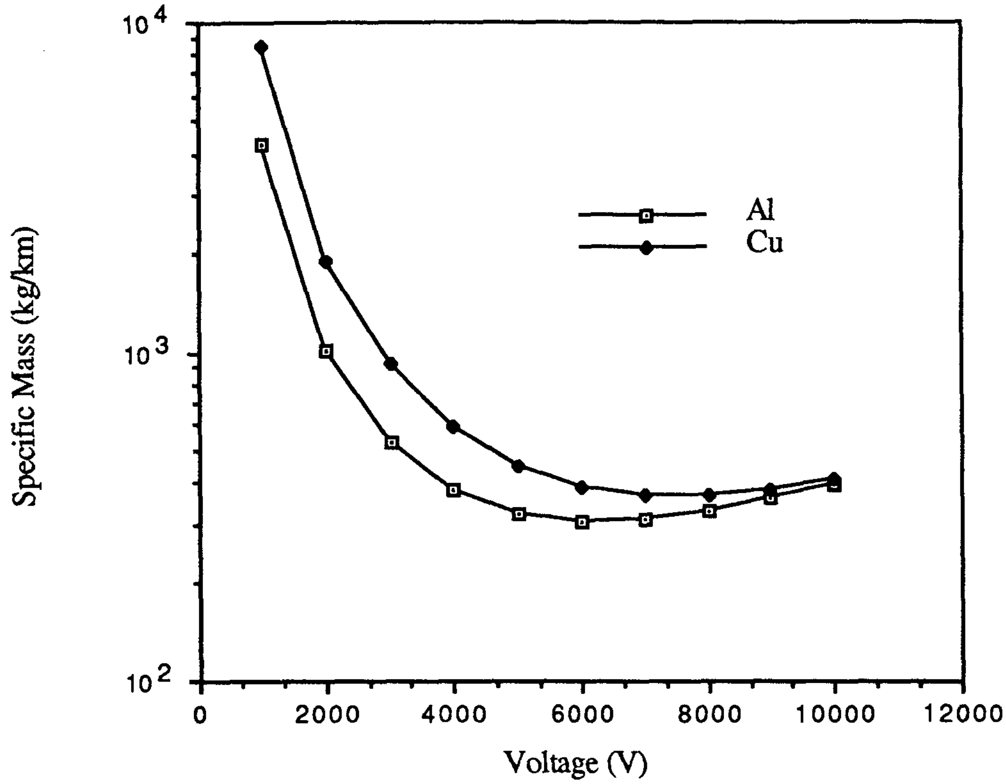
Transmission Line Parameters

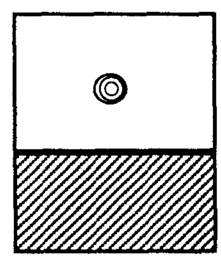
Application	100 kW, 5 km
Geometry	coax
Location	above
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

Comments

1) The temperature is inversely following the radius due to surface area available for radiation (see comment Case 1.C).

Case 4.E





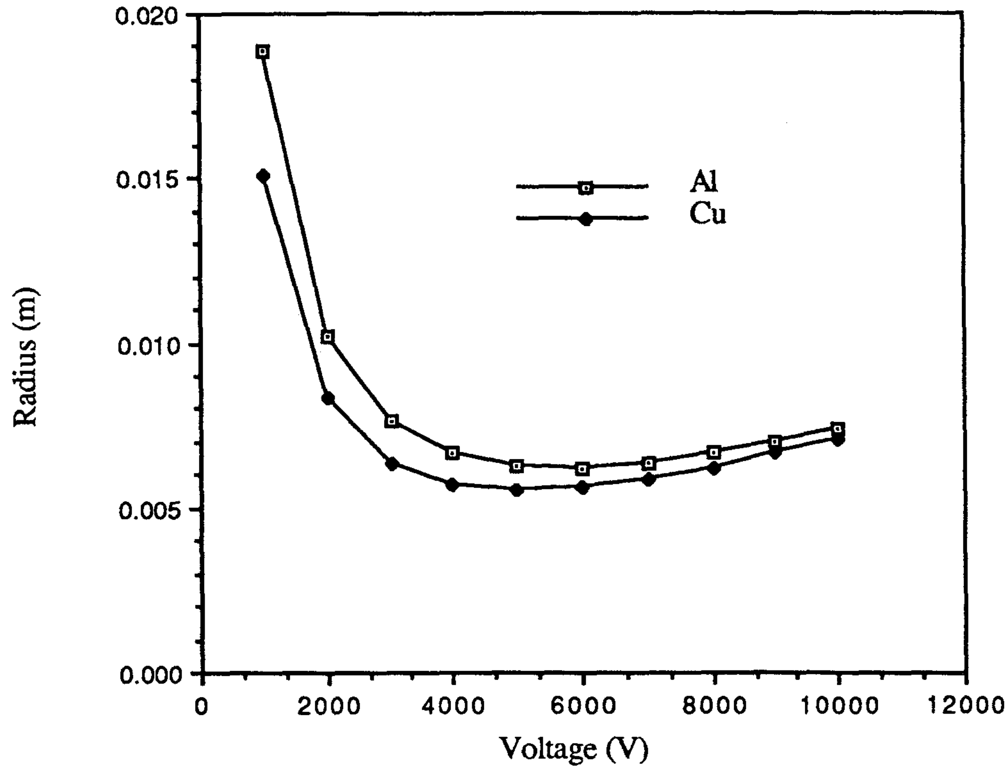
<u>Transmission Line Parameters</u>

Application	100 kW, 5 km
Geometry	coax
Location	above
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

<u>Comments</u>

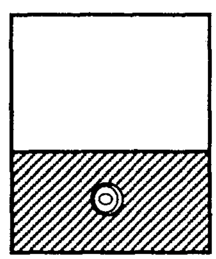
see comments plot 4.B

Case 5.A



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



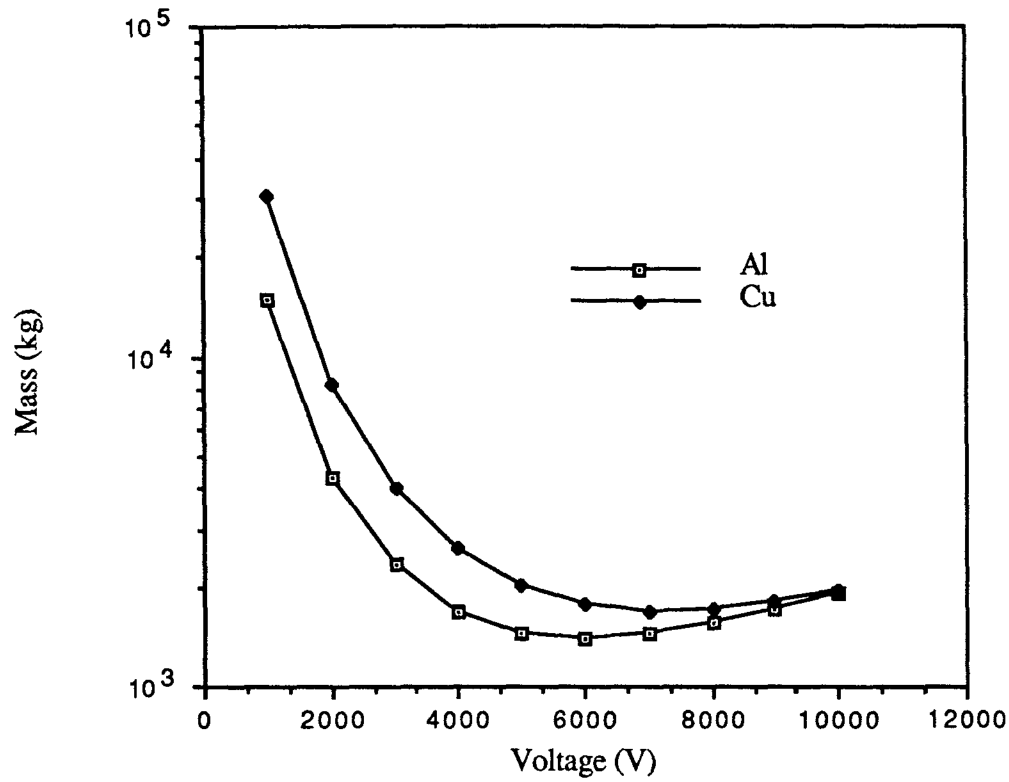
depth 25 cm

Comments

1) For the coaxial design an increase in the voltage decreases the size of the conductors, exactly as it did for the two-wire line (Case 2.A). However, as the voltage increases the insulation thickness must increase. At low voltages (from 1 to 4 kV) the decreasing size of the conductors dominates the overall radius of the line. Above 4 kV, however, the increasing size of the dielectric soon dominates over the conductor.

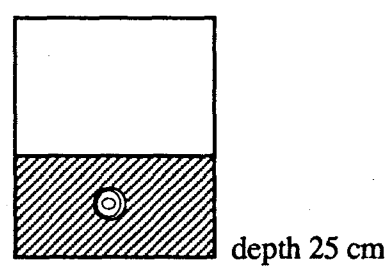
2) As with the two-wire line the below ground coaxial line is slightly smaller than the above ground coaxial line due to the lower temperatures, resulting in higher conductivities, and allowing smaller conductors. (See Case 6.A for comparison).

Case 5.B



Transmission Line Parameters

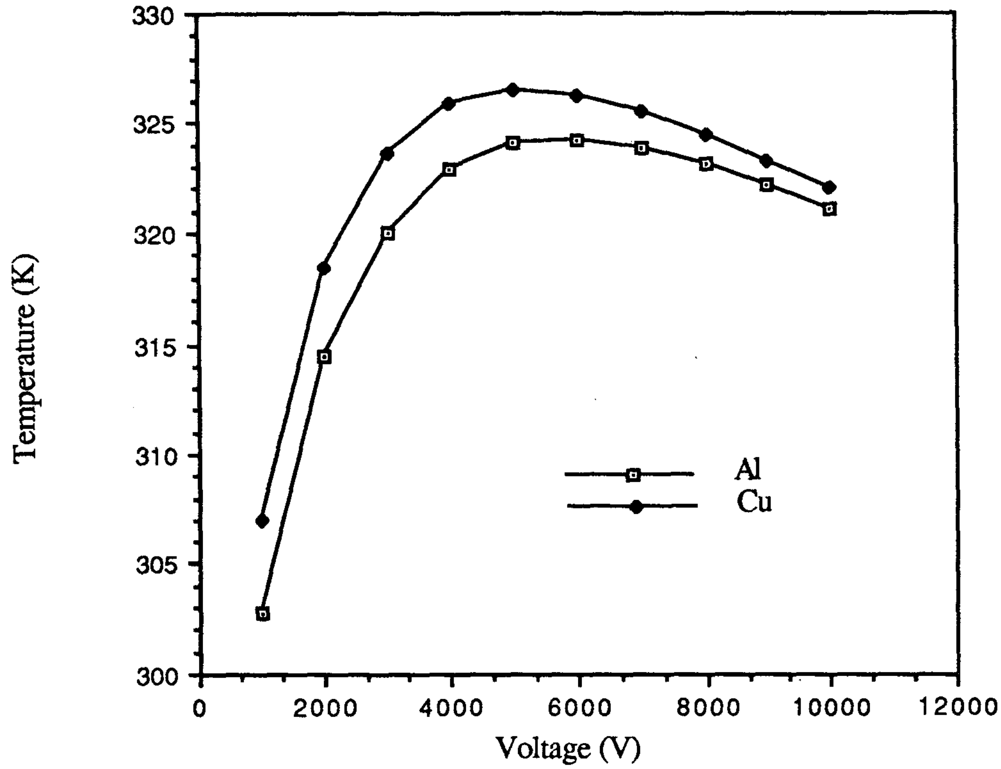
Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



Comments

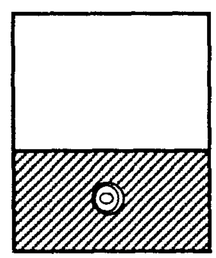
1) Same as Case 4.B, the mass of the dielectric dominates at higher voltages.

Case 5.C



Transmission Line Parameters

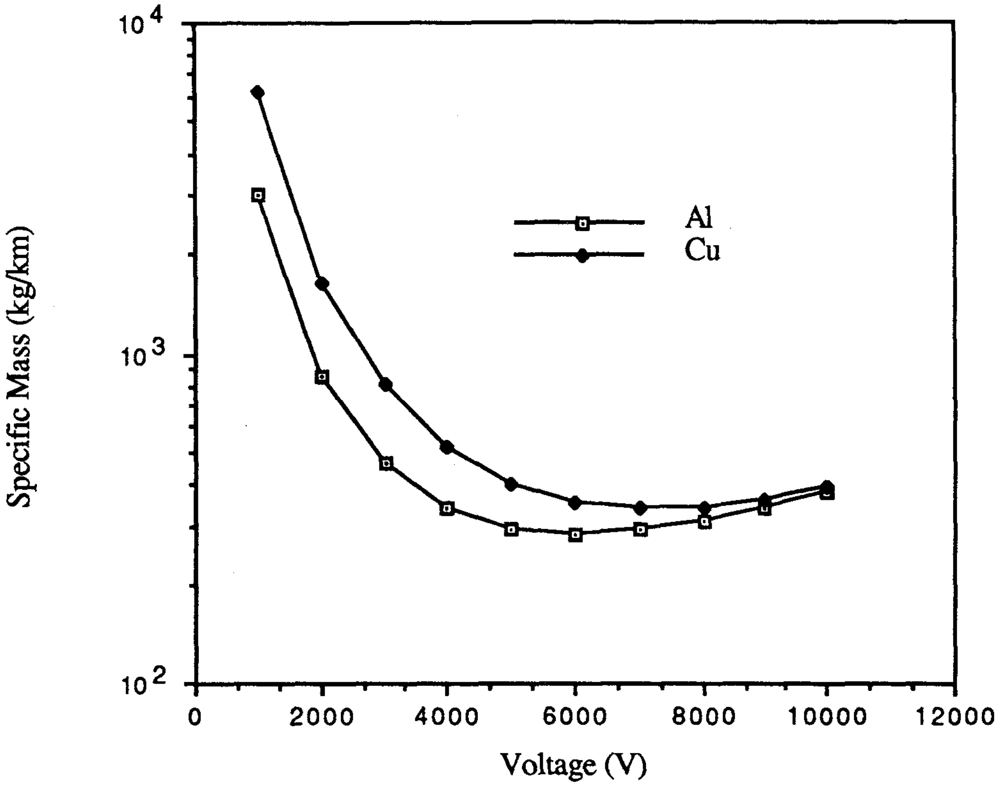
Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



Comments

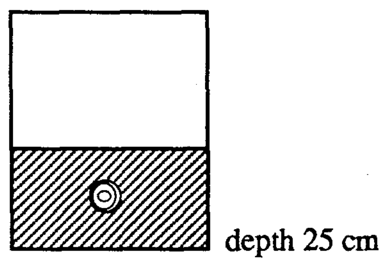
1) Don't try to compare this plot with the temperature plot for the above ground coaxial line (Case 4.C). Although they might appear to have the same shape the vertical scales cover different ranges. Instead refer to the comparison plots (Case 6.C).

Case 5.E



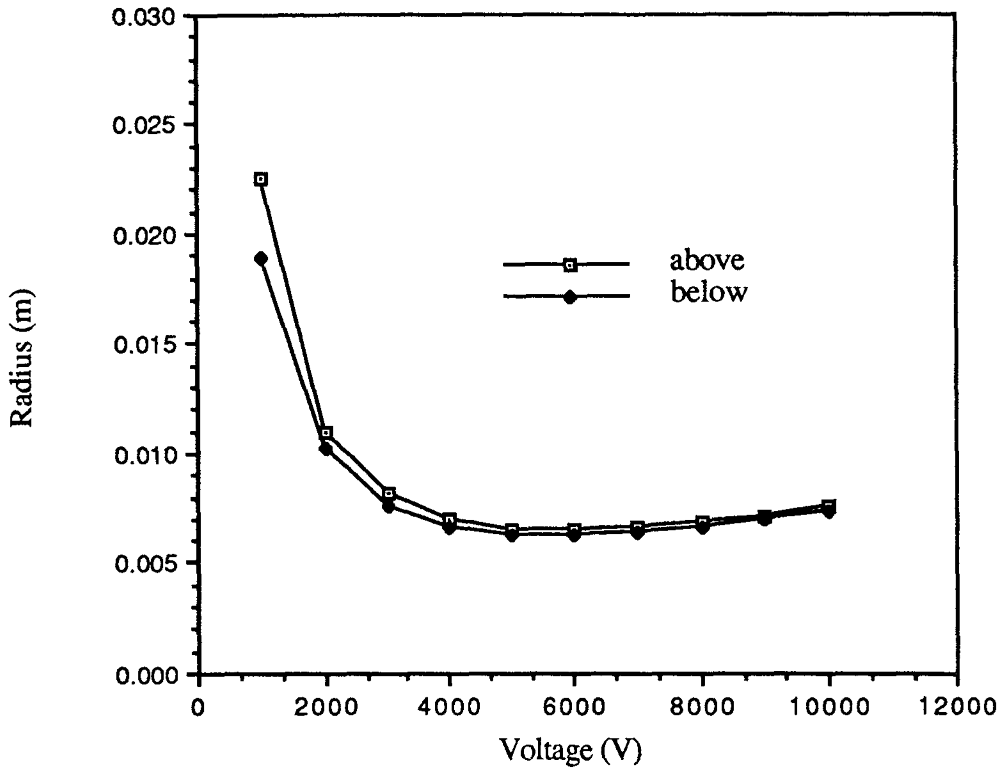
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	*aluminum, copper*
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



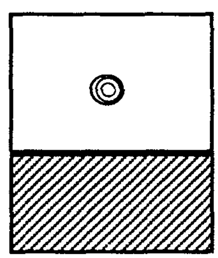
Comments

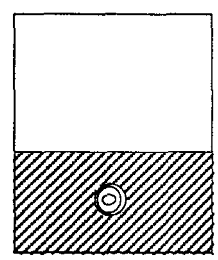
Case 6.A



<u>Transmission Line Parameters</u>

Application	100 kW, 5 km
Geometry	Coaxial
Location	*above, below*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

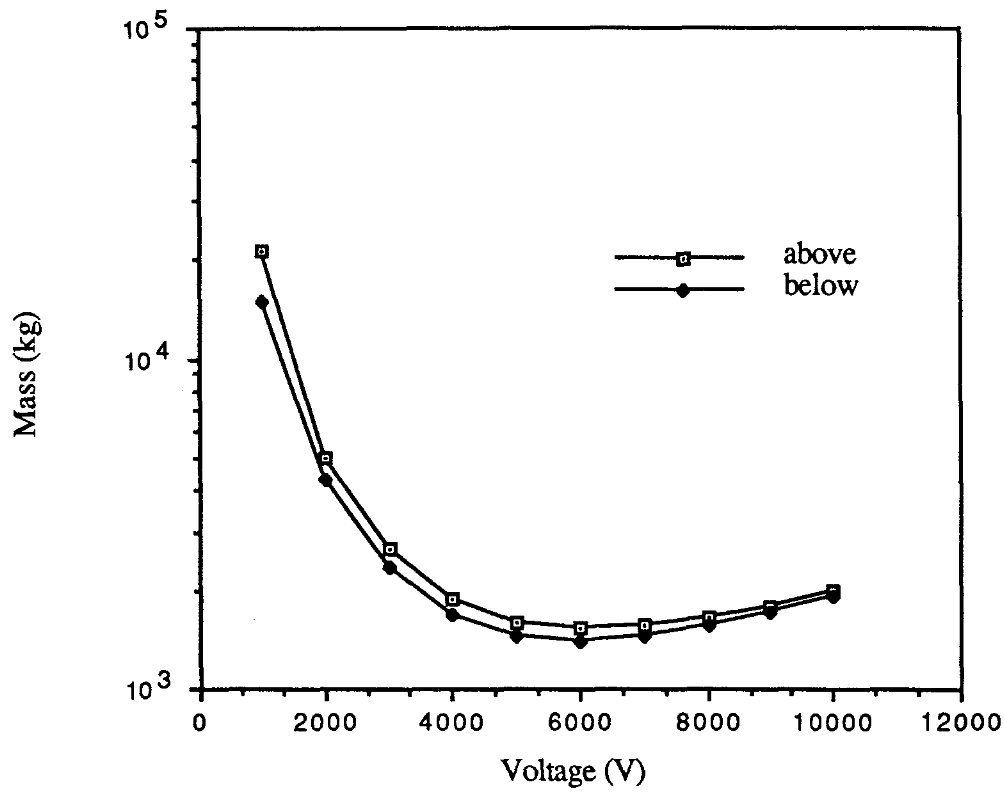




Comments

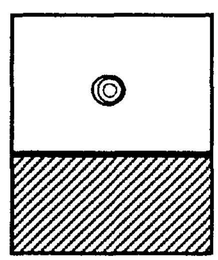
1) Radii of coaxial above and below ground are approximately the same.

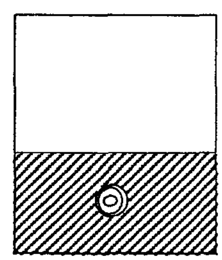
Case 6.B



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	Coaxial
Location	*above, below*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

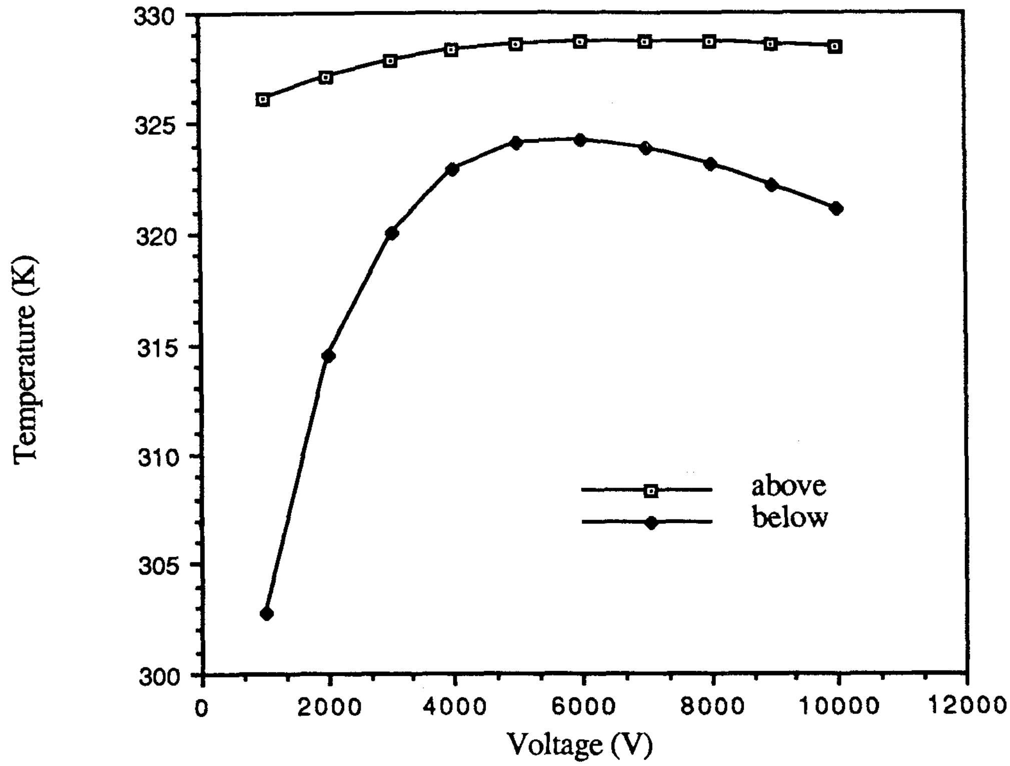




Comments

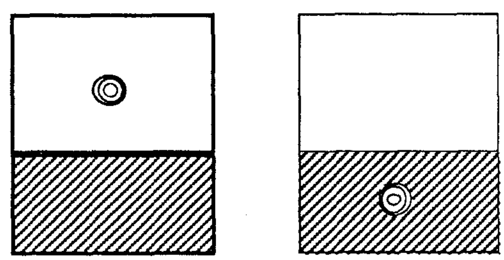
1) Mass of coaxial lines above and below ground are approximately the same.

Case 6.C



Transmission Line Parameters

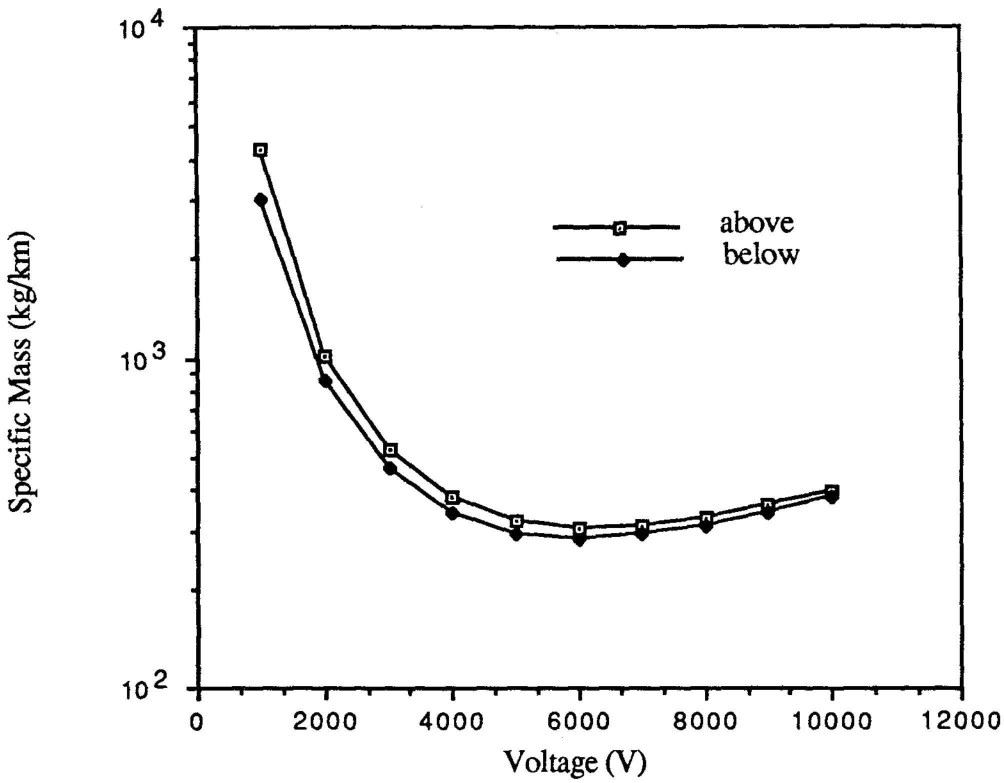
Application 100 kW, 5 km
Geometry Coaxial
Location *above, below*
Conductor aluminum
Insulator solid (TFE)
Day/Night day
Power loss 5 %

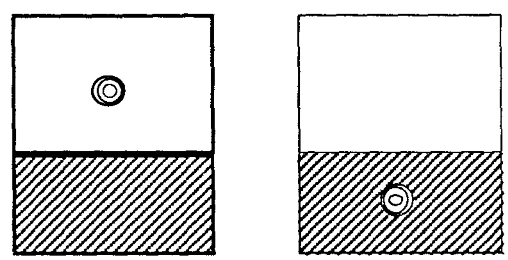


Comments

1) The temperature swing as a function of voltage for the above ground coaxial transmission line (3 K) is smaller than the temperature swing for the below ground coaxial transmission line (22 K). This is due to the fact that because of the thermal characteristics of the soil (low thermal conductivity) and the nature of the conductive cooling process cooling below ground is much more sensitive to the line surface area than is the radiation process for the above ground line.

Case 6.E



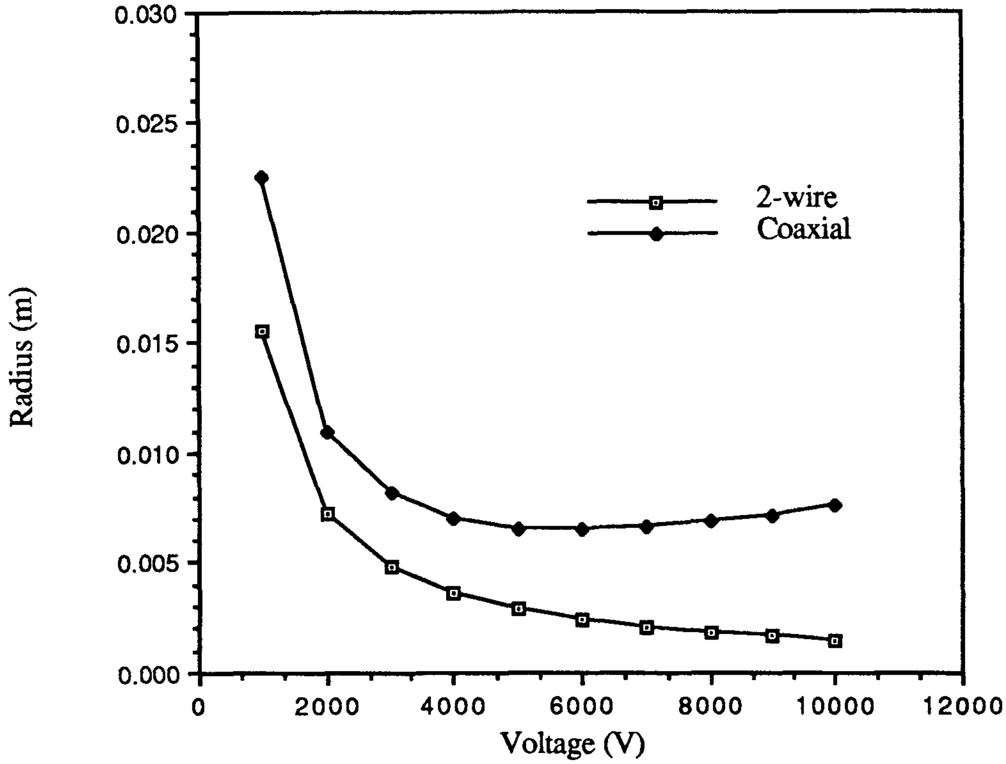


Transmission Line Parameters

Application	100 kW, 5 km
Geometry	Coaxial
Location	*above, below*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

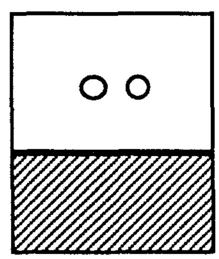
Comments

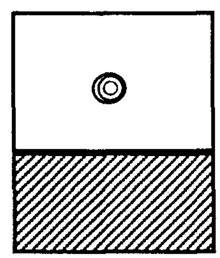
Case 7.A



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %



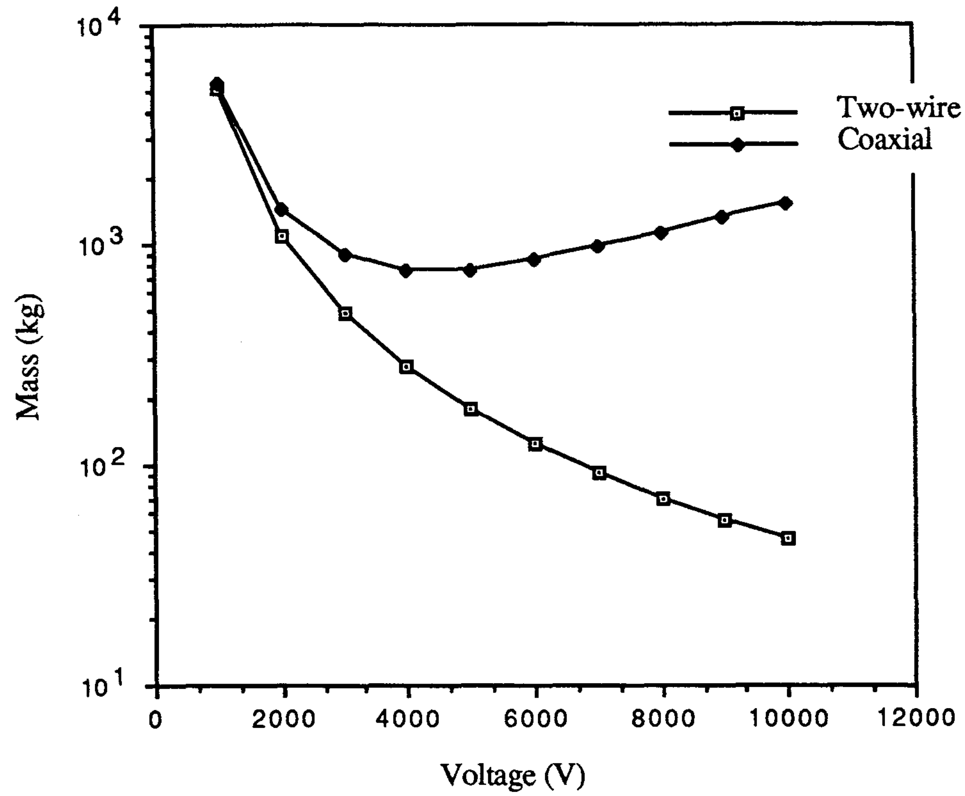


Comments

1) The radius of the two-wire transmission line is for only one of the two conductors, while the radius of the coaxial transmission line is for the complete line including both conductors and the dielectric.

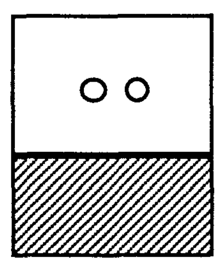
2) The comparison is useful to show that increasing voltage continues to decrease the size of the two-wire line while the coaxial line has an optimum voltage for minimum radius above which the increasing dielectric thickness causes the line size to increase.

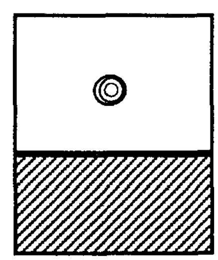
Case 7.B



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

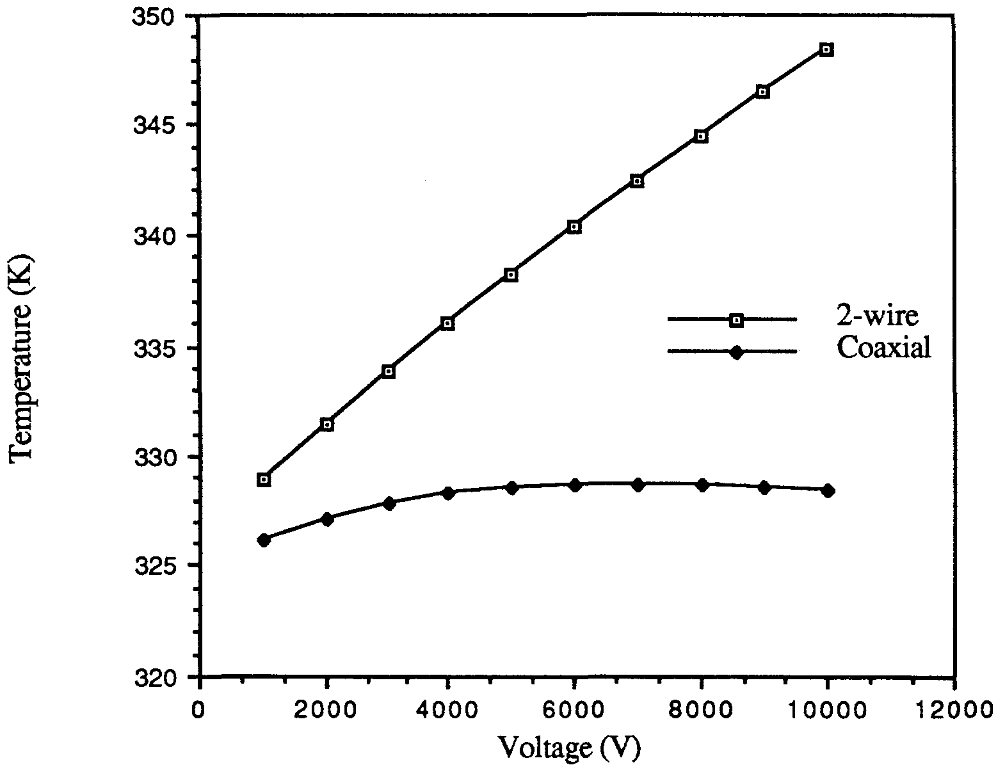




Comments

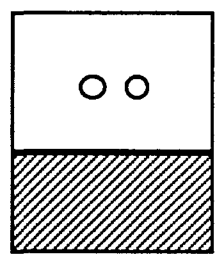
1) The mass of the two-wire transmission line includes both conductors, and the mass of the coaxial line includes both conductors and the insulator.
2) At low voltage the mass of the dielectric in the coaxial line is a very small portion of the total line mass so that the two line types have approximately the same mass.
3) As the voltage increases the difference caused by the mass of the dielectric in the coaxial line becomes significant.

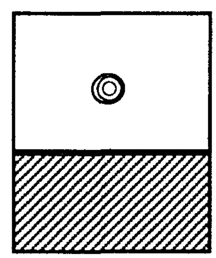
Case 7.C



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

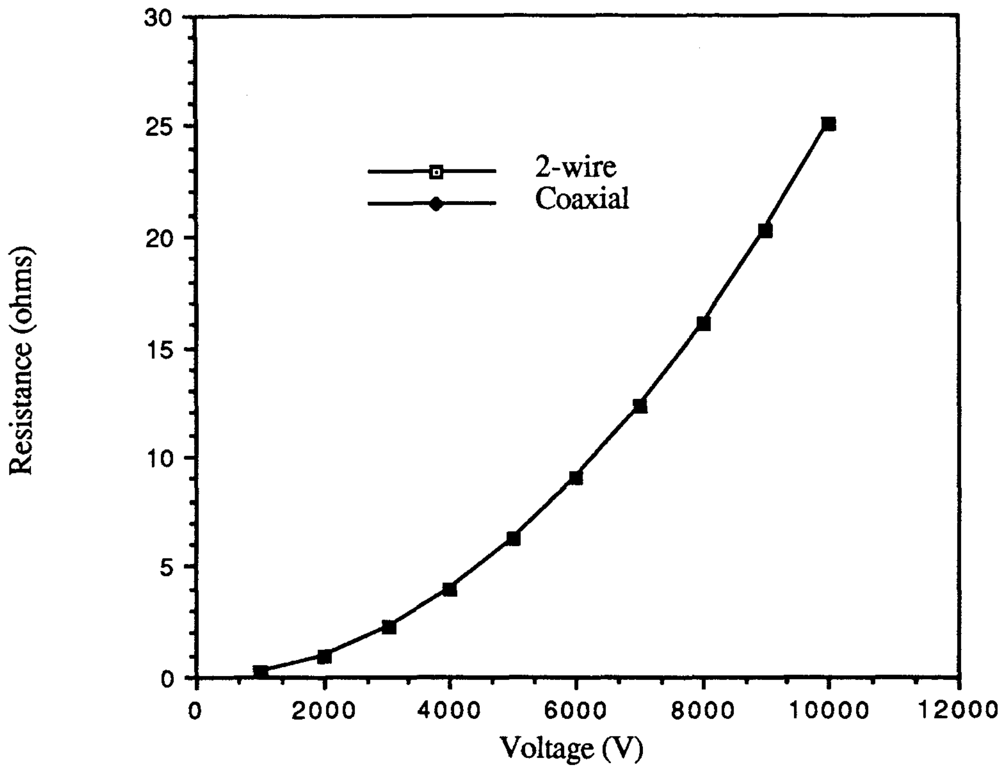




Comments

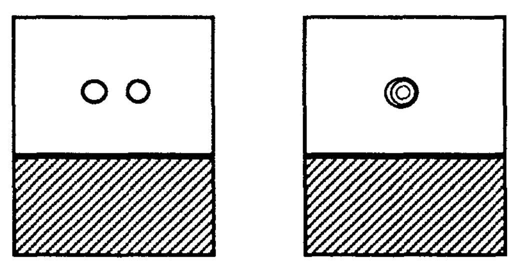
1) The two-wire and coaxial transmission lines have approximately the same temperature at low voltages since the total surface area of the two conductors of the two-wire line and the total surface area of the outside of the coaxial cable are approximately the same.
2) As the voltage increases, the surface area of the two-wire line decreases; the coaxial surface area decreases until about 4 kV, but then increases due to the increasing dielectric thickness (see Plot 7.A). Thus, at higher voltages the coaxial transmission line has a greater surface area than the two-wire transmission line to radiate the same power.
3) Also, don't forget that the radiation of the two-wire line is complicated by the view factor effect, where one line sees the other, and thus reducing its radiation efficiency. The coaxial cable does not experience the view factor effect.

Case 7.D



Transmission Line Parameters

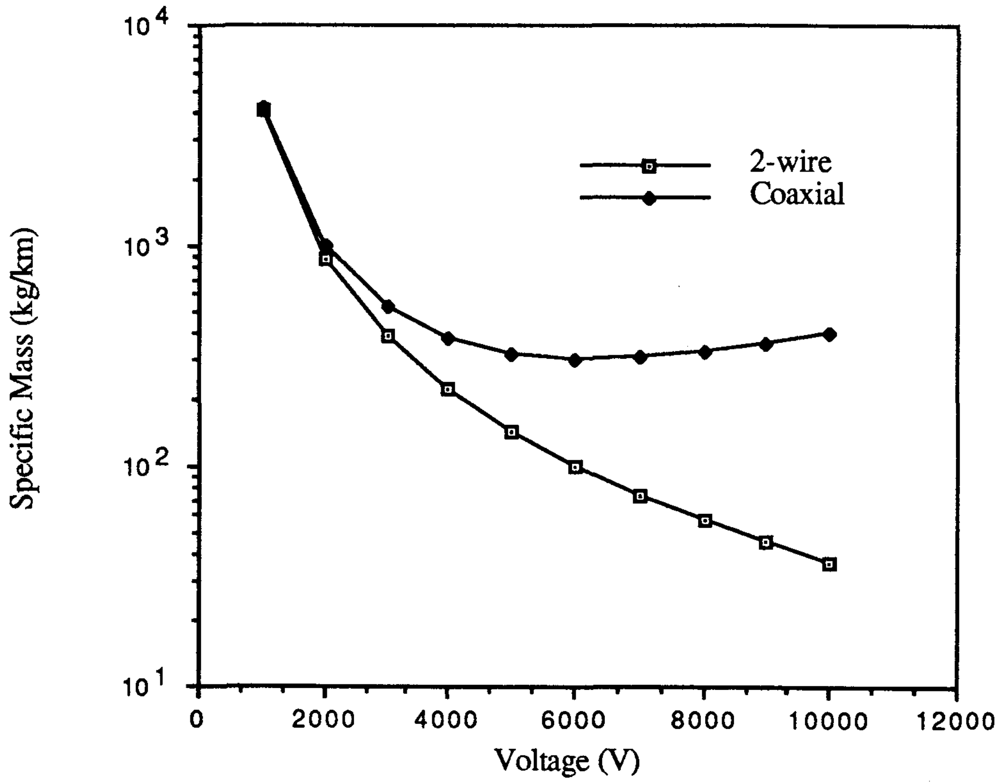
Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %



Comments

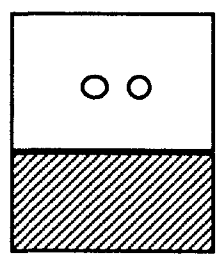
1) Since the power to be transmitted and the power loss determines the resistance, the resistance of the two different geometries is identical.

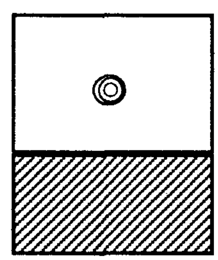
Case 7.E



<u>**Transmission Line Parameters**</u>

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

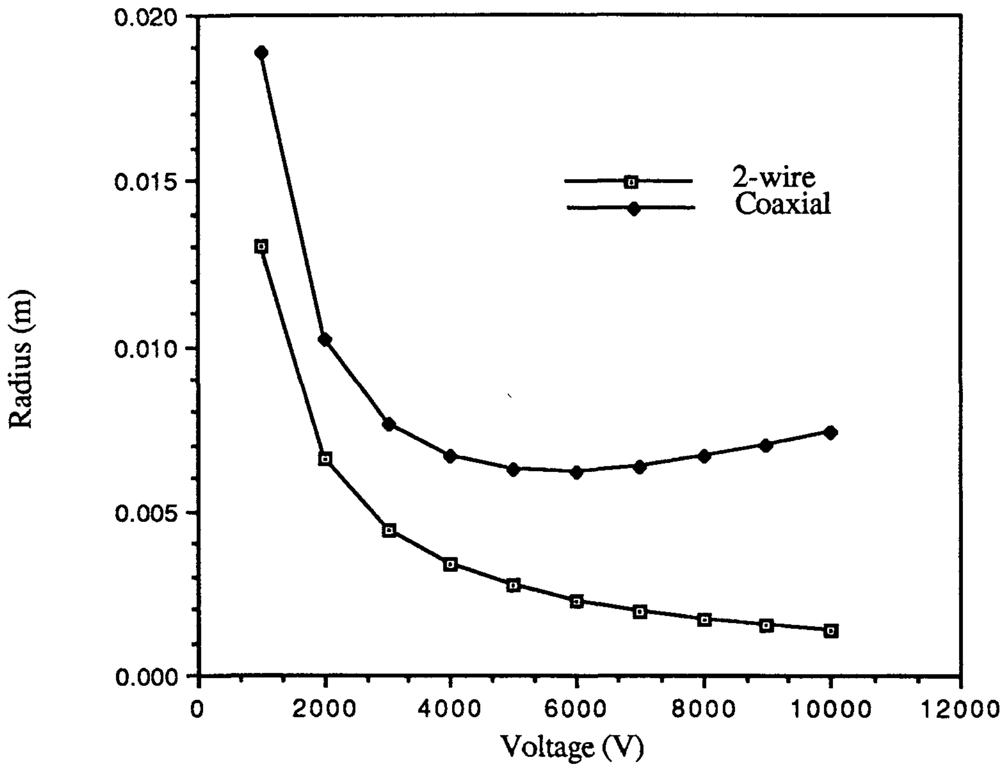




<u>**Comments**</u>

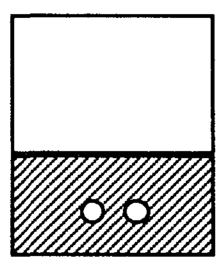
see comments for plot 7.B

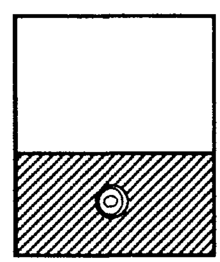
Case 8.A



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %



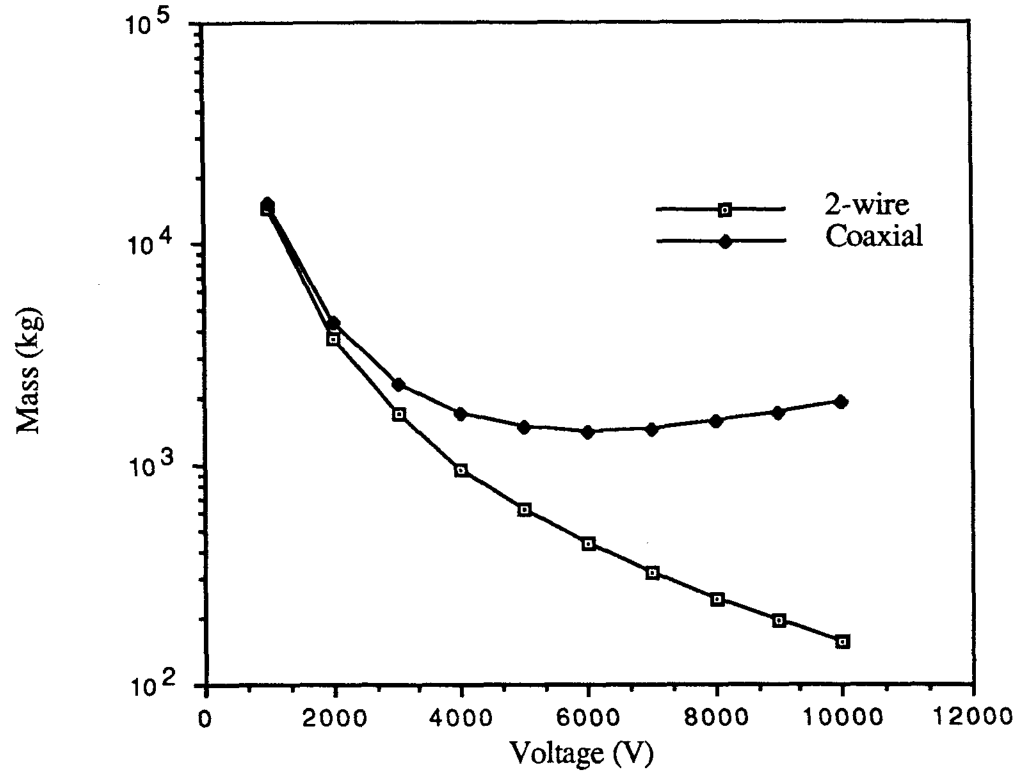


Comments

1) As in the above ground case the radius of the two-wire transmission line is for only one of the two conductors, while the radius of the coaxial transmission line is for the complete line including both conductors and the dielectric.

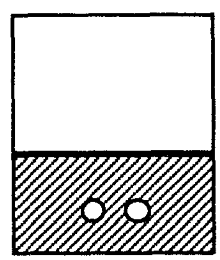
2) The comparison is useful to show that increasing voltage continues to decrease the size of the two-wire line while the coaxial line has an optimum voltage for minimum radius above which the increasing dielectric thickness causes the line size to increase.

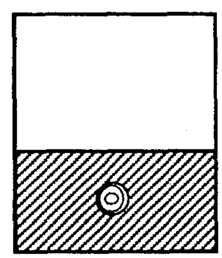
Case 8.B



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %

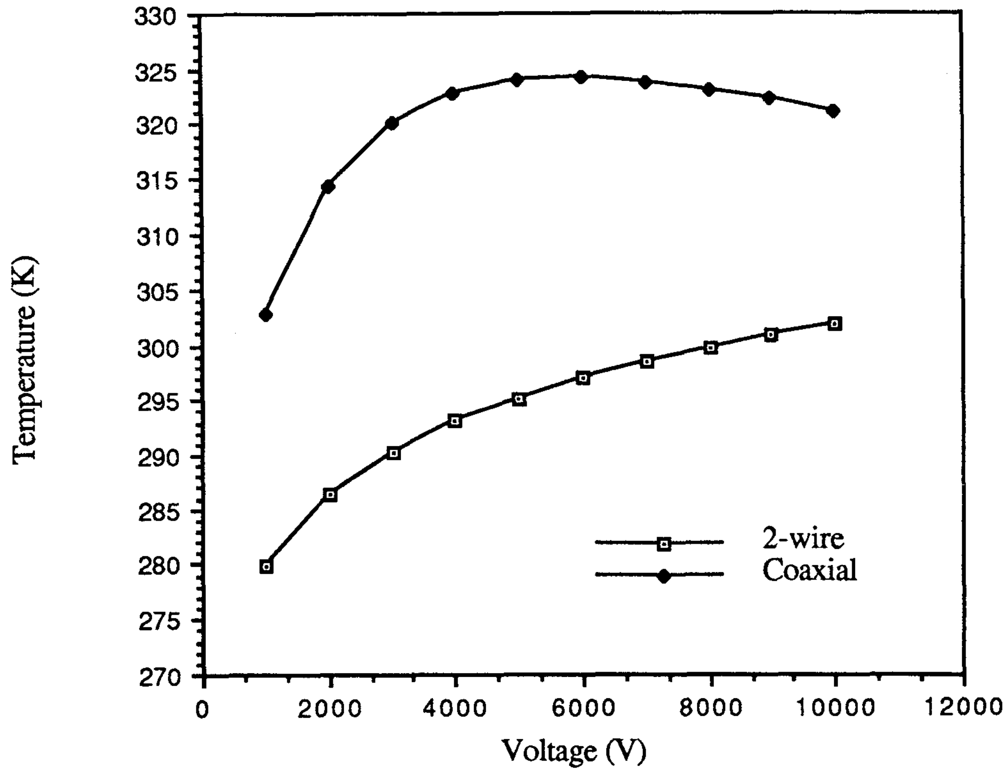




Comments

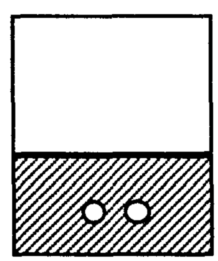
1) The mass of the two-wire transmission line includes both conductors, and the mass of the coaxial line includes both conductors and the insulator.
2) At low voltage the mass of the dielectric in the coaxial line is a very small portion of the total line mass so that the two line types have approximately the same mass.
3) As the voltage increases the difference caused by the mass of the dielectric in the coaxial line becomes significant.

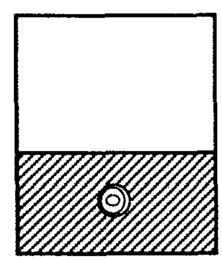
Case 8.C



__Transmission Line Parameters__

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %

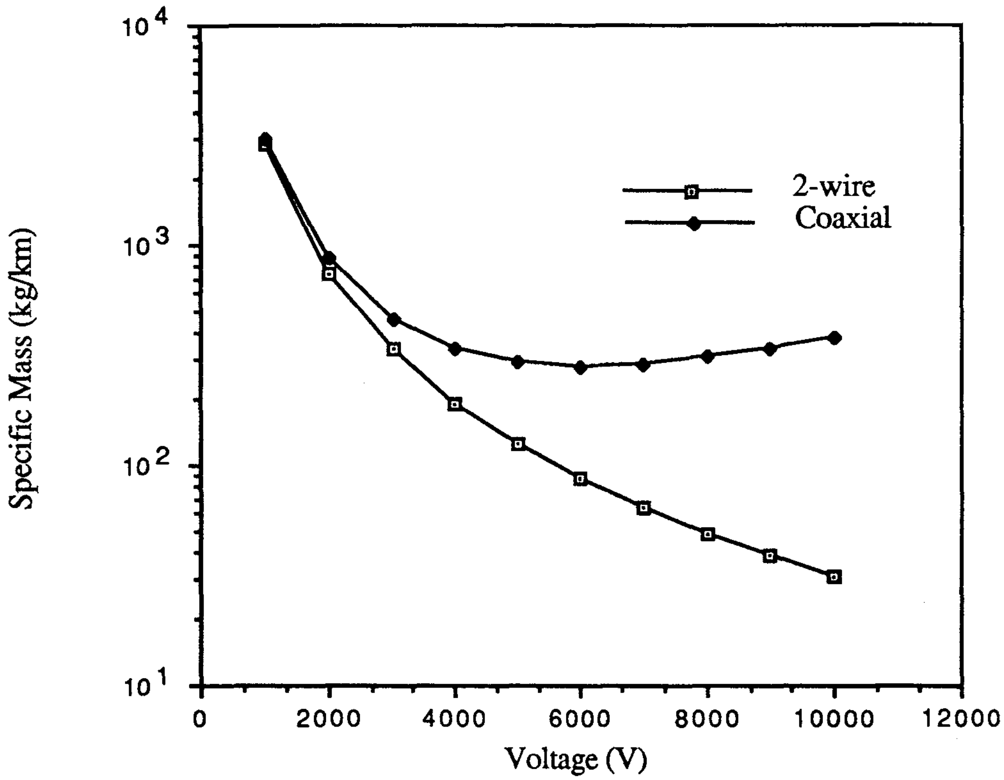




__Comments__

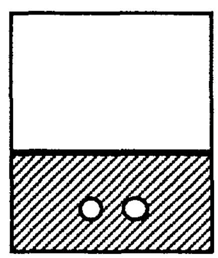
1) The coaxial line was cooler above ground than the two-wire line (see Case 7.C), because of the increased line surface area allowing for more radiation. However, below ground lines are limited in the ability to dissipate heat due to the poor thermal conductivity of the soil, resulting in a very limited heat flux. Even though the underground coaxial line might have a greater surface area than the two-wire line twice the heat (per cable) for the coax line must be conducted away by the soil than a single conductor of the two-wire line. In other words having the spacing of the two-wire line aids in dispersion of the heat by splitting the resistive heat into two separately located dispersal points. The soil can not conduct away the heat generated by the coax line and it will run hotter.
2) There is a maximum thermal flux that can travel through the soil and once this is exceeded the temperature of a below-the-surface transmission line rises rapidly. The rate of heat flow does not increase with the 4th power of the temperature as it does for the radiation process.

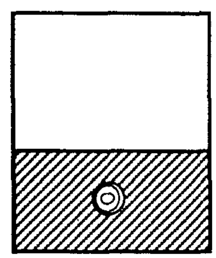
Case 8.E



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %

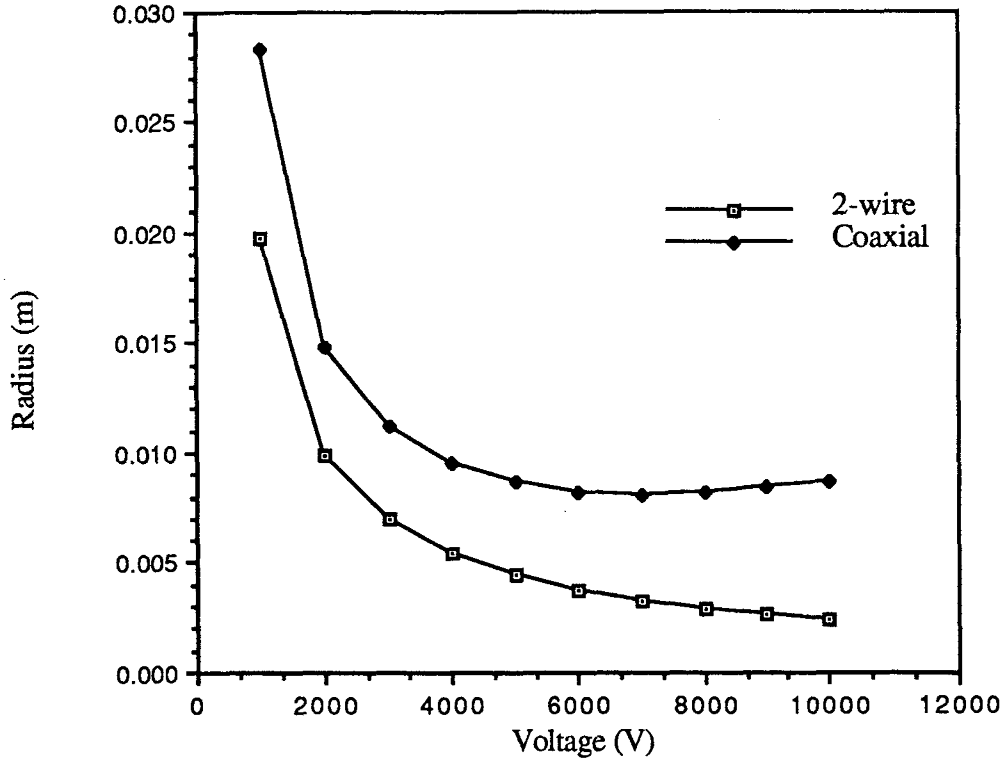




Comments

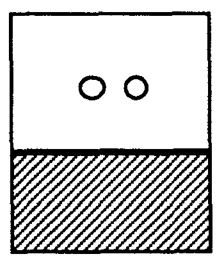
see comments for plot 8.B

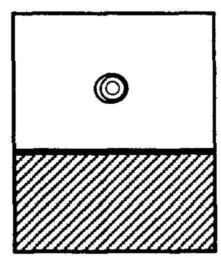
Case 9.A



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

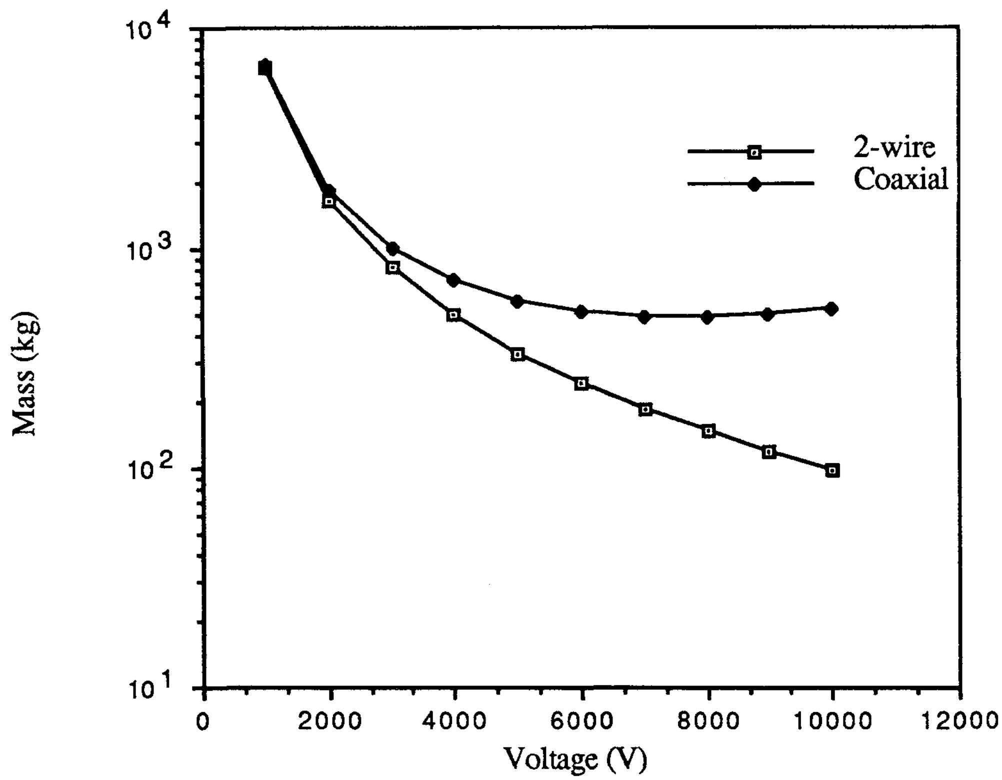


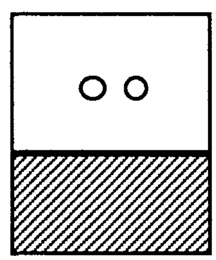


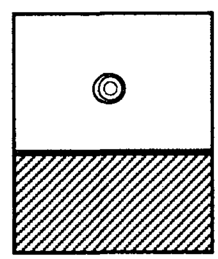
Comments

1) The radius of the two-wire transmission line is for only one of the two conductors, while the radius of the coaxial transmission line is for the complete line including both conductors and the dielectric.
2) The comparison is useful to show that increasing voltage continues to decrease the size of the two-wire line while the coaxial line has an optimum voltage for minimum radius above which the increasing dielectric thickness causes the line size to increase.
3) The shape of the radius vs voltage is the same for the 800 kW line as for the 100 kW line. The line is merely larger.

Case 9.B







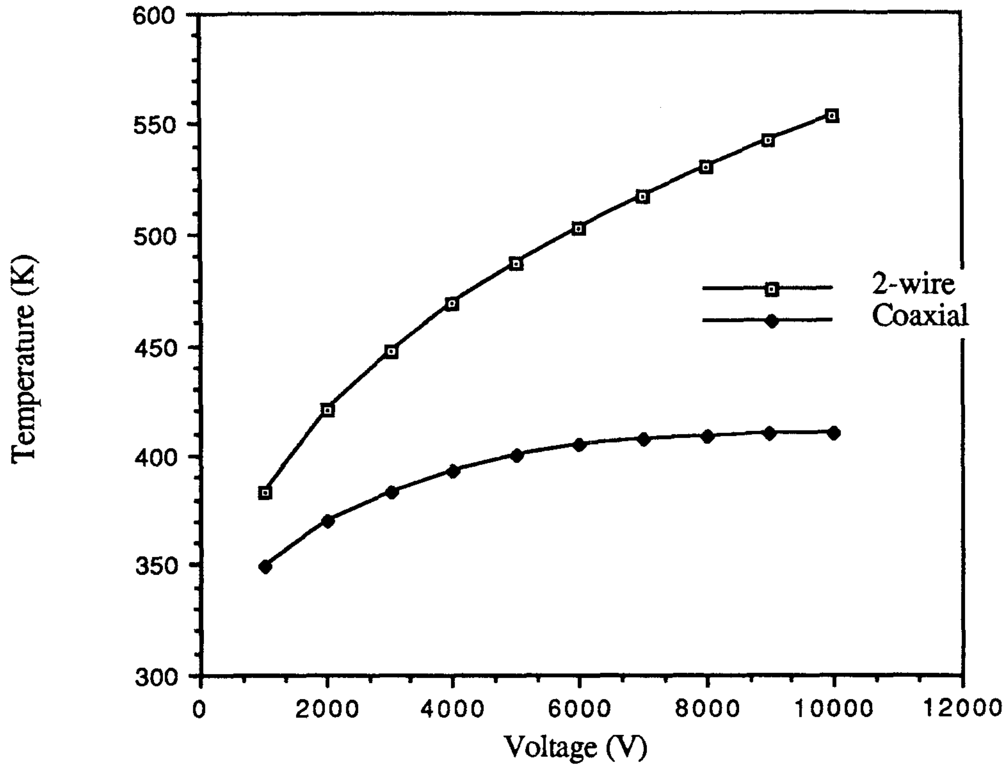
Transmission Line Parameters

Application	800 kW, 1 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

Comments

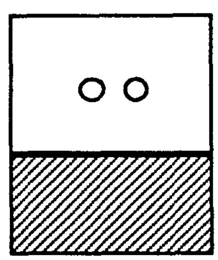
1) For the coaxial transmission design the mass of the 100 kW line (Case 7.B) does not rise as rapidly for higher voltages for the 800 kW line. This is because the conductor masses are larger and thus the dielectric mass at high voltages does not have as much of a dominating effect.

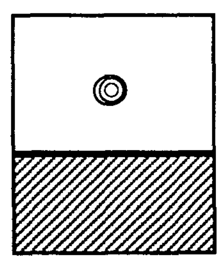
Case 9.C



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %



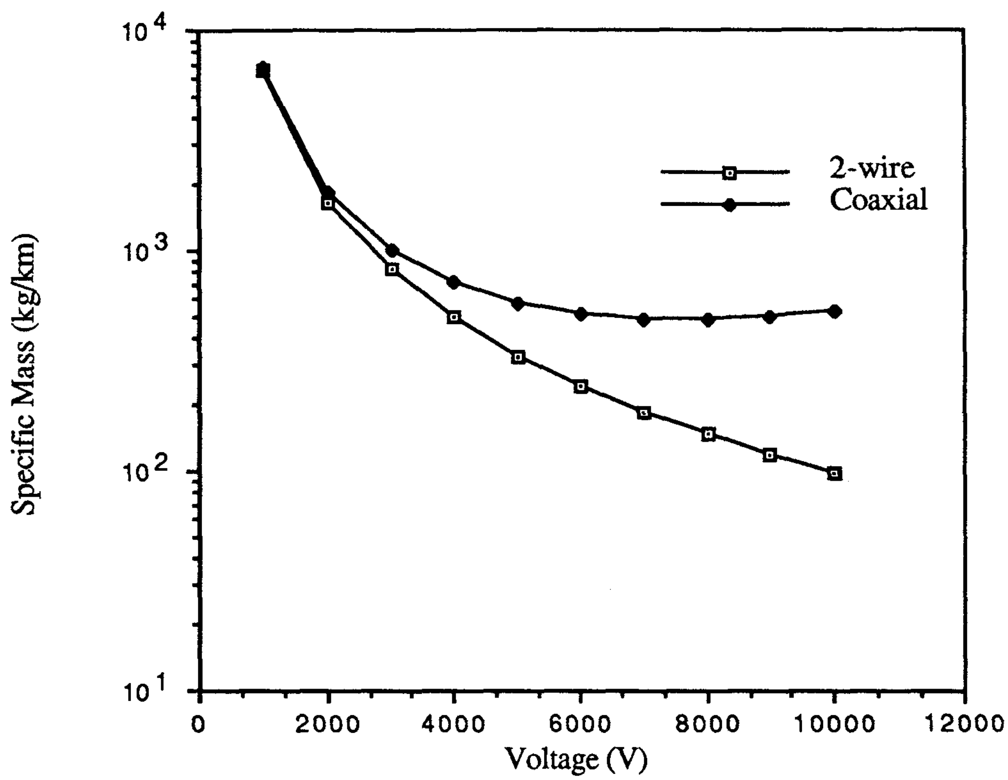


Comments

1) The higher power line runs hotter (compare to Case 7.C) since for a fixed 5 % power loss more power must be dissipated per unit length than for a lower power line. This results in a hotter transmission line.

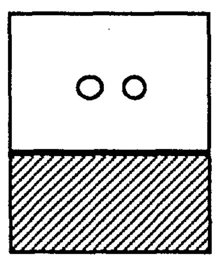
2) A vacuum insulated line could probably operate at 500 to 600 K without failure, but few dielectrics would withstand this thermal stress (for solid dielectric insulated lines).

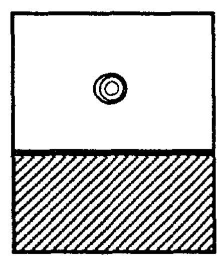
Case 9.E



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	*two-wire, coaxial*
Location	above
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	day
Power loss	5 %

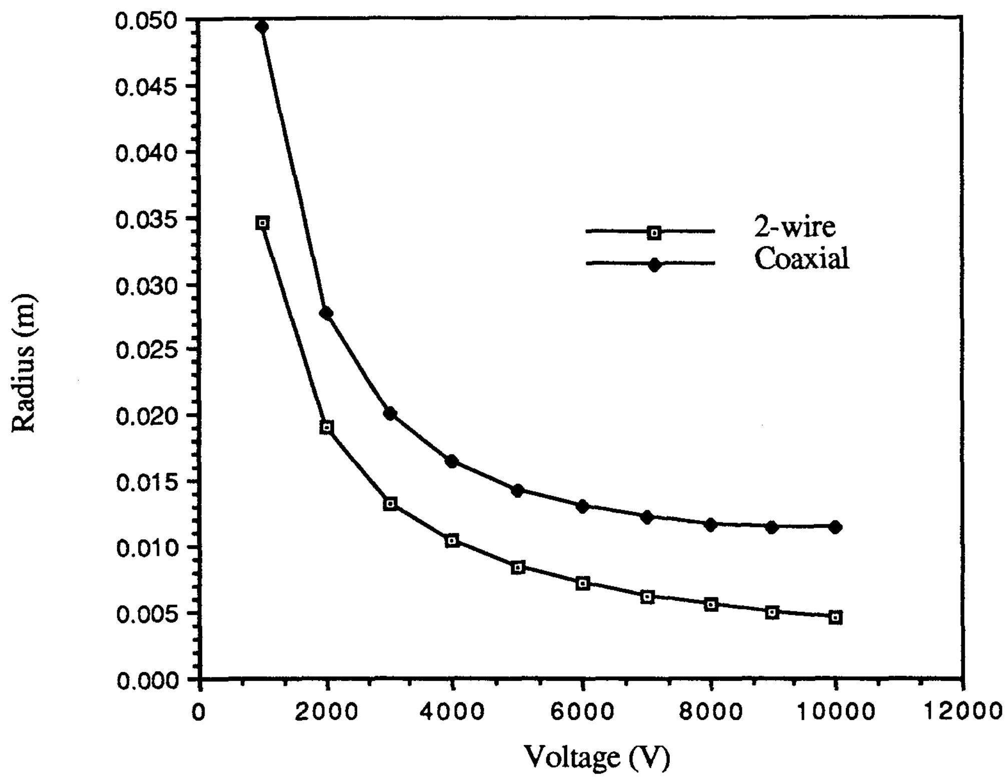




Comments

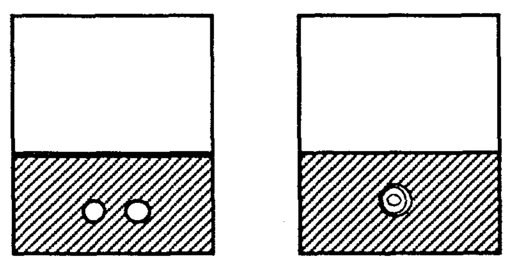
see comments for plot 9.B

Case 10.A



Transmission Line Parameters

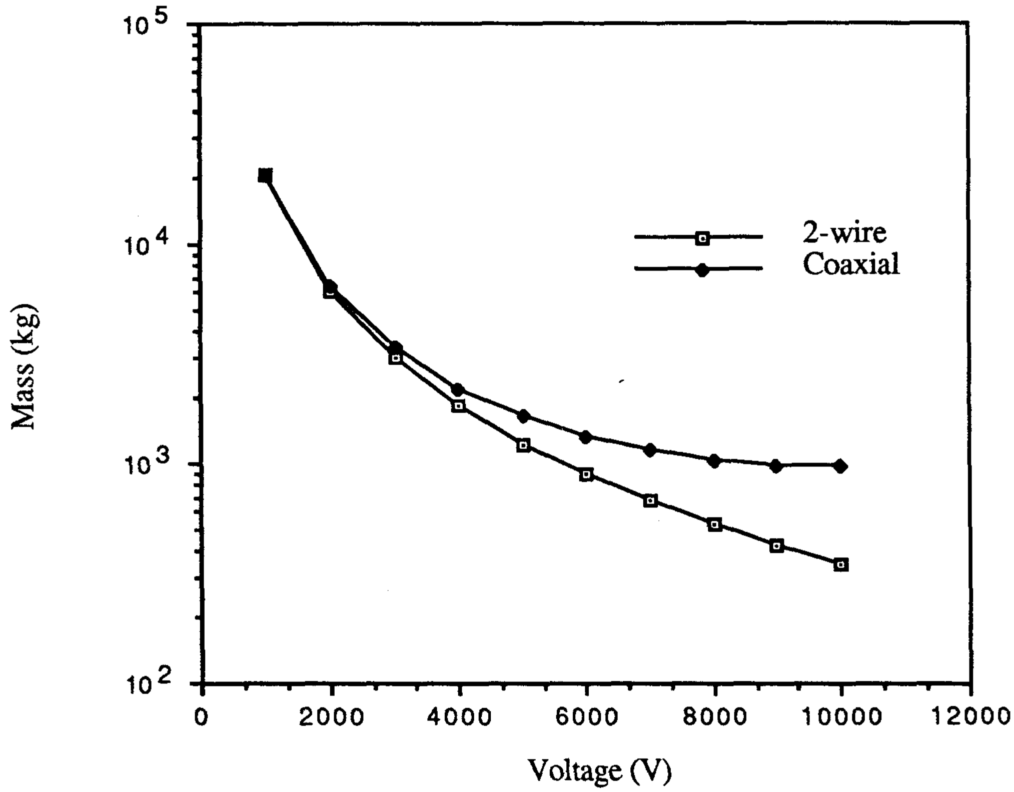
Application	800 kW, 1, km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %



Comments

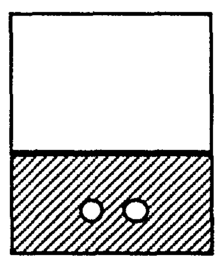
1.) Note that the high power line is at its optimum dielectric to conductor ratio from approximately 5 to 10 kV, and that the dielectric will not dominate until some voltage much larger than 10kV.

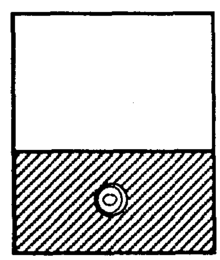
Case 10.B



Transmission Line Parameters

Application	800 kW, 1, km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %

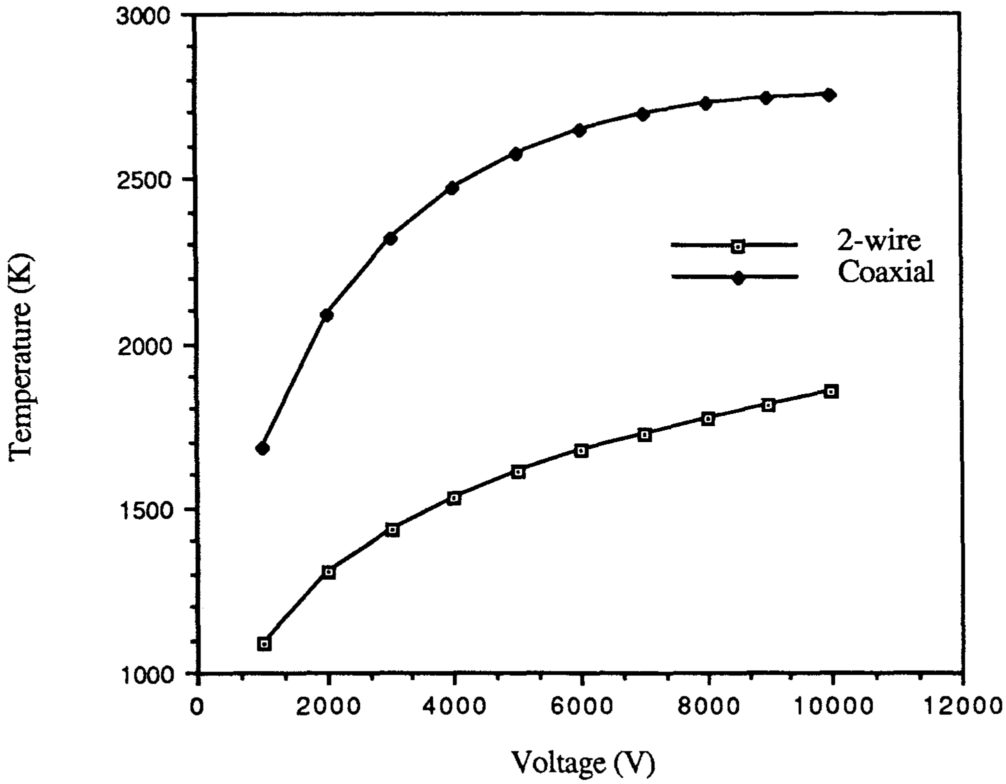




Comments

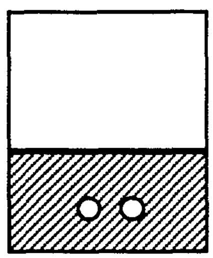
1) In general the mass of the two-wire transmission line and the coaxial line are closer to the same for high power lines than for low power lines due the lesser effect of the dielectric material.

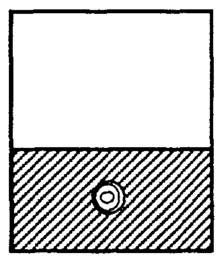
Case 10.C



Transmission Line Parameters

Application	800 kW, 1, km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %

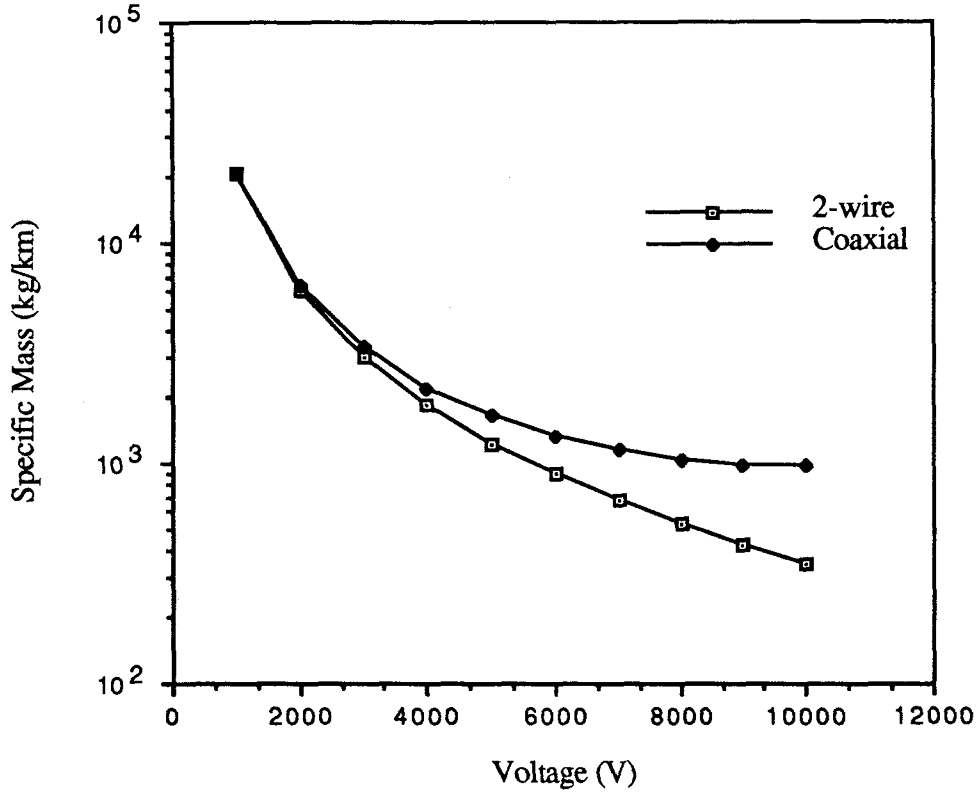




Comments

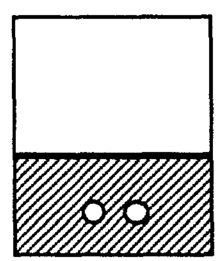
1) Due to the limited ability of the soil to conduct away heat, below-the-surface high power lines at 5 % power loss would get very hot.
2) Obviously lines could not operate at these temperatures, which are above the limits for even the conductor materials. They are shown to illustrate the insulating effect of the soil.
3) The effect of twice the heat at one location for the coaxial cable as opposed to the two-wire line is obvious, as the temperature of the coaxial line is almost twice as high.
4) Although the effect of the temperature on the conductivity of the conductors is taken into account in the model no effect on other physical properties as a function of temperature is taken into account. Also, no effects on the properties of the dielectric materials (such as breakdown strength or lifetime) is taken into account.

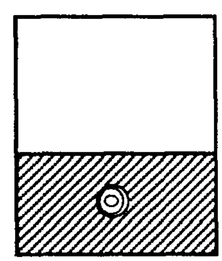
Case 10.E



Transmission Line Parameters

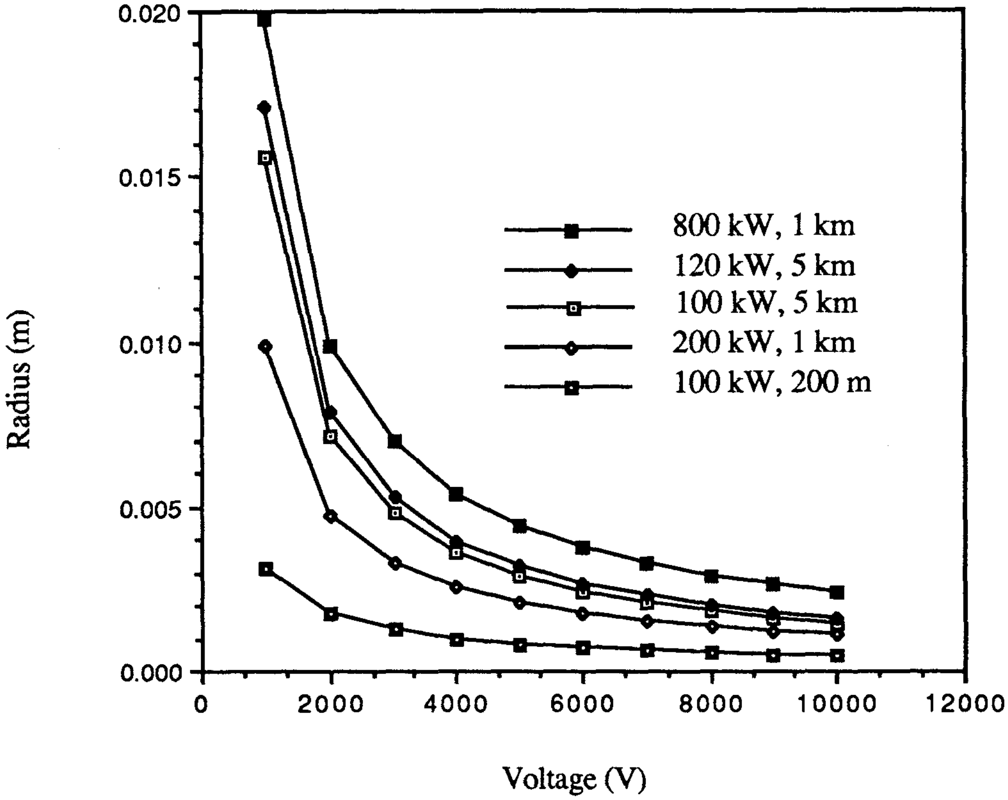
Application	800 kW, 1, km
Geometry	*two-wire, coaxial*
Location	below
Conductor	aluminum
Insulator	vacuum, solid (TFE)
Day/Night	
Power loss	5 %





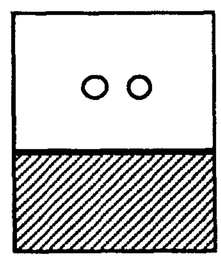
Comments

Case 11.A



<u>**Transmission Line Parameters**</u>

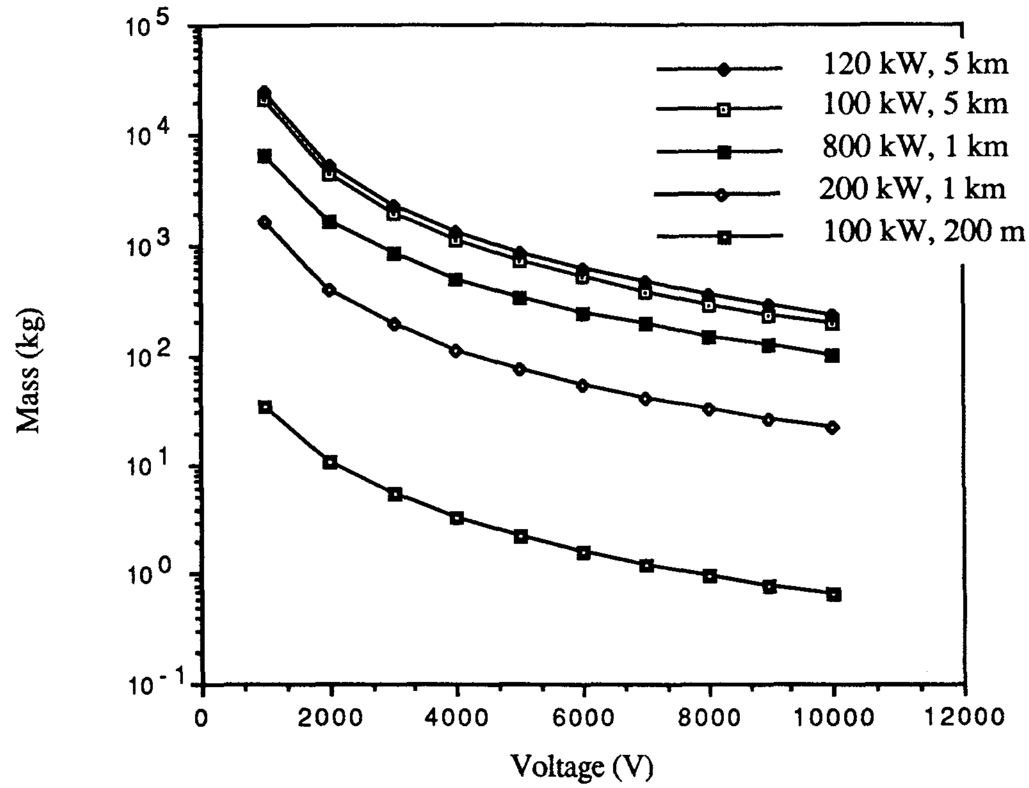
Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %



<u>**Comments**</u>

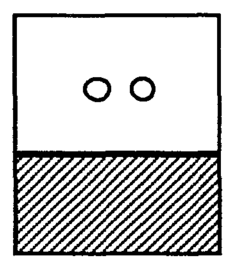
1) Forcing a 5 % power loss on a transmission line regardless of its length or power level is impractical. Thus, this multiple line comparison doesn't convey much information, except that higher power long lines are larger.

Case 11.B



Transmission Line Parameters

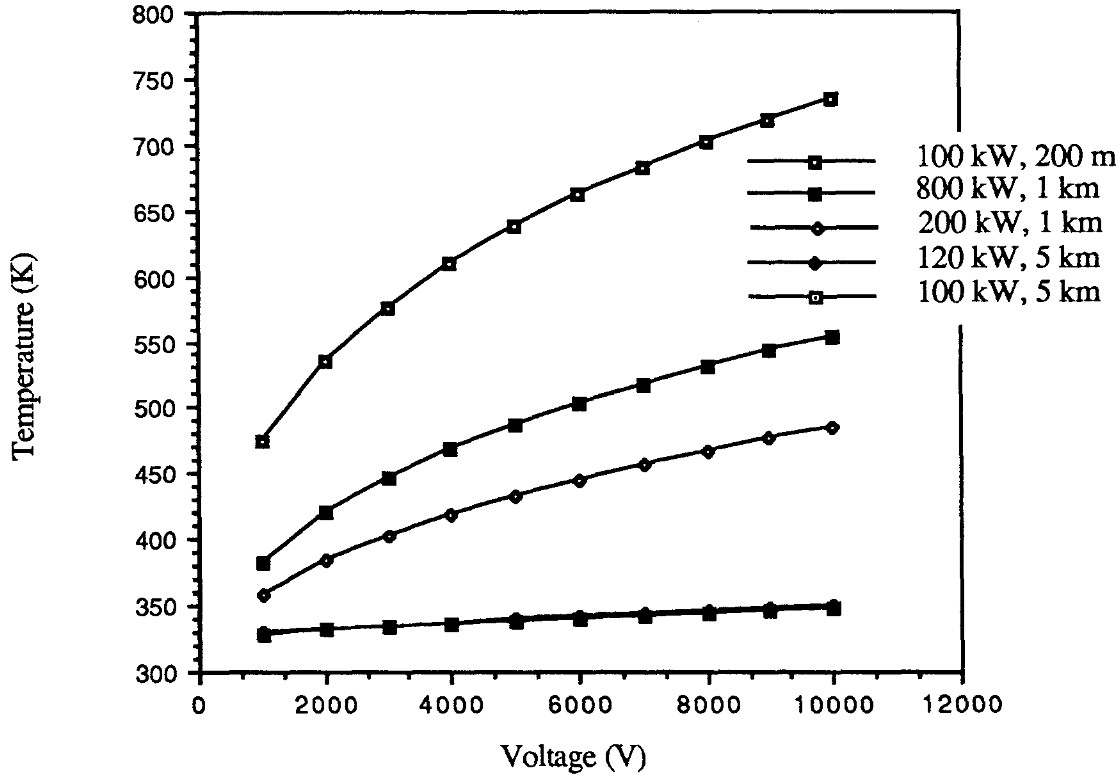
Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

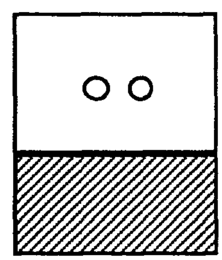


Comments

1) Total mass comparison for the different lines doesn't really reveal anything outstanding. Obviously longer lines are more massive. See the specific mass plot 11.E.

Case 11.C





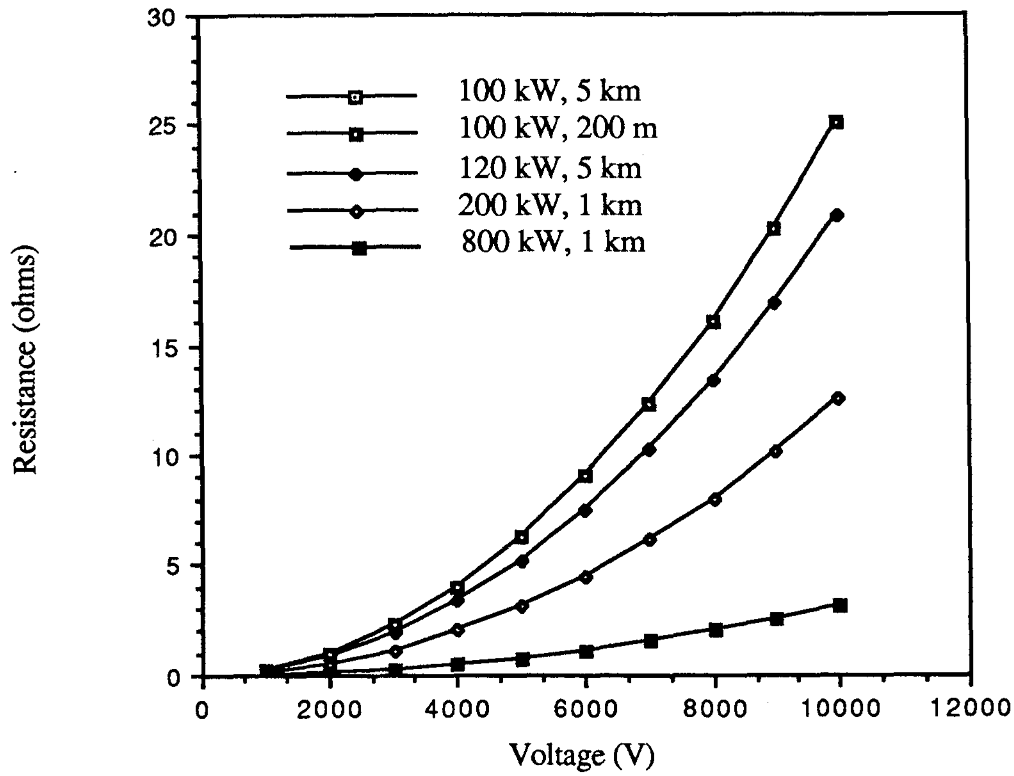
Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

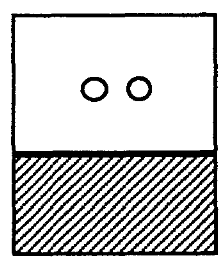
1) The 100 kW, 200 m line is hot because of the 5 % loss requires it to dissipate 5 kW over 200 m
2) Comparing the 800 kW, 1 km line and the 200 kW, 1 km line, the larger power line runs hotter because it dissipates more power per unit length.

Case 11.D



Transmission Line Parameters

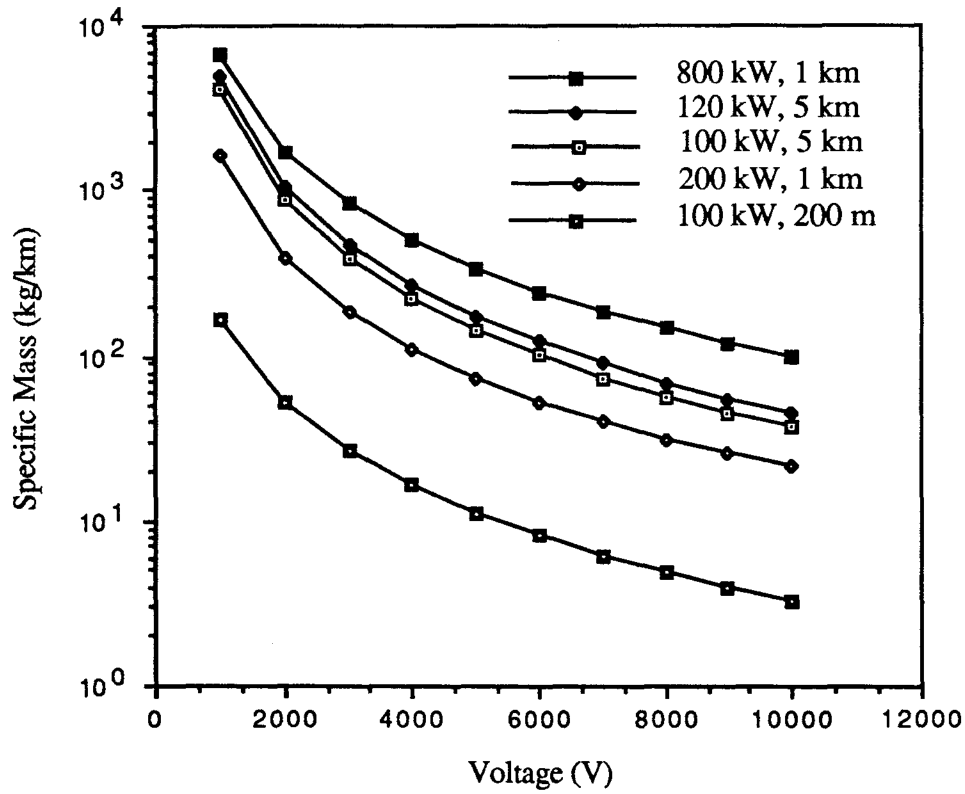
Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

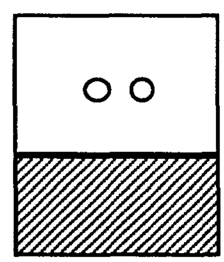


Comments

1) This plot just compares the total line resistances that were required to obtain the power loss that would result in a 5 % loss for the specific power and length of the line.

Case 11.E





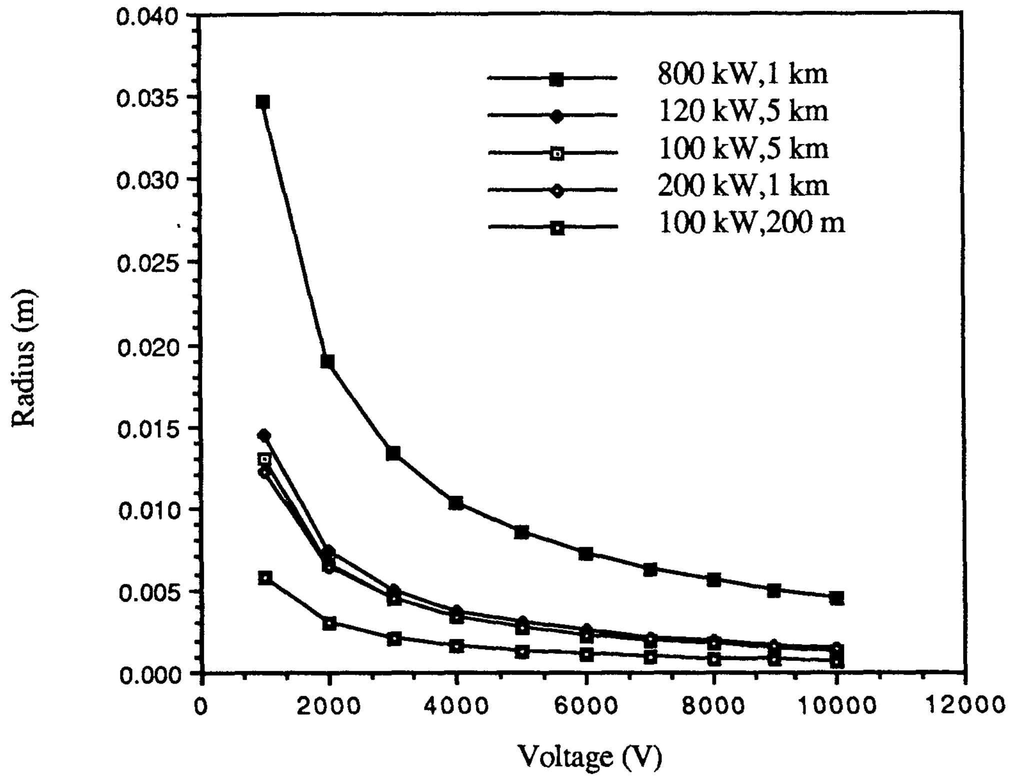
Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	5 %

Comments

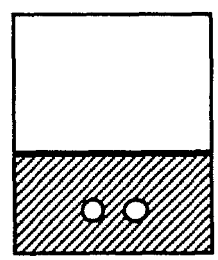
1) The decreasing order of specific mass corresponds to the decreasing size of the radius.

Case 12.A



Transmission Line Parameters

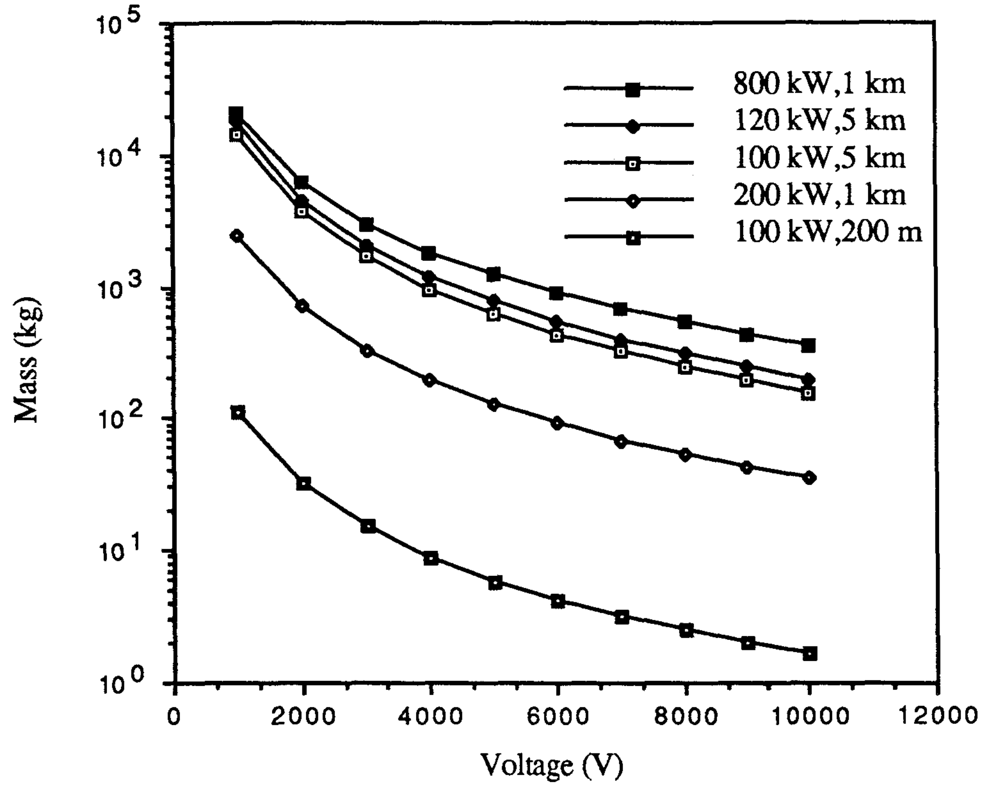
Application	*five different lines*
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %



Comments

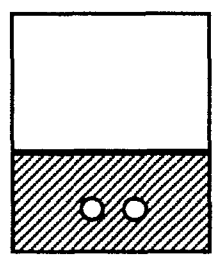
1) Compare these plots to the above ground plots (11.A). The 800 kW, 1 km line is nearly twice as large in diameter for the underground case; the 200 kW, 1 km and 100 kW, 200 m lines are slightly larger; and, the two 5 km lines (100 and 120 kW) are a little smaller. This is due to the effect of the temperature of these lines underground as opposed to above ground. Referring to plot 12.C it can be seen that the two 5 km lines run cooler underground than above ground, and the other three run hotter underground. Again, a hotter conductor material requires a larger radius conductor because of the lower conductivity.

Case 12.B



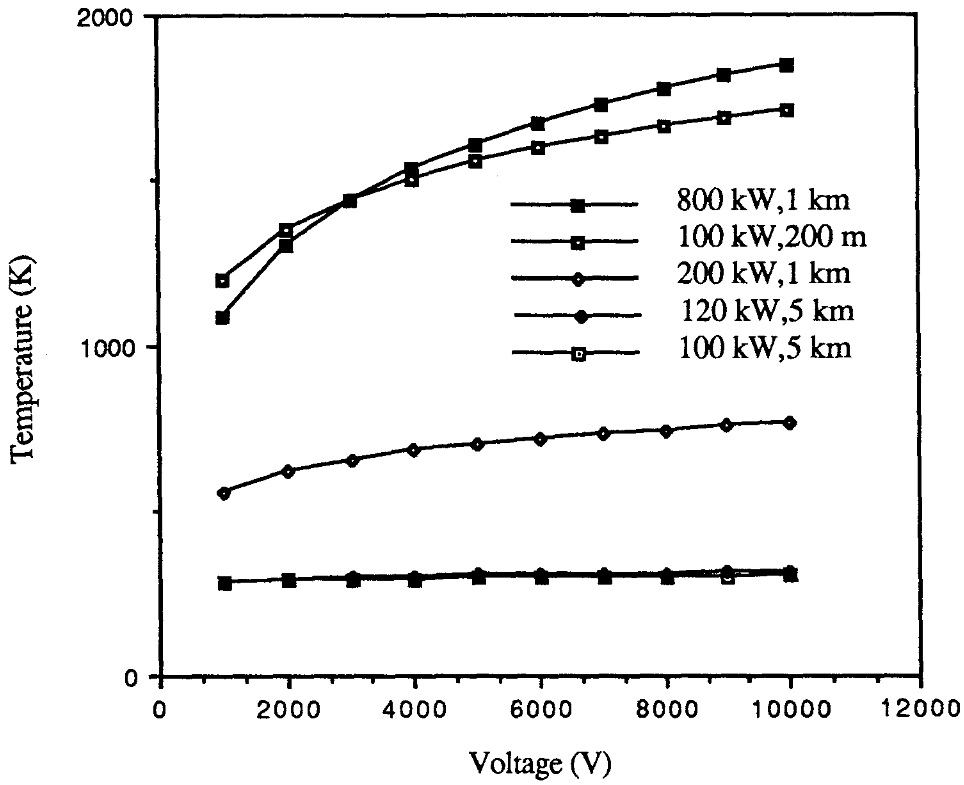
Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %



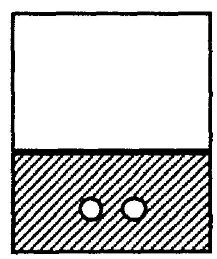
Comments

Case 12.C



Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %

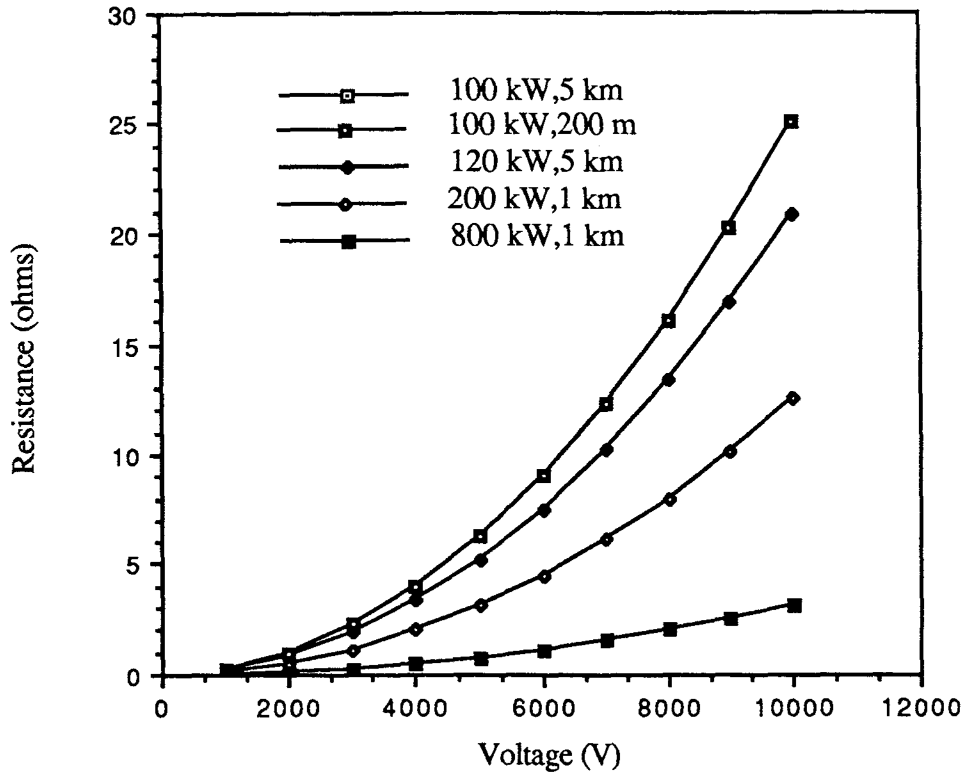


depth 25 cm

Comments

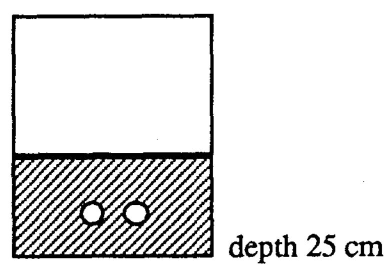
1) The temperatures for the high power line and the short line are too high at 5 % power loss.
2) High power lines and short medium power lines must run at less than 5 % power loss.

Case 12.D



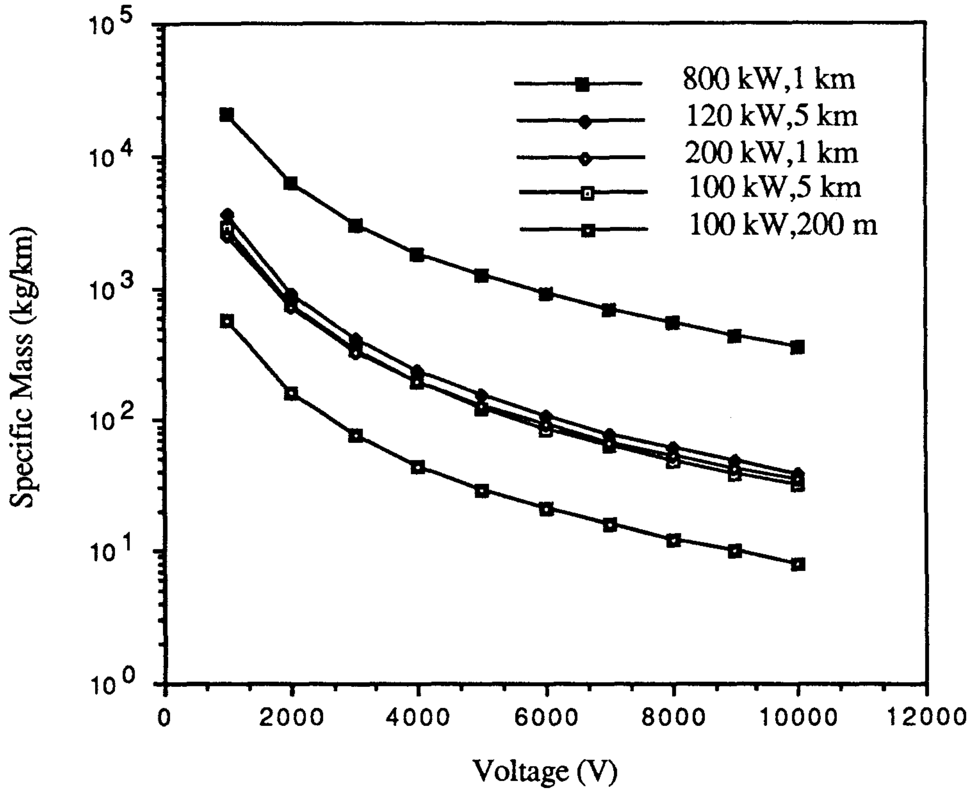
Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %



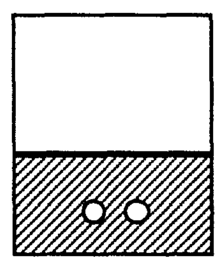
Comments

Case 12.E



Transmission Line Parameters

Application	*five different lines*
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %

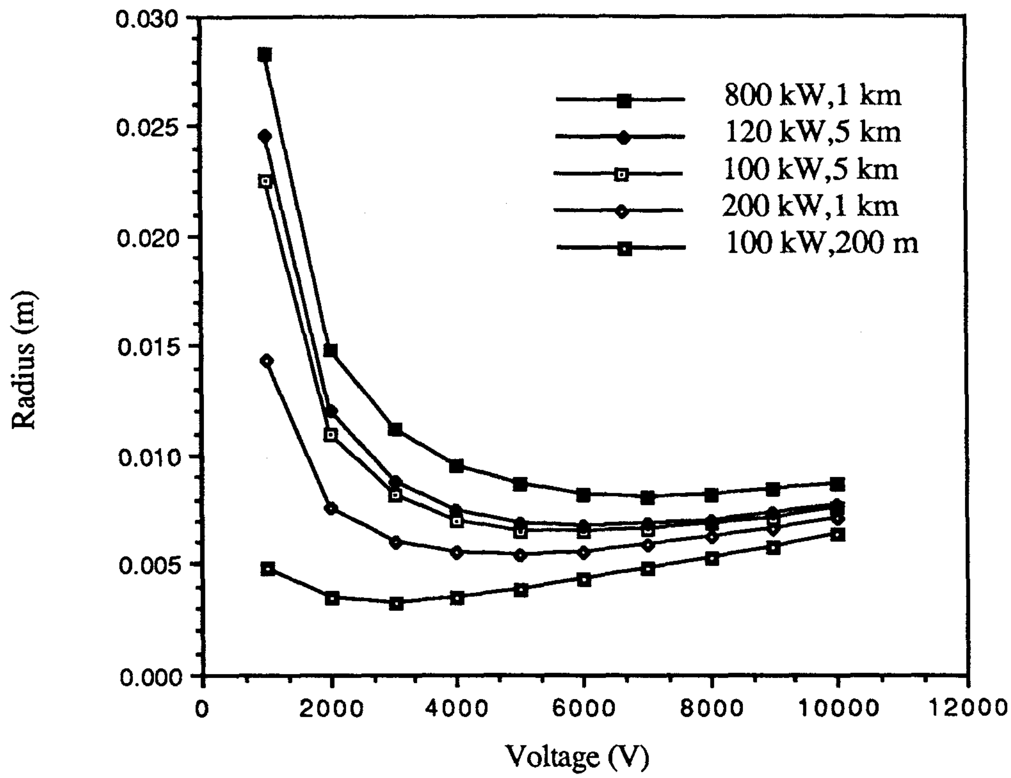


depth 25 cm

Comments

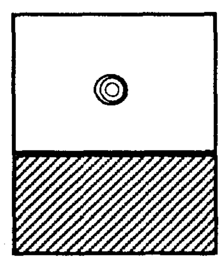
1) The 800 kW, 1 km line has the greatest specific mass since it must transmit the greatest power and has the largest cross section.
2) The 100 kW, 200 m line has the lowest specific mass, since it has the lowest cross section. This line has a smaller radius than longer 100 kW lines since it must lose 5 % of its power in a shorter distance, and thus needs a higher resistance (see 12.D).

Case 13.A



<u>**Transmission Line Parameters**</u>

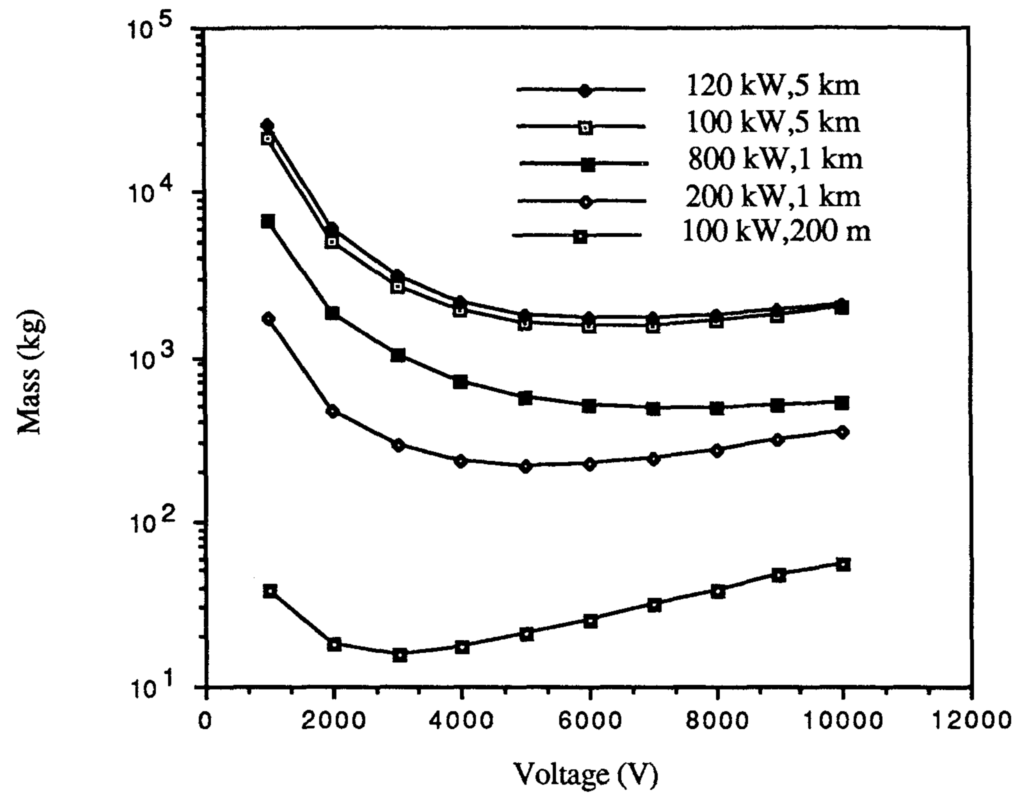
Application	*five different lines*
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

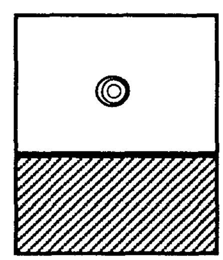


<u>**Comments**</u>

1) The 100 kW, 200 m line starts off at its minimum radius for low voltage. This is because for this power, length, and efficiency the dielectric volume and mass starts dominating immediately as the voltage is raised. For the other lines the mass of the conductors dominate at low voltages.
2) The magnitudes of the radii of the coaxial lines are larger than for each two-wire line (compare to 11.A), but the descending order of the size of the various lines is the same.

Case 13.B





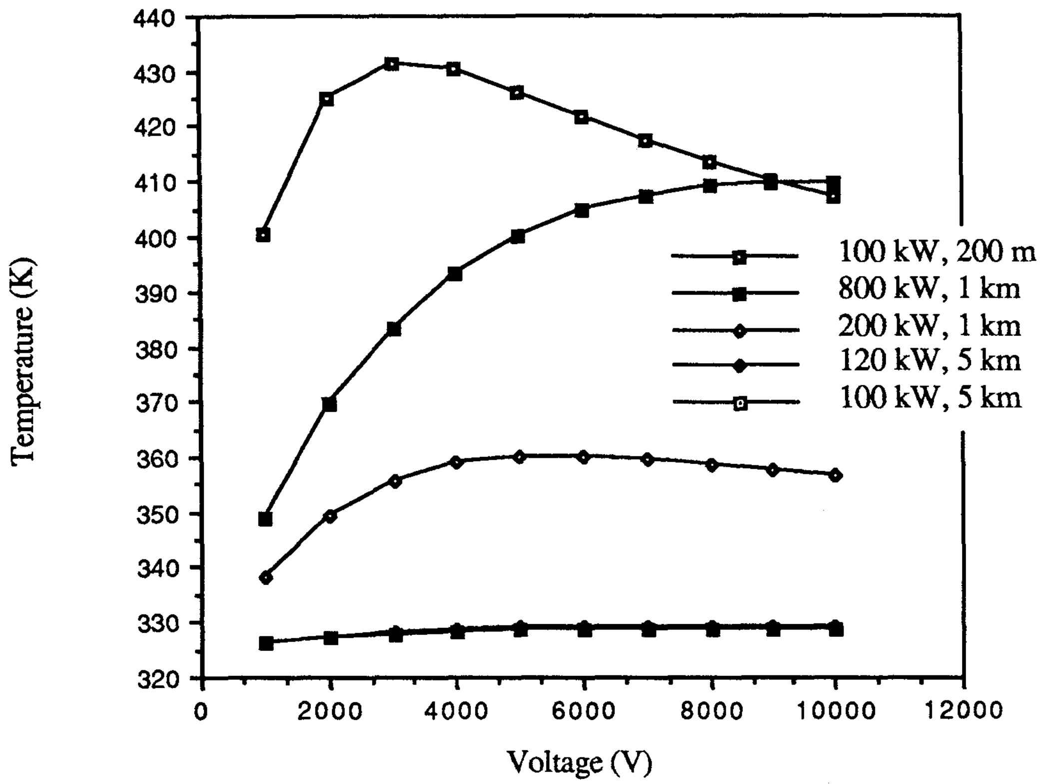
Transmission Line Parameters

Application	*five different lines*
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

Comments

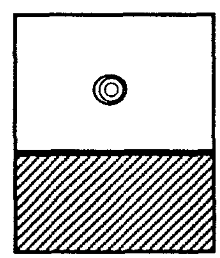
1) Total transmission line mass does not contain much information for a parameter study. For instance the total mass will not consistently follow the same descending order as the radii plots (13.A), since the length of the line effects its mass.
2) This plot is useful for observing the total mass of the lines for design and costs studies.
3) See the specific mass plot (13.E) to compare how the power level and line efficiency effects mass per unit length.

Case 13.C



<u>**Transmission Line Parameters**</u>

Application	*five different lines*
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %



Comments

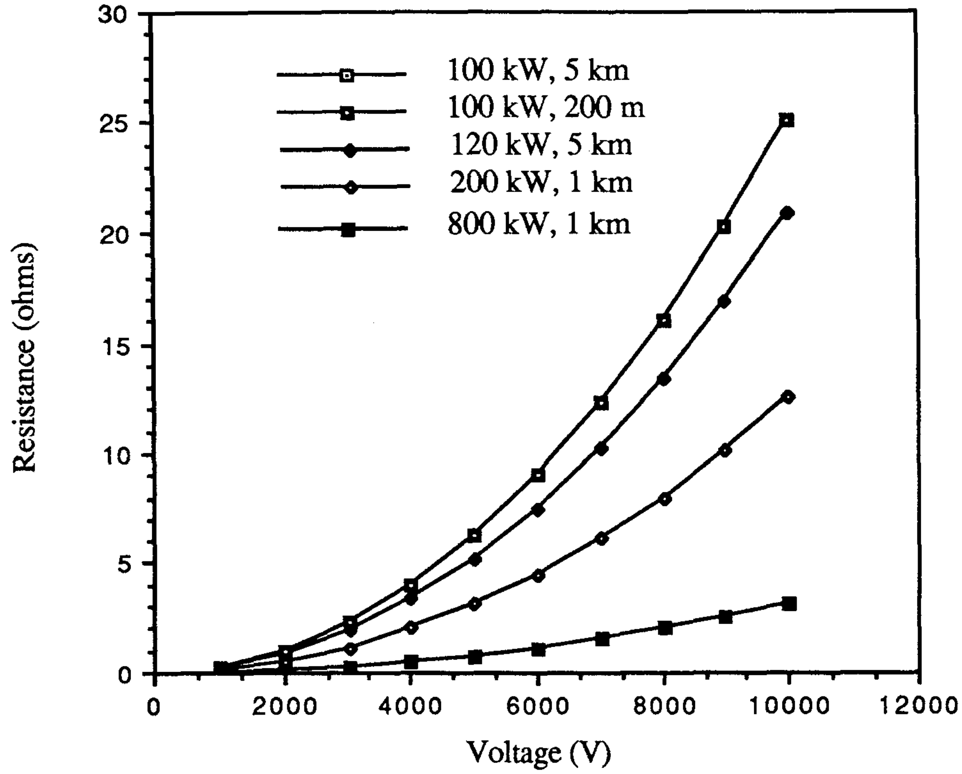
1) The temperature curves for the various transmission lines are complicated by a number of factors leading to a variety of curve shapes. These factors include the power level and length of the line, which with the 5 % loss gives different power per unit length to be dissipated for each line; the effect of the dielectric mass on the line radius; and, the temperature at which the line operates.

For example, the top curve (the 100 kW, 200 m line) is a very sensitive function of the line radius (compare to 13.A). At 1 kV the line radius is 5 mm decreasing to 3 mm at 3 kV, and gradually increasing to 6 mm at 10 kV. Since this line has to dissipate a lot of power per unit length (in order to loss 5 % over 200 m) its temperature is very sensitive to line radius (inversely related).

The second curve down (the 800 kW, 1 km line) gradually increases its temperature as its radius decreases. The two upper curves actually cross due to the complex interaction between the amount of power to be dissipated per unit length and the line radius.

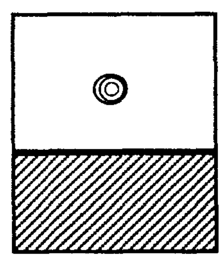
The lower two curves (the two 5 km lines) have the least amount of power per unit length to dissipate and are not sensitive functions of line radius.

Case 13.D



Transmission Line Parameters

Application	*five different lines*
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %

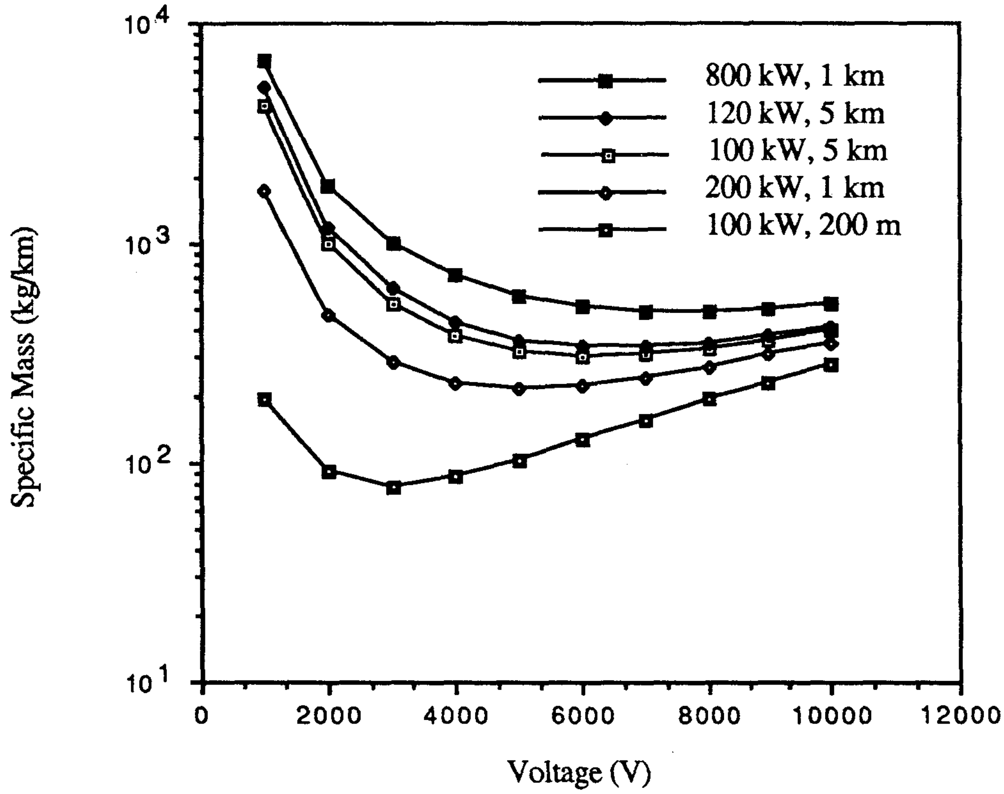


Comments

1) Remember that the resistance of a transmission line is determined by finding the amount of current that must flow in a line for each voltage, given that the power transmitted and the % power loss are fixed. Once the line resistance is determined the necessary conductor radius is calculated for the given conductor material knowing the length of the line.

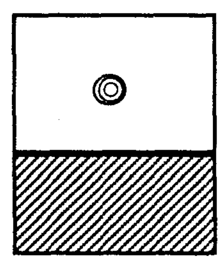
2) Given the power transmitted and the percent power loss the resistance is determined. Thus, the two 100 kW lines have the same total resistance even though they are different lengths (these two resistances are superimposed on the graph). The two different length lines must have different resistance per unit length to achieve identical total resistance and thus the two different length lines will have different radii (see 13.A).

Case 13.E



Transmission Line Parameters

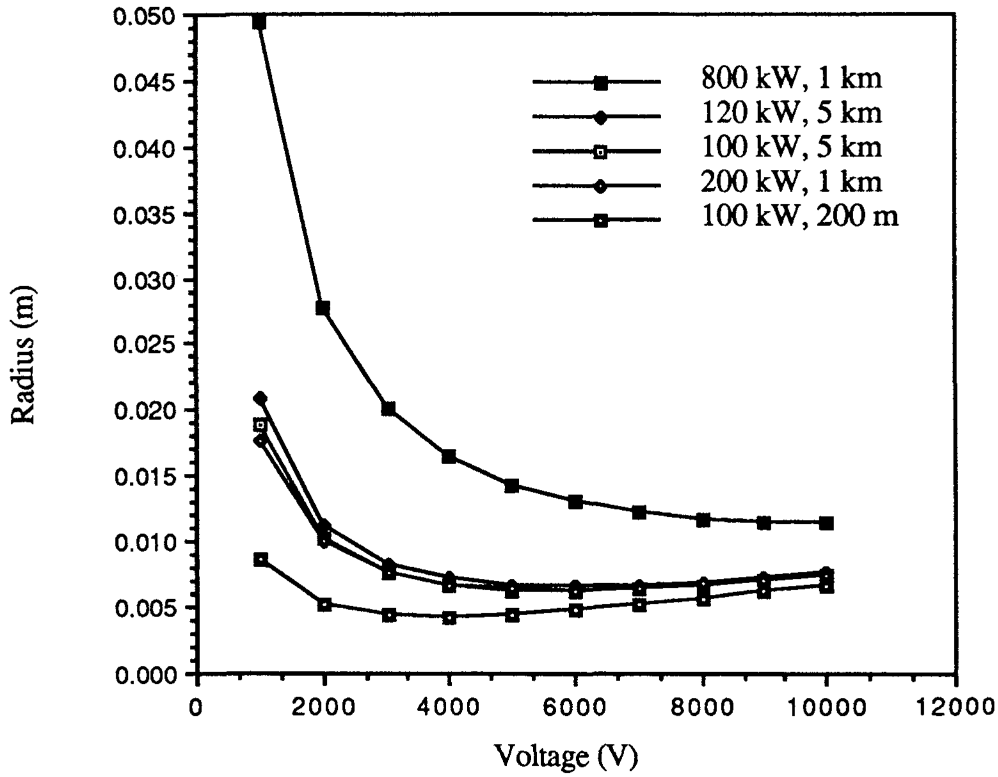
Application	*five different lines*
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	5 %



Comments

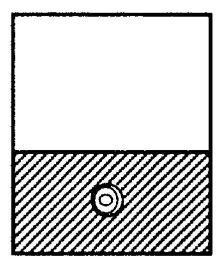
1) These curves inversely follow the radii (13.A).

Case 14.A



<u>Transmission Line Parameters</u>

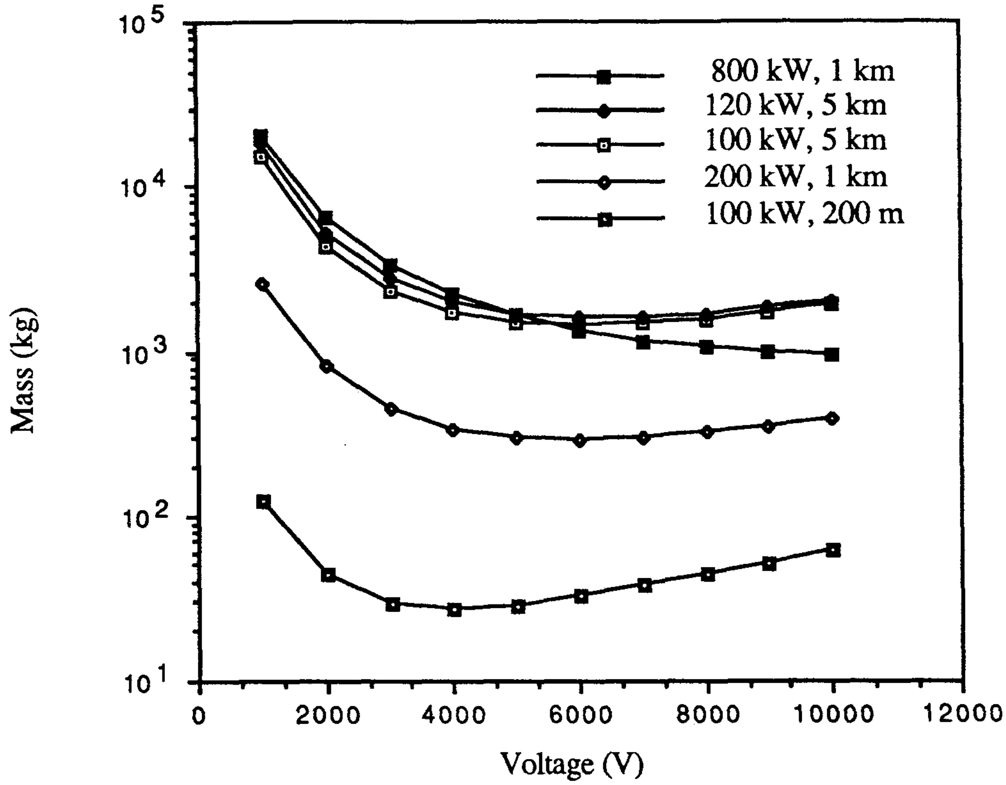
Application	*five different lines*
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



<u>Comments</u>

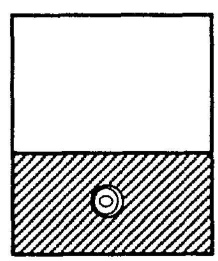
1) Compare these plots to the above ground plots (13.A). At low voltages the 800 kW, 1 km line is nearly twice as large in diameter for the underground case, but for higher voltages it is only about 50 % larger. The 200 kW, 1 km and 100 kW, 200 m lines are slightly larger. The two 5 km lines (100 and 120 kW) are actually a little smaller. This is due to the effect of the temperature of these lines underground as opposed to above ground. Referring to plot 14.C and 13.C it can be seen that the two 5 km lines run about the same temperature underground compared to above ground, and the other three run much otter underground. Again, a hotter conductor material requires a larger radius conductor because of the lower conductivity.

Case 14.B



Transmission Line Parameters

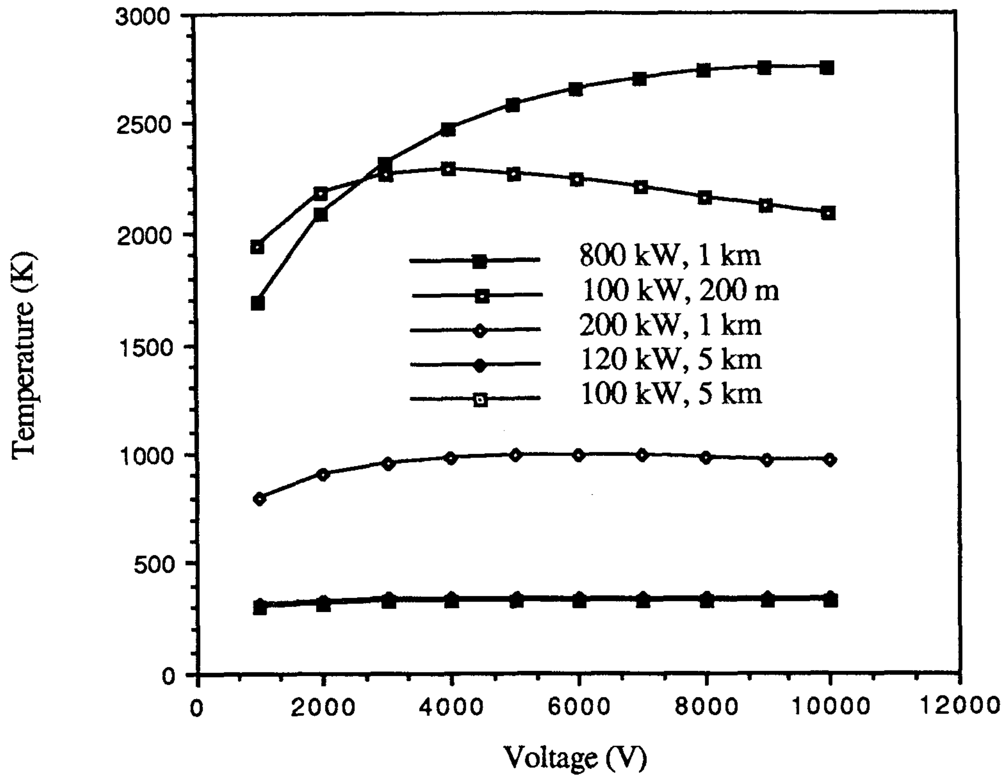
Application	*five different lines*
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



Comments

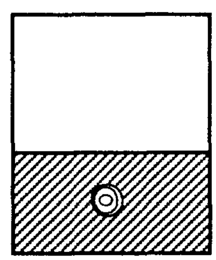
1) Total mass comparison difficult to interpret due to complex interaction between line temperature on line radius, the thermal characteristics of the soil, the voltage, and the line length. See 14.E for mass per unit length comparisons.

Case 14.C



Transmission Line Parameters

Application	*five different lines*
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %

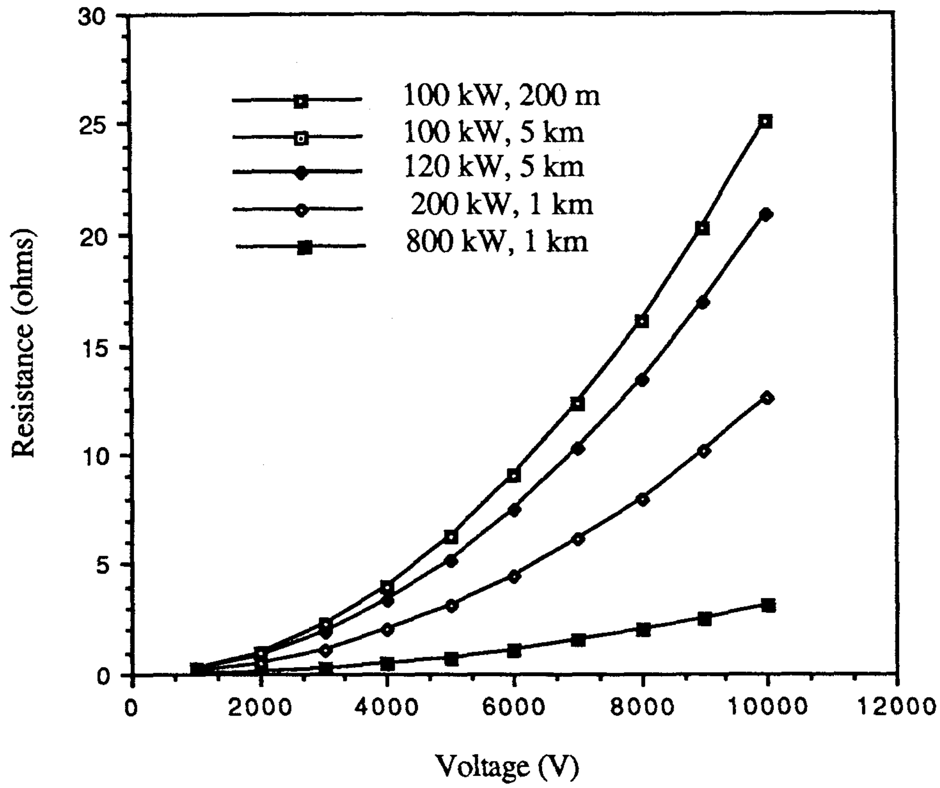


depth 25 cm

Comments

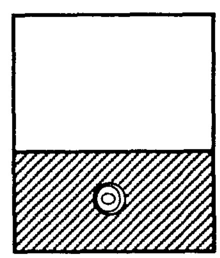
1) The temperatures for the high power line and the short line are too high at 5 % power loss.
2) High power lines and short medium power lines must run at less than 5 % power loss.

Case 14.D



Transmission Line Parameters

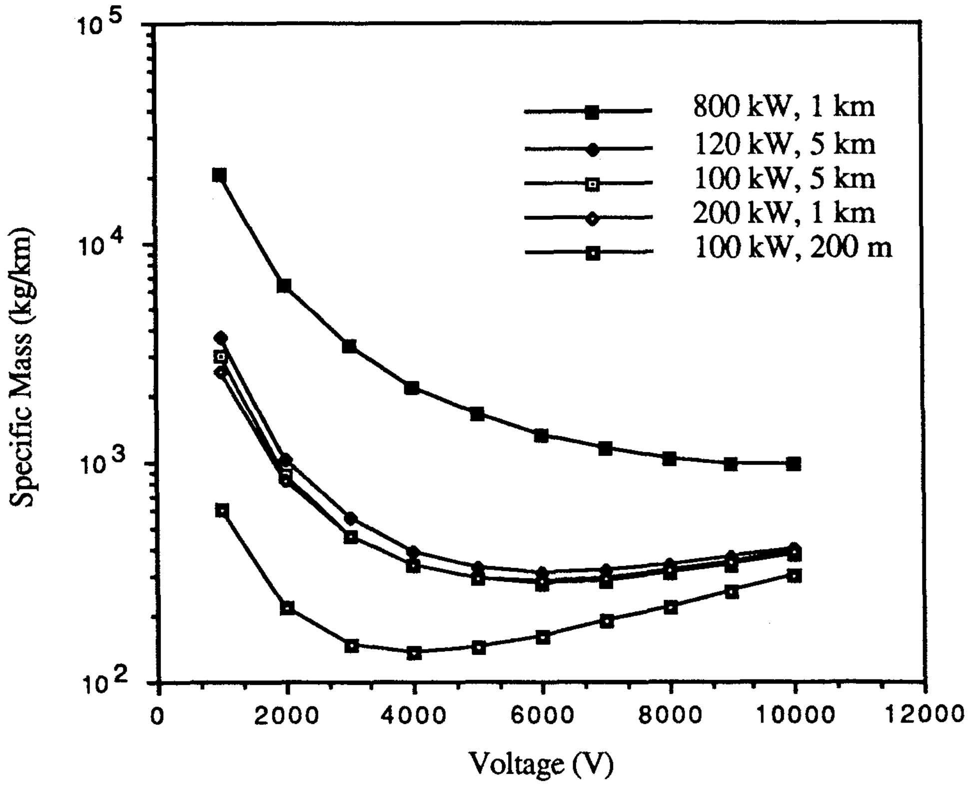
Application	*five different lines*
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %



Comments

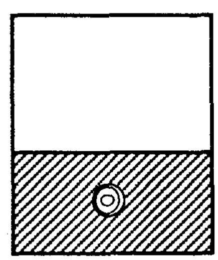
see comments 13.D

14.E



Transmission Line Parameters

Application	*five different lines*
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %

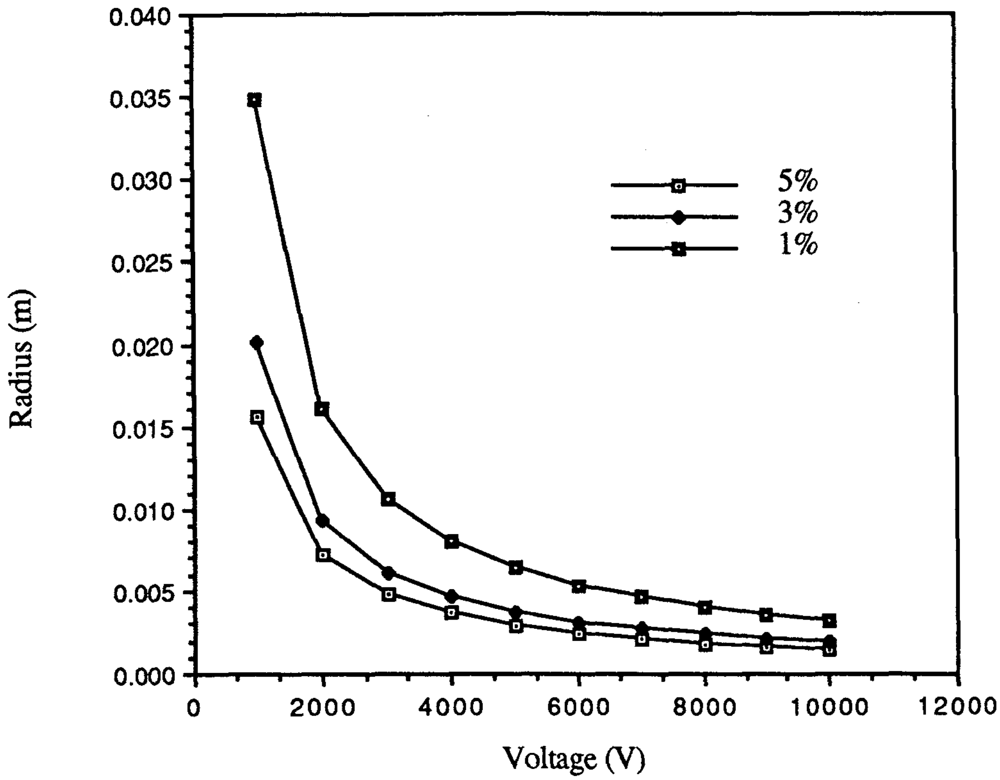


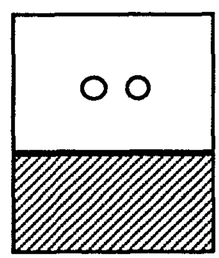
depth 25 cm

Comments

1) Note log axis for specific mass
2) Agrees with curve shape and descending transmission line order as radii (14.A).

Case 15.A





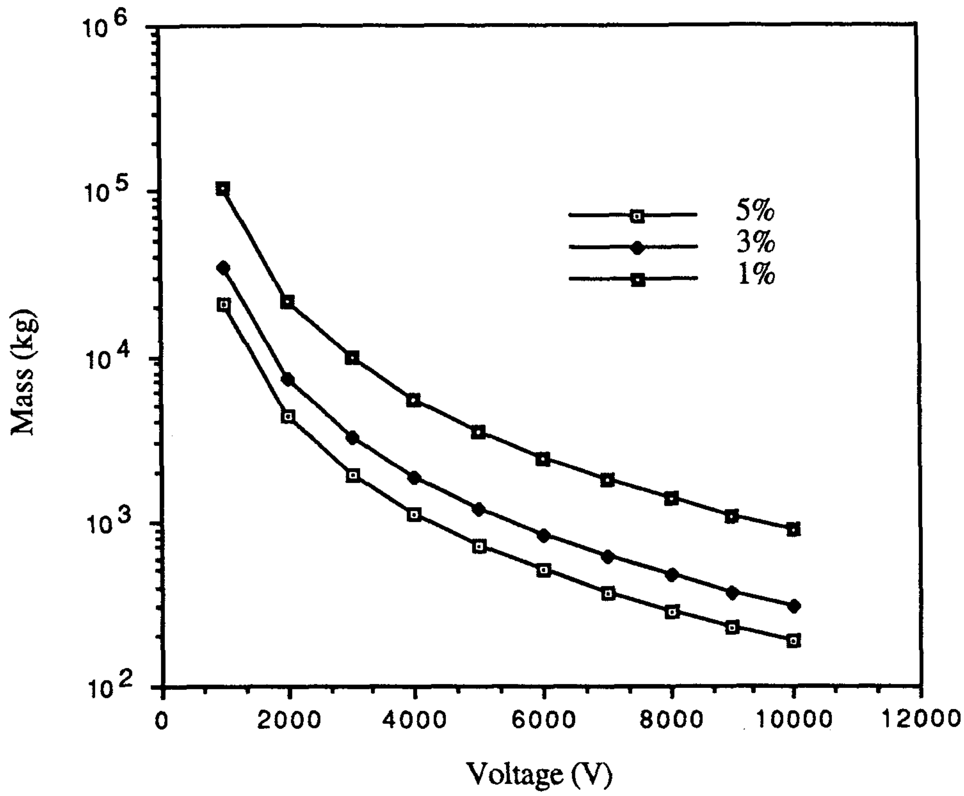
Transmission Line Parameters

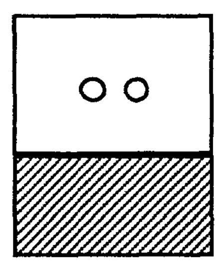
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3,5 %*

Comments

1) Remember that % efficiency + % power loss = 100 %.
   Thus, 5 % power loss = 95 % efficient line
   3 % power loss = 97 % efficient line
   1 % power loss = 99 % efficient line
2) More efficient lines are larger to achieve lower resistance.
3) At higher voltages changes in efficiency have less impact on radius than at lower voltages.

Case 15.B





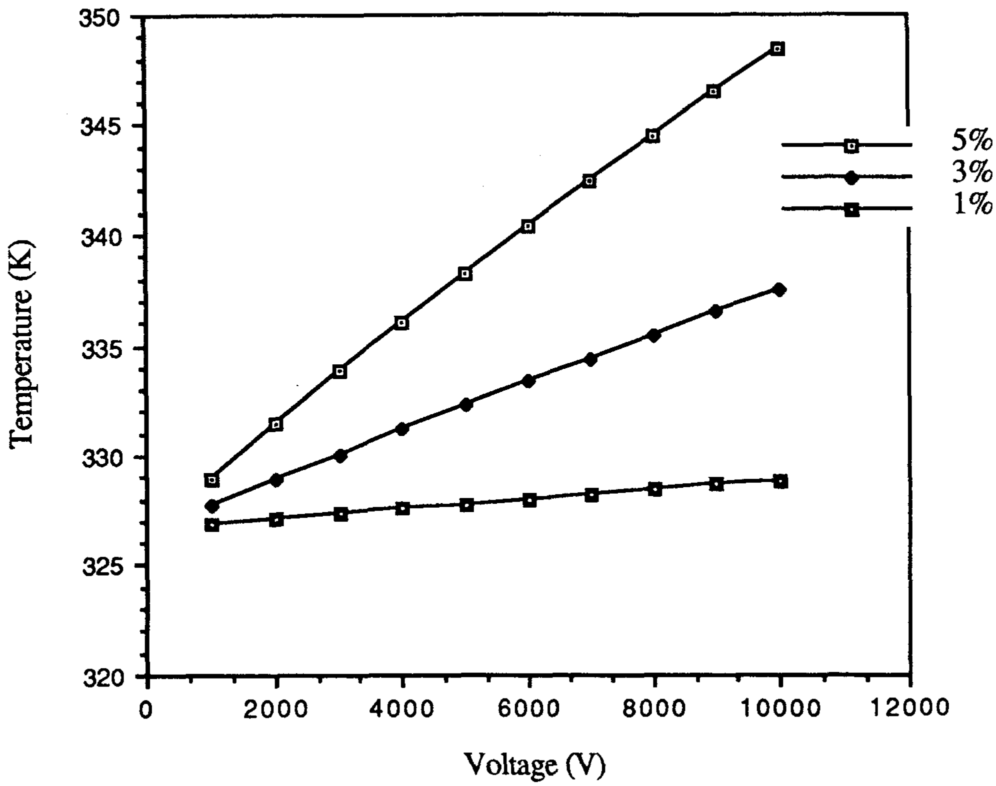
Transmission Line Parameters

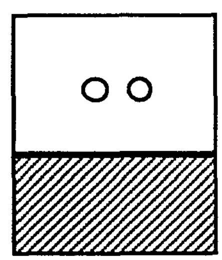
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3,5 %*

Comments

1) Higher efficiencies (lower power losses) require more massive lines.

Case 15.C





Transmission Line Parameters

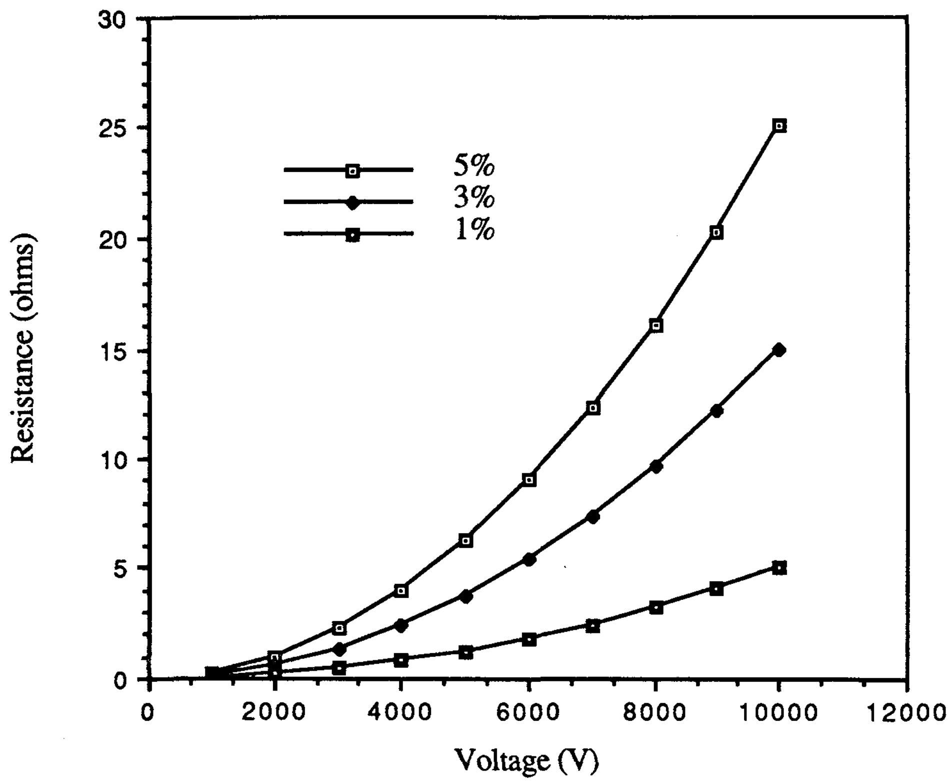
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3,5 %*

Comments

1) The less efficient lines are hotter because they must dissipate more energy per unit length.
2) At high voltages (resulting in smaller radii) small improvements in efficiencies (i.e., lowering the power lost) result in significant reductions in temperature.
3) For this transmission line the power that must be dissipated per unit length is:

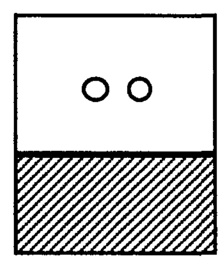
5% power loss	or	95 % efficient line =	1.0 W/m
3 % power loss	or	97 % efficient line =	0.6 W/m
1 % power loss	or	99 % efficient line =	0.2 W/m

Case 15.D



Transmission Line Parameters

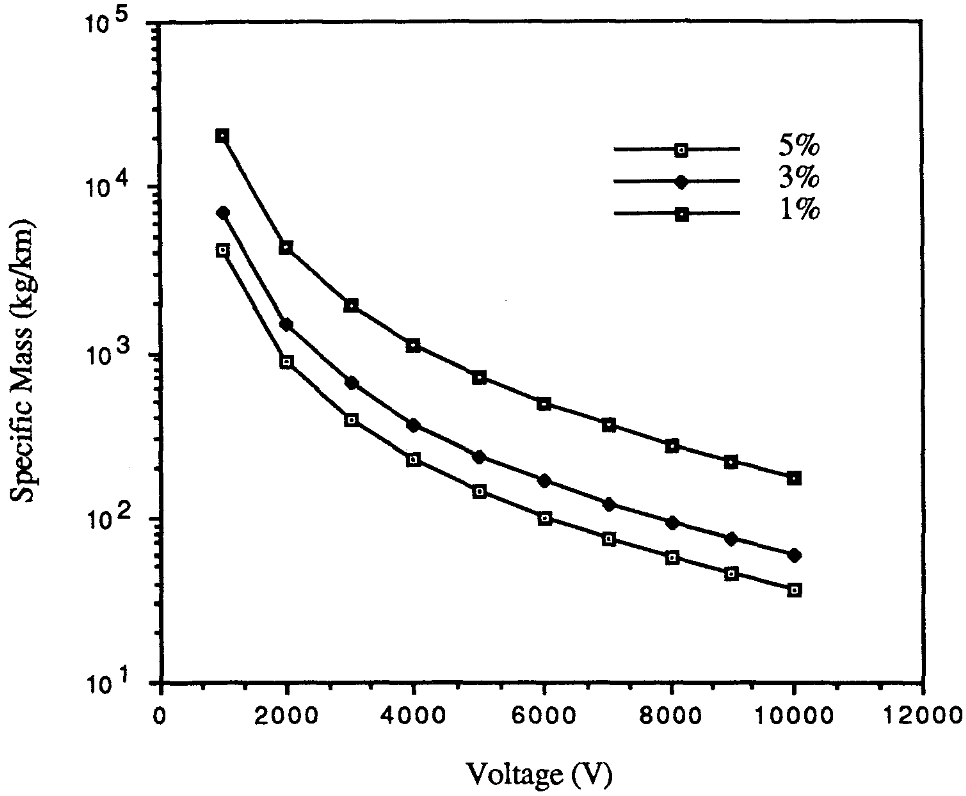
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3,5 %*



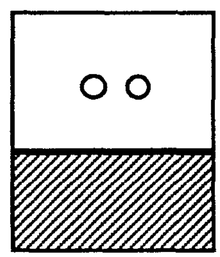
Comments

1) Better efficiency (lower power loss) requires a lower resistance for the transmission line.

Case 15.E



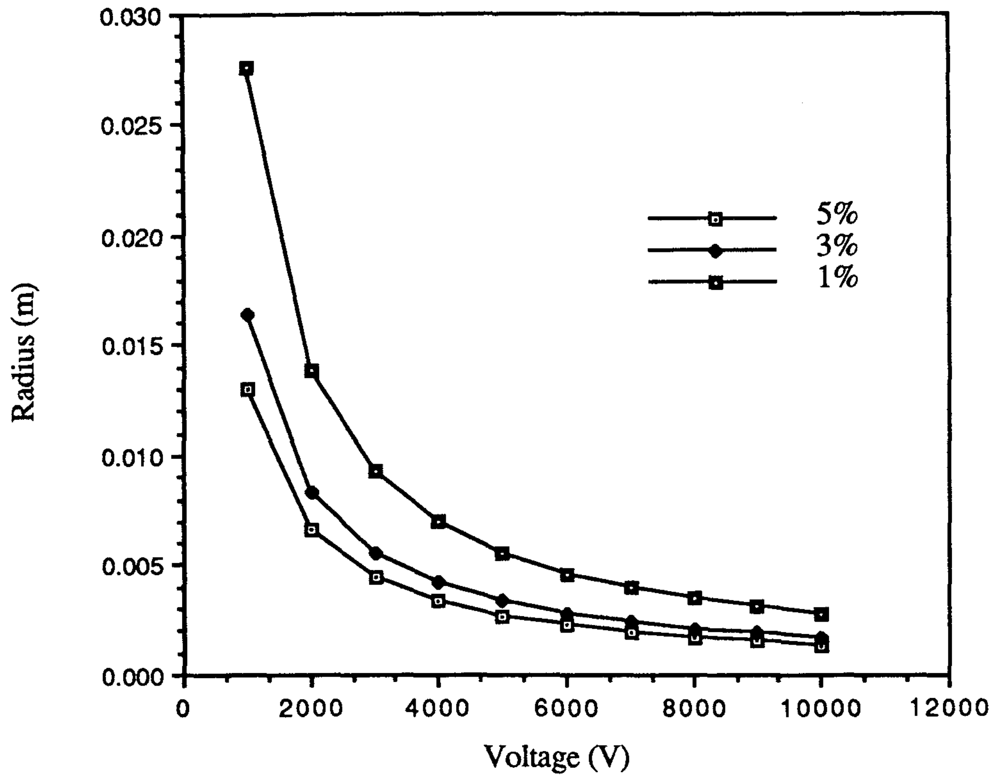
Transmission Line Parameters

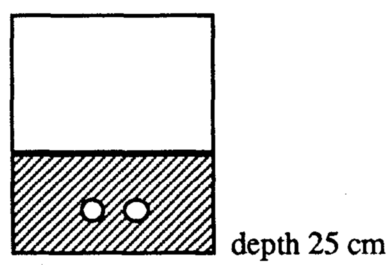


Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3,5 %*

Comments

Case 16.A





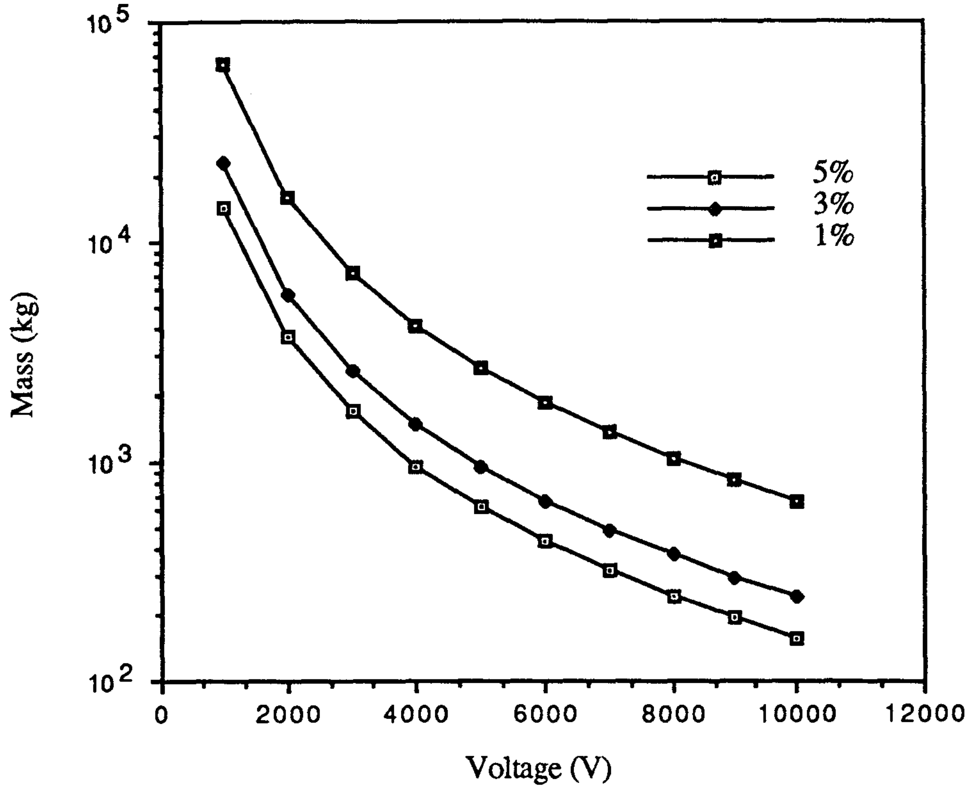
Transmission Line Parameters

Application	100kW, 5km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1%, 3%, 5%*

Comments

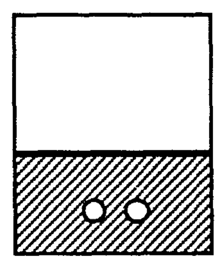
1) For this transmission line the radius is smaller for the below ground because the low power dissipated per unit length (1 W/m) allows the line to run cooler below the ground.
2) Lower power loss requires a larger radius to lower the resistance.

Case 16.B



Transmission Line Parameters

Application	100kW, 5km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1%, 3%, 5%*

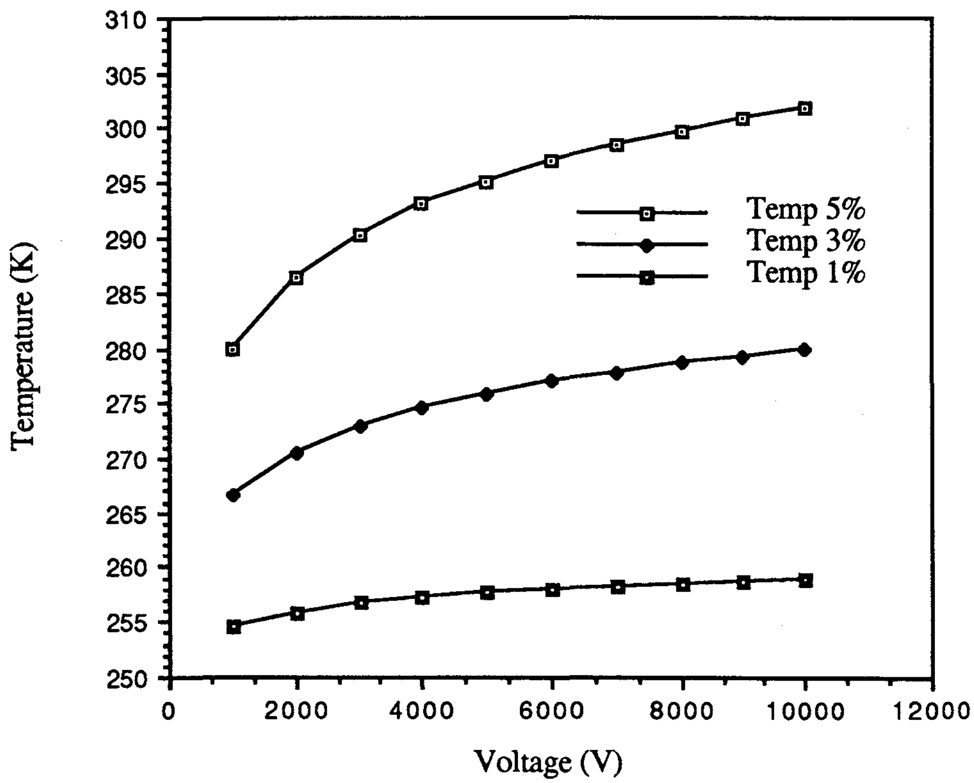


depth 25 cm

Comments

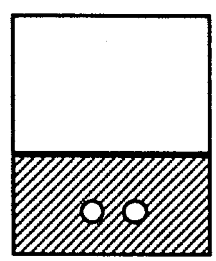
1) Lower power loss requires more massive cable.

Case 16.C



Transmission Line Parameters

Application	100kW, 5km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1%, 3%, 5%*

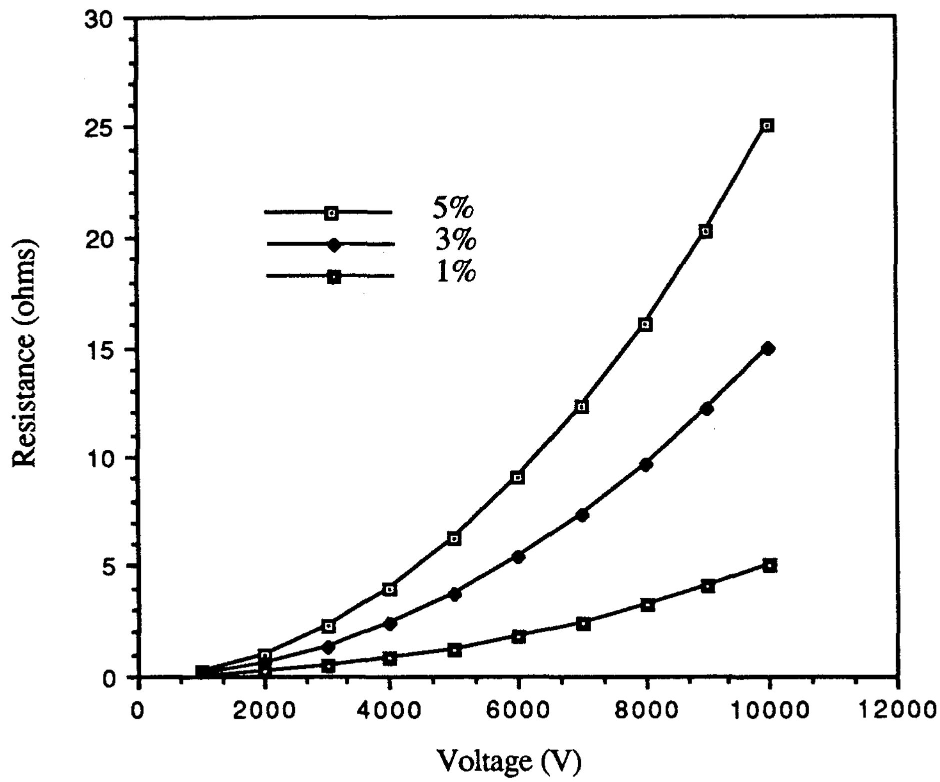


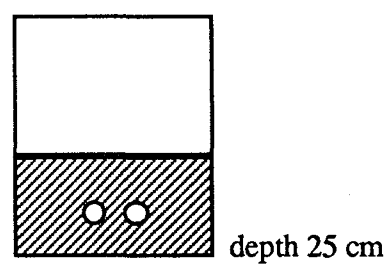
depth 25 cm

Comments

1) Note that the temperatures for this line are lower for below the surface (compare to 15.C).
2) For the two-wire above ground (15.C) increased efficiency at the lower voltages makes little difference in the temperature (1 to 2 K). At higher voltages increased efficiency makes a more significant difference (20 to 25 K). For the two-wire below ground shown above increased efficiency improves the temperature at all voltages.
3) At a power loss of 1 % (99% efficient line) the temperature is a very weak function of the voltage. This means that below 1 W/m of power dissipation in the soil the actual radius of the line is not too important

Case 16.D





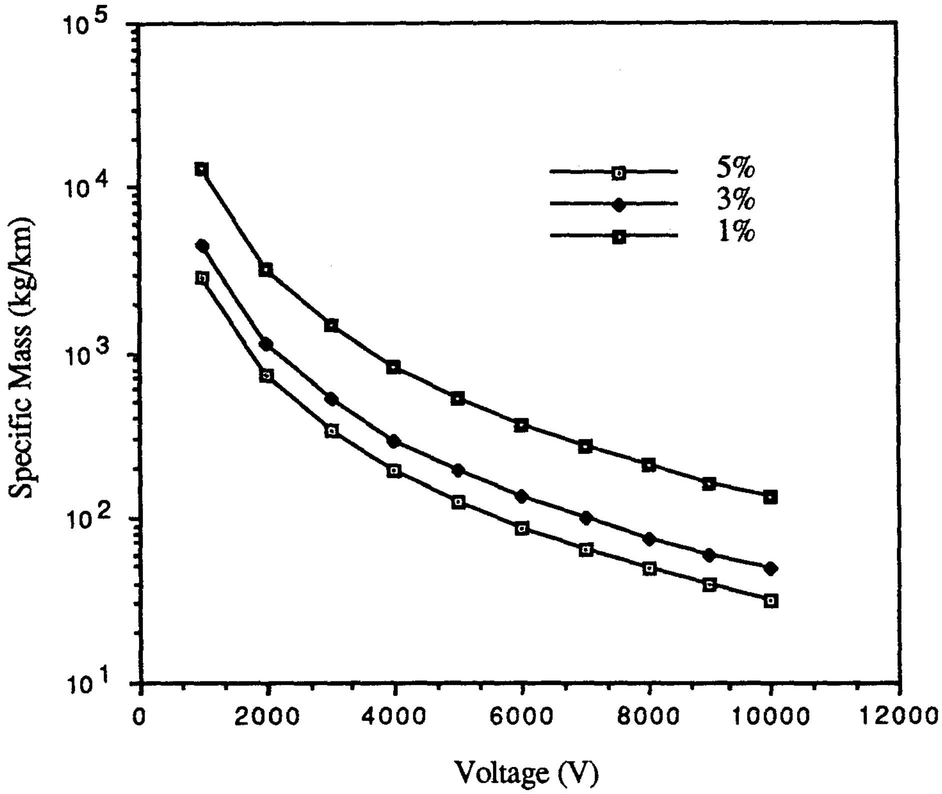
Transmission Line Parameters

Application	100kW, 5km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1%, 3%, 5%*

Comments

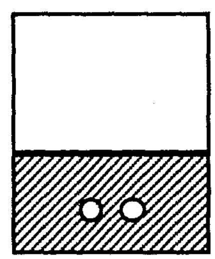
1) Lower power loss requires lower total line resistance.

Case 16.E



Transmission Line Parameters

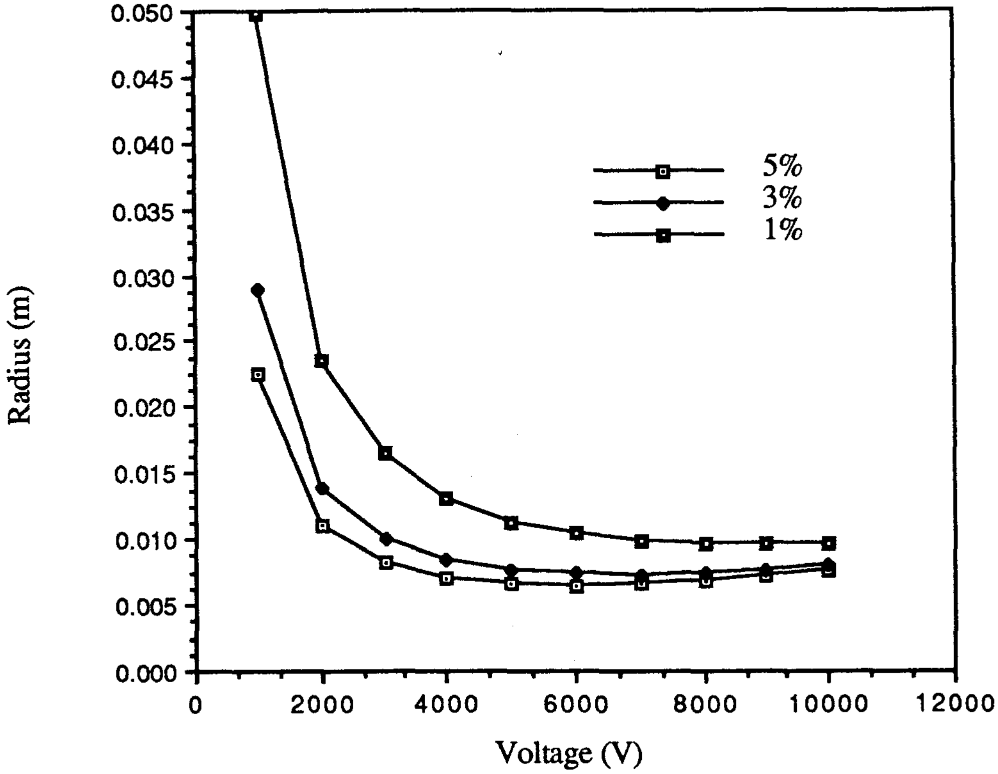
Application	100kW, 5km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1%, 3%, 5%*



Comments

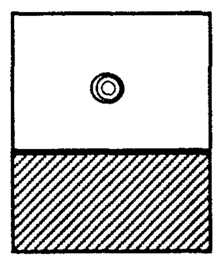
1) Higher efficiency (lower power loss) requires more mass.

Case 17.A



Transmission Line Parameters

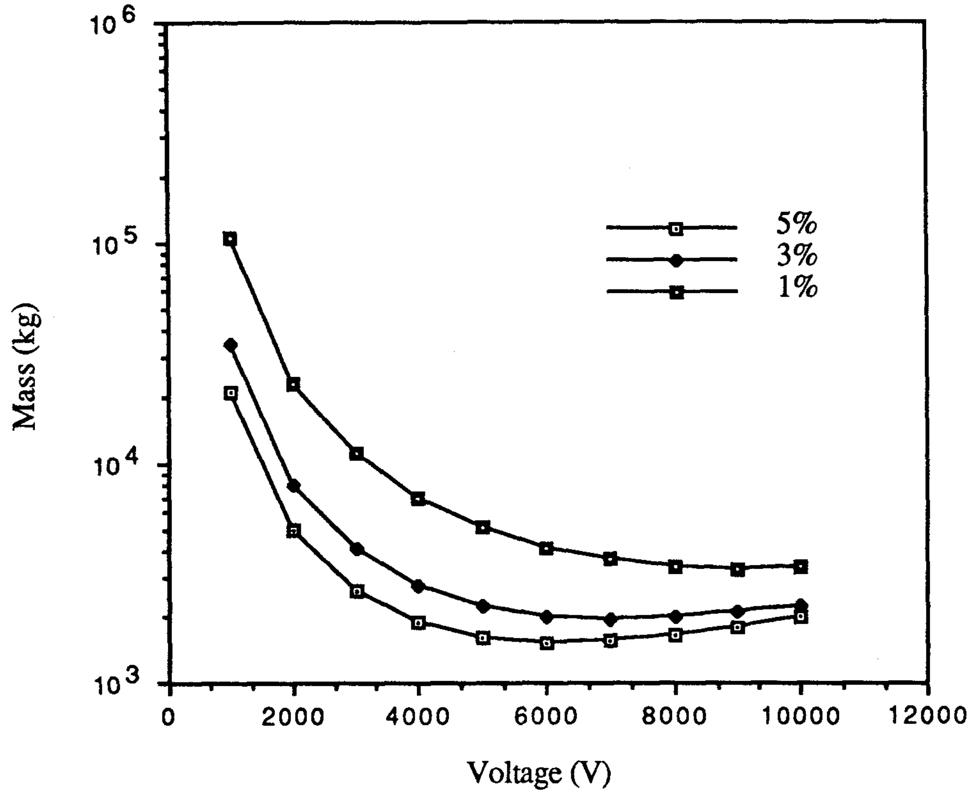
Application	100kW,5km
Geometry	coax
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1%, 3%, 5%*



Comments

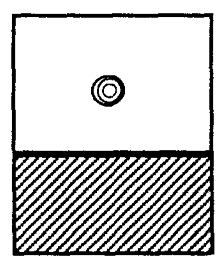
1) The optimum operating voltage (for minimum radius and minimum mass) doesn't change much with efficiency.
2) Lower power loss at low voltages requires very large lines.
3) More efficient lines are larger to achieve lower resistance.
4) At higher voltages changes in efficiency have less impact on radius than at lower voltages.

Case 17.B



Transmission Line Parameters

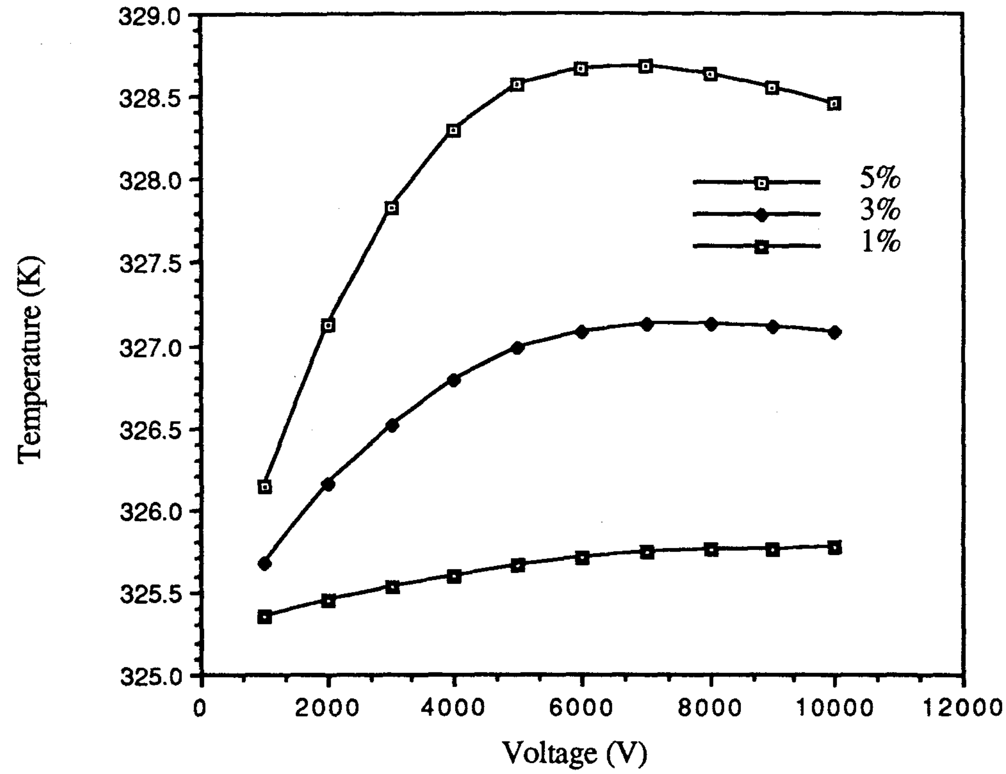
Application	100kW,5km
Geometry	coax
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1%, 3%, 5%*

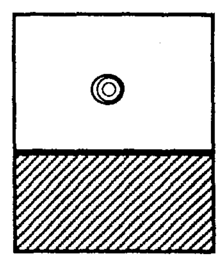


Comments

1) An efficiency of 95 to 97 % increases mass moderately, but from 97 to 99 % the increase in mass is more significantly.

Case 17.C





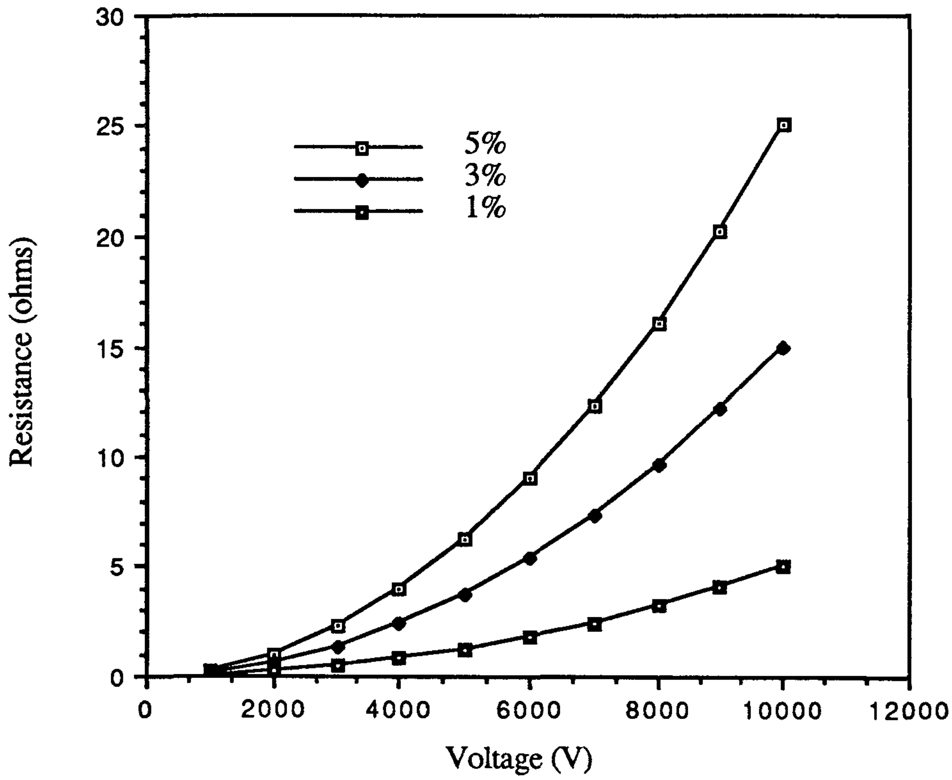
Transmission Line Parameters

Application	100kW,5km
Geometry	coax
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1%, 3%, 5%*

Comments

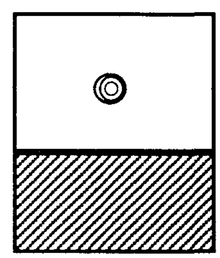
1) The higher power loss line (5 %) has a greater swing in temperature as a function of voltage than the lower power loss line (1 %). This is because dissipating 1 W/m will be more sensitive to line radius than dissipating 0.2 W/m, respectively.
2) Note that the maximum temperature of the coaxial line is cooler than the maximum temperature for the two-wire line (15.C). This is primarily because the radius is larger.

Case 17.D



<u>**Transmission Line Parameters**</u>

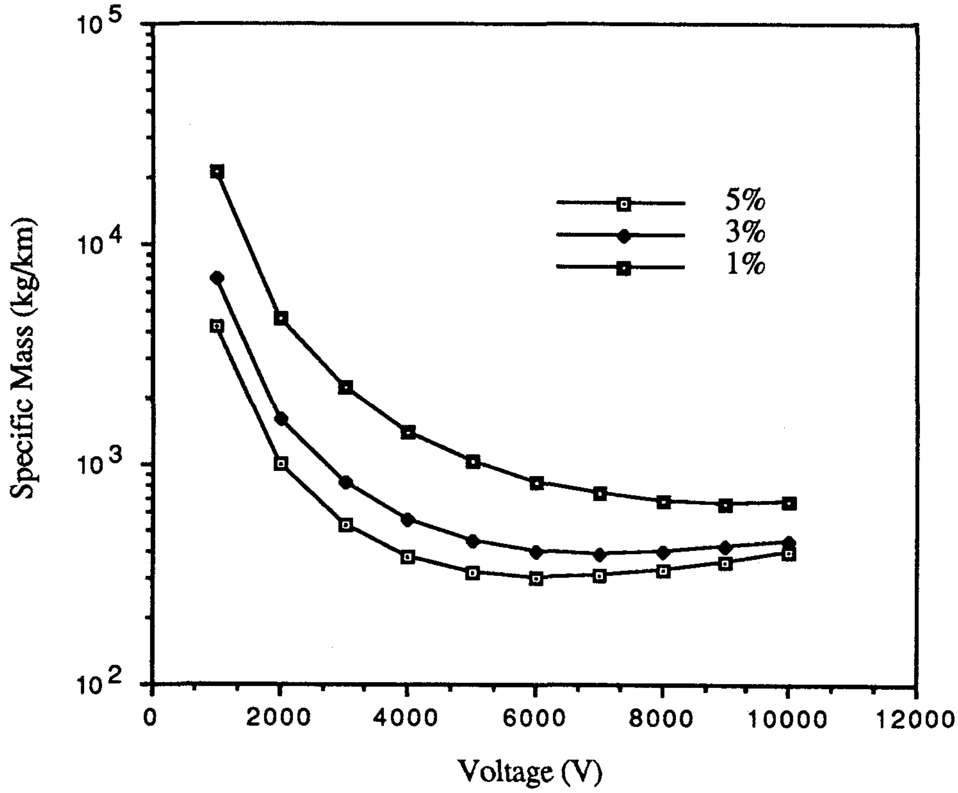
Application	100kW,5km
Geometry	coax
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1%, 3%, 5%*



<u>**Comments**</u>

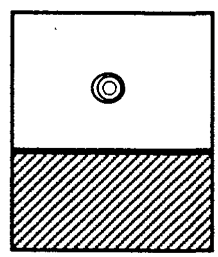
1) Higher efficiency lines require lower resistance.

Case 17.E



<u>**Transmission Line Parameters**</u>

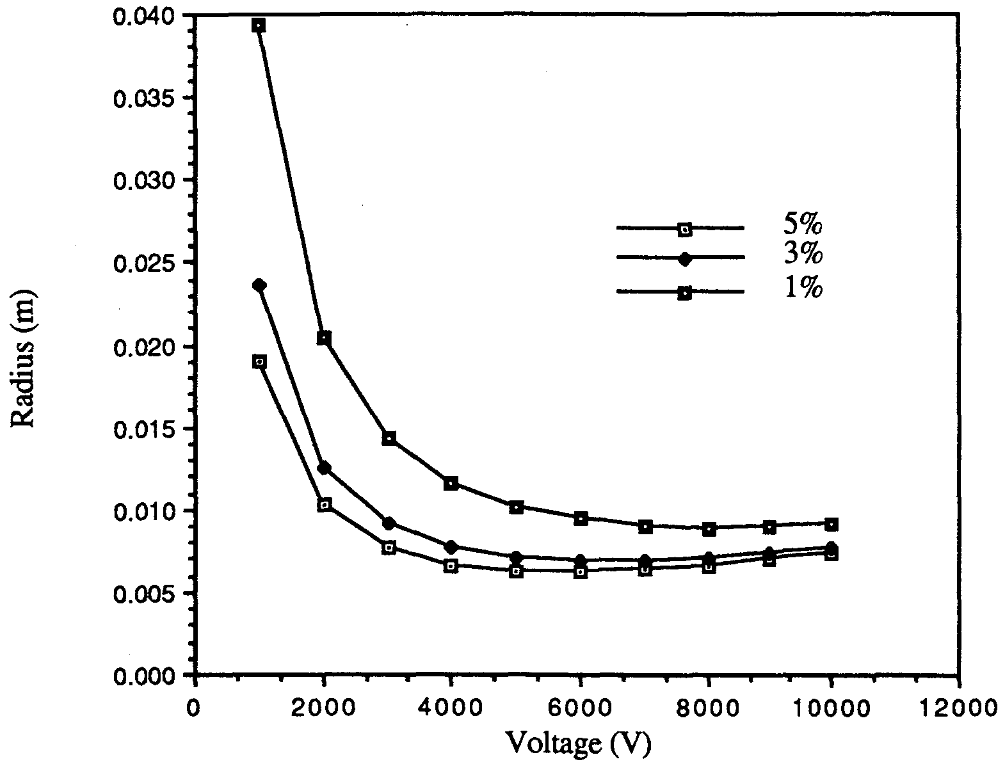
Application	100kW,5km
Geometry	coax
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1%, 3%, 5%*



<u>**Comments**</u>

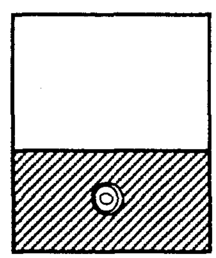
1) Higher efficiency requires larger specific mass.

Case 18.A



Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1,3,5 %*

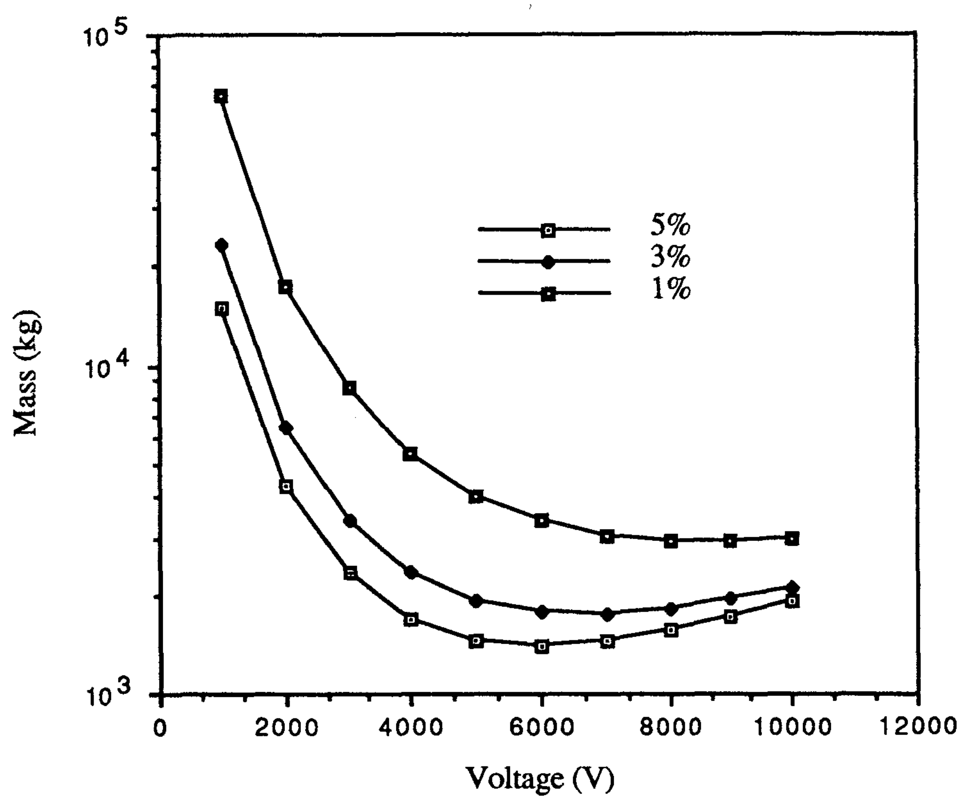


depth 25 cm

Comments

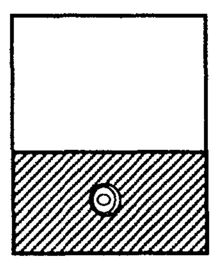
1) Higher efficiency line requires larger radius.

Case 18.B



Transmission Line Parameters

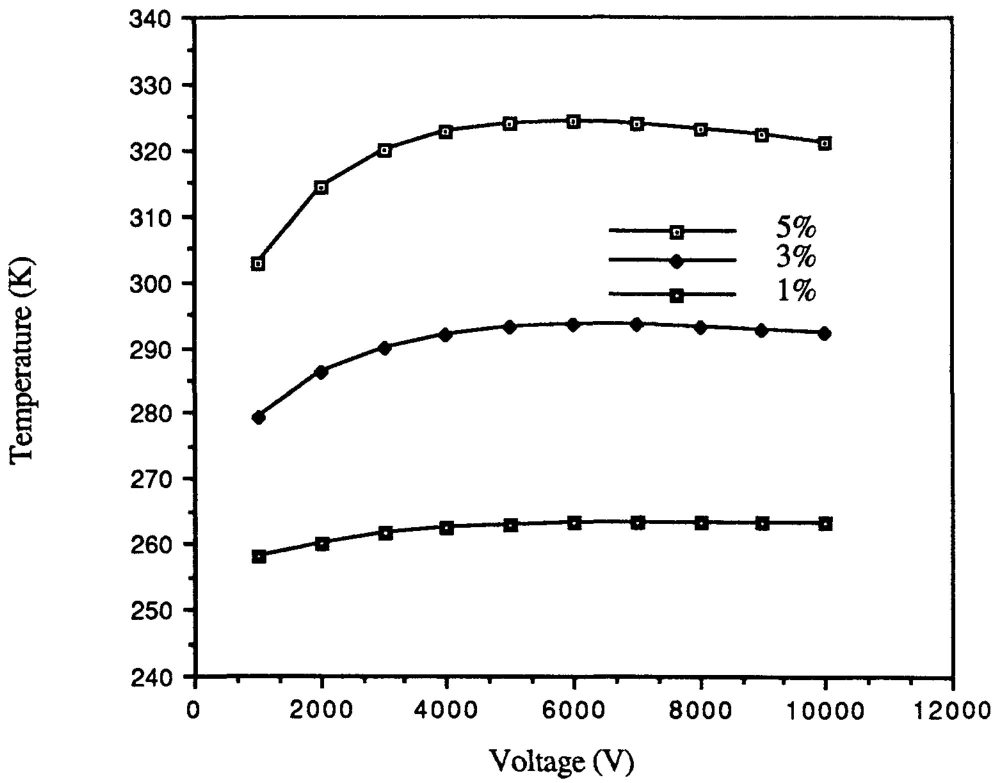
Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1,3,5 %*



Comments

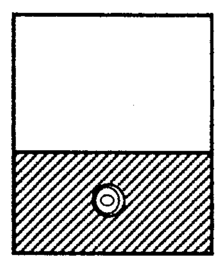
1) Higher efficiency line requires more mass.
2) Note that for higher efficiency (lower power loss) the mass minimum (the point at which the dielectric mass increase with voltage starts to dominate over the reduction in mass of the conductor) shifts to the right. This is because the higher efficiency is requiring a higher conductor to insulator ratio than a lower efficiency.

Case 18.C



<u>Transmission Line Parameters</u>

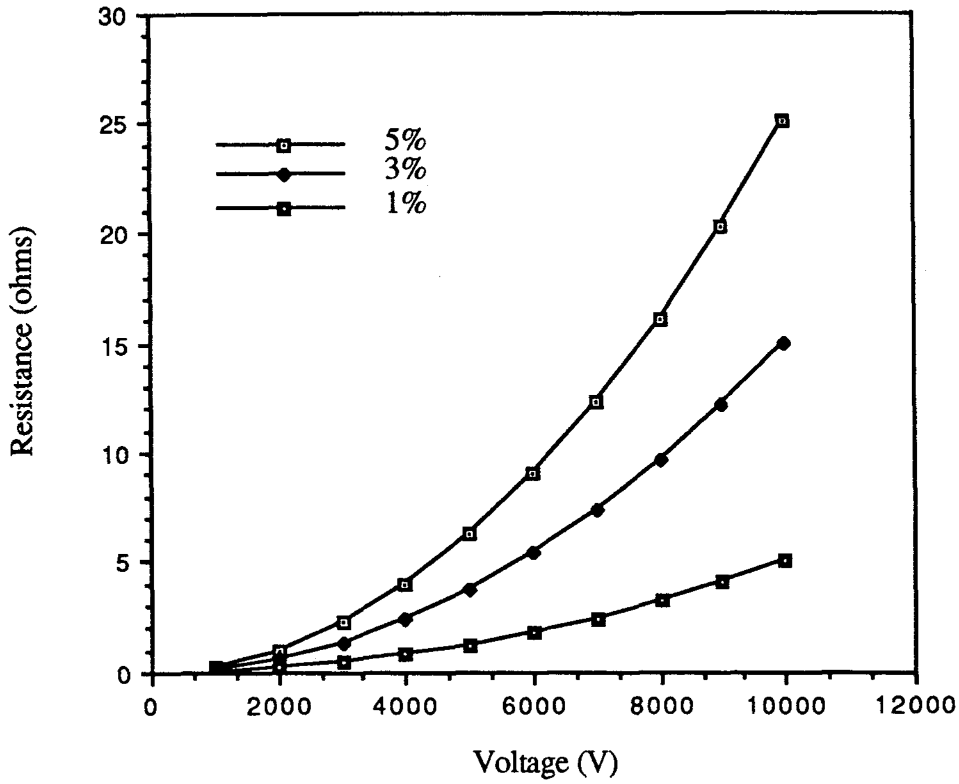
Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1,3,5 %*



<u>Comments</u>

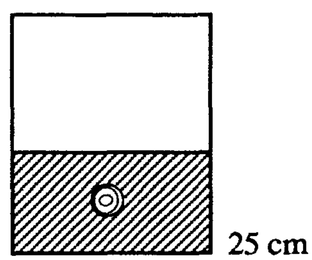
1) For transmission lines with low power loss per unit length (100 kW, 5 km, 5 % power loss) the temperature is substantially decreased by lowering the power loss.

Case 18.D



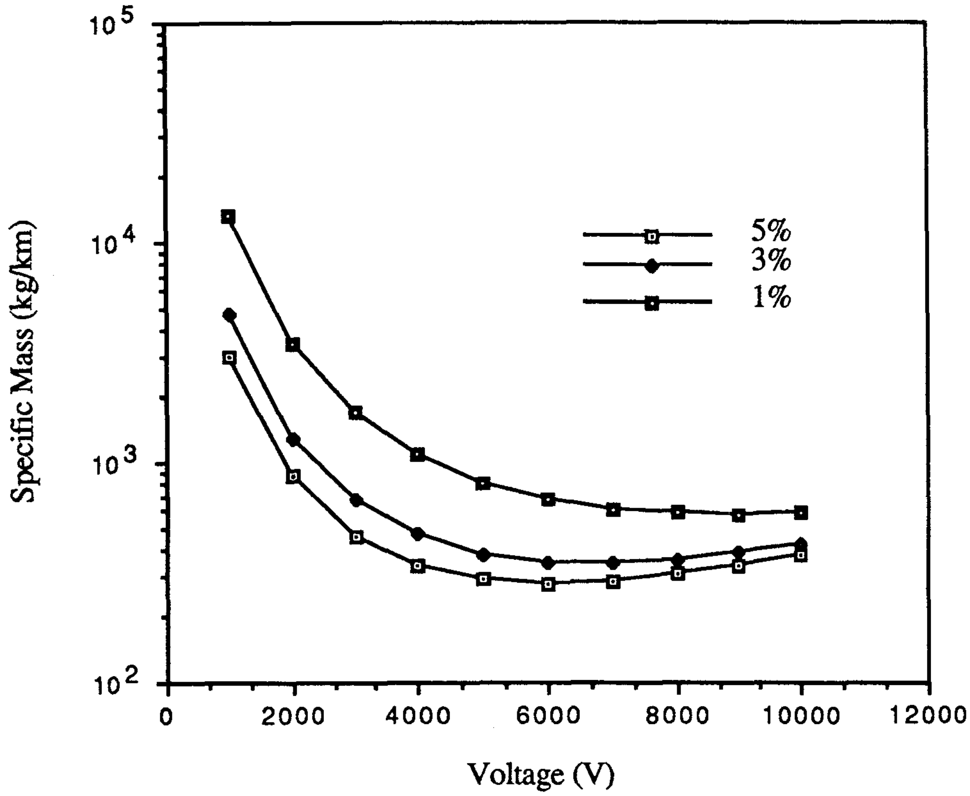
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1,3,5 %*



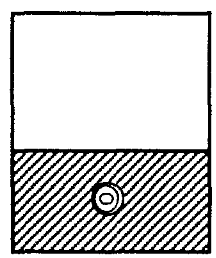
Comments

Case 18.E



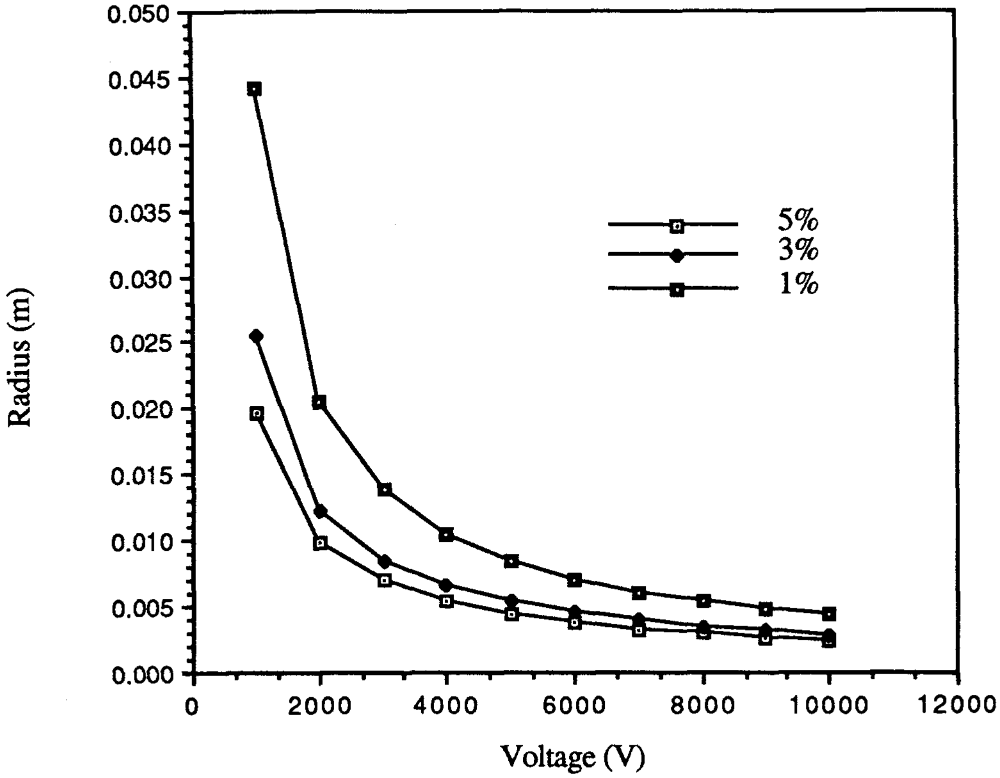
<u>**Transmission Line Parameters**</u>

Application	100 kW, 5 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1,3,5 %*



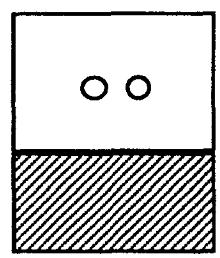
<u>**Comments**</u>

Case 19.A



Transmission Line Parameters

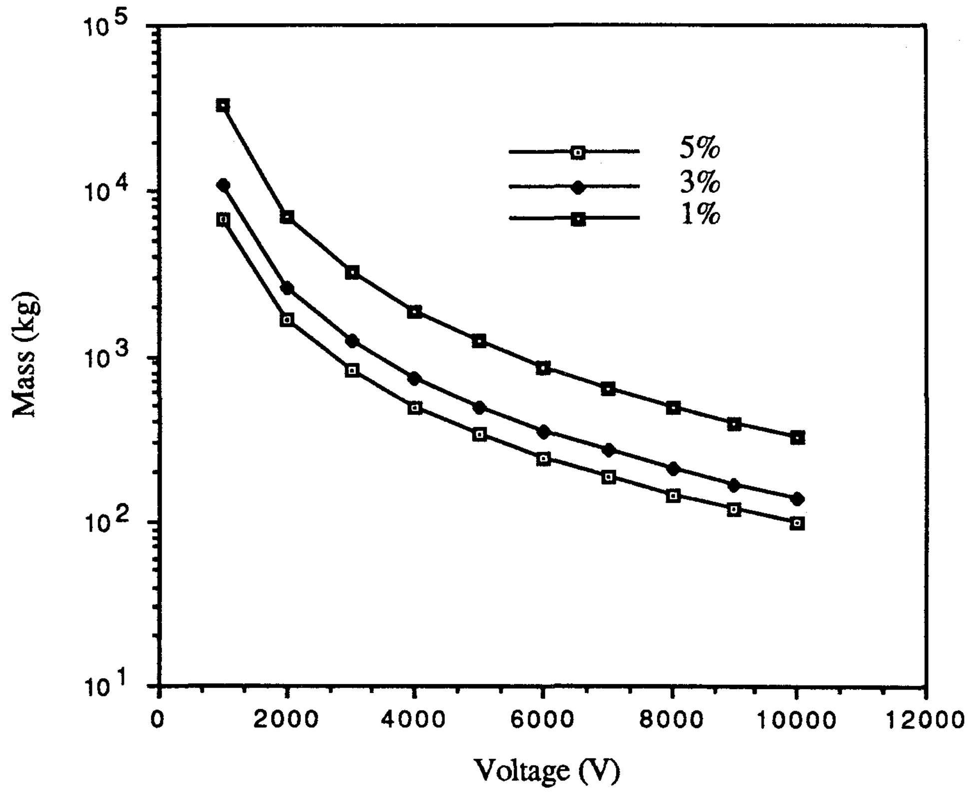
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3, 5 %*



Comments

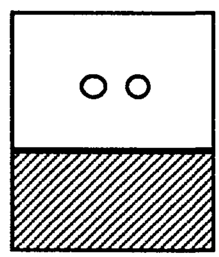
1) More efficient lines are larger.

Case 19.B



Transmission Line Parameters

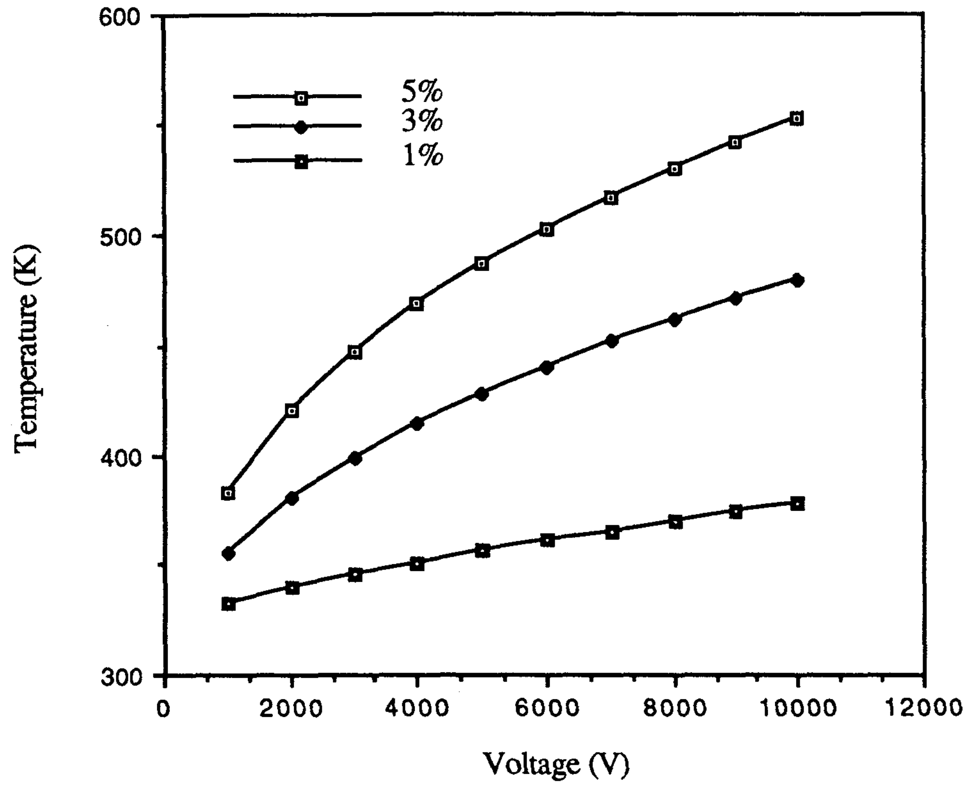
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3, 5 %*

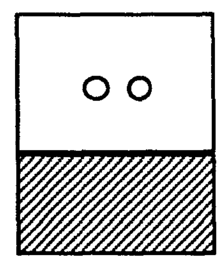


Comments

1) More efficient lines are heavier.

Case 19.C





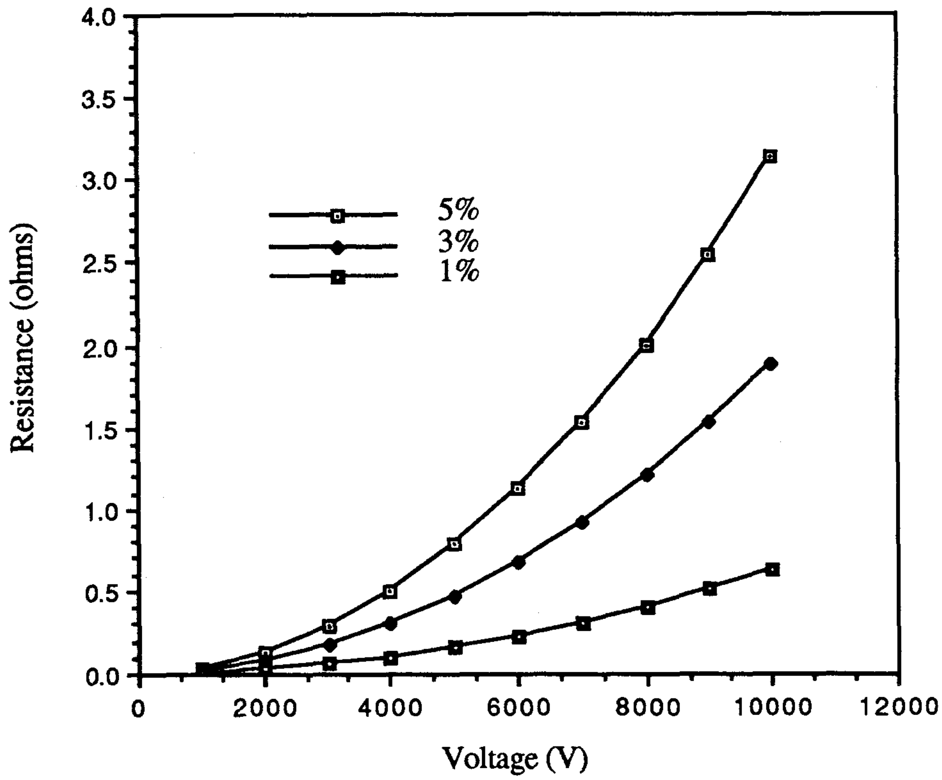
Transmission Line Parameters

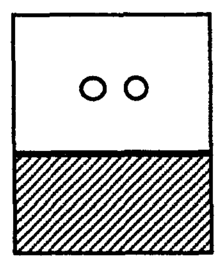
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3, 5 %*

Comments

1) More efficient lines are cooler.

Case 19.D





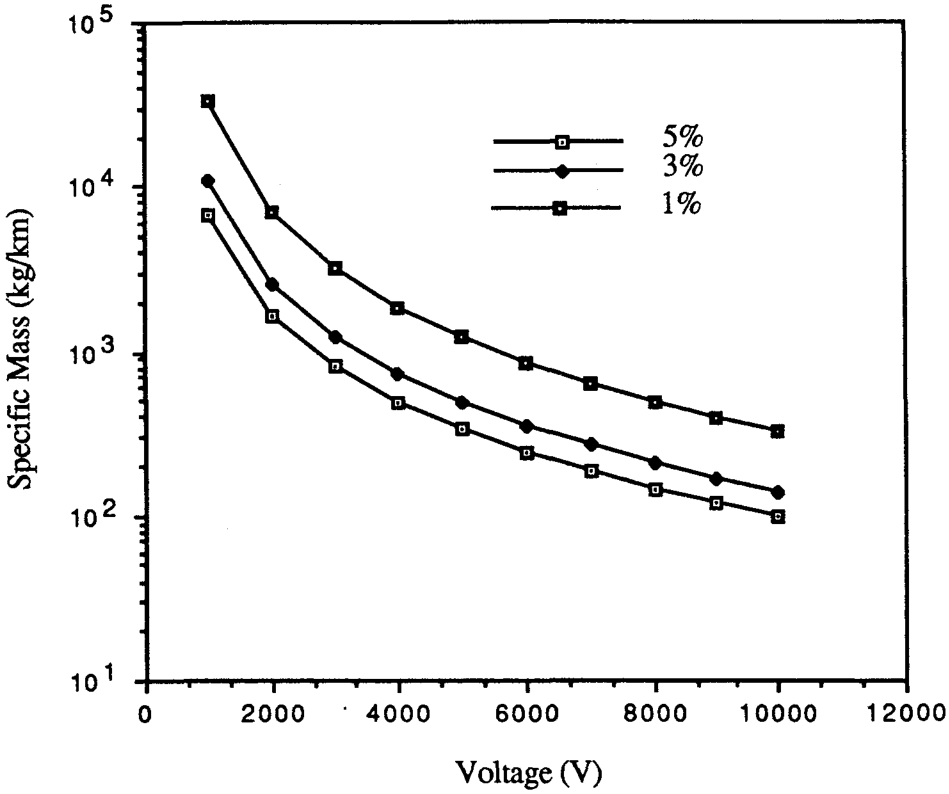
Transmission Line Parameters

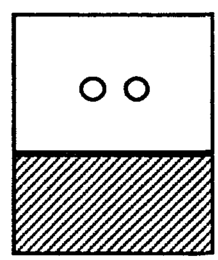
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3, 5 %*

Comments

1) More efficient lines have a lower resistance.

Case 19.E





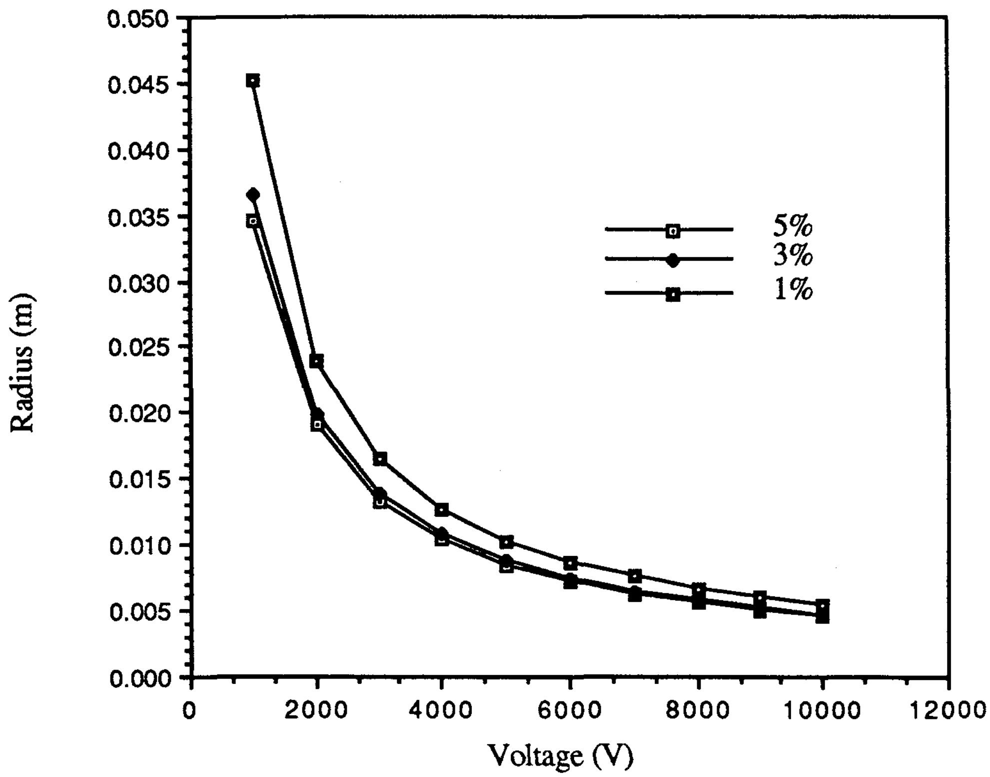
<u>Transmission Line Parameters</u>

Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	day
Power loss	*1,3, 5 %*

<u>Comments</u>

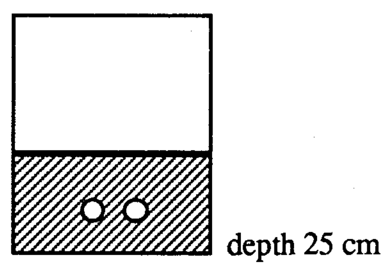
1) More efficient lines are heavier.

Case 20.A



Transmission Line Parameters

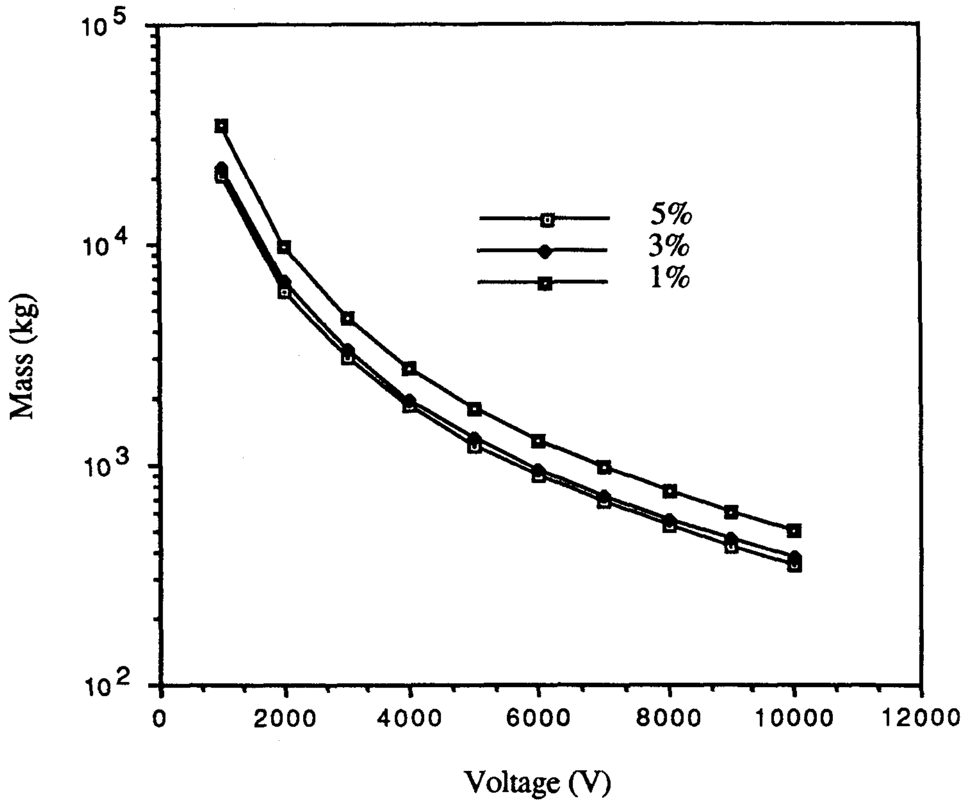
Application	800 kW, 1 km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1,3,5 %*



Comments

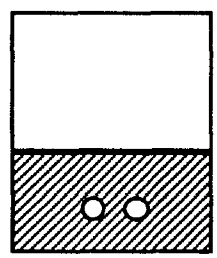
1) For a high power line 5 % to 3 % power loss makes very little difference in size.

Case 20.B



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1,3,5 %*

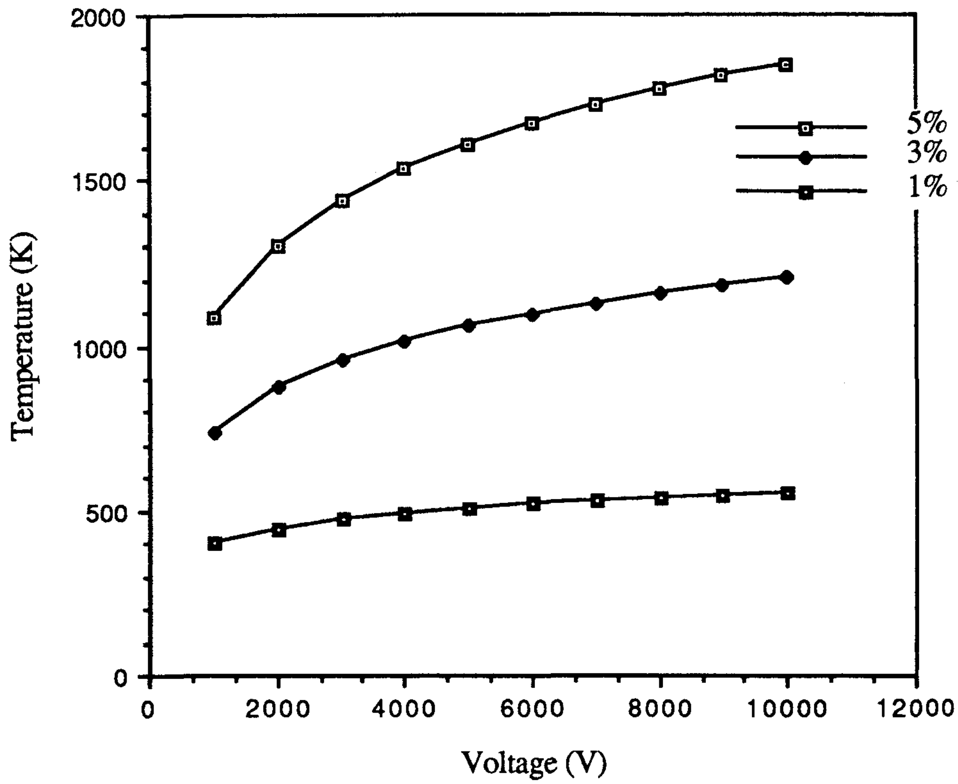

depth 25 cm

Comments

1) For high power lines, 5 % to 3 % change in power loss has less of an effect on the total line mass.

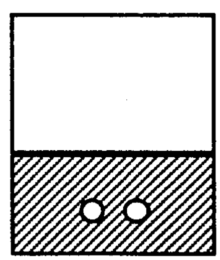
This is because an improved efficiency lowers the power to be dissipated, which greatly lowers the material temperature. This improves the conductivity of the conductor material, allowing the line to be smaller and lighter.

Case 20.C



<u>**Transmission Line Parameters**</u>

Application	800 kW, 1 km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1,3,5 %*



depth 25 cm

<u>**Comments**</u>

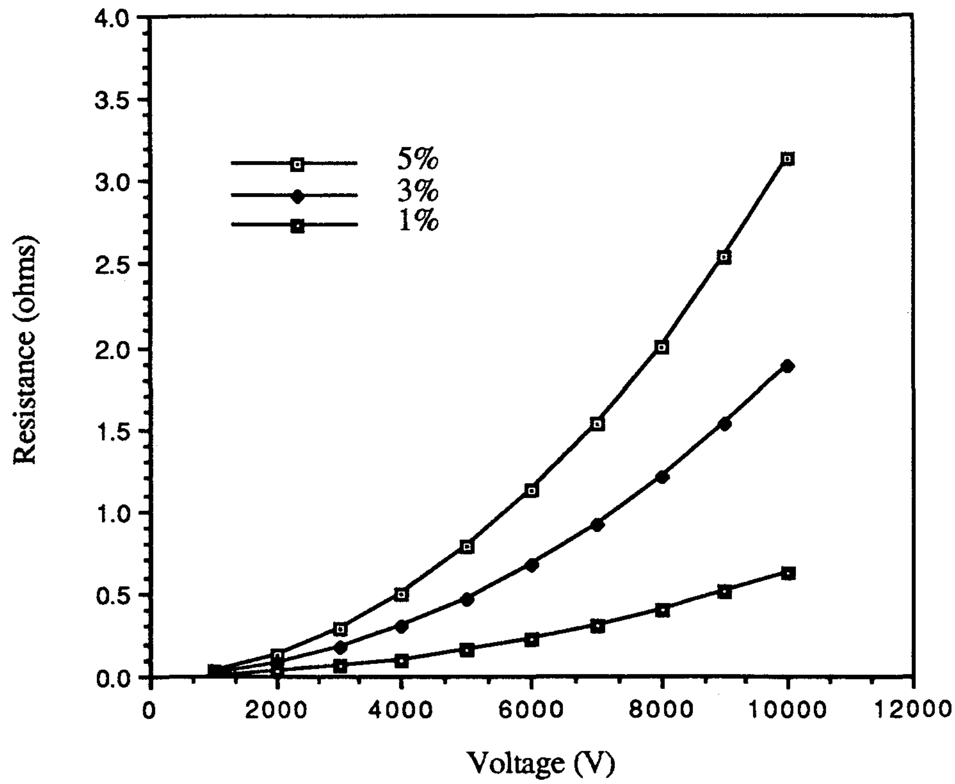
1) Increasing the efficiency (decreasing the power loss) has drastically reduced the line temperature.

2) For this transmission line (800 kW, 1 km) the following power are dissipated per unit length:

95 % efficiency	or	5 % power loss	=	40 W/m
97 % efficiency	or	3 % power loss	=	24 W/m
99 % efficiency	or	1 % power loss	=	8 W/m

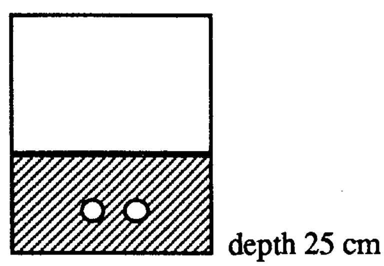
3) For this transmission line 3 or 5 % power loss is unacceptable, 1 % power loss is possible.

Case 20.D



Transmission Line Parameters

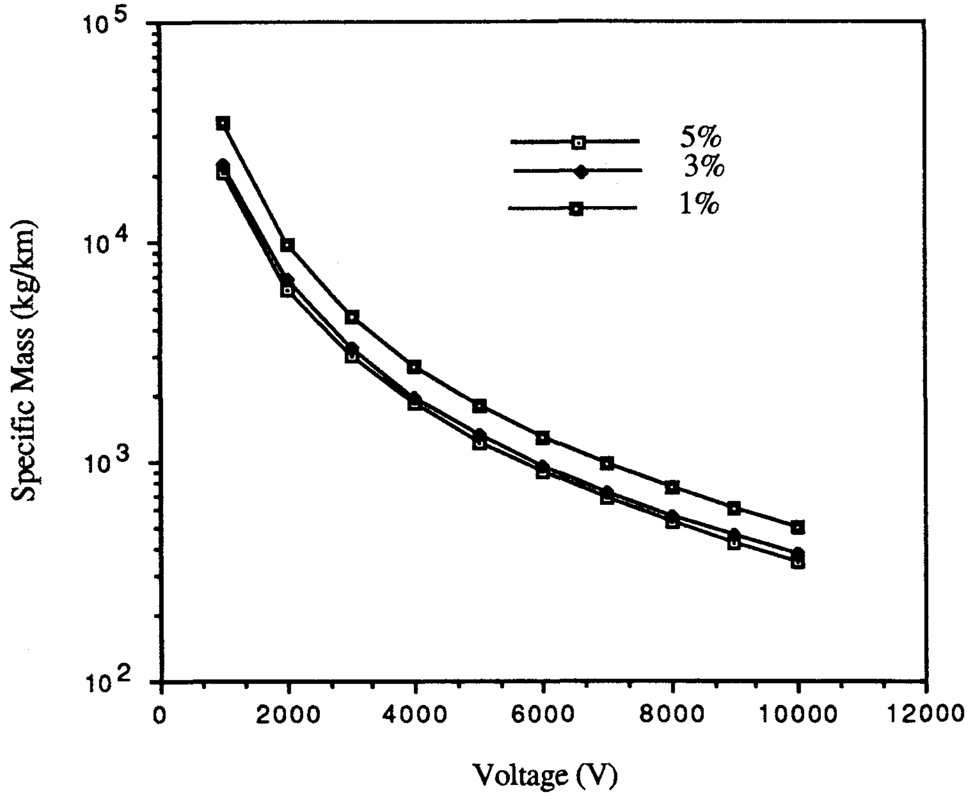
Application	800 kW, 1 km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1,3,5 %*



Comments

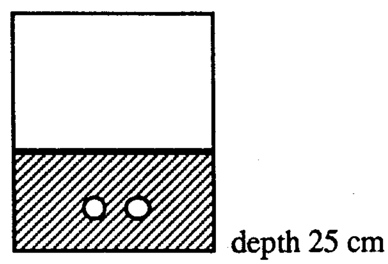
1) Lower power loss requires lower resistance.

Case 20.E



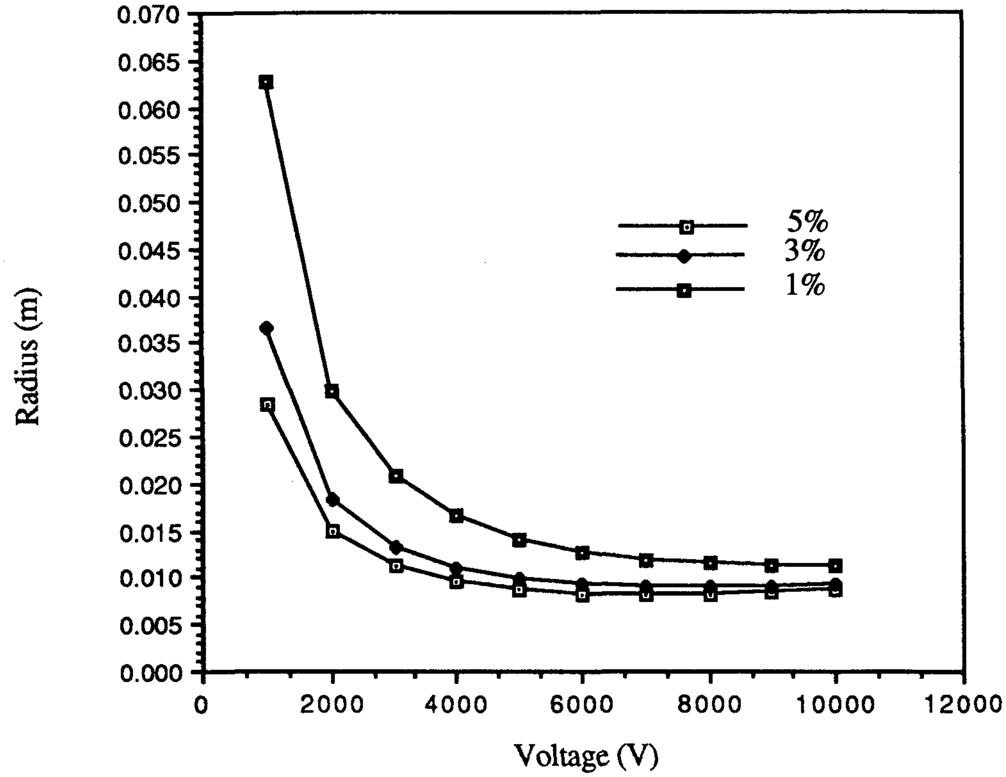
Transmission Line Parameters

Application	800 kW, 1 km
Geometry	two-wire
Location	below
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	*1,3,5 %*



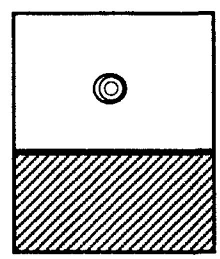
Comments

Case 21.A



Transmission Line Parameters

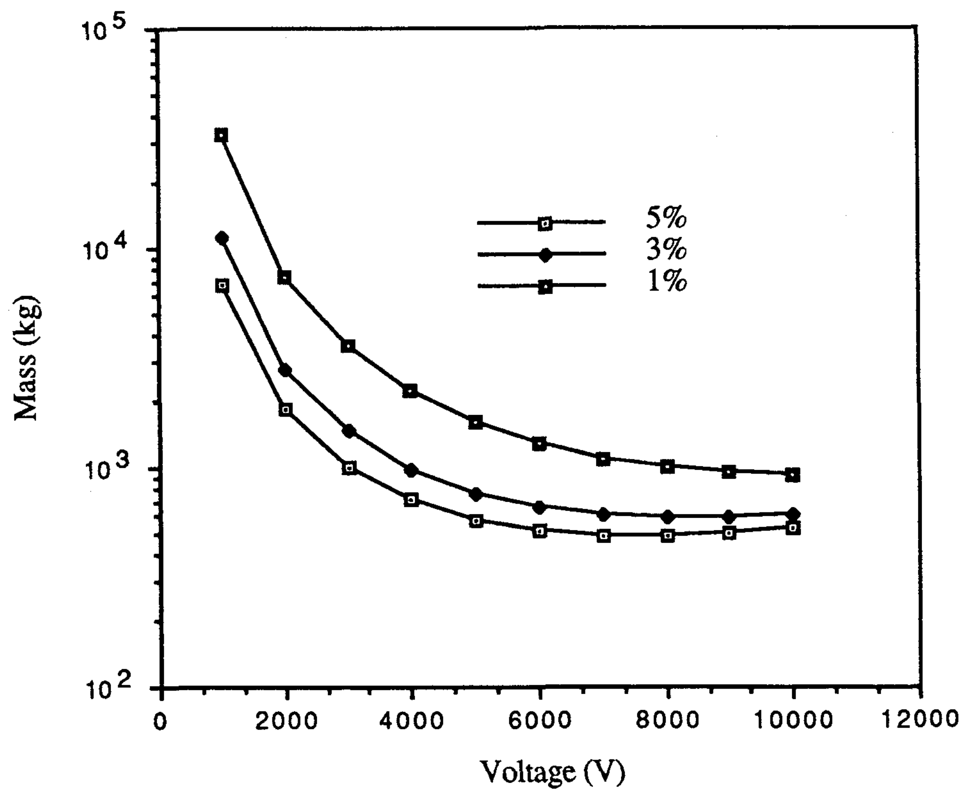
Application	800 kW, 1 km
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1, 3, 5 %*

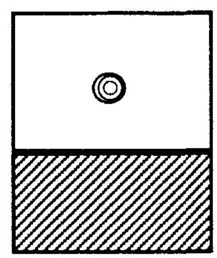


Comments

1) Lower power loss requires larger lines.

Case 21.B





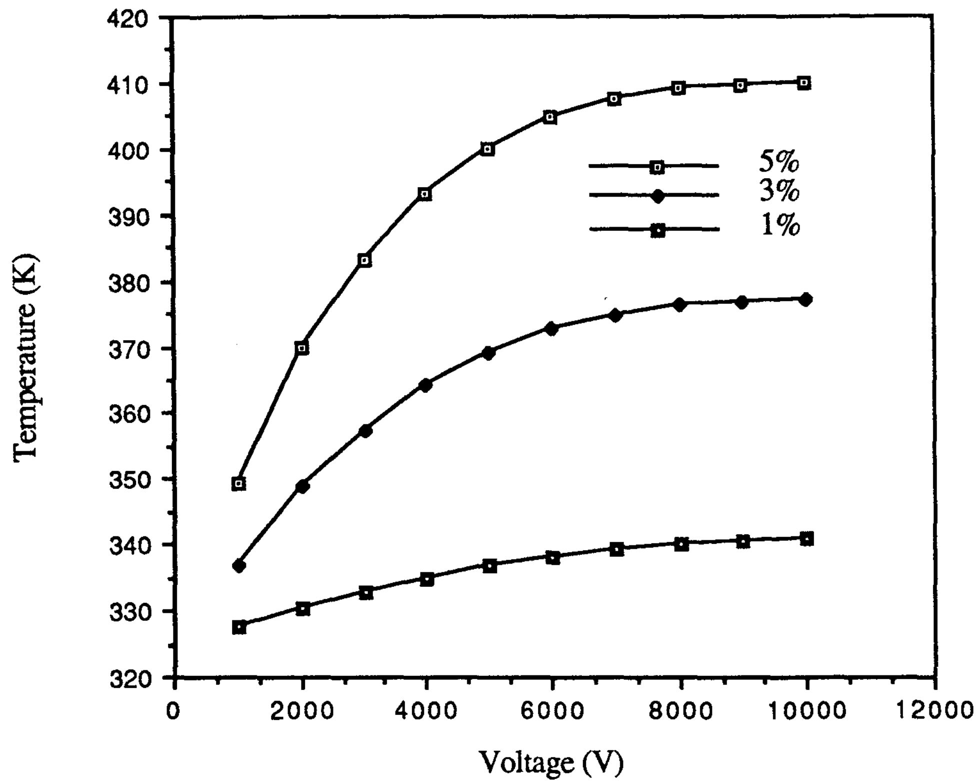
Transmission Line Parameters

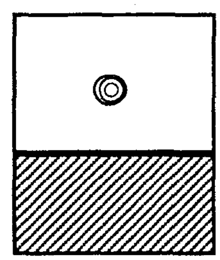
Application	800 kW, 1 km
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1, 3, 5 %*

Comments

1) Lower power loss requires more conductor mass.

Case 21.C





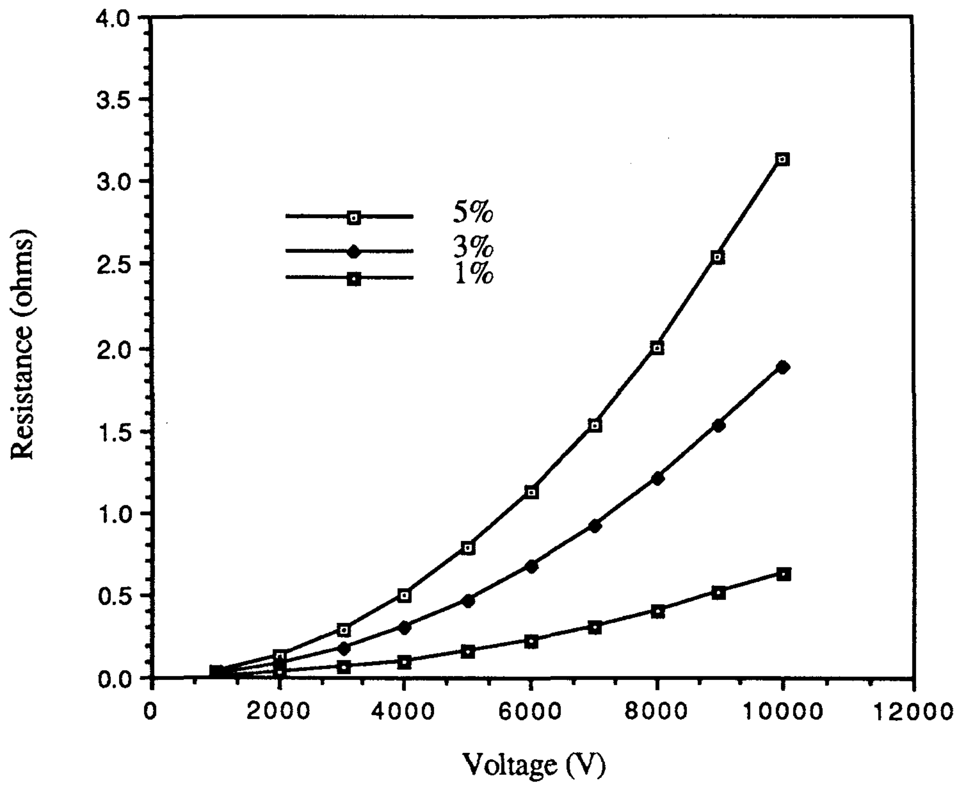
Transmission Line Parameters

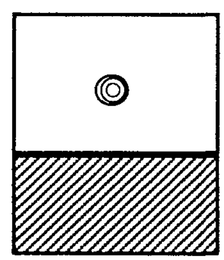
Application	800 kW, 1 km
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1, 3, 5 %*

Comments

1) Higher efficiency (lower power loss) reduces temperature.
2) Temperature reduction is more dramatic at high voltages.

Case 21.D





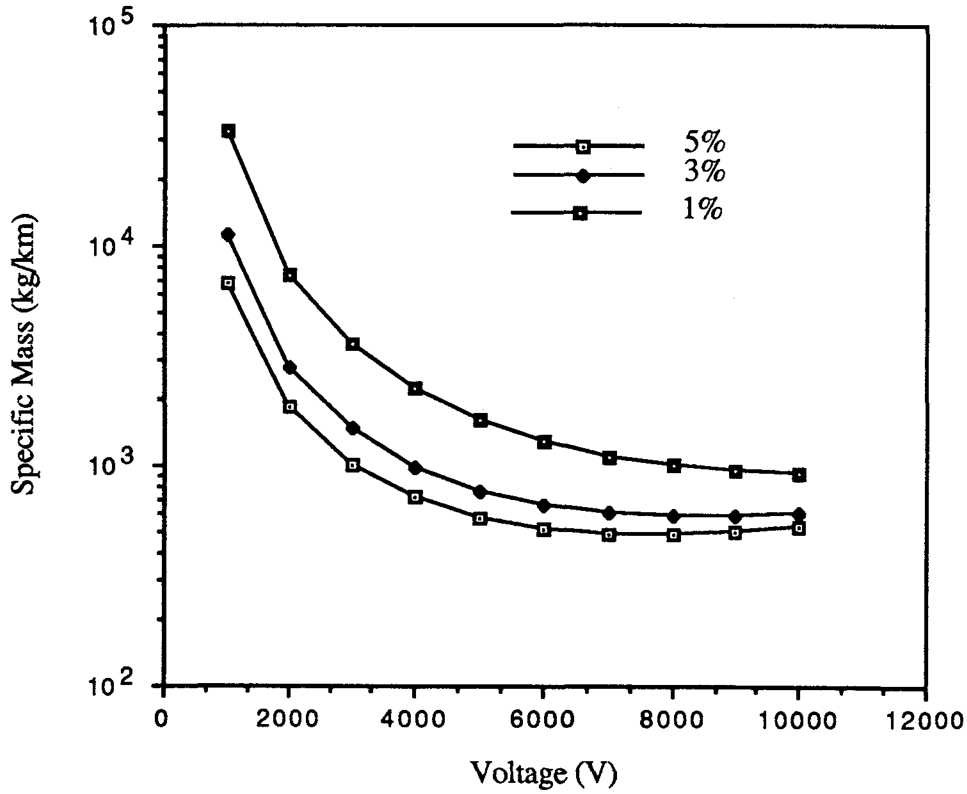
Transmission Line Parameters

Application	800 kW, 1 km
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1, 3, 5 %*

Comments

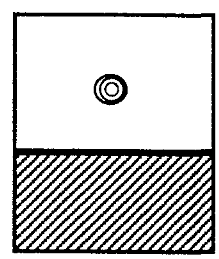
1) Higher efficiency requires lower resistance.

Case 21.E



Transmission Line Parameters

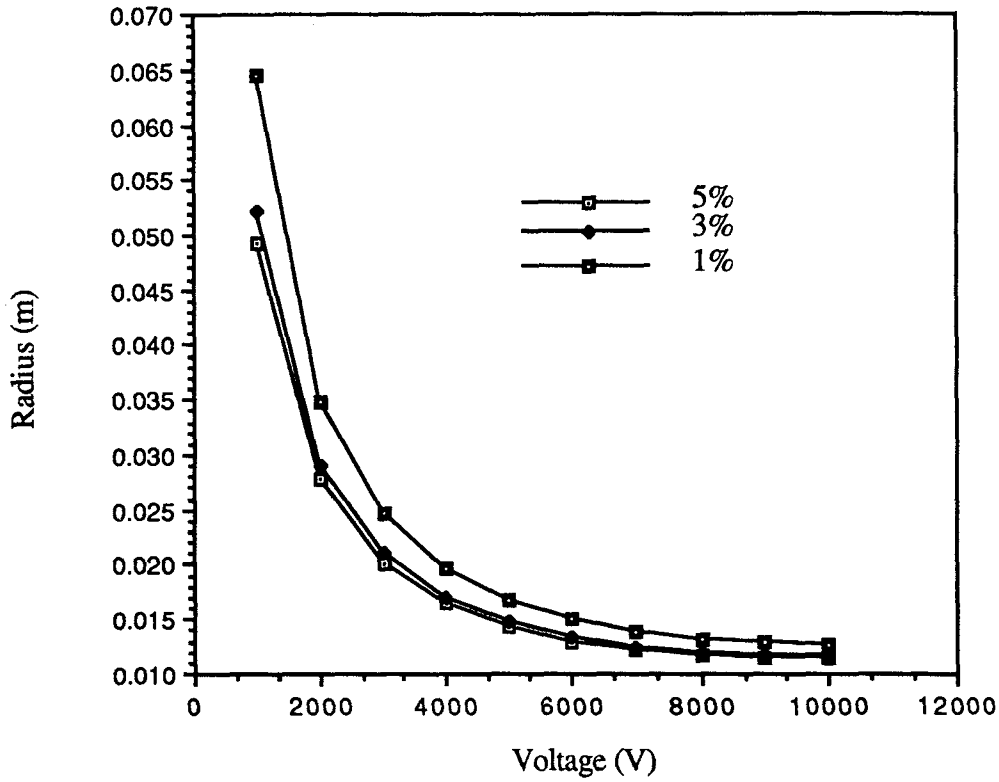
Application	800 kW, 1 km
Geometry	coaxial
Location	above
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	day
Power loss	*1, 3, 5 %*



Comments

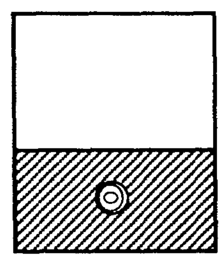
1) Higher efficiency requires more mass per unit length.

Case 22.A



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1, 3, 5 %*

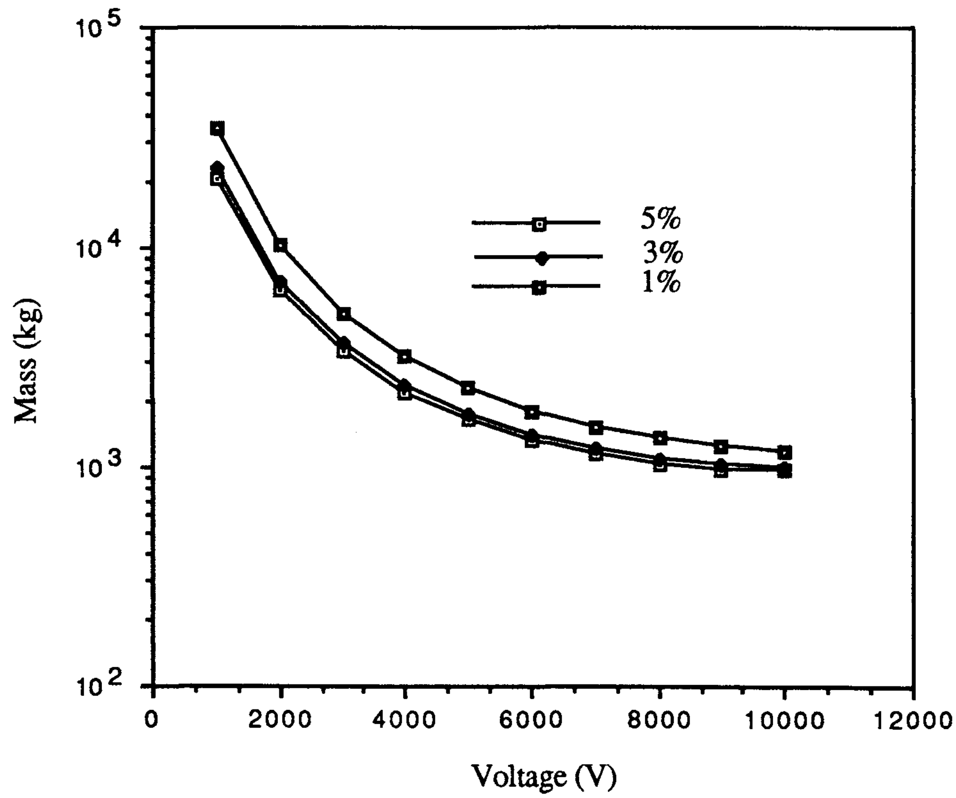


depth 25 cm

Comments

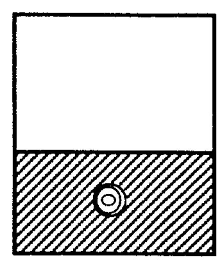
1) Buried, high power transmission lines are not as influenced by increases in efficiency.

Case 22.B



<u>Transmission Line Parameters</u>

Application	800 kW, 1 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1, 3, 5 %*

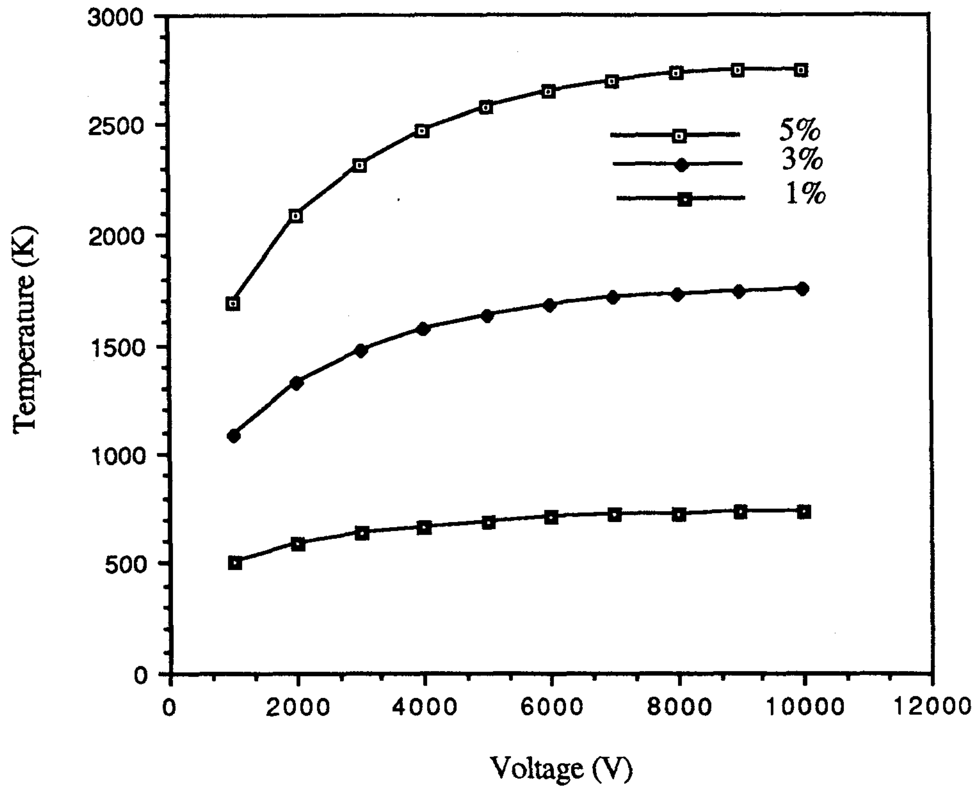


depth 25 cm

<u>Comments</u>

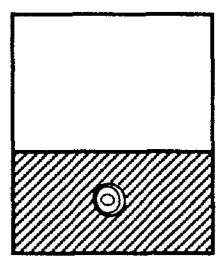
1) Small improvements in efficiency has less of an effect on the mass of high power lines than on low power lines (Case 18.B). This is due to the fact that size and mass gains are realized by lowering the temperature.

Case 22.C



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1, 3, 5 %*

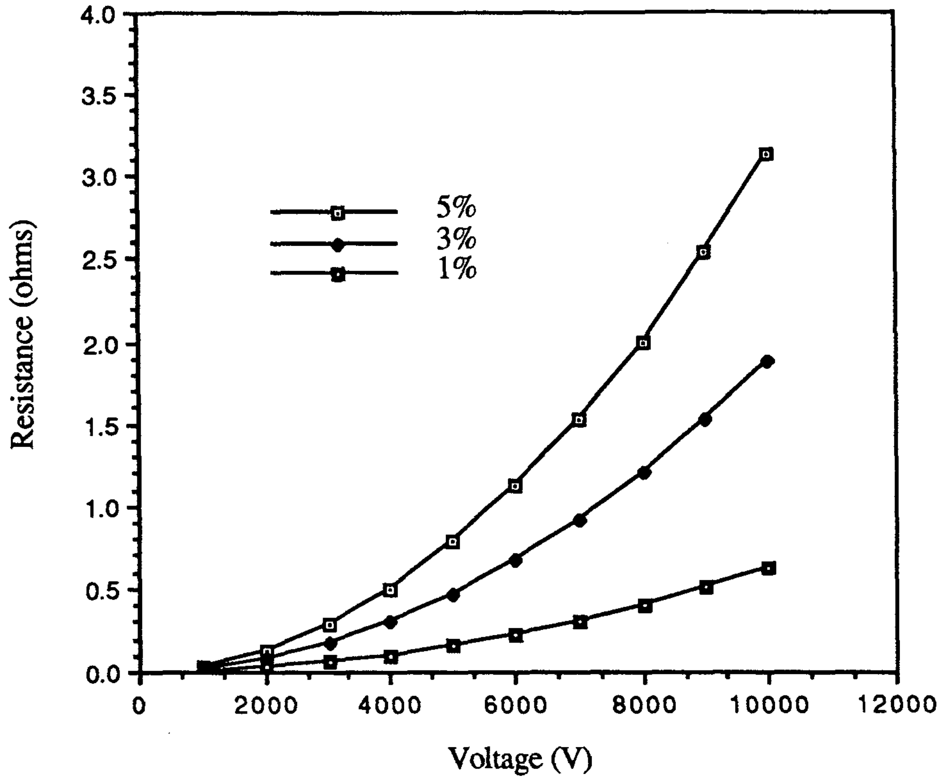


depth 25 cm

Comments

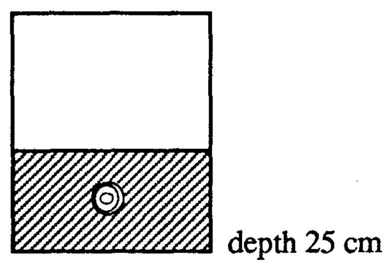
1) Small improvements in efficiency vastly lowers the temperature.

Case 22.D



Transmission Line Parameters

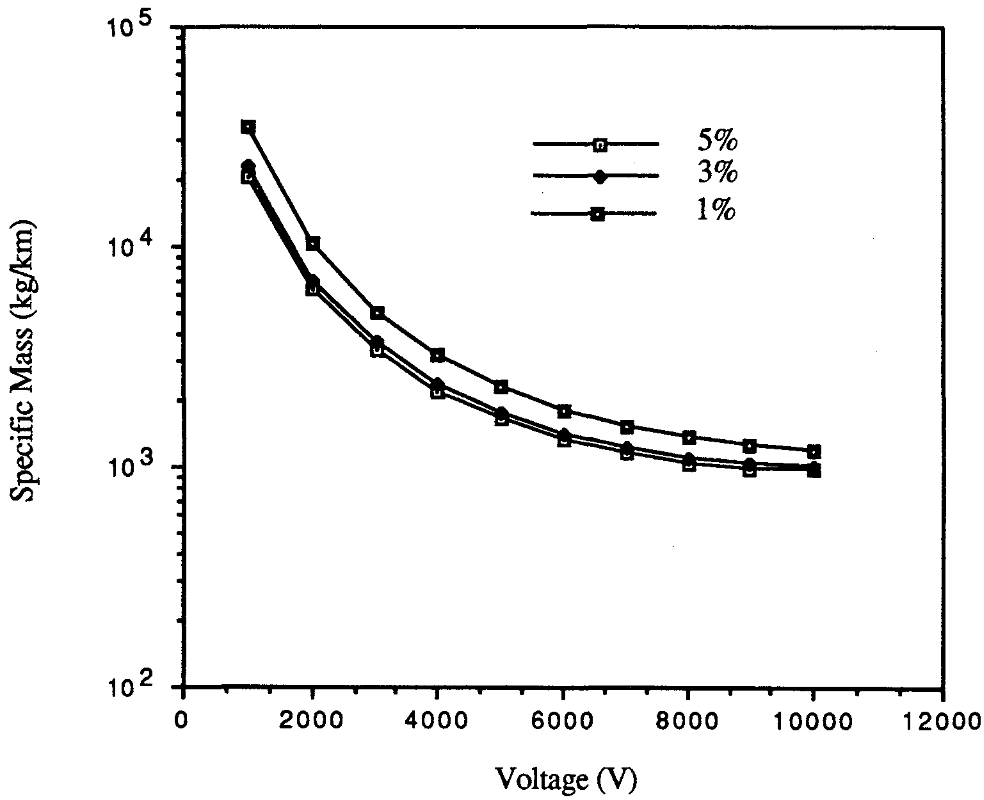
Application	800 kW, 1 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1, 3, 5 %*



Comments

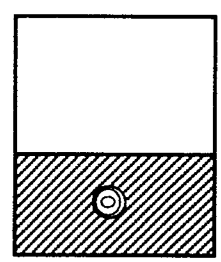
1) Increased efficiency requires lower resistance.

Case 22.E



Transmission Line Parameters

Application	800 kW, 1 km
Geometry	coaxial
Location	below
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	*1, 3, 5 %*

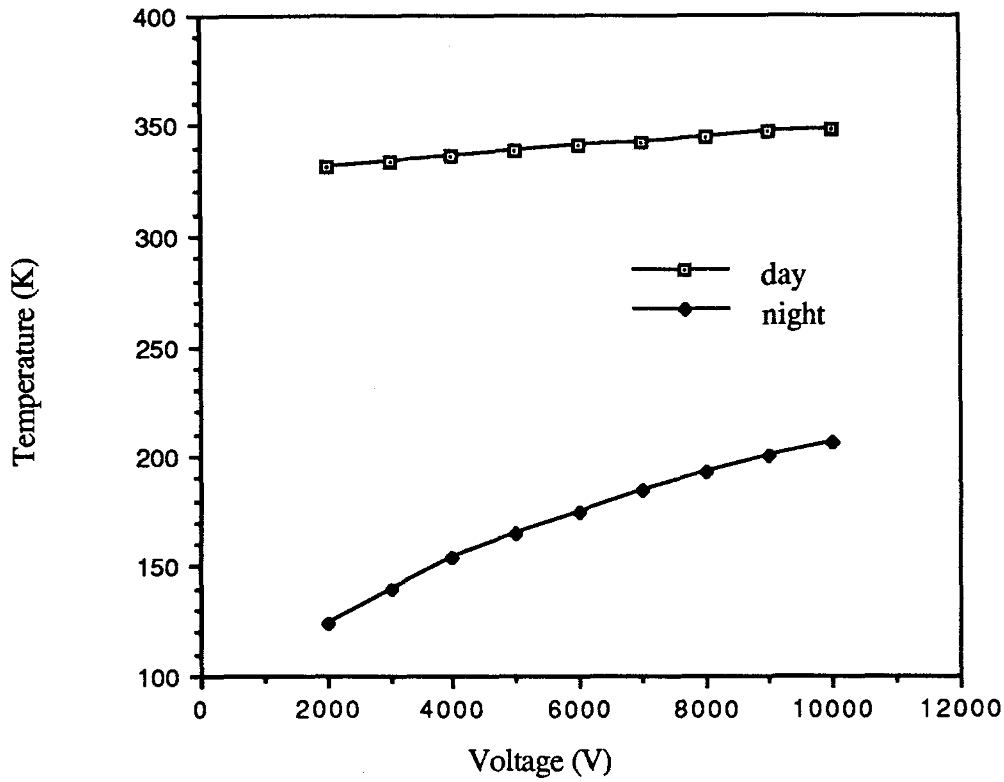


depth 25 cm

Comments

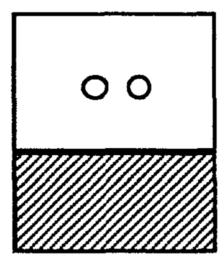
1) Small improvements in efficiency has less of an effect on the mass of high power lines than on low power lines (Case 18.E). This is due to the fact that size and mass gains are realized by lowering the temperature.

Case 23.C



Transmission Line Parameters

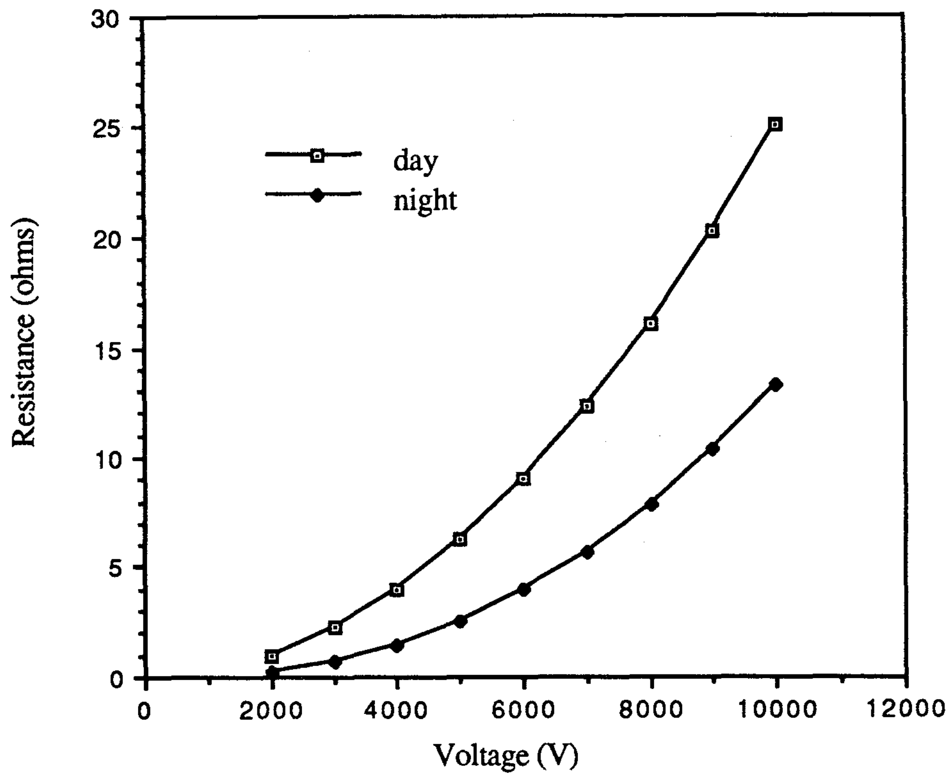
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day

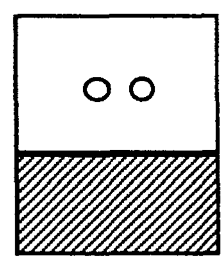


Comments

1) This case starts at 2 kV.
2) The power loss is 5 % during the day. It will be considerably less at night (see 23.F).
3) Transmission lines above the surface of the moon will experience a wide temperature swing (over 200 K due just to the environment).
4) Conductors could become embrittled or annealed, and dielectrics become embrittled at these wide temperature swings.
5) It may be necessary to keep the transmission line warm at night by power flow regulation. For instance, running the line at 10 kV raises the temperature only 10 K during the day over that at 1 kV, but keeps the line over 100 K warmer at night.

Case 23.D





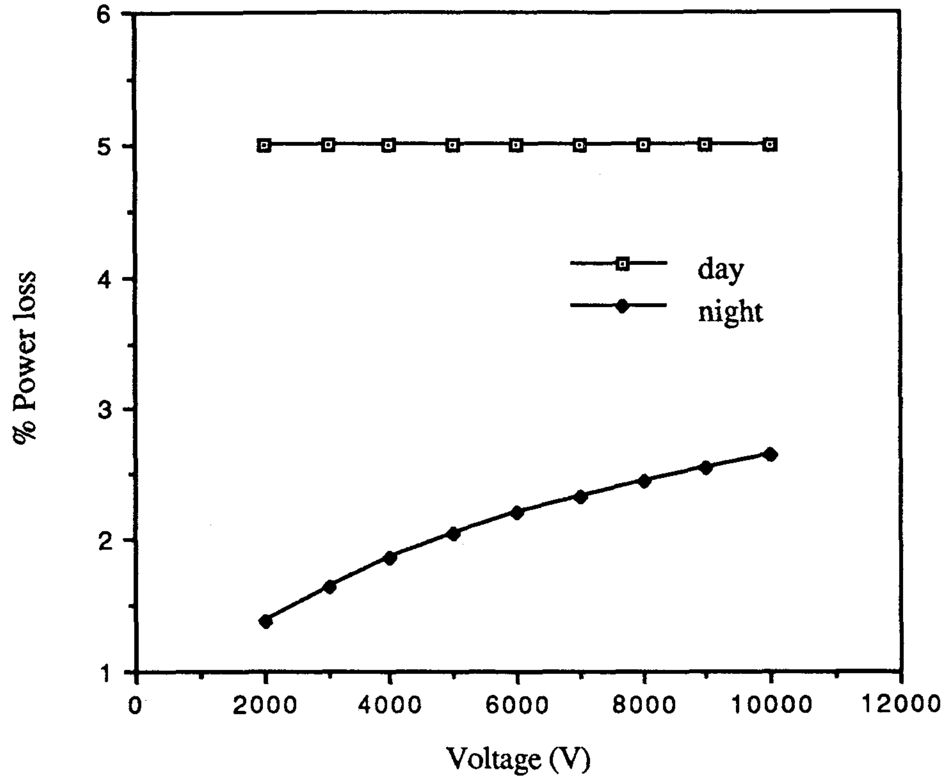
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day

Comments

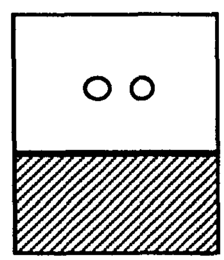
1) This case starts at 2 kV.
2) This illustrates the significant decrease in the resistance of the line due to the increase in conductor material conductivity at the lower night temperatures.
3) The lower temperatures will lead to much better efficiencies for a line designed to operate at 5 % power loss in the day (see 23.F).
4) The line resistance during the night is approximately 1/2 that during the day.

Case 23.F



Transmission Line Parameters

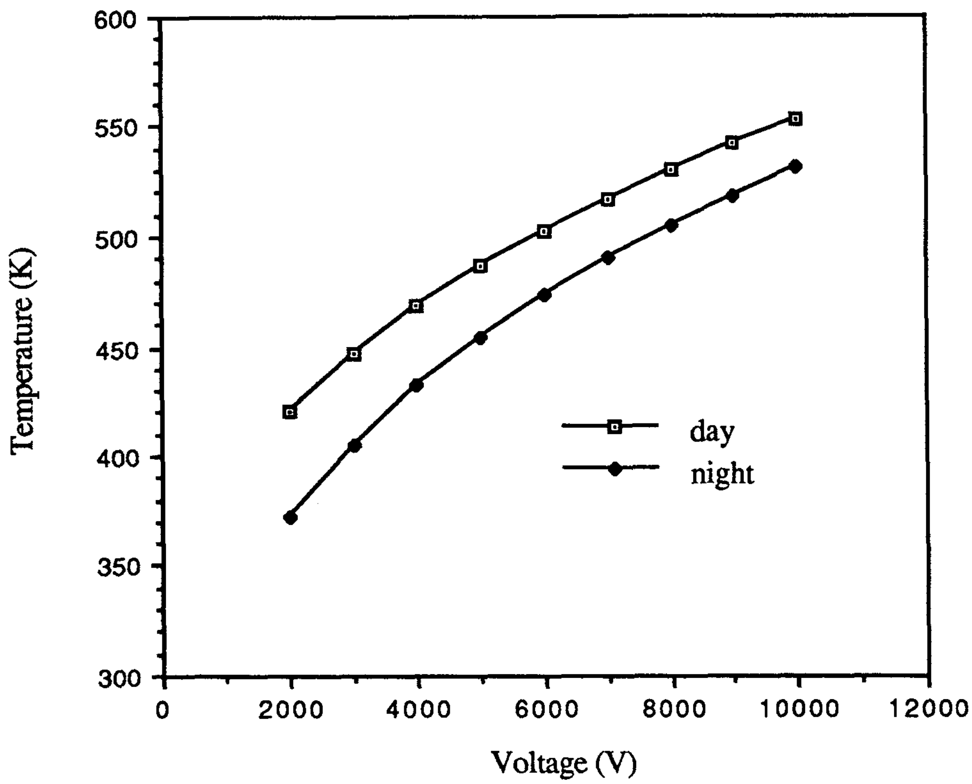
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day

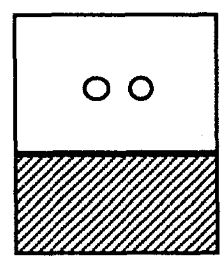


Comments

1) This case starts at 2 kV.
2) The power loss drops from 5 % to as much as 1 % at low voltages. This means that the efficiency increases from 95 % to 99 %.
3) At high voltages the radius of the line is smaller, with less current flowing and an improvement in conductivity has a smaller effect (5 % power loss down to 2 % power loss).

Case 24.C





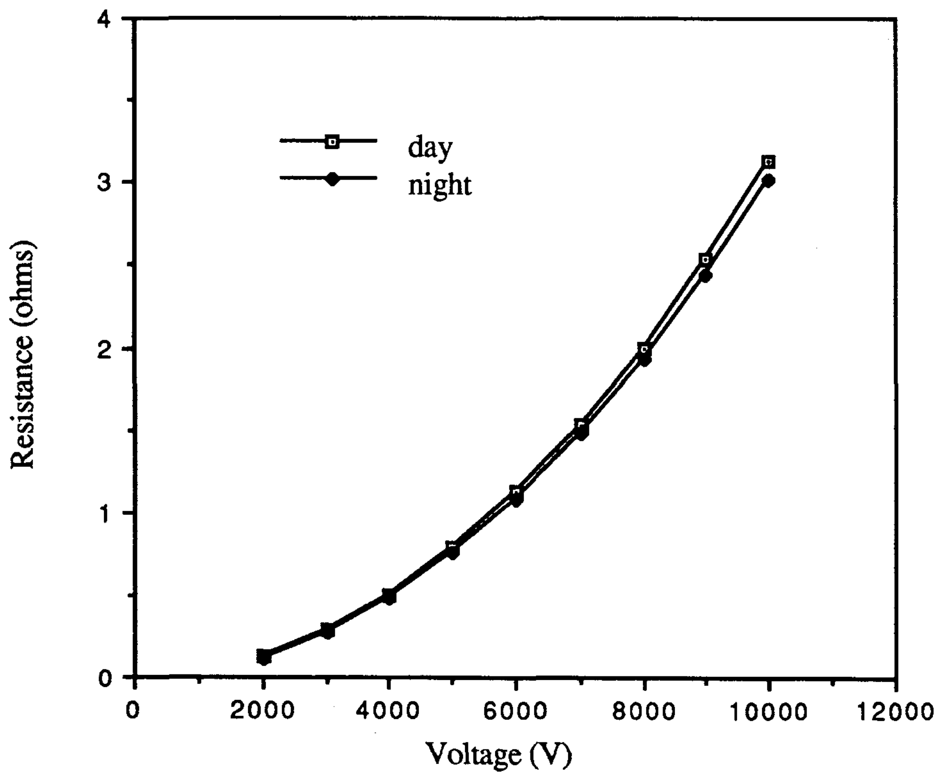
Transmission Line Parameters

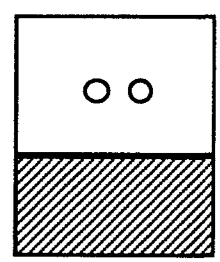
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day

Comments

1) This case starts at 2 kV.
2) The temperature swing for a high power line is much lower than for a low power line.
3) For voltages above 3 kV if the transmission line can withstand the line temperatures for the 5 % power loss case, then the line will operate successfully over the day/night cycle, since the temperature swing will be only about 50 K. No temperature control will be needed.
4) At very low voltages (1 kV) the temperature swing is fairly large (almost 100 K).

Case 24.D





Transmission Line Parameters

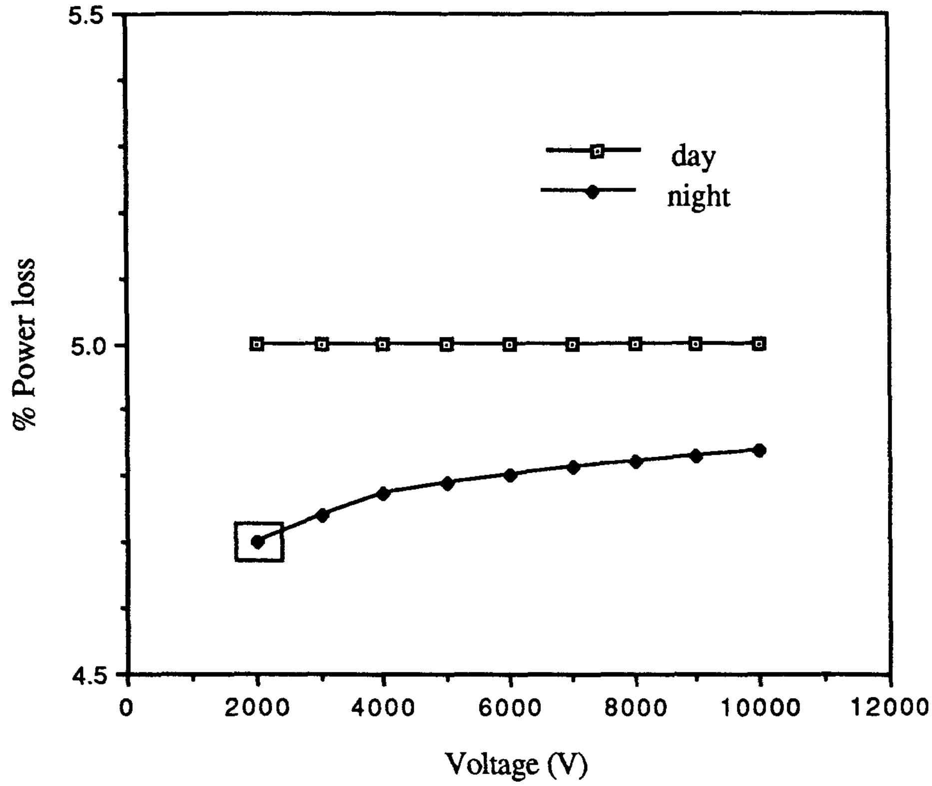
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day

Comments

1) This case starts at 2 kV.

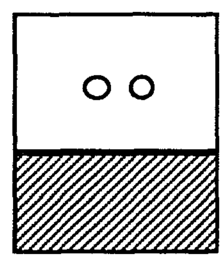
2) Since the temperature of the above ground high power line is relatively stable over the day/night cycle the resistance will not vary significantly.

Case 24.F



Transmission Line Parameters

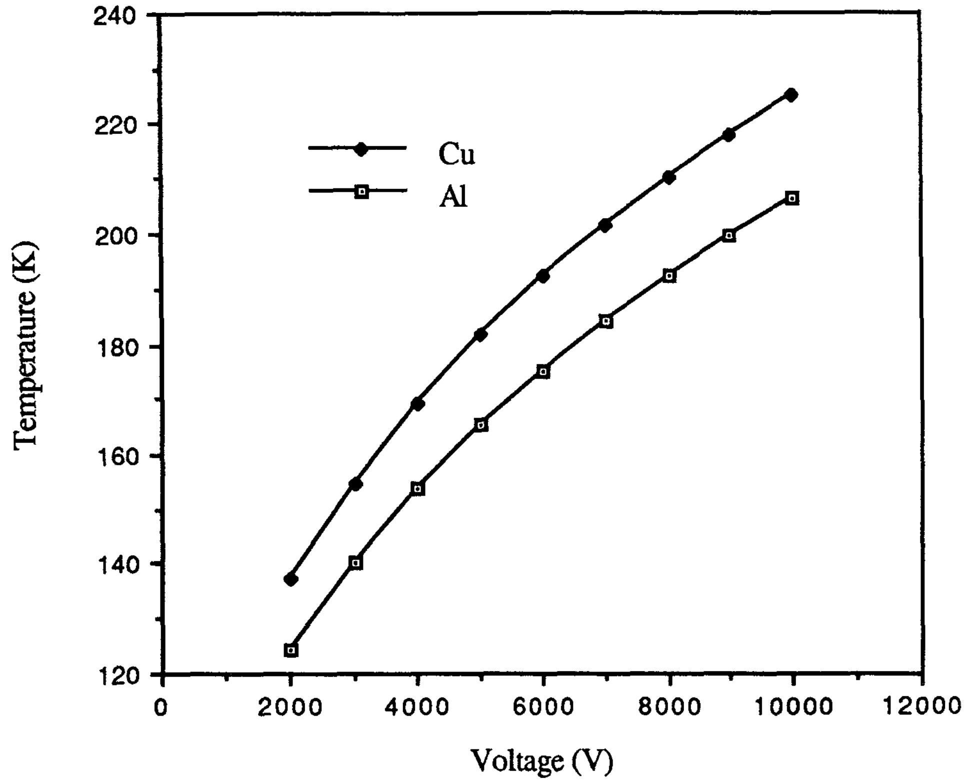
Application	800 kW, 1 km
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*day/night*
Power loss	5 % during the day



Comments

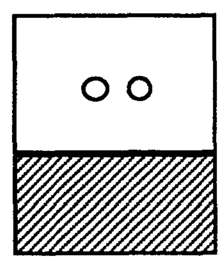
1) This case starts at 2 kV.
2) The value at 2 kV is extrapolated from the following points. Otherwise an initial condition to the model for this calculation causes a significant error.

Case 25.C



Transmission Line Parameters

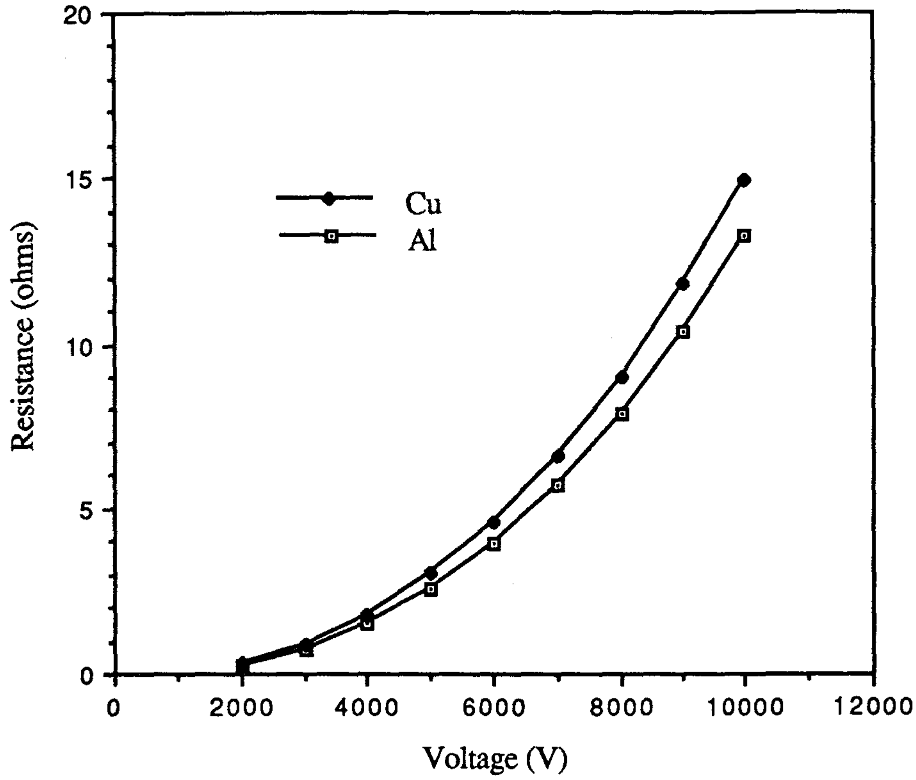
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*Al/Cu*
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

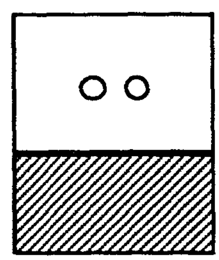


Comments

1) This case starts at 2 kV.
2) This is the same as Case 1 except that it is at night instead of the day.
3) Compare to plot 1.C. Note that the curves are straight (temperature as a function of voltage). Remember that the efficiency was fixed at 5 %, regardless of the temperature of the line, for operation in the day. For such a design, as the temperature drops the conductivity will change, resulting in a change in the line resistance and in the line efficiency. The line efficiency will in turn effect the temperature plots for this night study. In other words all day cases (as voltage is varied) have the same power loss per unit length (i.e., 5 %), so that the effect of the power loss on the line temperature is constant and the line temperature plot shape (straight line) is determined by the line radius and its radiation characteristics. For this night case, however, the efficiency is changing, and thus the power loss per unit length is also changing. This means that the shape of the plot (curved) is determined both by the radius of the line and its efficiency at that voltage.

Case 25.D





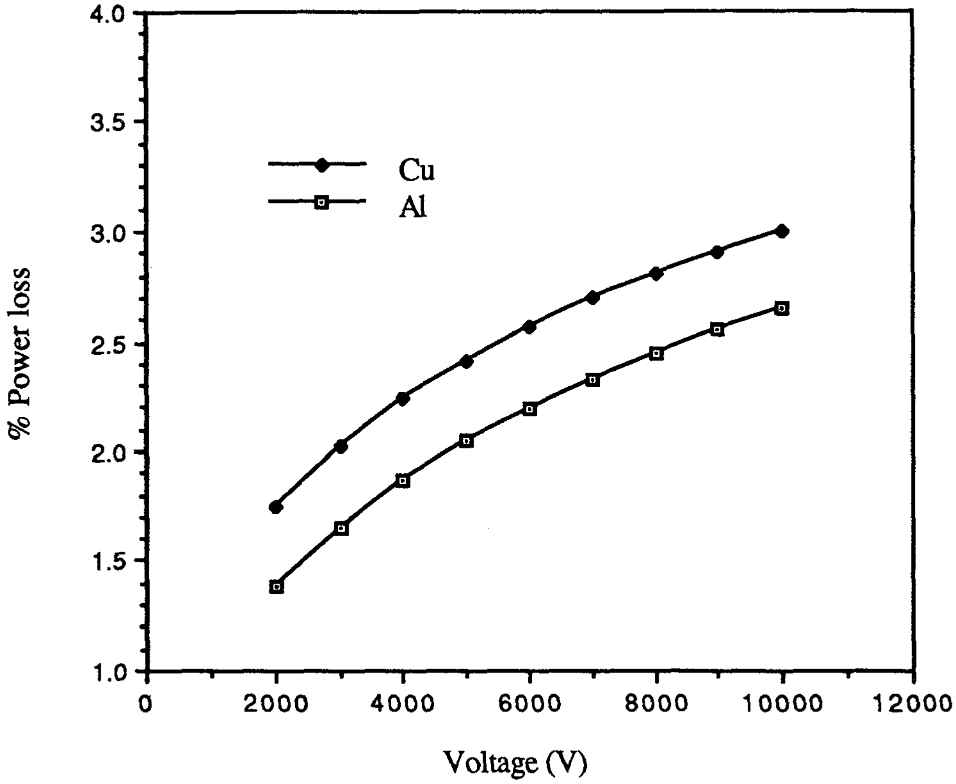
Transmission Line Parameters

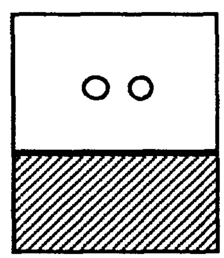
Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*Al/Cu*
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

Comments

1) This case starts at 2 kV.
2) Compare to 1.D, the day case of this transmission line geometry.

Case 25.F





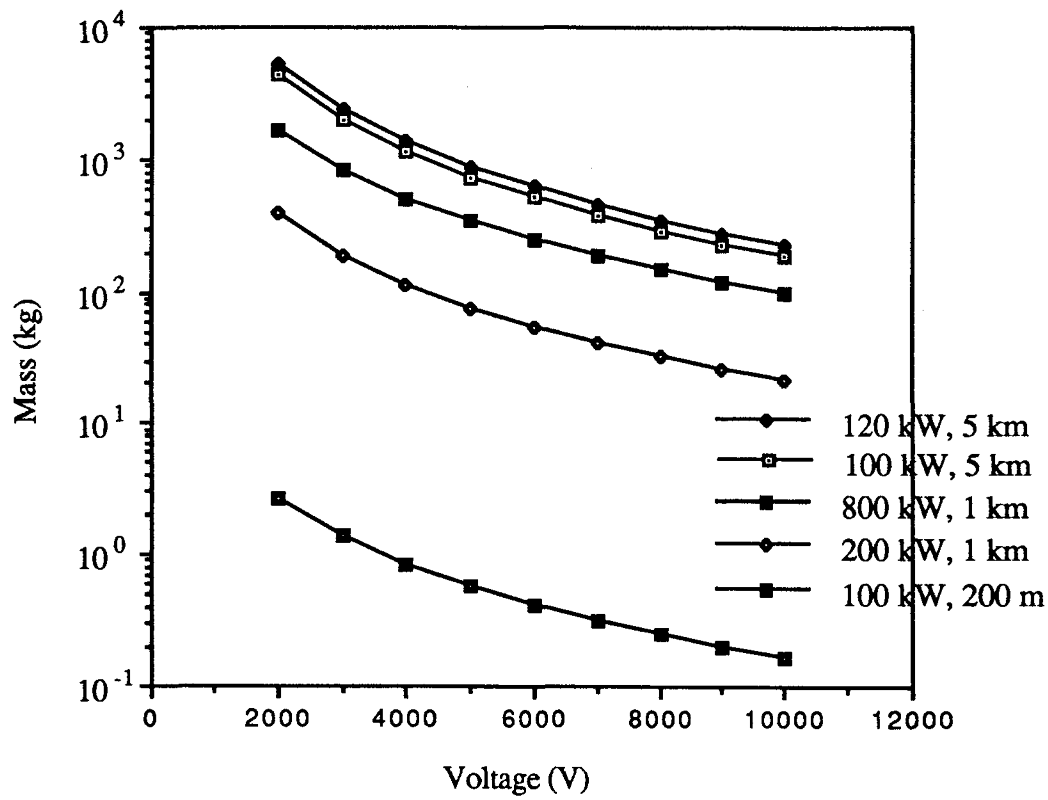
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	two-wire
Location	above
Conductor	*Al/Cu*
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

Comments

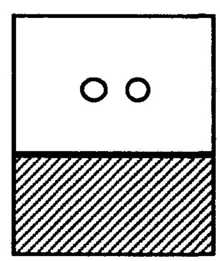
1) This case starts at 2 kV.

Case 26.B



Transmission Line Parameters

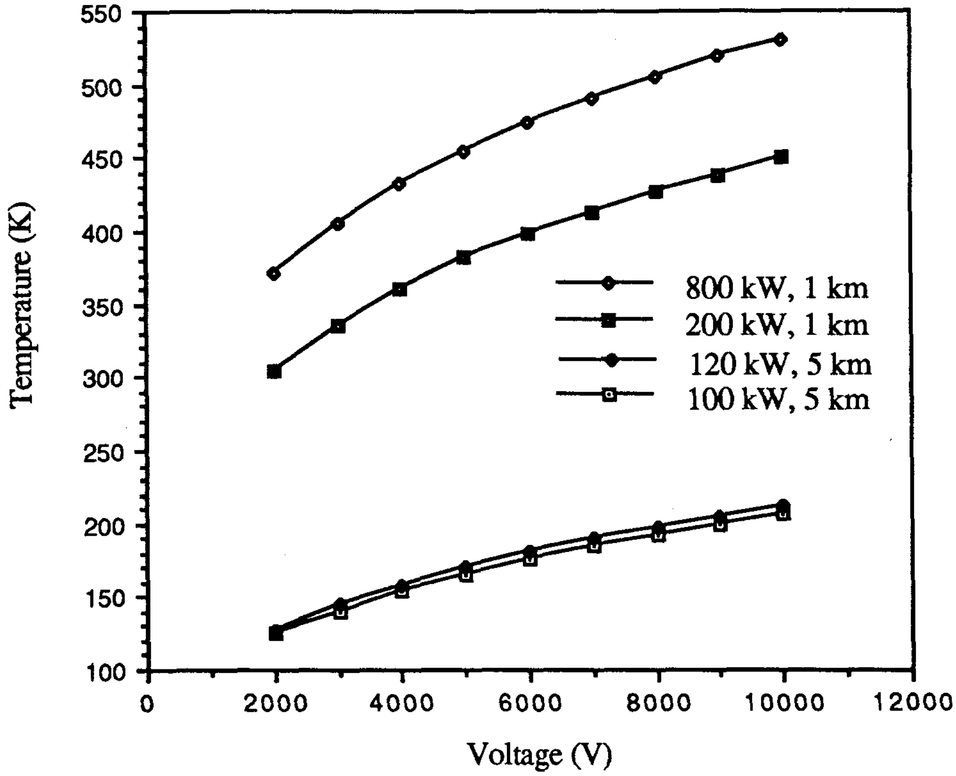
Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

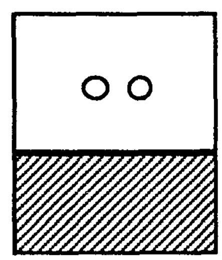


Comments

1) This case starts at 2 kV.
2) Compare this to Case 11.B the equivalent plot for this transmission line in the day.
3) The transmission line designs (geometry and mass) are the same as they were in the day, thus this plot is the same plot as 11.B (minus the 1 kW, 200 m line).

Case 26.C





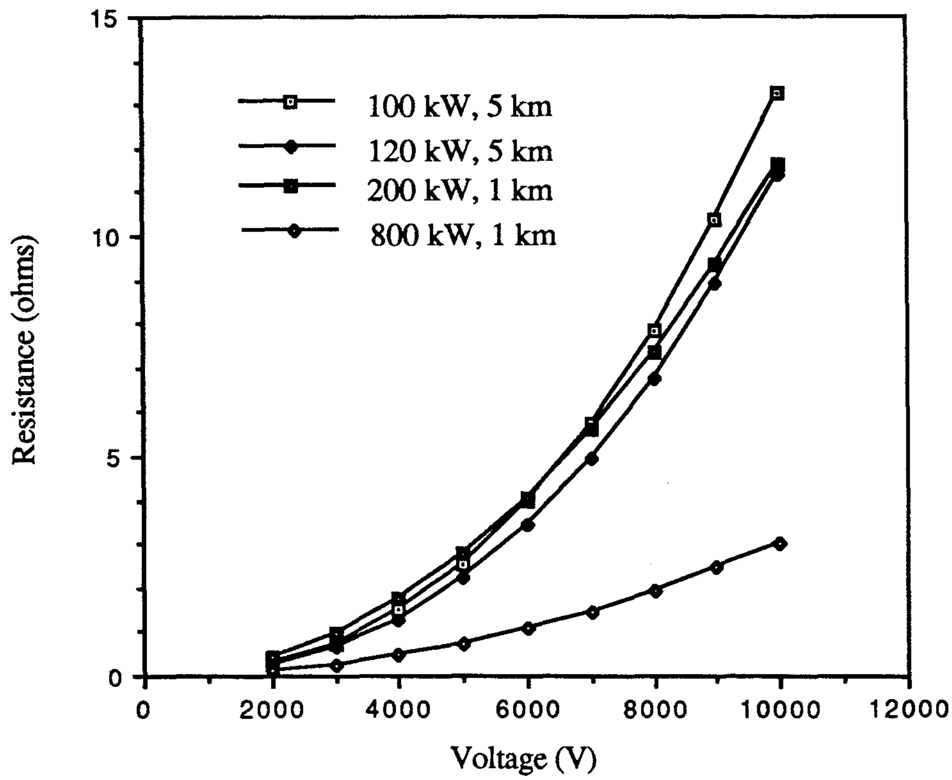
Transmission Line Parameters

Application	*four different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

Comments

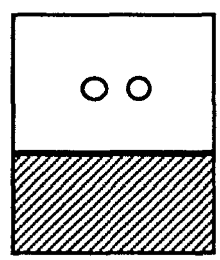
1) This case starts at 2 kV.
2) The 100 kW, 200 m line is not included.
3) See case 11.C.
4) All lines are significantly cooler during the night. The low power loss per unit length lines approach the ambient temperature of the surface of the moon, especially at low voltages.

Case 26.D



Transmission Line Parameters

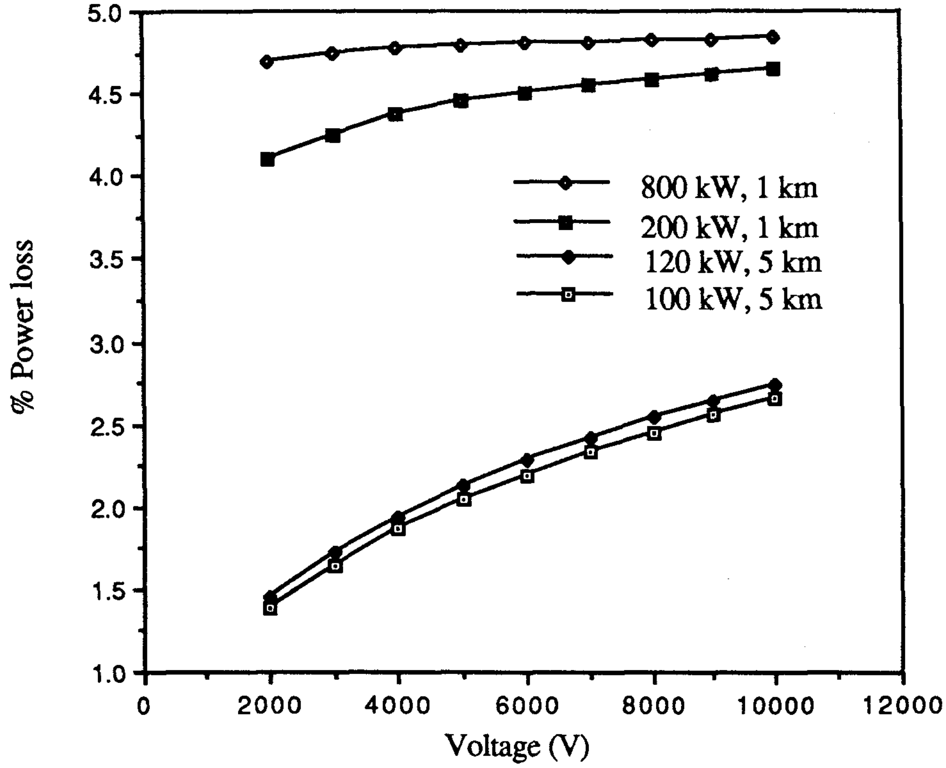
Application	*four different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day



Comments

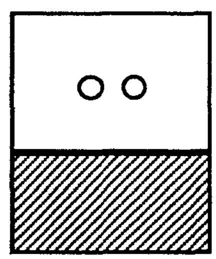
1) This case starts at 2 kV.
2) The 100 kW, 200 m line is not included.

Case 26.F



Transmission Line Parameters

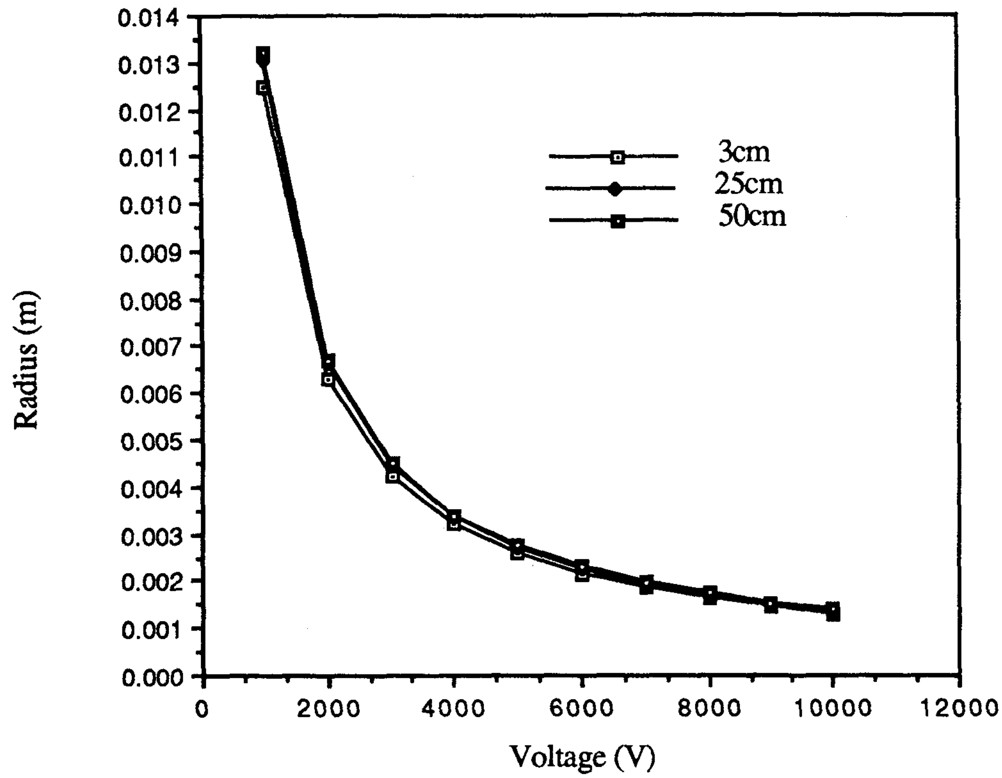
Application	*five different lines*
Geometry	two-wire
Location	above
Conductor	aluminum
Insulator	vacuum
Day/Night	*night*
Power loss	5 % during the day

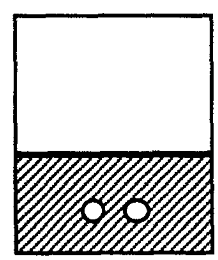


Comments

1) This case starts at 2 kV.
2) The 100 kW, 200 m line is not included.

Case 27.A





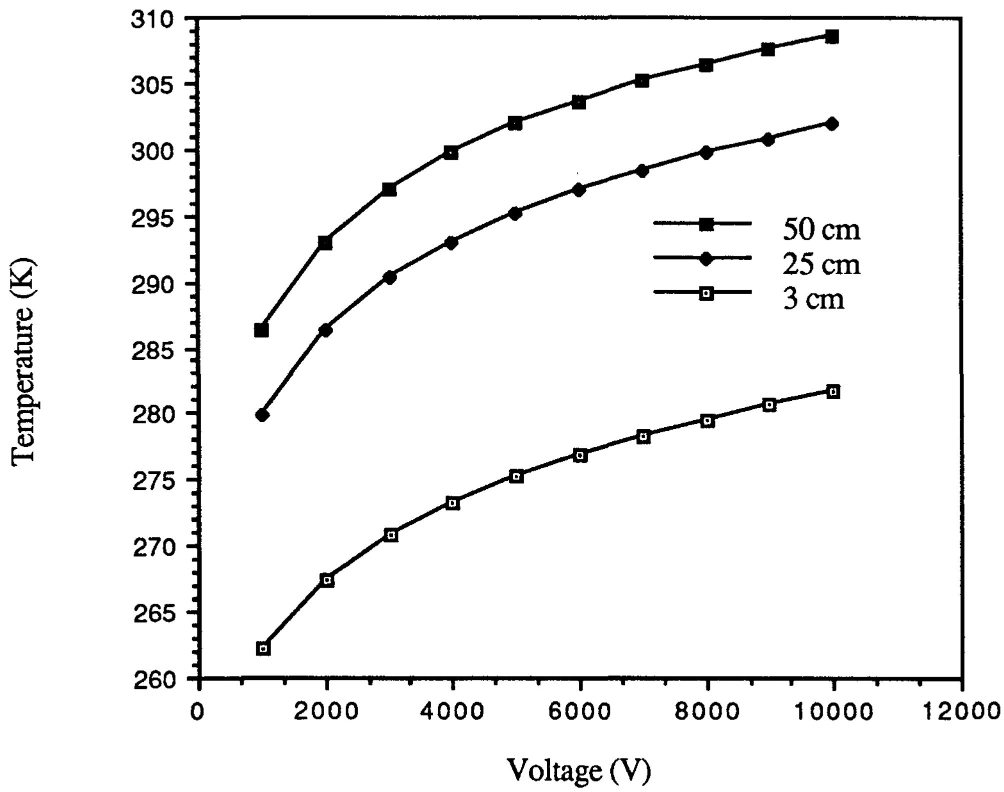
Transmission Line Parameters

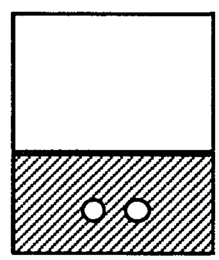
Application	100 kW, 5 km
Geometry	two-wire
Location	*below: 3, 25, 50 cm*
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %

Comments

1) The size of the lines are the same to produce the 5 % power loss at the voltage for the 100 kW, 5 km line. In other words burying the line at different depths will not effect its size.

Case 27.C





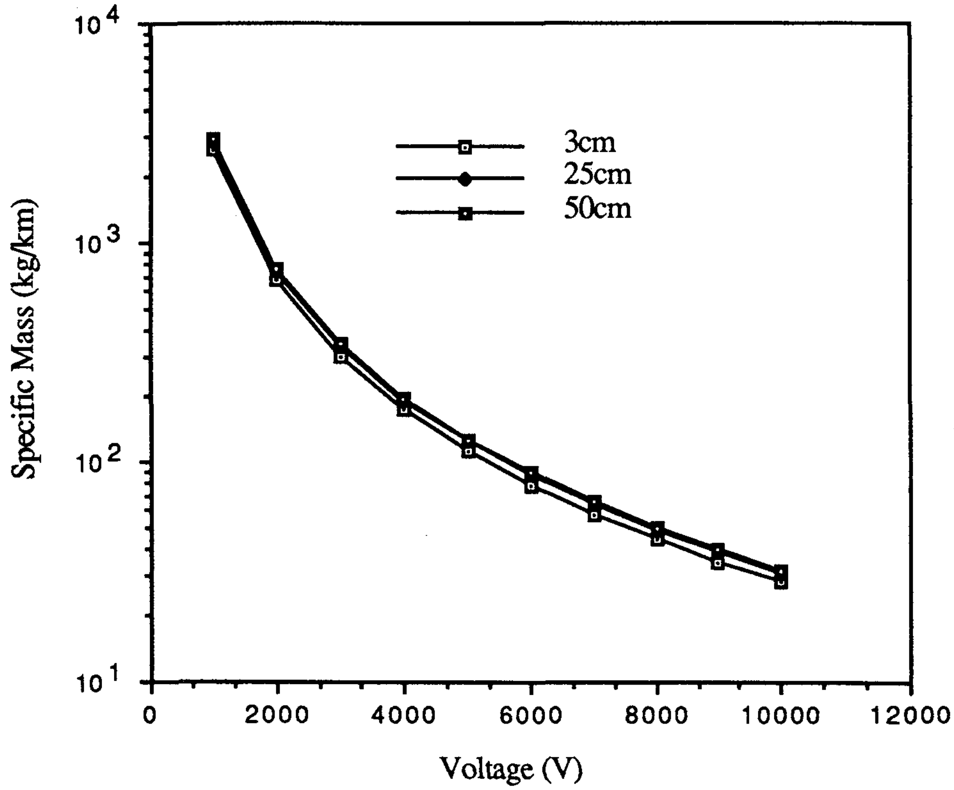
Transmission Line Parameters

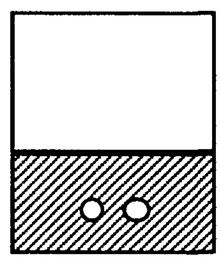
Application 100 kW, 5 km
Geometry two-wire
Location *below: 3, 25, 50 cm*
Conductor aluminum
Insulator vacuum
Day/Night
Power loss 5 %

Comments

1) The line temperature is a strong function of the line radius, thus the temperature goes up (for any depth) as the voltage increases.

Case 27.E





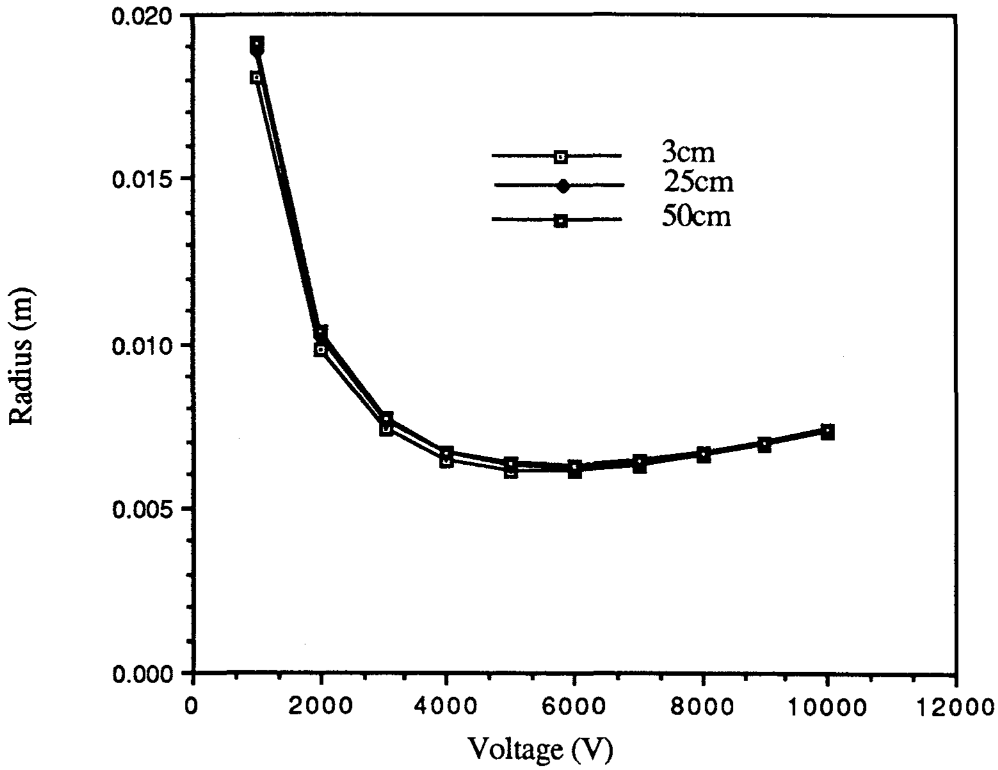
Transmission Line Parameters

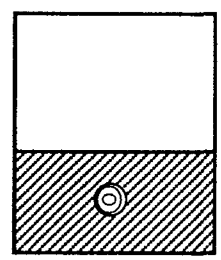
Application	100 kW, 5 km
Geometry	two-wire
Location	*below: 3, 25, 50 cm*
Conductor	aluminum
Insulator	vacuum
Day/Night	
Power loss	5 %

Comments

1) The mass of the three lines at the different depths will be slightly different since the conductor material will effect the conductivity.

Case 28.A





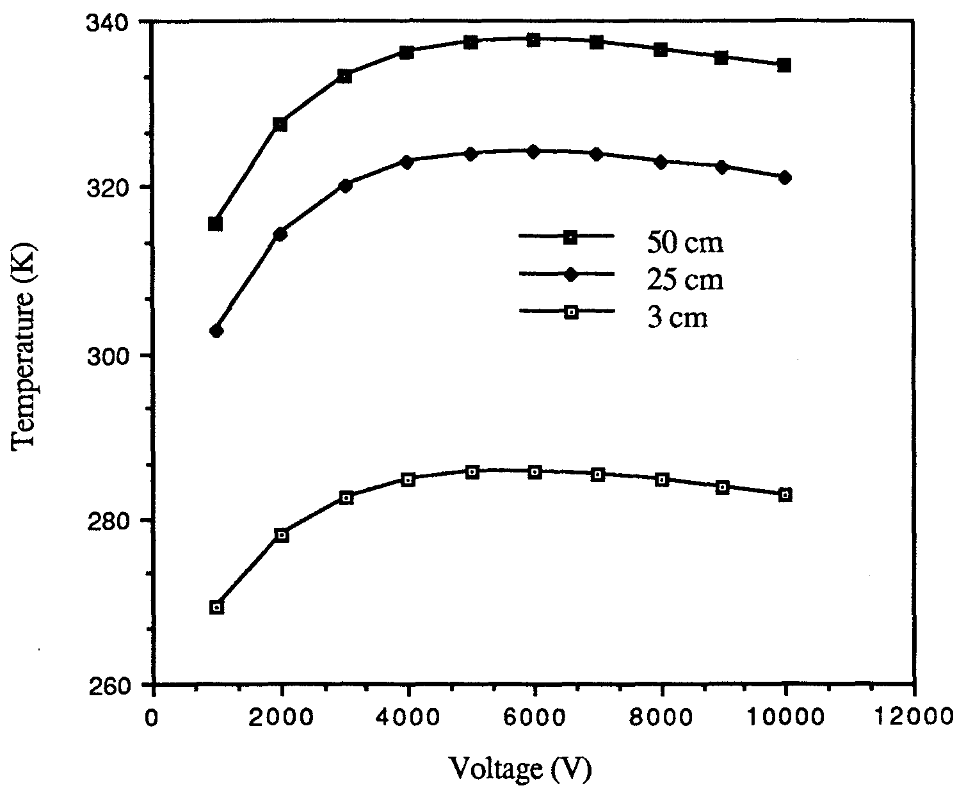
Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	*below:3, 25, 50 cm*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %

Comments

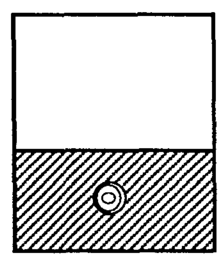
1) The small variation of temperatures of the coaxial lines at the three depths will not be enough to significantly effect the radius and mass of the line design.
2) The radius, as before, is controlled both by the decrease in the conductor size as the voltage increases, and by the increase in the dielectric size as the voltage increases.

Case 28.C



Transmission Line Parameters

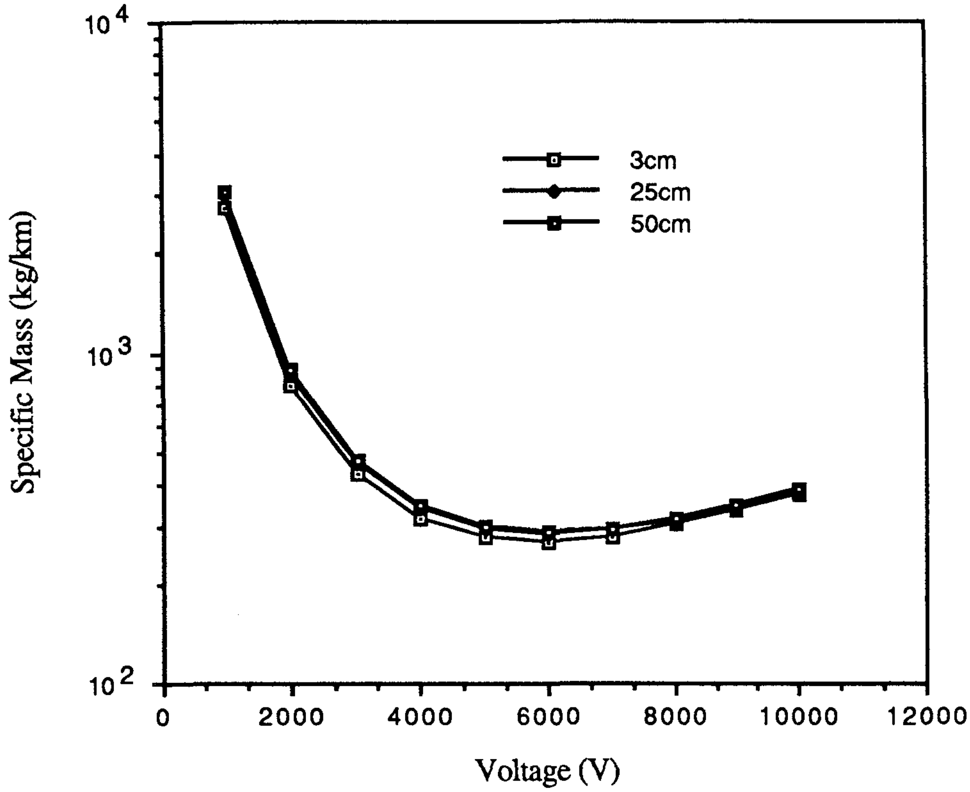
Application	100 kW, 5 km
Geometry	coaxial
Location	*below:3, 25, 50 cm*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %

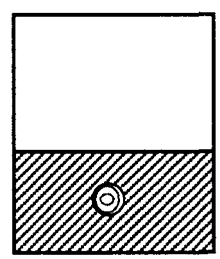


Comments

1) The line temperature is a strong function of the line radius, thus the temperature goes up (for any depth) as the voltage increases at first, but then decreases as the effect of the dominating dielectric causes the radius to increase.

Case 28.E





Transmission Line Parameters

Application	100 kW, 5 km
Geometry	coaxial
Location	*below:3, 25, 50 cm*
Conductor	aluminum
Insulator	solid (TFE)
Day/Night	
Power loss	5 %

Comments

1) The small variation of temperatures of the coaxial lines at the three depths will not be enough to significantly effect the radius and mass of the line design.

VIII. SUMMARY AND CONCLUSIONS

There is a significant amount of information in the data from the parameter studies that can be used to develop some general design guidelines for the design of dc power transmission lines for use on the lunar surface. First, it is important to emphasize some important points:

1) This report does not promote dc transmission. It is a study of the interaction of many of the parameters of dc lines and how the design of these transmission lines might be effected by the lunar environment.
2) This study of the dc transmission line does not take into account the characteristics or requirements of the electrical power loads or sources.
3) The efficiency of most of the transmission lines in this study were chosen to have a 5 % power loss regardless of power transmitted or length.
4) Specific lines were chosen for this study that may be implemented for the initial lunar base. They include specific powers and lengths for connection between specific sites.

General observations will be grouped by parameter category.

Conductor Material

- Copper will result in a lower volume, requiring less space for transport.
- Copper lines are thinner and thus more flexible.
- Copper will require more mass, thus transportation costs for aluminum may be lower.
- At low voltages copper lines are significantly smaller than aluminum, at high voltages the differences are less.

Voltage Level

- Higher voltages result in lower volume, lower mass, and better line flexibility **except** for solid dielectric insulated lines in which the dielectric mass and volume may dominate over the conductor mass and volume at high voltages.
- As the voltage increases and the radius decreases (for the same efficiency) the line resistance increases. Thus, the resistive power per unit volume increases while the surface area is decreasing (for higher voltages). This means that higher voltage lines will operate at a higher temperature.
- Radii below a few mm may be too small to be handled without breakage. A larger line at the higher voltages would result in lower line resistances and lower currents, thus a more efficient line.
- Coaxial lines have an optimum voltage at which the radius and mass are minimized.
- At high voltages, high power coax lines do not have the same mass-dominating effects of the dielectric as seen at lower power levels. This is because the conductor for high power lines is much larger than the conductor for low power lines, while the insulator size is a function of only the voltage and not the power.
- At high voltages the effects of efficiency on size is less significant.
- At high voltages small improvements in efficiency result in significantly lowering in the temperature.
- Low voltage, low power loss, coaxial lines require very large lines.

Efficiency

- Efficiency is important to determine the total power lost compared to the total power transmitted, but as far as optimum transmission line design (lowest mass for a reliable line that will survive the environment) the more pertinent issue that determines the line temperature is the power loss per unit length. For instance, it is impossible to dissipate more than a few W/m of power for conductors beneath the soil. Thus, high power or short lines must be better than 95 % efficient to keep the power loss per unit length low.
- The efficiency drops with increasing conductor temperatures.
- If the power loss per unit length is greater than a few W/m (for instance if it is 10 to 20 W/m) then the line must be operated above ground and it will be unlikely that many solid dielectrics could withstand the combined thermal and radiation stresses.
- Decreasing the mass of a cable by lowering the line efficiency is, in general, not a good approach, since the line temperature will rapidly increase.
- Higher efficiency lines require more mass of conductor but run cooler, since they are larger.
- Small improvements in efficiency at high voltages result in significant lowering of the temperatures.
- At a power loss of 1% (99% efficient line) the temperature is a very weak function of the voltage. This means that below 1W/m of power dissipation in the soil the actual radius of the line is not too important.
- For higher efficiency (lower power loss) the mass minimum (the point at which the dielectric mass increase with voltage starts to dominate over the reduction in mass of the conductor) shifts to the right (i.e. toward higher voltages). This is because the higher efficiency is requiring a higher conductor to insulator ratio than a lower efficiency
- A power loss in the 10s of W/m results in such a high material temperature that more conductor material is needed to compensate for the decreased value of conductivity. Must keep power loss to less than 10 to 15 W/m.
- Improving the efficiency of a high power buried line does not increase the size or mass much, but it does lower the temperature significantly.
- The efficiency of an above ground line improves at night when the conductor temperature drops. For low power-loss-per-unit-length lines this increase is dramatic (although the temperature may be too low for the materials), while at a higher power loss per unit length, the increase in efficiency is not so large.

Temperature

- Higher temperatures increase the resistance, thus lowering the efficiency.
- Lower temperature lines can be smaller since the conductivity is greater than for high temperature lines.
- High temperature lines would require derating of the dielectric which was not done in this analysis.
- Coaxial cables are more difficult to cool underground than two-wire lines.
- Buried transmission lines will only be possible for low power, long distance applications, or where the power loss per unit distance is small.
- At a power loss of 1% (99% efficient line) the temperature is a very weak function of the voltage. This means that below 1W/m of power dissipation in the soil the actual radius of the line is not too important.
- A power loss in the 10s of W/m results in such a high material temperature that more conductor material is needed to compensate for the decreased value of conductivity. Must keep power loss to less than 10 to 15 W/m.
- The temperature of a high power buried line is significantly improved with increasing efficiency.
- Low power loss per unit length, above ground transmission lines will reach very low temperatures at night, possibly damaging the conductor and dielectric materials.
- It may be necessary to artificially warm above ground transmission lines during the night. This could be done with load control.

- During the low temperatures at night the line resistances drop, as much as by a factor of 1/2.
- High power lines have a lower temperature swing over the day/might cycle, and can operate without temperature control.
- A high power loss per unit length line will not operate below the surface without developing very high temperatures, but does provide reasonable temperature stability above the surface by keeping the line at a reasonably constant temperature.
- Low power underground lines run cooler below a depth of about 20 cm the soil than they would close to the surface during the daytime -- and would probably run warmer during the night.

Location

- For low power loss per unit length lines (around a few W/m) the lunar soil can actually cool the lines enough so that they operate at a lower temperature than they would above ground.
- For transmission lines that dissipate relatively small amounts of power per unit length, the below ground location will provide slightly lower mass than above ground because the lower conductor temperature keeps the conductivity high.
- Lines with high power loss per unit length (greater than 3 or so W/m) must be operated above ground.

Conductor Size

- Radii below a few mm may be too small due to fragility. A larger line at the higher voltages would result in lower line resistances and lower currents, thus a more efficient line.

Conductor Geometry

- For coaxial lines (with solid dielectrics) there is an optimum voltage to minimize radius and mass.
- Larger coaxial lines at high voltage run cooler than two-wire lines for above ground lines.
- Coaxial cables are more difficult to cool underground.
- For high powers, high voltage coax lines do not have the same mass dominating effects of the dielectric as at lower power levels.
- For coaxial lines, lower power loss at low voltages requires very large lines.

Miscellaneous

- Total mass plots have limited usefulness, except for observing a general magnitude of the total masses of lines considered for actual applications.
- Many of the temperatures shown and some of the radii are unrealistic.

Insulation

- In general different types of insulation were not studied in this report. However, several observations can be made comparing the solid dielectric insulation chosen for the coaxial line with vacuum insulation chosen for the two-wire line.
- Vacuum insulation provides mass and size reductions over solid dielectric insulation. This becomes very significant at high voltages where the dielectric mass can dominate over the conductor mass.
- Many configurations of lunar transmission lines will result in relatively high temperatures, posing significant reliability and degradation problems for solid dielectrics.
- If the lunar soil has a high enough resistivity then vacuum insulation might work even for bare cables buried in or laying on top of the soil.
- Radiation damage has little effect on vacuum insulation but may degrade solid dielectric insulation.

IX. RECOMMENDATIONS AND FURTHER WORK

Further Modeling Studies

From the information obtained in generating this document, it was determined that several new transmission line geometries need to be modeled, and that another transmission line location needs to be examined in order to complete the dc analyses. The geometries that are to be added are a stranded two-wire line, a coaxial line and a hollow coaxial line. Stranding the conductor improves the flexibility of the line; this could be beneficial if the power requirements necessitate a large diameter cable. A hollow coaxial line may also be beneficial for high power lunar transmission because of the improvement in thermal operation which occurs as a result of the line's increased surface area. Another possibility for transmission line location is on the surface. No supporting structures will be necessary, nor will there be any need to utilize digging equipment in order to deploy them. In addition to the new studies, improvements to the existing models will be made to increase their accuracy. Also, a comparative study of insulator characteristics could be conducted by running the solid dielectric models for a variety of dielectrics.

The study of ac transmission on the lunar surface is currently underway. The transmission of an ac waveform requires the examination of a number of parameters that were not pertinent to dc transmission. These include inductance and capacitance effects, skin effect, increased losses, EMI problems, dielectric constant, and frequency values. The analyses will include the generation of plots similar to those provided in this report with some additional options. These options will include a choice of frequency (60 Hz and 20 kHz), and a conductor spacing option to determine the effects of inductance on different transmission line geometries. The 20 kHz option is included because of the reducing effect frequency has on the size and mass of the conversion equipment.

A study of power transmission would not be complete without addressing the problem of power conversion, both at the source and the load. Power conditioning equipment will influence, and be influenced by the operating characteristics of the transmission line, and it is therefore recommended that a thorough study of ac transformers and dc converters is performed.

Recommended Experimental Investigations

In order to determine the synergistic effects the environment will have on transmission line operation and on the transmission line itself (both conductor and dielectric material), experiments need to be conducted, simulating as accurately as possible, the operation of transmission lines in the lunar environment. These experiments should include the combined effect of thermal stress, vacuum, and radiation. The variation of above, below, and on the surface operation should also be examined. Lunar soil can be approximated with terrestrial soil with similarly electrical and thermal properties. These studies are essential in understanding the limitations/restrictions of transmission line design for the lunar environment.

Some of the questions that may be answered by experimental research are listed below.

Were the computer generated values for temperature accurate?
What are the voltage level restrictions with respect to the environment, i.e. electrostatic charging of dust charging, breakdown, etc..?
What are the frequency level restrictions with respect to the environment?
Is one conductor material operation superior to another?
Is there a presently available dielectric which will operate in the lunar environment?
If there are dielectrics available that will perform adequately in the lunar environment, which of these will be better suited for ac or dc transmission?
How feasible is vacuum insulation?
If vacuum insulation is an option, will there be a minimum height from the ground required for a given voltage to prevent electrostatic charging of the dust?
At what line spacing will vacuum insulated lines operate safely?
Will electrostatic charging of the dust be a problem for either on the surface or suspended locations?
Ac or dc waveform?
Will effluents or local area outgassing effect the line's operation?
Should the lines be coated with a protective coating to improve their operation?
Will surface flashover be a problem?

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13. ABSTRACT ***(Maximum 200 words)***

This report summarizes a portion of the results from a grant at Auburn University to study the electrical and thermal energy management for lunar facilities. Over the past year (June 1989 to May 1990) the following topics have been investigated: June 1989 to November 1989—Literature survey, assessment of lunar power needs, and overview study of the requirements of a lunar power system; November 1989 to April 1990—Develop models for the study of dc electrical power transmission lines for the lunar surface; March 1990 to May 1990—Develop models for the study of ac electrical power transmission lines for the lunar surface. Because of the large amount of information in the model development and application to a wide parameter space this report is being bound separately. This report specifically contains the model development and parameter study for dc electrical power transmission lines. The end of the funding year (May 1990) will conclude with an annual report including the literature survey, the overview of the requirements of a lunar power system, and summaries of the dc and ac models of electrical transmission lines.

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