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HOT SPOT REMOVAL OF UNDERGROUND E.H.V. CABLES BY EVAPORATIVE COOLING

BY

HARDEV S. SODHI

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Electrical Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science
University of Windsor

Windsor, Ontario
1968
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A.F. BALJET

ROBERT A. STAGER
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ABSTRACT

A study of the effect of hot spots in H.V. cables on their load carrying capacity has been made by analogue model and experimental studies. The hot spots studies are those caused by cable joints and steam pipes running parallel to the cable. On the basis of the results of these studies, a new method to control the temperature of hot spots has been proposed and tested in laboratory on a scale model.
ACKNOWLEDGEMENTS

The author expresses his sincere thanks to Dr. O.P. Malik for his guidance throughout the course of this work.

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The author is obliged to Mr. A.F. Baljet of Ontario Hydro for useful discussions and Mr. L. Adamo also of Ontario Hydro for assisting in the experiments carried out at the Research Centre.
LIST OF SYMBOLS

\( \rho_c \) = Thermal resistivity of soil °C-cm/w.
\( \rho_i \) = Thermal resistivity of insulation °C-cm/w.
\( d \) = Outer Diameter of Cable in.
\( D_s \) = Diameter of steam pipe w/o insulation in.
\( D_i \) = Diameter of steam pipe with insulation in.
\( a \) = Burial depth of cable in.
\( A \) = Burial depth of pipe in.
\( q \) = Rate of Heat dissipation of cable w/ft.
\( Q \) = Rate of heat dissipation of pipe w/ft.
\( b \) = Spacing of cables in.
\( H \) = Spacing of steam pipe in, i.e., Horizontal distance between pipe insulation and centre of middle cable surface.
\( \Delta T \) = Means temperature rise.
\( T_c \) = Temperature at cable diameter to its load °C.
\( T_{pc} \) = Temperature at cable due to steam pipe °C.
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CHAPTER 1

INTRODUCTION

General Problem

In recent years considerable interest has been shown in improving the load capacity of Underground high voltage cables by changing thermal environments around them.

The methods adopted principally consist of use of low thermal restivity backfill material, watercooling and oil circulation.

The cables rated at 230kv and above have large current rating and operate at high load factor. As such, both the conductor resistance losses and dielectric losses are significantly high. Serious problems can arise when a certain section of a cable has a higher temperature than the rest of the section. This section, known as the hot spot of the cable can be local, i.e., cable joint or can be due to the presence of external heat sources, e.g., steam pipes.

Unless these hot spots are removed, the whole cable has to be run at a lower capacity than it is rated for.

In this dissertation, a study of the effect of
presence of steam pipes on the load capacity of high-voltage cables (132kv and above) has been made. For the study of cable joint problems the data reported in literature (1,2) has been taken to form the basis of analysis.

On the basis of analogue and experimental studies, a new method for controlling the temperature of hot spots in cables has been proposed. This method is suitable for the removal of hot spots generated by either of the two causes mentioned earlier.
CHAPTER 2

CABLE JOINTS

2.1 Introduction

The thermal resistivity and dielectric losses of cable joints are higher than the normal cable because of added insulation. Since the cable joints are mostly hand made, the exact mathematical analysis of the joints is not possible. Direct measurement of temperature rise inside the joint by the method of current injection and thermo couples is not possible for 275kv and above rated cables, because of higher dielectric losses.

As such, the analysis of cable joints reported by different investigators\textsuperscript{1,2} has been done mainly by setting up an equivalent resistance mesh network and assuming distinct concentric layers of dielectrics used for insulation.

\textsuperscript{1} Weedy and Perkin have given a maximum temperature of 107\textdegree C at the centre of 400kv cable joint for current rating of 1600 amperes. The dielectric loss angle and ambient temperature for this case are 0.008 and 12.5\textdegree C respectively.

Similarly Thelwell and Lis\textsuperscript{2} give a maximum
temperature of 103°C for a 275kv cable joint with ambient temperature as 15°C. In both cases the cables are normally buried and have no integrated cooling system.

The analysis of cable joint done in the present work by resistance paper analogue assumes that the dielectrics are of uniform thickness throughout the cable joint. Therefore, the whole length of cable joint runs at the same temperature.

However, since actually the dielectrics taper off at the ends, there will be a decrease in temperature as one moves away from the centre of cable joint. This assumption as such, will lead to conservative results. Figure 1 shows in general the actual temperature distribution and the assumed one.

A method of estimating the approximate temperature reduction of field model beforehand is explained on page 22.

2.2 Analogue Model Analysis of Cable Joints

The circuit used for the analogue studies is shown in figure 2.

For all the studies performed, the following dimensions have been adopted:

1. Size of cable 3" diameter external.
2. Spacing of cable, centre to centre 4.8".
Fig. 1 Assumed and Actual Temperature Distribution of Cable Joint.
Fig. 2 Analogue Circuit for Cable Joint.
3. Depth of burial to cable centre 48".
4. Voltage of centre cable 0.5 volts.

The equipotential lines correspond to isothermal lines and current flow in the centre cable analogue represents heat dissipation from it to the ground.

Although the cable is a constant heat source, for the observation it has been taken to be a constant temperature source. This makes it convenient to appreciate and interpret the results.

2.3 Observations
2.3.1 Without Cooling

A plot of isothermal lines for normal burial conditions is shown in figure 3. It can be seen that 0.5AT isothermal line lies at 16.5 inches above centre cable. Thus although total depth of burial is 48" inches, the high temperature region is confined up to a height of 16.5" inches.

The ideal conditions for cooling will be when heat is conducted from cable to ground surface instantly. This will keep the temperature at the ambient level. Such a requirement will involve short circuiting all the thermal resistance up to ground level. This in itself is impossible and as such, to reduce the thermal resistance to a reasonable degree economically, attention has been
concentrated in reducing the thermal resistance of the high temperature region. Under new conditions, the isothermals are more drawn out towards ground level and the heat dissipation is quicker.

2.3.2 Cooling Sheath Above Cable

A cooling sheath can be represented on Teledeltos paper by lines drawn with silver paint on the same scale as for the cables. The shape enclosed by silver lines represents the cross section of cooling sheath.

A cooling sheath with L-shaped cross section was first tried, placing it 1.5" above the cable. The height of its arm was 15 inches and width 9.6 inches. Then a U-shaped cross section cooling sheath with the same conditions of spacing and voltage was tried. It was found that the isothermal lines are more prominently drawn out in the latter case and increase of height on both arms is more effective than equivalent increase on one side only.

2.3.3 U-Shaped Cooling Sheath Above Cable

Fig. 5 shows position of maximum drawn out isothermals of a U-shaped cooling sheath placed 1.5 inches above the cable. When the height of arms of the sheath was increased by 3 inches at a time.
Although the height can not be increased beyond 24 inches due to practical difficulties, (road clearance, etc.) for this particular layout readings were taken up to a height of 33 inches.

As can be seen from figure 5, the maximum drawn out isothermal for 18 inches height is $0.7796 \Delta T$ and for 24 inches height it is $0.738 \Delta T$. These isothermals lie at a height of 7.5 inches and 13 inches above the centre cable. From figure 3, the corresponding isothermals of uncooled cable at these heights are $0.69 \Delta T$ and $0.58 \Delta T$.

The uncooled centre cable current of analogue model is 104\muamps compared to 136\muamps and 147\muamps for the other two cases.

Figure 6 gives relation between thermal resistance and height. The graph is linear except near the origin, i.e., just above the cable. A reduction of 25 percent for 18 inches and 32 percent for 25 inches height of cooling sheath arms, in the thermal resistance of uncooled cable as observed, compared to that of uncooled cables as shown in figure 7.

2.3.4 U-Shaped Cooling Sheath Below Cable

In the fourth case, observations were taken by placing cooling sheath 3/4 inches below the cables. The centre cable current of analogue model for 19 inches
Fig. 5  Maximum Drawn Out Isothermals for 3-Cable System Using Cooling Sheath
Fig. 6 Relative Reduction of Thermal Resistance for a Cooled 3 Cable System
height of sheath was 129 μamps and for height of 24 inches it was 138.5 μamps. The uncooled centre cable was 104 μamps. Height of sheath implies the height of the two arms of the U-section.

Figure 6 of thermal resistance v.s. height shows linear relationship except near origin. Figure 7 shows a reduction of 18 percent for 18 inches height and 25 percent for 24 inches height of sheath.

From figure 7, it can be seen that placing of the cable above the sheath is more effective than placing it below the cable. This is quite obvious, considering the fact that the aim of the sheath is to reduce the thermal resistance between the cable and ground level. By placing the cooling sheath below the cable, the effective thermal resistance required to be reduced, has been increased.

2.3.5 6 Cable Unit

This study has been made to analyse the situation when instead of 3 cables, there is a layout of 6 cables in horizontal formation.

The burial depth, spacing and size of cables are same as for 3 cables case. In place of one U-shaped cross section cooling sheath two separate sets are used. The arrangement is shown in figure 8.

Figure 9 gives the position of different isothermals
Fig. 7 Resistance Characteristics of 3 Cable.

Analogue Model With Different Cooling Sheath Positions.
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Fig. 11 Thermal Resistance and Relative Thermal Resistance Reduction Characteristics of Balanced 3 Phase 6 Cable Unit.
for uncooled cables where as figure 10 gives maximum drawn out isothermals for different height of cooling sheaths. The height of the arms of both cooling sheaths are increased simultaneously.

For cooling sheath height of 24 inches maximum drawn out isothermal is \(0.826 \Delta T\) lies at 14.5 inches above the cables 2 and 5 compared to \(0.55 \Delta T\) for the uncooled cables. From figure 11 the respective resistance cut is 35% and 23%.

2.3.6 Cooling Sheath With Increased Cable Diameter

The cable diameter at the cable joints is much greater than the normal cable due to increased insulation material. Therefore readings were taken for 7.5" diameter cables with same burial depth, side to side cable spacing and separation between cooling sheath and cables as for the 3" diameter cables done earlier.

The results obtained are shown in figure 12. There is a reduction of 27 percent for 18 inches height and 30 percent for 21 inches cooling sheath height compared to 25 percent and 27 percent for 3" cable diameter case, in the thermal resistance compared to that of uncooled cables. The slight increase in thermal resistance reduction is due to reduction of overall effective thermal resistance of soil due to increased diameter of cable and use of larger size of cooling sheath.
Fig. 12 Thermal Resistance Reduction by Cooling Sheath for Increased Diameter
2.4. Method of Finding Expected Temperature Drop On Field Cable Joints

The temperature distribution on a 400 kv cable joint for a load of 1600 amps, joint power factor of 0.008 and ambient temperature of 12.5°C taken from reference is shown in figure 13 as curve A.

Curve B is the straight line approximation of curve A where as curve C is the assumed cable joint temperature distribution on the resistance paper analogue.

The cooling sheath is supposed to be extended well beyond distance indicated by point Z in figure 13. Therefore temperature of cable at this distance is unaffected by the rest of cable.

From analogue studies for cooling sheath height of 21 inches a temperature reduction of 27 percent is expected.

Therefore the joint temperature for cooled cable under conditions of curve C will be:

$$= 107 - 107 \cdot \frac{12.5}{1} \cdot \frac{27}{100}$$

$$= 107 - 25.5$$

$$= 81.5°C.$$  

The new temperature curve is given by curve D.

Two possible extreme conditions are considered:

(1) Copper tubes of cooling sheath are isolated
Fig. 13 Approximate Estimation of Temperature Reduction in Field Cable Joints
from each other.

(2) Copper tubes are perfect conductors and so packed that heat conduction from one tube to the other is perfect.

Under condition (1) when tubes are isolated from each other, each tube or a set of tubes is cooling a particular section of cable joint. The new temperature distribution in this case will be given by curve E.

The condition (2) when the tubes are conducting heat between them perfectly, will tend to distribute the temperature uniformly on the cable joint as shown in curve F.

A practical system will work in between these two extreme conditions, (nearer to condition #2) and as such the highest temperature on the cable joint of a field cable should fall in the range of 73°C and 81.5°C.

Therefore by assuming the temperature distribution of the Type C, a certain safety margin is available. Its exact value can be ascertained only after a number of field tests are made.
3.1 Assumptions

The mathematical analysis of the steam pipe problem has been done on the following assumptions:

1. The soil has been considered as an isotropic heat conducting medium.

2. Steam pipe has been taken as a constant temperature heat source.

3. Dielectric losses are important only for cables rated at 132kv and above and are assumed to be generated at the conductor.

4. All cables in the system carry the same load current and are assumed to be operating under same load cycle.

The first assumption is valid as long as the temperature of cable does not run as high as to cause moisture migration from the soil near the cable. Reduction in moisture content increases the resistivity of the soil and starts the phenomenon known as thermal runway of soil.\(^3\)

Since the drop of temperature along the steam pipe is very small, the 2nd assumption will give quite accurate
results.

There is sufficient experimental and theoretical\textsuperscript{4,5} data which allows the adoption of the 3rd assumption without introducing much error.

The fourth assumption holds good under normal load conditions, i.e., when there are no faults in the system.

3.2 General Principle

The analysis of the problem has been done by image method similar to the problem of pending potential distribution around a uniformly charged infinite conductor above a semi-infinite equipotential surface. According to the hypothesis enunciated by Kennelly\textsuperscript{6} consider two parallel cylinders lying in an infinite medium of uniform temperature and thermal resistivity, one acting as sink and the other as source.

When the axial separation of the cylinders is twice the actual burial depth, and the source and sink generate and absorb heat at equal rates, such a heat flow will result in temperature at horizontal mid plane between cylinders being the same as that of the ground surface.

For multiheat source system, i.e., more than one cable and/or steam pipe, the principle of superposition has been used. In thermal term it states that if a thermal
network has more than one heat source, the heat flow between any two points or the temperature difference between any two points is the sum of the heat flows and temperature differences at these points which could exist if each heat source were considered separately.

3.3 Specific Cases

Two cases of cables and steam pipe have been considered here:

1. Cable and steam pipe are running parallel to each other.

2. Steam pipe runs perpendicular to direction of the cable.

3.3.1 Steam Pipe Running Parallel to Cable

When one or a number of cables or steam pipes are buried at different depths, as shown in figure 14, the temperature rise at any point \((x,y)\) is given by

\[
T_c = 0.012q\rho e \sum \log \frac{r_i'}{r_i}
\]  
(3.1)

where

- \(r_i'\) = distance of point \((x,y)\) from image of \(i\)th heat source.
- \(r_i\) = distance of point \((x,y)\) from \(i\)th heat source.
Fig. 14

Cables and Their Images

Fig. 15

Horizontal Formation of Cables and Their Images
$\rho_e = \text{thermal resistivity of soil.}$

$\rho_e = \frac{695}{K} \text{cm./watts}$

$K = \text{coefficient of conductivity of soil}$

$\text{B.T.U.-in./ft.}^2\text{-hr.}$

The conversion factors for evaluating $\rho_e$ from different units are given in reference 7.

Consider a common configuration, i.e., when three cables are buried at the same depth. The hottest will be the centre one.

Taking the cable surface to be isothermal, the temperature rise of the centre cable surface, $(o,a-d/2)$ equation (3.1) becomes:

$$\Delta T^0_c = 0.012 q \rho_e \sum \log \left[ \frac{(x-b_i)^2 + (y+a_i)^2}{(x-b_i)^2 + (y-a_i)^2} \right]^{1/2}$$

$$= 0.012 q \rho_e \left[ \log \left( \frac{b_1^2 + (2a-d/2)^2}{b_1^2 + d/2^2} \right) \right]^{1/2}$$

$$+ \log \left( \frac{(2a-d/2)^2}{(d/2)^2} \right) \right]^{1/2} \log \left( \frac{b_1^2 + (2a-d/2)^2}{b_3^2 + (d/2)^2} \right)$$

(3.2)

Since $a \gg d$

And for symmetrical distribution of cables about $y$ axis, i.e., $b_1 = b_3$, equation (3.2) becomes
\[
(Eq. 3) \quad \rho_c \left[ 2 \log \frac{b_1^2 + 4a^2}{b_1^2 + (d/2)^2} + \frac{\log 4a}{d} \right] = 0.012 \rho_c \log \left[ \frac{b_1^2 + 4a^2}{b_1^2 + (d/2)^2} + \frac{\log 4a}{d} \right] \quad (3.3)
\]

\( T_c \) will be the actual temperature of cable if ground temperature is zero \( ^\circ C \), otherwise the formula gives the temperature difference between cable surface and ground.

Actual temperature of cable surface is \( T_c + T_{amb} \)

where \( T_{amb} \)

= Ambient temperature of ground surface.

Equation 3 gives the temperature rise at cable due to its current load.

Consider now a steam pipe running parallel to the cables as shown in figure 16. The thermal equivalent network for the steam pipe is given in figure 17. Taking the insulation surface of steam pipe to be isothermal,

\[
(Eq. 4) \quad T_s - T_{amb} = Q \left[ \rho_{i \text{ eff}} + \rho_{e \text{ eff}} \right] \quad (3.4)
\]

\( \rho_{i \text{ eff}} = \text{effective insulation thermal resistance.} \)

\[
= 0.012 \rho_i \log \frac{D_i}{D_s} \quad \text{C-cm/w.} \quad (3.5)
\]

\( \rho_{e \text{ eff}} = \text{effective soil thermal resistance.} \)

\[
= 0.012 \rho_e \log \frac{2A - D/2}{D_i/2} \quad (3.6)
\]
Fig. 16 Steam Pipe and Cables

Fig. 17 Thermal Circuit of Steam Pipe
\[ T_s - T_{amb} = Q \times 0.012 \left( \rho \left[ \log \frac{2A - D_{i/2}}{D_{i/2}} \right] + \frac{\rho \log D_i}{D_s} \right) \] (3.7)

Since both \( T_s \) and \( T_{amb} \) are known, the value of \( Q \), i.e., heat dissipation watt/ft, can be determined and \( Q \) is constant for a particular position.

\[ Q = \frac{T_s - T_{amb}}{0.012 \left( \rho \left[ \log \frac{2A - D_{i/2}}{D_{i/2}} \right] + \frac{\rho \log D_i}{D_s} \right)} \] (3.8)

The steam pipe for that particular position is a constant heat source and so applying the equation (3.1)

Temperature rise at any point \((x, y)\) is given by

\[ \Delta T_p (x, y) = Q \times 0.012 \rho e \log \left( \frac{(x-H)^2 + (y+A)^2}{(x-H)^2 + (y-A)^2} \right) \] (3.9)

Temperature rise at centre cable surface \((o, a-d/2)\) \((o, a)\) when \( a \gg d/2 \) is

\[ \Delta T_{pc} (o, a) = Q \times 0.012 \rho e \log \left( \frac{H^2 + (a+A)^2}{H^2 + (a-A)^2} \right) \] (3.10)

Equations above can be put in a more compact form by substituting for \( Q \) from equation 6.
\[ \Delta T_{pc} = T_s - T_{amb} \]
\[ \frac{0.012 \left( \Phi e \log \left( \frac{4A-D_i}{D_i} \right) + \Phi l \log \frac{D_i}{D_s} \right)}{x} \]

\[ 0.012 \Phi e \log \left( \frac{H^2 + (a+A)^2}{H^2 + (a-A)^2} \right)^{\frac{1}{2}} \]

\[ = 0.5 \left( \frac{T_s - T_{amb}}{\log \left( \frac{4A-D_i}{D_i} \right) + \frac{\Phi l \log \frac{D_i}{D_s}}{\Phi e} \right) \] (3.11)

\[ \times \left( \frac{\log \frac{H^2 + (a+A)^2}{H^2 + (a-A)^2}}{x} \right) \] (3.12)

Total temperature rise at the centre cable is given by the sum of equation (3.3) and (3.12).

Temperature rise at centre cable,
\[ \Delta T = \Delta T_c + \Delta T_{pc}^0 \text{C.} \] (3.13)

Thus given the load conditions of the cable and information regarding steam temperature and insulation, the expected total temperature rise at the cable surface for specific conditions, can be calculated.

However to study in general the effect of the presence of steam pipe on load capacity of different high voltage cables the following procedure can be adopted.
Let,

\[ I_{m} = \text{maximum load current corresponding to conductor temperature of } T_{\text{max}}, \text{i.e., maximum allowable temperature.} \]

\[ I_{m}' = \text{maximum load when steam pipe is introduced and maximum allowable conductor temperature is still } T_{\text{max}}. \]

\[ P_d = \text{Power losses in dielectric at } T_{\text{max}}. \]

Total power dissipated

\[ P_t = I^2R + P_d. \quad (3.13) \]

Neglecting sheath losses

\[ P_t = \frac{T_{\text{max}} - T_{\text{amb}}}{R_t} \]

\[ = K (T_{\text{max}} - T_{\text{amb}}) \quad (3.14) \]

where

\[ R_t = \text{effective thermal resistance of soil and dielectric.} \]

If \( T_s \) is the temperature rise due to steam pipe then

\[ I_{m}'^2R + P_d = K (T_{\text{max}} - T_s - T_{\text{amb}}) \quad (3.15) \]

From equation (3.13) and (3.15) above,

\[ \frac{I_{m}'^2R + P_d}{I_m^2R + P_d} = \frac{T_{\text{max}} - T_s - T_{\text{amb}}}{T_{\text{max}} - T_{\text{amb}}} \quad (3.16) \]
\[
\left( \frac{\text{Im}'}{\text{Im}} \right)^2 + \frac{\text{Pd}}{\text{Im}^2 \text{R}} = \frac{T_{\text{max}} - T_{\text{B}} - T_{\text{amb}}}{T_{\text{max}} - T_{\text{amb}}} \quad (3.17)
\]

\[
\frac{\text{Pd}}{\text{Im}^2 \text{R}} \text{ is the ratio of dielectric and conductor losses at the maximum cable conductor design temperature } T_{\text{max}} \text{ under normal burial conditions.}
\]

\[
\frac{\text{Im}'}{\text{Im}} = \left[ \frac{T_{\text{max}} - T_{\text{B}} - T_{\text{amb}}}{T_{\text{max}} - T_{\text{amb}}} \left( 1 + \frac{\text{Pd}}{\text{Im}^2 \text{R}} \right) - \frac{\text{Pd}}{\text{Im}^2 \text{R}} \right]^\frac{1}{2} \quad (3.18)
\]

Equation (3.18) above gives the relation between ratio of allowable load and maximum load capacity vs. the temperature rise at cable due to steam pipe if \( \frac{\text{Pd}}{\text{Im}^2 \text{R}} \) is known.

Dielectric losses are functions of the temperature and increase rapidly with the increase of temperature.

Figure 18 taken from reference # 4 gives the \( \frac{\text{Pd}}{\text{Im}^2 \text{R}} \) ratio for 132 kv, 275 kv, and 400 kv rated cables when buried in the soil of resistivity 120° cm/cm normally encountered.

All h.v. cables in general are designed to operate at maximum conductor temperature in this case, 85° C.
Fig. 18 Effect of Temperature on Dielectric Losses of E.H.V. Cables.
Ambient temperature in this case is taken as 25°C.

From figure 18,

\[
\begin{align*}
\frac{P_d}{Im^2R} & \quad \text{for} \quad 400\text{kV at 85°C} = 0.78 \\
275\text{kV at 85°C} & = 0.48 \quad \text{Data 1} \\
132\text{kV at 85°C} & = 0.18
\end{align*}
\]

A typical case has been taken to illustrate the effect on load capability due to steam pipe and is illustrated below:

\[
\begin{align*}
D_s & = 3'' \\
D_i & = 6'' \\
\rho_i & = 1737°C\cdot\text{cm/w} \equiv 0.4 \text{ B.T.U.-in/ft}^2\text{-hr.} \\
a & = 42'' \\
A & = \text{variable} \\
H & = \text{variable} \\
\rho_e & = 120°C\cdot\text{cm/w} \\
T_{\text{max}} & = 85°C \\
T_{\text{amb}} & = 25°C \\
T_S & = 175°C
\end{align*}
\]

Using data 1 and data 2 in equation (3.12) and (3.16), the relation between temperature rise, \( \frac{Im'}{Im} \) of centre cable and burial depth of steam pipe for \( H = 10 \) inches (Fig. 19) is drawn.

It can be seen that under the worst conditions, i.e., when \( A = 45 \) inches, a temperature rise of 23°C
Fig. 19 Temperature and Load Capacity Effect of Burial Depth of Steam Pipe on E.H.V. Cables
on centre cable limits the load capability to 0.72, 0.64 and 0.54 of rated value for 132kv, 275kv and 400kv rated cables respectively.

Incidentally this figure can also be used to find out the improvement in load capacity for a given reduction in temperature.

Say that

\[
T_{\text{max before cooling}} = 23^\circ C \text{ for } 400kv, \quad (3.19)
\]

from graph of 400kv,

\[
\frac{I_{23}}{I_m} = 0.54. \quad (3.20)
\]

Reduce temperature rise by 10°C, then

\[
\frac{I_{13}}{I_m} = 0.78 \quad (3.21)
\]

\[
\therefore \text{ Improvement in load capacity } = 0.78 - 0.54 = 0.24.
\]

Thus it can be seen that considerable economy can be achieved by controlling the temperature even by 10°C.

Figure 20 shows rise relation between load capacity and temperature rise with horizontal spacing of steam pipes when the steam pipes and the cables are buried nearly at the same depth \((a = 42'' , A = 45'')\). This shows that in order to safeguard the cable, it should be at
least five feet away from the steam pipe.

Figure 21 shows the effect of thickness of insulation in the steam pipe in reducing the temperature rise of cables.

For,
\[ \rho_i = 12000^\circ C \cdot cm/w = 0.58 \text{ B.T.U.-in/ft}^2\text{-hr}. \]
\[ D_s = 3" \]
\[ l_e = 12000^\circ C \cdot cm/w \]
\[ H = 10" \]
\[ \Delta T = 150^\circ C \]

The curves for \( D_i = 6", 7.5" \) and \( 9" \), have been drawn and can serve as a guide in selection of insulation of pipe when they are to be laid after the cables.

The exact value of thermal resistance of insulation can be supplied by the manufacturer. However, reference 8 is quite useful for selecting the proper type of insulation and the most economical thickness of insulation for a given temperature difference.

3.3.2 Length of Cable Requiring Improvement

Since the steam pipe runs parallel to the cable the whole length of the cable that runs along the steam pipe will require the temperature reduction method.

3.3.3 Steam Pipe Running Perpendicular to The Cable

The layout is shown in figure 22 when the
Fig. 21  Temperature and Load Capacity Effect of Insulation of Steam Pipe on E.H.V. Cables
Fig. 22 Steam Pipe Running Perpendicular to Cables
cables are long enough on either side of the steam pipe. The temperature distribution is symmetrical about the y-axis.

The temperature rise due to steam pipe at any point (x, y) is still governed by equation (3.12). However in this case the effective length of cable which requires cooling arrangement will be computed as follows.

From equation (3.12),

\[ \Delta T_p(x, y) = \frac{0.5(T_S - T_{amb})}{\log \frac{4A - D_i}{D_i} + \frac{\rho_i}{\rho_e} \frac{\log D_i}{D_S}} \]

\[ \log \frac{(x-H)^2 + (y+\Delta)^2}{(x-H)^2 + (y-A)^2} \]  \hspace{2cm} (3.22)

The coordinates of the points in the cable buried at depth (a) will be given by (x, a). Since the distribution of isothermals is symmetrical, only one side of the cable need be calculated.

\[ T_p(x, a) = 0.5 x \frac{T_S - T_{amb}}{\log \frac{4A - D_i}{D_i} + \frac{\rho_i}{\rho_e} \frac{\log D_i}{D_S}} \]  \hspace{2cm} (3.23)
Fig. 23  Temperature Rise on Cables for Steam Pipe Running Perpendicular to Cable
\[
\log \frac{x^2 + (a + A)^2}{x^2 + (a - A)^2} \quad \text{where } H = 0 \quad (3.23)
\]

By assigning different values of \( x \), the temperature rise along the length of the cable can be calculated. For such values of \( (x, a) \) where the temperature rise due to steam pipe is within safe limits gives the half of the length of cable requiring cooling arrangement.

Figure 23 gives the temperature rise and the actual temperature at cable for the following particular layout.

Burial depth of cable = 42"
Soil thermal resistivity = 120°C-cm/w
Insulation thermal resistivity = 1737°C-cm/w.

Three sets of graphs for burial depth of steam pipe of 45", 50" and 60" are shown in figure 23.

For steam pipe burial depth of 45" the highest temperature is 122.5°C and it will not be possible to utilize the cooling sheath method to get the desired temperature reduction, where as in the later two cases the cable can operate to their rated capacity if the cooling sheath is used at the hot spot.

Again since the temperature distribution on the cables in this case is of the same type as that for cable joints, the effective temperature reduction should be more than for the case of the steam pipe running parallel to the cables.
CHAPTER 4

ANALOGUE MODEL ANALYSIS OF STEAM PIPE PROBLEM

4.1 Assumptions

Since the simulation of pipe insulation resistance on the resistance paper is difficult to achieve because of poor contact in two resistance paper sheets, the analysis of the steam pipe problem has been done on the following assumptions:

(1) The outer surface of the steam pipe insulation is isothermal.

(2) The reduction in thermal resistance of soil due to cooling sheath does not affect the temperature at the insulation surface.

While the first assumption is valid for all cases, the 2nd assumption can give reasonably accurate results only in normally encountered cases. The following example is given for illustration.

4.2 Example

Consider the following case:

Thermal resistance of soil  =  120°C-cm/w.
Burial depth of cable  =  42"
Diameter of cable  =  3"
Burial depth of pipe  =  54"
Diameter of pipe with insulation  =  6"
Diameter of pipe = 3"

Thermal resistivity of pipe insulation = 1737°C·cm/w.

From equation (3.8),

\[ Q = \frac{T - T_{amb}}{0.012 \left( \frac{\rho e \log 2A - D_i/2}{D_i/2} + \frac{\rho_i \log D_i}{D_s} \right)} \text{ °C·ft/ft} \]

If \( T_i \) = Temperature at insulation surface.

Then

\[ Q = \frac{T - T_i}{0.012 \rho_i \log D_i} \]

\[ = \frac{T_i - T_{amb}}{0.012 \rho e \log 2A - D_i/2} \]

\[ \times \frac{\rho_i \log D_i}{D_s} \]  

(4.1)

From equation (3.8) and (4.1),

\[ \frac{T_i - T_{amb}}{T_i - T_{amb}} = \frac{\rho e \log 2A - D_i/2}{D_i/2} \frac{\rho_i \log D_i}{D_s} \]  

(4.2)

For this layout,

\[ \rho_{eff} = \frac{0.012 \times \log \frac{2.54 - 3}{3}}{2.22} = 2.22 \]  

(4.3)
From analogue studies the soil thermal resistance reduction for steam pipe is 12%. 

Comparing results of (4.6) and (4.7) there is error of 8.5 percent in the analogue method.

4.2.1 Circuit

The circuit used for the steam pipe problem insulation is given in figure 24.

The cables are taken as constant heat source and the steam pipe as constant temperature source.

The problem selected for analogue studies is a particular one, normally encountered. Any other case can be dealt on similar lines.
Fig. 24 Analogue Circuit for Steam Pipe and Cables
From heat and electrical analogue,

Volts $\rightarrow$ $\Delta T$ °C

Current $\rightarrow$ heat energy watts/

Let 0.5 volts correspond to $T_{\text{max}} - T_{\text{amb}} = 60^\circ\text{C}$ (4.8)

where

$T_{\text{max}} = \text{maximum cable conductor temperature} = 85^\circ\text{C}$. (4.9)

$T_{\text{amb}} = \text{Ambient temperature} 25^\circ\text{C}$. \hfill (4.10)

If

$T_{\text{steam}} - T_{\text{amb}} = 150^\circ\text{C}$ \hfill (4.11)

from equation 15,

$T_i - T_{\text{amb}} = \frac{150}{3.86} = 39^\circ\text{C}$ \hfill (4.12)

which corresponds to

$\frac{39}{60} \times 0.5 = 0.324 \text{ Volts}$ \hfill (4.13)

For the following layout of steam pipe and cables
given in figure 25.

4.2.2 For Uncooled Cables

Corresponding to 0.4 Volts of steam pipe voltage

on right cable = 0.305. volts \hfill (4.14)

Corresponding to 0.324 Volts of steam pipe voltage

on right cable = 0.236. volts \hfill (4.15)

This is equivalent to temperature rise of

$60 \times \frac{0.236}{0.5} = 28.3^\circ\text{C}$. \hfill (4.16)
Temperature rise at centre cable
temperature rise at centre cable due to load
\[ T = 0.275 \times 324 \times 60 \times 0.5 = 23.25^\circ C \] (4.17)

Temperature rise at centre cable due to load
0.5 volts \( = 60^\circ C \). (4.18)

Temperature rise at right cable due to load
\[ T = 0.48 \times 60 \]
\[ = 58.6^\circ C. \] (4.19)

\[ \Delta T_{\text{total at centre cable}} \]
\[ = 60 + 23.25 \]
\[ = 83.25^\circ C. \] (4.20)

\[ \Delta T_{\text{total at right cable}} \]
\[ = 28 + 58.6 \]
\[ = 86.6^\circ C. \] (4.21)

From figure 26 for 21" of cooling sheath height,
\[ \Delta T \text{ at centre cable due to load} \]
\[ = \frac{0.37}{0.5} \times 60 = 44.4^\circ C. \] (4.22)

\[ \Delta T \text{ at centre cable due to steam pipe} \]
\[ = \frac{0.178}{0.5} \times 60 = 21.3^\circ C. \] (4.23)

\[ \Delta T \text{ at right cable due to load} \]
\[ = \frac{0.36}{0.5} \times 60 = 43.2^\circ C. \] (4.24)
Fig. 25  Layout for Steam Pipe Buried at Same Depth as Cable
\[ \Delta T_{\text{at right cable due to steam pipe}} = \frac{0.202 \times 60}{0.5} = 24^\circ C. \] (4.25)

\[ \Delta T_{\text{total at centre cable}} = 65.7^\circ C. \] (4.26)

\[ \Delta T_{\text{total at right cable}} = 67.2^\circ C. \] (4.27)

Since maximum allowable temperature rise is 60\(^\circ\)C, with this arrangement the cable will have to run at 78\(^\circ\)C to accommodate for the temperature rise of 7.2\(^\circ\)C which can not be tackled by the cooling sheath. In other words, from figure 19, 400kV cable will have to run at 90\% of the rated load capacity compared to 54\% for the uncooled cables.

To run the cables at 100 percent load capacity, and to give some safety margin, the cable will have to be laid down farther from the steam pipe.

A similar analysis for the layout shown in figure 27 is shown in figure 28.

In this case, the centre cable is the hottest cable and a cooling sheath of 21 inches height brings down the temperature rise at centre cable to 60\(^\circ\)C. (fig 28)
Fig. 26  Temperature Reduction by Cooling Sheath for Layout of Fig. 25

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Fig. 27  Layout for Steam Pipe Vertically Below Centre Cable
Fig. 28 Temperature Reduction by Cooling Sheath for Layout of Fig. 27.

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5.1 Laboratory Model

The main aspects of the apparatus are explained below.

5.1.1 Sand Box

The size and insulation of the sand box was selected after making the analogue studies on the Teledeltos paper. The size and insulation are such that they simulate the semi-infinite nature of ground. The insulation on the sides extended to 7 inches below the top of the box. To minimise the end effects, the ends of the box are insulated up to the surface.

The dimensioned sketch of the box is given in figure 29.

5.1.2 Cables

The cables were simulated by using 1\(\frac{1}{2}\) inch diameter brass pipes. For heating, Pyrotenax cables running through centre of the brass pipes were used. To ensure uniform heating of the pipes, they were filled with sand and fitted with Bakelite spacers. The simulated cables are shown in figure 30.
5.1.3 Cooling Sheath

A thermal resistance short circuit comparable to silver paint lines on the Teledeltos resistance paper can be made by using U-shaped copper tubes filled with refrigerant.

The refrigerant should be such that it remains liquid at ambient temperatures and also has high latent heat of evaporation to ensure quick heat dissipation. The temperature difference provided by natural distribution of isothermals in the soil. On the limbs of the U-shaped copper tubes should be enough to ensure condensation of refrigerant vapours.

The two refrigerants that fill the above requirements are given below along with their properties.

<table>
<thead>
<tr>
<th>REFRIGERANT</th>
<th>PRESSURE</th>
<th>BOILING POINT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freon 11</td>
<td>14.5 p.s.i.</td>
<td>19°C</td>
</tr>
<tr>
<td>(Trichlorofluoro-</td>
<td>20 p.s.i.</td>
<td>35.5°C</td>
</tr>
<tr>
<td>methane)</td>
<td>30 p.s.i.</td>
<td>42.2°C</td>
</tr>
<tr>
<td>Freon 216</td>
<td>14.5 p.s.i.</td>
<td>35.5°C</td>
</tr>
<tr>
<td>(1,3 Dichloro-1,1,2,)</td>
<td>20 p.s.i.</td>
<td>46°C</td>
</tr>
<tr>
<td>2,3,3,Hexafluoropropene)</td>
<td>30 p.s.i.</td>
<td>60°C</td>
</tr>
</tbody>
</table>

The base and one inch of the limbs of each tube...
Fig. 30 Simulated Cables and Thermo Couples

Fig. 31 Layout of Cooling Tubes and Sand Box
was filled with refrigerant. The tubes were soldered together. A thin insulation was provided on copper tubes to prevent corrosion of the surface. Figure 31 shows the cooling sheath and the laying arrangement.

Freon 11 has been used in this experiment. The amount of the refrigerant required in each tube was found after comparing the condensation rates experimentally.

First, the experiment was carried out using enough refrigerant so as to fill the base and 1 inch height of each copper tube.

The layout of the laboratory model is given below and is shown in figure 29:

Length of 3 unit cable = 20 ft.
Size of cable = 1\frac{1}{2} inch
Spacing centre to centre of cable = 3 inch
Depth of burial = 24 inches
Inside diameter of tube = 1/8 inch
Width of tube = 7 inches
Height of tube = 10\frac{1}{2} inches
Spacing between cable and tubes = 0\frac{1}{5} inches

5.2 Discussions

Figure 32 shows the comparative distribution of isothermals in the soil around the cable in the uncooled section. The difference between the analogue and experimental
studies of the temperature distribution is due to personal error.

Figure 33 shows the relative isothermal distribution in the cooled section. The points A, A', B, B', C, C' indicate the bottom, mid section and top of the cooling sheath as observed by analogue and experimental studies respectively.

The isothermals on the top section of the cooling sheath are less drawn out than expected from the analogue study. Therefore the cooling in the tubes is not sufficient enough as to provide an effective thermal short circuit.

Figure 34 gives temperature distribution along the cable surface. It can be seen that the temperature at the cooled cable surface lying about 2 ft. from the uncooled cable section is not affected by its presence.

Figure 35 and 36 give the temperature at various depths above the centre cable and the side cable respectively. Figure 35 shows that under similar conditions of soil and ambient temperature, the temperature of the cooled cable is 3.7°C below the uncooled cable. Points A, B and C show the position of the cooling blanket.

This cooling sheath gives a reduction of 19.5 percent in thermal resistance compared to 27.75 expected from analogue studies.

Later studies were made using glass tubes of
Fig. 32 Uncooled Isothermals of Side Cable

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Fig. 33  Cooled Isothermals of Side Cable
Fig. 35 Temperature Distribution Curves for Centre Cable
Fig. 36 Temperature Distribution Curve for Side Cable
the same size and shape as the copper tubes and filled with the same amount of refrigerant. It showed that a slight amount of unequal heating forces the refrigerant to rush to one side of the U-tube.

The 2nd difficulty encountered was the slow process of boiling of pure liquid refrigerant. As such it was decided to make a comparative study of rate of boiling using different forms of impurities. Three similar tubes were taken:

(1) tube with iron wire and cotton wick
(2) tube with fibre glass
(3) tube with no impurity

Each tube had Freon 11 sufficiently enough to fill the base. The arrangement is shown in figure 37.

Table 1 gives the rate of condensation in the three different cases.

It can be seen that the tube with cotton wick supported by iron wire gives the most satisfactory results.

Using cooling sheath made of tubes containing cotton wick, four different sets of readings under different temperature conditions were taken. The results are given in table 2.
Fig. 37 Arrangement for Comparison of Condensation Rate of Refrigerant
<table>
<thead>
<tr>
<th>TUBES</th>
<th>TEMPERATURE DIFFERENCE</th>
<th>CONDENSATION</th>
<th>TIME TAKEN IN MINUTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube 1</td>
<td>3°C</td>
<td>100%</td>
<td>48</td>
</tr>
<tr>
<td>(pure refrigerant)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube 2</td>
<td>3°C</td>
<td>100%</td>
<td>32</td>
</tr>
<tr>
<td>(Fibre glass)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube 3</td>
<td>3°C</td>
<td>100%</td>
<td>22½</td>
</tr>
<tr>
<td>(cotton wick and iron wire)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube 1</td>
<td>8°C</td>
<td>100%</td>
<td>12½</td>
</tr>
<tr>
<td>Tube 2</td>
<td>8°C</td>
<td>100%</td>
<td>11</td>
</tr>
<tr>
<td>Tube 3</td>
<td>8°C</td>
<td>100%</td>
<td>9½</td>
</tr>
<tr>
<td>Hot side placed at 20 degrees to horizontal plane</td>
<td>Tube 1 3°C 30% 21</td>
<td>Tube 2 3°C 40% 21</td>
<td>Tube 3 3°C 60% 21</td>
</tr>
</tbody>
</table>
### TABLE 2

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncooled Cable</td>
<td>39.5°C</td>
<td>49°C</td>
<td>56.7°C</td>
<td>77.4°C</td>
</tr>
<tr>
<td>Temp.°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooled Cable</td>
<td>35.1°C</td>
<td>42.9°C</td>
<td>48.5°C</td>
<td>63.9°C</td>
</tr>
<tr>
<td>Temp.°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Temp.°C</td>
<td>20.5°C</td>
<td>20°C</td>
<td>20.6°C</td>
<td>22°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T uncooled</td>
<td>19.0°C</td>
<td>29°C</td>
<td>36.1°C</td>
<td>55.4°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T cooled</td>
<td>14.6°C</td>
<td>22.9°C</td>
<td>27.9°C</td>
<td>41.9°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% ge Reduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in thermal Resistance</td>
<td>23.1</td>
<td>21.1</td>
<td>22.1</td>
<td>24.4</td>
</tr>
</tbody>
</table>

The analogue studies show a maximum reduction of 27.75% in the thermal resistance. The higher results in this case can be due to better electrical contact and their better conduction between silver paint and resistance paper than copper tubes and soil.
A comparison of the temperature distribution on the cooling sheath with pure refrigerant and with cotton wick and iron wire is given below in Table 3.

**TABLE 3**

<table>
<thead>
<tr>
<th></th>
<th>Bottom</th>
<th>Mid-section</th>
<th>Top</th>
<th>Uncooled Cable Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogue</td>
<td>0.84</td>
<td>0.79</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>Cooling Sheath</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pure Freon 11</td>
<td>0.81</td>
<td>0.73</td>
<td>0.555</td>
<td>49.5°C</td>
</tr>
<tr>
<td>Cooling Sheath</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cotton and iron</td>
<td>0.88</td>
<td>0.75</td>
<td>0.66</td>
<td>39.5°C</td>
</tr>
<tr>
<td>wires</td>
<td>0.88</td>
<td>0.77</td>
<td>0.71</td>
<td>49°C</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.78</td>
<td>0.76</td>
<td>56.7°C</td>
</tr>
<tr>
<td></td>
<td>0.87</td>
<td>0.8</td>
<td>0.77</td>
<td>77.4°C</td>
</tr>
</tbody>
</table>

It can be seen that with new cooling sheath the isothermals at the top section of cooling are more in agreement with analogue studies. Figure 38 gives the temperature distribution in the soil for improved cooling sheath.
Fig. 38 Temperature Distribution with Improved Design

(Refer Table 2)

---

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CHAPTER 6

ECONOMY OF THE SYSTEM

6.1 Cost of Cooling Sheath

The cost of fabricating the cooling sheath per foot of a phase 3 underground cable system in laboratory is given below.

Material - COPPER

30 tubes 5\(\frac{1}{2}\) feet long

<table>
<thead>
<tr>
<th>ITEM</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(\frac{7}{8}) outer diameter copper tube 165 feet</td>
<td>$12.50</td>
</tr>
<tr>
<td>1(\frac{7}{8}) outer diameter copper tube for sealing 10 feet</td>
<td>.50</td>
</tr>
<tr>
<td>Wicks and wire to support the wicks</td>
<td>1.50</td>
</tr>
<tr>
<td>Freon 11, 487 grams</td>
<td>.50</td>
</tr>
<tr>
<td>Coating of coal tar epoxy 5 to 10 mil.</td>
<td>2.50</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>$17.50</strong></td>
</tr>
</tbody>
</table>

Labour per foot of cable

7 hours x $4.00 | $28.00

**TOTAL** | **$45.50**

For industry which has a semiautomatic assembly line the cost is expected to be the following.
Parts $ 15.00  
Paint $ 2.50  
Labour 2 hours x $4. $ 8.00  
\[ \text{TOTAL} \quad \$ 25.50 \]

Profit of 30% $ 7.05  
\[ \text{TOTAL} \quad \$ 32.55 \] per foot of cable.

6.2 Comparison with Water Cooling System

For water cooling system which has two polythlene \( \frac{3}{4} \)" diameter pipes, the cost of pipe and labour is $ 2000 per mile. The flow of water through the pipe can be done either manually or through an automatic control system. Ralston and West have discussed the disadvantages of a manual control and have given preference to the automatic control system. Such a system, which has been developed by Ontario Hydro costs about $ 25000.

Although the installation and pipe costs are nominal, the cost of the automatic control system prohibits its use for small sections of cable, where it will be more economical to use the cooling sheath method.

Figure 39 gives a rough comparison of the relative cost of the cooling sheath and the water cooling for different lengths of hot spots.

It can be seen that beyond 800 feet of cable section, it is more advantageous to use water cooling.
Fig. 39 Cost Comparison of Water Cooling and Cooling Sheath Systems

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CHAPTER 7
CONCLUSION

The studies show that for a given cable type, the higher the operating voltage, the greater is the load derating effect of external heat sources. Therefore with trends towards higher transmission voltage (275kv - 500kv), more attention should be given to hot spot removal techniques.

The proposed method of temperature control of cables by cooling sheath method has both its advantages and disadvantages.

The main disadvantages are the limitation on the degree of reduction in effective thermal resistance of soil possible and that it is uneconomical for large sections of cable. Therefore in instances like when the steam pipe runs near the cable joint or for a long distance along the cable, some other cooling method like water cooling will have to be used.

Compared to these two disadvantages, the advantages are numerous. The apparatus is simple and easy to assemble. The method is most suitable in areas open to traffic. It is practically free from day to day maintenance problems.

The reduction in effective thermal resistance of soil achieved by cooling sheath is greater than by the use of low thermal resistivity back fill material (24 percent
by cooling sheath compared to 12 percent by back fill material). Therefore at such places where availability and transportation costs of back fill material are high, the cooling sheath method can be a good substitute.

It will be of interest to carry out field tests to find out the reduction in thermal resistance possible by the combined use of low thermal resistance back fill material and the cooling sheath. Such a set up should result in better performance than possible by either of the two methods individually.

The choice of number of tubes in each section of the cooling sheath depends upon the individual case. The smaller the section, the lesser is the probability of the cooling sheath becoming ineffective due to leakage and therefore a longer life for the cooling sheath. The smaller sections in turn may be difficult to assemble at site. In the event of leakage in a small section, the temperature rise of the cable will not be so quick as to cause damage and enough time will be available to check the faulty section and replace it.
REFERENCES


1942 Born on July 21, Kasauli, Simla Hills, India.
1959 Completed I.Sc. at Mohindra College, Patiala, India,
1963 Graduated with B.E. (Electrical) from Thapar Institute of Engineering and Technology, Patiala, India.
1968 Candidate for degree of M.A. Sc. in Electrical Engineering at the University of Windsor.