DETERMINATION OF TRANSMISSION LINE AMPACITIES

BY PROBABILITY AND NUMERICAL METHODS

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Don Orest Koval

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Student: Don Orest Koval Supervisor: Dr. R. Billinton

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ABSTRACT

The transmission line is the primary medium by which electrical power is transmitted and distributed within a power system. The maximum load current that can be carried by the conductor is designated as the conductor ampacity and is normally determined from a single set of weather conditions. In recent years, it has been suggested that traditional ampacities are conservative and that local weather and operating practices should be utilized in evaluating a given conductor ampacity.

This thesis presents the numerical and statistical methods for establishing the ampacity of an existing transmission line considering actual hourly weather and load current data collected over a period of one year. These methods are generalized to be applicable to any transmission line located in a given weather environment. A statistical weather model has been developed utilizing the Pearson Family of Curves, the Method of Least Squares and some elements of correlation theory. Digital computer programs have been developed to study conductor ampacities based on the maximum conductor temperature and the permanent loss of strength in the conductor due to annealing. The actual weather data, the statistical weather model and various load current distributions have been studied to establish the ampacity for an existing transmission line. General conclusions reached concerning ampacities agreed with published data. The statistical weather model approach was found to be accurate, quite flexible and requires less digital computer time than the sequential utilization of actual data.

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1. INTRODUCTION

1.1 General

The overhead transmission line is the primary medium by which electrical power is transmitted and distributed within a power system. Overhead lines provide the necessary links between sources of economical power and the load centers. The electrical properties of transmission lines are significant in all power system studies. These lines are generally operated within the predetermined voltage and current limits dictated by these properties. The continual demand for more electrical power by industrial and urban loads each year results in transmission lines exceeding or approaching these limits. Studies on reliability, stability, fault current and load flow are continually performed to examine the operating limits of existing and proposed transmission facilities subjected to these demands.

The current limit or ampacity of a transmission line is traditionally obtained from tables prepared by the conductor manufactures. These ampacity tables are based on a single set of weather conditions and an upper conductor temperature limit. Many excellent papers (1,4,6,12,15,16) in recent years have been written on transmission conductor ratings. Their main object is to establish conductor ratings that are based on the permanent loss of strength (annealing) in the aluminum portion of the ACSR conductor and to accumulate these losses over the lifetime of the conductor. These papers also emphasize the use of local weather conditions and operating practices.

The purpose of this thesis is to evaluate and simulate the cumulative effects of actual weather and load current observations on an existing transmission line. Numerical and statistical methods are used to study the thermal and mechanical ampacity limits for this transmission line and are generalized so as to be applicable to any transmission line.

1.2 The Problem

Generally line losses, voltage drop, reliability, associated equipment ratings and stability considerations limit the current in the high voltage transmission lines to values much lower than that permitted by the annealing or conductor temperature criteria. The ampacity of the conductor becomes the limiting factor in short transmission lines and particularly in low voltage distribution lines. Ampacity limits are also an important consideration in designing D.C. transmission lines.

The rating or ampacity of an overhead conductor is dependent upon three main factors:

1. weather
2. load characteristics (flat or distributed loads)
3. transmission line characteristics

Weather can be considered to be composed of the three elements which influence the conductor temperature, namely wind, ambient temperature and solar radiation. Cooling of the conductor is dependent upon the air temperature and wind while conductor heating is influenced by solar radiation. The principal source of heat tending to raise the conductor temperature is the load current.

The transmission line characteristics that are involved in establishing a maximum temperature are:

1. Increased sag due to high operating temperatures.
2. Ability of the line hardware to handle thermal stresses.
3. The permanent loss of strength in the conductor due to annealing.

The following areas are examined in detail in this thesis:

1. The development of a digital computer program for solving the steady state conductor surface temperature for a given set of weather conditions using the following methods:

   a) McAdam's heat balance equations for heat loss

   b) Newton-Raphson Method

The results obtained were compared with data supplied by the Aluminum Company of America.

2. The development of digital computer programs to statistically represent the individual elements of the weather by the Pearson Family of Curves. The method of application together with detailed examples for several Pearson type curves are presented.

3. Correlation and linear regression methods used to establish a joint frequency weather model were examined.

A digital computer program was developed to calculate the permanent loss in conductor strength. The results of this program were then compared with results presented in several I.E.E.E. papers which used graphical methods. The concepts outlined above were combined and used to analyze and compare the ampacity limits of an existing transmission line subjected to various load patterns. The digital computer flow charts for each of these programs are shown in the Appendix.

1.3 Power System Data

The weather observations used in this thesis were obtained from the records of the Metereological Branch of the Department of Transport at the Vancouver International Airport. The hourly ambient temperature, wind velocity, and solar radiation for one year (1967) were coded from Monthly Metereological summaries and transferred to computer cards by the author. A 138 kv double circuit transmission line was selected in the vicinity of the weather station. The hourly load currents of this line were coded from records maintained by the British Columbia Hydro and Power Authority. The electrical characteristics for this line were also obtained from B.C. Hydro.

1.4 Facilities for Studies

The preparation and verification of the data was performed on th I.B.M. facilities at B.C. Hydro. The digital programs outlined in section 1.2 were developed by the author using the IBM/360 computer at the University of Saskatchewan.

2. METHOD OF SOLVING OVERHEAD TRANSMISSION CONDUCTOR SURFACE TEMPERATURE

2.1 General

An overhead transmission line consists of electrical conductors supported by either steel or wooden structures and separated from the structure by insulators. The conductors, which provide the current carrying path, are generally aluminum stranded with a steel core for reinforcement (ACSR). The conductor is exposed to the weather elements ; ie. the wind, ambient temperature and solar radiation.

2.2 Heat Balance Equation

The conductor surface temperature is dependent upon the heating and cooling mechanisms associated with the interaction of the load current and the weather. The conductor temperature is also dependent upon the physical properties of the conductor. The principal heat source tending to raise the conductor temperature is the load current. A secondary source is the heat received from the sun. Heat is transferred from the conductor primarily by convection in the surrounding air. The degree of cooling is dependent upon the ambient temperature and mainly upon the wind velocity. Another mechanism involved in heat transfer from the conductor is thermal radiation. The amount of heat transferred by radiation is dependent upon the temperature level of the conductor.

Under steady state conditions of load current, ambient temperature, wind velocity and solar radiation, the conductor heat gained is equal to the amount lost by the conductor. This relationship can be expressed as follows:

$$Q_a + Q_s = Q_c + Q_r \quad \text{watts/ lineal foot of conductor} \tag{2.1}$$

where:
Q_a - heat generated by the conductor current

Q_s - heat gained from the sun

Q_c - heat loss due to convection

Q_r - heat loss due to radiation

2.2.1 Heat generated by conductor current

The resistance of the conductor is a function of the conductor temperature. The resistance at any desired conductor temperature (t_c) can be found as follows:

$$R(t_c) = R_{25} \left(1 + \alpha_{25}(t_c - 25)\right) \quad \text{ohms/foot} \tag{2.2}$$

where:
t_c - conductor temperature in degrees centigrade

α_{25} - temperature coefficient of aluminum at 25°C in 1/C°

R_{25} - a.c. resistance of the conductor at 25°C in ohms/foot

The effects of spiraling, skin effect, and the presence of magnetic material in the inner portion of the ACSR conductor have been neglected as in practice they have been found to be relatively small. The current density is assumed to be uniform over the cross- sectional area of each strand. The heat generated by the conductor current is given by:

$$Q_a = I^2 R_{25}\left(1 + \alpha_{25}(t_c - 25)\right) \text{ watts /lineal foot of conductor} \tag{2.3}$$

2.2.2 Heat gained by solar radiation

Solar radiation is commonly measured in Langleys per minute (1 calorie per square centimeter which is approximately 65 watts per square foot). The main factors which affect the intensity of solar radiation are discussed in detail in Chapter 4.

The amount of heat received from the sun is given by:

$$Q_s = \epsilon \; S \; A \quad \text{watts / lineal foot of conductor} \tag{2.4}$$

where:

ϵ - solar-absorption coefficient

S - solar radiation in watts per square foot

A - projected area of the conductor in square feet

2.2.3 Radiation heat loss

Boltzman showed that energy is radiated from a body in proportion to the fourth power of its absolute temperature. The resulting interchange of heat by radiation between the conductor and the surrounding air is given by:

$$Q_r = \sigma \epsilon A \; (T_c^4 - T_a^4) \quad \text{watts / lineal foot of conductor} \tag{2.5}$$

where:

σ - Stefan-Boltzman constant which is equal to 0.5275×10^{-8} watts per sq. ft. per T^4

ϵ - thermal emissivity of the conductor

T_a - temperature of surrounding air in degrees Kelvin

T_c - conductor surface temperature in degrees Kelvin

A - area of circumscribing cylinder per lineal foot in square feet
- 3.14 x D where D is the diameter of the conductor in feet

Inserting the appropriate constants into equation 2.5 results in:

$$Q_r = 0.138 \; D \; \epsilon \; \left(\frac{Tc^4}{100} - \frac{Ta^4}{100} \right) \quad \text{watts per lineal foot of conductor} \tag{2.6}$$

2.2.4 Convection heat loss

Convection is divided into two classes: natural convection and forced convection. The boundary between the classes is determined by the magnitude of the wind velocity. Wind velocities below approximately 0.4 feet per second are in the natural convection class.[1]

(a) Natural convection

If the conductor temperature is greater than the air temperature enveloping it, heat will be first conducted by the air immediately adjacent to the conductor surface. The density of the air near the heated conductor surface will be less than that of the main body of air. Buoyant forces will cause an upward flow of air near the surface carrying heat away from the conductor . The emperical formula developed at the ALCOA Research Laboratories in a room free from drafts gives quite accurate results for natural convection heat loss.[1] The expression is as follows:

$$Q_{nc} = 0.072\ D^{0.75}\ (\ t_c - t_a\ )^{1.25} \text{ watts / lineal foot of conductor} \qquad (2.7)$$

where: Q_{nc} - denotes heat loss by natural convection

D - conductor diameter in inches

t_c - conductor surface temperature in degrees C

t_a - ambient temperature in degrees C

(b) Forced convection

Forced convection is defined as a movement of air (wind) over the conductor surface in excess of 0.4 feet per second. The emperical heat loss formulas developed by McAdams for single horizontal tubes and wires have been found to give accurate results for stranded conductors.[1,2] McAdam's formula is divided into two portions depending upon the Reynolds number of the air adjacent to the conductor. For a Reynolds number between 0.1 and 1000.0 the following convected heat-loss equation is valid:

$$Q_{c1} = 1.01 + 0.371 \left(\frac{D \cdot p_f(t_c,t_a,X) \cdot V}{u_f(t_c,t_a)} \right)^{0.52} \cdot k_f(t_c,t_a) \cdot (t_c-t_a) \quad (2.8)$$

watts per lineal foot of conductor

For a Reynolds number between 1000 and 50,000 the following convected heat loss equation is valid:

$$Q_{c2} = 0.1695 \left(\frac{D \cdot p_f(t_c,t_a,X) \cdot V}{u_f(t_c,t_a)} \right)^{0.6} \cdot k_f(t_c,t_a) \cdot (t_c-t_a) \quad (2.9)$$

watts per lineal foot of conductor

where: Q_{c1}- convected heat loss for a Reynolds number between 0.1 and 1000

Q_{c2}- convected heat loss for a Reynolds number between 1000 and 50,000

V- wind velocity in feet per hour

t_c- conductor surface temperature in degrees C

t_a- ambient temperature in degrees C

p_f- air density in lbs. per cubic feet

u_f- absolute viscosity of air in lb-mass/ft-hr.

k_f- thermal conductivity of air (watts)(ft.)/sq.ft./C

X--indicates that air density is a function of elevation above sea level

D- diameter of conductor in feet

Reynolds number - $(D \cdot V \cdot p_f) / u_f$

The density, viscosity and thermal conductivity of air are a function of the film temperature. The equations expressing these properties are shown in the Appendix. The film temperature is defined by the following relationship:

$$t_f = 0.5\ (t_c + t_a) \quad (2.10)$$

where: t_f - film temperature

t_a - ambient temperature

t_c - conductor temperature

The heat equation (2.1) has three general forms depending upon the wind velocity. If the wind velocity is calm or below 0.4 feet per second, the natural convection equation (2.7) is used. The other two equations (2.8 and 2.9) are dependent upon the Reynolds number of the air film surrounding the conductor. The Reynolds number is a function of the density and viscosity of the air film which are in turn a function of the unknown conductor temperature.

2.3 Newton-Raphson Method

All the terms of the heat balance equation 2.1 are transposed to one side and the resulting equation is denoted as $f(t_c)$. The iterative process for solving the real root (conductor surface temperature) of $f(t_c)$ for fixed weather and load current data is:

$$t_{i+1} = t_i - f(t_i)/ f'(t_i) \qquad (2.11)$$

where:
t_i - initial estimate of conductor surface temperature
t_{i+1} - successive estimate of conductor surface temperature

The development of the Newton-Raphson Method as used in equation 2.11 is shown in the Appendix. The general expression for $f(t_c)$ is also shown in the Appendix.

2.3.1 Initial estimate of conductor surface temperature

In solving $f(t_c)$ containing the natural convection heat loss equation, the "Regula Falsi" method is used to obtain the initial estimate of the conductor surface temperature for the Newton-Raphson Method. The Regula Falsi method consists of finding two roots (t_1 and t_2) for $f(t_c)$ having opposite signs and assuming that the exact root lies on a straight line between t_1 and t_2.

In solving $f(t_c)$ containing the forced convection heat loss equation, the initial estimate of the conductor surface temperature is taken as the ambient temperature. The Reynolds number is then calculated to determine the appropriate forced convection equation. The equation $f(t_c)$, containing the convection equation dictated by the Reynolds number, is expanded by the binomial theorem and linearized. From the linear equation, a second estimate of the conductor surface temperature and Reynolds number are calculated and used for the first estimate in the Newton-Raphson Method. The Reynolds number is calculated within the Newton-Raphson iterative process to insure that the appropriate convected heat loss equation is used.

2.3.2 Discussion of the Newton-Raphson Method

In Chapter 6 dealing with "Application and Results" the conductor surface temperature is solved 8760 times for a one year study based on hourly weather and load current data. This study represents the "actual" conductor surface temperatures of the transmission line. These actual conductor temperatures are compared with the "probable" conductor surface temperatures based on theoretical frequency distributions of the weather.

If the exact expression for the derivative of $f(t_c)$ is used, the time per iterative solution is 0.202 seconds or 30 minutes for the one year study as the convergence is quite slow. The method for solving the function $f(t_c)$ with the exact expression for $f'(t_c)$ will be referred to as the "Exact Method". An approximate method was developed which assumes that the physical properties of air (based on two successive linear approximations) are constant during the iterative process in the Newton-Raphson Method. This assumption reduces the length of the expression of the derivative of $f(t_c)$. Convergence is accelerated by the Atken-Delta Squared Method. An error of approximately two percent is introduced by the approximate method but a three hundred percent gain in computational time is realized.

2.4 Discussion and Results

2.4.1 Weather effects

The wind velocity is one of the major factors affecting the conductor surface temperature. A slight change in wind velocity produces a marked change in conductor surface temperature. This effect is particularly evident in the low wind velocity range but becomes less noticeable with increasing wind velocities. This is shown in Table 2.1.

Table 2.1 CONDUCTOR TEMPERATURE VRS AMBIENT TEMPERATURE -WIND VARIABLE
conductor size - 477 MCM ACSR load current - 576 amperes

AMBIENT TEMPERATURE	CONDUCTOR SURFACE TEMPERATURE				REYNOLDS NUMBER
	0 MPH WIND VELOCITY		1 MPH WIND VELOCITY		
°F	°C	°F	°C	°F	
0	47.26	117.07	23.08	73.54	749.0
5	50.04	122.07	26.02	78.84	735.0
10	52.80	127.04	28.96	84.13	721.0
15	55.56	132.00	31.88	89.38	707.0
20	58.31	136.96	34.80	94.64	694.0
25	61.05	141.89	37.72	99.90	681.0
30	63.79	146.82	40.63	105.13	669.0
35	66.51	151.72	43.53	110.35	656.0
40	69.23	156.61	46.43	115.57	645.0
45	71.94	161.49	49.32	120.78	633.0
50	74.64	166.35	52.20	125.96	622.0
55	77.33	171.19	55.08	131.14	612.0
60	80.02	176.04	57.96	136.33	601.0
65	82.70	180.86	60.83	141.49	591.0
70	85.37	185.67	63.69	146.64	581.0
75	88.30	190.45	66.55	151.79	571.0
80	90.69	195.24	69.40	156.92	562.0
85	93.35	200.03	72.25	162.05	553.0
90	95.99	204.78	75.09	167.16	544.0
95	98.63	209.53	77.93	172.27	535.0
100	101.26	214.27	80.76	177.37	527.0

Many investigators have neglected the effects of solar radiation in establishing conductor temperature limits. Variation in the level of solar radiation from 0 to a maximum of 4.25 watts per lineal foot of conductor will result in a rise of up to $10^{\circ}C$ in conductor temperature provided all the other parameters remain fixed. This temperature difference is significant during summer when some transmission lines are heavily loaded. A discussion of the factors affecting solar radiation is given in Chapter 4. The variation in conductor temperature with ambient temperature for various solar radiation conditions is shown in Figure 2.1.

2.4.2 Load Current Effects

The load current is the major factor affecting the conductor surface temperature and for small load current values the conductor temperature is approximately equal to the ambient temperature. The conductor temperature increase is approximately proportional to the square of the current. The variation in conductor temperature as a function of the conductor current is shown in Figure 2.2.

2.4.3 Emissivity of the conductor surface

Changes in the emissivity of the conductor produce a noticeable change in the conductor surface temperature as is shown in Figure 2.3. It has been recognized for many years that well-weathered ACSR conductors in service have a dark surface resulting in an emissivity sometimes as high as 0.98,whereas a new conductor has an emissivity of approximately 0.23. Conductor weathering as a function of time is discussed in detail in Reference 10.

This chapter has illustrated the basic elements which influence the variation in conductor temperature. The actual temperature for a given set of parameters can only be obtained by an iterative process. The effects on the conductor temperature of certain fixed weather parameters have been illustrated. The variability associated with these parameters are discussed in detail in the next chapter.

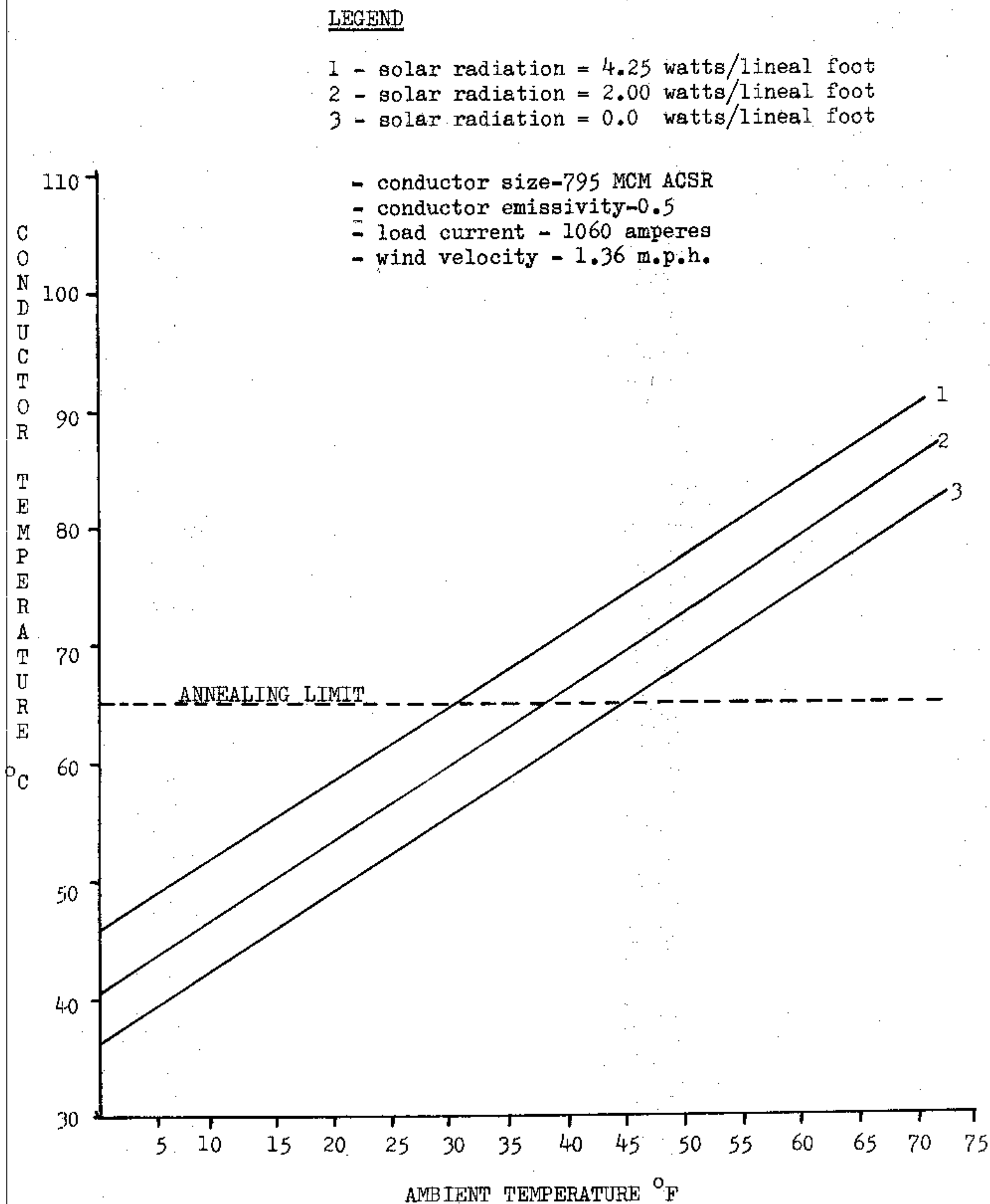

Figure 2.1 Conductor Temperature versus Ambient Temperature
(variable Solar Radiation)

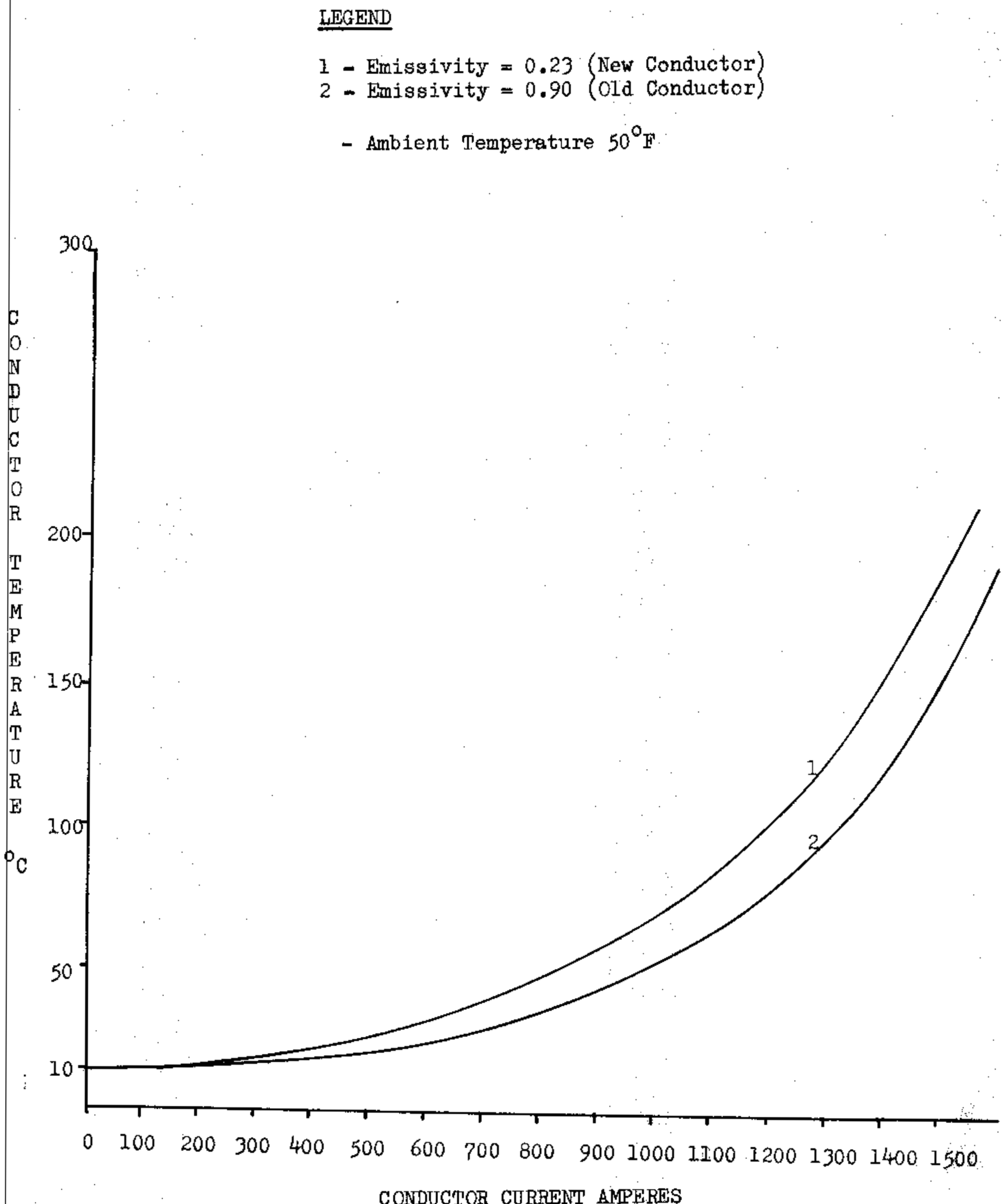

Figure 2.2 Conductor Temperature versus Load Current
(Fixed Ambient Temperature)

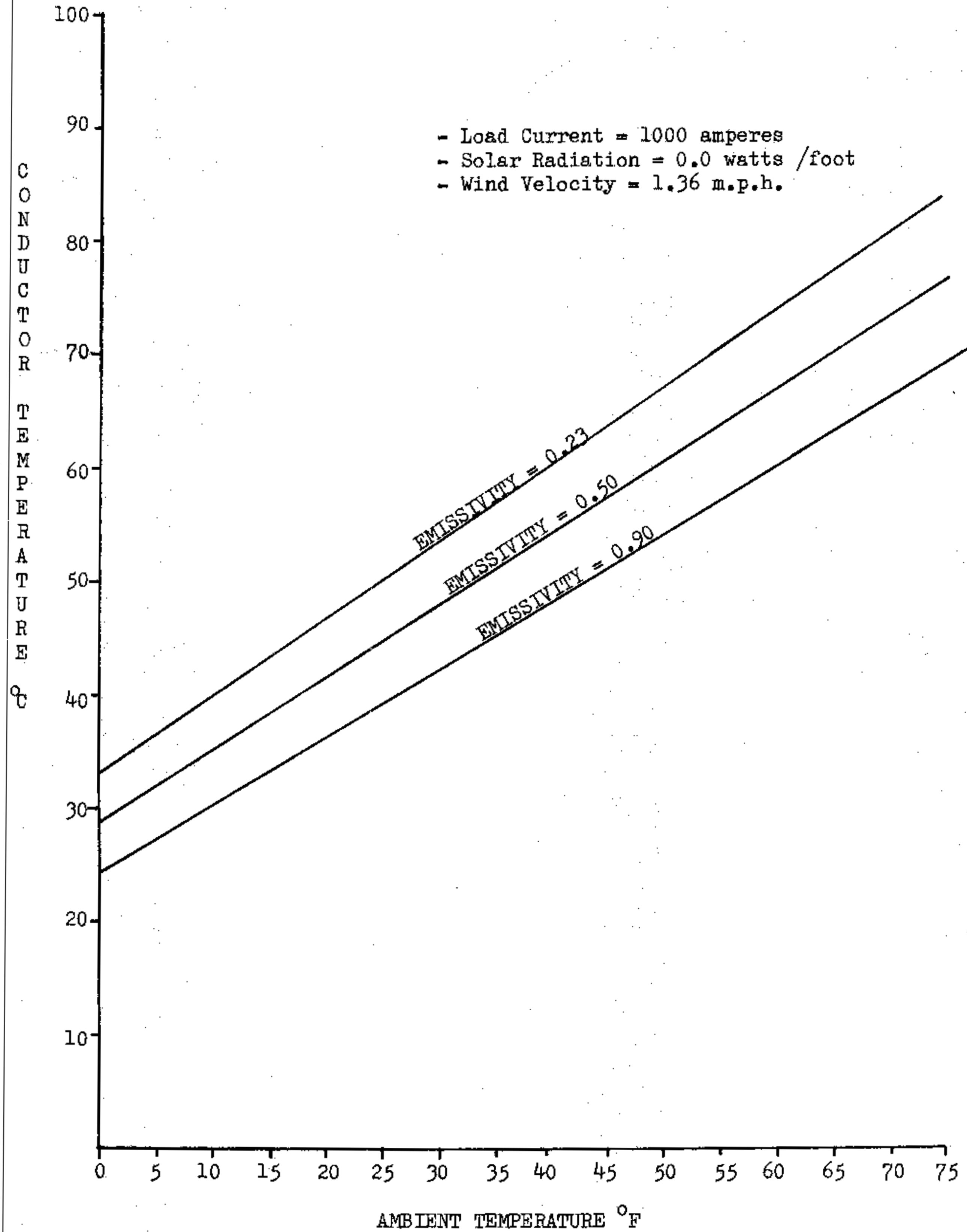

Figure 2.3 Conductor Temperature versus Ambient Temperature
(variable Conductor Emissivity)

3. PEARSON FREQUENCY DISTRIBUTIONS

3.1 General

A one year data set of hourly weather and load current values represents approximately 50,000 individual readings. Handling this amount of data on cards, tapes or disks can consume a considerable amount of computer storage and computer time,especially for multiple studies. These studies of conductor temperatures involve the superposition of various load current patterns and conductor sizes on the weather data for a particular geographical area. The multiple study aspect is discussed in Chapter 6.

A considerable saving in computer storage and time can be realized if the weather (ambient temperature, wind and solar radiation) can be represented by frequency distributions. In order to do this it was first assumed that the components of the weather, being a natural phenomena, could be represented by the two parameter normal curve (specified by the mean and standard deviation). It was found that the normal curve did not give a good representation of the weather data when examined using the Chi-Squared test. In the majority of the cases, a visual comparison of the frequency histograms representing the actual and theoretical distributions indicated that the normal curve was quite inadequate. The observed frequency distributions of weather were markedly skewed either positively or negatively or excessively peaked or flattened in relation to the normal curve.

The Gram-Charlier Method[14],which seeks to represent a given function as a series of derivatives of the normal frequency function was tried next. This method was not successful as the resulting theoretical frequency distributions contained negative frequency terms which can not be handled statistically.

Edgeworth's Method [14] was then applied. This approach seeks a transformation of the variate which will throw the distribution at least approximately into a known form. This method is sometimes used when prior knowledge of the variations in the variable are known. The lognormal, exponential, n^2, $1/n$ and many other transformations were tried, but the transformations failed to throw the weather distributions into any standard or known form.

In an attempt to find a known or standard distribution from this amount of data, the transformation and histogram plotting methods proved to be quite time consuming with no positive results. Some type of an elastic system of frequency distributions dependent upon the statistical properties of the data and independent of visual classification was required. This requirement is satisfied by the Method of Moments[13], developed by Karl Pearson. Most frequency distributions start at zero, rise at some rate to a maximum, and then fall at a different rate to zero. These characteristics are incorporated in the underlying assumptions in the development of the Pearson Family of Curves and can be expressed as follows:

1. unimodal (one maximum) ie. $f'(\text{mode}) = 0$
2. high contact at the ends of the curve ie. $f'(x)=0$

   where x is the upper and lower limits of the frequency distribution

The development of the Pearson Family of Curves is shown in considerable detail in Reference 13. The visual shapes generated by the Pearson Family are quite numerous and diversified.[13] Some of the possible forms are shown in Figure 3.1. A practical application of the U-shaped curve is to describe the degree of cloud cover.[13]

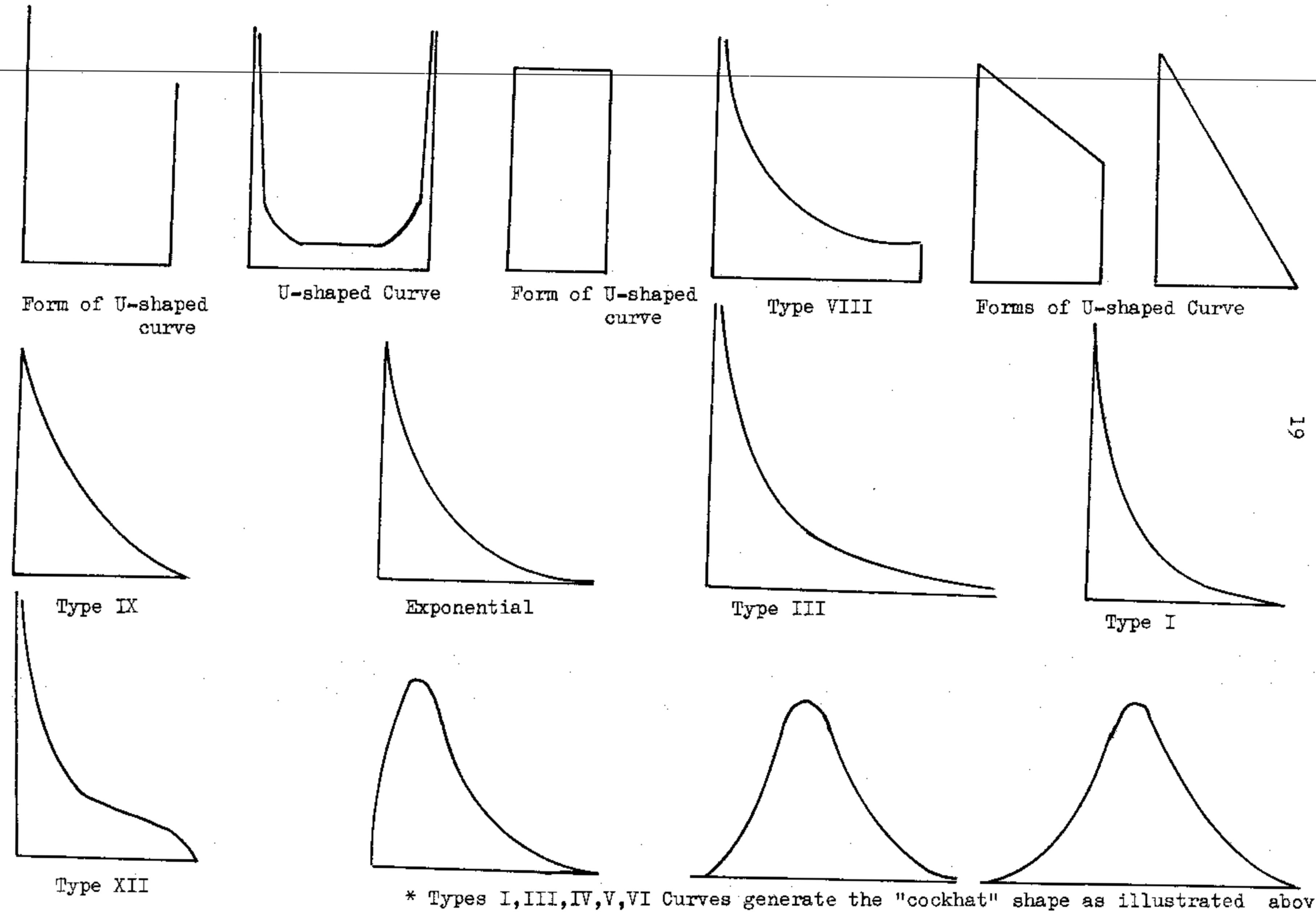

Figure 3.1 Visual Shapes Generated by the Pearson Family of Curves

3.2 Method of Application

Pearson's method of curve fitting consists of four steps.

STEP 1

The numerical values of the first four moments about the mean of the observed distribution are determined. With a small data set, the mean is first calculated by manipulating (adding) the entire data set once. The data set is then processed again to calculate the deviations from the mean and the statistical moments. With a large data set, containing many distributions, the above method of handling the entire data set twice can consume a considerable amount of computer time. The amount of data handling and computation can be reduced by scanning the entire data set only once to obtain the frequencies of occurrence of all the variables and the sum of all the frequencies.

The mean is then calculated as follows:

$$\bar{X} = \sum_{i=1}^{K} f_i X_i \Big/ \sum_{i=1}^{N} f_i \qquad (3.1)$$

where:

$\bar{X}$ - sample mean

f_i - frequency of occurrance of X_i

k - number of different value of the variable X

N - total number of observation in sample

X - random variable

The moments are calculated as follows:

$$u_i = \sum_{i=1}^{K} f_i \, (X - \bar{X})^i \Big/ \sum_{i=1}^{N} f_i \qquad (3.2)$$

where: u_i - the ith moment of the observed distribution

STEP 2

Calculate the numerical values of B_1 and B_2 from the first four moments obtained in Step 1.

$$B_1 = u_3^2 \;/\; u_2^3 \tag{3.3}$$

$$B_2 = u_4 \;/\; u_2^2 \tag{3.4}$$

STEP 3

Calculate the Kapa Criterion and determine the type to which the distribution belongs. Each curve in the Pearson Family of Curves is referred to as a type. The Kapa Criterion is a function of B_1 and B_2 . Kapa (k) is given by:

$$k = \frac{B_1 \quad (B_2 + 3)^2}{4\ (4B_2 - 3B_1)\ (2B_2 - 3B_1 - 6)} \tag{3.5}$$

The Pearson Family of Curves consists of three main types and many transition types. The three main types are Type I, when kapa is negative;Type IV, when kapa is greater than zero and less than 1 and Type VI when kapa is greater than 1. The transition types are: Type III, when kapa is negative or positive infinity; Type II, when kapa is zero and B_2 is not equal to 3; Normal, when kapa is equal to zero and B_2 equal to 3; and Type V when kapa is equal to 1. These classifications are shown in Figure 3.2.[13]

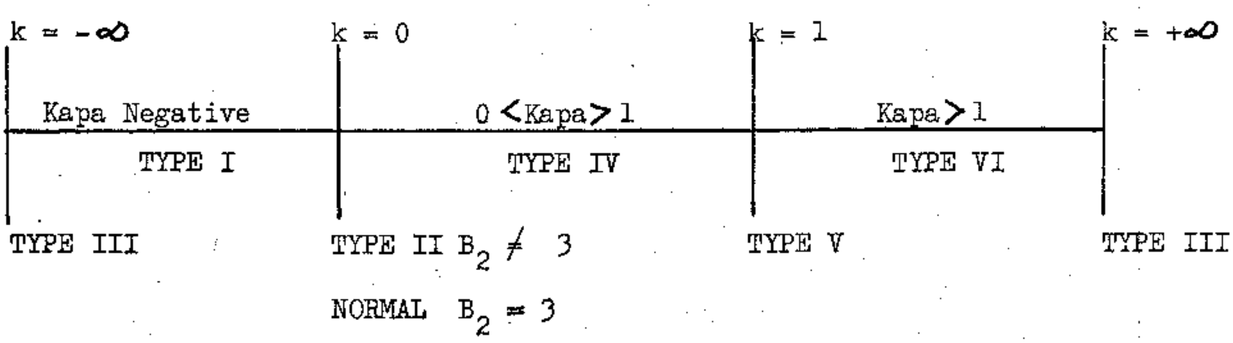

Figure 3.2 Pearson Family of Curves

STEP 4

Having determined the curve type which will best represent the actual distribution, the constants for the curve type are calculated.

3.3 Calculation of constants for some Pearson Type Curves

3.3.1 Pearson Type I Curve

$$y = y_o \left(1 + \frac{x}{a_1}\right)^{m_1} \left(1 - \frac{x}{a_2}\right)^{m_2} \qquad (3.6)$$

The Type I distribution is sometimes referred to as the Beta distribution.' In this form the origin of the curve is at the mode. Some properties of the Type I distribution are:

1. limited range
2. skewed
3. usually bell-shaped, but may be:
   a) U-shaped
   b) J-shaped
   c) twisted J-shaped

The constants for the distribution are calculated as follows:

a) calculate r from B_1 and B_2 as follows:

$$r = 6(B_2 - B_1 - 1) \;/\; (6 + 3B_1 - 2B_2) \qquad (3.7)$$

b) calculate the root m_i as follows:

$$m_i = 0.5 \left((r - 2) \pm \frac{r(r + 2) \sqrt{B_1}}{\sqrt{B_1(r + 2)^2 + 16(r + 2)}}\right) \qquad (3.8)$$

When the third moment of the observed distribution is positive, m_2 is the positive root, and when the third moment is negative, m_2 is the negative root.

c) calculate the sum of a's as follows:

$$a_1 + a_2 = \tfrac{1}{2}\, u_2 \sqrt{(B_1(r - 2)^2 + 16(r + 1)\,)} \qquad (3.9)$$

d) a property of the Type I distribution is:

$$m_1 a_2 = m_2 a_1 \tag{3.10}$$

e) solve the two linear equations (3.10) and (3.9) for a_1 and a_2.

f) calculate the theoretical mode of the distribution as follows:

$$\text{mode} = \text{mean} - \frac{1}{2}\frac{u_3\ (r + 2)}{u_2\ (r - 2)} \tag{3.11}$$

g) x is defined as the deviation from the mode:

$$x = X - \text{mode} \quad \text{where X is the random variable} \tag{3.12}$$

h) calculate y_o as follows:

$$y_o = \frac{N}{a_1 + a_2} \cdot m_1^{m1}\ m_2^{m2} \cdot \frac{1}{(m_1 + m_2)^{(m_1 + m_2)}} \cdot \frac{\Gamma(m_1+m2-2)}{\Gamma(m2-1)\Gamma(m1-1)} \tag{3.13}$$

where N is the sample size

An approximation[13] is used for the Gamma distribution due to the difficulty in evaluating the function when its argument is a non-integer. The approximation is:

$$\Gamma(x+1) = (\sqrt{2\pi x})\ x^x\ e^{-x}\ e^{1/12x} \tag{3.14}$$

Some of the weather data was found to belong to the Type I class. For example, the summer ambient temperature measured at 1 pm. (Figure 3.3) has the following statistical properties:

kapa= -0.08061 sample size= 183.0 sample mean = 63.19

u_2(2nd moment)=80.7554 u_3(3rd moment) = -315.3262

u_4(4th moment)=15216.2187

From these properties the constants calculated for the Type I distribution are:

y_o = 7.2

a_1 = 32.33707

m_1 = 1.30073

a_2 = 7.79608

m_2 = 0.31359

mode = 69.98093

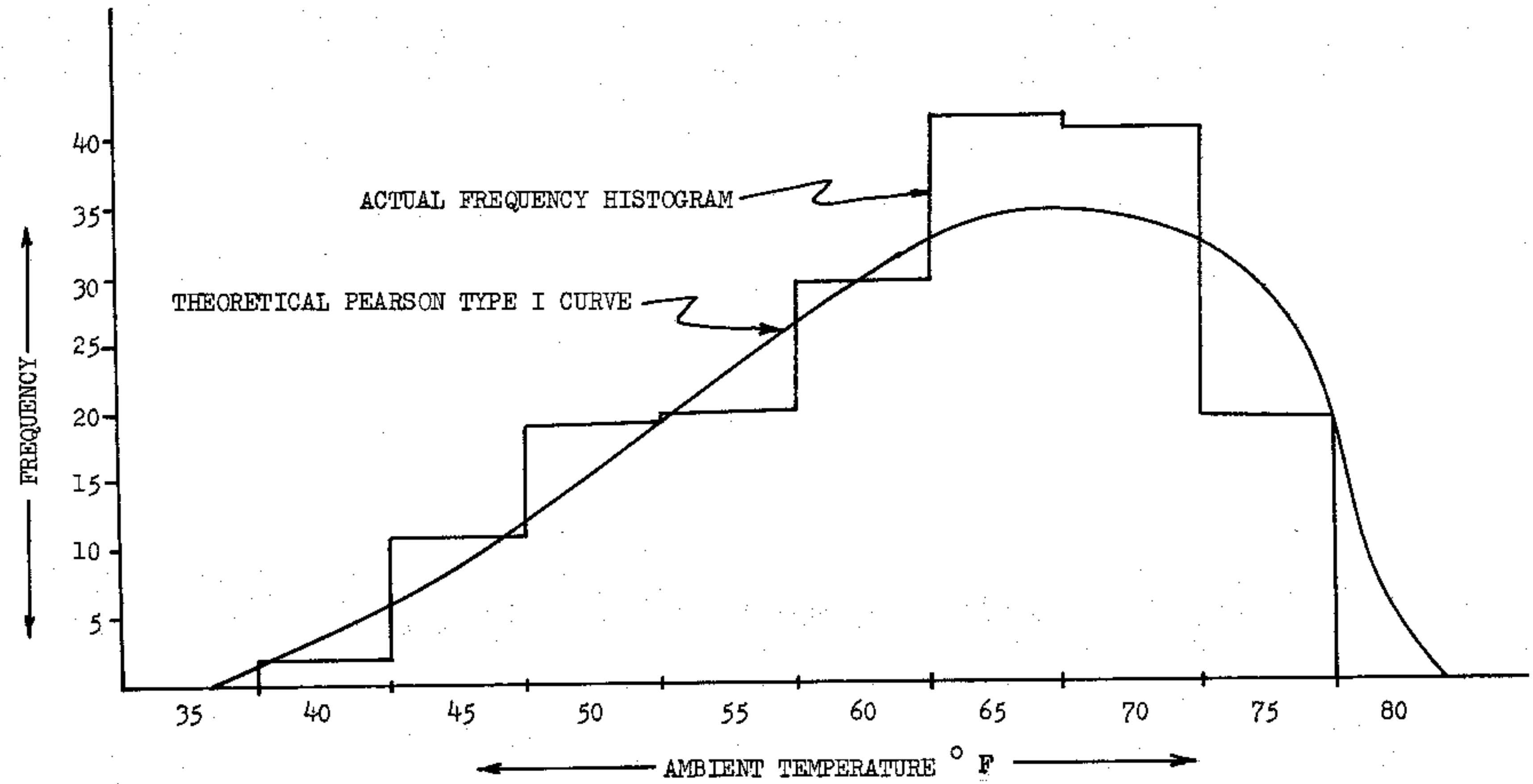

Figure 3.3 Summer Ambient Temperature (1pm) Histogram and Theoretical Curve

This actual distribution and the derived Pearson Type I distribution are shown in Figure 3.3.

3.3.2 Pearson Type IV Curve

The equation for the Type IV distribution is:

$$y = y_o \left(1 + \frac{x^2}{a^2}\right)^{-m} e^{-v \tan^{-1} x/a} \tag{3.15}$$

Some properties of the Type IV distribution are:

1. unlimited range in both directions
2. skewed
3. bell-shaped
4. most difficult to calculate of all Pearson's Type curves

The constants for the distribution are calculated in the following order:

a) calculate r from B_1 and B_2 as follows:

$$r = 6(B_2 - B_1 - 1) \,/\, (2B_2 - 3B_1 - 6) \tag{3.16}$$

b) calculate m as follows:

$$m = \tfrac{1}{2}\,(r + 2) \tag{3.17}$$

c) calculate v as follows:

$$v = \frac{r(r - 2)\, B_1}{\sqrt{16\,(r - 1) - B_1\,(r - 2)^2}} \tag{3.18}$$

Note: u_3 the third moment and v have opposite signs

d) calculate a as follows:

$$a = \sqrt{(u_2/16)}\,\sqrt{(16\,(r - 1) - B_1(r - 2)^2} \tag{3.19}$$

e) calculate y_o as follows:

$$y_o = \frac{N}{a} \cdot \sqrt{\frac{r}{2\pi}} \cdot \frac{e^{(\cos^2\phi\,/3r \,-\, r/12 \,-\, \phi v)}}{(\cos\phi)^{r+1}} \tag{3.20}$$

where: N - sample size
ϕ - $\tan^{-1}(v/r)$

The above expression is an approximation to y_o and is valid for v greater than 2.

f) The mode of the distribution is equal to :

$$\text{mode} = \text{mean} - \frac{1}{2}\frac{u_3}{u_2}\frac{(r-2)}{(r+2)} \tag{3.21}$$

g) The origin of the distribution is given by:

$$\text{origin} = \text{mean} + va/r \tag{3.22}$$

h) x is the deviation from the origin

Winter ambient temperatures tended to follow the Type IV distribution. For example, the winter ambient temperature measured at 12 noon has the following statistical properties:

kapa = 0.04775	sample size = 183.0
sample mean = 45.84	u_2(2nd moment) = 37.7966
u_3(3rd moment) = 58.4288	u_4(4th moment) = 5146.0156

From these properties, the constants calculated for the Type IV distribution are:

y_0 = 9.0278

origin = 40.81071

r = 15.01346

a = 22.45813

v = -3.36212

The actual distribution and the derived Pearson Type IV distribution are shown in Figure 3.4.

3.3.3 Pearson Type III Curve

The equation of the Type III distribution is:

$$y = y_o \left(1 + \frac{x}{a} \right)^{\gamma a} e^{-\gamma a} \tag{3.23}$$

Some properties of the Type III curve are:

1. range is limited in one direction only
2. usually bell-shaped

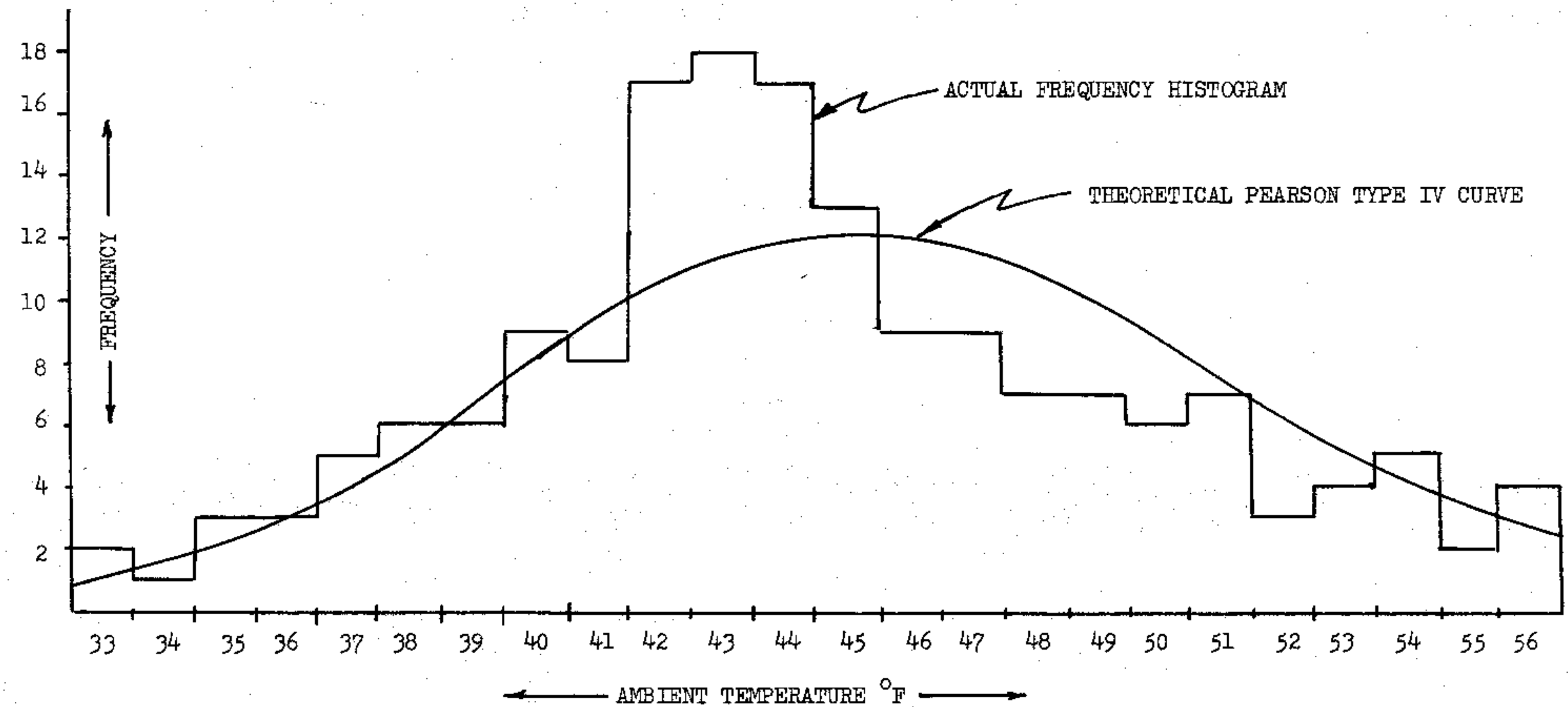

Figure 3.4 Winter Ambient Temperature (12 noon) Histogram and Theoretical Curve

3. becomes J-shaped when B_1 is greater than 4

4. Kapa criterion $2B_2 = 6 + 3B_1$

5. sometimes called the Gamma Distribution

The constants for the distribution are calculated as follows:

a) calculate as follows:

$$= 2u_2 / u_3 \tag{3.25}$$

b) calculate p as follows:

$$p = a = (4/B_1)-1 \tag{3.26}$$

c) calculate a as follows:

$$a = 2 u_2^2 / u_3 - u_3/2u_2 \tag{3.27}$$

d) calculate y_o as follows:

$$y_o = \frac{N}{a} \frac{p^{p+1}}{e^p \Gamma(p+1)} \tag{3.28}$$

where N is the sample size

$\Gamma(p+1)$ is approximated by equation 3.14

e) calculate the origin (mode) of the distribution as follows:

$$\text{mode} = \text{mean} - u_3/u_2 2 \tag{3.29}$$

f) x is the deviation from the mode

g) Care must be given to the signs of γ and a. The following rules are suggested:

i) when u_3 is positive:

- γ and 'a' are positive
- the generated curve is valid only up to a distance 'a' before the mode

ii) when u_3 is negative

- γ and 'a' are negative
- the graduated curve is valid only up to a distance 'a' after the mode

iii) if B_1 is greater than 4

$-\gamma$ and 'a' have different signs

Summer wind velocities around noon tended to follow the Type III distribution. For example, the summer wind velocities measured at 12 noon have the following statistical properties:

kapa = -0.37534 sample size = 183.0

sample mean = 7.79 u_2(2nd moment) = 12.1765

u_3(3rd moment) = 33.3189 u_4(4th moment) = 47.50354

From these properties the constants calculated for the Type III distribution are:

mode = 6.59893

y_o = 22.40692

a = 7.53166

γ = 0.73090

p = 5.50493

The observed summer wind velocities and the derived Pearson Type III distribution are shown in Figure 3.5. Winter wind velocities during the day tended to follow the Type I while those during the evening followed the Type III distribution. This is shown in Figure 3.6.

3.4 Application to Univariant Frequency Distributions

After calculating the constants for the distribution, it is necessary to calculate the expected frequency of the variable x by first calculating the probability of x as follows:

$$p(x) = \int_a^b f(x)\, dx \tag{3.30}$$

where: p(x) - probability of occurence of the random variable x

f(x) - frequency distribution function

a - lower class boundary of x

b - upper class boundary of x

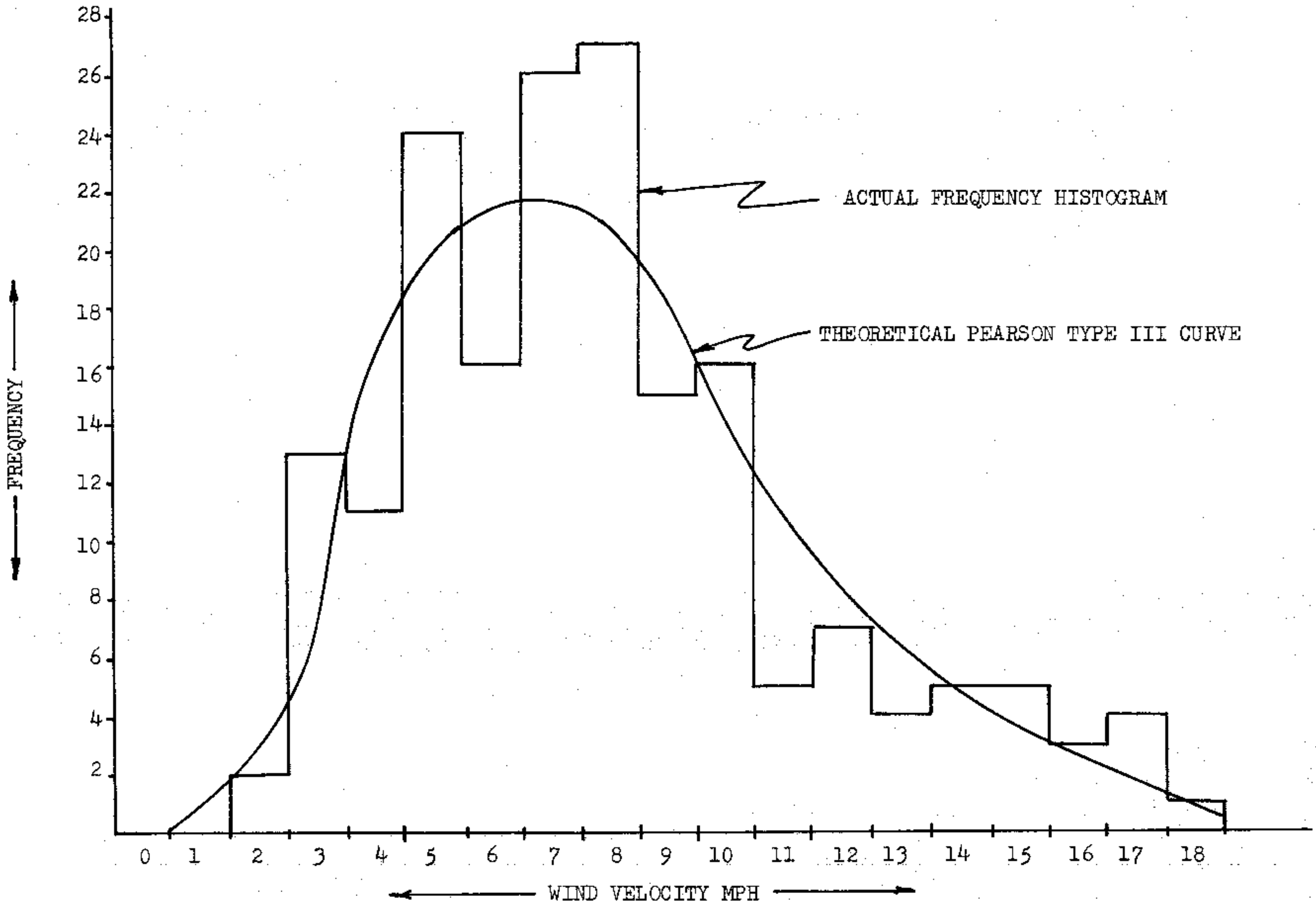

Figure 3.5 Summer Wind Velocity (12 noon) Histogram and Theoretical Curve

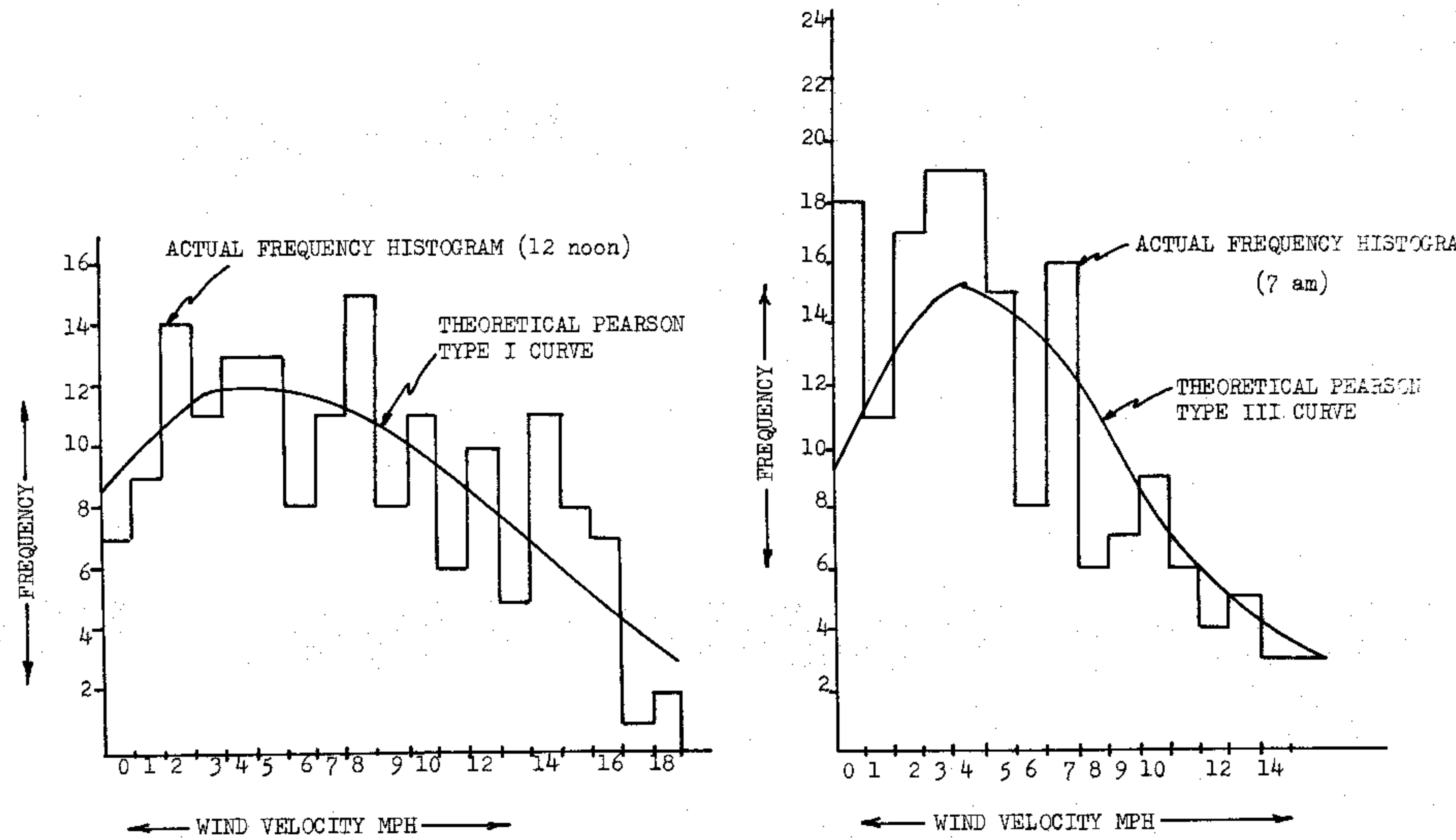

Figure 3.6 Winter Wind Velocity (12 noon and 7 am) Histograms and Theoretical Curves

The integrals of the Pearson distribution functions are difficult to evaluate analytically. Numerical integration methods must be used, ie. the process of mechanical quadrature. The method used is known as Simpson's Rule[19], which is stated as follows:

$$\int_{X_o}^{X_o+nh} y\,dx = \frac{h}{3}\left(y_o + 4\,(y_1 + y_3 + \cdots\cdots y_{n-1}) + 2(y_2 + y_4 + \cdots\cdots y_{n-2}) + y_n)\right) \quad (3.31)$$

where: y - frequency distribution function

h - sub-interval width

n - number of sub-intervals (must be an even number)

y_i - ith ordinate at the end of the sub-interval

For distributions having a large standard deviation, an approximation to equation (3.30) can be used. If the class width is small in comparison to the standard deviation then:

$$p(x) = (y\,\Delta x) \,/\, n \quad (3.32)$$

where: Δx - class width = 1.0 for all distributions

y - ordinate at the mid-point of the class width

n - sample size

Given the probability of x, the theoretical frequency of x is calculated as follows:

$$f_e = p(x)\, n \quad (3.33)$$

where: f_e - expected or theoretical frequency

p(x) - probability of occurence of the random variable x

n - sample size

Given the theoretical frequencies of a particular distribution it is possible to determine if the theoretical frequency distribution represents the actual frequency distribution using the Chi-Squared Test.

$$\chi^2 = \sum \frac{(f_o - f_e)^2}{f_e} \tag{3.34}$$

where: f_e - expected or theoretical frequency

f_o - actual or observed frequency

A significance level of 0.05 was assumed. The probability of making a Type One Error and rejecting a valid distribution is 0.05. The Null Hypothesis is made which suggests that the actual distribution and the theoretical distribution are drawn from the same population. If the calculated Chi-Squared value is found to exceed the actual value at the 0.05 level of significance for the appropriate number of degrees of freedom then the Null Hypothesis is rejected. The two distributions are then said to be significantly different. If the distribution is multimodal, the Pearson Family of Curves fail to graduate the distribution.

This Chapter has illustrated the basic method of calculating the Pearson theoretical frequency distributions that will best represent an observed distribution. Detailed calculation of the parameters for several type distributions and an example of each type are presented. The application of the Pearson Family of curves to represent the main elements of the weather are discussed in detail in the next chapter.

4 WEATHER MODEL

4.1 General

The main weather effects that influenced the conductor surface temperature were assumed to be the ambient temperature, the wind velocity and the solar radiation. The effect of these variables was discussed in Chapter 2.

The year was divided into the two seasons, summer and winter. Summer is defined as the months of April, May, June, July, August and September. Winter being defined as the remaining months in the year. Each season was then divided into six time zones shown in Table 4.1.

In order to evaluate the individual weather properties for a time zone, the hourly weather properties within the zone were analysed assuming that the properties remain constant for one half hour on either side of the hourly readings. Each zone was selected by plotting the hourly weather frequency histograms over a season and noting the histograms and Pearson Type Curves that exhibited similar frequency patterns or shapes

Table 4.1 Definition of Time Zones

TIME ZONE	RANGE OF TIME ZONE
1	1 am to 6 am
2	7 am to 9 am
3	10 am to 12 noon
4	1 pm to 3 pm
5	4 pm to 6 pm
6	7 pm to 12 midnight

The weather characteristics were analysed individually following which the interaction between the wind, ambient temperature and solar radiation were studied. Correlation and regression analysis was applied to determine the degree of dependence between these variables. The selection of the time zones shown in Table 4.1 was ultimately based on obtaining a number of periods during which the two main variables wind and ambient temperature exhibited a maximum degree of independence. The determination of time zones for which the two variables were found to be independent allows the weather model to be postulated in the form of a multi-variable frequency distribution.

The aim of the multi-variant frequency approach is not to predict the weather hourly variations during a particular day, week or month. The objective, instead, is to predict the probable number of hours that a certain wind-temperature-solar radiation combination will occur during a seasonal time zone.

4.2 Ambient Temperature

The lower levels of the atmosphere are not heated directly from the sun. Solar energy in the form of short wave lengths pass unhindered through these lower levels and are absorbed by the earth's surface, thus raising the surface temperature of the earth. The earth then re-radiates energy (long wave lengths) which are absorbed by the lower levels of the atmosphere. The expression ambient temperature is used to indicate the temperature of the air near the earth'surface.

The ambient temperature is affected by :

1. Advection[18] (air mass moving over a relatively warm surface)
2. Compression (when air is compressed its temperature rises)

During the daytime, clouds intercept a portion of the incoming solar radiation effectively lowering the ambient temperature. At night, clouds absorb the earth's outgoing radiation and re-radiate a portion back to earth, thus increasing the ambient temperature slightly.

The intensity of solar radiation varies with many factors which in turn affect the ambient temperature and are discussed in section 4.3. Many of the factors that influence the ambient temperature can not be evaluated or even predicted with any degree of accuracy or certainty. The hourly frequencies of summer and winter ambient temperatures are shown in Tables 4.2 and 4.3 respectively.

The Pearson Family of curves fit the seasonal ambient temperatures quite well. Each zone is characterized by a Pearson Type curve as shown in Table 4.4.

Table 4.4 Zoned Seasonal Ambient Temperatures vrs Pearson Type Curves

TIME ZONE	SUMMER AMBIENT TEMPERATURE	WINTER AMBIENT TEMPERATURE
1 am to 6 am	I	I
7 am to 9 am	I	IV
10 am to 12 noon	I	IV
1 pm to 3 pm	I	IV
4 pm to 6 pm	I	IV
7 pm to 12 midnight	I	IV

Table 4.2 Summer Ambient Temperature versus Time of Day

(Frequency of Observations)

HOUR OF DAY	AMBIENT TEMPERATURE °F 53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73
1	14	17	15	13	14	7	14	8	6	2	2	0	0	0	0	0	0	0	0	0	0
2	10	15	17	11	10	10	9	9	5	2	0	0	0	0	0	0	0	0	0	0	0
3	16	10	11	22	10	11	9	3	3	0	1	0	0	0	0	0	0	0	0	0	0
4	16	14	17	10	13	7	10	2	2	1	0	0	0	0	0	0	0	0	0	0	0
5	19	13	12	13	11	8	5	4	1	1	1	0	0	0	0	0	0	0	0	0	0
6	9	13	13	17	21	8	9	9	1	2	2	0	0	0	0	0	0	0	0	0	0
7	9	9	13	9	12	15	14	14	3	7	8	1	2	0	0	1	0	0	0	0	0
8	2	7	8	8	17	20	8	8	13	11	6	6	4	6	3	1	1	1	0	0	0
9	2	3	4	9	8	13	12	12	11	11	11	12	7	5	5	2	1	2	5	1	0
10	4	2	4	5	6	12	7	8	10	8	10	13	13	12	1	8	4	1	4	3	2
11	3	5	0	3	6	9	7	10	7	7	11	6	13	17	5	11	5	1	4	4	4
12	4	4	4	2	3	6	12	4	7	5	9	8	7	14	16	5	4	10	3	6	4
13	3	5	6	3	3	3	7	7	5	7	8	6	9	8	11	9	14	8	8	2	4
14	0	6	2	5	3	4	6	8	4	5	6	6	8	11	10	5	9	17	5	6	6
15	1	5	5	2	5	4	6	7	4	4	11	4	8	11	10	8	11	7	10	5	5
16	3	1	6	4	3	4	5	5	6	7	7	4	11	8	12	6	10	6	8	8	6
17	2	3	4	4	4	4	6	7	6	10	4	8	10	4	6	10	10	7	6	5	7
18	3	4	4	5	3	6	5	7	9	6	7	8	8	7	12	8	7	6	4	4	6
19	3	3	6	7	4	8	5	7	8	3	13	9	11	9	9	7	5	5	4	3	7
20	5	4	4	6	5	8	19	4	8	12	9	12	7	16	5	4	2	3	4	1	0
21	4	2	11	9	11	11	13	12	15	10	6	12	7	5	2	1	2	0	0	0	0
22	8	4	9	18	12	8	18	14	12	10	3	6	4	5	1	0	0	1	0	0	0
23	10	8	11	17	12	15	14	10	9	6	4	3	4	0	0	0	0	0	0	0	0
24	9	15	13	14	14	16	13	10	8	3	2	1	0	0	0	0	0	0	0	0	0

Table 4.3 Winter Ambient Temperature versus Time of Day
(Frequency of Observations)

	AMBIENT TEMPERATURE °F																					
HOUR OF DAY	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
1	0	5	3	4	7	5	7	9	7	9	10	12	16	11	9	7	9	6	10	6	5	5
2	2	3	5	3	5	7	8	5	13	11	3	17	15	4	14	7	9	10	3	9	3	6
3	1	5	3	6	8	5	1	11	12	13	5	13	12	10	8	11	6	7	8	5	4	5
4	3	4	3	4	9	6	3	6	11	8	20	9	7	10	8	9	9	8	8	6	5	1
5	6	2	4	7	7	4	9	6	6	15	13	11	5	8	14	5	13	10	6	4	2	6
6	2	2	3	5	13	6	7	11	4	9	10	14	6	11	12	12	10	5	6	5	2	4
7	4	3	7	3	5	10	2	11	4	13	8	12	11	10	9	14	8	6	9	4	3	5
8	3	2	4	5	3	6	5	9	9	13	9	12	10	12	6	14	8	6	11	5	2	5
9	1	0	1	3	5	7	2	3	8	14	10	10	14	10	12	12	8	12	6	8	6	3
10	2	3	0	3	1	2	4	3	7	6	9	8	11	15	12	17	16	11	7	8	5	7
11	0	1	1	1	0	1	3	5	6	4	9	5	6	18	12	18	18	11	8	8	9	6
12	0	0	2	0	0	2	1	3	3	5	6	6	9	8	17	18	17	13	9	9	7	7
13	0	0	1	0	1	0	2	3	3	3	5	8	10	5	21	8	15	17	13	13	7	7
14	0	0	1	0	1	1	1	2	3	4	4	5	11	9	16	13	14	15	11	19	7	7
15	0	1	0	1	0	2	2	2	3	3	4	5	13	8	13	13	15	15	19	14	9	5
16	0	1	0	1	2	0	3	6	3	0	7	4	8	11	17	10	18	20	13	13	9	4
17	1	0	0	3	3	2	2	2	3	5	5	9	12	11	15	17	16	16	12	11	5	2
18	1	2	1	2	1	2	3	2	4	5	10	11	13	15	14	18	17	14	8	2	7	4
19	2	1	0	1	3	4	2	2	5	8	7	18	13	14	17	17	10	10	6	7	8	5
20	2	2	0	0	3	4	2	7	4	8	12	18	11	15	18	17	3	10	7	7	5	6
21	2	2	0	1	3	3	7	7	7	8	12	14	14	13	13	17	5	6	10	7	5	3
22	1	2	0	1	6	1	5	12	13	3	11	11	12	13	15	11	7	4	11	7	4	9
23	0	1	1	4	3	7	3	8	17	6	7	15	16	11	13	7	9	2	6	12	5	6
24	1	1	4	4	8	6	7	4	14	7	6	13	18	13	7	5	11	6	7	10	4	6

4.3 Wind

Wind is a horizontal movement of air commonly measured in miles per hour. The movement of surface wind is due to the three main forces; pressure gradient, a deflective force due to the earths rotation, and the friction force between the air and the ground. Wind also varies with topographical effects. The prediction of surface wind velocity is difficult even from a weather map because of the many external variables which affect it. The hourly readings do not indicate transient effects such as gusts or squalls but are the prevailing wind velocities over an hour. Wind direction was neglected in evaluating the conductor surface temperature.

Tables 4.5 and 4.6 show the frequency of various wind velocities as a function of the time of day for summer and winter conditions respectively. It can be seen that the wind velocities during the daytime tend to be higher than those during the night. This phenomena is known as the Diurnal Effect.[18]

The Diurnal Effect is based on the property that the surface wind velocity and direction are variable at different levels in the atmosphere. The wind velocity increases in speed with distance from the earth's surface up to a height of approximately 3000 feet. During daytime heating, the eddying motion in the form of mechanical turbulence caused by the friction between the air and the ground often extends to 3000 feet or higher. This turbulent region acts as a mixing zone and results in the direction and speed of the upper wind velocities being transferred to the surface. During the night, the surface cooling tends to reduce the mechanical

Table 4.5 Summer Wind Velocity versus Time of Day
(Frequency of Observations)

HOUR OF DAY	WIND VELOCITY MPH 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	27	18	15	19	28	13	21	14	7	10	3	1	2	2	1	0	0	0	0	0	0
2	30	11	22	22	20	18	16	13	14	3	4	4	2	1	1	0	0	0	0	0	0
3	35	14	25	14	17	21	16	13	6	7	9	1	0	2	2	1	0	0	0	0	0
4	31	16	27	15	16	13	14	16	11	9	7	1	2	1	2	0	2	0	0	0	0
5	28	23	21	8	14	18	22	13	12	2	9	3	3	2	1	2	1	1	0	0	0
6	47	10	14	10	10	24	20	18	7	5	4	2	4	1	2	2	1	1	0	0	0
7	35	14	13	11	12	18	19	12	9	12	2	7	5	4	4	1	2	0	0	0	1
8	21	13	12	21	18	12	10	13	16	9	10	7	6	5	0	7	1	1	0	1	0
9	15	7	23	10	12	15	17	15	12	14	13	2	9	5	3	4	3	3	1	0	0
10	6	6	12	12	16	19	23	12	12	14	11	5	13	3	4	3	5	4	1	1	0
11	1	2	1	4	18	26	24	29	16	16	9	7	5	2	5	8	3	7	0	0	0
12	0	0	2	13	11	24	16	26	27	15	16	5	7	4	5	5	3	4	1	0	0
13	0	1	3	9	19	20	23	30	20	12	13	8	4	5	7	2	6	0	0	1	0
14	0	2	3	10	12	27	29	26	22	11	14	2	6	3	7	3	2	1	3	0	0
15	1	0	6	8	15	28	34	25	18	8	16	3	6	3	3	4	4	0	0	1	0
16	1	1	7	11	17	35	26	22	21	13	8	4	3	6	1	1	5	0	0	0	0
17	7	4	8	16	23	38	16	14	23	7	9	3	1	6	4	2	1	1	0	0	0
18	5	5	20	19	27	23	20	16	18	6	6	3	6	3	1	1	1	1	1	1	0
19	20	14	19	22	22	19	13	12	14	7	4	4	4	2	2	0	2	1	0	0	0
20	37	11	18	14	29	16	13	13	8	7	7	2	3	1	3	0	0	0	1	0	0
21	35	14	24	12	25	13	16	17	6	4	4	1	5	2	2	2	1	0	0	0	0
22	34	14	24	23	15	21	13	14	9	5	3	0	4	1	2	0	0	1	0	0	0
23	30	14	19	18	29	17	15	11	7	7	7	3	0	0	1	0	1	0	0	0	0
24	28	13	14	24	28	21	14	7	12	7	9	3	1	1	1	0	0	0	0	0	0

Table 4.6 Winter Wind Velocity versus Time of Day
(Frequency of Observations)

	WIND VELOCITY miles per hour																				
HOUR OF DAY	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	24	14	15	9	17	9	14	9	13	6	11	5	9	8	3	2	4	0	1	1	2
2	17	12	19	11	21	8	12	8	13	8	9	7	7	9	7	0	2	1	2	2	1
3	19	9	22	12	13	15	11	14	7	8	7	6	6	8	7	4	1	1	4	0	0
4	27	13	14	12	21	13	9	8	12	5	13	4	8	5	5	2	3	1	0	0	1
5	27	6	22	14	12	13	12	14	6	4	9	5	12	5	5	2	4	1	1	2	1
6	20	7	19	16	16	18	12	9	6	7	15	3	9	3	3	4	5	0	3	2	0
7	18	11	17	19	19	15	8	16	6	7	9	6	4	5	3	3	6	2	0	2	3
8	24	11	17	14	20	12	8	6	11	11	8	6	5	7	3	4	4	2	4	0	1
9	16	15	19	15	12	7	14	10	10	12	6	10	7	4	5	4	4	3	2	1	1
10	15	19	15	10	10	11	17	8	6	13	13	8	8	3	3	5	5	2	4	2	3
11	13	6	14	12	15	15	14	10	11	7	10	6	12	9	4	3	5	2	0	4	1
12	7	9	14	11	13	13	8	11	15	8	11	6	10	5	11	8	7	0	1	2	3
13	9	6	13	9	17	13	7	7	9	16	10	10	12	7	8	8	4	3	3	1	2
14	4	9	10	9	13	14	6	15	11	8	20	10	9	5	3	7	10	2	4	2	4
15	5	9	9	15	10	7	13	12	12	14	11	12	9	8	9	7	2	3	2	2	3
16	7	5	7	13	20	14	6	11	15	13	12	11	9	7	10	1	5	1	6	2	2
17	8	6	13	12	11	15	12	12	17	10	15	4	6	7	6	3	8	4	4	1	1
18	12	8	9	17	13	17	15	15	9	6	13	4	13	4	4	4	2	3	3	1	3
19	18	14	9	12	12	17	16	12	10	6	7	12	10	8	2	1	3	2	1	1	0
20	17	10	20	11	14	17	8	9	14	9	12	7	9	4	6	5	0	0	0	2	3
21	26	17	12	15	12	7	14	10	16	6	7	7	5	6	6	4	2	2	1	1	2
22	17	14	23	11	12	15	13	10	7	8	9	4	11	3	10	1	2	3	1	0	0
23	22	9	21	15	12	12	16	8	9	10	6	9	6	4	2	7	2	2	3	0	0
24	28	13	13	17	12	12	11	8	9	9	6	9	7	6	6	3	1	1	3	1	3

turbulence in the lower levels and the surface winds assume their normal direction and speed.

The Pearson Family of curves was used to fit the seasonal wind velocities. Each time zone is characterized by a Pearson Type curve as shown in Table 4.7.

Table 4.7 Zoned Seasonal Wind Velocities vrs Pearson Type Curves

TIME ZONE	SUMMER WIND VELOCITIES	WINTER WIND VELOCITIES
1 am to 6 am	I	I
7 am to 9 am	I	I
10 am to 12 noon	III	I
1 pm to 3 pm	III	I
4 pm to 6 pm	I	I
7 pm to 12 midnight	IV	I

4.4 Solar Radiation

Solar radiation is defined as all the wavelengths of solar energy received at the surface of the earth. It is normally measured in langleys per minute where one langley is equivalent to one calorie of radiation energy per square centimeter.

The incoming solar radiation from the sun is scattered by the agents in the atmosphere. Some of these agents[9] are:

1. air molecules (Rayleigh's theory)
2. number, size and composition of dust particles
3. amount of water vapor present

The scattering can be foreward, which results in sky radiation or backwards, depending upon the size of the particles in the atmosphere.

Ozone absorption[9] in the upper atmosphere plays an important role in modifying the solar energy before it reaches the earth. Ozone absorbs the shorter wavelength (ultra-violet) radiation. The infra-red regions of the solar spectrum are absorbed by the water vapor in the atmosphere.

Solar radiation is also dependent upon the position of the sun in the sky which in turn is dependent upon three independent variables:

1. geographical co-ordinates (longtitude and latitude)
2. solar declination, which is a function of the date
3. amount of water vapor present

Many of the factors that affect solar radiation are very difficult to evaluate. Some researchers[1] use an approximation to account for the solar heating of the conductor. This approximation is as follows:

$$S = Q_D \sin \theta + Q_d \tag{4.1}$$

where:

S - amount of direct and sky solar radiation

Q_D - direct solar radiation

Q_d - indirect or sky solar radiation

θ - is defined as follows:

$$\theta = \cos^{-1}(\cos H_c \cdot \cos(Z_c - Z_1)) \tag{4.2}$$

where:

H_c - altitude of the sun above the horizon

Z_c - azimuth of the sun

Z_1 - azimuth of the transmission line

Tables[1] are used to evaluate the constants in equations 4.1 and 4.2 for geographical locations where solar energy is not measured by the Department of Transport.

Tables 4.8 and 4.9 show the hourly frequencies of occurence of solar radiation for summer and winter conditions respectively.

4.5 Bi-varient Frequency Distribution - Ambient Temperature vrs Wind Velocity

4.5.1 Correlation Coefficient

The correlation coefficient, often called the Pearson product-moment correlation coefficient is a measure of the way in which two normally distributed variables correlate. The two variables are said to correlate positively when, as one variable increases, the other shows some tendency to increase in a uniform way. If the second variable decreases in a uniform manner the correlation is said to be negative. The two variables are said not to correlate at all, when as one of them changes, the other shows absolutely no over-all tendency to change in a uniform way with respect to it. The values of the correlation coefficient can vary from minus one to plus one. The correlation coefficient is given by:[14]

$$r_{xy} = \frac{1}{N}\sum_{i=1}^{N}\left(\left(\frac{x_i - \bar{x}}{p_x}\right)\left(\frac{y_i - \bar{y}}{p_y}\right)\right) \tag{4.3}$$

where: r_{xy} - correlation coefficient

x_i and y_i - random variables

$\bar{x}$ and $\bar{y}$ - sample means

p_x and p_y - sample standard deviations

N - sample size

Table 4.8 Summer Solar Radiation Hourly Frequencies

	SOLAR RADIATION langleys per hour																				
HOUR OF DAY	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	141	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	61	84	16	20	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	53	21	14	18	11	11	4	11	3	5	4	7	8	5	3	0	0	0	0	0
7	0	5	6	11	6	18	11	4	8	17	9	6	7	3	5	5	7	6	2	3	3
8	0	2	0	2	3	2	1	2	3	4	4	5	7	7	10	4	11	9	6	5	4
9	0	0	0	1	1	2	1	1	3	2	0	1	6	0	5	6	2	2	5	0	2
10	0	0	1	0	1	1	2	1	1	0	1	1	1	1	2	2	2	3	1	4	1
11	0	1	0	1	0	0	1	1	0	1	1	1	0	2	5	3	2	2	0	2	4
12	0	0	0	0	1	2	0	1	2	0	0	1	1	0	0	2	1	5	2	0	0
13	0	0	0	0	0	1	1	1	1	2	0	0	1	0	0	2	1	1	3	0	2
14	0	0	0	0	0	2	2	0	0	1	1	1	0	0	0	1	1	0	2	1	1
15	0	0	0	0	1	2	0	3	1	3	2	2	1	4	4	0	2	1	1	3	2
16	0	0	0	0	0	1	1	1	0	0	1	3	1	1	0	3	0	1	1	4	1
17	0	0	0	3	3	2	3	4	3	3	5	2	3	4	5	3	6	1	3	5	1
18	0	2	10	7	5	9	7	8	3	7	6	4	8	4	3	9	3	4	4	4	7
19	4	48	13	20	6	9	9	8	7	3	10	8	2	12	8	5	6	2	1	0	0
20	62	72	19	17	12	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
21	138	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.9 Winter Solar Radiation Hourly Frequencies

	SOLAR RADIATION langleys per hour																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	169	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	109	60	5	3	0	0	3	1	0	1	0	0	0	0	0	0	0	0	0	0	0
8	6	111	13	16	6	8	4	2	1	5	4	0	0	1	0	0	1	0	0	0	0
9	0	42	30	24	13	7	2	5	6	4	3	5	4	4	5	4	2	2	1	1	1
10	1	7	24	14	13	10	5	10	6	7	5	7	6	4	4	7	6	4	4	3	2
11	0	0	12	12	15	11	12	5	4	8	4	5	7	5	3	1	4	5	2	5	5
12	1	0	8	6	17	8	9	3	9	6	5	4	5	4	4	2	8	5	0	3	2
13	0	0	7	13	12	15	5	7	6	3	4	3	4	3	4	4	5	5	2	4	3
14	0	2	11	14	7	9	7	7	10	7	8	9	1	7	4	5	3	5	3	2	1
15	1	36	29	12	14	6	11	8	10	5	3	6	2	3	3	2	2	3	4	1	1
16	8	100	19	13	8	4	6	0	3	2	4	4	3	1	0	2	0	0	1	0	1
17	102	65	6	3	1	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	0
18	171	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The correlation coefficients for ambient temperature and wind for both seasons averaged 0.40. This indicates that approximately 16 percent of the variation in the wind may be accounted for or may be attributed to variations in the ambient temperature. For practical purposes, they may be assumed to be independent.

4.5.2 Contingency Tables and Chi-Squared Test

Contingency tables are generally used to determine if two variables are dependent or independent of each other. Two variables are called unrelated or independent in a population if at every value of one of them the distribution of the other is unchanged. When two variables are so related that the values of one depend on the values of the other, then the variables are said to be related or dependent.

A contingency table is defined as a two way table in which the categories are discrete. It can also be defined as a matrix in which each element contains the actual or observed joint frequency of the two variables under study. In this case the variables were ambient temperature and wind.

Grouping of the ambient temperature and wind velocity frequencies was required in order to obtain cell frequencies greater than 5 as frequencies below 5 will result in the actual sampling distribution exhibiting marked discontinuities.

To test for independence the following proceedure was used:

1. The number of degrees of freedom were determined as follows:

$$df = (r - 1)\,(c - 1) \tag{4.4}$$

where: df - number of degrees of freedom

r - number of rows in table or matrix

c - number of columns in table or matrix

2. The marginal totals of the rows and columns of the matrix were determined. A marginal total is defined as the sum of the frequencies of either a row or a column as follows:

$$SR_i = \sum_{j=1}^{N} f_{ij} \qquad (4.5)$$

$$SC_j = \sum_{i=1}^{N} f_{ij} \qquad (4.6)$$

where:

SR_i - sum of the ith row frequencies

SC_j - sum of the jth column frequencies

3. The marginal totals were summed to give the grand total (T) as follows:

$$T = \sum_{i=1}^{j} SR_i = \sum_{j=1}^{i} SC_j \qquad (4.7)$$

4. The expected cell frequencies (fe_{ij}) are calculated assuming that the two values are independent.

$$fe_{ij} = (SR_i \cdot SC_j) / T \qquad (4.8)$$

5. The cell Chi-Squared frequencies were calculated for each cell and summed as follows:

$$\chi^2_T = \sum_{i=1}^{r} \sum_{j=1}^{c} \frac{(fo_{ij} - fe_{ij})^2}{fe_{ij}} \qquad (4.9)$$

6. The 0.05 significance level was used to test if the independence hypothesis was true.

If:

$\chi^2 \leq \chi^2(0.05)$ ..... variables are independent

$\chi^2 \geq \chi^2(0.05)$ ..... variables are dependent

The test results for temperature and wind are shown for summer and winter time zones in Table 4.10.

Table 4.10 Independence test results for summer and winter ambient temperature and wind

* TIME ZONE *	* SUMMER df	χ^2 actual	$\chi^2(.05)$ *	* CONCLUSION *
1 am to 6 am	16	23.7	26.3	INDEPENDENT
7 am to 9 am	16	25.2	26.3	INDEPENDENT
10 am to 12 noon	24	34.0	36.4	INDEPENDENT
1 pm to 3 pm	24	30.7	36.4	INDEPENDENT
4 pm to 6 pm	18	19.1	28.8	INDEPENDENT
7 pm to 12 midnight	21	32.6	32.7	INDEPENDENT

* TIME ZONE	* WINTER df	χ^2 actual	$\chi^2(.05)$ *	* CONCLUSION *
1 am to 6 am	27	50.0	40.1	DEPENDENT
7 am to 9 am	18	33.8	28.8	DEPENDENT
10 am to 12 noon	18	30.0	28.8	DEPENDENT
1 pm to 3 pm	10	9.6	18.3	INDEPENDENT
4 pm to 6 pm	10	6.1	18.3	INDEPENDENT
7 pm to 12 midnight	27	54.9	40.1	DEPENDENT

Some winter time zones exploded the hypothesis that the temperature and wind are independent variables. An examination of Table 4.11 indicates that the largest Chi-Squared values are in the cells with wind velocities in excess of 10 m.p.h. and in those cells in the low temperature range; ie. 35^{O}F and lower. If the 35^{O}F column and the 10 m.p.h. row are deleted, the remaining table suggests that the temperature and wind are independent.

No satisfactory method has yet been found of setting up bi-variant frequency surfaces from the Pearson Family of curves when the variables are dependent.[14] It can be seen from Table 4.11 that the regions of temperature and wind that significantly affect the conductor surface temperature are independent. Wind velocities in excess of 10 m.p.h. also generally result in a conductor surface temperature close to the ambient temperature. It was therefore assumed that from a practical viewpoint the two variables could be considered to be independent for the purposes of computing the probability of the simultaneous occurrence of any two wind and ambient temperature values. A contingency table for summer ambient temperature vrs wind is shown in Table 4.12.

4.6 Ambient Temperature-Solar Radiation

Contingency tables for ambient temperature-solar radiation indicated that the variables are dependent for all seasons and time zones. Correlation coefficients were calculated to determine the degree of dependency. The results obtained are shown in Table 4.15. Solar radiation versus ambient temperature results are shown in Tables 4.13 and 4.14 for summer and winter.

On a clear cloudless day, the correlation between solar radiation and ambient temperature is quite high. However, solar radiation on a given hour during a day can take on values from 0.0 to a maximum of about 70 langleys per hour depending upon the degree of cloud cover at that time. For simplicity, the Method of Least Squares was used to obtain a linear relationship between the ambient temperature and solar radiation, such that given the ambient temperature the solar radiation could be determined.

Table 4.11 Winter Ambient Temperature versus Wind Contingency Table (Time Zone 7 pm to 12 midnight)

AMBIENT TEMPERATURE ^{o}F

Sum of row χ^2	35			40			45			50			WIND VELOCITY MPH
16.9	44	26.8	11.0	43	40.9	—	23	34.0	3.5	18	25.9	2.4	0
3.4	22	16.2	2.1	24	24.6	—	20	20.4	—	11	15.6	1.3	1
6.7	30	20.6	4.3	30	31.4	—	25	26.1	—	13	19.9	2.4	2
9.6	26	17.0	4.8	28	25.9	0.2	19	21.5	0.3	8	16.4	4.3	3
9.1	18	15.3	0.5	19	23.4	0.8	26	19.4	2.2	10	4.8	5.6	4
1.2	19	17.0	0.2	22	25.9	0.6	21	21.5	—	19	16.4	0.4	5
—	16	16.4	—	25	25.0	—	20	20.7	—	17	15.8	—	6
1.9	11	12.0	—	22	18.2	0.8	11	15.2	1.1	13	11.5	—	7
3.2	8	13.2	2.0	25	20.1	1.2	16	16.7	—	14	12.8	—	8
1.9	7	10.0	0.9	16	15.4	—	12	12.8	—	13	9.8	1.0	9
35.2	27	62.7	20.0	93	95.7	—	95	79.6	2.9	88	60.7	12.3	10+
Sum of column χ^2			45.8			3.6			10.0			29.7	

sum of column χ^2

sum of row χ^2

actual frequency

theoretical frequency

cell Chi-Squared value

Table 4.12 Summer Ambient Temperature versus Wind Contingency Table
(Time Zone 1pm to 3pm)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	55			60			65			70		
0	7	3.8	2.7	1	2.2	0.6	2	3.3	0.5	6	6.6	—
1	7	6.4	—	5	3.8	0.5	7	5.6	0.3	8	11.0	0.8
2	11	10.8	—	4	6.4	0.8	8	9.6	0.2	23	18.9	0.9
3	12	17.7	1.8	13	10.5	0.6	11	15.6	1.3	39	30.8	2.2
4	21	19.8	—	13	11.8	—	16	17.5	0.2	34	34.4	—
5	15	15.1	—	7	11.3	1.6	19	16.8	0.3	40	33.2	1.4
6	11	14.1	0.7	13	8.4	2.5	12	12.5	—	24	24.6	—
7	8	7.3	—	6	4.3	0.7	4	6.4	0.9	13	12.7	—
8+	35	28.1	1.7	14	17.6	0.7	34	24.8	3.4	36	49.1	3.4

actual frequency

theoretical frequency

cell Chi-Squared value

Degrees of Freedom = 24

$$\sum \chi^2 = 30.7$$

$$\chi^2(.05) = 36.4$$

The Principle of Least Squares states that the best or most probable value of a measured quantity is the value for which the sum of the squares of the errors is least or a minimum.

$$e = \sum (S_i - a - bT_i)^2 \tag{4.10}$$

where: e - sum of the squares of the errors

S_i - actual value of solar radiation

T_i - actual temperature on the hour

a and b - polynomial coefficients of a straight line

In order to satisfy the condition of the sum of the squares of the errors being a minimum, the partial derivatives of e with respect to a and b must be zero. Differentiating e with respect to a and re-arranging the equation results in:

$$\sum S_i = na + b\sum T_i \tag{4.11}$$

Differentiating e with respect to b and re-arranging the equation results in:

$$\sum S_i T_i = a\sum T_i + b\sum (T_i^2) \tag{4.12}$$

Solving equations 4.11 and 4.12 simultaneously for a and b results in:

$$\left.\begin{aligned} a &= \frac{(\sum(T_i)^2)\ (\sum S_i) - (\sum T_i)\ (\sum T_i S_i)}{n\ (\sum(T_i)^2) - (\sum T_i)^2} \\ b &= \frac{n\sum(T_i S_i) - (\sum S_i)\ (\sum T_i)}{n(\sum(T_i)^2) - (\sum T_i)^2} \end{aligned}\right\} \tag{4.13}$$

The solar radiation can be predicted during a particular time zone given the ambient temperature and the coefficients a and b of Equation 4.13. These coefficents are listed for each time zone in Table 4.15.

Table 4.13 Summer Solar Radiation versus Ambient Temperature Bi-varient Frequency Table
(Time Zone 1pm to 3pm)

SOLAR RADIATION LANGLEYS PER HOUR	AMBIENT TEMPERATURE $^{\circ}F$																				
	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
50	0	0	0	0	1	0	0	1	0	0	0	0	0	1	3	0	0	0	0	0	0
51	0	0	0	0	1	0	0	1	0	0	2	1	3	0	0	1	0	0	0	0	0
52	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	1	0	0
53	0	0	0	0	1	0	0	0	0	1	0	0	2	1	1	0	0	0	1	0	0
54	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
55	0	1	0	0	1	0	1	0	0	0	0	0	0	0	4	1	1	1	0	0	0
56	0	1	0	0	0	0	0	0	0	1	0	0	1	0	2	0	0	1	1	0	0
57	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	1	1
58	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0	0
59	0	0	0	0	0	1	1	1	0	0	0	1	0	0	2	0	0	1	0	0	0
60	0	0	0	1	0	2	0	0	1	0	1	1	1	0	0	0	0	0	1	1	0
61	0	0	0	0	0	1	0	1	1	0	1	3	1	1	0	2	0	0	0	0	0
62	0	0	0	0	0	3	1	0	0	1	2	2	3	1	0	2	0	1	0	0	0
63	0	0	0	0	0	0	0	0	1	0	0	1	2	0	1	0	0	1	0	2	0
64	0	0	0	0	0	1	0	1	0	2	0	2	2	1	0	0	1	0	1	1	1
65	0	0	0	0	0	0	0	1	1	1	1	1	0	0	1	0	1	0	1	2	0
66	1	0	0	0	1	1	1	1	0	1	2	0	2	0	1	0	2	1	1	0	1
67	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0
68	1	0	0	0	0	0	1	0	0	1	0	1	1	0	0	1	0	0	0	0	0
69	0	0	0	0	0	0	1	0	0	0	0	0	2	1	0	0	1	0	0	1	2
70	1	0	0	0	0	0	1	2	1	0	0	2	1	1	1	1	0	0	3	0	0
71	0	0	0	0	0	0	0	0	0	1	0	0	1	2	0	1	0	1	0	0	0
72	0	1	0	0	1	0	0	1	0	0	1	1	1	0	2	0	0	0	0	0	0
73	1	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	0	1	0	0
74	0	0	0	1	0	0	0	1	1	0	2	2	3	2	0	0	2	0	0	0	0
75	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0
76	0	0	0	1	1	0	0	1	0	1	0	0	2	1	0	0	0	1	1	1	0
77	1	0	0	0	0	0	0	0	0	1	0	0	2	1	0	0	0	0	0	0	0
78	0	1	0	0	0	0	0	0	0	2	1	0	2	2	0	1	1	0	0	0	0
79	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	1	0	0	0	0	0

Regressional Line

Table 4.14 Winter Solar Radiation versus Ambient Temperature Bi-varient Frequency Table
(Time Zone 4pm to 6pm)

AMBIENT TEMPERATURE °F

SOLAR RADIATION LANGLEYS PER HOUR	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
0	2	1	2	2	3	2	2	5	5	7	6	6	11	11	11	10	9	4	3	3	0
1	0	0	4	3	1	4	2	4	5	11	7	16	11	14	18	14	17	14	10	10	6
2	0	0	0	0	0	0	3	0	0	4	4	2	5	5	5	4	4	1	1	1	0
3	1	0	0	1	0	0	1	0	0	0	2	0	2	1	3	2	3	2	2	1	1
4	0	0	0	0	0	2	0	1	0	0	1	4	0	0	0	3	1	1	2	1	1
5	0	0	0	0	0	0	1	0	0	0	1	0	0	3	1	0	0	1	0	0	1
6	0	0	0	0	0	0	0	0	0	0	1	1	1	2	1	1	1	3	1	1	0
7	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	3	0	1	0	2	0
8	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	2	2	2	3	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	1	0	0	0	1
11	0	0	0	0	0	0	0	0	0	0	0	0	2	1	1	1	3	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	2	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
15	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
28	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Regressional Line

Table 4.15 Summer and Winter Correlation Coefficients and Regressional Coefficients for Ambient Temperature and Solar Radiation

* SUMMER *

TIME ZONE	SLOPE	INTERCEPT	CORRELATION COEFFICIENT
1am to 6am	0.06001	-2.13437	0.16392
7am to 9am	1.00390	-33.95892	0.54773
10am to 12 noon	1.84642	-64.19217	0.64813
1pm to 3pm	2.08084	-82.13531	0.67920
4pm to 6pm	0.65251	-14.84256	0.40426
7pm to 12 midnight	0.13321	-6.32510	0.35067

* WINTER *

TIME ZONE	SLOPE	INTERCEPT	CORRELATION COEFFICIENT
1am to 6am	0.00724	-0.25636	0.06989
7am to 9am	0.07234	0.45143	0.08648
10am to 12 noon	0.37985	-0.88836	0.17061
1pm to 3pm	0.45457	-4.45429	0.19084
4pm to 6pm	0.16392	-3.43141	0.16492
7pm to 12 midnight	0.01123	-0.43096	0.06249

4.7 Combined Effects

The probability of the joint occurrence of two or more mutually independent events is the product of the separate event probabilities. Over a given time period if the wind and temperature are independent events, the probability of a certain wind-temperature combination is the product of the individual probabilities of occurrence. The individual probabilities can be obtained from the areas of the respective Pearson Type Curve and the level of solar radiation determined from the linear relation with the ambient temperature.

In this chapter the elements of the weather were grouped according to season and time of day. The Pearson curves that represented the classified wind and ambient temperatures were tabulated. The probable number of hours of occurrence of a certain wind-ambient temperature-solar radiation joint combination can be determined as indicated above. These weather occurrences are combined with the transmission line load current probabilities to determine the probable number of hours of occurrence of conductor surface temperatures in Chapter 6. The effects of conductor heating on the conductor strength are also discussed in the next chapter.

5 PERMANENT LOSS OF STRENGTH IN AN ACSR CONDUCTOR

5.1 General

ACSR conductors consist of strands (wires) of aluminum and strands of steel spiralled together with the steel strands placed in the center of the conductor. The aluminum strands provide the current carrying path while the steel core strands provide additional strength to support the conductor. As illustrated in Chapter 2 the conductor temperatures of overhead transmission lines are affected by the weather elements and the load current passing through the aluminum portion of the ACSR conductor. Aluminum has its crystals so arranged that overheating of the conductor will start new crystal growth which weakens the conductor. This permanent loss of strength due to overheating of the aluminum portion of the conductor is referred to as the annealing process. A detailed metallurgical description of the annealing process is beyond the scope of this thesis. The graphical approach[4] to the calculation of the results of the annealing process is illustrated. A numerical method is developed which is more applicable to the digital determination of the loss of strength under varying weather and load current conditions.

It has been found that annealing conductor temperatures below $65^{\circ}C$ produce negligible loss of strength in the aluminum portion of the conductor. Loss of strength in the steel core of the ACSR conductor generally begins with conductor temperatures in excess of $140^{\circ}C$. The amount of annealing in the aluminum portion of the ACSR conductor is dependent upon two variables:

1. conductor temperature
2. duration of heating at a given conductor temperature

Typical annealing curves are shown in Figure 5.1.

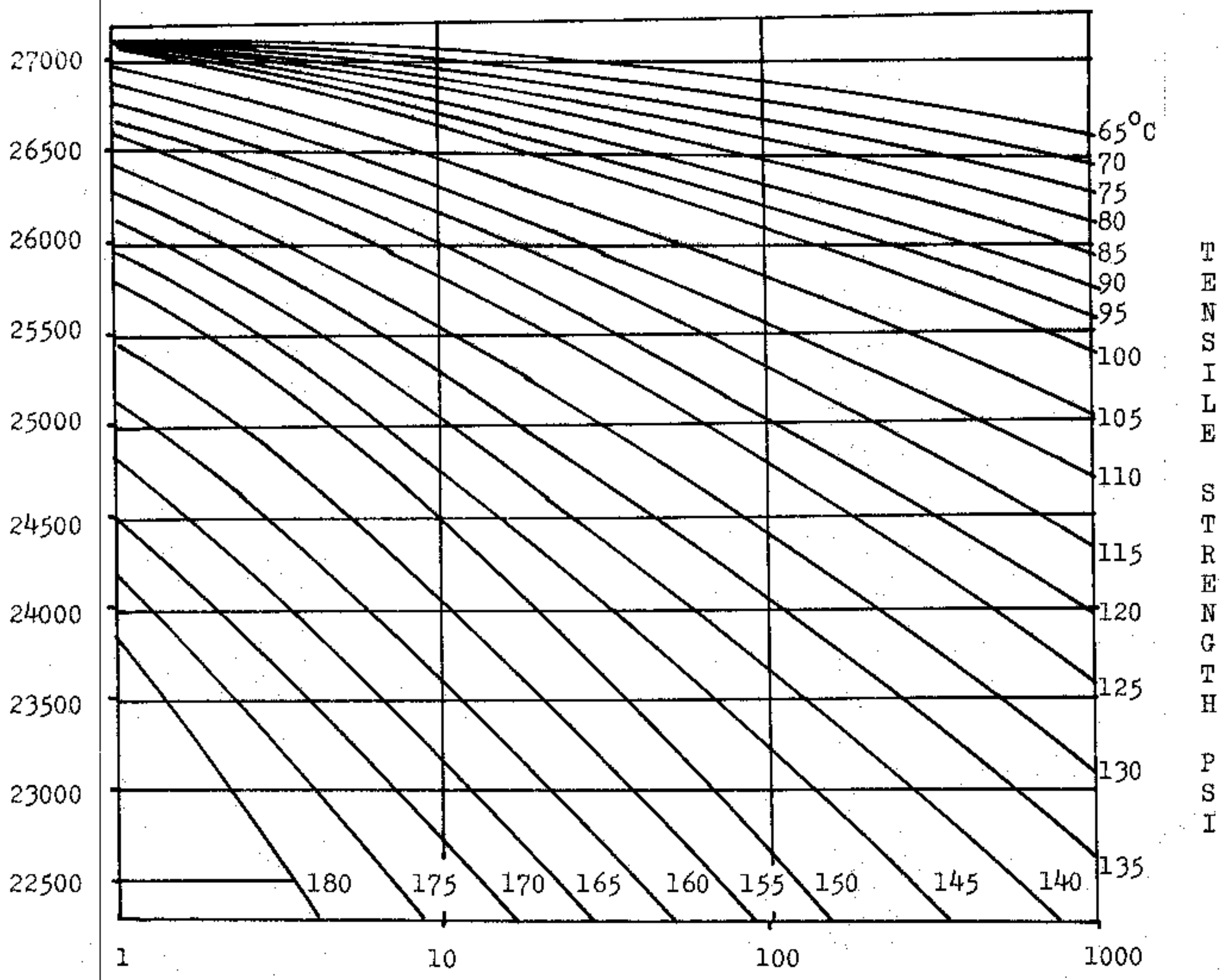

Figure 5.1 Typical Annealing Curves for Aluminum

The most important characteristic of the annealing process is that the loss of strength effect for a given time period is cumulative. For example, if a conductor is heated at 75°C for 10 hours, then at 80°C for 2 hours and again at 75°C for 2 hours, then 6 hours at 80°C or heated for 12 hours at 75°C and then 8 hours at 80°C, the total loss of strength due to annealing is approximately the same in both cases at the end of the 20 hours.

5.2 Calculation of the Maximum Allowable Loss of Strength in the Aluminum portion of a given ACSR conductor size

In Canada, the strengths of ACSR conductors are calculated according to CSA Standard C49-1965, " Aluminum Stranded Conductors and Aluminum Conductors Steel Reinforced." It is stated that:" The rated ultimate strength of a complete aluminum conductor steel reinforced shall be taken as the strength of the aluminum portion plus the stress developed in the steel portion at an elongation corresponding to the ultimate elongation of the aluminum wires." The rated ultimate strength of a complete aluminum stranded conductor is calculated from the nominal area of the conductor and the appropriate minimum tensile strength for the nominal wire (strand). Tables indicating the ultimate tensile strengths for various aluminum and wire diameters are shown in the Appendix.

The total loss of strength due to annealing in the composite conductor (steel plus aluminum) is generally set at 10 percent.[4,12] The number of aluminum and steel strands forming the given ACSR conductor must be known. The ultimate strengths of the individual wires (strands) of the aluminum and steel are calculated and summed to give the total original conductor strength. The ultimate strength of the aluminum strands are reduced by a certain percentage (ie. 15 percent) attributed to the annealing process that is assumed to occur during the conductor's lifetime. The composite conductor strength of the assumed annealed conductor is recalculated and the percent loss of total conductor strength compared with the original conductor strength. The percent loss of strength in the aluminum portion of the conductor is adjusted until the overall ultimate strength of the annealed conductor is 10 percent less than the original conductor's ultimate tensile strength. The percent loss of strength in the aluminum portion of the conductor varies from 12 to 20 percent depending upon the number of steel and aluminum strands in the

ACSR conductor.

5.2.1 An example of calculating the Maximum Loss of Strength in the aluminum portion of an 1/0 ACSR conductor

The 1/0 ACSR conductor consists of:

1. 6 aluminum strands each with a diameter of 0.1327 inches

2. 1 steel strand of diameter 0.1327 inches

From the CSA Standard C49-1965, the ultimate tensile strength in pounds per square inch of an aluminum strand is 25,000. The stress in the steel at an elongation corresponding to the ultimate elongation of the aluminum wires (1 percent elongation in a 10 inch gauge length) is 160,000 psi.

The ultimate tensile strength contribution of an individual aluminum strand is the product of the area of the strand times the ultimate tensile strength:

$$(3.14/4.0) \times (0.1327)^2 \times 25000.0 = 345.3 \text{ lbs. per strand}$$

Six aluminum strands contibute 2072 pounds to the ultimate conductor tensile strength.

The ultimate tensile strength contribution of the steel strand is:

$$(3.14/4.0) \times (0.1327)^2 \times 160000.0 = 2208 \text{ pounds}$$

The total original conductor ultimate tensile strength is then the sum of the contribution of steel and aluminum ultimate tensile strengths which is 4280 pounds.

If the aluminum loses 20 percent of its strength due to annealing, then the total conductor strength is calculated as follows:

6 aluminum strands = 0.80 x 2072 = 1658 lbs.

1 steel strand = 2208 lbs.

Total conductor strength after assumed annealing 3886 lbs.

The total conductor strength on the basis of a 20 percent loss in strength in the aluminum is approximately 90 percent of the original conductor ultimate tensile strength. The maximum allowable loss of strength in the aluminum portion of the 1/0 ACSR conductor is then set at 20 percent.

5.3 Calculation of the Permanent Loss of Strength due to Annealing by Graphical Methods

The conductor temperatures are calculated initially as a function of the assumed transmission line currents and the elements of the local weather; wind, ambient temperature and solar radiation as outlined in Chapter 2. The conductor temperatures are grouped in 5°C intervals and the frequency of occurrence of each conductor temperature calculated. An example[4] of such a conductor temperature histogram is shown in Table 5.1.

Table 5.1 795 MCM (47/7) ACSR Conductor Accumulated Hours at Annealing Temperatures for 1060 Amperes, Normal Operation

CONDUCTOR TEMPERATURE °C	EXPECTED HOURS IN 30 YEARS
130	1
125	4
120	4
115	4
110	11
105	13
100	21
95	42
90	60
85	59
80	117
75	99
70	76
65	42

* Hours below 65°C cause only negligible annealing

The total loss of tensile strength due to the annealing temperatures (Table 5.1) are calculated graphically as shown in Figure 5.2 The duration of exposure of the 65°C conductor temperature is first plotted on the 65°C annealing curve. The equivalent heating time of the 65°C loading on the 70°C annealing curve is determined by projecting a horizontal line from the operating point on the 65°C curve until it intersects the 70°C curve. The duration of conductor exposure at 70°C is then added to this equivalent time. This process is continued until all the conductor temperatures in Table 5.1 have been completed and the final conductor tensile strength determined. The difference between the original tensile strength of 27100 psi and the final tensile strength of 25600 psi was determined and the percent loss of strength found to be 5.7 percent.

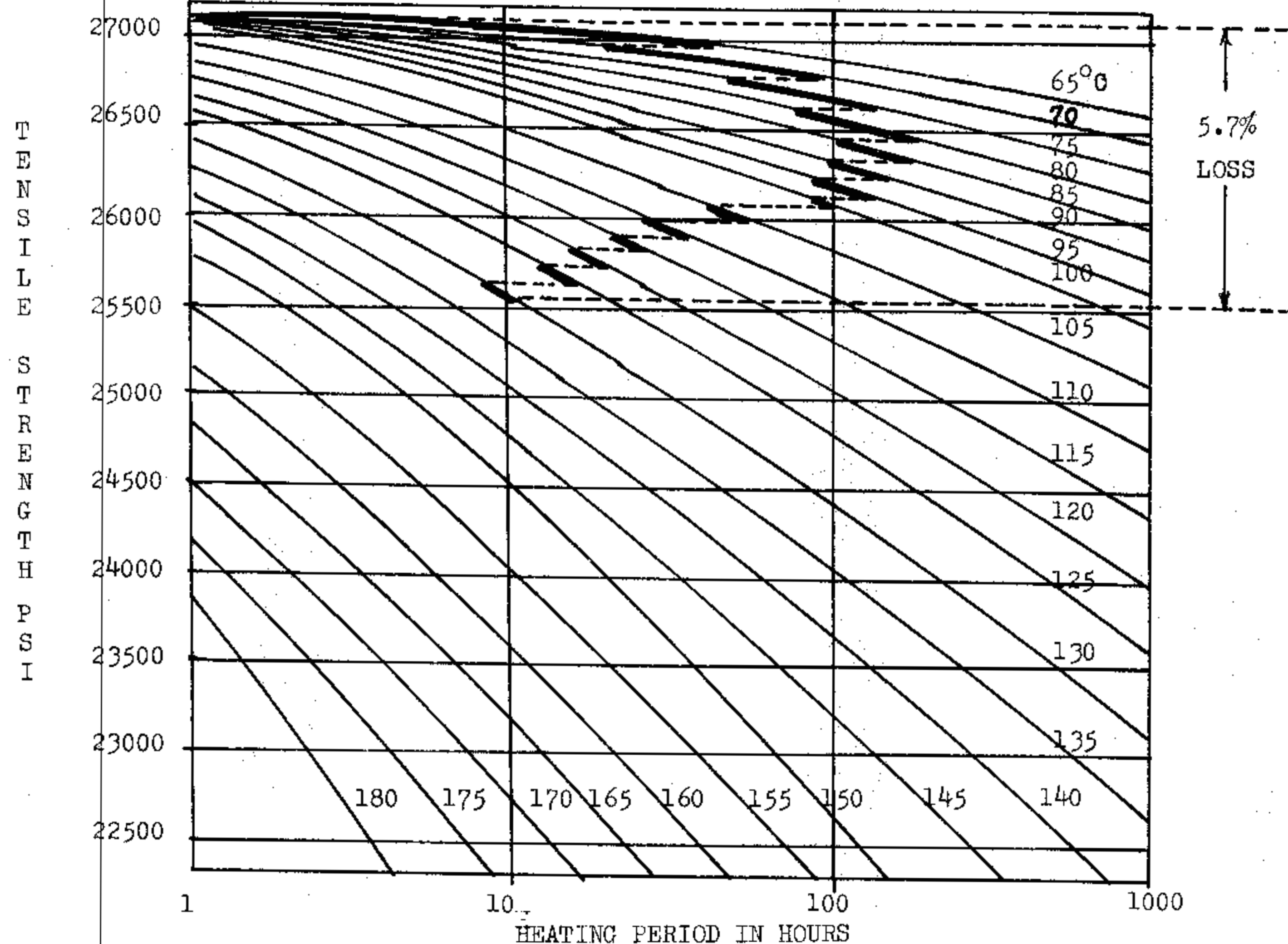

Figure 5.2 Graphical Method of calculating the Permanent Loss of Strength due to Annealing

The difficulty with the graphical method is that considerable time and care must be spent in plotting the results of conductor temperature frequencies solved by the digital computer even for a single load current distribution. This is particularly a disadvantage in establishing the ampacity of a conductor based on many load current distributions that must be studied in order to establish the maximum ampacity for a given conductor size.

5.4 Digital Method

The loss of conductor strength due to annealing was calculated by the digital computer using the annealing family of curves expressed mathematically. For a given conductor temperature in degrees centigrade (t_1) and the duration of loading at the given conductor temperature "$TIME(t_1)$" in hours, the loss of strength $S(t_1)$ in the aluminum portion of the conductor as shown in Figure 5.1 can be approximated by the following polynomial:

$$S(t_1) = A0(t_1) + A1(t_1)\cdot\log(TIME(t_1)) + A2(t_1)\cdot(\log(TIME(t_1)))^2 \quad (5.1)$$

Given the time loading at a specified conductor temperature t_1, the loss of strength $S(t_1)$ can be calculated. The equivalent time loading at another conductor temperature t_2 is given by:

$$TIME_{eq}(t_2) = 10^{\left[-\frac{1}{2}\frac{A1(t_2)}{A2(t_2)} \pm \sqrt{\frac{S(t_1) - A0(t_2)}{A2(t_2)} + \frac{1}{4}\left\{\frac{A1(t_2)}{A2(t_2)}\right\}^2}\right]} \quad (5.2)$$

To evaluate the total loss of strength due to annealing, the duration of all conductor temperatures must be known over the assumed lifetime of the conductor. The loss of strength is first calculated due to the loading time at 65°C. The equivalent time of the 65°C loading is then expressed in terms of the 70°C loss of strength curve using equation 5.2. The loading time at 70°C is added to this equivalent time and the total loss of strength due to 65°C and 70°C loading is calculated. This procedure is continued until the final loss of strength value is determined. The difference between this value and the original strength is expressed in terms of a percent loss of the original strength. The total loss of strength in the aluminum portion of the 795 MCM ACSR conductor subjected to the annealing temperatures shown in Table 5.1 was calculated digitally and found to be 5.6 percent as compared with 5.7 percent graphically. The coefficients of the approximating logarithmic polynomials for the annealing curves are shown in Table 5.2.

Table 5.2 Annealing logarithmic polynomial coefficients for different conductor temperatures

CONDUCTOR TEMPERATURE	ANNEALING LOGARITHMIC POLYNOMIAL COEFFICIENTS		
°C	A0 x 10^{-3}	A1 x 10^{-3}	A2 x 10^{-3}
65	27.10721	-0.00176	-0.05627
70	27.10912	-0.06428	-0.05347
75	27.10866	-0.08994	-0.06703
80	27.09802	-0.13453	-0.06876
85	27.09964	-0.21688	-0.05557
90	27.09775	-0.29301	-0.04859
95	27.07974	-0.35204	-0.03992
100	27.07935	-0.42492	-0.03496
105	26.98817	-0.61601	-0.03061
110	26.84888	-0.52086	-0.04588
115	26.78171	-0.54121	-0.80631
120	26.70703	-0.68418	-0.06483
125	26.62898	-0.79134	-0.06364
130	26.45332	-0.89277	-0.05645
135	26.32222	-1.00840	-0.06038
140	26.17218	-1.12496	-1.12496
145	26.01894	-1.17585	-0.09088
150	25.85678	-1.22139	-0.17434
155	25.48030	-1.30557	-0.16372
160	25.17284	-1.56819	-0.05620
165	24.86942	-1.79502	-0.02694
170	24.49788	-1.74174	0.0
175	24.09790	-1.93583	0.0
180	23.85080	-2.53248	0.0

The rate of loss of strength with respect to duration of loading at a given conductor temperature is quite high for the first forty hours, then decreases rapidly with increased time loadings. This is shown in Figure 5.3 and indicates that increased temperature loading beyond forty hours at a specified conductor temperature will result in a negligible increase in loss of conductor strength.

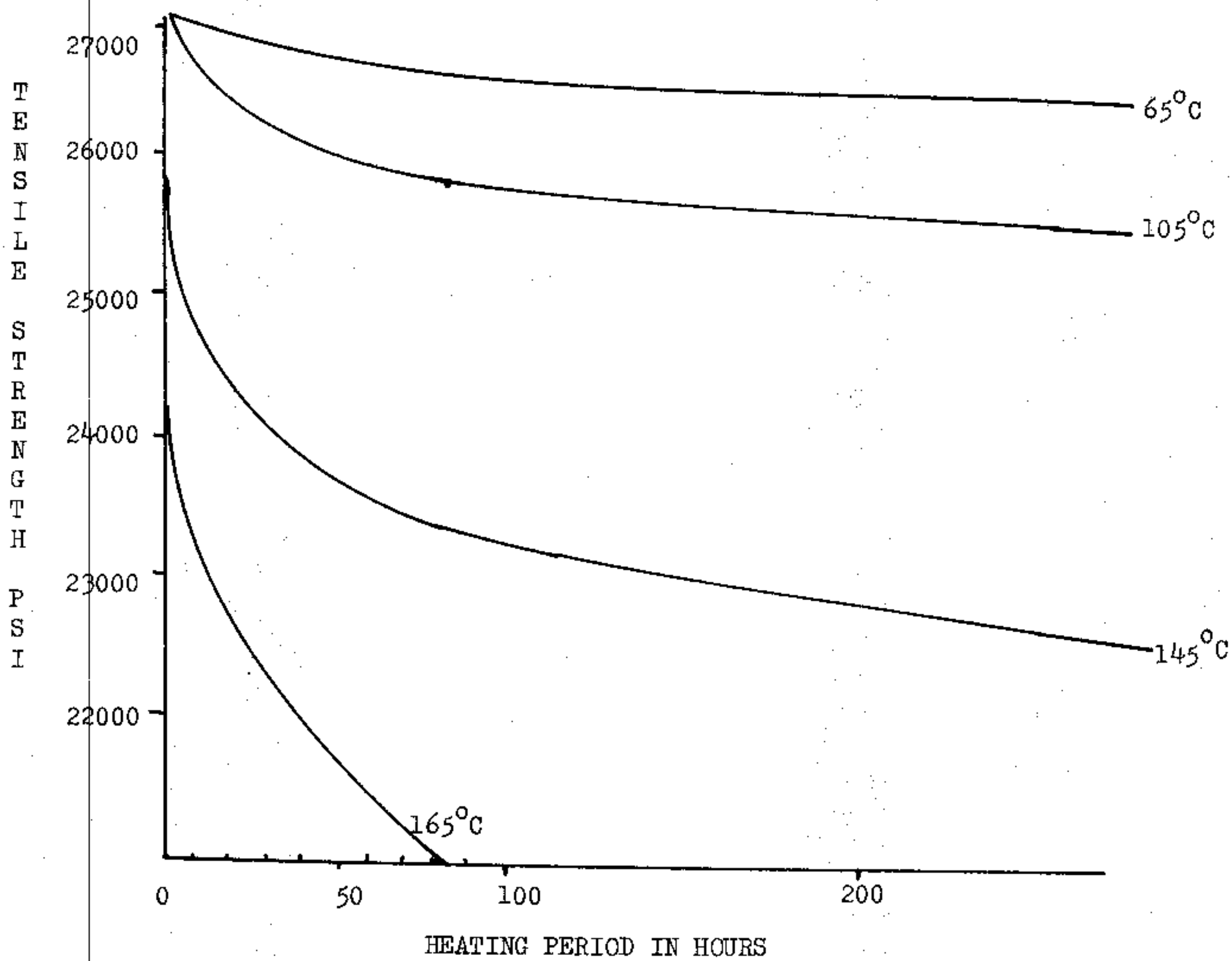

Figure 5.3 Annealing Curves for Aluminum - rectilinear scale

The digital method of calculating the annealing losses as outlined in this chapter was used in the theoretical and actual conductor temperature studies. The results and application of these studies are presented in the next chapter.

6 APPLICATION AND RESULTS

6.1 General

In a multiple study, the conductor currents are allowed to vary in any predetermined manner during the assumed lifetime of the conductor. The weather data in either actual or statistical form for the one year is assumed to be representative of each year during the study. The conductor temperature frequencies are determined in order to evaluate the total loss of strength of the conductor due to annealing and to establish the maximum operating temperature of the transmission line.

6.2 Actual Conductor Temperature Approach

The actual conductor temperature approach refers to the sequential use of actual hourly weather and load current data in determining the hourly conductor temperatures. These temperatures were obtained for the one year data set using the heat equation outlined in Chapter 2. The mean summer conductor temperature was found to be 26.9°C (79°F) and the winter mean to be 17°C (62°F). The variation in conductor temperatures for a typical day due to fluctuations in the weather and in the load current is shown in Figure 6.1. The hourly variations in conductor temperatures over several days during summer and winter are shown in Tables 6.1 and 6.2.

The conductor temperature frequencies were re-grouped using a 5°C interval in order to compare these frequencies with the theoretical frequencies obtained from the Pearson Family of Curves and to determine the total loss of strength in the aluminum portion of the ACSR conductor at the end of the assumed lifetime. In evaluating annealing losses, the conductor temperature is assumed to remain constant for one half

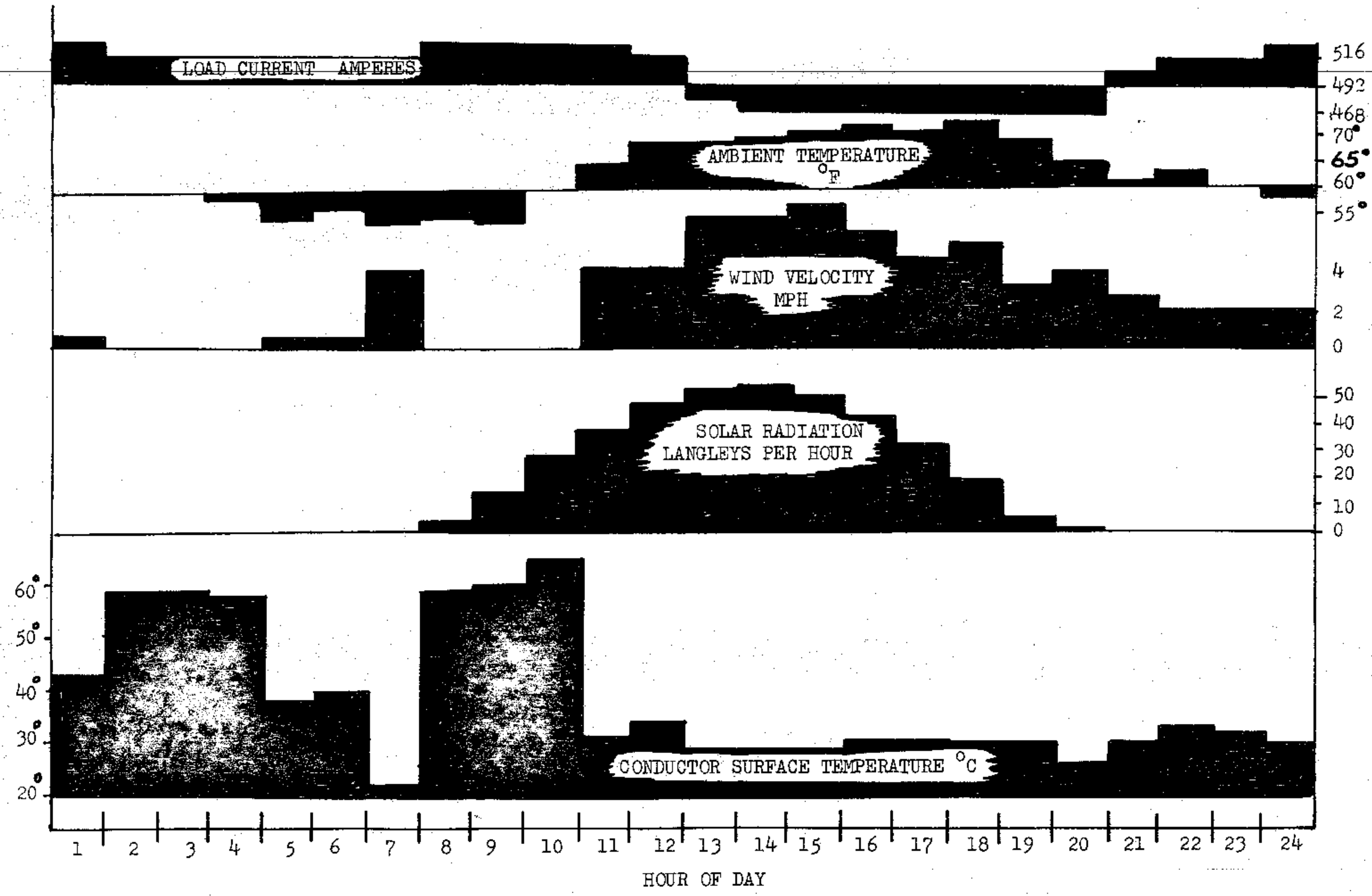

Figure 6.1 Hourly Variations in Conductor Temperature due to Variations in Weather and Load Current

Table 6.1 Summer Hourly Conductor Temperature Variations

DAY NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	HOUR OF DAY																							
235	36	30	34	26	25	25	23	24	25	26	28	27	29	31	33	30	31	29	30	30	30	29	23	21
236	22	25	32	32	38	28	24	25	31	46	34	27	26	21	29	30	30	28	25	26	26	30	29	32
237	39	33	55	55	37	37	41	27	26	26	27	27	27	29	29	29	28	27	25	26	27	26	26	41
238	60	56	32	31	39	60	63	68	40	39	35	34	36	38	39	36	37	39	60	58	36	29	31	32
239	30	57	57	56	28	30	32	36	32	35	36	35	35	39	40	40	37	38	63	62	30	42	36	39
240	60	59	58	58	58	60	70	35	40	36	35	35	35	36	36	38	38	41	37	32	33	45	46	44
241	22	43	58	41	34	60	32	33	36	36	41	41	41	41	39	47	39	41	61	28	29	27	24	25
242	23	25	24	23	23	26	26	29	32	37	36	30	35	35	35	35	36	42	30	26	25	24	23	24
243	24	23	23	24	24	26	34	31	31	35	34	34	31	32	31	30	29	29	29	28	26	25	30	25
244	24	25	23	23	23	23	24	24	24	25	25	26	25	27	30	28	26	26	29	30	26	25	26	16
245	27	28	27	29	24	23	25	25	26	29	31	33	35	37	30	30	30	31	33	29	25	25	24	23
246	22	20	21	22	21	20	18	16	18	20	21	23	23	23	24	24	22	21	19	19	17	16	14	18
247	29	17	16	17	14	15	15	14	19	25	29	30	32	41	32	27	26	21	22	21	20	22	23	22
248	18	14	14	14	14	14	14	14	16	28	27	33	32	30	30	29	31	27	25	29	30	27	21	15
249	18	20	21	23	19	17	21	28	29	36	37	38	35	30	31	29	28	28	25	24	32	53	51	42
250	29	39	22	27	26	26	25	30	46	36	32	32	29	30	31	30	32	30	34	33	34	52	47	29
251	15	28	12	15	15	19	21	22	24	27	30	33	32	32	34	41	45	62	38	38	28	43	29	31
252	37	26	30	27	23	30	27	25	26	23	22	24	27	27	27	26	27	26	27	26	28	40	40	36
253	28	20	20	30	49	50	36	25	33	28	25	24	28	30	27	28	43	27	26	26	22	21	32	32
254	34	23	27	27	25	31	32	38	45	28	28	25	25	25	25	24	23	23	21	21	22	24	20	17
255	18	17	17	16	21	25	35	44	61	38	32	30	27	26	28	29	31	29	41	32	26	31	46	22
256	23	42	39	21	40	44	23	29	33	39	29	30	29	32	31	30	27	25	35	59	34	39	57	41
257	25	53	53	50	31	19	26	27	35	64	37	33	30	30	30	28	27	47	80	61	57	57	56	56
258	56	56	30	31	29	31	31	44	40	43	31	33	34	34	33	31	29	31	38	62	61	37	35	43
259	59	59	58	38	40	22	59	60	65	31	34	29	29	29	31	31	30	30	26	30	32	33	30	23

<u>NOTE</u>: Conductor Surface Temperatures are in Degrees Centigrade

Table 6.2 Winter Hourly Conductor Temperature Variations

	HOUR OF DAY																							
DAY NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
73	5	4	2	3	4	3	5	7	8	9	10	12	8	8	11	11	14	12	12	9	9	8	8	6
74	6	6	7	7	7	8	9	10	11	11	7	11	7	6	11	13	12	12	11	11	10	10	10	9
75	9	8	7	7	8	9	10	8	14	16	14	17	14	12	11	11	8	20	46	12	11	10	9	9
76	7	6	6	6	7	7	8	9	10	11	10	12	7	11	14	7	13	13	18	21	16	13	9	9
77	9	7	6	6	6	7	6	8	13	15	14	14	15	13	12	11	7	7	6	19	21	11	7	6
78	4	4	5	5	5	4	5	6	9	10	10	10	10	10	9	10	11	11	12	9	9	10	9	7
79	8	8	7	6	5	6	9	9	4	11	13	14	15	15	16	9	14	19	15	14	13	11	9	10
80	8	7	7	7	8	8	9	11	11	6	13	13	13	7	12	13	14	14	14	11	12	11	10	9
81	8	8	8	8	8	8	8	9	10	11	11	12	10	10	11	12	14	15	14	15	15	10	9	11
82	10	10	10	10	9	10	11	11	12	8	11	12	11	12	11	10	11	11	10	10	10	9	9	7
83	7	6	6	7	6	6	6	7	8	9	9	9	10	10	11	7	15	13	4	39	9	9	6	6
84	5	3	4	4	5	4	4	6	9	10	10	11	10	10	9	9	9	9	9	8	7	6	6	8
85	7	7	6	5	5	5	6	6	8	9	9	11	13	12	9	10	8	10	21	19	17	16	11	11
86	3	5	4	3	4	3	3	3	4	7	8	8	9	9	8	7	7	6	5	4	4	4	5	4
87	4	4	4	4	5	4	4	5	4	7	7	7	7	7	7	5	10	11	16	15	7	7	4	10
88	4	5	2	4	4	2	5	2	11	10	11	11	11	13	12	7	15	14	26	14	10	8	6	6
89	5	5	4	3	3	3	7	9	17	13	12	11	10	10	10	10	10	9	10	11	13	19	13	23
90	20	15	6	15	15	14	24	34	37	16	18	16	13	13	13	12	14	18	16	17	13	10	16	15

<u>NOTE</u>: Conductor Surface Temperatures are in Degrees Centigrade

hour on either side of the hourly readings. The frequency of the given conductor temperature then represents the duration of exposure at that temperature in hours. The total loss of strength in the aluminum portion of the conductor in 30 years due to annealing was found to be 2.2 percent of its initial strength. The maximum conductor temperature was found to be 80°C.

Examination of the conductor temperatures grouped according to season and time zone indicated that summer early morning (1am to 6am) and evening (6pm to 12 midnight) are critical time periods for annealing if day time load current levels are applied to these time zones. These zones are critical because of the higher probabilities of low wind velocities in these zones as compared with the other time zones.

6.3 Theoretical Conductor Temperature Approach

The theoretical conductor temperature approach refers to the use of the statistical weather model and the actual load current data in solving the conductor temperatures. Histograms of winter and summer load currents are shown in Figures 6.2 and 6.3. The ambient temperature probabilities were grouped in intervals of 5°F and wind velocities in intervals of 1 m.p.h.. The load current frequencies were grouped in intervals of 12 amperes. A minimum load current value of 264 amperes was selected for the given conductor size. Currents below this value will not produce conductor temperatures above 65°C (the annealing limit) even under severe weather conditions (100°F ambient temperature, 0.0 m.p.h. wind velocity and maximum solar radiation).

An initial computer program was used to calculate the conductor temperatures and the results were stored on magnetic tape.

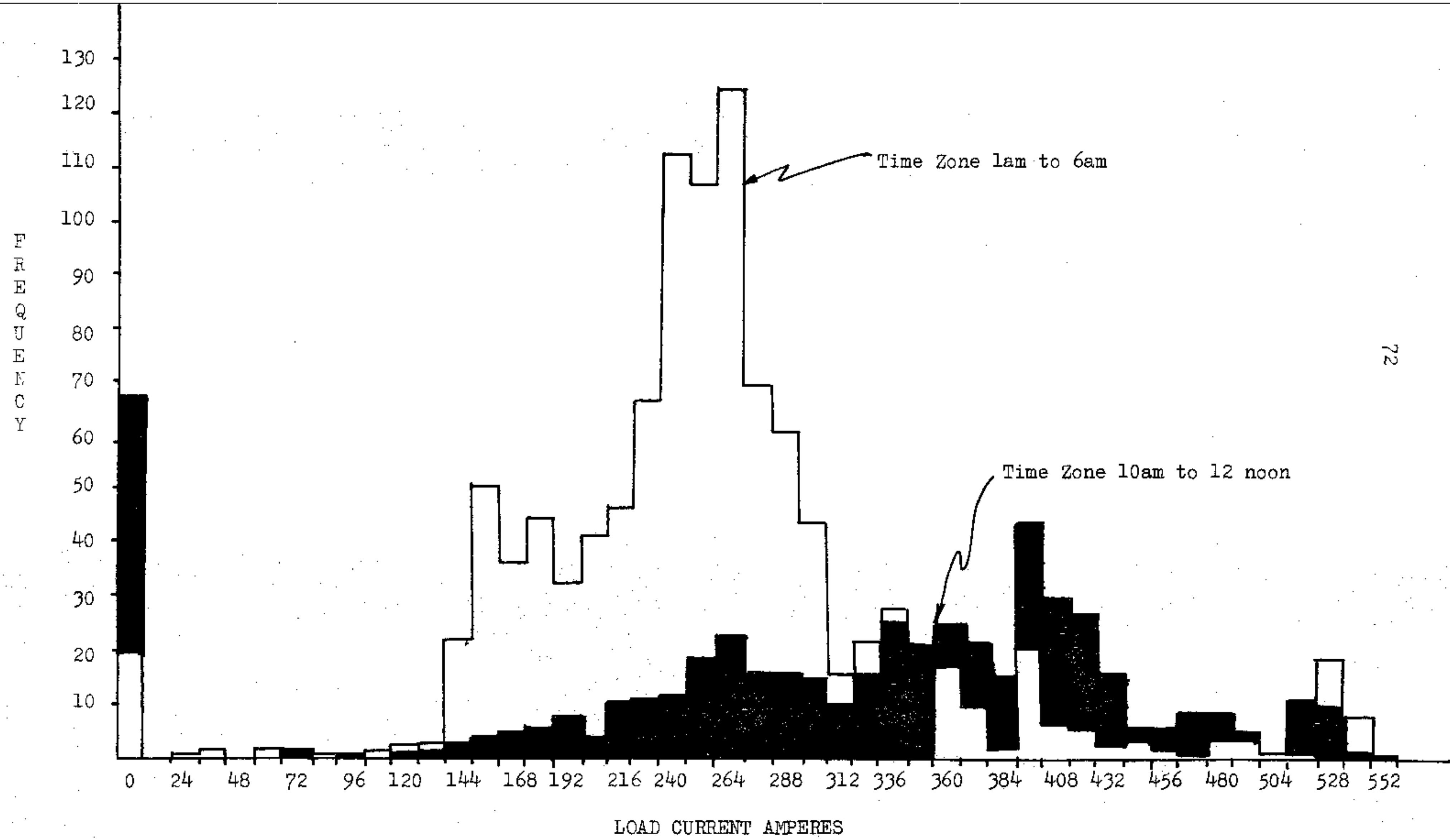

Figure 6.2 Winter Load Current Histograms

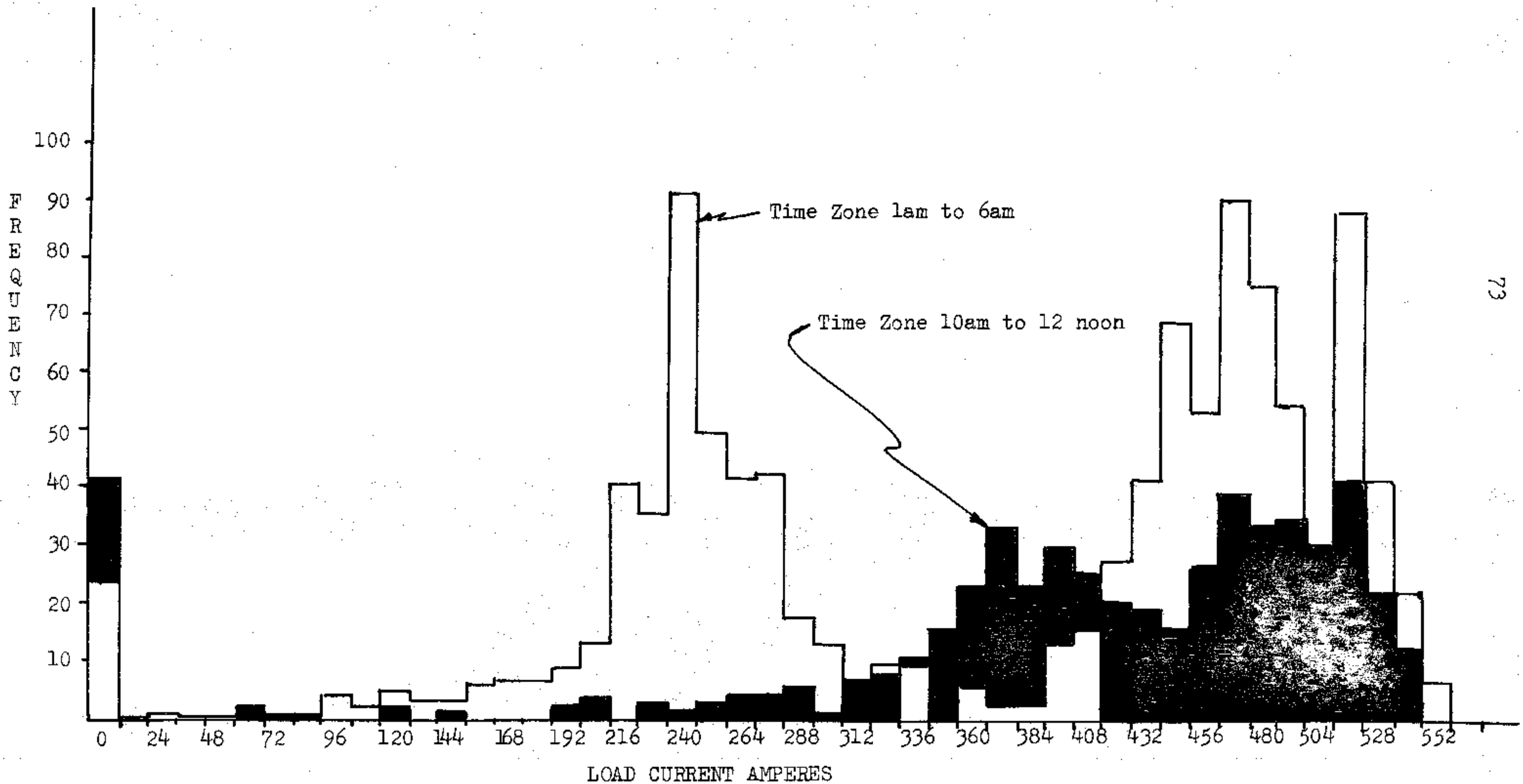

Figure 6.3 Summer Load Current Histograms

This data tape for the given conductor size and properties contains the iterative solutions of the conductor temperatures within each time zone for all possible combinations of ambient temperature, wind velocity (below 10 m.p.h.) and load currents (above 264 amperes). Within each time zone, the appropriate value of solar radiation was determined from its assumed linear relationship with ambient temperature. No conductor temperature iterations are performed within the main computer program. The conductor temperatures are read in from this data tape and stored as a four dimensional matrix within the main program. Each element of the matrix represents a conductor temperature which is keyed to a definite time zone, ambient temperature, wind velocity and load current value.

Load currents were assumed to be independent of the weather over any given time zone. The actual load current frequencies for each class are read in and converted into probabilities within the main program. Ambient temperature and wind velocity probabilities together with study cards are also read in by the main program. The joint probabilities of all weather and load current combinations are then calculated and keyed to a specific conductor temperature for each combination. The expected number of hours of operation (joint probability times the total number of hours within the time zone) of these conductor temperatures are calculated and grouped for the annealing study.

The total loss in strength in the aluminum portion of the 477 MCM ACSR conductor over a period of 30 years with the actual load current distributions was found to be 2.78 percent and the maximum conductor temperature to be 85°C.

Conductor temperature frequencies calculated by use of actual weather data were compared with the frequencies calculated by the statistical weather model. There was no significant difference between the conductor temperature frequencies produced by the two methods in all the winter time zones and all summer daytime time zones. The actual weather conductor temperature frequencies were higher than the theoretical weather frequencies during the early morning(1am to 6am) and late evening (6pm to 12 midnight) summer time zones. The maximum conductor temperature of the actual weather study in these two time zones was 80°C while the theoretical weather model maximum was 85°C. The total loss of strength due to annealing as calculated from the theoretical weather model was greater than the loss of strength calculated using the actual weather data. This difference in loss of conductor strength in the theoretical study is a result of operating for a short period of time (ie. 8 hours in 30 years in these two time zones) at the higher conductor temperature of 85°C with the resulting higher loss of conductor strength rate.

In order to illustrate the effect of transmission load level on the loss of conductor strength,all the load current variables with their associated frequencies were shifted upwards by a constant factor. This was done for all the time zone distributions. This factor was determined by taking a fixed percentage of the mean for each load current distribution and adding this amount to each variable in the distribution. The shape of the adjusted load current distributions remain the same as the original distributions. The shifted load current distributions were assumed to remain constant over the lifetime of the annealing study. The conductor temperature frequencies and the total loss of strength due to annealing were determined for various percentage adjustments in the mean values of the load current distributions. Loss of strength and conductor temperature frequency results are shown in Figures 6.4 and 6.5.

The load current was then assumed to be constant at several different load levels expressed as a percentage of the traditional ampacity and the demand factor. The demand factor is defined as the percent of the time in a given period for which the current remained constant at the given level. The current is assumed to be zero for the remainder of the period. The conductor temperature frequencies, the total loss of strength due to annealing, and the maximum temperatures determined for different demand factors are shown in Figure 6.6.

This chapter has illustrated the application of the Theoretical Conductor Temperature Approach to determine the loss of strength due to annealing for various load current patterns. The theoretical conductor temperatures were based on:

1. Solution of the conductor temperatures by the iterative procedures outlined in Chapter 2.

2. Representation of the weather elements by the Pearson Family of Curves as outlined in Chapters 3 and 4.

3. Solution of the loss of conductor strength by the digital method outlined in Chapter 5.

The Actual Conductor Temperature Approach has also been illustrated and the results obtained compared with those of the theoretical approach.

NOTE:

1. Each curve represents the percentage of the mean the actual load current distributions have been shifted upward.
2. The load current distributions are assumed to remain constant over the lifetime of the transmission line.

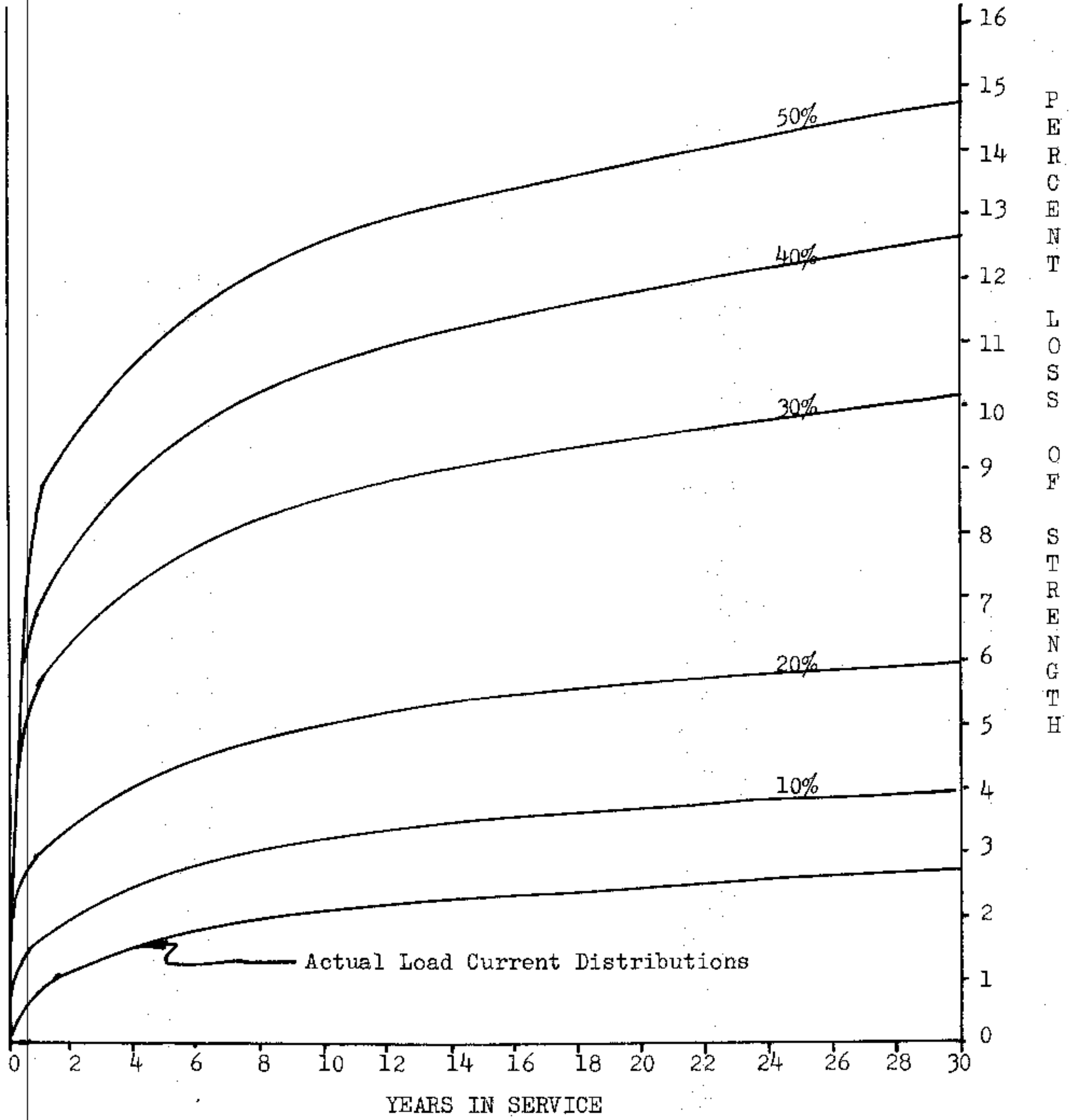

Figure 6.4 Percent Loss of Strength versus Years in Service (Distributed Load)

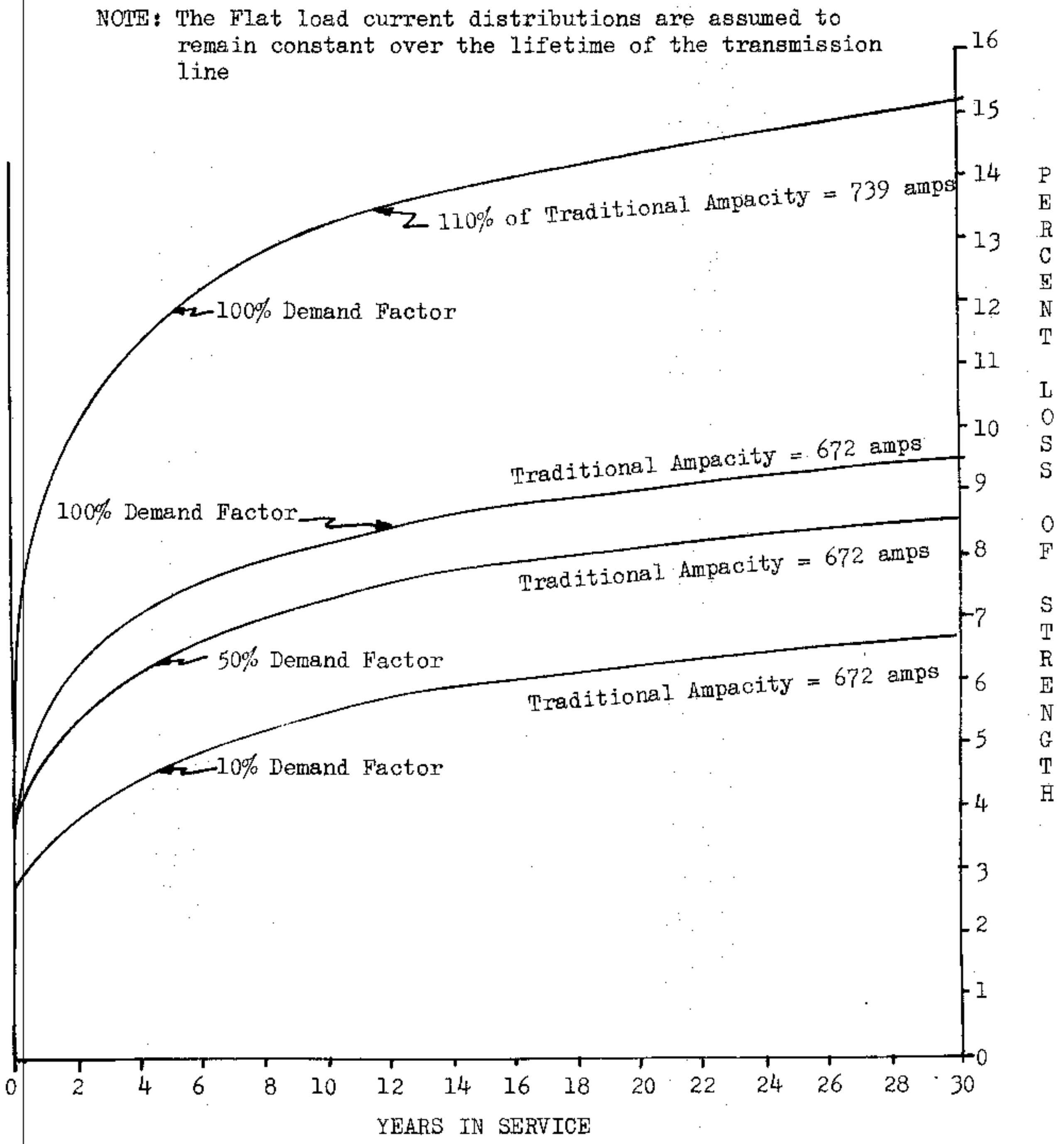

Figure 6.5 Percent Loss of Strength versus Years in Service

(Flat Load)

PERCENT SHIFT	PERCENT OF TIME CONDUCTOR TEMPERATURE IN ANNEALING RANGE	MAXIMUM CONDUCTOR TEMPERATURE
0	0.6	85°C
10	1.7	90°C
20	3.8	105°C
30	7.6	125°C
40	10.6	135°C
50	12.6	145°C

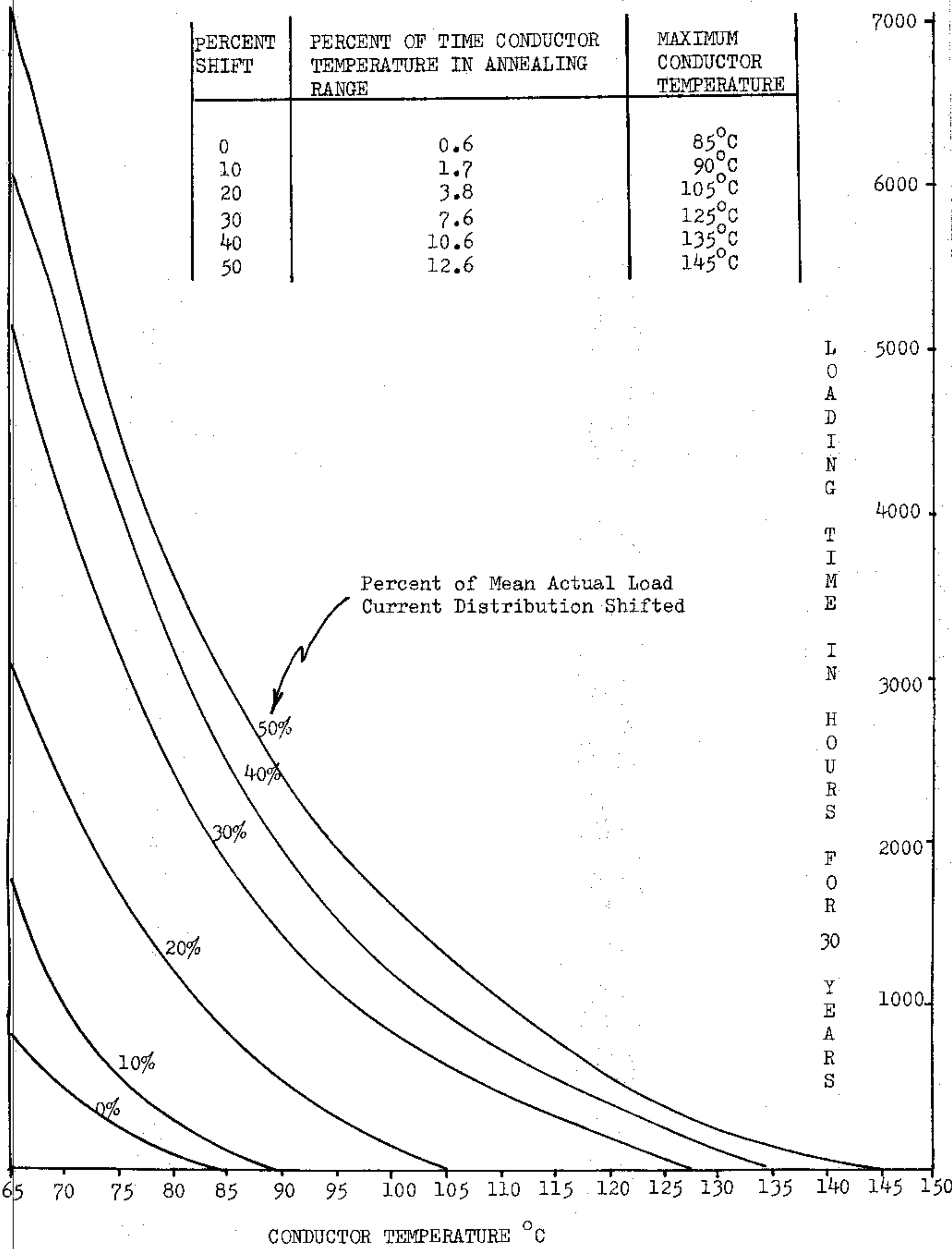

Figure 6.6 Conductor Temperature versus Loading Time

The Actual Conductor Temperature Approach which sequentially processes the hourly weather and load current data is based on:

1. Solution of the conductor temperatures as outlined in Chapter 2

2. Determination of the loss of conductor strength by the digital method as outlined in Chapter 5.

The results obtained by the theoretical approach involving statistical models of the weather data are very close to those obtained using the actual chronological data. The use of a valid and comprehensive weather model provides a consistent approach to the prediction of future annealing conditions

7 CONCLUSION

In the initial attempts to obtain a statistical weather model, the main weather variables of ambient temperature and wind velocity were grouped over the entire year, then according to the four seasons and finally in terms of the individual months and combinations of these months. In each case, tests of independence between ambient temperature and wind velocity resulted in the two variables being dependent. No statistical joint probability distribution functions have been developed for two variables that are dependent, differently skewed and non-normal. Grouping the weather variables according to season and time zone resulted in ambient temperatures and wind velocities being independent variables. This simplified the calculation of the probability of the joint occurrence of the two variables to simply the product of their individual probabilities. It also reduced the required computer storage space considerable as only the individual probabilities of the two variables are stored and not all the actual combinations of them.

It was found that the solution of the conductor surface temperature equations by the Newton-Raphson and Reguli-Falsi methods produced results that agreed with those published in several I.E.E.E. papers.[1,4,12] In some papers,[4,12] the wind velocity data is expressed in fractions of miles per hour or in feet per second and the assumption made that the probability of zero wind is negligible. In this thesis, the wind velocity data was measured in miles per hour. The empirical formula developed by the Aluminum Company of America[1] was used for the zero miles per hour wind velocity to calculate the conductor surface temperature. This results in temperatures approximately 10 percent higher than some published results in this region. In the remaining wind velocity regions there is no significant difference between the conductor temperatures obtained by these methods.

It was found the the Pearson Family of Curves provided a reasonable fit for the ambient temperature and wind velocity frequencies. The curves failed to graduate the actual load current frequencies as the frequency distributions were found to be multimodal and discontinuous in many cases. In order to graduate a multimodal distribution with a Pearson type curve, the distribution must be subdivided into a series of unimodal distributions. The main advantage of the Pearson Family of Curves in fitting unimodal distributions is that the constants generated by the Method of Moments will identify the appropriate Pearson distribution that will best represent the actual data. This procedure can be performed entirely on the digital computer.

It was found that a second order logarithmic polynomial can be used to represent the annealing curves. The total loss of strength in the aluminum portion of the conductor due to annealing by combining the conductor temperature frequencies given in Reference 4 with the polynomial approximations was found to be 5.6 percent as compared with the graphical results in Reference 4 of 5.7 percent.

The ampacity of a transmission conductor normally establishes the maximum allowable load current that can be tolerated on the transmission line. To determine the ampacity of an existing or a proposed transmission line it is necessary to first set the maximum allowable conductor temperature considering line hardware thermal limits and the resulting sags at this maximum temperature. The maximum allowable loss of strength due to annealing is then set for the specified conductor. The total amount of annealing over the assumed lifetime of the conductor with existing or proposed load current distributions is calculated to check if the maximum temperature or the total loss of strength due to annealing limits have been exceeded. The load current distributions are adjusted until both limits have been satisfied. Having established the ampacity of the transmission line, reliability, stability, voltage and economic limits must be studied. If any of these additional limits are exceeded, then the load current distributions are lowered to comply with the governing restrictions.

Assuming that the actual load current distributions are valid for the life of the conductor, the total loss of strength in the aluminum portion of the conductor examined in this thesis was found to be 2.78 percent and the maximum conductor temperature to be 85°C. This loss of strength is well below the maximum allowable of 15 percent.[7] Assuming that the transmission line hardware will not fail at a conductor temperature of 125°C and no abnormal sags will result from operation at this maximum temperature, the present load current distributions may be increased by 30 percent of their mean values. The maximum allowable load current during any time zone or any season is then equal to the original peak value plus 30 percent of the load current distribution mean for that period.

If the load current is equal to the traditional ampacity and is assumed to remain constant for every hour during the lifetime of the conductor (30 years), the total loss of aluminum strength due to annealing was found to be 9.8 percent with a maximum conductor temperature of 125°C. If the load current level is increased by 10 percent, the total loss of strength will just exceed the allowable value of 15 percent and the maximum conductor temperature will be 150°C. Assuming that no other restricting limits have been exceeded, a flat load equal to the traditional ampacity with a 100 percent demand factor may be applied to the 477 MCM ACSR conductor considered. If the demand factor is reduced, the load current level may be increased by one or two percent provided that the new maximum conductor temperature does not cause abnormal sags on the existing line or the failure of line hardware.

For the actual load current distributions studied, it was found that the conductor temperatures were in the annealing range of 65°C or greater for only 0.6 percent of the time during the lifetime of the conductor. With the load current distributions shifted by 30 percent of their mean value or with the flat traditional ampacity load, the conductor annealing temperatures would occur approximately 7.6 percent of the time.

Energy losses associated with transmission lines are a function of the square of the load current and the resistance of the conductor which is a function of the conductor temperature. The annealing program can easily be extended to include the calculation of energy losses for various actual or proposed load current distributions. These results would be more accurate than the traditional methods used in economic studies that assume an average conductor temperature and load current.

More research is required into wind velocities along transmission lines and variations in wind speed with respect to topography and height. With the recent advent of automatic portable recording weather stations some of these weather problems may be solved. Research is also required in studying the temperature gradients that exist within the conductor as these gradients are significant in larger diameter conductors.

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9. APPENDICES

9.1 The Thermal Properties of Air

9.1.1 Density of Air

The density of air varies with changes in elevation above sea level. A second order polynomial is used to approximate this change. The resulting equation is:

$$p_x = p_{sl} \times k_{el} \tag{9.1}$$

where: $k_{el} = (-0.00277X + 0.000038X^2)$

p_x - density of air at elevation X

p_{sl} - density of air at sea level at STP

X - elevation above sea level expressed in thousands of feet

The density of air also varies with film temperature (t_f) as follows:[22]

$$p_{sl} = 0.765 \times (288.16/(t_f + 273.16)) \quad \mathrm{lb/ft^3} \tag{9.2}$$

9.1.2 Viscosity of Air

The viscosity of air varies with film temperature (t_f) according to the following equation[22]:

$$u_f = 0.0242 \times 0.1458 \times (t_f + 273.16)^{1.5} \ \mathrm{lbm/ft.hr} \tag{9.3}$$

9.1.3 Thermal Conductivity of Air

The thermal conductivity of air varies with film temperature (t_f) according to the following equation[22]:

$$k_f = \frac{10^{12/A} \times 0.01275 \times 0.06325 \times A^{1.5}}{A^{1.5} \times 10^{12/A} + 245.4} \tag{9.4}$$

where: $A = t_f + 273.16$

9.2 Development of the Newton-Raphson Method

The equation $f(t_c)$,(section 2.3) will equal zero when t_c (conductor surface temperature) is an exact root.

Let t_o - approximate value of the desired root

h - deviation from exact root

Then $$t_c = t_o - h \tag{9.5}$$

Expanding by Taylor's theorem about t_o we have:

$$f(t_o-h) = f(t_o) + hf'(t_o) + h^2/2!\ f''(t_o) + \ldots\ldots \tag{9.6}$$

If h is small the term containing h^2 can be neglected resulting in:

$$f(t_o) + hf'(t_o) = 0 \tag{9.7}$$

The function $f(t_c)$ (section 2.3) is once continuously differentiable in t_c.

From equation 9.7 the solution of h is as follows:

$$h_o = f(t_o) / f'(t_o) \tag{9.8}$$

where h_o is the approximate deviation from the real root

The improved root is then:

$$t_1 = t_o - h_o = t_1 - f(t_o) / f'(t_o) \tag{9.9}$$

The succeeding approximations are:

$$t_2 = t_1 - h_1 = t_1 - f(t_1) / f'(t_1)$$

$$\vdots$$

$$t_{i+1} = t_i - h_i = t_i - f(t_i) / f'(t_i) \tag{9.10}$$

The magnitude of the inherent error in the Newton-Raphson Method is given by[6]: $$E_i = h^2 \tag{9.11}$$

It can also be stated that ' the number of reliable significant figures in h is equal to the number of zeros between the decimal point and the first significant figure'.[6]

9.3 General Equation for $f(t_c)$

$$f(t_c) = A44 \cdot (t_c/100)^4 + A33 \cdot (t_c/100)^3 + A22 \cdot (t_c/100)^2 + A11 \cdot t_c + A00 \qquad (9.12)$$

9.3.1 Terms for Reynolds Number greater than 1000

t_c - conductor surface temperature °C

t_a - ambient temperature °C

a - temperature coefficient for aluminum

D - conductor diameter in inches

e - emissivity of conductor surface

p - density of air

v - viscosity of air

k - thermal conductivity of air

R - resistance of conductor in ohms/foot

I - current in amperes

A44 - $0.1378 \times D \times e$

A33 - $A44 \times 2.7316$

A22 - $A44 \times (2.7316)^2 \times 6$

A1A - $A44 \times (2.7316)^3 \times 10^{-2} - I^2R$

A1B - $0.169 \times (DpV/v)^{0.6} \times k$

V - wind velocity in feet per hour

A01 - -1.0x(solar radiation in watts/lineal foot of conductor)

A02 - $-I^2R(1 - a25)$

A03 - $A44 \times (2.7316)^4 - ((t_a + 273.16)/100)^4$

A04 - $0.1695 \times (DpV/v)^{0.6} \times k \times t_a$

A11 - A1A + A1B

A00 - A01 + A02 + A03 + A04

9.3.2 Terms for Reynolds Number less than 1000 and greater than 0.1

- same as 9.3.1 with the following exceptions:

$$A1B = 1.01 + 0.371 \times (DpV/v)^{0.52} \times k$$

$$A04 = 1.0. + 0.371 \times (DpV/v)^{0.52} \times k \times t_a$$

9.3.3 Terms for Natural Convection

- same as 9.3.1 with the following exceptions:

$$A1B = 0.0$$

$$A04 = 0.072 \times D^{0.75} \times (t_c - t_a)^{1.25}$$

9.4 Aitken Delta Squared Method Development

Assume that the error in the Newton-Raphson Method per iteration converges approximately as a geometric progression.

Let x = the exact solution

e_i = error terms for the ith iteration

q = common ratio

The geometric error progression considering three terms is as follows:

$$e_{i-1}\ ,\ e_i\ ,\ e_{i+1} \tag{9.13}$$

where:

$$\begin{aligned} e_{i-1} &= x - x_{i-1} \\ e_i &= x - x_i \\ e_{i+1} &= x - x_{i+1} \end{aligned} \tag{9.14}$$

The geometric error progression can also be written as:

$$e_{i-1}\ ,\ (e_{i-1})q\ ,\ (e_{i-1})q^2 \tag{9.15}$$

Equating progressions 9.13 and 9.15 term by term and substitution of equation 9.14 results in the following equations:

$$e_{i-1} = \quad e_{i-1} = x - x_{i-1} \tag{9.16}$$

$$e_i = (e_{i-1})q = q(x - x_{i-1}) = x - x_i \tag{9.17}$$

$$e_{i+1} = (e_{i-1})q^2 = q(x - x_i) = x - x_{i+1} \tag{9.18}$$

Division of equation 9.17 by equation 9.18 to eliminate q, results in the solution of x as follows:

$$x = \frac{x_{i-1} \cdot x_{1+1} - x_i^2}{x_{i-1} + x_{i+1} - 2x_i} \qquad (9.19)$$

Equation 9.19 may be put into a more convenient form by adding and subtracting the term $(x_{i+1} - x_i)^2$ and re-arranging the terms to form:

$$x = x_{i+1} - (x_{i+1} - x_i)^2 / (x_{i-1} + x_{i+1} - 2x_i) \qquad (9.20)$$

The following finite differences are defined accordingly:

$$\Delta x_i = x_{i+1} - x_i$$
$$\Delta x_{i-1} = x_i - x_{i-1} \qquad (9.21)$$
$$\Delta x_{i-1} = \Delta x_i - \Delta x_{i-1} = x_{i-1} + x_{i+1} - 2x_i$$

Equation 9.20 may be expressed as:

$$x = x_{i+1} - (\Delta x_i)^2 / \; x_{i-1} \qquad (9.22)$$

If the sequence of errors is diverging the Aitken Delta Squared Method only increases the diverging problem. Given three successive values in an iterative process, an estimate of the final value can be calculated from equation 9.22. Then the q ratios can be determined to see if the sequence of errors is diverging ie ($q > 1$).

9.4.1 Example of iterative process in calculating the Conductor Surface Temperature.

WITHOUT AITKEN DELTA SQUARED METHOD

x_{i-1}	....	72.543
x_i	....	71.014
x_{i+1}	....	70.401
		70.165
		70.076
		70.042
		70.024
x_f	....	70.020

Check for common ratio:

$$q_1 = (x_f - x_{i+1}) \;/\; (x_f - x_i) = 0.381/0.994 = 0.38$$

$$q_2 = (x_f - x_i \;\;) \;/\; (x_f - x_{i-1}) = 0.994/2.523 = 0.39$$

Given x_{i-1}, x_i and x_{i+1} the next estimate of the final value is obtained from equation 9.22 as follows:

$$x^*_{i+1} = 70.401 - (0.613/0.916)^2$$
$$= 69.991$$

On the next iteration the final result of 70.020 was obtained.

If the Aitken Delta Squared Method was not used three additional iterations would be required to obtain the final result.

9.5 Conductor Properties of the Transmission Line studied in this thesis

- -conductor size - 477.0 MCM ACSR (Hawk)
- -resistance at 25°C = 0.196 ohms per mile
- -diameter = 0.858 inches
- -emissivity =0.23 (assumed)
- -number of aluminum strands = 26
- -number of steel strands = 7
- -traditional ampacity = 672 amperes
- -ultimate tensile strength = 19430 pounds
- -26 aluminum strands contribute 9360 lbs. to the conductor ultimate tensile strength
- -7 steel strands contribute 10070 lbs. to the conductor ultimate tensile strength

9.6 Input Data and Digital Computer Flow Charts

The actual weather and load current data had the following general format as illustrated in Table 9.1.

Table 9.1 Typical Weather and Load Current Data Format

HOUR OF DAY IN YEAR hour	LOAD CURRENT CIRCUIT A amps	LOAD CURRENT CIRCUIT B amps	AMBIENT TEMPERATURE $^{\circ}F$	WIND VELOCITY mph	SOLAR RADIATION langley/hr
1					
.					
.					
6633	528.0	528.0	56.0	11.0	9.0
6634	540.0	528.0	55.0	8.0	0.0
.					
.					
8760					

The conductor characteristics were fixed within each program involving the given conductor. The actual weather and load current data were stored on magnetic tape. In order to study the actual weather and load current data statistically, the programs had to be developed in parts. This was necessary because the data occupied a considerable amount of computer storage within a given program. In some cases the computer storage (170 K) was exceeded. On the IBM /360 HASP system at the University of Saskatchewan,programs with smaller time cards have a better turn around time. These programs in parts were characterized by their low turn around time and ease of removing syntax errors during the development of them. Once each part was tested successfully, they were linked together to form individual main programs. The digital computer flow charts for the main programs are shown in Figures 9.1 to 9.7.

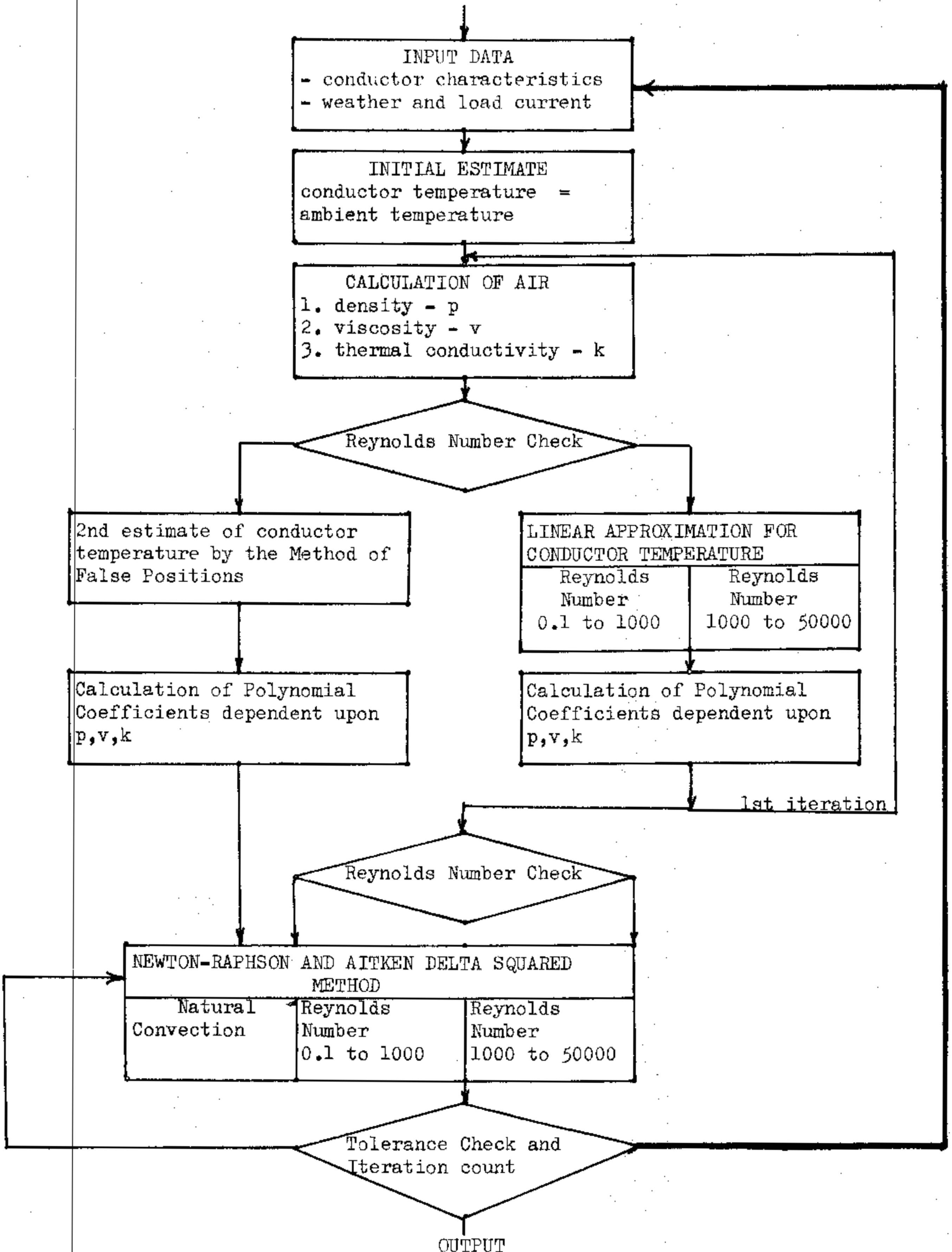

Figure 9.1 Digital Computer Flow Chart For Solving Conductor Temperature

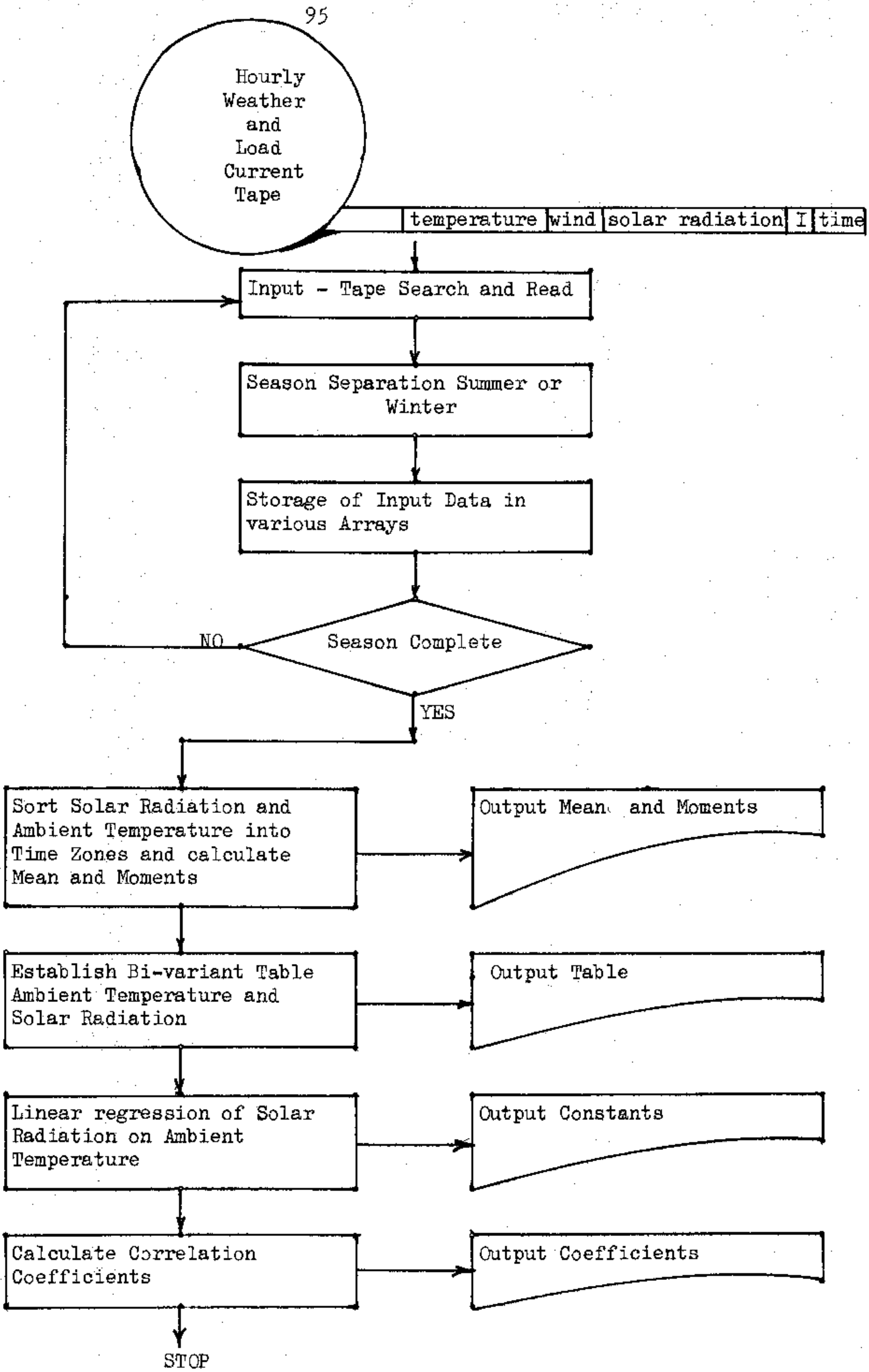

Figure 9.2 Digital Computer Flow Chart for Ambient Temperature and Solar Radiation Study

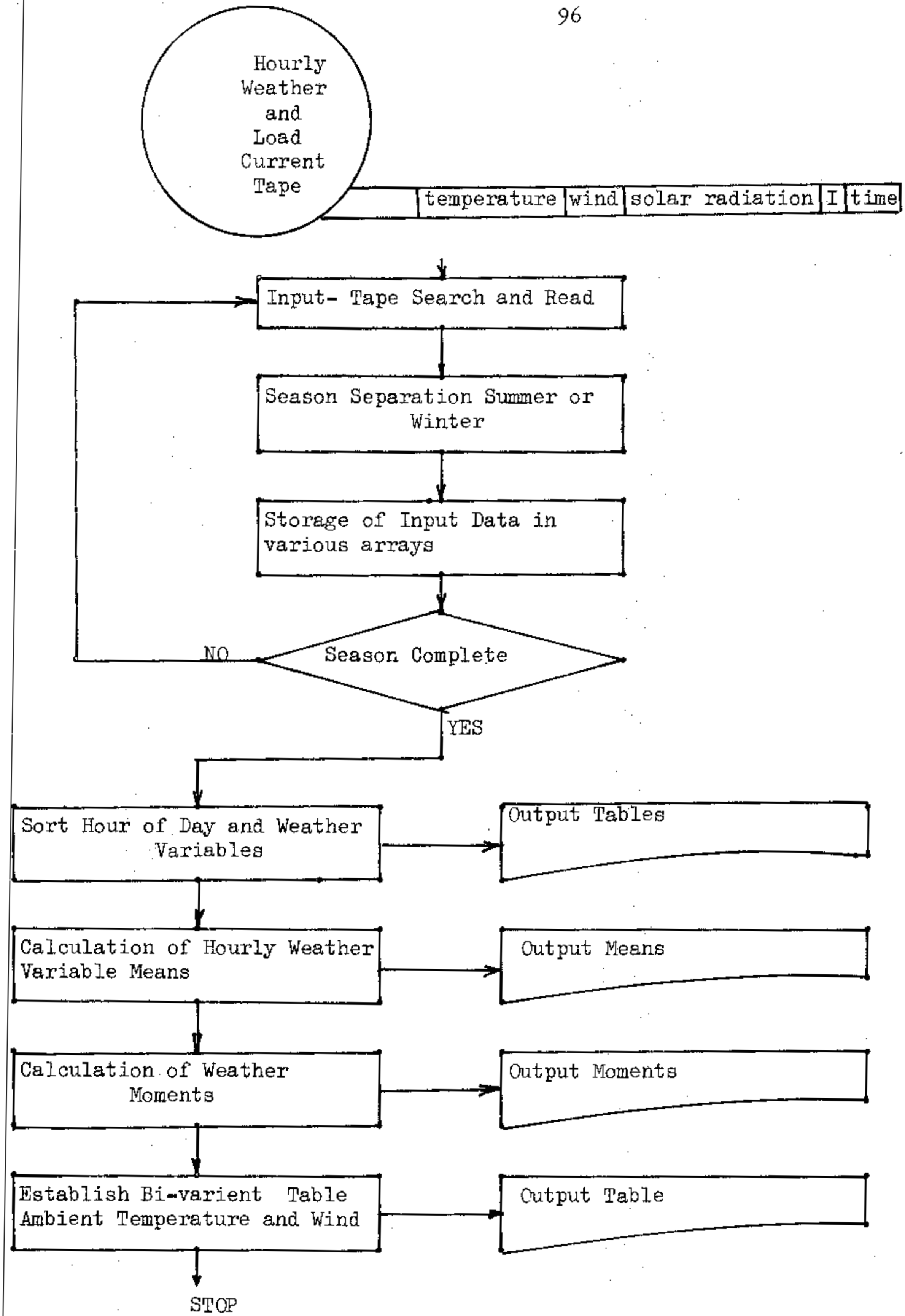

Figure 9.3 Computer (Digital) Flow Chart for Calculating Weather Statistics for Pearson Curves

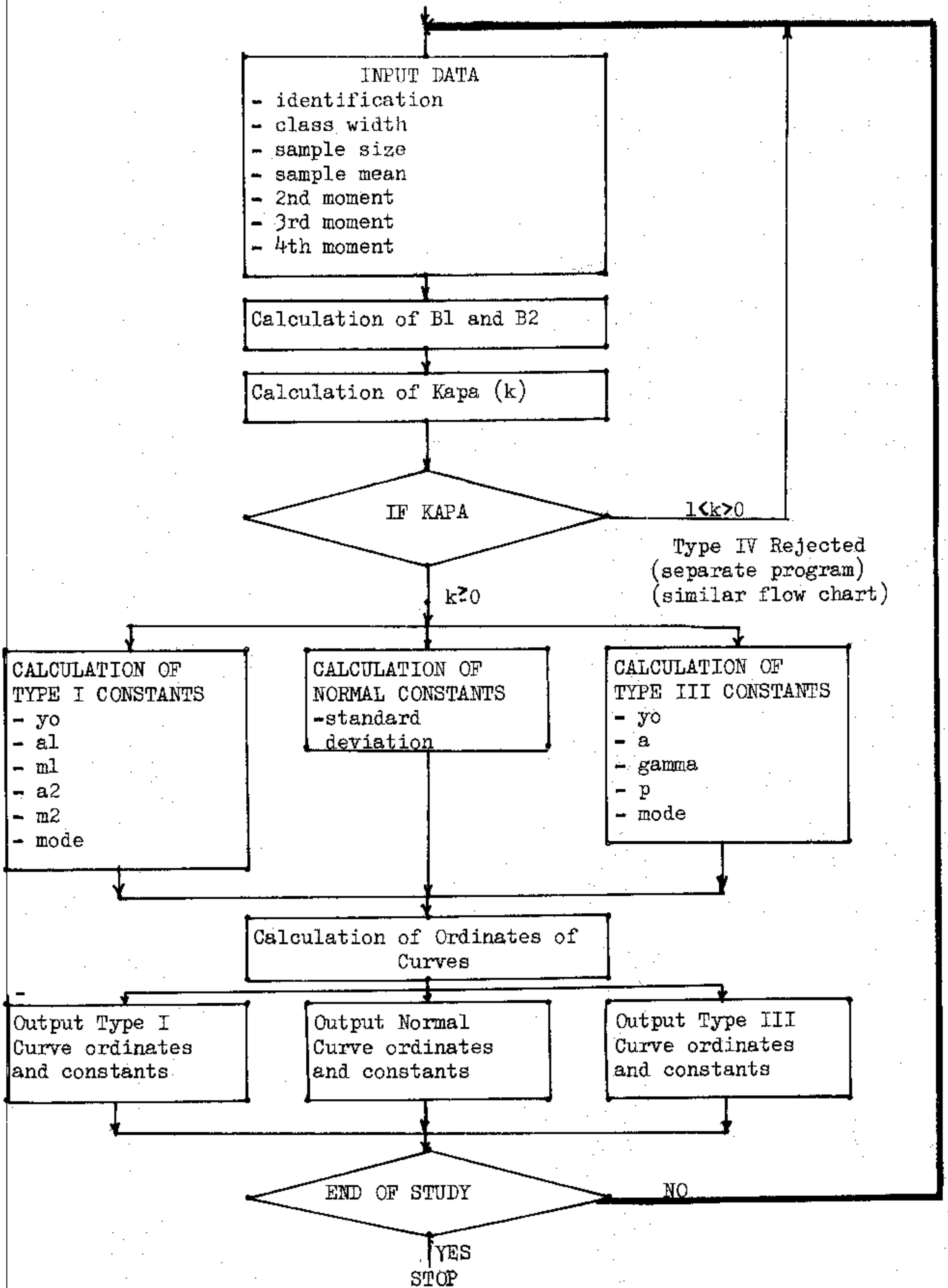

Figure 9.4 Digital Computer Flow Chart for Pearson Curves

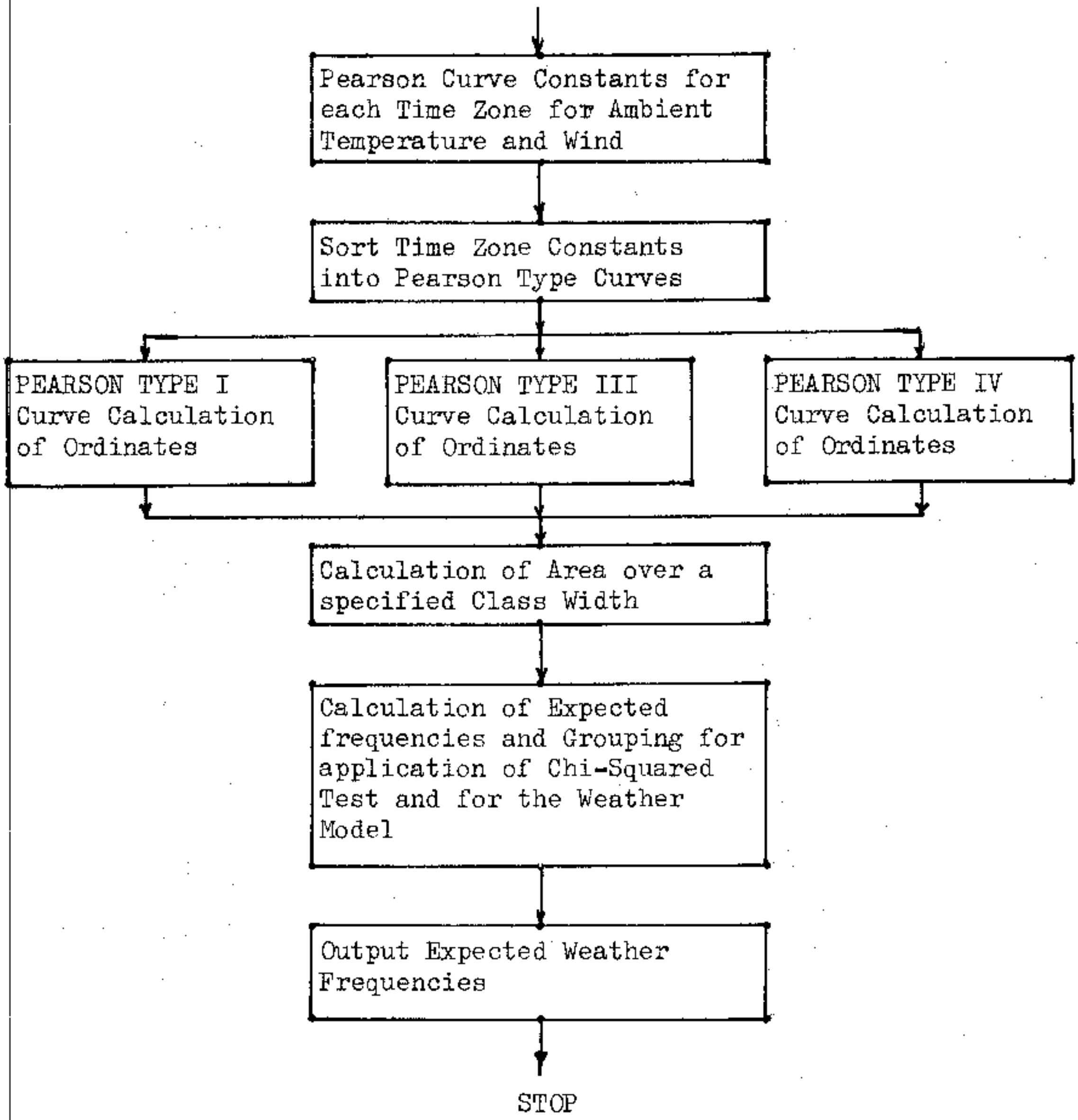

Figure 9.5 Digital Computer Flow Chart for Calculating Probabilities of Pearson Type Curves

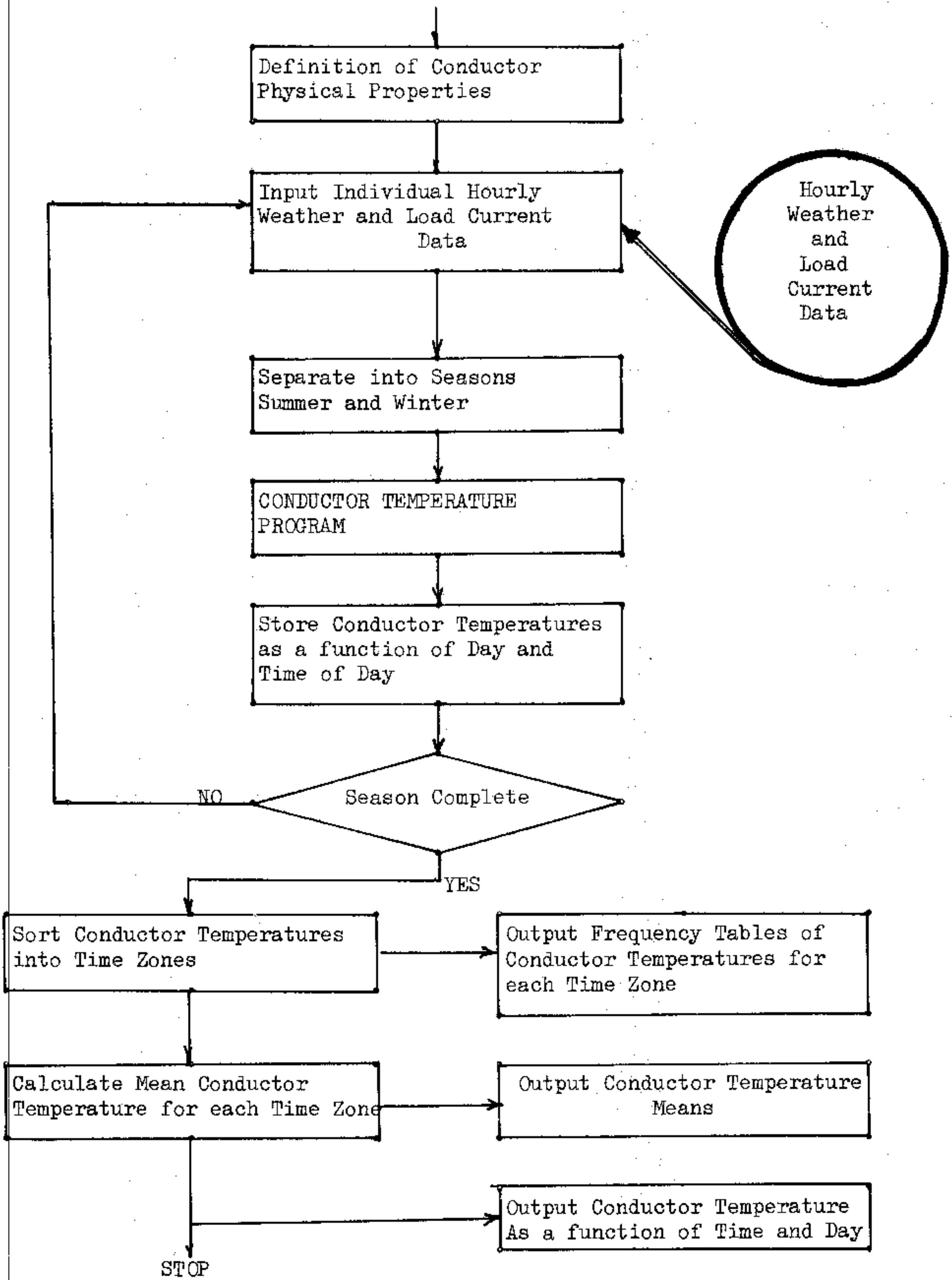

Figure 9.6 Digital Computer Flow Chart for Solving Hourly Conductor Temperatures using Actual Weather and Load Current Data

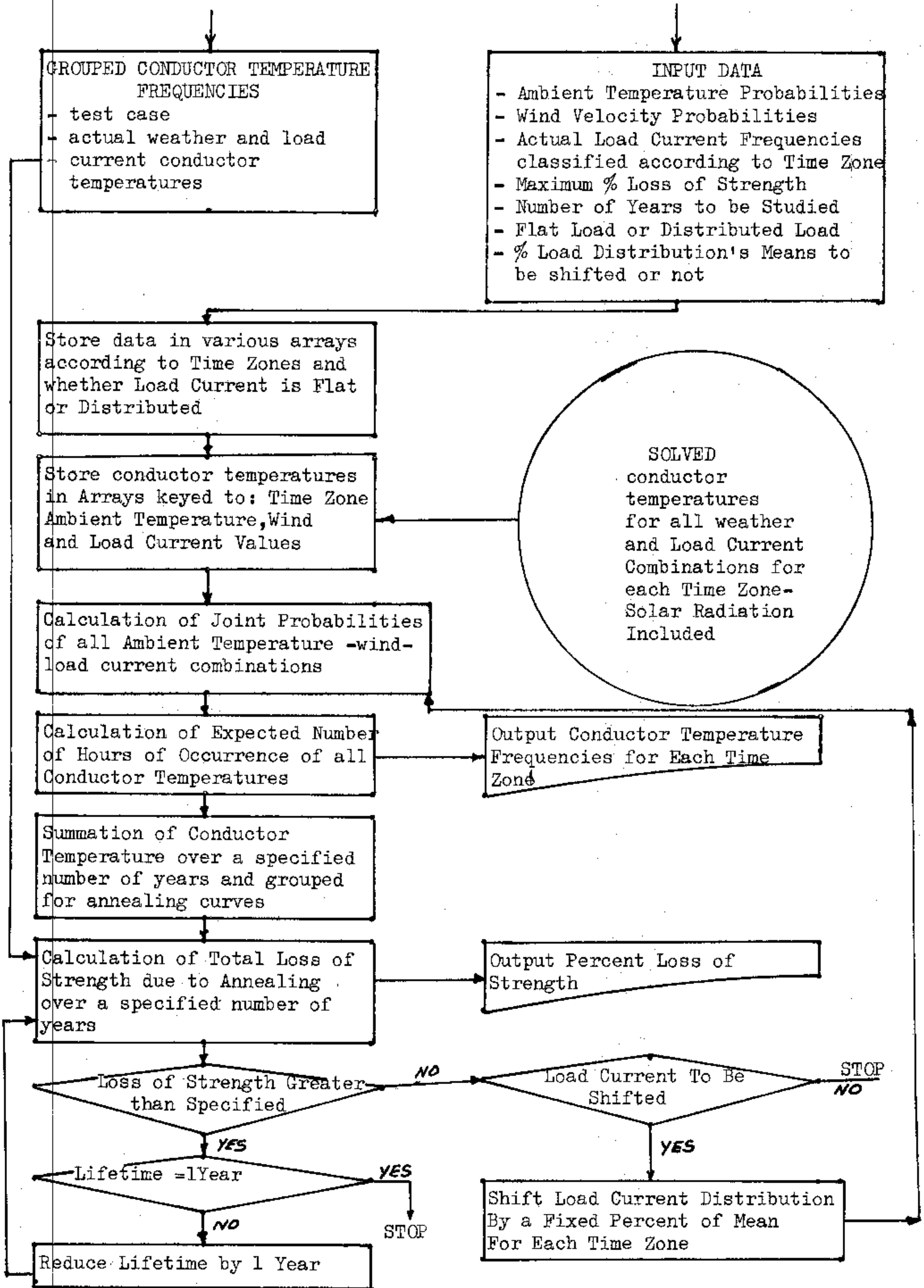

Figure 9.7 Digital Computer Flow Chart For Calculating Annealing Losses using Statistical Methods to represent the Weather

9.7 Actual Load Current Frequencies for Summer and Winter

Tables 9.2 and 9.3 represent the actual load current frequencies classified according to time zone. These frequencies were used in the theoretical conductor surface temperature approach as discussed in Chapter 6.

Table 9.2 Actual Load Current Frequencies for Summer

LOAD CURRENT AMPERES	1am to 6am	7am to 9am	10am to 12 noon	1pm to 3pm	4pm to 6pm	7pm to 12 midnight
0	24	50	42	24	10	26
12	0	0	0	1	0	0
24	1	0	0	1	0	0
36	0	0	0	0	0	0
48	0	0	0	0	0	0
60	0	0	2	0	0	0
72	0	1	1	0	0	0
84	0	0	1	0	0	1
96	4	0	0	0	0	1
108	2	0	0	0	0	0
120	5	3	2	2	2	3
132	3	0	0	0	1	4
144	3	1	1	1	0	0
156	6	1	0	2	0	0
168	7	1	0	2	3	4
180	7	1	0	1	0	7
192	9	1	2	1	2	0
204	13	3	4	1	1	4
216	41	2	0	3	1	7
228	36	3	3	2	2	3
240	92	8	1	5	1	10
252	50	12	3	5	2	13
264	42	9	4	13	14	11
276	43	8	4	8	6	24
288	18	6	6	10	10	23
300	13	11	1	9	8	25
312	8	11	7	19	13	24
324	10	8	8	21	15	40
336	10	22	11	21	17	43
348	0	14	16	31	17	36
360	6	21	23	15	22	39
372	3	14	34	17	25	26
384	3	10	23	10	19	31
396	14	22	30	19	17	31
408	16	16	24	18	19	22
420	28	14	20	17	32	46
432	42	15	19	21	17	28
444	70	21	16	22	23	35
456	54	23	27	53	41	61
468	91	35	40	30	37	60
480	76	37	34	28	39	77
492	55	33	35	25	35	87
504	31	17	30	36	26	69
516	89	48	42	30	35	88
528	42	36	22	26	28	68
540	22	9	13	5	7	20
552	7	0	0	0	2	1

Table 9.3 Actual Load Current Frequencies for Winter

LOAD CURRENT AMPERES	1am to 6am	7am to 9am	10am to 12 noon	1pm to 3pm	4pm to 6pm	7pm to 12 midnight
0	20	67	60	49	54	32
12	0	0	0	0	3	11
24	0	1	4	4	0	5
36	0	2	0	0	2	1
48	0	0	3	1	0	2
60	2	2	0	1	3	4
72	0	2	0	0	1	2
84	1	1	2	1	0	0
96	0	0	3	2	2	1
108	2	1	1	1	1	2
120	3	2	2	3	0	1
132	2	3	0	0	0	1
144	23	3	0	0	1	0
156	51	4	0	1	0	0
168	37	5	0	1	0	1
180	45	6	0	0	1	2
192	33	8	1	1	0	4
204	42	4	1	1	2	6
216	47	11	2	1	0	7
228	67	11	1	1	2	12
240	113	12	2	5	5	19
252	107	19	1	1	0	6
264	125	23	6	8	2	15
276	70	16	6	2	3	9
288	61	16	3	8	2	18
300	44	15	9	9	5	34
312	16	10	8	25	9	22
324	22	16	14	20	9	33
336	28	26	17	27	16	56
348	21	22	20	40	14	32
360	18	25	24	50	9	49
372	10	22	21	46	21	58
384	2	15	37	31	20	59
396	21	44	47	43	23	62
408	7	30	54	34	38	76
420	6	27	44	28	33	73
432	3	16	43	22	44	78
444	4	6	26	14	32	62
456	2	6	27	11	34	61
468	1	9	11	9	34	52
480	4	9	15	9	38	45
492	4	5	4	6	35	24
504	1	1	2	3	17	10
516	1	11	9	7	9	13
528	19	10	10	9	11	14
540	8	1	6	8	4	3
552	1	0	0	2	5	6
564	0	0	0	0	2	2

9.8 Summer and Winter Ambient Temperature versus Wind Contingency Tables

These contingency tables present the actual and theoretical bi-varient frequencies of wind and ambient temperature for each time zone during summer and winter. They also contain the calculated cell Chi-Squared values. These results indicated whether wind and ambient temperature were independent variables. A summary of these tables is as follows:

Table 9.4 Summer Ambient Temperature versus Wind Contingency Table
(Time Zone 1am to 6am)

AMBIENT TEMPERATURE °F

WIND VELOCITY MPH	50			55			60		
0	128	117.6	0.9	97	105.2	0.6	65	67.0	——
1	48	50.2	——	48	45.2	0.2	28	28.6	——
2	27	35.6	2.1	43	31.9	3.9	18	20.3	0.3
3	43	42.6	——	37	38.1	——	25	24.2	——
4	37	43.3	0.9	49	38.8	2.7	21	24.7	0.5
5	51	44.1	1.1	41	39.5	——	17	25.1	2.6
6	38	35.2	——	31	31.5	——	18	20.0	0.2
7	25	22.7	0.2	15	20.3	1.4	16	12.9	0.7
8	11	14.5	0.9	13	13.0	——	12	8.6	1.3
9+	35	36.1	——	22	32.2	3.2	32	20.8	6.0

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of Freedom = 18

$\sum \chi^2 = 29.7$

$\chi^2(.05) = 28.87$

Table 9.5 Summer Ambient Temperature versus Wind Contingency Table (Time Zone 7am to 9am)

AMBIENT TEMPERATURE °F

WIND VELOCITY MPH	55			60			65		
	actual	theoretical	chi-sq.	actual	theoretical	chi-sq.	actual	theoretical	chi-sq.
0	56	45.7	2.3	25	34.3	2.5	22	22.8	—
1	20	20.9	—	14	15.7	0.2	13	10.4	0.7
2	14	18.7	1.2	13	14.0	—	15	9.3	3.5
3	24	16.9	3.0	8	12.7	1.7	6	8.4	0.7
4	20	20.9	—	14	15.0	—	11	10.0	0.1
5	21	20.5	—	15	15.4	—	10	10.2	—
6	15	17.7	0.4	19	13.3	2.4	6	8.9	1.0
7	11	16.4	1.8	17	12.4	1.7	9	8.2	—
8+	58	63.0	0.4	55	47.5	1.2	28	31.4	0.4

actual frequency
theoretical frequency
Cell Chi-Squared value

Degrees of Freedom = 16

$\sum \chi^2 = 25.2$

$\chi^2(.05) = 26.3$

Table 9.6 Summer Ambient Temperature versus Wind Contingency Table (Time Zone 10am to 12 noon)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	50			55			60			65		
0	20	15.6	1.2	9	11.4	0.5	17	14.7	0.3	13	12.1	—
1	14	13.2	—	6	9.5	1.3	12	12.3	—	13	10.1	0.8
2	11	20.0	4.1	13	14.5	—	21	18.8	0.2	24	15.6	4.5
3	17	18.3	—	15	13.3	0.1	17	17.2	—	14	14.2	—
4	19	19.5	—	11	14.1	0.6	17	18.2	—	20	15.1	1.6
5	16	15.7	—	16	11.4	1.8	11	14.7	0.9	11	12.2	—
6	11	13.0	0.3	14	9.5	2.1	8	12.3	1.5	12	10.1	0.4
7	11	10.5	—	7	7.6	—	13	9.8	1.0	5	8.1	1.2
8+	38	30.5	1.8	23	22.2	—	34	28.7	1.0	10	23.7	6.8

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of Freedom = 24
$\sum \chi^2 = 34.0$
$\chi^2(.05) = 36.42$

Table 9.7 Summer Ambient Temperature versus Wind Contingency Table (Time Zone 4pm to 6pm)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	55			60			65		
0	18	15.0	0.6	20	20.0	—	20	20.0	0.4
1	6	11.8	2.8	18	15.9	—	22	18.3	0.7
2	19	16.5	0.4	16	22.1	1.7	29	25.4	0.5
3	20	24.8	1.0	30	33.1	0.3	46	38.1	1.6
4	23	16.0	3.0	22	21.4	—	17	24.6	2.3
5	13	13.4	—	15	17.9	0.4	24	20.6	0.5
6	16	16.0	—	27	21.4	1.5	19	24.6	1.3
7	4	6.7	1.1	11	9.0	—	11	10.3	—
8	6	5.9	—	10	8.0	0.5	7	9.1	0.5
9+	13	12.7	—	17	16.8	—	19	19.6	—

ACTUAL FREQUENCY
THEORETICAL FREQUENCY
CELL CHI-SQUARED VALUE

Degrees of Freedom = 18

$\sum \chi^2 = 19.1$

$\chi^2 (.05) = 28.87$

Table 9.8 Summer Ambient Temperature versus Wind Contingency Table (Time Zone 7pm to 12 midnight)

AMBIENT TEMPERATURE °F

WIND VELOCITY MPH	45			50			55			60		
0	65	70.4	0.4	57	53.2	0.3	67	77.0	1.3	74	65.5	1.1
1	23	31.6	2.3	24	23.8	—	39	34.6	0.5	32	29.4	0.2
2	26	30.3	0.6	18	22.8	1.0	39	33.1	1.0	30	28.1	—
3	42	39.6	0.1	22	29.9	2.0	50	43.4	1.0	34	36.9	0.2
4	26	28.6	0.2	24	21.6	0.2	34	31.4	0.2	23	26.6	0.5
5	27	22.5	0.9	19	17.0	0.2	24	24.6	—	14	20.9	2.3
6	15	19.8	1.1	22	14.9	3.3	23	21.7	—	14	18.4	1.0
7+	67	49.2	6.4	34	31.5	0.2	43	55.0	2.6	37	45.8	1.6

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of Freedom = 21
$\sum \chi^2 = 32.6$
$\chi^2(.05) = 32.7$

Table 9.9 Winter Ambient Temperature versus Wind Contingency Table (Time Zone 1am to 6am)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	35			40			45		
0	60	41.7	8.0	38	39.0	——	37	53.5	5.1
1	35	19.0	13.5	11	17.8	2.6	15	24.3	3.6
2	48	34.5	4.5	36	32.2	0.3	27	44.3	6.8
3	43	23.0	17.4	15	21.5	1.9	16	29.5	6.2
4	46	31.1	7.2	22	29.1	1.7	32	40.0	1.6
5	27	23.6	0.5	17	22.1	1.2	32	30.3	——
6	30	21.7	3.1	22	20.3	——	18	27.9	3.5
7	9	19.2	5.4	19	18.0	——	34	24.8	3.4
8	12	17.7	1.8	22	16.6	1.7	23	22.8	——
9	6	11.2	2.4	11	10.5	——	20	14.4	2.2
10+	20	62.2	28.6	104	88.5	2.7	182	113.5	41.0

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of Freedom = 20

$\sum \chi^2 = 177.9$

$\chi^2_{(.05)} = 31.4$

Table 9.10 Winter Ambient Temperature versus Wind Contingency Table
(Time Zone 7am to 9am)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	40			45			50		
0	38	33.7	0.5	13	15.0	0.3	7	9.1	0.5
1	23	21.5	0.1	7	9.6	0.7	7	5.8	0.2
2	40	30.8	2.7	10	13.8	1.0	3	8.4	3.4
3	39	27.9	4.4	6	12.5	3.4	3	7.6	2.8
4	33	29.6	0.4	13	13.3	—	5	8.1	1.2
5	16	19.7	0.7	10	8.8	0.2	8	5.4	1.2
6	18	17.4	—	3	7.8	2.9	9	4.7	3.9
7	19	18.6	—	8	8.3	—	5	5.1	—
8	13	15.7	0.5	7	7.0	—	7	4.3	1.7
9	16	17.4	—	7	7.8	—	7	4.7	1.1
10+	58	83.0	7.5	57	42.9	4.6	28	22.6	1.3

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of freedom = 20

$\sum \chi^2 = 47.2$

$\chi^2(.05) = 31.41$

Table 9.11 Winter Ambient Temperature versus Wind Contingency Table (Time Zone 10am to 12 noon)

AMBIENT TEMPERATURE °F

WIND VELOCITY MPH	40 actual	40 theoretical	40 cell Chi-Squared	45 actual	45 theoretical	45 cell Chi-Squared	50 actual	50 theoretical	50 cell Chi-Squared
0	15	11.6	1.0	12	13.1	—	8	10.1	0.4
1	16	11.4	1.8	11	12.8	0.2	7	9.9	0.8
2	23	14.4	5.1	10	16.1	2.3	10	12.5	0.5
3	13	11.0	0.4	7	12.4	2.3	13	9.6	1.2
4	13	12.7	—	13	14.3	—	12	11.0	—
5	19	13.0	2.7	12	14.6	0.5	8	11.3	1.0
6	7	13.0	2.7	17	14.6	0.3	15	11.3	1.2
7	8	10.0	0.4	10	11.3	—	12	8.7	1.2
8	15	10.7	1.8	7	12.0	2.0	10	9.3	—
9	11	9.4	0.2	12	10.5	0.1	5	7.8	1.0
10+	42	65.4	8.4	93	73.1	5.4	61	56.8	0.3

actual frequency
theoretical frequency
cell- Chi-Squared value

Degrees of Freedom = 20

$\sum x^2 = 44.0$

$x^2_{(.05)} = 31.4$

Table 9.12 Winter Ambient Temperature versus Wind Contingency Table
(Time Zone 1pm to 3pm)

AMBIENT TEMPERATURE °F

actual frequency / theoretical frequency / cell Chi-Squared value

WIND VELOCITY MPH	45			50		
0	14	11.5	0.5	4	6.6	1.0
1	16	14.7	0.1	7	8.4	0.2
2	23	19.8	0.6	8	11.2	1.0
3	23	21.1	0.1	10	12.0	0.3
4	21	25.6	0.9	19	14.6	1.3
5	19	21.7	0.3	15	12.4	0.6
6	13	16.6	0.8	13	9.5	1.3
7	23	21.7	0.2	11	12.4	0.1
8	22	20.5	0.1	10	11.6	0.2
9	24	24.3	—	14	13.8	—
10+	148	149.6	—	86	88.0	—

Degrees of Freedom = 10
$\sum \chi^2 = 9.6$
$\chi^2\,(.05) = 18.31$

Table 9.13Winter Ambient Temperature versus Wind Contingency Table
(Time Zone 4pm to 6pm)

AMBIENT TEMPERATURE ^{o}F

WIND VELOCITY MPH	40 actual	40 theoretical	40 cell χ^2	45 actual	45 theoretical	45 cell χ^2
0	23	20.0	0.5	4	6.9	1.2
1	14	13.3	——	4	4.6	——
2	22	21.5	——	7	7.5	——
3	29	31.1	0.2	13	10.8	0.5
4	33	31.1	0.1	9	10.8	0.3
5	35	34.0	——	11	11.8	——
6	26	24.4	0.1	7	8.5	0.3
7	24	28.1	0.6	14	9.8	1.8
8	32	30.3	0.1	9	10.5	0.2
9	21	21.5	——	8	7.5	0.1
10+	143	144.9	——	53	50.6	0.1

actual frequency
theoretical frequency
cell Chi-Squared value

Degrees of Freedom = 10
$\sum \chi^2 = 6.1$
$\chi^2(.05) = 18.31$

9.9 Pearson Constants for Summer and Winter Hourly Wind Velocities and Ambient Temperatures

Table 9.14 Pearson Constants for Hourly Summer Ambient Temperatures

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY SUMMER AMBIENT TEMPERATURES	
1	I	mode = 56.37489 yo = 11.2 a1 = 37.26181	m1 = 4.27874 a2 = 6.61199 m2 = 0.75925
2	I	mode = 56.31763 yo = 11.2 a1 = 39.90991	m1 = 5.33735 a2 = 7.87699 m2 = 1.05343
3	I	mode = 56.37498 yo = 11.2 a1 = 37.26181	m1 = 4.27874 a2 = 6.61199 m2 = 0.75925
4	I	mode = 55.45091 yo = 11.4 a1 = 38.08481	m1 = 5.13438 a2 = 7.54803 m2 = 1.01756
5	I	mode = 54.86224 yo = 11.2 a1 = 51.10458	m1 = 8.50947 a2 = 8.95532 m2 = 1.49116
6	I	mode = 57.17621 yo = 11.1 a1 = 44.57681	m1 = 5.50783 a2 = 6.63981 m2 = 0.82040
7	I	mode = 58.39470 yo = 10.1 a1 = 41.92792	m1 = 5.15175 a2 = 8.91625 m2 = 1.09556
8	I	mode = 59.78642 yo = 9.9 a1 = 56.71373	m1 = 9.76490 a2 = 12.28004 m2 = 2.11436
9	I	mode = 61.15959 yo = 9.4 a1 = 84.42685	m1 = 19.40636 a2 = 17.53676 m2 = 4.03100

Table 9.14 continued

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY SUMMER AMBIENT TEMPERATURES	
10	I	mode = 64.47968 yo = 8.2 a1 = 32.50987	m1 = 2.29496 a2 = 10.22650 m2 = 0.72192
11	I	mode = 65.28461 yo = 7.9 a1 = 32.25725	m1 = 2.23286 a2 = 11.06058 m2 = 0.76561
12	I	mode = 68.99860 yo = 7.4 a1 = 31.61047	m1 = 1.29030 a2 = 7.19155 m2 = 0.29355
13 14	I I	mode = 69.98093 yo = 7.2 a1 = 32.33703	m1 = 1.30073 a2 = 7.79608 m2 = 0.31359
15	I	mode = 69.32834 yo = 7.2 a1 = 30.86186	m1 = 1.51292 a2 = 10.56518 m2 = 0.51793
16	I	mode = 68.32008 yo = 6.9 a1 = 29.05669	m1 = 1.31783 a2 = 11.76692 m2 = 0.53367
17	I	mode = 68.32008 yo = 6.9 a1 = 29.05669	m1 = 1.31783 a2 = 11.76692 m2 = 0.53367
18	I	mode = 66.42189 yo = 7.0 a1 = 29.17459	m1 = 1.55492 a2 = 13.20400 m2 = 0.70374
19 to 24	IV	origin = 62.53532 yo = 50.78550 r = 5.70949	a = 15.82404 v = 2.05278

Table 9.15 Pearson Constants for Hourly Winter Ambient Temperatures

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY WINTER AMBIENT TEMPERATURES	
1 to 6	I	mode = 40.28194 yo = 61.8 a1 = 37.75648	m1 = 13.33041 a2 = 37.18875 m2 = 13.28184
7 to 9	IV	origin = 50.91856 yo = 11.06760 r = 38.13792	a = 40.86615 v = 9.33293
10	IV	origin = 43.36246 yo = 11.85420 r = 13.75810	a = 23.18814 v = -0.32011
11	IV	origin = 42.30452 yo = 11.81120 r = 11.19462	a = 19.27950 v = -1.50763
12	IV	origin = 40.81071 yo = 9.02780 r = 15.01346	a = 22.45813 v = -3.36212
13	IV	origin = 40.10783 yo = 7.64980 r = 14.79480	a = 21.69719 v = -4.16773
14	IV	origin = 40.18762 yo = 7.70450 r = 14.42916	a = 21.06688 v = -4.15909
15	IV	origin = 42.77289 yo = 11.29170 r = 11.33295	a = 19.09164 v = -1.95125
16	IV	origin = 50.06413 yo = 10.51710 r = 4.48399	a = 11.54437 v = 1.83104

Table 9.15 continued

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY WINTER AMBIENT TEMPERATURES	
17	IV	origin = 44.68919 yo = 13.42820 r = 10.70908	a = 18.21309 v = 0.06715
18	IV	origin = 43.31018 yo = 13.35740 r = 10.07267	a = 17.70782 v = -0.31445
19	IV	origin = 43.94524 yo = 13.34230 r = 10.68543	a = 18.18982 v = 0.40020
20	IV	origin = 41.70985 yo = 12.98230 r = 11.82645	a = 19.40947 v = -0.67581
21	IV	origin = 40.94539 yo = 12.12510 r = 17.59096	a = 24.93170 v = -1.00797
22	IV	origin = 44.48262 yo = 11.07690 r = 18.88136	a = 26.95184 v = 1.71961
23	IV	origin = 2.85736 yo = 0.00005 r =143.93968	a = 65.17200 v =-85.98274
24	I	mode = 40.68806 yo = 10.7 a1 = 29.81140	m1 = 10.98363 a2 = 46.07761 m2 = 16.97672

Table 9.16 Pearson Constants for Hourly Summer Wind Velocities

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY SUMMER WIND VELOCITIES	
1	IV	origin = -2.66900 yo = 0.11980 r = 6.10479	a = 4.13622 v =-10.30498
2	IV	origin = -3.89979 yo = 0.03990 r = 9.44851	a = 5.84536 v =-13.18635
3	I	mode = 1.65060 yo = 21.6 a1 = 2.84682	m1 = 0.56719 a2 =20.44955 m2 = 4.07435
4	I	mode = 1.65060 yo = 21.6 a1 = 2.84682	m1 = 0.56719 a2 = 20.44955 m2 = 4.07435
5	I	mode = 1.77364 yo = 20.6 a1 = 3.02469	m1 = 0.59139 a2 = 22.46053 m2 = 4.39150
6	I	mode = 1.81764 yo = 19.9 a1 = 3.76230	m1 = 0.85247 a2 = 25.45177 m2 = 5.76685
7	I	mode = 2.05851 yo = 17.3 a1 = 3.71220	m1 = 0.58244 a2 = 21.98688 m2 = 3.44981
8	I	mode = 2.44519 yo = 16.2 a1 = 3.42932	m1 = 0.38896 a2 = 18.53825 m2 = 2.10266
9	I	mode = 3.81499 yo = 15.6 a1 = 4.88179	m1 = 0.61934 a2 = 17.65024 m2 = 2.23926

Table 9.16 continued

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY SUMMER WIND VELOCITIES	
10	I	mode = 4.68584 yo = 16.4 a1 = 4.83505	m1 = 0.73240 a2 = 19.13144 m2 = 2.89797
11	III	mode = 6.30502 yo = 21.48383 a = 6.93989	= 0.62423 p = 4.33207
12	III	mode = 6.59893 yo = 22.40692 a = 7.53166	= 0.73090 p = 5.50493
13	III	mode = 6.24485 yo = 23.09061 a = 6.87964	= 0.71167 p = 4.89603
14 15 16	III	mode = 5.81912 yo = 71.38017 a = 5.34928	= 0.59777 p = 3.19766
17	I	mode = 4.60456 yo = 22.6 a1 = 5.50658	m1 = 2.48297 a2 = 40.05266 m2 = 18.06020
18	I	mode = 3.59769 yo = 24.0 a1 = 3.57516	m1 = 1.37246 a2 = 67.58078 m2 = 25.94337
19 to 24	IV	origin = -1.80805 yo = 21.78540 r = 10.63849	a = 9.32193 v = -6.97186

Table 9.17 Pearson Constants for Hourly Winter Wind Velocities

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY WINTER WIND VELOCITIES	
1 to 6	I	mode = 1.76639 yo = 99.6 al = 2.43062	ml = 0.38743 a2 = 74.10022 m2 = 11.81129
7	III	mode = 3.60579 yo = 15.43687 a = 7.31102	= 0.34877 p = 2.54987
8	III	mode = 3.93697 yo = 14.51937 a = 9.41234	= 0.38940 p = 3.66519
9	I	mode = 2.32558 yo = 14.5 al = 3.49852	ml = 0.43087 a2 = 32.82820 m2 = 4.04309
10	I	mode = 2.32558 yo = 14.5 al = 3.49852	ml = 0.43087 a2 = 32.82820 m2 = 4.04309
11	I	mode = 3.24608 yo = 13.6 al = 3.89632	ml = 0.44657 a2 = 32.68637 m2 = 3.74628
12	I	mode = 4.55939 yo = 12.3 al = 5.38576	ml = 0.54262 a2 = 25.85580 m2 = 2.60500
13	I	mode = 5.67095 yo = 12.4 al = 7.45979	ml = 1.08701 a2 = 30.57904 m2 = 4.45586
14	I	mode = 5.93080 yo = 12.5 al = 6.83589	ml = 0.83835 a2 = 24.87518 m2 = 3.05069

Table 9.17 continued

HOUR OF DAY	PEARSON TYPE CURVE	PEARSON CONSTANTS FOR HOURLY WINTER WIND VELOCITIES	
15	I	mode = 5.97904 yo = 12.8 al = 7.43922	ml = 1.17759 a2 = 30.71227 m2 = 4.86159
16	I	mode = 5.35618 yo = 13.5 al = 6.06592	ml = 0.87796 a2 = 28.97876 m2 = 4.19429
17	I	mode = 5.40979 yo = 14.1 al = 7.83459	ml = 2.14121 a2 = 97.18117 m2 = 26.55981
18	I	mode = 3.12062 yo = 15.4 al = 3.49834	ml = 0.61729 a2 = 97.49683 m2 = 17.20374
19 to 22	I	mode = 2.05867 yo = 61.6 al = 2.62917	ml = 0.37375 a2 = 58.08099 m2 = 8.25668
23	I	mode = 1.83260 yo = 15.9 al = 2.88721	ml = 0.40945 a2 = 39.73213 m2 = 5.63460
24	I	mode = 1.83260 yo = 15.9 al = 2.88721	ml = 0.40945 a2 = 39.73213 m2 = 5.63460

9.10 Sample Results obtained by the Exact Method and Approximate Method of solving for the Conductor Surface Temperature

Conductor surface temperature results obtained from the exact method are slightly greater than those obtained from the approximate method. A sample of these results is shown in Table 9.18.

Talbe 9.18 Sample of Conductor Temperature Results produced by the Exact and Approximate Methods

AMBIENT TEMPERATURE °F	*	EXACT METHOD CONDUCTOR TEMPERATURE °C	EXACT METHOD REYNOLDS NUMBER	*	APPROXIMATE METHOD CONDUCTOR TEMPERATURE °C	APPROXIMATE METHOD REYNOLDS NUMBER	*
0		34.08	1797.0		33.22	2138.0	
5		37.28	1764.0		36.42	2097.0	
10		40.46	1731.0		39.60	2057.0	
15		43.64	1700.0		42.78	2018.0	
20		46.82	1669.0		45.96	1980.0	
25		49.98	1640.0		49.12	1944.0	
30		53.14	1611.0		52.27	1909.0	
35		56.28	1583.0		55.42	1874.0	
40		59.42	1556.0		58.56	1841.0	
45		62.55	1530.0		61.69	1808.0	
50		65.67	1505.0		64.81	1777.0	
55		68.78	1480.0		67.93	1746.0	
60		71.89	1456.0		71.03	1717.0	
65		74.98	1432.0		74.13	1688.0	
70		78.07	1409.0		77.22	1660.0	
75		81.15	1387.0		80.30	1632.0	
80		84.22	1366.0		83.37	1605.0	
85		87.28	1345.0		86.44	1579.0	
90		90.33	1324.0		89.49	1554.0	
95		93.38	1304.0		92.54	1530.0	
100		96.41	1285.0		95.58	1506.0	

9.11 Minimum Mechanical Properties of ACSR Conductor Components

To calculate the approximate ultimate tensile strength of an ACSR conductor as illustrated in Chapter 5, the ultimate tensile strengths for various sized aluminum and steel strands (wires) is required. The Canadian Standards Association (CSA) have tabulated these strengths in their CSA Standard C49-1965 as shown in Table 9.19.

Table 9.19 Minimum Mechanical Properties of ACSR Conductor Components

1. MINIMUM MECHANICAL PROPERTIES OF HARD-DRAWN ALUMINUM WIRE

NOMINAL WIRE DIAMETER Inches	ULTIMATE TENSILE STRENGTH Pounds per Square Inch	ULTIMATE ELONGATION IN 10 INCHES Per Cent
0.0501-0.0600	29,000	1.2
0.0601-0.0700	28,500	1.3
0.0701-0.0800	28,000	1.4
0.0801-0.0900	27,500	1.5
0.0901-0.1000	27,000	1.5
0.1001-0.1100	26,000	1.5
0.1101-0.1200	25,500	1.6
0.1201-0.1400	25,000	1.7
0.1401-0.1500	24,500	1.8
0.1501-0.1600	24,000	1.9
0.1601-0.2100	24,000	2.0
0.2101-0.2200	23,500	2.1

2. MINIMUM MECHANICAL PROPERTIES AND ZINC COATING REQUIREMENTS FOR STEEL CORE WIRE

NOMINAL WIRE DIAMETER inces	ULTIMATE TESILE STRENGTH Pounds per Square Inch	ULTIMATE ELONGATION PER CENT IN 10 INCHES	STRESS AT 1 PERCENT ELONGATION UNDER LOAD Pounds per Square Inch
0.0500-0.0599	190,000	4.0	170,000
0.0600-0.0749	190,000	4.0	170,000
0.0750-0.0899	190,000	4.0	170,000
0.0900-0.1039	190,000	4.5	165,000
0.1040-0.1199	190,000	4.5	165,000
0.1200-0.1399	190,000	5.0	160,000
0.1400-0.1799	190,000	5.0	160,000
0.1800-0.1899	190,000	5.0	160,000