FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES

DESIGN MANUAL, PART I OF III

PROCEDURES FOR THERMAL AND HYDRAULIC DESIGN

Energy Laboratory Report No. MIT-EL 78-014
Heat Transfer Report No. 80619-101
FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES

DESIGN MANUAL, PART I OF III

PROCEDURES FOR THERMAL AND HYDRAULIC DESIGN

by

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Sponsored by
Consolidated Edison Company of New York Inc.
New York, New York

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Heat Transfer Laboratory Report No. 80619-101

June 1978
FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES
Design Manual, Part I of III

ABSTRACT

The methodology utilized for the design of a forced-cooled pipe-type underground transmission system is presented. The material is divided into three major parts: (1) The Forced-cooled Pipe-Type Underground Transmission System Design Manual-Part I, (2) The Design Manual-Part II, and (3) the Forced-Cooled Pipe-Type Underground Transmission System Computer Program Design Manual.

The Design Manual Part I provides the thermal and hydraulic design analyses required for the design of a forced-cooled cable system of specified geometry. The thermal design establishes the relationship between the cable amperage, oil flow, and the conductor-to-oil temperature difference and provides a coolant loop energy balance which includes an analysis of the pipe-to-soil heat transfer. Combination of both permits the maximization of the cable amperage while maintaining the cable temperature below the maximum allowable value.

The hydraulic design establishes the pressure-flow characteristics for pipe-type cable systems and a systematic analysis is provided which allows for calculation of the pressure drop in the cable line and return line of the flow circuit as well as the circuit absolute pressure profile. The pressure drop governs the selection of circulation pumps, pipe strength characteristics, and strongly influences coolant loop length.

The Design Manual-Part II presents a description of the experimental and analytical research performed at M.I.T.'s Heat Transfer Laboratory which provides the relationships used in the design analysis of Design Manual-Part I.

The Computer program design manual provides a detailed description of the forced-cooled system computer program and the necessary program documentation. The computer program is basically a straightforward computerization of the design procedure of Design Manual-Part I. Six different computer design options are provided which permit complete flexibility for the design and optimization of the forced-cooled system. Four of the design options allow for the selection of alternative independent and dependent design variables and two design options provide for the system optimization based on specified optimization criteria.
ACKNOWLEDGEMENTS

This research work was supported by the Consolidated Edison Company of New York.

The cooperation of Mr. Michael D. Buckweitz of the Consolidated Edison Company is gratefully acknowledged.
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This report is concerned with the forced-cooling of underground pipe-type transmission lines as a means of optimizing the high voltage underground transmission systems for a minimum size and maximum ampacity. This work culminates a five-year research program studying the thermal and hydraulic aspects of the forced-cooling technique. The report combines all of the research work into a form that can be utilized for the design and optimization of the forced-cooled system.

The report is divided into three main parts:

PART I: The Forced-Cooled Pipe-Type Underground Transmission System Design Manual-Part I,

PART II: The Forced-Cooled Pipe-Type Underground Transmission System Design Manual-Part II,


The three parts are presented as three separate volumes, each of which contains its own introduction, list of tables, list of figures, nomenclature, references, etc. This has been done to facilitate the use of the material.

Design Manual-Part I provides the design procedure(s) for specifying the specific heat transfer and fluid mechanical parameters associated with the design of a forced-cooled underground pipe-type
transmission system.

Design Manual-Part II presents a description of the experimental and analytical research from which the design procedure of Part I is derived.

The computer program design manual-Part III provides a detailed description of the forced-cooled system computer program and the necessary program documentation. The computer program is basically a straightforward computerization of the Design-Manual-Part I. Six different computer design options are provided which permit complete flexibility for the design and optimization of the forced-cooled system. Four of the design options allow for the selection of alternative independent and dependent design variables and two design options provide for the system optimization based on specified optimization criteria.
PART I
DESIGN MANUAL - PART I:

THERMAL AND HYDRAULIC DESIGN OF A FORCED-COOLED PIPE-TYPE CABLE SYSTEM
ABSTRACT

The design manual provides for a complete thermal and hydraulic design of a forced-cooled pipe-type underground transmission line. The design manual is presented in two separate parts.

The Design Manual-Part I provides the thermal and hydraulic design analyses required for the design of a forced-cooled cable system of specified geometry. The thermal design establishes the relationship between the cable amperage, oil flow, and the conductor-to-oil temperature difference and provides a coolant loop energy balance which includes an analysis of the pipe-to-soil heat transfer. Combination of both permits the maximization of the cable amperage while maintaining the cable temperature below the maximum allowable value.

The hydraulic design establishes the pressure-flow characteristics for pipe-type cable systems and a systematic analysis is provided which allows for calculation of the pressure drop in the cable line and return line of the flow circuit. The pressure drop governs the selection of circulation pumps, pipe strength characteristics, and strongly influences coolant loop length.

The Design Manual-Part II presents a description of the experimental and analytical research performed at M.I.T.'s Heat Transfer Laboratory which provides the relationships used in the design analysis of Part I.
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NOMENCLATURE

Lower Case Letters

- $d_i$: cable insulation inside diameter (conductor diameter); in
- $d_o$: cable insulation outside diameter; in
- $e$: skid wire height; in
- $f$: friction factor; dimensionless
- $f_{c,ref}$: cable line reference friction factor; dimensionless
- $f_c$: cable line friction factor; dimensionless
- $f_r$: return line friction factor; dimensionless
- $h$: convective heat transfer coefficient at cable surface; BTU/hr-ft$^2^\circ$F
- $\Delta h$: elevation difference; ft
- $k_{\text{oil}}$: oil thermal conductivity; BTU/hr-ft$^2^\circ$F
- $k_{\text{tape}}$: cable metallic tape thermal conductivity; BTU/hr-ft $^\circ$F
- $m$: oil mass flow rate; lb$_m$/hr
- $q$: heat generation per unit area; BTU/hr ft$^2$
- $r$: radius; in
- $s$: skid wire axial spacing; in
- $t$: cable metallic tape thickness; in
- $z$: axial distance; ft

Upper Case Letters

- $A$: cross-sectional area; in$^2$
- $C_p$: oil specific heat capacity; BTU/lb$_m$ $^\circ$F
- $CF_1$: convection correction factor for pipe-type cable system heat transfer correlation; dimensionless
- $CF_2$: metallic tape correction factor for pipe-type cable system heat transfer correlation; dimensionless
- $D$: inside diameter of cable pipe; in
- $D_r$: inside diameter of return pipe; in
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<td>( D_H )</td>
<td>hydraulic diameter; in</td>
</tr>
<tr>
<td>( E )</td>
<td>line-to-line voltage; kilovolts</td>
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<td>( F_{11}, F_{12}, F_{22} )</td>
<td>factors which describe the steady state heat transfer relationship between the cable line, return line and sill [4]; BTU/hr-ft °F</td>
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<td>( Gr )</td>
<td>Grashoff number; dimensionless</td>
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<tr>
<td>( I_{fc} )</td>
<td>forced-cooled cable ampacity [Amps]</td>
</tr>
<tr>
<td>( I_{fc,avg} )</td>
<td>average cable ampacity [Amps]</td>
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<td>( I_{fc,max} )</td>
<td>maximum allowable cable ampacity [Amps]</td>
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<tr>
<td>( L )</td>
<td>axial flow length (cable segment length); ft</td>
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<td>( L_e )</td>
<td>equivalent length; in</td>
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<td>return line length; ft</td>
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<td>( L_r^* )</td>
<td>equivalent return line length; ft</td>
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<td>( N_u )</td>
<td>Nusselt number; dimensionless</td>
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<td>( Pr )</td>
<td>Prandtl Number; dimensionless</td>
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<td>( P_s )</td>
<td>static oil pressure; ( lb_f/in^2 )</td>
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<td>maximum permitted cable line oil pressure; ( lb_f/in^2 )</td>
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<td>minimum permitted cable line oil pressure; ( lb_f/in^2 )</td>
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<td>( P_{return,max} )</td>
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<td>( \Delta P )</td>
<td>pressure drop; ( lb_f/in^2 )</td>
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<td>total loop pressure drop (pump differential pressure); ( lb_f/in^2 )</td>
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<tr>
<td>( \Delta P_{HE} )</td>
<td>heat exchanger pressure drop; ( lb_f/in^2 )</td>
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<td>( \Delta P_D )</td>
<td>dynamic pressure drop; ( lb_f/in^2 )</td>
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<tr>
<td>( \Delta P_{EL} )</td>
<td>static pressure difference due to height elevation difference; ( lb_f/in^2 )</td>
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<td>( Q )</td>
<td>oil flow rate; gal/min</td>
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<td>( Q_{1a}, Q_{2a} )</td>
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<td>$R_{AC}$</td>
<td>AC electrical resistance; ohms</td>
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<td>$R_{DC}$</td>
<td>DC electrical resistance, ohms</td>
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<td>$R_e$</td>
<td>Reynolds number; dimensionless</td>
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<td>$R_a = Gr \cdot Pr$</td>
<td>Rayleigh number; dimensionless</td>
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<td>$T_{avg}$</td>
<td>average loop oil temperature; °F</td>
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<td>$T_c$</td>
<td>conductor temperature; °F</td>
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<td>$T_{cable,max}$</td>
<td>maximum permitted cable temperature; °F</td>
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<td>$T_{oil,min}$</td>
<td>minimum permitted oil temperature; °F</td>
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<td>$T_{oil,max}$</td>
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<td>$T_{cold}$</td>
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<td>heat exchanger inlet temperature; °F</td>
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<td>$T_1(z)$</td>
<td>cable line oil temperature at a distance z from the hot end of the heat exchanger; °F</td>
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<td>$T_2(z)$</td>
<td>return line oil temperature at a distance z from the cold end of the heat exchanger; °F</td>
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<td>heat exchanger temperature drop; °F</td>
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<td>air pre-cooler temperature drop; °F</td>
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<td>$T_{s-o}$</td>
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<tr>
<td>$W_c$</td>
<td>conductor energy loss per conductor-foot; w/ft</td>
</tr>
<tr>
<td>$W_d$</td>
<td>dielectric loss-per conductor-foot; w/ft</td>
</tr>
<tr>
<td>$W_p$</td>
<td>pipe induced voltage energy loss per conductor-foot; w/ft</td>
</tr>
<tr>
<td>$W_s$</td>
<td>sheath (tape) induced voltage energy loss per conductor-foot; w/ft</td>
</tr>
<tr>
<td>$W_{HE}$</td>
<td>total heat exchanger pre-cooler cooling capacity; BTU/hr</td>
</tr>
</tbody>
</table>
\( W_{AC} \)  heat exchanger pre-cooler cooling capacity; BTU/hr

\( W_{pump} \)  pump shaft power (hp)

\( Y_c \)  percentage increase in AC/DC resistance ratio at the conductor; dimensionless

\( Y_p \)  percentage increase in AC/DC resistance ratio at the cable pipe; dimensionless

\( Y_s \)  percentage increase in AC/DC resistance ratio at the cable sheath (tape); dimensionless

**Greek Letters**

\( \alpha \)  skid wire helix angle; degrees

\( \Delta \)  difference

\( \varepsilon_0 \)  dielectric constant; farad/meter

\( \varepsilon \)  dielectric constant of free space \((8.85 \times 10^{-12})\); farad/meter

\( \mu \)  absolute oil viscosity, CP

\( \rho \)  oil density; lbm/ft\(^3\)

\( \xi \)  dimensionless radius; dimensionless
1. INTRODUCTION

High-pressure oil-filled pipe-type cable circuits have been used for underground electrical power transmission for a number of years. In the early applications, oil was not circulated through the pipe. In such a "self-cooled" system, heat generated in the cables is transferred from the cable insulation to the pipe wall by natural convection through the oil and from the pipe to the atmosphere via conduction through the soil. The ampacity of the cables is limited by the maximum permitted insulation temperature which depends upon the rate of heat removal from the system. If heat is generated by losses in the cable faster than it is removed by conduction through the earth, the cables will heat up and exceed the maximum allowable cable temperature. Thus, in the case of a static oil circuit, the heat transfer characteristics of the surrounding soil limit the power-carrying capacity of the system.

In order to increase the ampacity of present-sized cables and thereby reduce the dependence of the cable-rating on the soil environment, forced-cooling can be utilized. In a forced-cooled cable system, chilled oil is circulated through the pipe-type cable circuit and the absorbed heat is transferred from the oil to the atmosphere at refrigeration stations located in the oil return line of the system. Heat continues to be transferred to the soil, but is now of secondary importance to the thermal operation of the cable circuit. Use of such
a cooling technique can significantly increase the load-carrying capacity of pipe-type electrical cable lines over that of similar self-cooled systems.

This design manual is intended to provide the necessary information required for the design of a forced-cooled cable system of specified pipe-type cable geometry. The design analysis includes a complete thermal design of the cable circuit and the design of the system flow circuit. The thermal design establishes the relationship between the cable amperage, oil flow, and the conductor-to-oil temperature difference (for a specified voltage) and provides for analysis of the pipe-to-soil heat transfer. Combination of both permits the maximization of the cable amperage while maintaining the cable temperature below the maximum allowable value.

The system flow circuit design establishes the pressure-flow characteristics for pipe-type cable systems and a systematic analysis is provided which allows for calculation of the pressure drop in the cable line and return line of the flow circuit. This pressure drop governs the selection of circulation pumps, pipe strength characteristics and strongly influences coolant loop length.

Creation of the flow circuit design and thermal design analyses required the solution of unique fluid mechanical and heat transfer problems. The manual consolidates the solutions into simple correlations and presents a concise design procedure. Additional information is also presented which is necessary for the complete under-
standing of the forced-cooled design concepts.

1.1 Design Manual Goals

The design manual is presented in two separate parts. Part I provides the procedure for specifying the specific heat transfer and fluid mechanical parameters associated with the design of a forced-cooled pipe-type cable system. Part II presents a description of the experimental and analytical research from which the design procedure is derived. Specifically, the manual has three basic design goals:

(1) Determination of the pressure-head losses of the circulating oil in a pipe-type cable system consisting of three circular power cables enclosed within a circular pipe. This permits calculation of the system pumping requirements and, combined with the static pressure profile, allows for specification of the maximum and minimum pressure points within the system.

(2) Establishment of the design relationships between the cable amperage, the circuit flow length, the fluid flow rate and the required cooling capacity. This is accomplished by:

   (a) Establishment of the relationship between the cable conductor temperature and the temperature of the circulating oil.

   (b) Evaluation of the proportion of generated heat which is transferred to the surrounding soil environment. The analysis includes both steady-state and transient system operation and is required for accurate prediction of the temperature rise of the circulating oil.
(3) Optimization of the forced-cooled cable system operation with respect to (1) and (2), taking into account transient operation, varying environmental conditions, and alternative operating schemes. (Complete system optimization requires coupling the design manual with the engineer's own economic analysis.) The manual includes information concerning alternative methods of operation and can be used only as a guide to achieve optimum system design. The corresponding computer program allows for more complete and simpler optimization of the forced-cooled system.

The flow chart on the following page represents an outline of the Design Manual - Part I and indicates the essential steps in achieving the design goals. The manual initially examines the physical make-up of the forced-cooled system in Chapter 2 and then proceeds to describe in Chapter 3 the design constraints (e.g. maximum cable temperature and maximum and minimum oil pressures), the design variables (e.g. amperage, oil flow rate, and length of coolant loops), and the fundamental relationships between the variables. The design relationships are subsequently used to qualitatively examine the design variable interrelationships. The following Chapter provides a general outline of the design analysis which explains the important parts of the analysis. Utilizing this background information, an explicit design analysis is presented in Chapter 5. The final Chapter of the manual examines the various design strategies which play an important role in optimizing the system operation.
2. DESCRIPTION OF THE FORCED-COOLED PIPE-TYPE CABLE SYSTEM

Initially, it is important to become familiar with the physical makeup of the forced-cooled pipe-type cable system. In the simplest form, the forced cooled circuit consists of a series connection of the cable line, oil return line, heat exchanger and oil circulation pump. Such an arrangement is shown in Figure 1. A pressure head-tank, also shown in this figure, maintains a minimum cable line pressure which insures the dielectric stability of the circulating oil.

The conventional three phase underground transmission line consists of three cables enclosed within a large diameter steel pipe with pressurized dielectric oil as shown in Figure 2. Details of important pipe-cable dimensions are shown in Figure 3. The cable pipe is normally covered with approximately 1/2 inch thick coal tar and enamel coating to provide cathodic protection. All underground transmission lines require trench digging for installation of cable and oil return pipes. The profile of a proposed double forced-cooled system, containing two parallel cable lines and oil return lines, is shown in Figure 4.

Each transmission line cable consists of a copper conductor covered with high quality insulating paper impregnated with dielectric oil (Figure 5). A thin copper tape is usually wrapped under the moisture seal assembly to smooth out the electric fields in the insulation. (Because of its high thermal conductivity it also tends to smooth out
the circumferential temperature distribution.) Each cable is provided with skid wires coiled around its circumference to ease pulling of the cable into the pipe and to protect it against damage. The longitudinal view of a single cable, Figure 6, describes the geometry associated with the skid wire. Although the cables are pictured in one particular configuration (relative positioning of the cables within the pipe) in the previous figures, in reality they assume a variety of different configurations along the length of the cable line. Five possible pipe-cable configurations, which were used for analytical study, are presented in Figure 7 and the geometry used to describe the relative positions of the cables is indicated. The dimension $e$ accounts for the presence of the skid wires and shows that the cables cannot be closer to each other or the pipe than the skid wire height.

Charging currents in the cables of AC circuits limit the length of underground transmission lines (about 15 miles for 345 kV cables) unless reactive compensation is used. However, even over such a "short" distance both the cable line and the oil return line can offer prohibitively large resistance (yielding high pressure losses) to the expected high flow rates. Therefore, in order to reduce circuit flow resistance while maintaining a desired cable cooling capability, the total transmission line must be divided into smaller segments (loops) with each cable line segment being cooled separately within an individual coolant loop. Presently, the best configuration for such a multiloop flow system has been found to be one of the type depicted in Figure 8 [1].
As observed, there are an even number of coolant loops of approximately equal length and the oil flow direction in each loop is opposite that of adjacent loops. This type of flow arrangement assures that a minimum pressure will occur at the end-of-line potheads. (A pothead is a complex cable termination and sealing device - sealed to contain system pressure and exclude contamination - which reinforces the cable insulation in a precise and predetermined fashion to accomplish the control of electrical stresses developed at the termination point.Externally, the pothead resembles a large spark plug.) Another important advantage of this dual direction flow scheme is that oil flow blocking diaphragms are not required. These diaphragms are used to divert oil flow in a specified direction in other types of circuit configurations and are usually subject to pressure limits that are well below the maximum strength of the pipe. (If diaphragms are utilized in some capacity in the system, their pressure limits must be taken into account when determining system pressure constraints.)

The design of a forced-cooled pipe type cable system of the type described requires specification of the important design variables and an understanding of the interrelationships between these variables. The following Chapter presents this information.
3. FORCED-COOLED PIPE-TYPE CABLE SYSTEM FUNDAMENTALS

The overall goal of the forced-cooled technique is to optimize high voltage underground transmission systems for a minimum size and a maximum ampacity. The maximum continuous current that a given electric power cable can carry is determined by the maximum permissible temperature at which its components may be operated (with a reasonable factor of safety). Subsequently, it is necessary to establish the values of the design variables which will safely and efficiently permit a forced-cooled power carrying capacity of amperage, $I_{fc}$. In order to do so, it is of prime importance to examine the basic design variables of a forced-cooled system and the "laws" which govern their interrelationship.

Section 3.1 presents the two thermal design relationships which must be satisfied in order to ensure safe thermal operation of the forced-cooled system. The third governing relationship examined is required in order to establish safe hydraulic operation. Section 3.2 continues with a discussion of the variables which make-up these three design relationships and the value constraints which limit certain variables. Section 3.3 concludes with a quantitative examination of the effects of certain variable interrelationships on the system design.

3.1 Basic System Governing Laws

3.1.1 Loop Energy Balance

The first thermal relationship which must be satisfied by a
coolant loop of a forced cooled system is the first law of thermodynamics: the amount of heat generated by the cables must equal the sum of the amounts of heat absorbed by the soil and the heat removed from the oil by the heat exchanger. Calculation of the cable heat generation is discussed first, below.

CABLE HEAT GENERATION

A selected forced-cooled cable ampacity, \( I_{fc} \), will produce specific cable power losses. These cable losses can be essentially divided into two groups: current induced losses, and voltage induced losses. The electric current carried by a copper conductor generates heat proportional to the square of \( I_{fc} \). Similarly the induced currents in the cable sheath and pipe generate heat proportional to the square of the induced currents. Due to the cyclic nature of the alternating current, the current density is not uniform in the copper conductor and only a small portion flows through its center. This phenomenon, called the skin effect, further increases the current induced losses in the cable. (The cable proximity also contributes to the cable heat generation.)

An expression developed for these current induced losses in the conductor, sheath and pipe, in terms of the AC/DC resistance ratio of the cable system, is as follows [2],

\[
\frac{R_{AC}}{R_{DC}} = 1 + Y_c + Y_s + Y_p \quad (3.1)
\]
where

\[ Y_c = \text{increment due to the skin and proximity effects} \]
\[ Y_s = \text{increment due to induced currents in the sheath} \]
\[ Y_p = \text{increment due to induced currents in the pipe} \]

The corresponding losses physically generated in the conductor, sheath and pipe are, respectively

\[ W_c = I_{fc}^2 R_{DC}(1 + Y_c) \]
\[ W_s = I_{fc}^2 R_{DC} Y_s \]
\[ W_p = I_{fc}^2 R_{DC} Y_p \]  \hspace{1cm} (3.2)

The voltage induced losses or dielectric losses \((W_d)\) result from the cyclic change in the cable voltage polarity. The dielectric heating is distributed throughout the insulation and is inversely proportional to the square of the radius. The total dielectric loss for a shielded cable is [3]

\[ W_d = \frac{0.00276 E^2 \varepsilon / \varepsilon_0 \cos \phi}{\log \left( \frac{2d_o - d_i}{d_o} \right)} \text{ w/ft} \]  \hspace{1cm} (3.3)

where

\[ W_d = \text{dielectric loss per conductor foot at 60 cycles per second (w/ft)} \]
\[ E = \text{line-to-line voltage (kilovolts)} \]
\[ \varepsilon = \text{relative dielectric constant (Farads/meter)} \]
\[ \varepsilon_0 = \text{dielectric constant of free space (8.85 \times 10^{-2}) (Farads/meter)} \]
\( d_o \) = cable insulation outside diameter (in)

\( d_i \) = cable insulation inside diameter (in)

\( \cos \phi \) = cable power factor (dimensionless)

The total heat generated by the three cables of the forced-cooled system is equal to

\[
W = 3 \left( W_C + W_S + W_P + W_d \right)
\]

\[
= 3 \left[ I_{fc}^2 R_{DC} (1 + Y_c + Y_s + Y_p) + W_d \right] \quad (3.4)
\]

**ADIABATIC PIPE ENERGY BALANCE**

The dissipated energy is transferred to the circulating oil and to the surrounding soil environment. If soil heat transfer is neglected, the total heat dissipated by the cables must be absorbed by the oil, and the relation governing this energy conservation is given as:

\[
\rho \ Q \ C_p \ \Delta T = WL \quad (3.5)
\]

where

\( \rho \) = oil density

\( C_p \) = oil specific heat

\( Q \) = oil flow rate

\( \Delta T \) = coolant loop temperature drop

\( L \) = coolant loop length
Equation 3.5 provides a conservative coolant loop energy balance and is therefore not recommended to be used for design purposes.

**NON-ADIABATIC PIPE ENERGY BALANCE**

Accurate prediction of the forced-cooling requirements of an underground transmission line requires the determination of the amount of heat transferred from the pipes (cable and return) to the soil environment. The major factors which influence the rate of heat flow are oil temperature level in the pipes, time of year, soil thermal properties, and the proximity of the pipes to each other and to the ground surface (all of which establish the oil-to-soil thermal resistance.) Other parameters which influence the thermal behavior of the system are pipe size, rate of heat generation, rate of oil flow and the thermal properties of the oil (the last three of which are also important in the adiabatic case) [4].

Due to the complex nature of this problem a numerical method is used by KOCI [4] to model the pipe-soil system. The results of this work are formulated as the oil temperature distribution along the axes of the cable and return lines (for a given loop) which accounts for heat transferred to the oil and to the soil environment:

\[
T_1(z) = A_1 + B_1 \exp \left( \frac{\lambda_1}{C_p \dot{m}} z \right) + C_1 \exp \left( \frac{\lambda_2}{C_p \dot{m}} z \right) \quad (3.5a)
\]


\[ T_2(z) = A_2 + B_2 \exp\left(\frac{\lambda_1}{c_p m} z\right) + C_2 \exp\left(\frac{\lambda_2}{c_p \dot{m}} z\right) \] (3.5b)

where

- \( T_1(z) = \) cable oil temperature at a distance \( z \) from the hot end of the heat exchanger
- \( T_2(z) = \) return line oil temperature at a distance \( z \) from the cold end of the heat exchanger
- \( A_1, B_1, A_2, B_2 = \) constants which are determined from the results of the computer model of the oil-to-soil heat transfer
- \( C_1, C_2 \)
- \( c_p = \) oil specific heat
- \( \dot{m} = \) oil mass flow rate

Further details concerning the application of the non-adiabatic energy balance can be found in Section 5.1.

**3.1.2 Cable-to-Oil Heat Transfer Correlation**

A second heat transfer relationship, which exists between the cable conductor temperature and the bulk oil temperature for a specified cable amperage and voltage, is required in order to prevent the cable from exceeding its temperature limit. This relationship is complex since the cable-to-oil heat transfer is complicated by the close proximity of one cable to another, (when two cables come into close or direct contact, their mutual presence causes a large increase in the resistance to heat transfer near the point of contact. Consequently, the cable insulation near this point experiences an increase
in temperature, which in turn elevates the conductor temperature.)
The solution of this two-dimensional problem for arbitrary cable configurations (relative positions of the cables within the pipe) has been obtained by means of a numerical method [5].

Results of the numerical analysis have been used to formulate a pipe-type cable heat transfer correlation:

\[
\frac{W_c}{W_d} = (1.764 \times K_{oil} \left( \frac{T_c - T_{oil}}{W_d \times \ln \frac{d_o}{d_i}} \right) -0.53) \times CF_1 \times CF_2 \quad (3.7)
\]

where

- \( W_c \) = conductor resistive losses
- \( W_d \) = oil dielectric losses
- \( T_c - T_{oil} \) = conductor-to-oil temperature drop
- \( CF_1 \) = convection correction factor
- \( CF_2 \) = metallic tape correction factor
- \( d_o \) = cable insulation outer diameter
- \( d_i \) = conductor diameter

Equation 3.7 can be used to predict the conductor-to-oil temperature drop for a specified cable ampacity or the cable ampacity for a specified temperature drop. Further details as to the creation and application of the pipe-type cable system heat transfer correlation are provided in Appendix D and Section 5.2, respectively.

3.1.3 Oil Pressure-Flow Loss

An important part of the design of a forced-cooled pipe-
type cable system is the determination of the pressure drop developed along the circuit when the chilled oil is being circulated through the system. The pressure loss governs the selection of pumps, pipe strength characteristics, and strongly influences coolant loop length. The following relation, the definition of the friction factor, permits such pressure drop calculations;

\[
\Delta P = \frac{\rho L f P}{2A^3} Q^2
\]  

(3.8)

where

\[
\begin{align*}
\Delta P & = \text{pressure drop} \\
L & = \text{flow length} \\
P & = \text{pipe-cable wetted perimeter} \\
A & = \text{cross-sectional flow area} \\
Q & = \text{oil flow rate} \\
f & = \text{friction factor}
\end{align*}
\]

and the values of the friction factor as a function of Reynolds number (for the cable line and return line) are obtained experimentally or are predicted using numerical techniques (based on experimental information.) Friction factor values for the cable and return line are provided for in Section 3 of Chapter 5. Application of Equation (3.8) is also discussed in this section.

Equations (3.5) and (3.8) can be combined into one equation, eliminating \( Q \), which predicts the pressure losses for a specific cooling requirement.
Thus, the pressure drop increases substantially with loop length and with heat dissipation per unit length.

3.2 **System Variables and Constraints**

The variables appearing in the governing relations are now examined along with the specific system constraints which limit their design values. The variables can be categorized as dependent of independent, although the choice of which variables are independent is somewhat arbitrary and based on the design situation. One case has been selected in order to clarify the presentation of the variables.

3.2.1 **System Constraints**

Important to the safe design of the forced-cooled pipe-type cable system are the constraints placed on the system design variables. The primary temperature constraints are:

1. \( T_{\text{cable, max}} \) - maximum allowable cable temperature (usually the maximum temperature that the paper insulation will tolerate or approximately 185°F.)

2. \( T_{\text{oil, min}} \) - minimum permissible oil temperature which prevents pumping of the circulating oil due to high viscosity.

3. \( T_{\text{oil, max}} \) - maximum allowable oil temperature which maintains the cable below its temperature constraints (Calculated from Equation (3.7).)
The primary flow constraints are:

(4) $P_{\text{cable, max}}$ - maximum allowable cable-line oil pressure based on pipe mechanical strength characteristics (hoop strength.)

(5) $P_{\text{return, max}}$ - maximum allowable return line oil pressure based on pipe mechanical strength characteristics (hoop strength.)

(6) $P_{\text{cable, min}}$ - minimum allowable cable-line oil pressure corresponding to the pressure at which the circulating oil will break down and lose its dielectric properties.

The primary electrical constraint is:

(7) Charging current - In AC power transmission cables, the distance from the outer surface of the conductor to the metal sheath (zero potential) is so small (approximately one inch) that there exists a continuous "charging current" between conductor and sheath. This current serves no useful purpose. Its magnitude varies inversely with insulation thickness and directly with the length of the cable and the voltage. Subsequently, there exists a critical length, such that the accumulated current is equal to the current rating of the cable. In a 345 KV system, all the current carrying capability of the conductor is utilized in approximately 26 miles. Fifteen miles is a typical length for 345 KV cables and 25 miles for 138 KV cables (without compensation equipment.)

3.2.2 Independent Variables

(1) OIL - The type of oil utilized in a forced-cooled system has an important impact on the design. Low viscosity oils which maintain adequate dielectric characteristics, as well as reduce flow losses, are highly desirable.
(2) $d_0$ - Cable outer diameter (excluding skid wire.) For a specified conductor diameter, proper insulation thickness is required to insulate the conductor from its outer sheath and the surrounding earth. A 345 KV system requires at least a one-inch thickness of oil impregnated paper.

(3) $D$ - Pipe Diameter. Since pressure losses are dependent upon pipe diameter (Equation 3.8), manipulation of this variable can be of importance in reducing head-losses in a forced-cooled system.

(4) $L$ - Cable line flow path length. The flow path length, combined with the inlet and outlet temperatures, determines the required flow rate (Equation (3.5)) and subsequently, the flow losses. Constraints placed on system pressures limit the coolant loop length. (The maximum coolant loop length corresponds to the length at which the minimum allowable flow rate required for energy removal yields pressure losses equal to the maximum permissible pressure drop.) The combined value of the cable line lengths must not exceed $L_{\text{critical}}$.

(5) $I_{fc}$ - Forced-cooled cable ampacity rating. This variable implicitly appears in Equation (3.5) in terms of the losses, $W$. The value selected can be based on a peak amperage or some weighted amperage.

(6) $Q$ - Coolant loop oil flow rate. The loop flow rate determines the value of the heat exchanger outlet temperature, $T_{\text{cold}}$ which is important in terms of system optimization. The value of $Q$ also determines the value of the loop pressure losses, $\Delta P$. The maximum value, $Q_{\text{max}}$, corresponds to the flow rate which produces the maximum permissible loop pressure drop. The minimum value, $Q_{\text{min}}$, corresponds to the flow rate which produces a value of $T_{\text{cold}}$ such that the oil cannot be pumped.

3.2.3 Dependent Variables

(7) $T_{\text{Hot}}$ - Cable line outlet oil temperature. Equation (3.7) describes the fundamental relationship between $T_{\text{Hot}}$
and the independent variables ($T_{\text{Hot}}$ also depends slightly on the oil flow rate, $Q$). A typical forced-cooled cable system design allows the value of $T_{\text{Hot}}$ to achieve that maximum oil temperature, $T_{\text{oil,max}}$, which maintains the conductor temperature just below the cable temperature constraint.

(8) $T_{\text{Cold}}$ - Return line inlet temperature (heat exchanger outlet temperature.) The value of this temperature must satisfy the coolant loop energy balance of Equation (3.6a) and (3.6b) for a given mass flow rate, cable line length, $T_{\text{Hot}}$, and cable ampacity. The temperature level at which the coolant loop operates is determined by the value of $T_{\text{Cold}}$ and therefore plays an important role in the design optimization (see Chapter 6.)

(9) $\Delta P$ - Coolant loop pressure drop. Equation (3.8) describes the relationship between $\Delta P$ and the selected independent variables.* The value of the pressure drop is subject to system pressure constraints and to constraints placed on pump power input.

*(Notice that the pressure drop is also dependent upon the dependent variable $T_{\text{oil,max}}$ or $Q$, if Equation (3.7) is utilized.)*

3.3 Examination of Variable Interrelationships

Using the governing laws, the interrelationships between the dependent and independent variables are qualitatively examined in Table 1. One independent variable at a time is permitted to increase or decrease from its initial value while the remaining independent variables are held constant; the effects on the dependent variables are established along with the functional dependence on the changing independent variable (and other variables which also change.) As an example, assume that the preliminary design of a forced-cooled system (of selected amperage) is being undertaken, and for the particular design it is desired
to maintain a specific cable line temperature differential, $\Delta T$ (in order to check the effect of a specific cable line temperature in the operation of the system.) The designer is interested in determining the effect of variable loop lengths on the required flow rate, $Q$, and the resulting pressure drop, $\Delta P$. If, for simplicity sake, an adiabatic system is considered, Equation (3.5) shows that the flow rate is a direct linear function of the flow length, whereas the pressure drop, according to Equation (3.9), is a direct function of $L^3$ (for constant $\Delta T$, $f_c$ and $A$.) Thus, if the designer replaced an original four loop design by an 8-loop system (assuming equal loop lengths), the required flow rate in each loop would be halved and the pressure loss would be reduced by a factor of approximately 8 (friction factor is also a function of $Q$.) If, however, only four pumping stations are permitted (due to siting constraints), and it so happens that the loop lengths will be of such a length as to bring about flow losses in excess of pre-design constraints, another approach must be used to reduce the flow losses.

Since loop length, the temperature rise, and the flow rate must remain constant, the only alternative is to change the pipe-type cable geometry. Table 1 shows that an increase in flow area is a viable means of reducing flow losses. In this case, the pressure drop is a function of $P/A^3$. Consequently, if the standard 10.25" I.D. pipe increased in diameter by one inch, an approximate 56% reduction in losses will result.

For the same preliminary design, the engineer is interested in determining the effects (on the system operation) of increasing the
ampacity rating of the cables by 50% above that of the original system (identical loops.) Initially, it is decided to maintain the same loop length and loop pressure drop which subsequently fixes the oil flow rate at its original value. Table 1 shows that the resultant temperature rise approximately varies according to the square of the current; (if $W_d$ is small compared to the conductor losses and the conservative adiabatic pipe case is considered) therefore, if $I_{fc}$ is increased by 50% the oil temperature rise will increase by a factor of about 2.75. This extreme effect is considered inappropriate (based on established design criteria) and so it is decided to maintain $\Delta T$ at its original value, but to allow $\Delta P$ to change. In this case, the flow rate increased by a factor of $(1.5)^2$ or 2.25 which increases the pressure drop by approximately 5 times the original value (friction factor change is ignored as a first approximation.) Again, this effect is extreme, which leads to determining the effect of maintaining the loop pressure drop and temperature rise at the original value. Table 1 shows that the flow rate will increase by a factor of $(1.5)^{2/3}$ (or 1.3), while the loop length must decrease by a factor of $(1.5)^{4/3}$ (or 1.72) which results in the utilization of an 8 loop system.

The above examples have been presented in order to illustrate some of the important design variable relationships and the ability to compare design alternatives without performing tedious calculations. Besides using Table 1, the fundamental equations can be used if a number of variables are to be changed by some specified incremental values.
In Chapter 6 the strategy of choosing certain values of the design variables is discussed.
4. GENERAL OUTLINE OF THE DESIGN PROCEDURE

The material presented in the previous sections provides the necessary background information required for the presentation of the forced-cooled pipe-type cable system design procedure. The outline of this procedure is shown in flow chart form in Figure 9 and consists of four fundamental analysis steps:

(A) The forced-cooled pipe-type cable system energy balance;
(B) the pipe-type cable system conductor-to-oil heat transfer analysis;
(C) the pipe-type cable system flow-pressure drop analysis (and pressure profile determination); and
(D) the system optimization.

The independent design variables are shown as inputs to the blocks and the dependent variables as the outputs. The interdependence of the design steps is indicated by the interconnecting line segments.

4.1 Step A - Pipe-Type Cable System Energy Balance

Step A of the design analysis satisfies the energy balance between the heat dissipated by the cables and the heat absorbed by the oil and the surrounding soil environment. If the pipe wall is considered to be an adiabatic surface, all of the dissipated energy is absorbed by the circulating oil and Equation 3.5 can be used to satisfy the relationship between the flow rate, the temperature profile and the system energy losses. However, since soil heat transfer has been ignored, utilization of Equation 3.5 results in a conservative estimate of the
required system cooling requirements. Rather, Equations 3.6a and 3.6b can be utilized to predict the temperature profiles of the cable line and return line while accounting for the energy exchange between the pipes and the soil and for the important interaction between the cable and return pipe. The results of the latter analysis are an accurate determination of the cooling capacity required to maintain a specified cable ampacity. Since the amount of heat transferred to the soil depends upon the temperature of that environment, the required cooling capacity will vary throughout the year.

The input variables to design Step A depend upon the particular design situation. In Figure 9 the inputs include the cable ampacity, the loop length, the heat exchanger outlet temperature, the heat exchanger inlet temperature (cable line maximum temperature), the oil properties, and the necessary parameters which define the system pipe-soil interaction. The analysis, in this case, determines the flow rate which produces the proper temperature profiles (in the cable and return lines) needed to satisfy the imposed heat exchanger temperatures. Another design situation may arise in which it is desired to calculate the heat exchanger outlet temperature for a specified flow rate and inlet temperature. In a third case, Step A can be used to find loop length required to produce a specific heat exchanger temperature drop for a specified flow rate.
4.2 **Step B - Pipe-Type Cable System Conductor-to-Oil Heat Transfer Analysis**

Step B of the design analysis satisfies the heat transfer relationship, Equation 3.7, which exists between the cable conductor temperature and the bulk oil temperature. Thus, for a given cable amperage and voltage it is possible to determine that oil temperature which will prevent the conductor temperature from exceeding its maximum value. It is typical to operate the system so that the heat exchanger inlet temperature is maintained at this maximum allowable oil temperature while permitting the outlet temperature to vary.

The input variables to design Step B, for the case shown in Figure 9, include the cable ampacity, the cable temperature constraint, the pipe-cable geometry, the oil flow rate, and the oil properties. The output given by the analysis is the maximum possible bulk oil temperature. Other possible variations of this analysis can provide the conductor temperature per specified oil temperature or the required cable ampacity per specified conductor-to-oil temperature drop.

4.3 **Step C - Pipe-Type Cable System Flow Pressure-Drop Analysis**

Step C of the design analysis determines the resulting pressure profile for a flow loop of specified pipe-cable geometry and flow rate. The analysis utilizes Equation 3.7 and the friction factor-Reynolds Number relationship (for the cable line and the return line) so as to determine the dynamic pressure loss within the loop. The
The total system pressure profile is then determined by calculating the static pressure profile and adding to it the dynamic pressure losses.

All inputs to Step C are shown in Figure 9 and include the loop length, head-tank pressure, pipe-cable geometry, oil properties, and topographic information.

4.4 Step D - Forced-Cooled Pipe-Type Cable System Optimization

System optimization is not covered in the design manual in a quantitative manner. (Chapter 6 qualitatively examines the effects of the various design variables on system operation.) Typically this design step will systematically examine the overall system operation while varying certain design parameters and select the best design on the basis of predesignated design criteria. This design criteria can be, for example, the minimum required system energy input per year (minimum operational outlay of funds) or perhaps the minimization of the number of system loops (initial capital expenditures.) The accompanying computerized design manual can easily be used to compare design alternatives.

The forced-cooled pipe-type cable system design analysis is found in the following section. Design steps (A), (B) and (C) are presented separately and can be used in any order that is desired (Step (D) is not explicitly presented.) The analyses contained in each design step have been constructed in a step-wise fashion to facilitate usage. The total analysis combines the work of several MIT re-
searchers on the prediction of pressure head losses and heat transfer in pipe-type cable circuits [1,4,5,6,7] and is presented in conjunction with several well-known experimental and analytical relationships in graphical form. Additional analysis required to complete the design manual was performed by the authors and is contained in the appendices.
5. **FORCED-COOLED PIPE-TYPE CABLE SYSTEM DESIGN ANALYSIS PROCEDURE**

5.1 **Step A - Coolant Loop Energy Balance**

5.1.1 **Design Procedure Explanation**

The coolant loop energy balance can be stated as

\[
\text{TOTAL CABLE ENERGY LOSS} = \text{CABLE-TO-OIL HEAT TRANSFER} + \text{PIPE-TO-SOIL HEAT TRANSFER}
\]

Satisfaction of this relationship allows for the determination of the forced cooling requirements per specified cable amperage, circuit flow length, and fluid flow rate. As a matter of completeness, the loop energy balance relations will be examined for both the adiabatic (no heat transfer to soil) and non-adiabatic systems (see section 3.1.1).

Since the cable energy loss used in these energy balance relations depends upon the value of the ampacity utilized, a few pertinent remarks are necessary. The ampacity of an underground cable transmission system does not remain constant but, rather, oscillates between the peak value \(I_{fc,\text{max}}\) and some minimum value. Therefore, the cable energy loss (in the form of heat) changes with the changing values of the instantaneous current. Use of the peak current value to calculate the total cable energy loss will, subsequently, result in a very
conservative forced-cooled system design. It is therefore recommended to use the daily average value of the cable ampacity, $I_{fc,avg}$ in the cable energy loss calculations. This value is based on previous records of cable power generation.

5.1.2 Design Calculations

A.1 Adiabatic System

1. Calculate the total cable energy loss per foot of cable length, $W$, for the selected cables and for the desired ampacity, $I_{fc}$:

$$W = 3[I_{fc}^2 R_{DC}(1 + Y_c + Y_s + Y_p) + W_d]; \text{w/ft}$$

where:

- $R_{DC} =$ cable DC electrical resistance [$\Omega$]
- $Y_c =$ percent increase of AC/DC resistance ratio at conductor [dimensionless]
- $Y_s =$ percent increase of AC/DC resistance ratio at cable sheath [dimensionless]
- $Y_p =$ percent increase in AC/DC resistance ratio at pipe [dimensionless]
- $I_{fc} =$ the cable ampacity on which the total cable loss is to be based (see section 5.1.1) [amps]
- $W_d =$ total dielectric loss per cable [w/ft]

If required, Equation 3.3 can be used to determine the value of the total dielectric loss, $W_d$.

2. Figure 10 graphically represents the equation governing
the energy conservation for the coolant loop of the forced-cooled system (assuming no soil heat transfer-no return line temperature drop)

$$\rho \ Q \ \frac{C_p}{W} \ \Delta T = 0.4245WL$$

where:

- $\rho = \text{oil density \ [lbm/ft}^3\text{]}$
- $C_p = \text{oil specific heat \ [BTU/lbm}{^\circ F]}$
- $Q = \text{coolant loop oil flow rate \ [gal/min]}$
- $\Delta T = \text{cable line oil temperature drop \ [^\circ F]}$
- $L = \text{cable line axial length \ [ft]}$

Using this figure in conjunction with the average loop oil properties (based on average loop temperature) and the selected values of the independent variables, determine the resultant value of the desired dependent variable. (Certain dependent variables, whose values are calculated in other parts of the design procedure, may be inputs to the energy balance.)

Example 1: Determine, for a specified cable ampacity, the value of the flow rate, $Q$, which is required to produce a temperature rise, $\Delta T$, across a specified cable line length, $L$. (In this case, the heat exchanger inlet temperature, $T_{hot}$, may be a dependent variable whose value ($T_{oil, max}$) is calculated in Step C of the Design Procedure and $T_{cold}$ may be a specified independent variable.)
a) Utilizing the value of $T_{hot}$ (or $T_{cold}$) and the desired $\Delta T$, calculate the average oil temperature, $T_{avg}$, of the cable line. Use this average temperature to calculate the required oil properties.

b) Calculate the value of $\Delta T/L$ in the units indicated in Figure 10.

c) Read from this figure the value of the product, $C_p \rho Q$, using the dimensions indicated, and solve for the required oil flow rate $Q$ from known values of $\rho$ and $C_p$ for the oil.

Example 2: Determine the required inlet temperature of the cable line, $T_{cold}$, for a specified outlet temperature, $T_{hot}$, oil flow rate, $Q$, and the cable line length, $L$.

a) Since the inlet temperature is unknown, the average values of the oil properties cannot be initially determined. An iterative procedure is utilized which initially assumes oil property values which correspond to $T_{hot}$. (The oil properties required are density and specific heat.)

b) Calculate the value of the product $C_p \rho Q$ in the units indicated in Figure 10.

c) Utilizing the calculated value of $W$, read from Figure 10 the value of $\Delta T/L$. Multiply this value by the cable line length, $L$, in order to determine $\Delta T$.

d) $T_{cold} = T_{hot} - \Delta T$

e) Recalculate the value of $T_{cold}$ (steps b & c) using the oil properties corresponding to the new value of $T_{avg}$. Iterate until the value of $T_{cold}$ does not change.

A.2 **Non-Adiabatic System** (includes soil heat transfer)

1. Calculate the total cable loss per foot of cable length, $W$, for the selected cables and for the desired amapcity, $I_{pC}$ (see A1 - part 1).
2. Utilize Equations 3.6(a) and 3.6(b) in conjunction with the average loop oil properties and the selected values of the independent variables in order to determine the resultant value of the desired dependent variable. Equations 3.6(a) and 3.6(b) are reprinted below.

\[
T_1(z) = A_1 + B_1 \exp \left( \frac{\lambda_1}{C_p} z \right) + C_1 \exp \left( \frac{\lambda_2}{C_p} z \right) \quad (3.6a)
\]

\[
T_2(z) = A_2 + B_2 \exp \left( \frac{\lambda_1}{C_p} z \right) + C_2 \exp \left( \frac{\lambda_2}{C_p} z \right) \quad (3.6b)
\]

where:

\[
A_1 = -\left( a_{22} Q_g^* + a_{12} Q_{2a} \right)
\]

\[
A_2 = a_{12} Q_g^* + a_{11} Q_{2a}
\]

\[
B_1 = \frac{(\lambda_2 - 1) A_1 + A_2 - \lambda_2 T_1(o)}{\bar{\lambda}_1 - \lambda_2}
\]

\[
B_2 = \frac{\lambda_1 - F_{11}}{F_{12}} B_1
\]

\[
C_1 = T_1(o) - A_1 - B_1
\]

\[
C_2 = \frac{\lambda_2 - F_{11}}{F_{12}} C_1
\]

and

\[
a_{11} = \frac{F_{11}}{F_{12} - F_{11} F_{22}}
\]
\[ a_{12} = \frac{F_{12}}{F_{12} - F_{11}F_{22}} \]
\[ a_{22} = \frac{F_{22}}{F_{12} - F_{11}F_{22}} \]
\[ \lambda_1 = \frac{1}{2} (F_{11} - F_{22} + \sqrt{F_{11}^2 + F_{22}^2 + 2F_{11}F_{22} - 4F_{12}^2}) \]
\[ \lambda_2 = \frac{1}{2} (F_{11} - F_{22} - \sqrt{F_{11}^2 + F_{22}^2 + 2F_{11}F_{22} - 4F_{12}^2}) \]
\[ \bar{\lambda}_1 = \frac{F_{11} + F_{12} - \lambda_1}{F_{12}} \exp \left( \frac{-\lambda_1}{C_p^m} L \right) \]
\[ \bar{\lambda}_2 = \frac{F_{11} + F_{12} - \lambda_2}{F_{12}} \exp \left( \frac{-\lambda_2}{C_p^m} L \right) \]
\[ Q_g^* = W - Q_{1a} \]

where:

\[ T_1(z) = \text{cable line oil temperature at a distance } z \text{ from the hot end of the heat exchanger [°F]} \]
\[ T_2(z) = \text{return line oil temperature at a distance } z \text{ from the cold end of the heat exchanger [°F]} \]
\[ F_{11}, F_{12}, F_{22} = \text{factors which describe the steady state heat transfer relationship between cable line, return line, and soil. The factors are determined from the computer program of Koci [4] [BTU/hr-ft²°F]} \]
\[ Q_{1a}, Q_{2a} = \text{soil heat transfer values which take into account the dynamic heat transfer effects from the cable and return lines to the soil. Determined from Koci [4]. [BTU/hr-ft]} \]
\[ C_p = \text{oil specific heat based on the average loop temperature } [\text{BTU/lbm }^\circ \text{F}] \]

\[ \dot{m} = \text{oil mass flow rate based on oil properties taken at the average loop temperature } [\text{lbm/hr}] \]

\[ L = \text{axial line length (see Figure 11) } [\text{ft}] \]

Figure 11 provides insight into the application of Equations 3.6a and 3.6b. Shown is a typical oil temperature profile for a coolant loop where the oil leaving the heat exchanger is further cooled in the sending pipe (return pipe) by the surrounding soil and then heated by the generated heat in the cable pipe. Observe that the temperature profile for the cable line starts from the hot end \( T_1(o) = T_{\text{hot}} \) and proceeds along the line until the cable line segment (of the loop under study) ends \( T_1(L) = T_2(L) \). Likewise, the temperature profile for the sending line starts at the cold end \( T_2(o) = T_{\text{cold}} \) and proceeds along the line until the sending line ends \( T_2(L) = T_1(L) \).

**Example 1:** Determine the value of the flow rate, \( Q \), which is required to produce a specified heat exchanger outlet temperature, \( T_{\text{cold}} \), for a specified axial line length, \( L \), ampacity \( I_{\text{fc}} \), soil properties, and time of year.

a) Obtain from "The Transient Heat Conduction In-The-Soil" computer program [4] the values of \( F_{11} \), \( F_{12} \), \( F_{22} \), \( Q_{1a} \), and \( Q_{2a} \).

b) Calculate the average loop oil temperature, \( T_{\text{avg}} \), in order to determine the average loop oil properties.

c) Equation 3.6(b) can be used in an iterative manner in order to determine the required loop flow rate, \( Q \).
At the heat exchanger outlet, the equation becomes

\[ T_{2(o)} = T_{\text{cold}} = A_2 + B_2 + C_2 \]  \hspace{1cm} (5.2)

The values of \( B_2 \) and \( C_2 \) are dependent on the value of the oil flow rate and therefore values of \( m \) are selected until Equation 5.2 is satisfied.

(The value of \( B_1 \) directly depends upon the value of \( m \) (in terms of \( \lambda_1 \) and \( \lambda_2 \)). The values of \( B_2, C_1 \) and \( C_2 \) depend on the value of \( B_1 \).)

d) The flow rate \( Q \) is determined from the equation

\[ Q = 0.124 \frac{\dot{m}}{\rho} \]  \hspace{1cm} (5.3)

where:

- \( Q \) = loop oil flow rate \([\text{gal/min}]\)
- \( \rho \) = oil density \([\text{lbm/ft}^3]\)
- \( \dot{m} \) = mass flow rate \([\text{lbm/hr}]\)

Example 2: Determine the required heat exchanger outlet temperature, \( T_{\text{cold}} \), for the specified inlet temperature, \( T_{\text{hot}} \), axial line length, \( L \), ampacity, \( I_{\text{fc}} \), oil flow rate, \( Q \), soil properties and time of year.

a) Obtain from "The Transient Heat Conduction in the Soil" computer program [4] the values of \( F_{11}, F_{12}, F_{22}, Q_{1a}, \) and \( Q_{2a} \).

b) The average loop oil properties are initially unknown. An iterative procedure is utilized which initially assumes oil property values which correspond to \( T_{\text{hot}} \). (This is not a bad approximation since the values of specific heat and density do not change a great deal with temperature (see Appendix B.2.).)
c) Calculate the values of $A_1$, $B_1$, $C_1$ and $A_2$, $B_2$ and $C_2$. Use Equation 5.2 to calculate $T_{\text{cold}}$.

$$T_{\text{cold}} = A_2 + B_2 + C_2$$ (5.2)

d) Recalculate the value of $T_{\text{cold}}$ (steps b & c) using the values of the oil properties corresponding to the new value of $T_{\text{avg}}$. Iterate until the value of $T_{\text{cold}}$ does not change.

A.3 **Heat Exchanger Cooling Capacity and Energy Requirements**

1. The total heat exchanger cooling capacity is calculated from the equation,

$$W_{\text{HE}} = 8.04 \rho Q C_p \Delta T_{\text{HE}}$$ (5.4)

where:

- $W_{\text{HE}}$ = heat exchanger cooling capacity [BTU/hr]
- $\rho$ = oil density (average value) [lbm/ft$^3$]
- $Q$ = oil flow rate [GPM]
- $C_p$ = oil specific heat (average value) [BTU/lbm$^\circ$F]
- $\Delta T_{\text{HE}}$ = heat exchanger oil temperature drop
  
  $(T_{\text{hot}} - T_{\text{cold}})$ [$^\circ$F]

2. When calculating the energy requirements of the heat exchange unit, use of the pre-cooler must be taken into consideration. The pre-cooler lowers the temperature of the incoming oil to a specified value based on a known value of the ambient air temperature. The refrigeration unit is used as necessary to further lower the oil temp-
erature to the final outlet value. The energy requirements of the pre-cooler fans are much lower than the refrigerator energy requirements which must be taken into account for the total system design. This becomes important when trying to optimize the loop flow rate in order to achieve minimum energy input for the entire year.

The cooling power of the air pre-cooler is given as

$$W_{AC} = \frac{\Delta T_{AC}}{\Delta T_{HE}} W_{HE}$$  \hspace{1cm} (5.5)

where:

- $W_{AC}$ = pre-cooler cooling capacity [BTU/hr]

- $\Delta T_{AC}$ = oil temperature drop in pre-cooler [°F]

3. The largest portion of the total power input of a forced-cooled system is required by the refrigeration equipment. Here the oil is chilled from the pre-cooler outlet temperature down to the thermodynamically required temperature, $T_{cold}$, obtained for a given load from Equation 3.6. The power needed to drive the refrigeration equipment varies throughout the year since the air temperature and the required cold oil temperature vary. Therefore, sizing of the refrigeration system for design purposes must be accomplished for the most severe operating conditions. The worst conditions occur during the period of least heat transfer to the soil, the summer months. Thus the pipe-soil heat transfer computer program [4] must be utilized in order to determine the values of $Q_{1a}$ and $Q_{2a}$ (smallest absolute values) which mini-
mize soil heat transfer. Once the heat exchanger temperature drop has been calculated, Equations 5.4 and 5.5 can then be used to determine the required capacity of the pre-cooler and refrigeration unit.

5.2 Step B - Cable-to-Oil Heat Transfer

5.2.1 Design Procedure Explanation

It is necessary to determine the maximum bulk oil temperature which still permits sufficient heat transfer through the cable insulation so as to maintain the cable conductor and insulation at or just below the cable maximum temperature rating. (The maximum insulation temperature is equal to the conductor temperature.) The conductor-to-oil temperature difference for a given cable ampacity and voltage is determined from the amount of heat dissipation and the overall conductor-to-oil heat transfer resistance which is due to (1) the resistance to conduction heat transfer through the oil impregnated paper insulation, metallic sheath and moisture seal, and (2) the combined forced and natural convection resistance at the outer surface of the cable. The resistances act approximately in series, with the former being an order of magnitude greater than the latter (for pipe-type cable systems designed for 138 KV or higher voltages - see Appendix D2). Consequently, precise prediction of the convection at the cable surface is not necessary.

The pipe-type cable heat transfer correlation, Equation 3.7, is used to analyze the conductor-to-oil heat transfer. This correlation
accounts for the thermal resistances discussed above as well as the important effects of close cable proximity. When the multiplying correction factors $CF_1$ and $CF_2$ are equal to unity, the correlation models the conductor-to-oil heat transfer for the reference pipe-type cable system (see Appendix D.2.) Under these reference conditions, specific ratio values exist for the cable convection resistance and the insulation resistance as well as the circumferential metallic sheath resistance and the insulation resistance. If the conditions are altered from the reference conditions, the correction factors account for changes in the values of the resistance ratios.

Formulation of the heat transfer correlation and the correction factors is provided in Appendix D. The details necessary for the application of the correlation are provided for in the following design procedure. This procedure permits calculation of the following:

a) Conductor-to-oil temperature drop for the pipe-type cable system per specified cable ampacity rating.

b) Maximum permissible oil temperature per maximum cable temperature and cable ampacity rating.

c) Cable temperature per specified oil temperature and cable ampacity rating.

d) Forced-cooled ampacity rating per specified conductor-to-oil temperature difference ($T_c - T_{oil}$).

5.2.2 Design Calculations

The pipe-type cable system conductor-to-oil heat transfer correlation is given as follows:
\[
\frac{W_c}{W_d} = (1.764 \frac{k_{oil} (T_c - T_{oil})}{d_0 \ln \frac{d_o}{d_i}} - 0.53) \times CF_1 \times CF_2 \tag{3.7}
\]

where:

- \(W_c\) = conductor resistive-type losses per foot per cable (W/ft)
- \(W_d\) = dielectric losses per foot per conductor (w/ft)
- \(T_c - T_{oil}\) = conductor-to-(bulk) oil temperature drop (°F)
- \(k_{oil}\) = oil thermal conductivity (BTU/hr-ft°F)
- \(d_o\) = cable outside diameter (excluding skid wires) (in)
- \(d_i\) = insulation inside diameter (in)
- \(CF_1\) = convection correction factor (dimensionless)
- \(CF_2\) = metallic tape correction factor (dimensionless)

1. Determine the conductor-to-oil temperature drop for the specified forced-cooled amacity, \(I_{fc}\). (The value of the cable amacity used must always correspond to the maximum (peak) value that the cable will utilize, \(I_{fc,\text{max}}\). This insures that the conductor temperature limit will never be exceeded.)

a) Calculate the cable conductor resistive-type losses (Per cable), \(W_c\), from the equation,

\[
W_c = (1 + Y_{c}) R_{DC} I_{fc}^2
\tag{5.6}
where:

\[ Y_\text{C} = \frac{\text{AC/DC resistance ratio at the conductor (dimensionless)}}{R_{\text{DC}}} \]
\[ R_{\text{DC}} = \text{DC electrical resistance of conductor (ohms)} \]
\[ I_{\text{fc}} = \text{Forced-cooled cable ampacity rating (Amps)} \]

b) Use the specified value of the dielectric losses, \( W_d \), in order to calculate the "nondimensional current", \( \frac{W_c}{W_d} \).

Should it be desired to compute the total dielectric loss per unit length \( W_d \) rather than specify it directly, Equation 3.3 can be used.

c) Calculate the convective correction factor, \( CF_1 \).

1) The value of \( CF_1 \) is dependent upon the oil properties at the particular cable line point in question (see part 2). Thus if the bulk oil temperature is initially unknown (the most likely case), it is necessary to initially approximate this value. An accurate first approximation is had by setting the value of \( CF_1 \) equal to unity and then continuing on to part d. After the initial determination of the oil temperature, oil properties can be evaluated and \( CF_1 \) can be recalculated by advancing to part 2. This iterative procedure (which shouldn't exceed two times) continues until the value of the oil temperature no longer changes. A flow chart of this analysis is shown in Figure 12.

2) The value of \( CF_1 \) is based upon the ratio of the cable convective heat transfer resistance and the cable insulation resistance, \( k_{\text{oil}}/h \ln d_\text{o}/d_i \). In order to calculate this parameter, the heat
transfer coefficient, \( h \), is first determined. Calculation of \( h \) is dependent upon the value of the Reynolds Number which can be calculated from Figure 14 in the units indicated.

**Laminar Flow (\( \text{Re} < 450 \))** (Use Figure 17 to calculate \( \text{Re} \))

i) In laminar flow, the convective heat transfer resistance may be high enough such that the temperature drop from the cable surface to the oil can be a substantial portion of the total conductor-to-oil temperature drop. Consequently, when evaluating the heat transfer coefficient, oil properties must be based on the average temperature between cable surface and the bulk oil. Since this temperature drop, \( \Delta T_{S-0} \), is initially unknown, an iterative procedure is required. A flow chart of this procedure is presented in Figure 13.

ii) Select an initial value of \( \Delta T_{S-0} \) (i.e. \( \Delta T_{S-0} = 5^\circ \text{F} \)) and calculate the average oil properties based on the average oil temperature,

\[
\frac{[T_{oil} + (T_{oil} + \Delta T_{S-0})]}{2}
\]  

(5.7)

iii) Calculate the Rayleigh Number in the units indicated in Figure 14 (see Appendix D-3 for details of this Figure.) Read from Figure 14 the value of the Nusselt Number, \( \text{Nu} \).

iv) Calculate the heat transfer coefficient, \( h \):

\[
h = \frac{12 \text{ Nu} \ k_{oil}}{d_o}
\]  

(5.8)

where:

\( h \) = convective heat transfer coefficient \\
(\text{BTU/hr-ft}^2\circ\text{F})

\( d_o \) = cable outer diameter (in)
v) The actual cable surface-to-oil temperature drop which must exist for the calculated heat transfer coefficient \( h \), and the amount of cable heat dissipation is calculated from the following equation (the definition of the heat transfer coefficient):

\[
\Delta T_{S-o} = 13.04 \left( T_{f_{DC}}^2 R_{DC} (1 + Y_c + Y_r) + W_d \right) / h d_o
\]  

(5.9)

If this value does not agree with the previous value used, utilize the new value of \( \Delta T_{S-o} \) and return to step ii. Continue iteration until the value of \( \Delta T_{S-o} \) does not change. Utilize the corresponding value of \( h \) to calculate \( CF_1 \).

TURBULENT FLOW (\( Re > 450 \))

1) Choose the value of \( CF_1 \) to be equal to unity:

\[ CF_1 = 1.0 \]

(see Appendix D-3)

3) Calculate the product \( 12 k_{oil} / hd_o \ln \frac{d_o}{d_i} \) in the units indicated in Figure 15 and read the value of \( CF_1 \). (Details of this figure appear in Appendix D-2.)

d) Determine the metallic tape correction factor \( CF_2 \). Calculate the product

\[
\frac{k_{tape} t \ln d_o / d_i}{k_{oil} d_o}
\]

in the units indicated in Figure 16 (terms explained in that figure) and read the value of \( CF_2 \). (Details of this figure appear in Appendix D-2.)
e) Calculate the conductor-to-oil temperature drop using Equation 3.8 in the following form:

\[ (T_c - T_{oil}) = \left[ \frac{W_c}{W_d} \times \frac{1}{CF_1 CF_2} + 0.53 \right] \times \]

\[ \frac{W_d \ln \frac{d_o}{d_i}}{1.764 k_{oil}} \]  

(3.7)

2. Calculate the maximum allowable oil temperature, 

\[ T_{cable,max} \]

\[ T_{oil,max} = T_{cable,max} - (T_c - T_{oil}) \]  

(5.10)

3. Calculate the cable temperature if the maximum oil temperature is specified:

\[ T_{cable,max} = T_{oil,max} + (T_c - T_{oil}) \]  

(5.11)

4. The following procedure is used to calculate the cable amperage, \( I_{fc} \), if the conductor-to-oil temperature difference, \( T_c - T_{oil} \), is designated:

a. Calculate the "nondimensional temperature drop", \( \phi \)

\[ \phi = \frac{k_{oil}(T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} \]  

(5.12)

b. Calculate the correction factors \( CF_1 \) and \( CF_2 \) as in parts c and d of Step 1.
c. Use Equation 3.7 in the following form in order to calculate the possible forced-cooled current, \( I_{fc} \):

\[
I_{fc} = \left[ (1.764 \cdot \frac{k_{oil} (T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} - 0.53) \right. \\
\left. \frac{C F_1 C F_2 W_d}{R_{DC} (1 + Y_c)^{1/2}} \right]
\]  

(3.7)

5.3 Step C - Coolant Loop Flow Losses and Loop Pressure Profile

5.3.1 Design Procedure Explanation

Calculation of the loop pressure-head loss is required in order to determine the required pump differential pressure, \( \Delta P \). In order to simplify this procedure, the flow loop is divided into three separate sections so as to analyze the different frictional losses which occur in (1) the cable line, (2) the return line, and (3) the heat exchanger. Major pressure-head losses occur in all three sections and the minor losses which occur in the valves, pipe bends and the various fittings of the return line are also accounted for.

The loop dynamic pressure profile is then used in conjunction with the static oil pressure profile in order to determine the absolute loop pressure profile. This is needed in order to make certain that loop pressures do not exceed their maximum values at speci-
fic points within the loop.

Further explanation of the information presented in this part of the design analysis is provided following the presentation of the design procedure.

5.3.2 Design Calculations

1. Calculate the loop pressure head loss for the cable-line, return line, and heat exchanger.

a. Figure 17 is a graphical representation of the definition of the Reynolds Number based on the hydraulic diameter:

\[ \text{Re} = 159.464 \frac{Q/\mu}{\rho} \]  

(5.13)

For use in this figure, calculate \( \mu \) for both return and cable line in the units indicated. Oil properties for the return line and cable line are to be based on the average temperature within the return line and the cable line, respectively.

b. Based on the flow rate, \( Q \), read from Figure 17 the respective Reynolds Numbers for the cable and return lines (or calculate from equation 5.14).

c. Figures 18 and 19 show the friction factor vs \( R_e \) relationship for the cable line (reference system) and return line [8], respectively. Using the Reynolds numbers just determined, read the value of \( f_{c,\text{ref}} \) for the cable line from Figure 18 and the value of \( f_r \) for the return line from Figure 19.

d. The cable line friction factor, \( f_c \), is obtained from \( f_{c,\text{ref}} \) by using the correlation obtained by Bečkenback [7] in conjunction with Appendix C-2.
Cable Line, Turbulent Flow ($R_e > 400$)

\[ f = f_{c, \text{ref}} \times 12.273 \left( \frac{e}{d_0} \right)^{0.387} \left( \frac{s}{e} \right)^{-0.373} \left( 2.725 \frac{d_0}{D} - 0.099 \right) x K \]  

(5.14)

where

\[ K = 1 \text{ for } \alpha \leq 15^\circ \]
\[ K = (1.135 - 0.00876\alpha) \text{ for } \alpha > 15^\circ \]

The symbols used in Equation 5.2 are defined as follows:

- $\alpha =$ skid wire angle (degrees)
- $s =$ axial distance between consecutive skid wire wrappings (in) (see Figure 6)
- $e =$ skid wire height (in)
- $d_0 =$ cable outside diameter (in)
- $D =$ pipe inside diameter (in)
- $f_{c, \text{ref}} =$ friction factor for the reference pipe-type cable configuration (described in Appendix C). The value is determined from Figure 18. (Dimensionless).
- $f_c =$ cable line friction factor (Dimensionless)
- $f_r =$ return line friction factor (see Figure 19) (Dimensionless)

Figures 5 and 6 show pictorially the symbols $d_0$, $D$, $e$, $s$ and $\alpha$. Equation 5.14 is valid for:

\[ 0.3 < \frac{d_0}{d} < 0.45 \]
The error between Equation 5.14 and experimental results is approximately ± 5% [6].

Cable Line, Laminar Flow ($R_e < 400$)

\[ f_c = f_{c, \text{ref}} \times (3.581 - 6.5 \frac{d_o}{D}) \]  

Equation 5.15 is valid for

\[ 0.35 < \frac{d_o}{D} < 0.45 \]

(for values of $d_o/D$ less than 0.35, refer to Figure 20 in order to determine values of $f_c$), and accurate to within ± 2% of the experimental data.

e. Figure 21 displays the definition of the friction factor based on the hydraulic diameter $D_H$.

\[ \frac{\Delta P}{L} = 1.3394 \times 10^{-4} \left( \frac{f \rho P Q^2}{A^3} \right) \]  

(3.8)

For use in this figure, using the respective friction factors for the cable and return lines, calculate $f_{\Delta P/A^3}$ in the units indicated. Read the respective values of $\Delta P/L$ for the cable line and return line (or use Equation 3.8 to calculate $\Delta P/L$).
f. Losses in valves and fittings located in the return line are accounted for by evaluating the length, $L_e$, of the same diameter pipe which produces the same pressure drop as the fitting at a particular Reynolds number. Determine the equivalent lengths of return line valves and fittings from Table 2. Add these lengths to the return line length when calculating return line pressure drop, $\Delta P_r$.

$$L_r^* = L_r + L_e \text{ (valves and fittings)} \quad (5.16)$$

g. Calculate the heat exchanger pressure drop, $\Delta P_{HE}$, using the flow rate and the manufacturers' specifications.

h. The total pressure drop around the loop is the sum of the pressure losses which occur in the three sections of the loop.

Calculate

$$\Delta P_{\text{Loop}} = \left( \frac{\Delta P_c}{L_c} \right)_c L_c + \left( \frac{\Delta P_r}{L_r} \right)_r L_r^* + \Delta P_{HE} \quad (5.17)$$

i. Calculate the theoretical pump power (in horsepower) to circulate the oil by using the following equation.

$$W_{\text{pump}} = 5.82 \times 10^{-4} Q \Delta P_{\text{Loop}} \text{; horsepower} \quad (5.18)$$

This relationship is plotted in Figure 22.

2. Calculate the system absolute pressure profile.

Calculation of the system pressure profile is handled in a manner such that each loop is considered separately. A reference point is selected in the loop which corresponds to a point at which the total pressure is known. As an example, refer to Figure 23a which portrays
the schematic diagram of a four loop system. In loop number 1 (loop adjacent to the operational head tank), point 1-1 is selected as the reference point because the pressure at this position is known to be the head tank pressure (and must always be so). The static pressures at all other points within Loop 1 are based on this pressure (see part (a) below). The dynamic pressure losses (section 1) are then calculated and added to the static pressures in order to determine the total loop pressure profile (see part b below).

The next adjacent loop, loop number 2, is dealt with in the same manner. Again returning to Figure 23a, point 2-4 is now chosen to be the reference point since it is identical to point 1-4 of loop 1 for which the total pressure is now known (loop pressures at a loop-loop connection point must be equal, i.e. $P_{1-4} = P_{2-4}$). The loop pressure profile is calculated and the process then moves to loop number 3 and continues until the entire system pressure profile has been calculated.

This analysis is provided below for a single loop. It is presented in a general format since it applies identically to all loops within a system.

a. Calculate the loop static oil pressure profile.

i) Select the reference point for the loop under study. The reference position will correspond to a point for which the total pressure, $P_{\text{ref}}$, is known.
ii) Figure 24 graphically displays the fundamental equation of fluid statics. This equation is given as

$$\Delta P_{EL} = 6.944 \times 10^{-3} \rho \Delta h \quad (5.19)$$

where

$\rho = \text{average loop oil density (lbm/ft}^3\text{)}$

$\Delta h = \text{height difference between reference point and point of interest (ft)}$

Read the change in pressure, $\Delta P_{EL}$, between the reference point and the point of interest for the height differential $\Delta h$, (or use equation 5.19).

iii) Calculate the loop static oil pressure, $P_s$, at the point of interest using the following equation:

$$P_s = P_{\text{ref}} \pm \Delta P_{EL} \quad (5.20)$$

where

$+$ denotes points lower than the reference point

$-$ denotes points higher than the reference point

b) Calculate the total loop pressure profile.

i) Superimpose the dynamic pressure drops found in Section 1 on the loop static pressure profile obtained above. At any location,

$$P = P_s + \Delta P_D \quad (5.21)$$
where

+ denotes movement between the reference point and the point of interest in the opposite direction of fluid flow.

- denotes movement between the reference point and the point of interest in the direction of fluid flow.

and \( \Delta P_D \) is the dynamic pressure drop (as calculated from part 1) from the reference point to the point of interest. As an example, Figures 23a and b calculate (symbolically) the pressure profiles for loops 1 and 2 of the four loop system. The pressure in loop 1 at point 3, for instance, is calculated as

\[
P_{1-3} = P_{s,1-3} + \Delta P_{cl} + \Delta P_{rl}
\]

where

\[
P_{1-3} = P_{s,1-3} + \Delta P_{cl} + \Delta P_{rl}
\]

where

\[
P_{1-3} = \text{total pressure at point 2 of loop 1}
\]

\[
P_{s,1-3} = \text{static pressure at point 3 of loop 1 (calculated from part a)}
\]

\[
\Delta P_{cl} = \text{cable line dynamic pressure drop between points 1-1 and 1-4 (calculated in section 1)}
\]

\[
\Delta P_{rl} = \text{return line dynamic pressure drop between points 1-4 and 1-3 (calculated in section 3)}
\]

The addition of \( \Delta P_{cl} \) and \( \Delta P_{rl} \) provides the total dynamic pressure drop between the reference point, 1-1 and the point of interest, 1-3. The + signs indicate movement between these points in a direction opposite that of the oil flow.
c. Pressure Profile Check

Check that at no point in a loop does an absolute pressure exceed the designated maximum pressure for that point (such as the maximum pot-head pressure or the pipe pressure) of that an absolute pressure is not below the minimum oil pressure. The loop must also be checked at interior points if the type of terrain traversed is unusual in that hills or valleys exist. If pressures are outside of design constraints, then the system flow rates and loop lengths must be re-examined (as well as other important design parameters such as pipe size or ampacity rating.) Also check to make certain that the pump pressure-head rating and pot-head pressure limit are not exceeded.

5.3.3 Further Design Procedure Explanation

Some aspects of the above flow circuit design procedure require explanation. Major pressure losses in the cable and return lines are determined from the friction factor vs. Reynolds number functional relationships shown in Figures 18 and 19 in conjunction with the definition of the friction factor. For the cable line, the friction factor depends upon the cable configuration within the pipe (relative position of the cables within the pipe), but becomes independent of the configuration in the fully turbulent region \( (R_e > 10^4) \). Since the cables twist as they are pulled into the pipe, and move around due to the thermal expansion, they assume a variety of different configurations such as those shown in Figure 7. As a result, that configuration which provides the most conservative values of the friction factor for all values of Reynolds number, the open-triangular arrangement, is used for design purposes.
Although the friction factor does become independent of cable configuration in the highly turbulent region, the friction factor is dependent upon the pipe-type cable geometry in all regions of flow (geometry refers to the values \( f, d_0, D, e, s \) and \( \alpha \) as defined in Figures 5 and 6). The curve plotted in Figure 18 for the pipe-type cable friction factor applies to a specific pipe-type cable geometry (designated as the reference geometry) and therefore, the values of this friction factor \( f_{c,\text{ref}} \) must be modified when the following dimensionless parameters are varied: \( s/e, e/d_0, d_0/D \) and \( \alpha \). Subsequently, the value of \( f_{c,\text{ref}} \) for the cable line must always be substituted into Equation 5.6 or 5.7, depending on whether the flow is turbulent or laminar, to take into account any variation of the parameters from the reference system. This results in a cable line friction factor which is correct for the specified design geometry.
6. FORCED-COOLED SYSTEM DESIGN ALTERNATIVES AND OPTIMIZATION

The design manual has so far concentrated on describing the actual physical system along with the important design variables, their constraints, and the system governing equations. Chapter 5 of the manual utilizes this background to present a design procedure from which the important design parameters can be determined. It is important now to systematically examine (in a qualitative manner) ways in which the system can be designed which will optimize the forced-cooling performance for a desired ampacity rating. This is accomplished by evaluating the effects that each (important) independent variable has on the total system operation. The various performance characteristics that result when utilizing different value combinations of the independent variables establishes the system design alternatives.

Initially it is important to define the objective(s) of the forced-cooled system design and to subsequently formulate measures of performance which will allow for relative evaluation of the design alternatives in achieving the stated objective(s). The constraints within which the design and function must also be defined.

The clear objective of the design is to maximize the performance of the forced-cooling system in order to achieve a specified cable ampacity rating. This objective is subject to specific constraints such as budget, land ownership rights, and physical constraints. The optimum design alternative within these constraints depends a great
deal on the choice of the measure of system performance. A desirable measure of the performance for a forced-cooled cable system of specified ampacity is the system energy input requirements. This measure of effectiveness is concerned with the two most important aspects of the forced cooling technique: (1) the system thermal efficiency, and (2) the system pumping requirements.

The thermal efficiency of a forced-cooled system deals with the two means by which heat is transferred from the pipe-type cable system, the heat exchanger and the soil environment. Although the purpose of forced-cooling is to remove the burden of heat transfer from the latter, it is still important to utilize soil heat transfer as much as possible so as to minimize the refrigeration requirements (the largest energy requirements of a forced-cooled system.) Thus, it is important to recognize that different system designs lend to or detract from the soil heat transfer. Also, different types of operating schemes produce more or less efficient heat exchanger operation and, typically, both heat transfer mechanisms are optimized by the same type of design. Pumping requirements can also be greatly affected by the system design. Typically, systems which maximize thermal performance are often ones that utilize high oil flow rates and therefore bring about large pumping needs. Within the context of the chosen measure of performance, this can make the system less optimal, in terms of energy input requirements, than one which has a lesser thermal performance.
The combination of both thermal efficiency and pumping needs is reflected in the total system energy input requirements. Ideally, in order to obtain the optimum design for this measure of performance the independent variables should be chosen so as to maximize the thermal efficiency while simultaneously minimizing the pumping power. The purpose of this section is to examine ways to accomplish this goal by studying the effects that each design variable has on the chosen measure of performance. In order to simplify the formulation of design alternatives, the values of certain independent variables are considered to be known: namely, the pipe-cable geometry and the type of oil that is to be circulated. Thus the remaining independent variables which determine system performance are: \( I_{fc} \), \( Q \) and \( L \). The selection of the ampacity rating is a prerequisite to beginning the design and is therefore discussed first.

6.1 Selection of the Cable Ampacity

In a self-cooled cable system the cable rating is heavily dependent upon environmental factors over which there is no control (some control results from variation of the cable size and placement of high conductivity backfill around the pipe.) However, the cable rating of a forced-cooled system is an independently selected value for which the cooling system is to be designed.

In selecting \( I_{fc} \), it is important to make the distinction between a forced-cooled ampacity based on an average (or weighted value of
a fluctuating amperage versus a cable ampacity designed for a continuous rating equal to some maximum emergency load. Design based on the former depends upon the assumption that short duration peak loads will be handled by the thermal capacitance of the system and its environment; however, in the case of severe operation over an extended period, this design may not be capable of providing such continuous service without cable failure. The latter design approach is more conservative and therefore more costly, but the system is capable of extended emergency operation and will provide flexibility in meeting future operating requirements.

The selected value of $I_{fc}$ has two important consequences in association with the design: (1) $I_{fc}$ fixes the cable energy losses and therefore the cooling requirements of the system, and (2) $I_{fc}$ coupled with the maximum allowable cable temperature, fixes the maximum cable line oil temperature, $T_{oil,max}$ (Equation (3.7)).

Subsequently, if $T_{oil,max}$ is considered to be the cable outlet temperature (heat exchanger inlet temperature), selection of the oil flow rate and line length (for a particular loop of the system) fixes the value the soil heat transfer and the required heat exchanger cooling capacity as well as the system pumping power. The flow rate and line length will now be examined to determine the variable effects that each has on the loop performance. $Q$ may also influence $T_{oil,max}$ by influencing the cable-to-oil heat transfer rate.
6.2 Effect of Varying the Coolant Loop Oil Flow Rate

This section examines the forced-cooled performance when operating a coolant loop of specified length at different values of flow rate. The upper bound placed on the value of the flow rate results from exceeding the loop pressure constraints (see Chapter 3.) The lower bound on this value results from the dependency of the loop temperature drop on the flow rate: lower flow rates yield higher loop temperature drops and lower average temperatures. Thus the lower bound corresponds to that value of flow rate at which the oil becomes too viscous to pump.

6.2.1 Effect of Flow Rate on Thermal Efficiency

The effect that the flow rate has on coolant loop thermal efficiency can be studied through the interrelationship between the flow rate and the oil temperature profile. Equation (3.5), although applying only to the adiabatic pipe wall, shows that the loop temperature differential varies inversely as the value of flow rate changes: large values of flow rate yield small loop temperature drops and, conversely, small values of flow rate produce large temperature drops. Manipulation of the flow rate within its bounds establishes a large range of operating temperature levels, where the coolant loop temperature level is defined as the average temperature between heat exchanger inlet and outlet points. The effects of these possible design alternatives are now examined by comparing "low temperature" level operation (low flow
rate) and "high temperature" level operation (high flow rate.)

a) Low Temperature Operation

This level of thermal operation is achieved by utilizing a low value of oil flow rate, thus providing a relatively large coolant loop temperature rise. The advantages of this form of operation are:

- Maximum permissible electric current increases
- The low average oil temperature results in a lower average conductor temperature which reduces electrical resistance and therefore cable losses. (A reduction in temperature level of 30°F reduces the conductor resistance by less than 10%.)

The disadvantages of this type are:

- The low average loop oil temperature minimizes pipe-to-soil heat transfer, thus placing most of the cooling load on the heat exchange equipment. Also, an increase in ampacity adds to the cooling load.
- The low average temperature level of the oil and low flow rate combine to yield low heat transfer coefficients, thus increasing the required evaporator surface area in the refrigeration unit.
- Air cooled condenser size increases with lower average oil temperatures and the increased magnitude of the cooling load.
- The low flow rate may result in laminar flow operation which substantially increases the convective heat transfer resistance from the cables to the oil and therefore minimizes the value of $T_{oil, max}$. This minimizes the heat transfer in the air pre-cooler and adds to the load of the refrigeration unit.

The overall result of the above effects is the maximization of the heat removed by refrigeration which maximizes the energy input requirements.

b) High Temperature Operation

This type of system operation utilizes a high oil flow rate
in order to maintain a low coolant loop temperature differential. The advantages of this form of operation are:

- The high average oil temperature maximizes the heat transfer to the surrounding soil environment, decreasing the cooling load of the heat exchanger equipment.

- The high oil flow rate assures turbulent flow in the loop which minimizes the convective heat transfer resistance from the cables to the oil and therefore maximizes the value of $T_{\text{oil, max}}$. This maximizes the amount of heat transfer in the air precooler which decreases the load of the refrigeration unit.

- The high average temperature and flow rate yields high heat transfer coefficients which reduces the refrigerator evaporator surface area.

- The high average oil temperature makes possible a higher evaporator operating temperature (and pressure) which reduces compressor work and increases the coefficient of performance of the refrigeration system.

- Since the magnitude and temperature of the refrigeration system load determines the air condenser size, the size is minimized for high temperature operations.

The disadvantages of high temperature operations are:

- Maximum permissible electric current decreases.

- Cable electrical resistance is maximized, which maximizes cable losses.

The overall result of the above effects is a reduction in refrigeration equipment size and heat exchanger energy input as compared to the low temperature operation.

6.2.2 Effect of Flow Rate on Pumping Requirements

Low flow rate operation minimizes the coolant loop pumping requirements, even though the low temperature level increases oil vis-
cosity (which partially negates the effects of the lower flow rate.)

High flow rate operation maximizes the coolant loop pumping requirements (although the low oil viscosity which results from the high temperature level partially negates this effect.) However, due to the low oil viscosity, pump work transferred to the oil in the form of heat is minimized.

6.2.3 Combined Effect of Alternative Flow Rates on the Total Loop Energy Input

In terms of the selected system measure of performance, neither operating schemes optimize its value of total loop energy input. The low temperature operation, although minimizing pumping power, maximizes the energy required to cool the circulating oil. On the other hand, the high temperature operation, although minimizing the energy required to operate the heat exchange equipment maximizes the pumping power. Consequently, a design alternative which utilizes some value of flow rate between the high and the low should optimize the value of energy input into the system for the specified cable ampacity.

6.3 Effect of Varying Coolant Loop Length

The purpose of this section is to look at the effects of choosing alternative coolant loop cable line lengths on the system thermal performance and the required pumping power. The relative advantages and disadvantages of long vs. short loop length are listed below.
6.3.1 **Long Loop Flow Lengths**

**Advantages**

- Long flow loops permit the use of large centralized pumping and refrigeration stations. This reduces the initial capital investment of equipment as well as real estate.

- The overall design is simplified for a minimum number of flow loops.

- System reliability is maximized.

**Disadvantages**

- In order to satisfy the loop energy conservation (Equation (1)) for independently chosen value of $I_fC$, while remaining within loop pressure drop constraints, the flow rate must be small and the temperature rise must be large. This results in low temperature level operation, with a low heat transfer performance efficiency and large heat exchange equipment requirements.

- If $I_fC$ is considered a dependent variable subject to variable loop lengths, then the value of $I_fC$ will be minimized for long loop flow lengths. This is so because the loop cooling power is maximized for long loop lengths, and therefore, if shorter lengths are used with the same cooling power, $I_fC$ is permitted to increase in value.

6.3.2 **Short Loop Flow Lengths**

**Advantages**

- Short loop lengths afford the opportunity to operate loops at high temperature levels while maintaining pressure losses within constraints. This results in high thermal efficiency and minimum sized heat exchanger equipment.

- Short loop lengths permit the use of higher system amperages.

**Disadvantages**

- The large number of coolant loops required yields increased capital expenditures for equipment, construction and real estate.
-The complexity of the design is maximized.
-System reliability is minimized.

In order to obtain a feel for the effect of alternative design strategies, low temperature vs. high temperature operation is compared. Using Equation (3.8), assuming equal loop pressure losses in both designs and assuming that the "cold" system temperature rise is to be 10 times that of the hot system, the ratio of the required flow lengths is as follows:

$$\frac{L_{\text{long}}}{L_{\text{short}}} = \frac{L_{\text{cold}}}{L_{\text{hot}}} \left[ \frac{\Delta P \rho D_h A^2}{2f} \left( \frac{C_p \Delta T}{w} \right)^2 \right]^{1/3} = 5$$

A considerable difference exists between the design strategies in terms of the number of flow loops utilized. If it is determined, for example, that the hot system requires an excess number of flow loops, either the design constraints or the thermal operating design strategy has to be re-examined and a design tradeoff made. Inevitably the final design must strike an appropriate balance between the current capacity, the pumping power, and the number of system coolant loops in order to produce a physically as well as economically practical system.

6.4 Conclusion

This section of the design manual has been included, not to provide steadfast rules concerning the design of a forced-cooled
cable system, but rather to inform and provide some insight into the importance of certain design variables and how variation of these variables can increase or decrease operational performance. Beyond this, it is difficult to provide a specific design strategy which will meet the needs of all designs; each design must be examined separately, using the design analysis which follows, taking into account the effect of alternative design strategies.*

*A computerized pipe-type cable system design analysis program has been created in conjunction with the written design manual which permits a systematic examination of alternative design configurations and design strategies.*
REFERENCES


Figure 1: A schematic drawing of a single coolant loop.
Figure 2: Cross-section of underground pipe-type cable system.
Figure 3: Pipe-Cable Geometry.
Figure 4: Crossectional view of trench, cable pipes and oil sending lines for a double forced-cooled circuit.
MOISTURE SEAL SHLDG. ASSEMBLY

SKID WIRES
Double start with a lay of approx. 1-1/2 in. between turns.

CONDUCTOR, COPPER
SEGMENT INSULATION
BINDER
STRAND SHIELDING
PAPER INSULATION
INSULATION SHIELDING

Figure 5: Cross-section of cable.
Figure 6: Longitudinal View of a Single Cable with Skid Wire Height $e$ Coiled Around the Cable with Two Starts and Skid Wire Spacing $s$. 
Figure 7: Cross sections of five pipe-cable configurations
Figure 8: A schematic drawing of a four-loop pipe-type underground transmission system.
FIGURE 9: FORCED-COOLED PIPE-TYPE CABLE SYSTEM DESIGN PROCEDURE FLOW CHART
Figure 10: The axial oil temperature drop per unit length as the function of the cable losses.

\[
\frac{\Delta T}{L} = \frac{0.425}{C_P \rho Q} \text{ W} 
\]

- \( C_P \) - Oil Specific Heat (BTU/lbm °F)
- \( \rho \) - Oil Density (lbm/ft\(^3\))
- \( Q \) - Oil Flow Rate (GPM)
Fig. 11: A typical heat exchanger vs. pipes arrangement and a typical oil temperature profile for light loads. Non-Adiabatic System.
Figure 12: Iterative procedure for calculating the value of the convection correction factor $CF_1$.
Figure 13: Iterative procedure for calculating the value of the laminar flow heat transfer coefficient.
FIGURE 14: Variation of the Nusselt Number with Rayleigh Number in laminar flow regime [10].
Figure 15: The Heat Transfer Correlation Correction Factor Accounting for the Cable Surface-to-Oil Temperature Difference as a Function of $12 \frac{k_{oil}}{h d_o \ln d_o/d_i}$.

- $h$: Heat Transfer Coefficient, BTU/hr-ft°F
- $d_o$: Insulation Outer Diameter (in)
- $d_i$: Insulation Inner Diameter (in)
- $k_{oil}$: Oil Thermal Conductivity, BTU/hr-ft°F
Figure 16: The Heat Transfer Correlation Correction Factor Accounting for the Presence of a Thin Metallic Tape on the Cable Periphery as a Function of $k_{\text{tape}} \cdot t \cdot \ln \left( \frac{d_0}{d_i} \right)$.

**Formula:**

$$CF_2 = \frac{k_{\text{tape}} \cdot t \cdot \ln \left( \frac{d_0}{d_i} \right)}{k_{\text{oil}} \cdot \frac{d_0}{d_i}}$$

- $t$ - Tape Thickness (in)
- $d_0$ - Insulation Outer Diameter (in)
- $d_i$ - Insulation Inner Diameter (in)
- $k_{\text{oil}}$ - Oil Thermal Conductivity ($\text{BTU/hr ft F}$)
- $k_{\text{tape}}$ - Tape Thermal Conductivity ($\text{BTU/hr ft F}$)
\[ R_e = 1.595 \times 10^2 \frac{Q}{\mu P} \]

\[ \frac{\mu P}{\rho} \left( \frac{\text{cp in Ft}^2}{\text{lbm}} \right) \]

\[ P = \pi(D + 3d) - \text{Cable} \]
\[ P = \pi D - \text{Return} \]
\[ A = \frac{\pi(D^2 - 3d^2)}{4} - \text{Cable} \]
\[ A = \frac{\pi D^2}{4} - \text{Return} \]

**FIGURE 17: THE DEFINITION OF THE REYNOLDS NUMBER BASED ON THE HYDRAULIC DIAMETER**

\[ D_H = \frac{4A}{P} \]
Figure 18: Friction factor vs. Reynolds Number for Standard Pipe-Type Cable System.
See Appendix A for Definition of the Reference Pipe-Type Cable System. (Also see Appendix C for Further Details of $f_{c,\text{ref}}$.)
Reynolds Number $R_e$ [Dimensionless]

Figure 19: Friction factor vs. Reynolds Number for return line of pipe-type cable system.
Figure 20: Effect of changing the cable-to-pipe diameter ratio on the friction factor in the laminar flow. ($f_{c, ref}$ Refersto the Friction Factor Associated with the Reference Pipe-Type Cable System—See Appendix C)
\[ \Delta P = 1.3396 \times 10^{-4} \cdot \frac{f \rho P}{A^3} \cdot Q^2 \]

\( \rho \) - Oil Density (lb/ft\(^3\))

\( f \) - Friction Factor (Dimensionless)

\( P \) - Wetted Perimeter (in)

\( A \) - Cross-Sectional Area (in\(^2\))

\[ \frac{f \rho P}{A^3} \left[ \frac{1 \text{ lb}}{3 \text{ ft}^3 \text{ in}^5} \right] \]

\( A = \frac{\pi}{4} D^2 \) - return

\( A = \frac{\pi}{4}(D^2 - 3d_o^2) \) - cable

\( P = \pi(D - 3d_o) \) - cable

\( P = \pi D \) - return

Figure 21: The definition of the friction factor
Figure 22: Theoretical power to drive any pump equals output fluid horsepower, $5.82 \times 10^{-4} Q \Delta P$, plotted here. Actual power required to drive pump is chart hp divided by over-all pump efficiency.
Figure 23(a): Schematic Diagram of Forced-Cooled System Indicating System Pressure Profile Numbering Format.

CL - Cable Line
RL - Return Line
HE - Heat Exchanger
LOOP 1 Pressure Profile:

Reference Point 1-1

\[ P_{1-1} = P_{\text{ref}} = P_{\text{Head Tank}} \]

\[ P_{1-2} = P_{s,1-2} + \Delta P_{\text{HE}1} \]

\[ P_{1-3} = P_{s,1-3} + \Delta P_{c1} + \Delta P_{r1} \]

\[ P_{1-4} = P_{s,1-4} + \Delta P_{c1} \]

LOOP 2 Pressure Profile:

Reference Point 2-4

\[ P_{2-1} = P_{s,2-1} - \Delta P_{c2} \]

\[ P_{2-2} = P_{s,2-2} - \Delta P_{c2} - \Delta P_{\text{HE}2} \]

\[ P_{2-3} = P_{s,2-3} + \Delta P_{r2} \]

\[ P_{2-4} = P_{\text{ref}} = P_{1-4} \]

Explanation of Symbols:

- \( P_{\text{ref}} \) - Total pressure at reference point
- \( P_{n-m} \) - Total pressure in loop \( n \) at point \( m \)
- \( P_{s,n-m} \) - Static pressure in loop \( n \) at point \( m \) \( \text{calculated in Section 5.3.2} \)
- \( \Delta P_{cn} \) - Cable line dynamic pressure drop in loop \( n \)
- \( \Delta P_{rn} \) - Return line dynamic pressure drop in loop \( n \) \( \text{calculated in Section 5.3.2} \)
- \( \Delta P_{\text{HE}n} \) - Heat exchanger pressure drop

Figure 23(b): Formulation of the pipe-type cable system pressure profile for a multi-loop system. (used in conjunction with Figure 23(a)).
Figure 24: The pressure change in the system due to the elevation difference.
<table>
<thead>
<tr>
<th>Independent Variable TO BE CHANGED</th>
<th>Variable CHANGE</th>
<th>Constants</th>
<th>Dependent Variable</th>
<th>Change ΔP</th>
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<td>L</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, Q, A</td>
<td>+L</td>
<td>+L&lt;sub&gt;fc&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, L, A</td>
<td>+Q</td>
<td>+fQ&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>A(D, d&lt;sub&gt;o&lt;/sub&gt;)</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, L, Q</td>
<td>L</td>
<td>+P/A&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;</td>
<td>Q, ΔT, A</td>
<td>≡I&lt;sub&gt;fc&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt;</td>
<td>+I&lt;sub&gt;fc&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, ΔT, A</td>
<td>+Q</td>
<td>+fQ&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>ΔT</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, Q, A</td>
<td>+ΔT</td>
<td>+ΔT</td>
</tr>
<tr>
<td></td>
<td>A(D, d&lt;sub&gt;o&lt;/sub&gt;)</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, Q, ΔT</td>
<td>Q</td>
<td>+P/A&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;</td>
<td>ΔP, A, ΔT</td>
<td>≡I&lt;sub&gt;fc&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt;</td>
<td>+fI&lt;sub&gt;fc&lt;/sub&gt;&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>ΔT</td>
<td>ΔP, A, I&lt;sub&gt;fc&lt;/sub&gt;</td>
<td>+ΔT&lt;sup&gt;1/3&lt;/sup&gt;</td>
<td>+fΔT&lt;sup&gt;2/3&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>A(D, d&lt;sub&gt;o&lt;/sub&gt;)</td>
<td>ΔP, I&lt;sub&gt;fc&lt;/sub&gt;, ΔT</td>
<td>ΔT</td>
<td>+fA/P&lt;sup&gt;1/3&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;</td>
<td>ΔP, A, L</td>
<td>+I&lt;sub&gt;fc&lt;/sub&gt;&lt;sup&gt;2&lt;/sup&gt;</td>
<td>+fL&lt;sup&gt;3/2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>I&lt;sub&gt;fc&lt;/sub&gt;, ΔP, A</td>
<td>+L&lt;sup&gt;1/2&lt;/sup&gt;</td>
<td>+fL&lt;sup&gt;3/2&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**TABLE 1**

Pipe-Type Cable System Variable Interrelationships
<table>
<thead>
<tr>
<th>Description of Valves and Fittings</th>
<th>Equivalent Length in Pipe Diameters Le/D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Globe Valves</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>With no obstruction in flat, bevel, or plug type seat. With wing or pin-guided disc</td>
</tr>
<tr>
<td>Y-pattern</td>
<td>No obstruction in flat, bevel or plug-type seat With stem 60° from run of pipe line with stem 45° from run of pipe line</td>
</tr>
<tr>
<td>Conventional</td>
<td>With no obstruction in flat, bevel or plug-type seat With wind or pin-guided disc</td>
</tr>
<tr>
<td><strong>Angle Valves</strong></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>With no obstruction in flat, bevel or plug-type seat. With stem 60° from run of pipe line with stem 45° from run of pipe line</td>
</tr>
<tr>
<td><strong>Gate Valves</strong></td>
<td>Conventional wedge disc, double disc, or plug disc.</td>
</tr>
<tr>
<td><strong>Check Valves</strong></td>
<td>Conventional swing 0.5+ 2.5 vertical and 0.25 horizontal+</td>
</tr>
<tr>
<td>In-Line Ball</td>
<td>Fully open</td>
</tr>
<tr>
<td><strong>Foot Valves with strainer</strong></td>
<td>With poppet lift-type disc 0.3+</td>
</tr>
<tr>
<td><strong>Butterfly valves (6&quot; and larger)</strong></td>
<td>Fully open</td>
</tr>
</tbody>
</table>

+ Minimum calculated pressure drop (psi) across valve to provide sufficient flow to lift discs fully.
Table 2 (continued)

<table>
<thead>
<tr>
<th>Description of Valves and fittings</th>
<th>Equivalent length in Pipe Diameter (Le/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fittings</strong></td>
<td></td>
</tr>
<tr>
<td>90° Standard Elbow</td>
<td>30</td>
</tr>
<tr>
<td>45° Standard Elbow</td>
<td>16</td>
</tr>
<tr>
<td>90° Long Radius Elbow</td>
<td>20</td>
</tr>
<tr>
<td>90° Street Elbow</td>
<td>50</td>
</tr>
<tr>
<td>45° Street Elbow</td>
<td>26</td>
</tr>
<tr>
<td>Square Corner Elbow</td>
<td>With flow through run: 20</td>
</tr>
<tr>
<td></td>
<td>With flow through branch: 60</td>
</tr>
<tr>
<td>Close pattern return bond</td>
<td>50</td>
</tr>
</tbody>
</table>
A.1 The Reference Pipe-Type Cable System

A "reference" pipe-type cable system is utilized to correlate the pressure drop and heat transfer data obtained for different system geometries and operating conditions. This reference system, with its pertinent pipe-type cable geometry, thermal parameters, and electrical parameters is described as follows:

A.1.1 Reference Geometry

- D, cable pipe inside diameter: 10.25 in
- \( d_0 \), cable insulation outside diameter: 4.135 in
- \( d_i \), conductor diameter: 1.657 in
- s, skid wire spacing: 1.50 in
- e, skid wire height: 0.10 in
- \( \alpha \), skid wire angle: 35.96 degrees

\[ \alpha = \tan^{-1}(ns/d_0); \text{ where } n \text{ - number of skid wire starts } = 2 \]

The definition of these variables is given in Figures 5 and 6.

A.1.2 Reference Thermal Parameters

- \( k_{tape} \), sheath thermal conductivity: 220 BTU/hr-ft°F
- \( k_{oil} \), oil thermal conductivity: 0.1153 BTU/hr-ft°F
- \( h \), surface heat transfer coefficient: 55.5 BTU/hr-ft²°F
### A.1.3 Reference Electrical Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{fc}$</td>
<td>the forced-cooled system cable ampacity</td>
<td>900 amps</td>
</tr>
<tr>
<td>$W_d$</td>
<td>total dielectric loss</td>
<td>2.68 w/ft</td>
</tr>
<tr>
<td>$R_{DC}$</td>
<td>conductor resistance for DC current</td>
<td>6.43 $\mu$Ω/ft</td>
</tr>
<tr>
<td>$E$</td>
<td>line-to-line voltage</td>
<td>345 kV</td>
</tr>
<tr>
<td>$Y_c$</td>
<td>increase of $R_{AC}$ due to skin and proximity effects, percent</td>
<td>0.13</td>
</tr>
<tr>
<td>$Y_s$</td>
<td>increase of $R_{AC}$ due to induced current in the sheath, percent</td>
<td>0.05</td>
</tr>
<tr>
<td>$Y_p$</td>
<td>increase of $R_{AC}$ due to induced current in the cable pipe</td>
<td>0.48</td>
</tr>
</tbody>
</table>

It should be noted that the cable dimensions used to describe the reference cable system do not correspond to a presently used cable.
APPENDIX B

EFFECT OF OIL PROPERTIES ON SYSTEM DESIGN

B.1 Oil Property Evaluation

All oil properties are evaluated at the mixed-mean oil temperature (outside the convective boundary layer.) In order to determine the possible effect of using this temperature to model the changing property values on design calculations, a typical oil (utilized in forced-cooled systems) is examined.

The oil examined is low viscosity Polybutene. The change in property values over a conservative operating range of 70°F to 160°F is shown below:

<table>
<thead>
<tr>
<th>Oil Property</th>
<th>Value @ 70°F</th>
<th>Value @ 160°F</th>
<th>% Change in Value from low temp. to high temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lbm/ft³)</td>
<td>51.77</td>
<td>49.78</td>
<td>3.8%</td>
</tr>
<tr>
<td>Specific Heat (BTU/lbm°F)</td>
<td>.477</td>
<td>.537</td>
<td>-12.6%</td>
</tr>
<tr>
<td>Viscosity (CP)</td>
<td>42</td>
<td>6</td>
<td>65.7</td>
</tr>
<tr>
<td>Thermal Conductivity (BTU/hr-ft°F)</td>
<td>0.1157</td>
<td>0.1153</td>
<td>—</td>
</tr>
</tbody>
</table>

As is seen, the only oil property to change significantly over the possible operating range of the forced-cooled system is the viscosity. This property is important to the accurate calculation of the pipe-type cable system pressure loss. The effects of the change in viscosity on the pressure drop calculations and the use of average
mixed-mean temperature to compensate for any of these effects is now examined.

B.2 Effect of the Change of Oil Viscosity on the Pipe-Type Cable System Pressure Drop Calculation

The oil temperature rise in a pipe-type cable system is a linear function of the axial distance if the pipe wall is considered to be adiabatic (and is still a reasonably good approximation otherwise.) If the oil viscosity linearly depends upon temperature, which is usually a good assumption, the value at any temperature is found to be:

\[ \mu = \mu_1 + \frac{\mu_2 - \mu_1}{L} X \]  

where

\[ \mu_1 = \text{oil viscosity at entrance of the line under study} \]
\[ \mu_2 = \text{oil viscosity at exit of line under study} \]
\[ L = \text{axial length of line under study (loop between line or cable line)} \]
\[ X = \text{axial distance from entrance} \]

The differential form of the definition of the friction factor is:

\[ \frac{dP}{dX} = \frac{2f \rho V^2}{D_H} \]  

where

\[ f = \text{pipe friction factor} \]
\[ \rho = \text{oil density} \]
\[ V = \text{average oil flow velocity} \]
For Laminar Flow:

\[ f = \frac{k}{Re} \]  \hspace{1cm} (B.3)

where

\[ k = 16 \text{ empty pipe} \]

\[ k = 13.3 \text{ pipe-type cable} \]

Substitute (B.1) and (B.3) into (B.2):

\[ \frac{dP}{dX} = \frac{2kV\mu}{D_H^2} = \frac{2k.V}{D_H^2} \left( \mu_1 + \frac{\mu_2 - \mu_1}{L} X \right) \]

Integrate over the entire line length:

\[ \Delta P = \frac{2kV}{D_H^2} \left( \mu_1 X + \frac{\mu_2 - \mu_1}{L} \frac{X^2}{2} \right) \bigg|_0^L \]

\[ \Delta P = \frac{2kV}{D_H^2} \left( \mu_1 + \frac{\mu_2 - \mu_1}{2} \right) = \frac{2kV \mu_{avg}}{D_H^2} \]  \hspace{1cm} (B.4)

Since the same answer can be obtained directly from (B.2) and (B.3) using \( \mu = \mu_{avg} \) instead of (B.1), there is no error in the prediction of \( \Delta P \) due to the dependence of viscosity on temperatuer in the laminar flow.

For Turbulent Flow in an Empty Pipe:

\[ f = \frac{0.046}{Re^{0.2}} \]  \hspace{1cm} (B.5)
Substitute (B.1) and (B.5) into (B.2) and integrate:

\[
\Delta P = \frac{0.092 \rho 0.8 1.8}{D_H^{1.2}} \left( \frac{\mu_1 - \mu_2}{L} \right)^{1.2} \frac{\left( \mu_1 + \frac{\mu_1 - \mu_2}{L} x \right)^{1.2}}{L^{1.2} \left( \frac{\mu_2 - \mu_1}{L} \right)} |_0^L
\]

\[
\frac{P}{L} = \frac{0.0767 0.8 1.8}{D_H^{1.2}} \left( \frac{\mu_2^{1.2} - \mu_1^{1.2}}{\mu_2 - \mu_1} \right)
\]

(B.6)

Using typical values for \( \rho, V, \mu, D_H \), the error between the pressure drop obtained from (B.6) and the pressure drop obtained assuming \( \mu = \mu_{\text{avg}} \) is less than 2%. Thus, it can be safely assumed that errors of the same magnitude exist in the prediction of the pressure drop in the pipe-type cable system.
APPENDIX C

PIPE-TYPE CABLE SYSTEM PRESSURE-FLOW LOSS

C.1 Pipe-Type Cable System Pressure Drop Determination

The pipe-type cable system pressure drop is determined by use of Equation 3.8, the definition of the friction factor. The friction factor, \( f \), defined here is called the Fanning friction factor and is often used in heat transfer and aerodynamics. (Another friction factor, the Darcy factor, is commonly used in hydraulics and is four times as large. Care should be exercised when using data from the literature to make certain of which factor applies.) Calculation of the friction factor values to be used in the equation is accomplished by first determining the Reynolds number of the flow and then using either the laminar flow friction factor correlation or the turbulent flow correlation depending on which applies (\( Re < 400 \) is laminar flow.)

C.1.1 Laminar Flow Pipe-Type Cable System Friction Factor Correlation

This correlation, equation 5.15 predicts the variation of the pipe-type cable friction factor relative to a reference friction factor, \( f_{c,ref} \), as a function of the pipe-type system geometric parameters, \( D, d_o, e, s \) and \( \alpha \). In the case of laminar flow, the only important variation in geometry is the change in cable-to-pipe diameter ratio, \( d_o/D \). This is so because the viscous forces predominate
in the laminar regime, with all disturbances being completely damped out. Therefore the skid wires (skid wire geometry) have no influence at all.

A computer model of the pipe-type cable system in laminar flow was created in order to perform the parametric study which examines the variation of cable-to-pipe diameter ratio on the values of the friction factor. The results of the study on the open-triangular cable configuration (which is the most conservative) with \( s = (0.115 - \frac{d}{D}) \) (see Figure 7), are shown in Table 3 and Figure 20. Table 3 shows the dependence of the friction factor, \( f_c \), on the cable-to-pipe diameter ratio, where \( f_{c,\text{ref}} \) is based on the friction factor of the reference pipe-type cable system of Appendix A and Figure 18 (actual experimental data taken for the reference system is used.) The greater the number of mesh points the more accurate the computer solution.

C.1.2 Turbulent Flow Pipe-Type Cable System Friction Factor Correlation

This correlation predicts the variation of the pipe-type cable friction factor, \( f \), relative to a reference friction factor, \( f_{c,\text{ref}} \) as a function of the system geometric parameters, \( D, d_o, e, s, \) and \( \alpha \). (\( f_{c,\text{ref}} \) is based upon the friction factor of the reference pipe-type cable system of Appendix A and Figure 18. Actual experimental data taken for the reference system is used.)

In the case of turbulent flow the skid wires are the major resistance to flow and therefore the skid wire geometry becomes impor-
tant. The friction factor has been found to be a function of the following dimensionless parameters: s/e, e/d₀, α, and d₀/D.

The correlation of Beckenbach [7] takes into consideration the first three of these parameters. His computer model was used to complete the parametric study and resulted in the data of Table 4 which shows the dependence of the friction factor on the cable-to-pipe diameter ratio d₀/D. The data has been plotted and correlated in Figure 25. The final turbulent flow friction correlation appears in Section 5.3.2 as Equation 5.14.
APPENDIX D
PIPE-TYPE CABLE SYSTEM HEAT TRANSFER CORRELATION

D.1 One-Dimensional Conductor-to-Oil Heat Transfer Analysis

A dimensional analysis shows that there are four independent non-dimensional groups which are required to obtain a relationship describing the pipe-type cable heat transfer. The relevant groups and their interrelationship are determined by modeling the conductor-to-oil heat transfer such that cable proximity effects are negligible (cables far apart) and assuming circumferential symmetry. The one-dimensional cable heat transfer model that results is shown in schematic form in Figure 26 and depicts the specific energy losses and heat transfer resistances.

The equation which describes the radial conduction heat transfer within the cable insulation is given as:

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

where

- $r$ = radius of point within the insulation
- $T$ = temperature of point within the insulation
- $k$ = insulation conductivity
- $\dot{q}$ = distributed heat source within the insulation (per unit volume) resulting from dielectric losses

The dielectric loss is expressed in terms of the distributed insulation heat source, $\dot{q}$, as
\[ W_d = \int_{r_i}^{r_o} \dot{q} \frac{2\pi r}{r_i} dr \quad (D.2) \]

where

- \( r_i = \) inside radius of the insulation
- \( r_o = \) outside radius of the insulation

However, since the distributed heat source is proportional to the inverse of the square of the radial distance from the center of the conductor, \( \dot{q} \) is replaced in (D.2) by

\[ \dot{q} = \frac{C}{r^2} \quad (D.3) \]

Equation (D.3) is integrated to obtain,

\[ W_d = \int_{r_i}^{r_o} 2\pi \frac{C}{r} \frac{dr}{r_i} = \frac{2\pi C \ln r_o}{\ln r_i} \quad (D.4) \]

Substituting for \( \dot{q} \) in (D.1) gives,

\[ \frac{1}{r} \frac{d}{dr} \left( r \frac{dT}{dr} \right) = - \frac{W_d}{2\pi k r^2 \ln r_o / r_i} = \frac{W_d}{2\pi k r^2 \ln r_i / r_o} \quad (D.5) \]

Substituting \( \epsilon = r / r_o \) gives the non-dimensional form,

\[ \frac{d}{d\epsilon} (\epsilon \frac{dT}{d\epsilon}) = \frac{W_d}{2\pi k \ln \epsilon_i} \]

which when integrated twice gives,

\[ \epsilon \frac{dT}{d\epsilon} \frac{W_d}{2\pi k \ln \epsilon_i} \ln \epsilon + C_1 \quad (D.6) \]
\[ T = \frac{W_d}{2\pi k \ln \varepsilon_i} \left( \ln \varepsilon \right)^2 + C_1 \ln \varepsilon + C_2 \]  

(D.7)

The insulation boundary conditions are as follows:

\[ \Theta r = \left. r_i \right| W_c = -2\pi \varepsilon_i k \frac{\partial T}{\partial \varepsilon} \right|_i \]

or \( \varepsilon = \varepsilon_i \)  

(D.8)

\[ \Theta r = \left. r_o \right| W_c + W_d + W_s = 2\pi r_o h(T_c - T_{oil}) \]

or \( \varepsilon = 1 \)

(D.9)

where

\( W_c \) = conductor resistance losses

\( W_s \) = sheath induction losses

Substitution of the boundary conditions into (D.6) and (D.7) yields,

\[ C_1 = -\frac{W_c + W_d}{2\pi k} \]  

(D.10)

\[ C_2 = \frac{W_c + W_d + W_s}{2\pi h} + T_{oil} \]  

(D.11)

Finally, the conductor-to-oil temperature drop is determined from equation (D.7) as,

\[ T_c - T_{oil} = -\frac{W_d + 2W_c}{4\pi k} \ln \frac{r_i}{r_o} + \frac{W_c + W_d + W_s}{2\pi h} \frac{r_i}{r_o} \]  

(D.12)
Nondimensionalizing this equation gives,

\[
\frac{k(T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} = \frac{1}{4\pi} + \frac{W_c/W_d}{2\pi} + \frac{(W_c + W_d + W_s)/W_d}{2\pi \frac{h \cdot r}{k} \ln \frac{d_o}{d_i}}
\]

However since \( W_s \ll W_c + W_d \)

\[
\frac{k(T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} = \frac{1}{4\pi} + \frac{W_c}{W_d} \left( \frac{1}{2} + \frac{k}{h \cdot d_o \ln \frac{d_o}{d_i}} \right) + \frac{k}{\pi \cdot h \cdot d_o \ln \frac{d_o}{d_i}}
\]

(D.13)

If \( W_c/W_d >> 1 \) (as is typical for high current values) and the ratio of the convection resistance and insulation conduction resistance, \( k/h \cdot d_o \ln \frac{d_o}{d_i} \), is much less than 1 (see Appendix D-3), then (D.13) can be written as

\[
\frac{k(T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} = \frac{1}{4\pi} + \frac{W_c}{W_d} \left( \frac{1}{2} + \frac{k}{h \cdot d_o \ln \frac{d_o}{d_i}} \right)
\]

or

\[
\frac{W_c}{W_d} = \left( \frac{\pi}{W_d \ln \frac{d_o}{d_i}} - \frac{1}{4} \right) \left( \frac{1}{2} + \frac{k}{h \cdot d_o \ln \frac{d_o}{d_i}} \right)
\]

(D.14)

D.2 Two-Dimensional Conductor-to-Oil Heat Transfer Analysis

Due to the close proximity of the three cables in the pipe-type cable system, the insulation conduction heat transfer becomes more...
complicated than in the one-dimensional case. However, the three non-dimensional groups of Equation (D.14) remain relevant in the two-dimensional analysis. The fourth dimensionless group required for the 2-D case is the ratio of the cable insulation resistance to that of the sheath circumferential conduction resistance.

\[ \frac{k_{tape} t \ln d_0/d_i}{k_{oil} d_0} \]

This ratio is important because the presence of the copper tape around the insulation significantly smooths out the temperature distribution in the cable insulation which prevents hot spots from occurring; the higher the ratio value, the greater the smoothing effect will be in the insulation.

Utilizing the four non-dimensional groups presented, it is reasonable to propose that the 2-D cable heat transfer relationship be in a similar form to that of the 1-D relationship, equation (D.14). This form is given as,

\[ \frac{W_c}{W_d} = (A \frac{k_{oil}(T_c - T_{oil})}{W_d \ln d_0/d_i} + B) \cdot CF_1 \left( \frac{k_{oil}}{h d_0 \ln d_0/d_i} \right) \cdot CF_2 \left( \frac{k_{tape} t \ln d_0/d_i}{k_{oil} d_0} \right) \]  \hspace{1cm} (D.15)

where

A and B = constants
$CF_1 = \text{correction factor which accounts for changes in the relationship between the convection heat transfer and the insulation resistance.}$

$CF_2 = \text{correction factor which accounts for changes in the relationship between the insulation heat transfer resistance and the sheath circumferential resistance.}$

The finite different computer program of Sanders [6], which solved the complete two-dimensional heat conduction equation with non-uniform convective cooling at the three cable surfaces, was used to perform a parametric study in conjunction with Equation (D.15). (The computer program models the closed-triangular cable configuration due to its thermally conservative nature.) The constants $A$ and $B$ are obtained by holding $\frac{k_{oil}}{h d_0 n d_0/d_i}$ and $\frac{k_{tape} t \ln d_0/d_i}{k_{oil} d_0}$ constant at the standard values of $6.597 \times 10^{-5}$ and $2.1097$, respectively, and by changing the values of the other two dimensionless groups. The results are given in Table 5 and plotted in Figure 27 with the relationship (in consistent units) given as,

$$\frac{W_c}{W_d}_{\text{ref}} = 1.764 \frac{k_{oil} (T_c - T_{oil})}{h d_0 n d_0/d_i} - 0.53 \quad (D.16)$$

In order to determine the value of $CF_1$ for changes in the dimensionless group $\frac{k_{oil}}{h d_0 n d_0/d_i}$, the computer program was run while maintaining $W_c/W_d$ and $\frac{k_{tape} t \ln d_0/d_i}{k_{oil} d_0}$ constant at the standard values of $2.196$ and $2.1097$, respectively. The results of the relationship between the other two groups are listed in Table 6. $CF_1$ is formed by composing the reference value of $\frac{k_{oil} (T_c - T_{oil})}{h d_0 n d_0/d_i}$, which occurs when
\[ \frac{k_{\text{oil}}}{h d_0 \ln \frac{d_0}{d_1}} = 6.597 \times 10^{-3}, \text{ with the non-reference values.} \]

\( CF_1 \) is plotted in Figure 15 as a function of \( \frac{k_{\text{oil}}}{W_d \ln d_0/d_1} \).

Similarly, the correction factor \( CF_2 \) is determined by holding \( \frac{k_{\text{oil}}}{W_d} \) and \( \frac{h d_0}{d_0 \ln d_0/d_1} \) constant and by changing the other two dimensionless groups. Results are provided in Table 7 and the values of \( CF_2 \) are determined from Figure 16.

The final result of the pipe-type cable heat transfer correlation is given as,

\[ \frac{W_c}{W_d} = \left( 1.764 \frac{k_{\text{oil}}(T_c - T_{\text{oil}})}{W_d \ln d_0/d_1} - 0.53 \right) CF_1 \times CF_2 \quad (D.17) \]

where

\[ W_c = Y_c R_{\text{DC}} I_{fc}^2 \]

Table 8 demonstrates that Equation (D.17) is accurate to within \( \pm 5\% \) of computer predictions of \( \frac{W_c}{W_d} \), and can be confidently used to predict, for a given conductor-to-oil temperature difference and the cable surface heat transfer coefficient, the ampacity of the pipe-type oil-filled underground transmission lines. The ranges of pipe-type cable parameters for which that equation is valid are as follows:

\[ 470 \leq I_{fc} \leq 2000 \text{ A} \]

\[ 2.11 \leq W_d \leq 3.5 \text{ W/ft} \]

\[ 5.36 \leq R_{\text{DC}} \leq 12.86 \mu\Omega \]

\[ 0.03 \leq Y_c \leq 0.2 \]
For a pipe-type cable system designed for 138 kV up to 345 kV, thermal conduction resistance across the cable insulation is on the order of five to ten times larger than the convection resistance from cable surface to the oil [6]. Cables designed for voltages higher than 345 kV will require thicker insulation and thus make the convection resistance almost negligible. Consequently, extremely accurate convection information is not required for most heat transfer predictions of Section 5.2. However, since in some designs the convection resistance may be up to 25% of the total cable heat transfer resistance, the most accurate information available is utilized to predict values of $h$.

In laminar flow ($Re < 400$), the natural convection effect on the heat transfer coefficient becomes significant. Since the value of $Nu_s$ obtained for no flow (and including the natural convection effects)
[6 and 10] is much greater than $N_u_t$ found for fully developed laminar flow parallel to a bank of circular tubes [9] ($N_u_s \approx 14 N_u_t$), only the natural convection needs to be examined. In such cases the Nusselt Number becomes a function of a single parameter, the product of the Grachof Number (Gr) and the Prandtl Number (Pr).

$$Nu = \text{function (Gr Pr)}$$

where the dimensionless product Gr Pr is termed the Rayleigh Number.

For the pipe-type cable system, this relationship changes for different cable configurations and therefore the most conservative experimental results are utilized in the design manual. These results are graphed in Figure 14 [10].

Analysis of the cable heat transfer coefficient in turbulent flow deals primarily with the study of the flow region close to the cable surface. This is so because the circulating oil has a high Prandtl Number (approximately 150) which results in the concentration of the heat transfer resistance in a small laminar sublayer close to the wall. (Thus, turbulent behavior out in the main stream has little influence on the heat transfer coefficient.) The skid wire geometry plays an important role in the analysis since the wires act as turbulence promoters which trip and break-up the sublayer region. Any such disturbance of the sublayer can be expected to substantially increase the heat transfer coefficient. Unfortunately, little information is available in the literature which is concerned with the convective
heat transfer of high Prandtl Number flow over repeated rough surfaces.

Work which gives an indication of the effect of high Prandtl Numbers has been done by Deissler [12], for fully developed turbulent pipe flow. He has shown that for very large Prandtl Numbers the following relationship exists between Nu and Pr:

\[ \text{Nu} = \frac{2n \sqrt{f}}{\pi} \text{RePr}^{1/4} \quad (D.17) \]

where \( n \) has a value of 0.124 and \( f \) indicates the cable friction factor. In order to use this equation so as to gain some indication of the value of the turbulent Nusselt Number for the pipe-type cable system, the following assumption is made: the pipe-type cable system which brings the onset of turbulent flow (approximately 450) can be effectively compared to that Reynolds Number which yields turbulent flow in fully developed pipe flow (approximately \( 2 \times 10^3 \)). The assumption asserts that the same turbulent effects occur in both types of systems, but that turbulence occurs earlier in the cable system because of the turbulence promotors. Thus, if the asymptotic value of cable friction factor \( (f_c = 0.132) \) is used, Equation (D.17) yields the following for the reference cable system:

\[ \text{Nu} = \frac{2 \times 0.124}{\pi} (1.132 \times 10^{-2}) \times 2 \times 10^3 \times (150)^{1/4} = 64 \]

The corresponding value of \( h \) is

\[ h = \frac{12 k \text{Nu}}{\pi} = \frac{12 \times 0.1153 \times 64}{3.681} = 24 \text{ BTU/hr-ft}^2\text{F} \]
The ratio of conduction resistance to convection resistance for this value of h is given as:

\[
\frac{R_{\text{cond}}}{R_{\text{conv}}} = \frac{h d_0 \ln d_0/d_1}{12k} = 50
\]

Based on this simplified analysis, the value of the heat transfer correlation convection correction factor, CF, for turbulent flow is based on the value of the reference pipe-type cable system \((CF = 1.0)\). The heat transfer coefficient of that system is quite high \((h=55)\) and therefore essentially ignores the convection resistance.
Two detailed example problems are presented so as to provide the engineer with an insight into the use of the design manual. The example problems will make use of most of the design relationships and provide important details concerning the manner in which design steps A, B, and C are utilized. All equations used will first be presented in symbolic form followed by the numerical form. Explanation of the individual design steps is provided when necessary.

E.1 Example Problem 1

E.1.1 Problem Statement

An existing self-cooled pipe-type underground transmission system is to be converted into a forced-cooled system in order to increase the cable power-carrying capacity. The cable system is approximately 15 miles in length and the topographic profile of the route is shown in Figure E.1. The present design consists of two separate parallel cable lines buried in close proximity; figure 4 depicts a cross-section of the modified design to which discharge lines (return lines) and the associated piping are added to form two separate, parallel forced-cooled lines (both are operated in an identical manner). A preliminary engineering survey of the cable line route suggests that the maximum number of coolant loops to be used in the system is eight. This is based on the maximum possible number of pumping station locations which will provide for an even number of coolant loops. The
Figure E.1: Forced-Cooled System Route Topographic Profile and Pumping Station Locations

- Denotes pumping and refrigeration station
pumping (and refrigeration) station locations are also shown in Figure E.1.

An engineer has subsequently been assigned the task of analyzing possible modes of hydraulic and thermal operation of a system which utilizes all eight loops. The design must be capable of safely utilizing a peak cable load of 1400 amps while typically operating at an average daily load of 1250 amps. Example Problem 1 will present a design analysis of the first loop of this system. A complete listing of the system design parameters is given below.

E.1.2 System Design Characteristics

a) cable physical characteristics
   size = 2000 KCM - 345 kV
   \( d_i = 1.631 \text{ in} \)
   \( d_o = 3.931 \text{ in} \)
   \( t = 0.005 \text{ in} \)
   \( e = 0.1 \text{ in} \)
   \( s = 1.5 \text{ in} \)
   \( \alpha = 14.54 \text{ degrees} \)
   3 cables/pipe

b) cable electrical characteristics
   \( R_{DC} = 6.63 \mu\Omega/\text{ft} \)
   \( Y_c = 0.19 \)
   \( Y_s = 0.05 \)
   \( Y_p = 0.48 \)
   \( W_d = 2.68 \text{ w/ft/cable} \)
   \( k_{tape} = 220 \text{ BTU/hr ft°F} \)
   \( T_{cable,max} = 185°F \)
Figure E.2: Specific Gravity vs. Temperature.
(Ref. to H₂O at 15.6°C, ρ = 62.3 lbm/ft³.)
Figure E.3: Specific Heat vs. Temperature-Low Viscosity Polybutene Oil
Figure E.4: Oil Viscosity vs. Temperature—Low Viscosity Polybutene Oil
c) cable pipe characteristics

D = 10.25 in

\( P_{\text{cable,max}} = 600 \text{ psia} \)

Material = commercial steel

d) return pipe characteristics

D = 5"

\( P_{\text{return,max}} = 800 \text{ psia} \)

Material = commercial steel

e) oil properties

\text{type} = \text{low viscosity polybutene}

\( k_{\text{oil}} = 0.1153 \text{ BTU/lbm}^\circ\text{F} \)

\( P_{\text{oil,min}} = 120 \text{ psia} \)

Viscosity, specific heat and density properties are provided in Figures E.2 through E.4.

f) route description

Figure E.1 diagrams the system elevation profile.

g) heat exchanger characteristics

\( \Delta P_{\text{HE}} \) (heat exchanger pressure drop) = 40 psi

h) cable load

\( I_{\text{fc,max}} = 1400 \text{ amps} \)

\( I_{\text{fc,avg}} = 1250 \text{ amps} \)
E.1.3 Preliminary Design Considerations

Initially it is critical to establish the independent and dependent design variables and the constraints on these variables. In this particular problem, it has only to be decided as to whether the oil flow rate or the heat exchanger outlet temperature is to be specified by the engineer (all other variables have been implicitly categorized). In this analysis, the heat exchanger outlet temperature is treated as an independent variable. Table E.1 lists all important variables and categorizes them as to their independent or dependent nature. The design constraints are also listed.

An analysis procedure can now be created in order to calculate the dependent variables. The procedure used to perform the coolant loop analysis is shown in flow chart form in Figure E.5. The flow chart presents the principal steps of the analysis (but does not contain all steps).

E.1.4 Design Calculation

The coolant loop design calculations are separated into two groups: loop thermal analysis and loop hydraulic analysis. The overall analysis follows the design procedure presented in the flow chart of Figure E.5. The individual analysis procedures of design steps A, B, and C are presented as they appear in the text.

Loop Thermal Analysis

I. Calculate the preliminary value of the heat exchanger
TABLE E.1
EXAMPLE PROBLEM INDEPENDENT AND DEPENDENT VARIABLES

INDEPENDENT VARIABLES

Oil type (see section E.1.2)
Cable geometry (see section E.1.2)
Cable inside pipe diameter (see section E.1.2)
Discharge line inside diameter (see section E.1.2)
Coolant loop length (see Figure E.1)
Peak ampacity rating (see section E.1.2)
Average daily ampacity (see section E.1.2)
Heat exchanger outlet temperature; \( T_{\text{cold}} = 80^\circ \text{F} \) (specified by engineer)

DEPENDENT VARIABLES

Heat exchanger inlet temperature (cable line outlet temperature)
Oil flow rate
Cable-line pressure-flow loss
Discharge pressure-flow loss
Loop pressure profile
Loop temperature profile

DESIGN CONSTRAINTS

Maximum cable temperature (see section E.1.2)
Maximum cable pipe pressure (see section E.1.2)
Maximum discharge pipe pressure (see section E.1.2)
Minimum oil pressure (see section E.1.2)
Figure E.5: Flow Chart Depicting Use of Design Analysis Steps for a Single Coolant Loop. Inputs are L, I_{fc}, and T_{cold}. 
inlet temperature (maximum permissible cable line outlet temperature).
Use design Step B of the Analysis Procedure (Chapter 5).

1. Determine the conductor-to-oil temperature drop for the specified peak cable ampacity.

a) \[ W_c = (1 + Y_c) R_{DC} a_c^2; \text{ w/ft} \]  
   \[ W_c = (1 + 0.13) \times 6.63 \times 10^{-6} \times 1400^2 = 14.68 \text{ w/ft} \]

b) \[ \frac{W_c}{W_d} = \frac{14.68}{2.68} = 5.48 \]

c) Since the cable line outlet temperature is initially unknown, \( CF_1 \) is set equal to unity as recommended.

\[ CF_1 = 1.0 \]

d) \[ \frac{k_{tape}}{k_{oil}} \frac{\ln \frac{d_o}{d_i}}{\frac{d_o}{d_i}} = \frac{220 \times 0.005 \times \ln (3.93/1.631)}{0.1153 \times 3.931} \]
   \[ = 1.19 \]

From Figure 16,

\[ CF_2 = 0.99 \]

e) \[ (T_c - T_{oil}) = \left[ \frac{W_c}{W_d} + \frac{1}{CF_1 CF_2} + 0.53 \right] \frac{W_d \ln (d_o/d_i)}{1.764 k_{oil}} \]  
   \[ = \left[ 5.48 \times \frac{1}{1.0 \times 0.99} + 0.53 \right] \frac{2.68 \times \ln (3.931/1.631)}{1.764 \times 0.1153} \]
   \[ = 70.3^\circ F \]
2. The preliminary value of the maximum cable line oil temperature (heat exchanger inlet temperature), \( T_{\text{oil, max}} \) is

\[
T_{\text{oil, max}} = T_{\text{cable, max}} - (T_c - T_{\text{oil}}) \tag{5.10}
\]

\[= 185 - 70.3\]

\[T_{\text{oil, max}} = T_{\text{hot}} = 114.7^\circ F\]

II. Calculate the value of the flow rate, \( Q \), which is required to produce the specified value of the heat exchanger outlet temperature, \( T_{\text{cold}} \) for the calculated inlet temperature, \( T_{\text{hot}} \) and the specified values of the cable line axial length, \( L \), average daily ampacity value, \( I_{fc}^{\text{avg}} \) and the time of year. Use design Step A of the Analysis Procedure (non-adiabatic case).

1. \[
W = 3[I_{fc}^2 R_{DC} (1 + Y_c + Y_s + Y_p) + W_d]
\]

\[= 3[1250^2 \times 6.63 \times 10^{-6} (1 + 6.13 + .05 + .48) + 2.68]\]

\[= 59.63 \text{ w/ft}\]

2. Follow Example 1 presented in Step 2.

   a) The values of \( F_{11}, F_{22}, F_{22}, Q_{1a}, \) and \( Q_{2a} \) have been determined from the "Transient Heat Conduction in the Soil" computer program for day 220, New York City. The values are listed in section E.1.2.

   b) \[
T_{\text{avg}} = \frac{T_{\text{hot}} + T_{\text{cold}}}{2}
\]

\[= \frac{114.7 + 80.0}{2} = 94.85^\circ F\]
From Tables E.2 and E.3, the values of the oil density and specific heat are:

\[ \rho = 51.21 \text{ lbm/ft}^3 \]

\[ C_p = 0.494 \text{ BTU/lbm}^\circ F \]

The values of the oil density and specific heat are:

\[ \rho = 51.21 \text{ lbm/ft}^3 \]

\[ C_p = 0.494 \text{ BTU/lbm}^\circ F \]
\[ \lambda_2 = \frac{1}{2}(F_{11} - F_{22} - \sqrt{F_{11}^2 + F_{22}^2 + 2F_{11}F_{22} - 4F_{12}^2}} \\
= \frac{1}{2}(1.576 - 1.843 + \sqrt{1.576^2 + 1.843^2 + 2\times1.576\times1.843 - 4(-0.931)^2}} \\
= -1.567 \text{ BTU/hr-ft°F} \\
\]

\[ \bar{\lambda}_1 = \frac{F_{11} + F_{12} - \lambda_1}{F_{12}} \exp \left( -\frac{\lambda_1}{C_p \hat{m}} \right) \left( \frac{1}{L} \right) \]

\[ = \frac{1.576 + (-0.931) - 1.30}{-0.931} \exp \left( \frac{1.3}{0.494 \hat{m}} \right) \text{10000} \]

\[ = 0.70 \exp \left( -\frac{26315.79}{\hat{m}} \right) \]

\[ \bar{\lambda}_2 = \frac{F_{11} + F_{12} - \lambda_2}{F_{12}} \exp \left( -\frac{\lambda_2}{C_p \hat{m}} \right) \left( \frac{1}{L} \right) \]

\[ = \frac{1.576 + (-0.931) - (-1.576)}{-0.931} \exp \left( -\frac{-1.567}{0.494 \hat{m}} \right) \text{10000} \]

\[ = -2.376 \exp \left( -\frac{31720.65}{\hat{m}} \right) \]

\[ Q_g^* = W - Q_{1a} \]

\[ = 59.63 \frac{W}{ft} \times 3.413 \text{ BTU/hr} - (-52.43) \text{ BTU/hr} \]

\[ = 255.95 \text{ BTU/hr} \]

\[ A_1 = -(a_{22}Q_g^* + a_{12}Q_{2a}) \]

\[ = -(-0.904 \times 255.94 + 0.457 \times (-87.50)) \]

\[ = 271.364 \text{ BTU/hr} \]
\[ A_2 = a_{12} Q_2^* + a_{11} Q_{2a} \]
\[ = 0.457 \times 255.95 + (-0.773) \times (-87.50) \]
\[ = 184.607 \text{ BTU/hr} \]

The values of \( B_1, B_2, C_1 \) and \( C_2 \) depend on the value of the oil mass flow rate, \( \dot{m} \) (or \( Q \)). Select an initial value of the flow rate and calculate the values of these parameters.

**Trial 1:** Select \( Q = 300 \text{ gal/min} \)

\[ \dot{m} = \rho \frac{Q}{0.124} = \frac{51.21 \times 300}{0.124} = 123,895.16 \text{ lbm/hr} \]

\[ \overline{\lambda}_1 = 0.7 \exp\left(\frac{26315.79}{123895.16}\right) \]

\[ = 0.87 \]

\[ \overline{\lambda}_2 = -2.376 \exp\left(\frac{-31720.65}{123895.16}\right) \]

\[ = -1.84 \]

\[ B_1 = \frac{(\overline{\lambda}_2 - 1) A_1 + A_2 - \overline{\lambda}_2 T_1(o)}{\overline{\lambda}_1 - \overline{\lambda}_2} \]

\[ = \frac{(-1.84-1) 271.364 + 184.607 - (-1.84)114.7}{0.87 - (-1.84)} \]

\[ = -138.38^\circ F \]

\[ B_2 = \frac{\overline{\lambda}_1 - F_{11}}{F_{12}} B_1 = \frac{-1.30 - 1.576}{-0.931} (-138.38) \]

\[ = -41.02^\circ F \]
\[ C_1 = T_1(o) - A_1 - B_1 \]
\[ = 114.7 - 271.364 - (-138.38) = 18.28^\circ F \]

\[ C_2 = \frac{\lambda_2 - F_{11}}{F_{12}} \quad C_1 = \frac{-1.567 - 1.576}{-0.931} \quad (-18.28) \]
\[ = -61.73^\circ F \]

Calculate the value of \( T_{\text{cold}} \) and compare it with the specified value:

\[ T_2(o) = T_{\text{cold}} = A_2 + B_2 + C_2 \]
\[ = 184.607 - 41.02 - 61.28 \]
\[ = 81.85^\circ F \]

Since the calculated value is approximately equal to the specified value of \( T_{\text{cold}} \) (80\(^\circ\)F), the oil flow rate is approximately 300 gal/min. If the first selection of the flow rate not been the correct one, a new value would have had to be selected (increase the flow rate if the calculated value of \( T_{\text{cold}} \) is less than the specified value or decrease the flow rate in the other case).

III. Recalculate the value of \( T_{\text{oil, max}} \) in order to check if the initial value is valid for the present value of the loop oil flow rate. Use design Step B of the Analysis Procedure.

1. 
   a) \( W_c = 14.68 \, \text{w/ft} \) - determined in Step I
b) \( \frac{\bar{W}_C}{\bar{W}_d} = 5.48 \)

c) Calculate the value of \( CF_1 \):

1) From Figure E.2 and E.4 determine the oil property values (density and viscosity) for the value of \( T_{oil,max} \).

\[
\rho = 50.77 \text{ lbm/ft}^3
\]

\[
\mu = 19 \text{ CP}
\]

Calculate the value of the Reynolds number (see Figure 17):

\[
Re = \frac{1.595 \times 10^2 \times Q}{(\mu \times P)/\rho} = \frac{1.595 \times 10^2 \times 300}{(19 \times 69.25)/50.77} = 1846.36
\]

2) Since the value of the cable-line Reynolds number, at the point of interest, indicates turbulent flow, the value of \( CF_1 \) is equal to unity.

\( CF_1 = 1.0 \)

3) Not needed

d) \( CF_2 = 0.99 \) - calculated in Step I

e) Since the values of \( CF_1 \) and \( CF_2 \) are identical to the values used in Step I, the conductor-to-oil temperature drop remains unchanged.

2. The value of \( T_{oil,max} (T_{hot}) \) remains unchanged. The thermal analysis is complete, except for calculation of the oil temperature profile. Use equations 3.6a and 3.6b to calculate the cable
line and return line temperature profile. The results are plotted in Figure E.6.

\[ T_1(z) = 271.364 - 138.38 \exp(2.123 \times 10^{-5} z) - 18.28 \exp(-2.559 \times 10^{-5} z) \]

(3.6a)

\[ T_2(z) = 184.607 - 41.02 \exp(2.123 \times 10^{-5} z) - 61.73 \exp(-2.559 \times 10^{-5} z) \]

(3.6b)

Use Section B of the energy balance to calculate the required heat exchanger cooling capacity (use average loop oil properties):

\[ W_{HE} = 8.04 \rho C_p Q \Delta T_{HE} \]

(5.4)

\[ W_{HE} = 8.04 \times 51.1 \times 0.49 \times 300 \times (114.7 - 81.8) \]

\[ = 1.987 \times 10^6 \frac{\text{BTU}}{\text{hr}} (5.822 \times 10^5 \text{ watts}) \]

Loop Hydraulic Analysis

IV. Calculate the resultant loop pressure profile and the required loop pumping power. Use design Step C of the Analysis Procedure.

1. Calculate the loop pressure-flow loss for the cable line, return line and heat exchanger.

a) \[ T_{\text{avg,cable}} = \frac{114.7 + 86.1}{2} = 100.4^\circ F \]

\[ \rho = 51.1 \text{ lbm/ft}^3 \]

\[ \mu = 18 \text{ CP} \]

\[ \left( \frac{\mu P}{\rho} \right)_{\text{cable}} = \frac{18 \times 69.25}{51.1} = 24.4 \]
Figure E.6: The Coolant Loop Temperature Profile.
\[ T_{\text{avg, return}} = \frac{81.8 + 86.1}{2} = 83.95^\circ \text{F} \]

\[ \rho = 51.5 \text{ lbm/ft}^3 \]

\[ \mu = 27 \text{ CP} \]

\[ (\frac{\text{LP}}{P})_{\text{return}} = \frac{27 \times 15.71}{51.5} = 8.24 \]

b) From Figure 17,

\( (Re)_{\text{cable}} = 1960 \rightarrow \text{turbulent flow (Re > 450)} \)

\( (Re)_{\text{return}} = 5800 \rightarrow \text{turbulent flow (Re > 2100)} \)

c) From Figure 18,

\[ f_{c, \text{ref}} = 1.9 \times 10^{-2} \]

From Figure 19

\[ f_r = 9 \times 10^{-3} \]

d) \[ f_c = f_{c, \text{ref}} \times 12.273 \left( \frac{e}{d_o} \right)^{0.387} \left( \frac{s}{e} \right)^{-0.373} \] \[ (2.725 \frac{d_o}{D} - 0.099) \times k \]

\[ = 1.9 \times 10^{-2} \times 12.273 \left( \frac{0.1}{3.93} \right)^{0.387} \left( \frac{1.5}{0.1} \right)^{-0.373} \]

\[ = 1.94 \times 10^{-2} \]

e) \[ (\frac{\Delta P}{L}) = 1.3394 \times 10^{-4} \frac{f \rho P}{A^3} Q \] (3.8)
\[ \frac{\Delta P_c}{L} = \frac{1.3394 \times 10^{-4} \times 1.94 \times 10^{-2} \times 51.1 \times 69.25 \times 300^2}{(\frac{\pi}{4}) (10.25^2 - 3 \times 3.931^2)^3} \]

\[ = 8.44 \times 10^{-3} \text{ psi/ft} \]

\[ \frac{\Delta P_r}{L} = \frac{1.3394 \times 10^{-4} \times 9 \times 10^{-3} \times 51.5 \times 15.71 \times 300^2}{(\frac{\pi}{4} \times 5^2)^3} \]

\[ = 1.16 \times 10^{-2} \text{ psi/ft} \]

f) Losses in valves and fittings will be ignored.

\[ L_e = 0.0 \]

\[ L^* = L_r \]

\[ \Delta P_{HE} = 40 \text{ psi (Specified in section E.1.2)} \]

h) \[ \Delta P_{\text{loop}} = \left( \frac{\Delta P_c}{L} \right)_c L_c + \left( \frac{\Delta P_r}{L} \right)_r L_r + \Delta P_{HE} \] (5.17)

\[ = (8.44 \times 10^{-3})10000 + (1.16 \times 10^{-2})10000 + 40 \]

\[ = 240.4 \text{ psi} \]

i) \[ P_{\text{pump}} = 5.82 \times 10^{-4} \times Q \Delta P_{\text{loop}} \] (5.18)

\[ = 5.82 \times 10^{-4} \times 300 \times 240.4 \]

\[ \approx 42 \text{ hp (31,287 watts)} \]

2. Determine the coolant loop absolute pressure profile, as an example, calculate the absolute pressure which exists at point 1-4 as shown in Figure E.7 (a schematic drawing of the coolant loop).
Figure E.7: A Schematic Drawing of a Single Coolant Loop and the Loop Evaluation Profile
The elevation profile is also shown.

a)  
  i) The loop reference point corresponds to point 1-1 in Figure E.7. The value of the reference pressure, $P_{ref}$, is equal to the head tank pressure, $P_{HT}$, which maintains all system static pressures above the minimum permissible cable line pressure, $P_{cable,min}$.

In order to calculate the head tank pressure, it is necessary to identify that loop profile point, located above the head tank in elevation, that maximizes the elevation difference between the head tank location and the rest of the system. In this case, the maximum height differential is equal to 150 feet. Calculate the static pressure difference, $\Delta P_{EL}$, for this height (use part ii). (Use a loop average value for the oil density).

\[
\Delta P_{EL} = 6.944 \times 10^{-3} \rho \Delta h 
\]

\[
= 6.944 \times 10^{-3} \times 51.1 \times 150 
\]

\[
= 53 \text{ psi}
\]

Calculate the head tank pressure using the following equation.

\[
P_{HT} = P_{ref} = P_{cable,min} + \Delta P_{EL}
\]

\[
= 125 + 53 = 128 \text{ psia}
\]

ii) The difference in height between point 4 and point 1 is as follows:

\[
\Delta h = 50 \text{ ft}
\]

\[
\Delta P_{EL} = 17.4 \text{ psi}
\]

iii) $P_{s,1-4} = P_{1-1} - \Delta P_{EL}$

\[
= 178 - 17.4 = 160.6
\]
b)  
   
i) \[ \Delta P_D = \left( \frac{\Delta P}{L} \right) \times z \]
   
   \[ = 8.44 \times 10^{-3} \times 10,000 \]
   
   \[ = 84.4 \text{ psi} \]

   \[ P_{1-4} = P_{s,1-4} + \Delta P_D \]  \hspace{1cm} (5.21)

   \[ = 160.6 + 84.4 = 245 \text{ psia} \]

   c) The entire loop pressure profile is plotted in figure E.8. All loop pressures lie within the pressure constraints.

E.2 Example Problem 2

This problem is presented in order to demonstrate the coolant loop thermal analysis when laminar flow exists in the cable line. Loop #2 of the forced-cooled system of example problem 1 will be examined. All independent and dependent variables remain unchanged except that the heat exchanger outlet temperature of loop #2 is specified to be 70°F.

E.2.1 Design Calculation

Only the loop thermal analysis will be performed. The design steps of example problem 2 which are identical in form to those steps of example problem 1 will not be repeated in detail.

Loop Thermal Analysis

I. This step remains unchanged from example problem 1. The initial value of the heat exchanger inlet temperature is
Figure E.8: The Coolant Loop Pressure Profile.
\[ T_{\text{oil,max}} = T_{\text{hot}} = 114.7^\circ F \]

II. Step A of the Design Analysis Procedure has been used to calculate the value of the oil flow rate.

\[ Q = 60 \text{ gal/min} \]

III. Recalculate the value of \( T_{\text{oil,max}} \) in order to check if the initial value is valid for the present value of the loop oil flow rate. Use design Step B of the Analysis Procedure.

1. 
   a) \( W_c = 14.68 \text{ w/ft} \)
   
   b) \( \frac{W_c}{W_d} = 5.48 \)
   
   c) Calculate the value of \( C_1 \)

1) From Figure E.2 and E.4 determine the oil property values (density and viscosity) corresponding to the value of \( T_{\text{oil,max}} \):

\[ \rho = 50.77 \text{ lbm/ft}^3 \]
\[ \mu = 19 \text{ CP} \]

Calculate the value of the Reynolds number (see Figure 17).

\[ Re = \frac{1.595 \times 10^2 Q}{(\mu x P)/\rho} \]
\[ = \frac{1.595 \times 10^2 \times 70}{(19 \times 69.23)/50.77} \]
\[ = 430 \]
2) The value of the cable line Reynolds Number, at the point of interest, indicates laminar flow.

ii) Trial 1: \( \Delta T_{s-o} = 5^\circ F \)

\[
T_{avg} = \frac{(114.7 + (114.7 + 5))}{2} = 117.2^\circ F
\]

\[
\rho = 50.7 \text{ lbm/ft}^3
\]

\[
C_p = 0.508 \text{ BTU/lbm}^\circ F
\]

\[
\mu = 12 \text{ CP}
\]

iii) \( R_a = 3.0992 \times 10^3 \times \frac{\bar{g} \Delta T_{s-o} d_o^2 \rho^2}{\mu^2} \times \frac{C_p \mu}{k_{oil}} \)

\[
= 3.0992 \times 10^3 \times \frac{32.2 \times 0.4 \times 10^{-3} \times 5 \times 3.931^3 \times 50.7^2}{12^2} \times \frac{0.508 \times 12}{0.1153}
\]

\[
= 1.14 \times 10^7
\]

From Figure 14,

\[
N_u = 20
\]

iv) \( h = \frac{12 N_u k_{oil}}{d_o} = \frac{12 \times 20 \times 0.1153}{3.931} = 7 \frac{\text{BTU}}{\text{hr-ft}^\circ F} \)

v) \( \Delta T_{s-o} = 13.04 \left( I_{r_c}^2 R_{DC} (1 + Y_c + Y_s) + W_d \right)/h d_o \) (5.9)

\[
= 13.04 \left[ 1400^2 \times 6.63 \times 10^{-6} (1 + 0.13 + 0.05) + 2.68 \right]/7 \times 3.931
\]

\[
= 8.5^\circ F
\]
Since the calculated value of $\Delta T_{S-o}$ is different from the specified value, repeat the procedure using $\Delta T_{S-o} = 8.54^\circ F$.

**Trial 2:**

\[
T_{avg} = 119^\circ F \quad \rho = 50.5 \text{ lbm/ft}^3 \\
\mu = 12 \text{ CP} \\
C_P = 0.510
\]

\[
Ra = 1.93 \times 10^7 \quad Nu = 22
\]

\[
h = 7.7 \text{ BTU/hr-ft}^2 \circ F
\]

\[
\Delta T_{S-o} = 7.8^\circ F
\]

**Trial 3:**

\[
T_{avg} = 118.6^\circ F \quad \rho = 50.5 \text{ lbm/ft}^3 \\
\mu = 12 \text{ CP} \\
C_P = 0.510 \text{ BTU/lbm}^\circ F
\]

\[
Ra = 1.76 \times 10^7 \quad Nu = 21
\]

\[
h = 7.4 \frac{\text{BTU}}{\text{hr-ft}^2 \circ F}
\]

\[
\Delta T_{S-o} = 8.1^\circ F
\]

The iterative procedure should continue until the value of $\Delta T_{S-o}$ does not change. In this case, the iteration converges on a value of $\Delta T_{S-o}$ equal to $7.9^\circ F$. The corresponding value of the heat transfer coefficient is $7.6 \frac{\text{BTU}}{\text{hr-ft}^2 \circ F}$.

\[
\frac{12k_{oil}}{h d_o \ln \frac{d_o}{d_1}} = \frac{12 \times 0.1153}{7.6 \times 3.931 \times \ln \frac{3.931}{1.631}} = 5.26 \times 10^{-2}
\]
From Figure 15,

\[ CF_1 = 0.838 \]

\[ d) \quad \frac{k_{tape} + \ln \left( \frac{d_o}{d_i} \right)}{k_{oil} \frac{d_o}{d_i}} = \frac{220 \times 0.005 \times n \left( \frac{3.931}{1.631} \right)}{0.1153 \times 3.931} = 1.19 \]

From Figure 16,

\[ CF_2 = 0.99 \]

e) \quad (T_c - T_{oil}) = \left[ \frac{W_c}{W_d} + \frac{1}{CF_1 + CF_2} + 0.53 \right] \times \frac{W_d \ln \frac{d_o}{d_i}}{1.764 k_{oil}} \quad (3.7) \]

\[ = \left[ 5.48 \times \frac{1}{0.838 \times 0.99} + 0.53 \right] \frac{2.68 \ln \left( \frac{3.931}{1.631} \right)}{1.764 \times 0.1153} \]

\[ = 82.71^\circ F \]

2. \[ T_{oil, max} = T_{cable, max} - (T_c - T_{oil}) \]

\[ = 185 - 82.71 \]

\[ = 102.3^\circ F \]

Since the calculated value of \( T_{oil, max} \) is different from the initial value (114.7°F), the entire thermal analysis must be repeated using the new value of \( T_{oil, max} \). When both the energy balance (Step A) and the pipe-type cable
heat transfer correlation are simultaneously satisfied and the value of $T_{oil,\text{max}}$ no longer changes, the thermal analysis ends.
Figure 25: Effect of changing the cable-to-pipe diameter ratio on the friction factor in the turbulent flow.

\[ \frac{f}{f_{c,\text{ref}}} = 2.725 \frac{d_0}{D} - 0.099 \]
$R_1$ - Insulation thermal resistance as seen by conductor losses

$R_2$ - Insulation thermal resistance as seen by distributed dielectric losses

$R_3$ - Convection resistance between cable and oil

$T_{\text{max}}$ - Maximum insulation temperature (conductor temperature)

$T_{\text{oil}}$ - Bulk oil temperature

Figure 26: One-dimensional heat conduction in the cable insulation with lumped thermal losses.
Figure 27: Correlation between the nondimensional current \( (1+Y_c)^2 R_{DC} I_{FC}^2 \) and the nondimensional conductor-to-oil temperature drop \( \phi \).
Table 4: Turbulent flow friction factor as a function of \(d_o/D\).

<table>
<thead>
<tr>
<th>(d_o/D)</th>
<th>(f_c)</th>
<th>(f/f_{c,ref})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4265</td>
<td>0.02394</td>
<td>1.078</td>
</tr>
<tr>
<td>0.4034</td>
<td>0.02220</td>
<td>1.000</td>
</tr>
<tr>
<td>0.3529</td>
<td>0.01887</td>
<td>0.850</td>
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<tr>
<td>0.2941</td>
<td>0.01589</td>
<td>0.716</td>
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</table>

Table 3: Laminar flow friction factor as a function of \(d_o/D\).

<table>
<thead>
<tr>
<th>(d_o/D)</th>
<th>(f/f_{c,ref})</th>
<th>no. of mesh points</th>
</tr>
</thead>
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<tr>
<td>0.0037</td>
<td>1.3843</td>
<td>79</td>
</tr>
<tr>
<td>0.0074</td>
<td>1.3591</td>
<td>79</td>
</tr>
<tr>
<td>0.0221</td>
<td>1.7842</td>
<td>79</td>
</tr>
<tr>
<td>0.0662</td>
<td>1.7563</td>
<td>77</td>
</tr>
<tr>
<td>0.1397</td>
<td>1.7096</td>
<td>74</td>
</tr>
<tr>
<td>0.2059</td>
<td>1.6463</td>
<td>90</td>
</tr>
<tr>
<td>0.2574</td>
<td>1.5908</td>
<td>81</td>
</tr>
<tr>
<td>0.2941</td>
<td>1.4963</td>
<td>97</td>
</tr>
<tr>
<td>0.3235</td>
<td>1.415</td>
<td>91</td>
</tr>
<tr>
<td>0.3529</td>
<td>1.2989</td>
<td>84</td>
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<tr>
<td>0.3971</td>
<td>1.0329</td>
<td>83</td>
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<tr>
<td>0.4034</td>
<td>1.0</td>
<td>79</td>
</tr>
<tr>
<td>0.4265</td>
<td>0.8162</td>
<td>74</td>
</tr>
<tr>
<td>$Y_c$</td>
<td>$R_{dc}$</td>
<td>$K_{oil}$</td>
</tr>
<tr>
<td>------</td>
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<td>--------</td>
</tr>
<tr>
<td>0.13</td>
<td>6.43</td>
<td>0.1153</td>
</tr>
<tr>
<td>0.04</td>
<td>6.43</td>
<td>0.1153</td>
</tr>
<tr>
<td>0.2</td>
<td>6.43</td>
<td>0.1153</td>
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<tr>
<td>0.13</td>
<td>6.70</td>
<td>0.1153</td>
</tr>
<tr>
<td>0.13</td>
<td>6.10</td>
<td>0.1153</td>
</tr>
<tr>
<td>0.04</td>
<td>6.43</td>
<td>0.1153</td>
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<td>0.1153</td>
</tr>
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</tr>
<tr>
<td>0.11</td>
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<td>0.1563</td>
</tr>
<tr>
<td>0.15</td>
<td>7.0</td>
<td>0.0800</td>
</tr>
</tbody>
</table>

\[ W_c = (1 + Y_c) R_{dc} T_{fc} \]
\[ = \frac{k_{oil}}{h d_o \ln d_o/d_i} = 6.597 \times 10^{-3} \]
\[ \frac{k_{tape} t \ln d_o/d_i}{k_{oil} d_o} = 2.1097 \]

**TABLE 5:** $k_{oil}(T_{c} - T_{oil})$ as a function of $W_c/W_d$
<table>
<thead>
<tr>
<th>Yc</th>
<th>Rd</th>
<th>K_oil</th>
<th>K_tape</th>
<th>h</th>
<th>t</th>
<th>d_o</th>
<th>d_i</th>
<th>Wd</th>
<th>T_c-T_oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>6.43</td>
<td>0.1153</td>
<td>220</td>
<td>70</td>
<td>0.005</td>
<td>3.681</td>
<td>1.631</td>
<td>2.68</td>
<td>29.13</td>
</tr>
<tr>
<td>0.135</td>
<td>6.43</td>
<td>0.1663</td>
<td>293.74</td>
<td>31.3</td>
<td>0.003</td>
<td>2.552</td>
<td>0.9239</td>
<td>2.68</td>
<td>24.11</td>
</tr>
<tr>
<td>0.11</td>
<td>7.00</td>
<td>0.0800</td>
<td>375.65</td>
<td>200.0</td>
<td>0.005</td>
<td>4.810</td>
<td>3.122</td>
<td>2.866</td>
<td>24.11</td>
</tr>
<tr>
<td>0.15</td>
<td>6.20</td>
<td>0.0997</td>
<td>192.85</td>
<td>5.0</td>
<td>0.006</td>
<td>5.135</td>
<td>1.950</td>
<td>2.63</td>
<td>37.51</td>
</tr>
</tbody>
</table>

\[
\phi = \frac{k_{oil}(T_c - T_{oil})}{3.413 \frac{W_d}{W} \ln \frac{d_o}{d_i}} + \frac{12 k_{oil}}{h \frac{d_o}{d_i} \ln \frac{d_o}{d_i}} I_{fe} \]

<table>
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<tr>
<th>[BTU/hr W]</th>
<th>[in/ft]</th>
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<tr>
<td>0.4511</td>
<td>6.597 x 10^{-3}</td>
<td>900</td>
</tr>
<tr>
<td>0.4313</td>
<td>2.459 x 10^{-2}</td>
<td>900</td>
</tr>
<tr>
<td>0.4562</td>
<td>2.309 x 10^{-3}</td>
<td>900</td>
</tr>
<tr>
<td>0.5543</td>
<td>7.699 x 10^{-2}</td>
<td>900</td>
</tr>
</tbody>
</table>

\[
\frac{W_c}{W_d} = 2.196 \frac{k_{tape} n d_i/d_o}{k_{oil} d_o} = 2.1097
\]

Table 6: \( \phi = \frac{k_{oil}(T_c - T_{oil})}{3.413 \frac{W_d}{W} \ln \frac{d_o}{d_i}} \) as a function of \( \frac{12 k_{oil}}{h \frac{d_o}{d_i} \ln \frac{d_o}{d_i}} \)
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<tbody>
<tr>
<td>0.13</td>
<td>6.43</td>
<td>0.1153</td>
<td>220</td>
<td>70</td>
<td>0.005</td>
<td>3.681</td>
<td>1.631</td>
<td>900</td>
<td>2.68</td>
</tr>
<tr>
<td>0.13</td>
<td>6.43</td>
<td>0.1153</td>
<td>220</td>
<td>70</td>
<td>0.0025</td>
<td>3.681</td>
<td>1.631</td>
<td>900</td>
<td>2.68</td>
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<td>0.1153</td>
<td>220</td>
<td>70</td>
<td>0.01</td>
<td>3.681</td>
<td>1.631</td>
<td>900</td>
<td>2.68</td>
</tr>
<tr>
<td>0.13</td>
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<td>50</td>
<td>0.0</td>
<td>4.125</td>
<td>1.995</td>
<td>900</td>
<td>2.68</td>
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<tr>
<td>0.13</td>
<td>6.00</td>
<td>0.0915</td>
<td>220</td>
<td>60</td>
<td>0.0012</td>
<td>4.0</td>
<td>2.0</td>
<td>900</td>
<td>2.50</td>
</tr>
<tr>
<td>0.2</td>
<td>6.43</td>
<td>0.1067</td>
<td>220</td>
<td>70</td>
<td>0.0286</td>
<td>4.0</td>
<td>2.0</td>
<td>900</td>
<td>2.846</td>
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\[
T_c - T_{oil} = \frac{\phi}{k_{oil}(T_c - T_{oil})} = \frac{K_{tape} t \ln d_o/d_1}{k_{oil} d_o}
\]

\[
\begin{align*}
\frac{W_c}{W_d} &= 2.196 \\
\frac{12 k_{oil}}{h d_o \ln d_o/d_1} &= 6.597 \times 10^{-3}
\end{align*}
\]

Table 7: $\phi = \frac{k_{oil}(T_c - T_{oil})}{3.413 W_d \ln d_o/d_1}$ as a function of $\frac{K_{tape} t \ln d_o/d_1}{k_{oil} d_o}$
These results were obtained for:  
\[ 0.03 < Y_c < 0.2 \]
\[ Y_d = 0.05 \]
\[ 5.66 < R_{dc} < 12.86 \ \mu \Omega/ft \]
\[ 2.11 < W_d < 3.18 \ \text{W/ft} \]
\[ 680 \leq I_{fc} < 2000 \ \text{A} \]
\[ 1.131 < d_i < 2.131 \ \text{in} \]
\[ 2.552 < d_o < 4.81 \]

**TABLE 8:** Check on the accuracy of the pipe-type cable system heat transfer correlation
FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES

DESIGN MANUAL, PART II OF III

EXPERIMENTAL AND ANALYTICAL RESULTS USED TO FORMULATE THE DESIGN

by

Jay A. Brown
Paul F. Koci
Leon R. Glicksman

Energy Laboratory
in association with
Heat Transfer Laboratory
Department of Mechanical Engineering
Massachusetts Institute of Technology

Sponsored by
Consolidated Edison Company of New York Inc.
New York, New York

Energy Laboratory Report No. MIT-EL 78-014
Heat Transfer Laboratory Report No. 80619-101

June 1978
FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES

Design Manual, Part II of III

ABSTRACT

The methodology utilized for the design of a forced-cooled pipe-type underground transmission system is presented. The material is divided into three major parts: (1) The Forced-cooled Pipe-Type Underground Transmission System Design Manual-Part I, (2) The Design Manual-Part II, and (3) the Forced-Cooled Pipe-Type Underground Transmission System Computer Program Design Manual.

The Design Manual Part I provides the thermal and hydraulic design analyses required for the design of a forced-cooled cable system of specified geometry. The thermal design establishes the relationship between the cable amperage, oil flow, and the conductor-to-oil temperature difference and provides a coolant loop energy balance which includes an analysis of the pipe-to-soil heat transfer. Combination of both permits the maximization of the cable amperage while maintaining the cable temperature below the maximum allowable value.

The hydraulic design establishes the pressure-flow characteristics for pipe-type cable systems and a systematic analysis is provided which allows for calculation of the pressure drop in the cable line and return line of the flow circuit as well as the circuit absolute pressure profile. The pressure drop governs the selection of circulation pumps, pipe strength characteristics, and strongly influences coolant loop length.

The Design Manual-Part II presents a description of the experimental and analytical research performed at M.I.T.'s Heat Transfer Laboratory which provides the relationships used in the design analysis of Design Manual-Part I.

The Computer program design manual provides a detailed description of the forced-cooled system computer program and the necessary program documentation. The computer program is basically a straightforward computerization of the design procedure of Design Manual-Part I. Six different computer design options are provided which permit complete flexibility for the design and optimization of the forced-cooled system. Four of the design options allow for the selection of alternative independent and dependent design variables and two design options provide for the system optimization based on specified optimization criteria.
ACKNOWLEDGEMENTS

This research work was supported by the Consolidated Edison Company of New York.

The cooperation of Mr. Michael D. Buckweitz of the Consolidated Edison Company is gratefully acknowledged.
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<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>cross-sectional area; in$^2$</td>
</tr>
<tr>
<td>$C_{F_1}$</td>
<td>convection correction factor for pipe-type cable system heat transfer correlation; dimensionless</td>
</tr>
<tr>
<td>$C_{F_2}$</td>
<td>metallic tape correction factor for pipe-type cable system heat transfer correlation; dimensionless</td>
</tr>
<tr>
<td>$D_H$</td>
<td>hydraulic diameter; in</td>
</tr>
<tr>
<td>$D$</td>
<td>inside diameter of cable pipe; in</td>
</tr>
<tr>
<td>$d_o$</td>
<td>cable outside diameter (excluding skid wire); in</td>
</tr>
<tr>
<td>$d_i$</td>
<td>cable insulation inside diameter; in</td>
</tr>
<tr>
<td>$e$</td>
<td>skid wire height; in</td>
</tr>
<tr>
<td>$f_c$</td>
<td>cable line friction factor; dimensionless</td>
</tr>
<tr>
<td>$f_{c,\text{ref}}$</td>
<td>cable line reference friction factor; dimensionless</td>
</tr>
<tr>
<td>$f_1$</td>
<td>friction factor in flow zone influenced by rough cable geometry; dimensionless</td>
</tr>
<tr>
<td>$f_2$</td>
<td>friction factor in flow zone influenced by smooth pipe geometry; dimensionless</td>
</tr>
<tr>
<td>$f_{12}$</td>
<td>friction factor for combined flow zones; dimensionless</td>
</tr>
<tr>
<td>$k_{\text{oil}}$</td>
<td>oil thermal conductivity; BTU/hr-ft$^2$°F</td>
</tr>
<tr>
<td>$L$</td>
<td>axial flow length (cable segment length); ft</td>
</tr>
<tr>
<td>$P$</td>
<td>wetted perimeter, in</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>pressure drop; psi</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number; dimensionless</td>
</tr>
<tr>
<td>$\dot{q}$</td>
<td>heat generator per unit area; BTU/hr ft$^2$</td>
</tr>
<tr>
<td>$r$</td>
<td>radius; in</td>
</tr>
<tr>
<td>$s$</td>
<td>skid wire axial spacing; in</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>temperature; °F</td>
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<td><strong>T_c</strong></td>
<td>conductor temperature; °F</td>
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<tr>
<td><strong>T_{oil}</strong></td>
<td>bulk oil temperature; °F</td>
</tr>
<tr>
<td><strong>U</strong></td>
<td>local oil flow velocity; ft/sec</td>
</tr>
<tr>
<td><strong>V</strong></td>
<td>average bulk fluid velocity; ft/sec</td>
</tr>
<tr>
<td><strong>W_d</strong></td>
<td>total dielectric loss per conductor-foot; w/ft</td>
</tr>
<tr>
<td><strong>W_c</strong></td>
<td>conductor energy loss per conductor-foot; w/ft</td>
</tr>
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**Greek Symbol**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>α</strong></td>
<td>skid wire helix angle; degrees</td>
</tr>
<tr>
<td><strong>Δ</strong></td>
<td>difference</td>
</tr>
<tr>
<td><strong>μ</strong></td>
<td>absolute oil viscosity; lbm/hr-ft</td>
</tr>
<tr>
<td><strong>ρ</strong></td>
<td>oil density; lbm/ft³</td>
</tr>
<tr>
<td><strong>φ</strong></td>
<td>azimuthal coordinate; radians</td>
</tr>
<tr>
<td><strong>γ</strong></td>
<td>shear stress; psi</td>
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</table>
1. Introduction and Objectives

Part II of the forced-cooled pipe-type cable system design manual presents a general description of the experimental and analytical research which provided the essential building blocks required for the creation of the forced-cooled system design analysis of Part I. An overview of the MIT research is presented so that those using Part I will have at their disposal a single, concise reference of the specific analysis techniques employed, together with the primary assumptions and limitations which are associated with the individual design analyses. The information contained in Part II is derived primarily from MIT Energy Laboratory reports and the reader is referred to those reports (and other references) if more detailed information is desired.

The Design Manual - Part II separates the forced-cooled system research into two general categories: (1) pipe-type cable system hydraulic research developments (Chapter 2) and (2) pipe-type cable system heat transfer developments (Chapter 3). Contained within these chapters are the general details of the specific research programs that were conducted in order to solve the fluid mechanical and heat transfer design problems associated with the forced-cooling technique (the results of which appear in the Design Analysis of Part I). The hydraulic problems which are detailed in Chapter 2 are:
2.1 Calculation of the dynamic pressure-flow losses in pipe-type cable systems for laminar and turbulent flow, and,

2.2 Determination of the most effective pumping system for the forced-cooled technique.

The thermal problems detailed in Chapter 3 are:

3.1 Calculation of the cable conductor-to-oil temperature drop for the pipe-type cable system and,

3.2 Calculation of the two-dimensional pipe-to-soil heater transfer for pipe-type cable systems and,

3.3 Prediction of the forced-cooling requirements for a non-adiabatic pipe-type cable system.

Descriptions of the experimental aspects of the research, include a description of the testing equipment, the measurement techniques employed (and the accuracy of the measurements), and the final test results. Description of the analytical research includes the details of the solution technique and its limits, the important assumptions involved, the final results and the accuracy of the results. Comparison of the analytical and experimental results is also presented.
2. PIPE-TYPE CABLE SYSTEM HYDRAULIC RESEARCH DEVELOPMENTS

2.1 Pressure-Flow Losses in Pipe-Type Cable Systems for Laminar and Turbulent Flow

An important part of the design of a forced-cooled pipe-type cable system (F.C.P.T.C.S.) is the determination of the pressure drop developed along the cable line when the chilled oil is being circulated through the system. Since the pressure drop governs the selection of pumps and pipe strength characteristics and influences coolant loop length, a designer must be able to confidently predict its value. In regard to the above, the purpose of this chapter is to review the experimental and analytical research performed at MIT's Heat Transfer Laboratory concerning the prediction of pressure losses in the F.C.P.T.C.S.

The chapter is organized so as to briefly introduce, in section 2.1.1, the physical make-up of the pipe-type cable system along with the customary manner in which pressure-loss data is presented. Section 2.1.2 examines the experimental techniques employed to obtain pressure-drop data along with the results of the experimental program. Finally, Section 2.1.3 reviews the analytical methodology used in order to create computer models of the pipe-type cable system for both laminar and turbulent flow and compares the results of the computer models with the experimental results.

2.1.1 Background Information

The pipe-type cable system consists of three round cables,
wrapped with skid wires, enclosed in a round pipe. The cross-sectional view of such a system is shown in Figure 2.1. Figure 2.2 shows a longitudinal view of a single cable. (The symbols used to describe the cable-pipe geometry are indicated in both Figures). Since the cables twist as they are pulled through the pipe and also move around in the pipe due to thermal expansion, they assume a variety of different positions or configurations along the length of the cable line. Duplication of a specific pipe-type cable line, with its myriad of configurations, is virtually impossible and therefore analysis consists of studying particular cable configurations so as to identify the worst configuration (highest pressure drop) to be used for a conservative design. Those configurations studied are shown in Figure 2.3 (the geometry used to describe the relative positions of the cables is indicated). The dimension e accounts for the presence of the skid wires (utilized to reduce friction when the cables are pulled through the conduit) and shows that the cables cannot be closer to each other or the pipe than the skid wire height.

As is commonly done for fluid flow in pipes, the data for pressure losses in the pipe-type cable system is tabulated as graphs of friction factor vs. Reynolds number. The use of the dimensionless friction factor and Reynolds number allows for direct comparison between geometrically similar systems. (Geometrically similar systems are ones in which all corresponding lengths are related by a single scale factor and any cross-section of one system is identical to
Fig. 2.1: Cross-section of underground pipe-type cable system.
Figure 2.2: Longitudinal View of a Single Cable with Skid Wire O.D. Diameter e Coiled Around the Cable with Two Starts and Skid Wire Spacing s.
Figure 2.3: Cross sections of five pipe-cable configurations
the cross-section of a second system when scaled by the scale factor.)

The friction factor, $f$, defined here is called the Fanning Friction Factor and is often used in heat transfer and aerodynamics,

$$f = \frac{D_H \Delta P}{2L \rho V^2}$$

(Another friction factor, the Darcy Factor, is commonly used in hydraulics and is four times as large. Care should be exercised when using data from the literature to make certain of which factor applies.)

The definition of the Reynolds number is

$$R_e = \frac{\rho V D_H}{\mu}$$

where (in consistent units)

$\Delta P$ = pressure drop across a length $L$, (psi)

$L$ = specified pipe length, (ft)

$\rho$ = fluid density (slugs/ft$^3$)

$D_H$ = the hydraulic diameter, (ft)

$V$ = average bulk fluid velocity ($\frac{\text{volume flow rate}}{\text{cross-sectional area}}$), (ft/sec)

$\mu$ = fluid viscosity, (slugs/ft·sec)

Since the flow area of the pipe-type system is of non-circular cross-section, an equivalent diameter, termed the hydraulic diameter, $D_H$, is utilized. A number of definitions of the hydraulic diameter exist, but the one found to be the most straightforward and easiest to use is defined as four times the area through which the fluid flows (A),
divided by the wetted perimeter (P),

\[ D_H = \frac{4A}{P} = \frac{D^2 - 3d_0^2}{D + 3d_0} \]  \hspace{1cm} (2.3)

2.1.2 Experimental Program

A. Experimental Model

Experimental data were taken on a scale model of a 345 kV, 2000 kcm cable system. This system is termed the "reference" pipe-type cable system and its corresponding geometry is designated as the reference geometry:

\begin{align*}
D &= 10.25" \\
d_o &= 4.135" \\
d_i &= 1.157" \\
s &= 1.5" \\
e &= 0.1" \\
\alpha &= \tan^{-1}\left(-\frac{n s}{d_o}\right); \text{ where } n \text{ is number of skid wire starts} = 2
\end{align*}

A small model was utilized since the use of a full-sized system for testing would have required a prohibitively large pump and long test section so as to eliminate entrance effects. The model was constructed so as to be geometrically similar to the real system and the range of Reynolds numbers investigated corresponds to the range of interest of the real system. The scale of the model, relative to the real system was 1:7.5 with the actual dimensions of both being given in Table 2.1 for comparison. Further description of the model can be
TABLE 2.1

COMPARISON BETWEEN DIMENSIONS OF THE
REAL SYSTEM AND THE PRESSURE-FLOW MODEL

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>MEASUREMENT IN REAL SYSTEM</th>
<th>MEASUREMENT IN MODEL</th>
<th>RATIO REAL/MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.D. of PIPE</td>
<td>10.25&quot;</td>
<td>1.36&quot;</td>
<td>7.55</td>
</tr>
<tr>
<td>O.D. of CABLE</td>
<td>4&quot;</td>
<td>0.54&quot;</td>
<td>7.40</td>
</tr>
<tr>
<td>SKID WIRE HEIGHT</td>
<td>0.100&quot;</td>
<td>0.0144&quot;</td>
<td>6.95</td>
</tr>
<tr>
<td>SKID WIRE WIDTH</td>
<td>0.200&quot;</td>
<td>0.0275&quot;</td>
<td>7.27</td>
</tr>
<tr>
<td>SKID WIRE LAY</td>
<td>1.5&quot;</td>
<td>0.215&quot;</td>
<td>6.95</td>
</tr>
</tbody>
</table>
Figure 2.4 shows a schematic of the entire test facility. Pressure drop measurements were made with a differential pressure gauge and the temperature of the fluid was monitored in the reservoir. The fluid was pumped by a centrifugal pump through one of several type of float type flowmeters and a throttle valve which controlled the flow. In order to cover the desired range of Reynolds numbers, two fluids of different viscosities were used; one of the fluids was water and the other was a mixture of Tridecylbenzene and polybutane oils (see [1] for viscosity data.)

Tests were run utilizing configurations b, c, d as shown in Figure 2.3, in order to determine the effects of the different cable locations. (It should be noted that the entrance region required for fully developed flow was less than one foot for high Reynolds numbers and less than six feet for any other Reynolds numbers need.) In order to apply the data to any similar system, the pressure drop data was transformed into a friction factor vs. Reynolds number relationship.

B. Experimental Results

The results of the experimental work are shown in Figure 2.5. An error analysis indicates an uncertainty in the results of \( \pm 3\% \) from the values given. As seen, the open-triangular configuration provides the most conservative friction factor values and should therefore be used for design purposes. For this configuration the transition be-
Figure 2.4: Schematic of Pressure Drop Experimental Apparatus
FIGURE 2.5: FRICTION FACTOR VERSUS REYNOLDS NUMBER

FOR PIPE-TYPE CABLE SYSTEMS [1]
between laminar and turbulent flow occurs gradually, beginning at a Reynolds number of approximately 400. (The transition region for other configurations occurs at different Reynolds numbers.) The friction factor is dependent upon cable arrangement in the laminar and transition regions, but becomes virtually independent of cable arrangement in the fully turbulent region \( (Re > 2000) \). (However, even within the turbulent flow regime, cable-pipe geometry remains important.) The skid wires which are almost perpendicular to the direction of flow have no effect on the friction factor in laminar flow, but are the major resistance to flow in the turbulent region.

2.1.3 Theoretical Prediction of Pressure-Losses in Pipe-Type Cable Systems

The theoretical research program is concerned with predicting the pressure loop for various cable geometries in terms of the friction factor vs. Reynolds number relationship for laminar and turbulent isothermal flow through the pipe-type cable system. Separate analyses are carried out for the laminar and turbulent flow regimes due to the different effects of the skid wires. A description of these analyses is provided below.

A. Laminar Flow Pressure Loss

Since the viscous forces predominate in the laminar regime, all disturbances are completely damped out and therefore the skid wires have no effect on the fluid flow. This greatly simplifies the geometry of the pipe-type cable system and, if bouyancy effects as
well as secondary flow (i.e. flow perpendicular to the pipe axis) are neglected, the equations governing the fluid behavior, the Navier-
stokes equations (in rectangular coordinates) at steady state reduce to:

$$\nabla^2 u = \frac{1}{\mu} \frac{dp}{dz}$$  \hspace{1cm} (2.4)

where:

- $u =$ local flow velocity [ft/sec]
- $\mu =$ fluid viscosity [lbm/ft$^2$]
- $dp/dz =$ differential change in pressure in the direction parallel with pipe axis [psi/ft]

Due to the complex boundary conditions of the cable-pipe system, the solution has to be found numerically, using a digital computer. The finite difference approximations which are utilized in the numerical procedure are explained in Chapter 3 of reference [2]. Comparison of the computer solutions with the theoretical results for several well known geometries are accurate to within 2% of the exact results [2]. These results apply to laminar isothermal fully developed flow through the pipe-type cable system.

A.1 Computer Model Results and Comparison of Computer-Predicted Friction Factors with Test Data

The five cable configurations analyzed by the laminar flow study are depicted in Figure 2.3. In Figures 2.6 thru 2.8, a comparison of the computer prediction with some laboratory results are shown. All of the test data is for isothermal or low Rayleigh number cases,
Fig. 2.6: Comparison of data from Reference 3 with the computer predicted values.
Fig. 2.7: Comparison of data from Reference 3 with computer predicted values.
Fig. 2.8: Comparison of data from Reference 1 with computer predicted values.
i.e., no significant cable heating. (Note that for all laminar flow cases the result is \( F \cdot \text{Re} = \text{constant} \). The value of the constant changes with cable configuration.) The predicted \( f \) vs. \( \text{Re} \) lines lie consistently lower than the data obtained by Abdulhadi [3], but there is an excellent agreement with Slutz's data [1].

In order to take into account variations in pipe-cable geometry, the computer program was used to perform a parametric study. Figure 2.9 shows \( F \cdot \text{Re} \) for the entire range of cable-to-pipe diameter ratios for the five configurations. Also shown in the Figure are experimental results from several laboratories and field tests. The large scatter of data should be expected since the effect of the cable configuration in the pipe has a very large effect on the results. The effect of changing the skid wire height to cable diameter ratio, \( e/d_o \), was found to be negligible. The skid wire height is important only in determining the standoff distance between the cables and the pipe.

Figure 2.10 shows a comparison of the prediction with the preliminary results from the full scale Waltz Mill Tests [4]. The results for the cradled cable configuration agree very closely. The other test results were taken with reduced tension in the cables, allowing them to "snake" in the pipe. The configuration varies for different cross-sections and tends to represent the random orientation in an actual operating system. Note that the friction factors are much higher than the cradled configuration and tend to approach the worst case - the open-triangular configuration.
Fig. 2.9: Effect of changing the Cable-to-Pipe Diameter Ratio on the Friction Factor vs. Reynolds Number Relationship
Fig. 2.10: Comparison of data from Reference 15 with the computer predicted values.
B. Turbulent Flow Pressure Loss

The turbulent flow theory differs from that of the laminar region in that the skid wires now become a major resistance to flow. This creates an irregularly shaped channel which is composed of a rough surface opposite a smooth surface. The Hall Transformation [5] is used to analyze this problem. The basic procedure is to isolate the effects of each wall on the flow and then to combine these separate effects so as to determine a single friction factor for the system.

The problem of friction factor prediction for turbulent flow can be divided into three parts:

1. Find a friction factor correlation for a surface containing semi-circular, helically wound wrappings (in order to model the skid wires.)

2. From a knowledge of smooth pipe friction factors, obtain a correlation which can be used for turbulent flow for a Reynolds number as low as 500 (since turbulent flow can exist in the pipe-type cable system at this Reynolds number.)

3. Utilize the Hall Transformation to combine the correlations obtained from parts 1 and 2 in order to obtain a friction factor vs. Reynolds number relationship for the total pipe-type cable geometry.

Parts 1, 2, and 3 will be examined with the idea of clearly establishing the correlations used for parts 1 and 2 and identifying the limitations of these correlations as well as the limitations on the method used to combine them (part 3). Actual use of these three parts to formulate the overall pipe-type cable friction factor is found in the
primary reference [6].

B.1 Examination of the Friction Factor Correlation for the Rough Surface (cables)

At the time of this study (1974) there did not exist a single correlation which could directly predict the friction factor for a pipe with a semi-circular helically wound cable around it. (Han [7] has since produced such a correlation.) Reference [6] describes the manner in which Beckenbach combined a correlation used for determining the friction factor for flow in tubes with rectangular, transverse ribs (on the inside wall) with other experimental results (which accounted for a varying helix angle and the roundness of the skid wire) in order to produce the following final correlation:

\[
f_1 = \frac{2k(\alpha)}{[2.5 \ln \left(\frac{D_{HI}}{2e}\right) - 3.75 + 0.95 \left(\frac{s}{e}\right)]^{0.53}} 2^{(2.5)}
\]

where:

- \(f_1\) = cable friction factor (dimensionless)
- \(k(\alpha)\) = function of the helix angle (Figure 2.6) (dimensionless)
- \(D_{HI}\) = hydraulic diameter of the area influenced by rough cable geometry (in)
- \(e\) = skid wire height (in)
- \(s\) = axial spacing between adjacent skid wire loops (in)

Equation 2.5 is subject to the following parameter limitations:

- \(0.01 < e/D_{HI} < 0.04\)
- \(0.71 < Pr < 37.6\)
- \(10 < s/e < 40\)
- \(e^+ = \frac{e}{d_0} Re^{\frac{\sqrt{f}}{e}} > 35\)
where:

\[ d_o = \text{diameter of the cable} \quad (D_c \text{ in reference [1](in)} \]
\[ R_e = \text{Reynolds number (dimensionless)} \]

It must also be pointed out that the correlation was derived from results which were obtained for high turbulent Reynolds numbers (>\(10^4\)). In this regime the boundary layer is quite small relative to the skid wire height. At lower turbulent Reynolds numbers the boundary layer is larger, and the effect of the rib profile will have more of an influence on the flow. However, due to lack of other existing information at the time, the correlation was assumed to hold for the low turbulent Reynolds numbers as well. Han [7] has since showed that the skid wire profile is of minor importance.

B.2 Friction Factor Correlation for the Smooth Surface (Pipe)

The final continuous correlation for the smooth pipe friction factor is as follows:

\[
 f_2 = \begin{cases} 
 16/R_{e_2} & \text{if } R_e < 1187 \\ 
 0.0791/R_{e_2} & \text{if } 1187 < R_e < 51094 \\ 
 0.046/R_{e_2}^{0.2} & \text{if } R_e > 51094 
\end{cases}
\]

(2.6a)

(2.6b)

(2.6c)

where:

\[ f_2 = \text{pipe friction factor (dimensionless)} \]
\[ R_{e_2} = \text{Reynolds number associated with the area influenced by the pipe (dimensionless)} \]
This correlation is simply a linear model of the well known Moody friction factor curve for a smooth pipe. A continuous model was utilized since it was found that no discontinuities existed in the experimentally determined friction factor curve for the pipe-type cable arrangement (open-triangular cable configuration.) See Figure 2.11.

It should be observed that this correlation utilizes a value of friction factor obtained from laminar theory when, in fact, laminar flow does not exist (for the open-triangular cable configuration.) It is experimentally observed that the lower limit of Reynolds number (based on height of the roughness element) at which turbulent flow may exist is approximately 600 (for the open-triangular configuration.) See Figure 2.5. However, if Equation 2.6b is used below a Reynolds number of 1187, the friction factor would be less than the laminar value predicted by Equation 2.6c. If the flow is turbulent, it should be expected that the friction factor be at least as large as the laminar value. For lack of any better information, Equation 2.6a is used for the range indicated.

B.3 Combination of Smooth and Rough Surface Friction Correlations to Obtain an Overall Friction Factor vs. Reynolds Number Correlation

The Hall Transformation is used to combine the effects of the rough and smooth surfaces. The assumptions of the Hall Transformation are:
Figure 2.11: Friction Factor vs. Reynolds Number for a smooth, circular, empty pipe. Moody.[16].
1) There is a position of zero shear which separates the effects of the rough surface from the smooth.

2) In each zone the pressure gradient, mean velocity, density, and viscosity are equal.

Figure 2.12(a) examines the Hall Transformation assumptions for the simple annular case. So that the manner of application of the Hall Transformation is fully understood, the simple annular type geometry (Figure 2.12b) is analyzed (the following is reprinted from Reference [6] - pages 34-37.)

We begin the development of the method by defining the following variables:

Hydraulic Diameter:

This is defined as being equal to four times the cross sectional area of the flow divided by the wetted perimeter. In an annulus shown schematically in Figure 2.12b, the hydraulic diameter of zone 1, \( D_{H1} \), is equal to four times the cross sectional area between the inner rough surfaces and the radius of zero shear \( (\tau = 0) \) divided by the perimeter of the inner rough surface, i.e.,

\[
D_{H1} = \frac{4A_1}{C_1}
\]

It should be noted that the perimeter along the zero shear boundary is not included in the wetted perimeter.

Similarly, \( D_{H2} = \frac{4A_2}{C_2} \), where \( A_2 \) is the area between the radius of zero shear and the smooth surface and \( C_2 \) is the circumference.
Figure 2.12a: Schematic of Velocity Distribution in an Annular Type Geometry with Inner Surface Rough and Outer Surface Smooth

Figure 2.12b: Cross Section of Annular Type Geometry
ence of the outer smooth pipe.

Following the same reasoning, \( D_{H12} \), the hydraulic diameter of the entire annuli is defined as follows:

\[
D_{H12} = \frac{4(A_1 + A_2)}{(C_1 + C_2)} = \frac{4A_{12}}{(C_1 + C_2)}
\]

Friction Factor:

\[
f = \left( \frac{dp}{dx} \right) \frac{D_H}{2\rho V^2}
\]

Reynolds Number:

\[
Re = \frac{V D_H}{\nu}
\]

Since \( \rho_1 = \rho_2, V_1 = V_2 \), we have,

\[
\frac{f_1}{D_{H1}} = \frac{f_2}{D_{H2}} \quad (2.7)
\]

To find a relationship between \( D_{H1} \) and \( D_{H2} \), we make use of the following identity:

\[
\frac{4A_1}{C_1} + \frac{4A_2}{C_1} = \frac{4(A_1 + A_2)}{C_1} \quad (2.8)
\]

Now, recalling the definition of hydraulic diameter as four times the cross sectional area divided by the wetted perimeter \( (D = \frac{4A}{C}) \), this reduces to

\[
D_{H1} + \frac{C_2}{C_1} D_{H2} = \frac{C_1 + C_2}{C_1} D_{H12} \quad (2.9)
\]
It should be realized that the following relation holds since it was assumed that the mean velocities, densities, and viscosities are equal on both sides of the zero shear plane.

\[
R_e_2 = \frac{D_H^2}{D_H^{12}} R_e^{12}
\]

(2.10)

where \( R_e_2 \) is the Reynolds number for zone 2 and \( R_e^{12} \) is the Reynolds number for the combined zones 1 and 2 (in this case, \( R_e^{12} = R_e^T \), where \( R_e^T \) is the Reynolds number of the entire geometry.)

We now have five equations (2.5, 2.6, 2.7, 2.9, 2.10) and six unknowns \( (f_1, f_2, D_H^1, D_H^2, R_e_2, R_e^{12}) \). We could pick a value for one of them and solve for the rest, which is what the computer program does. It picks a value \( D_H^1 \) and solves for \( R_e^{12} \). \( D_H^1 \) was chosen as the independent variable since it has definite limits which are easily found. The lower limit on \( D_H^1 \) is zero, which occurs at low Reynolds numbers when most of the flow is influenced by the smooth pipe friction correlation. The upper limit on \( D_H^1 \) occurs at very large Reynolds numbers when the flow is completely turbulent and influenced chiefly by the rough surface. This upper limit is:

\[
D_H^1(u_1) = \frac{4A_{12}}{C_1}.
\]

To obtain the corresponding overall friction factor, \( f_{12} \), (in this case, \( f_T = f_{12} \)) the same procedure is followed as before, only this time requiring that the pressure drop of the total passage
to be the same as each sub-channel.

\[ \left( \frac{-dp}{dx} \right)_{12} = \left( \frac{-dp}{dx} \right)_{1} \tag{2.11} \]

which reduces to,

\[ \frac{f_{12}}{D_{12}} = \frac{f_{1}}{D_{1}} \tag{2.12} \]

By using the same independent value of \( D_{H1} \) that was used to obtain \( Re_{12} \), we can solve Equations (2.11) and (2.12) simultaneously to obtain the friction factor \( f_{12} \) for the corresponding Reynolds number \( Re_{12} \).

The extension of this theory from the annular case to the pipe-type case is simple and straightforward. Details are provided in Reference [6] - Chapter V. The corresponding computer program developed by Beckenbach to perform this analysis for the pipe-type case is also presented in this reference.

B.4 Computer Model Results and Comparison with Test Data

Cable configurations A, B, C, and D were analyzed by the computer program for the reference geometry with the results appearing in Figure 2.13. The results from the most conservative approximation (Configuration B) are consistently 15-30% above the experimentally determined values. It should be mentioned that the predictions of configurations A or B are only approximately 15% above the experimentally determined values in the range \( 500 < Re < 1000 \), increasing to 25%
EXPERIMENTAL DATA FOR MODEL FROM [1]

- OPEN TRIANGULAR
- CRADLED

PREDICTED FROM THEORY

<table>
<thead>
<tr>
<th>CONFIGURATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPEN-TRIANGULAR</td>
</tr>
<tr>
<td>CLOSED-TRIANGULAR</td>
</tr>
<tr>
<td>CRADLED</td>
</tr>
<tr>
<td>CLOSED-TRIANGULAR PIPE</td>
</tr>
</tbody>
</table>

Note: Predictions are for full scale system.

Figure 2.13: Friction Factor vs. Reynolds Number for Pipe-Type Cable System. Experimental points are for scale model. Predicted values are for full scale system.
at a Reynolds number of 2000 and to 30% above 3000.

In order to reduce the computer program into a more manageable form, a parametric study was performed. Beckenbach [6] examined the effect of changing the following parameters: \( s/e, e/d_0, \) and \( \alpha \).

His resulting correlation is:

\[
\frac{f}{f_{ref}} = 12.273 \left( \frac{e}{d_0} \right)^{0.387} \left( \frac{s}{e} \right)^{-0.375} \times k \quad (2.9)
\]

where:

\[
k = 1 \text{ for } \alpha < 15^\circ
\]

\[
k = 1.135 - 0.00875\alpha \text{ for } \alpha > 15^\circ
\]

and where:

\[
f = \text{pipe-type friction factor for the system under study}
\]

\[
f_{ref} = \text{pipe-type friction factor for the reference system (see Figure 2.5)}
\]

Brown [8] and Koci [2] completed the parametric study by examining the effect of changing the cable diameter to pipe diameter \( (d_0/D) \).

The final correlation which will predict the variation of \( f/f_{ref} \) as a function of \( s/e, e/d_0, d_0/D, \) and \( \alpha \) is:

\[
\frac{f}{f_{ref}} = 12.273 \left( \frac{e}{d_0} \right)^{0.387} \left( \frac{s}{e} \right)^{-0.373} \left( 2.725 \frac{d_0}{D} - 0.099 \right) \times K \quad (2.10)
\]

and
\[ k = \begin{cases} 1 & \text{for } \alpha \leq 15^\circ \\ (1.135 - 0.00875\alpha) & \text{for } \alpha > 15^\circ \end{cases} \]

where:

- \( e \) = skid wire height (in)
- \( d_0 \) = cable outside diameter (excluding skid wire) (in)
- \( s \) = skid wire spacing (in)
- \( D \) = cable line inside pipe diameter (in)

This correlation is subject to the following parameter limitations:

\[
\begin{align*}
0.3 < \frac{d_0}{D} < 0.45 \\
0.005 < \frac{e}{d_0} < 0.04 \\
10 < \frac{s}{e} < 40 \\
0^\circ < \alpha < 60^\circ
\end{align*}
\]

It is believed that equation 2.6 is accurate to within +5% of the actual predicted value. Figure 2.14 compares turbulent computer predictions with the experimental results of [3] for three different geometries.

### 2.2 Analysis of Pumping Systems for the Cooling of Underground Power Transmission Lines

The forced-cooled technique consists of pumping refrigerated oil through the pipe-type cable system in order to remove the heat generated by the cables. The pressure loss which results from the circulation of the oil in the cable line has already been examined in Section 2.1. Because of charging currents cables of AC circuits cannot exceed a relatively short length (about 15 miles for 345 kV...
FIGURE 2.14: Comparison of MIT turbulent program friction factor predictions with the experimental results of [3].
cables) unless reactive compensation is used; however even over such a "short" distance the oil pressure drop (in the cable line, discharge line, and heat exchanger) at typical oil flow rates (200-400 gal/min) is prohibitively large. To alleviate this problem a loop concept has been adopted in which the transmission line is divided into segments (loops) with each cable line segment being cooled separately within an individual coolant loop. Each loop contains its own circulation pump and heat exchanger; a schematic diagram of a single loop is shown in Figure 2.15.

This multi-loop concept results in design situations in which the interaction of individual loops becomes a matter of concern. If each pair of coolant loops is provided with a pressure control head tank and is separated from the rest of the system by flow-blocking diaphragms in the cable pipe, then each loop is independent of the others and no interaction of the circuits is possible. However, it may not be practical to build head tanks along the entire transmission line route because of the economics involved and the issue of land ownership rights. Also, the diaphragms available today are not strong enough ($\Delta P_{\text{max}} \sim 40$ psi) for the differential pressures which may develop when certain line imbalances occur (a line imbalance is defined as a pipe-line blockage, pipe flow resistance change, pump flow reduction, or pump shutdown.) The only alternative left is to build the system with pressure control head tanks at the end of the pipeline. If this is the case, then imbalances are allowed to "propagate" outside the loop of their origin.
Fig. 2.15: A schematic drawing of a single loop.
and alter the pressure profile in the entire system.

Koci [9] analyzed different system loop arrangements and different pressure profile control methods in order to determine the most effective way of dealing with the problem of maintaining system pressures within their permissible limits while at the same time maintaining a flow through the cable line at, or close to normal. Section 2.2.1 discusses why the system loop arrangement utilized in Design Manual Part I (section 2.) is the best arrangement (at the present time.) Section 2.2.2 goes on to present the most important methods of loop pressure profile control. Section 2.2.3 briefly discusses the experimental method used by Koci to analyze pressure profile control schemes and Section 2.2.4 presents the results of the analysis.

2.2.1 The Optimum System Loop Configurations

A number of methods exist for implementing the multi-loop design technique. Each is subject to the following design limitations:

1) The length of each loop is selected according to available sites for pumping and refrigeration stations and on the basis of the pumps capacity and their pressure rating.

2) Due to the relatively low pothead strength (~ 400 psi), the flow direction in the terminal loops should always be toward the potheads and not away from them, so that the pressure drop across the main cable line of the last segment will reduce the pothead pressure.

3) Head-tanks are to be located at each end. The operating head tank pressure is governed by the route profile and the oil demand considerations.
Fig. 2.16: A schematic drawing of a four-loop pipe-type underground transmission system.
Those configurations considered by Koci are listed in Chapter 3 of Reference [9]. The optimum system configuration is shown in Figure 2.16 (this is the same type of system recommended in Design Manual - Part I.) This system was chosen because it satisfies the design limitations and, importantly, its operation does not require the use of flow blocking diaphragms. Flow blocking diaphragms may be subject to high differential pressures (~ 200 psi) and the possibility of forming hot spots in the neighborhood of the diaphragm exists.

2.2.2 **Important Methods of Loop Pressure Profile Control**

Since there can be pressure control head tanks at the line ends only, any imbalance can effect the pressure profile and the flow rates of the entire system. An ideal line pressure profile control should maintain all system pressures within their specified limits with no further reduction of flow due to the control application. Koci [9] examined a number of line pressure profile control methods. The viable methods are briefly discussed below.

A. **Pump Pressure Relief Valve as the Pump Discharge and Inlet Pressure Control**

A.1 **Pump and Its Relief Valve as a Constant Pressure Source**

The pump relief valve is adjusted for the desired flow rate and the resulting pump head is thereafter maintained constant by further proportional opening or closing of the relief valve. If the absolute pressure level of a loop is controlled by some other means
(head tank pressure), the relief valve can simultaneously control the pump head and pump discharge pressures.

A.2 Pump and Its Relief Valve as a Constant Flow Source

The pump pressure relief valve is initially adjusted for the proper cable line flow rate and further opening of the relief valve is delayed until the pump head reaches its specified maximum value. Then the valve maintains the pump pressure head constant. Additional control on the absolute loop pressure level must be provided also, so as to protect the pipes from overpressure.

B. Head Tank Pressure Adjustment as the Total Line Pressure Profile Control

The method consists of varying the head tank pressure according to the behavior of the line pressure profile. The control can be applied continuously or only at instances when a line pressure is outside its limits.

B.1 Single Pressure Control

The pressure at one end of the line is controlled by a head tank and the pressure at the other end is allowed to freely vary according to the conditions existing within the system. All inlet and discharge pressures of all pumps are monitored and if one or more of the pressures deviates from its limits, a new head tank pressure is determined in such a way that all the pump inlet and discharge pressures remain within their limits.
B.2 Dual Pressure Control

Pressures at both ends of the line are controlled by simultaneous operation of the head tanks located on both ends of the line. This method requires a return line or some other means of transferring the oil between the two head tanks.

C. Pump Shutdown as Emergency Pump Discharge Pressure Control

The pump inlet or the pump discharge pressure can be used as the control input to determine the instant at which the pump shutdown should occur.

D. Pump Bypass as the Discharge and Inlet Pressure Control

This method is used as an alternative to the head tank pressure adjustment or the pump shutdown and is best suitable for application on systems with constant flow sources. It can also be used as a secondary control to back-up the head tank pressure adjustment control. The pump bypass can be implemented by further opening the pump pressure relief valve, or by providing the pump with an additional pipe and valve. The valve control for the pump discharge pressure control can be based on either the pump discharge or inlet pressure. The bypass valve opens when the pump inlet pressure falls below a set limit or when the pump discharge pressure exceeds its set limit. (Reduction of the flow around the loop simultaneously raises the pump inlet pressure and lowers the pump discharge pressure.)
2.2.3 Experimental Analysis of the Optimum Pressure Profile Control Methods

In order to simplify the search for new solutions and to enable the analysis of the more complicated control schemes, Koci built an electric analogy model for steady state simulation of a forced-cooled system (simulation of Consolidated Edison's Six Loop Dunwoody-Rainey System). This model is based on the two fundamental analogies which exist between the performance of an incompressible fluid in a pipeline network and of electricity in a resistive circuit; (1) the total electric current approaching a terminal equals the total current leaving it, just as fluid flows balance at a pipeline junction and (2) with voltage drop representing friction head loss, the voltage drop around a closed circuit is equal to zero just as fluid head losses balance around a pipeline loop. Thus, if an electric circuit is connected to simulate a pipeline network, and suitable conversion factors are used to relate electric and hydraulic quantities, the performance of the pipeline network is indicated by conditions in the electric circuit.

The pipeline network modeling was accomplished by using linear variable resistors for each pipe segment. Increase in pressure due to elevation was simulated by battery and resistor circuits. The constant flow pump was modeled by batteries and linear resistors in series (same as a flow source and a resistor in parallel.) The head tank was modeled by a zener diode in parallel with a variable resistor and a battery. (See Chapter 4 of Reference [9] for further details of
The system voltage measurements were performed utilizing voltage follower circuits in order to limit current losses through the voltmeters. The voltmeter resolution was 0.02 volts. Each cable line current was measured by microameters and their internal resistance was included in the cable line resistance. All voltmeters and microameters were accurate within 2%. The overall uncertainty in the pressure drop and flow rates measurements was approximated by Koci to be $\approx 0.059$.

2.2.4 Experimental Results

The major results of the experimental work are listed below:

1) Only one head tank should be operated at a time, while the other is used as a standby.

2) The pump-relief valve arrangement operating as a constant flow source is, for practical imbalance sizes, superior to the pump-relief valve arrangement operating as a constant pressure source.

3) For existing installations the pump bypass is the simplest and most effective pressure profile control. For its application each pump must be provided with an extra bypass pipe and a valve. The valve position should be simultaneously controlled by the pump discharge and inlet pressures and whenever the discharge pressure exceeds a maximum specified value, or the inlet pressure drops below a set minimum the valve further opens and adjusts the out-of-line pressure.

4) For new designs, the best and most effective line pressure profile control was found to be the head tank pressure adjustment. For this purpose all pump inlet and discharge pressures must be monitored and whenever a pressure exceeds the maximum specified discharge pressure or falls below the minimum specified inlet pressure, the head tank pressure is automatically adjusted to a new value. (The advantage of the head tank adjustment over the pump bypass lies in the fact that no additional flow reduction occurs after an imbalance occurs.)
3. FORCED-COOLED PIPE-TYPE CABLE SYSTEM HEAT TRANSFER DEVELOPMENTS

3.1 Calculation of the Conductor-to-Oil Temperature Difference for the Pipe-Type Cable System

Given a system with a maximum allowable cable temperature, it is necessary to know the maximum oil temperature which should be allowed in order to avoid thermal failure of the cable. Thus, the conductor-to-oil temperature difference must be calculated. The conductor-to-oil temperature difference for a specified current and voltage is determined by the overall conductor-to-oil heat transfer resistance, which is due to two effects: the resistance to conduction heat transfer through the cable insulation and the resistance to convection heat transfer from the cable surface of the insulation to the bulk of the oil.

Conduction within the insulation is complicated by the proximity of one cable to another. When two cables come into direct contact, their mutual presence causes a large increase in the resistance to heat transfer near the point of contact. Subsequently, the cable insulation near the point of contact experiences a sharp increase in temperature which in turn elevates the conductor temperature. Analysis of this two-dimensional conduction heat transfer is too complicated for analytical methods and therefore numerical techniques are utilized. Section 3.1.2 examines the solution method and the results.
The convection heat transfer in the oil is too complicated to solve using either analytical or numerical techniques. Therefore, experimental measurements were made on a full sized model of the pipe-type cable system. Details and results of the experimentation are provided in the Section 3.1.1.

The final results of the heat transfer analysis are found in Section 3.3.3.

3.1.1 Experimental Heat Transfer Program

A. Experimental Model

Experimental data were taken on a full size model of an underground power transmission system. Figure 3.1 is a cross-section of the model. The model cables, shown in Figure 3.2, were made from 4" O.D. steel pipe inside of which were heaters to produce the desired heat transfer (the heaters were made with glass cores around which heater wire was wound.). Each cable was 4 feet in length and was made in 3 equal sections to allow the end sections to take up end effects while the middle section was used for test data. Insulating spacers were placed between sections and the three sections (cables) were held together by means of a central threaded rod and threaded end plates. The pipe part of the model was made of a 4 foot section of 10 inch I.D. steel pipe. A section of 12 inch pipe was fitted around the 10 inch pipe to create a water jacket. The presence of the water jacket allowed tests to be run either with constant pipe wall temperature or by draining the water and having an insulated
Figure 3.1: Cross-Section of Model for Heat Transfer Tests
Figure 3.2: DETAILS OF CABLE CONSTRUCTION
wall. The space between the 10 inch pipe and the 3 cables was filled with tridecylbenzene which is a dielectric oil (the oil is not circulated.) Further details of the model can be found in Chapter III-B of Reference [1 and 10].

Instrumentation consisted of thermocouples which were attached strategically around the cables and to the inside of the pipe wall. Three thermocouples were mounted on adjustable probes to allow measurement of the dielectric oil temperature profile. An null type galvanometer and an x-y recorder were used to read the thermocouple outputs. The power level in the heaters was measured with a precision watt-meter.

The experimental model utilized a static dielectric oil (natural convection heat transfer only) in order to simulate the convection resistance which would be found during laminar flow. This provides the most conservative values of the convection resistance for the forced-cooled operation. (In laminar flow, natural convection is superimposed on the forced flow. Order of magnitude calculations show that the resistance to natural convection is up to an order of magnitude larger than the resistance to fully developed forced convection for laminar flow [11]. Therefore, the resistance for combined natural and forced convection is approximately equal to the resistance for natural convection.)

Tests were run for the closed-triangular pipe cable configuration and the open-triangular configuration (see Figure 2.3.) The following section summarizes the experimental results.
Detailed results of the testing are found in Chapter III of Reference [1 & 10]. The highest natural convection resistance found was 6.8°C/watt cm which is 1/12 as large as the one-dimensional conduction resistance. All other natural convection resistances were smaller, showing that the conduction resistance is the major resistance to heat transfer. Table 3.1 gives the results for a range of geometries used in the pipe-type cable system. The assumption of negligible convection resistance is open to question only for the 69kV cables. Cables designed for voltages higher than 345 kV will have even thicker insulation and thus will conform very closely to the assumption of negligible convective resistance.

These results therefore show that whereas precise prediction of the convection outside the cable is typically not necessary, accurate modeling of the conduction within the insulation is required in order to calculate the conductor-to-oil temperature drop. The following section details the conduction heat transfer model.

3.1.2 Analysis of the Heat Conduction in the Cable Insulation

This section will present the major assumptions and fundamental governing equations which were used to create the conduction model for the cable insulation. The numerical method which utilizes this model to solve the conduction problem will then be reviewed. All information presented is derived from reference [12].
### TABLE 3.1

RATIO OF CONDUCTION TO CONVECTION RESISTANCE FOR A RANGE OF CABLE GEOMETRIES

<table>
<thead>
<tr>
<th>CABLE VOLTAGE</th>
<th>SIZE (Circular Mils)</th>
<th>CONDUCTOR DIAMETER (inches)</th>
<th>CABLE O.D. (inches)</th>
<th>PIPE O.D. (inches)</th>
<th>RATIO: CONDUCTION TO CONVECTION RESISTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>138 kV</td>
<td>2500-350</td>
<td>1.825-0.681</td>
<td>3.020-1.755</td>
<td>8.125-5.047</td>
<td>4.46-5.56</td>
</tr>
<tr>
<td>69 kV</td>
<td>2500-1000</td>
<td>1.825-1.152</td>
<td>2.560-1.855</td>
<td>8.125-6.065</td>
<td>2.65-2.92</td>
</tr>
</tbody>
</table>

See Appendix A for an analysis of the conduction to convection resistance ratio for different cable sizes (natural convection is assumed.)
A. Conduction Model Assumptions and Governing Equations

In order to simplify the geometrical problems which arise in handling configurations of three cables, it is initially assumed that the system possesses bilateral symmetry as shown in Fig. 3.3. This assumption reduces the system to one and one-half cables inside half of the steel pipe, while permitting arbitrary configurations of the one and one-half cables.

In developing a conduction model for the cable insulation, the following assumptions were made:

1. any axial conduction along the length of the cable is negligible, thus reducing the problem to two dimensions;
2. steady-state conditions prevail in the system;
3. the thermal conductivity throughout the insulation is assumed to be uniform;
4. the oil is assumed to be well-mixed, so that the oil temperature outside the convective boundary layer is uniform at a given cross-section in the system;
5. due to the very high thermal conductivity of copper, each cable conductor is assumed to be at a single, uniform temperature, and are known quantities in the temperature field. Using the first three assumptions, an energy balance on an infinitesimal element of the insulation cylindrical coordinate system) yields the following expression:
FIGURE 3.3

Bilateral Symmetry of the Underground Cable System
\[
\frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \phi^2} = - \frac{\dot{q}}{k}
\]  

(3.1)

where (for compatible dimensions)

\[r = \text{radial coordinate (in)}\]
\[\phi = \text{aximuthal coordinate (radians)}\]
\[T = \text{temperature at a point defined by } r \text{ and } \phi (\degree F)\]
\[\dot{q} = \text{heat generation term due to the dielectric loss which occurs throughout the insulation (BTU/in}^3/\text{hr)}\]
\[k = \text{insulation thermal conductivity (BTU/hr-in}\degree F)\]

The cable conduction problem essentially consists of finding the solution to this partial differential equation which satisfies certain initial and boundary conditions. Before examining the insulation boundary conditions, it is necessary to look at one other aspect of the conductive problem.

In order to model the situation which exists when cables 1 and 2 are lying together in direct contact (skid wires overlapping), a special conduction path is placed between the cable and the half cable. A conduction path is used because there is a small region between the cables in which the oil is essentially stagnant. The intercable conduction path is used as an extension of the cable insulation (same conductivity is assumed), joining cable 1 to cable 2 as depicted in Figure 3.4. As an estimate of how large an angle the path should subtend along the cable surfaces, it was decided to use the angle subtended by the overlapping skid wires. Since no heat sources are
FIGURE 3.4:
The **Inter-Cable** Conduction Path (Shaded)
present within the conduction path, the governing equation for its temperature distribution is Laplace's equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\partial^2 T}{\partial y^2} = 0$$  \hspace{1cm} (3.2)

where $x$ and $y$ are the normal and tangential coordinates, respectively, and where normal denotes an axis which joins the cable centers.

Using assumption 5, the conduction problem now has as its solution domain only the paper insulation surrounding the conductors and the inter-cable conduction path. The insulation boundary conditions form the last aspect of the model.

There are several different surface boundary conditions, all of which are convective in form. The convective boundary condition is obtained from an energy balance at the cable surface:

$$-\frac{q}{P} \frac{\partial T}{\partial r} (r_2, \phi) = -k \frac{\partial T}{\partial r} (r_2, \phi) = h[T(r_2, \phi) - T_{oil}]$$  \hspace{1cm} (3.3)

where $r_2$ is the outer radius of the cable insulation, $P$ is the perimeter of the cable, and $h$ is the local film coefficient, which may vary around the periphery of the cable. More details can be found in Chapter 2 of reference [12].

The aforementioned governing equations and boundary conditions constitute the formulation of the conduction problem. The complete formulation of the problem is found in the primary reference [12]. The numerical solution used to solve the conduction problem is discussed below.
B. Solution of the Insulation Conduction Problem

The numerical method used to generate the temperature field of the cable system is the finite-difference method. The basic approximation of this method involves the replacement of a continuous domain by a network of discrete points within the domain. Figure 3.5 shows a typical example of discretizing the cable domains by defining a network of radial and circumferential mesh points. Instead of obtaining a continuous solution defined throughout the domain, approximations to the true solution are found only at these isolated points.

The reduction of a governing equation and boundary conditions for a continuous domain to those of its discrete replacement is accomplished by replacing derivatives with finite-difference approximations. When this is done, the original system of governing partial differential equations is reduced to a set of \( n \) simultaneous algebraic equations, where \( n \) is the number of discrete points in the mesh. Since the original continuous system is linear, the algebraic system is also linear.

A Fortran IV computer program was written so as to generate and solve this system of equations. The program is listed in Appendix E of reference [12], together with user instructions. Reduction of this computer program into a closed form analytical expression is discussed in Section 3.1.3.

C. Conclusions Drawn from the Conduction Model

On the basis of the results obtained in reference [12],
FIGURE 3.5:
A Typical Mesh for the Equilateral Configuration
the following conclusions are stated concerning the pipe-type cable system

1. For a thermally non-conducting pipe, a cable system is most susceptible to thermal failure in the closed-triangular pipe configuration. For a thermally conducting pipe, the closed-triangular pipe and closed-triangular configurations are equally severe, and the latter represents the worst operating condition.

2. The presence of a thin copper tape in the cable insulation moisture seal assembly significantly smooths out the temperature distribution in the cable insulation and thus higher maximum allowable oil temperature and higher currents are permitted than if a homogeneous cable insulation is used. Numerically, the improvement is from about 4.3% for the oil temperature and approximately 9.5% for the current (with the tape thickness equal to 0.005 inches). If this figure is unacceptable, thicker copper tapes will smooth out temperatures even more.

3. Cable proximity effects are very important if the cable does not contain the copper tape. The cable configuration can account for 21% (closed-triangular configuration with no copper tape) to 26% (closed-triangular pipe configuration with no tape) of the total temperature rise between refrigeration stations as compared with the one-dimensional case.

3.1.3 The Pipe-Type Cable System Heat Transfer Correlation

In order to reduce the computer program into a more manageable

\[
\frac{W_c}{W_d} = (1.764 \frac{k_{oil} (T_c - T_{oil})}{W_d \ln \frac{d_o}{d_i}} - 0.53)CF_1 \times CF_2 \quad (3.4)
\]

where:

- \(W_c\) = conductor electrical losses \((=y_R C_{DC} I^2_{fC})\) (w/ft)
- \(W_d\) = total cable dielectric loss (w/ft)
- \(T_c\) = conductor temperature (°F)
- \(T_{oil}\) = oil temperature (°F)
- \(d_o\) = cable outside diameter (excluding skid wire) (in)
- \(d_i\) = insulation inner diameter (conductor diameter) (in)
- \(k_{oil}\) = oil thermal conductivity (insulation conductivity) (BTU/hr-ft°F)
- \(CF_1\) = convection correction factor (dimensionless)
- \(CF_2\) = metallic tape correction factor (dimensionless)

Equation 3.4 has been shown to be accurate within 5% of computer predictions (see Appendix E of reference [8]) and can be confidently used to predict, for a specified conductor-to-oil temperature difference and the cable surface heat transfer coefficient, the ampacity of the pipe-type oil filled underground transmission lines. Application of the correlation is explained in Chapter 5 - Section 5.2 of Design Manual Part I.
3.2 Calculation of the Two-Dimensional Pipe-to-Soil Heat Transfer for Pipe-Type Cable Systems

A cross-section of a typical forced-cooled underground transmission system is shown in Figure 3.6. In the self-cooled mode of operation the heat flow from pipes to earth is equal to the cable heat generation (which limits the amount of current that can be transmitted through the cable). During the forced-cooled operation a portion of the generated heat is still conducted into the soil, but a significant amount is absorbed by the oil and removed at refrigeration stations. In both cases, to confidently predict the cable ampacity, the rate of heat dissipation to the soil must be accurately determined.

The important factors which influence the amount of heat flow from the cable and sending pipes into the soil are the oil temperature level, soil conductivity, ground surface conditions (radiation, convection, functions of time of year), relative position of the pipes in the ground, depth of burial, pipe diameter, and thermal resistance between the oil in the pipes and the soil [12]. The complex geometry, non-uniform soil conductivity and the unsteadiness of the boundary conditions do not permit an exact analytical solution of the transient heat transfer in the soil and therefore the two-dimensional transient heat conduction is solved by Koci [2] using a numerical technique.
Fig. 3.6: Cross-sectional view of trench, cable pipes and oil sending lines for a double forced-cooled circuit.
3.2.1 Conduction Model Assumptions and Governing Equations

The equation which describes the transient heat conduction without heat generation in two-dimensions is the two-dimensional Fourier equation:

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]  

(3.5)

where (for compatible dimensions)

- \(x\) = horizontal coordinate, (in)
- \(y\) = vertical coordinate, (in)
- \(T\) = temperature at point, \(x,y\) (°F)
- \(\alpha\) = soil thermal diffusivity, (ft/hr²)

The continuous physical model to which equation 3.5 is applied is shown in Figure 3.7. This model utilizes the fact that the geometry of the forced-cooled system is symmetrical about the vertical axis drawn through the middle of the trench. Assuming that complete thermal symmetry about this axis also exists (equal current flow and cooling oil conditions in both cable pipes), no heat crosses the line of bilateral symmetry and consequently the problem is solved for only half of the area. That area which duplicates the pipe trench is modeled for the characteristics of specific type of soil backfill that is utilized. The soil surrounding the trench is modeled for the characteristics of the regular soil which exists. The soil properties are assumed to remain constant, i.e. moisture migration is not included.
Fig. 3.7: The region of interest and types of boundaries.
in the analysis.

The vertical soil boundary to the right of the trench and the deep soil boundary are located far enough from the trench so that they are not thermally affected by the transmission system. At the surface of the ground, heating by direct solar radiation and atmospheric radiation is allowed for and cooling by radiation from the surface and convection to the air is included. Daily variations of air temperature, solar and atmospheric radiation data are used in the program. The pipe conditions depend upon the mode of operation: in the self-cooled mode the heat generation at the cable pipe is given and the oil temperature has to be found, and in the forced-cooled mode the temperature of the oil inside the pipes is specified and the rate of heat flow from the pipes to the soil is to be determined. A complete discussion of the conduction model boundary conditions, together with the equations which govern the heat transfer at the boundaries, is presented in Chapter 5 of reference [2].

3.2.2 Solution of the Soil Conduction Problem

The numerical method used to generate the temperature field of the soil is the finite-difference method. The basic approximation of this method involves the replacement of the continuous soil domain (Figure 3.7) by a network of discrete points within the domain (Figure 3.8). Instead of obtaining a continuous solution throughout the domain, approximations to the true solution are found only at these isolated
Fig. 3.8: A typical mesh for the development of the finite difference equations.
points. A variable size mesh is established in the area of interest with a smaller mesh size in the trench (where higher temperature gradients occur) and two larger mesh sizes far away from the trench. At each mesh point the continuous terms of Equation 3.5 are replaced by their finite difference approximations. (In order to avoid the use of irregular boundary points around the circular pipes and the complex finite difference equations resulting from it, the round pipes are replaced by equivalent square pipes. See Section 5.2 of reference [2].) When this is done, the original system of governing partial differential equations is reduced to a set of simultaneous algebraic equations.

A Fortran IV Computer program was written so as to generate and solve this system of equations. The program is listed in Appendix D of reference [2], together with user instructions. The results of the computer program consist of the steady-state and transient solutions for the two-dimensional heat conduction in one cross-section of the soil surrounding the pipes. The computer solutions agree to within 4.5% with available analytical expressions.

Results show that the rates of heat flow from the pipes are strongly influenced by the temperatruhe level. The steady solutions and hence the overall solutions for the rate of heat flow from pipes to soil show a strong dependence on the soil thermal conductivity, pipe depth below the ground surface, relative positions of the pipes, overall heat transfer coefficient of a pipe wall, and pipe size.
3.3 Prediction of the Forced-Cooling Requirements for a Non-Adiabatic Pipe-Type Cable System

The two-dimensional conduction heat transfer problem discussed in Section 3.2 is directly applicable to the self-cooled mode of operation; the cable heat generation is uniform and, therefore, every cross-section of the pipe-type cable system is identical. However, during the forced-cooled operation, although the heat generation can still be considered as uniform, the circulating oil results in an axial temperature distribution of the oil, pipes, and soil which is no longer uniform. Figure 3.9 shows a typical oil temperature profile for one coolant loop; the oil leaving the heat exchanger is further cooled in the sending pipes by the surrounding soil and then heated by the generated heat in the cable pipe.

In order to predict the amount of heat transferred to the soil during the forced-cooled mode of operation (which is needed to predict the cable cooling requirements) a numerical method is used which utilizes the solutions obtained for the two-dimensional transient heat conduction in the soil (see Chapter 6 of reference [2]). The system is divided into a finite number of segments, each of length \( s \), and the two-dimensional heat transfer computer program is used at each cross-section to calculate the time dependent rate of heat flow to the soil. A "marching" computer program was written by Koci to accomplish this task and the instructions for its use can be found in Appendix E of reference [2].
Fig. 3.9: A typical heat exchanger vs. pipes arrangement and a typical oil temperature profile for light loads.
In addition to the computer solution of the forced-cooled system heat transfer problem, Koci [2] devised a quasi-steady solution to this problem. The results, which appear in Section 5.1 of Design Manual Part I, are formulated as the oil temperature distribution along the axes of the cable and return lines, which accounts for the heat transfer to the oil and the soil environment. When quasisteady conditions are satisfied, these results can be used to accurately predict the forced-cooling requirements of underground transmission lines for any day of the year without the necessity of using the "marching" computer program. However, the steady-state and transient solutions for the heat conduction in a cross-section of the soil surrounding the pipes (for a given day of the year) are required. (The "Transient Heat Conduction in the Soil" computer program need be run only once for specified system characteristics, to obtain the two-dimensional heat transfer solutions for the entire year's operation.)

3.3.1 Effects of Various System Parameters on Forced-Cooling Requirements

As a result of a study performed by Koci (Chapter 7 of reference [2]), the effects of the pipe diameter, overall pipe heat transfer coefficient, and the pipe trench configuration were found equally unimportant to forced-cooling requirements. It was found that the oil temperature level has a greater influence on the heat transfer.

*Quasi-steady conditions are defined here as those for which the thermal performance of the system reaches a cycle of a period of 1 year, corresponding to the seasonally varying ground surface conditions (an example of a quasisteady operation is the seasonally varying heat exchanger temperatures.)
to the soil, and hence the cable ampacity, than the variables previously mentioned. Thus the important design parameters for a system with a specified ampacity are the coolant loop length(s) and the oil flow rate(s), as they directly influence the required oil temperature level.

For electrical loads higher than 1400 amps at 345 kV, the power input to the oil cooling equipment is much higher than the power input to the oil-circulating pumps. The use of air coolers reduces the required temperature difference across the refrigeration equipment and thereby significantly reduces the energy consumption. For a given electrical load, the total energy consumption of the cooling and pumping plants can be minimized with respect to the oil flow rate (see Chapter 7 or reference [2].)
REFERENCES


15. Purnhagen, D., Personal Communication. Preliminary Data from the Forced-Cooling Research Facility at Waltz Mill, Pa. supplied with the permission of the sponsors, the Electric Power Research Institute and the Energy Research and Development Administration.

APPENDIX A

COMPARISON OF THE CABLE INSULATION CONDUCTION RESISTANCE WITH THE CONVECTION RESISTANCE FOR DIFFERENT CABLE SIZES

This section compares the insulation conduction resistance with the convection resistance (resulting from the cable-to-oil interface) for cables of different size. The cable sizes analyzed correspond to the limiting sizes listed in Table 2.1. A conservative approach is taken in the analysis in that only natural convection is assumed to exist. This is done because the resistance to natural convection is up to an order of magnitude larger than the resistance to fully developed forced convection for laminar flow (see section 3.1.1).

A.1 Thermal parameters for all cable sizes:

Oil conductivity = 0.1153 BTU/hr ft°F
Oil coefficient of thermal expansion = 3.9 x 10^{-4}°F
Tape conductivity = 220 BTU/hr ft°F
Maximum permitted cable temperature = 185°F

A.2 345 kV Cable

A.2.1. Cable 1

Geometry
Conductor diameter = 1.825 in - 2500 KCM (segmented conductor)
Cable diameter = 4.135 in
Tape thickness = 0.005 in

Thermal parameters
DC Electrical Resistance = 5.36 x 10^{-6} ohms
\gamma_c = 0.19
\[ Y_s = 0.05 \]
\[ W_d = 2.67 \text{ W/ft} \]

<table>
<thead>
<tr>
<th>I (amps)</th>
<th>( \Delta T_{\text{ins}} ) (°F)</th>
<th>( \Delta T_{\text{conv}} ) (°F)</th>
<th>Toil (l)</th>
<th>( R_a ) (1)</th>
<th>( h ) (BTU/hr-ft(^2)°F)</th>
<th>( R_{\text{cond}} )</th>
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</thead>
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<tr>
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<td>67.35</td>
<td>7.0</td>
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<td>7.14</td>
<td>9.6</td>
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<tr>
<td>1150</td>
<td>90.0</td>
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<td>2000</td>
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<td>54.7</td>
<td>7.8x10(^6)</td>
<td>6.02</td>
<td>8.1</td>
</tr>
</tbody>
</table>

A.2.2 Cable 2

**Geometry**

Conductor diameter = 1.289 in - 1250 KCM (segmented conductor)

Cable diameter = 3.555 in.

Tape thickness - 0.005 in.

**Thermal parameters**

DC Electrical Resistance = 10.02 x 10\(^{-6}\) ohms

\[ Y_c = 0.05 \]
\[ Y_s = 0.03 \]
\[ W_d = 2.15 \text{ w/ft} \]

<table>
<thead>
<tr>
<th>I (amps)</th>
<th>( \Delta T_{\text{ins}} ) (°F)</th>
<th>( \Delta T_{\text{conv}} ) (°F)</th>
<th>Toil (l)</th>
<th>( R_a ) (1)</th>
<th>( h ) (BTU/hr-ft(^2)°F)</th>
<th>( R_{\text{cond}} )</th>
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<td>6.86</td>
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A.3 138 kV Cable

A.3.1 Cable 1

Geometry

Conductor diameter = 1.825 in - 2500 KCM (segmented conductor)
Cable diameter = 3.020 in
Tape thickness = 0.005 in

Thermal parameters

<table>
<thead>
<tr>
<th>I (amps)</th>
<th>ΔT_{ins} (°F)</th>
<th>ΔT_{conv} (°F)</th>
<th>T_{oil} (°F)</th>
<th>R_{a} (1)</th>
<th>h (BTU/hr-ft^2°F)</th>
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<th>R_{conv}</th>
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<td>29.5</td>
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<td>2000</td>
<td>73.9</td>
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<td>97.2</td>
<td>1.03x10^7</td>
<td>8.75</td>
<td>5.37</td>
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A.3.2 Cable 2

Geometry

Conductor diameter = 1.152 in - 1000 KCM (segmented conductor)
Cable diameter = 2.252 in
Tape thickness = 0.005 in

Thermal parameters

DC Electrical Resistance = 13.28 x 10^{-6} ohms

<table>
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<tr>
<th>Y_c</th>
<th>Y_s</th>
<th>W_d</th>
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<tr>
<td>0.25</td>
<td>0.04</td>
<td>0.69</td>
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</table>
### A.3.3 Cable 3

**Geometry**

Conductor diameter = 0.681 in - 350 KCM (solid conductor)

Cable diameter = 1.755 in

Tape thickness = 0.005 in

**Thermal parameters**

DC Electrical Resistance = $37.99 \times 10^{-6}$ ohms

$Y_c = 0.02$

$Y_s = 0.01$

$W_d = 0.368 \text{ w/ft}$

<table>
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<th>$I$ (amps)</th>
<th>$\Delta T_{\text{ins}}$ (°F)</th>
<th>$\Delta T_{\text{conv}}$ (°F)</th>
<th>$T_{\text{oil}}$ (°F)</th>
<th>$R_a$ (1)</th>
<th>$h$ BTU/hr-ft°F</th>
<th>$R_{\text{cond}}$</th>
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<td>4.9</td>
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### A.4 69 kV Cable

#### A.4.1 Cable 1

**Geometry**

Conductor diameter = 1.825 in - 2500 KCM (segmented conductor)

Cable diameter = 2.560 in

Tape thickness = 0.005 in
Thermal parameters
DC Electrical Resistance = 5.36 x 10^-6 ohms
\( Y_c = 0.22 \)
\( Y_s = 0.11 \)
\( W_d = 0.257 \text{ w/ft} \)

\[
\begin{array}{cccccccc}
I (\text{amps}) & \Delta T_{\text{ins}} (\text{°F}) & \Delta T_{\text{conv}} (\text{°F}) & T_{\text{oil}} (\text{°F}) & R_a (\Omega) & h (\text{BTU/hr-ft}^2\text{°F}) & \frac{R_{\text{cond}}}{R_{\text{conv}}} \\
750 & 6.7 & 2.3 & 176.0 & 6.39 \times 10^6 & 9.3 & 2.96 \\
1000 & 12.6 & 2.44 & 170.0 & 4.9 \times 10^7 & 14.6 & 5.16 \\
1250 & 18.7 & 5.7 & 160.6 & 8.53 \times 10^6 & 9.9 & 3.26 \\
1500 & 26.9 & 8.0 & 150.0 & 1.0 \times 10^7 & 10.3 & 3.34 \\
1750 & 36.7 & 10.7 & 137.6 & 1.0 \times 10^7 & 10.4 & 3.43 \\
2000 & 48.0 & 13.8 & 123.2 & 1.1 \times 10^7 & 10.5 & 3.46 \\
\end{array}
\]

A.4.2 Cable 2

**Geometry**
Conductor diameter = 1.152 in - 1000 KCM (segmented conductor)
Cable diameter = 1.872 in
Tape thickness = 0.005 in

**Thermal parameter**
DC Electrical Resistance - 13.28 x 10^-6 ohms
\( Y_c = 0.04 \)
\( Y_s = 0.02 \)
\( W_d = 0.179 \text{ w/ft} \)

\[
\begin{array}{cccccccc}
I (\text{amps}) & T_{\text{ins}} (\text{°F}) & T_{\text{conv}} (\text{°F}) & T_{\text{oil}} (\text{°F}) & R_a (\Omega) & h (\text{BTU/hr-ft}^2\text{°F}) & \frac{R_{\text{cond}}}{R_{\text{conv}}} \\
750 & 18.8 & 5.13 & 161.0 & 2.8 \times 10^6 & 10.6 & 3.7 \\
1000 & 33.3 & 8.83 & 143.0 & 3.65 \times 10^6 & 11.24 & 3.8 \\
1250 & 52.2 & 13.44 & 119.4 & 3.8 \times 10^6 & 11.4 & 3.9 \\
1500 & 74.7 & 20.06 & 90.2 & 3.2 \times 10^6 & 11.0 & 3.7 \\
1750 & 100.3 & 30.2 & 54.6 & 2.1 \times 10^6 & 9.95 & 3.32 \\
\end{array}
\]
A.4.3 Cable 3

**Geometry**

Conductor diameter = 1.152 in - 1000 KCM (solid conductor)
Cable diameter = 1.872 in
Tape thickness = 0.005

**Thermal parameters**

DC Electrical Resistance = $13.28 \times 10^{-6}$ ohms

- $Y_c = 0.14$
- $Y_s = 0.04$
- $W_d = 0.179$

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<th>$\Delta T_{ins}$ ($^\circ$F)</th>
<th>$\Delta T_{conv}$ ($^\circ$F)</th>
<th>$T_{oil}$ ($^\circ$F)</th>
<th>$R_a$ (1)</th>
<th>$h$ (BTU/hr-ft$^2$°F)</th>
<th>$R_{cond}$</th>
<th>$R_{conv}$</th>
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<td>750</td>
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<td>81.4</td>
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<td>9.3</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

A.5 Nomenclature Used in Tables

- $I$ = cable ampacity
- $\Delta T_{ins}$ = cable insulation temperature drop
- $T_{conv}$ = temperature drop from cable surface to oil
- $T_{oil}$ = bulk oil temperature
- $R_a$ = Rayleigh number
- $h$ = convective heat transfer coefficient for cable surface
- $R_{cond}$ = conduction resistance through cable insulation
- $R_{conv}$ = convection resistance from cable surface to oil
FORCED COOLING OF UNDERGROUND ELECTRIC POWER TRANSMISSION LINES

DESIGN MANUAL, PART III OF III

COMPUTER PROGRAM DESIGN MANUAL

by

Jay A. Brown
Paul F. Koci
Leon R. Glicksman

Energy Laboratory
in association with
Heat Transfer Laboratory
Department of Mechanical Engineering
Massachusetts Institute of Technology

Sponsored by
Consolidated Edison Company of New York Inc.
New York, New York

Energy Laboratory Report No. MIT-EL 78-014
Heat Transfer Laboratory Report No. 80619-101

June 1978
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FORCED COOLING OF UNDERGROUND ELECTRIC
POWER TRANSMISSION LINES
Design Manual, Part III of III

ABSTRACT

The methodology utilized for the design of a forced-cooled pipe-type underground transmission system is presented. The material is divided into three major parts: (1) The Forced-cooled Pipe-Type Underground Transmission System Design Manual-Part I, (2) The Design Manual-Part II, and (3) the Forced-Cooled Pipe-Type Underground Transmission System Computer Program Design Manual.

The Design Manual Part I provides the thermal and hydraulic design analyses required for the design of a forced-cooled cable system of specified geometry. The thermal design establishes the relationship between the cable amperage, oil flow, and the conductor-to-oil temperature difference and provides a coolant loop energy balance which includes an analysis of the pipe-to-soil heat transfer. Combination of both permits the maximization of the cable amperage while maintaining the cable temperature below the maximum allowable value.

The hydraulic design establishes the pressure-flow characteristics for pipe-type cable systems and a systematic analysis is provided which allows for calculation of the pressure drop in the cable line and return line of the flow circuit as well as the circuit absolute pressure profile. The pressure drop governs the selection of circulation pumps, pipe strength characteristics, and strongly influences coolant loop length.

The Design Manual-Part II presents a description of the experimental and analytical research performed at M.I.T.'s Heat Transfer Laboratory which provides the relationships used in the design analysis of Design Manual-Part I.

The Computer program design manual provides a detailed description of the forced-cooled system computer program and the necessary program documentation. The computer program is basically a straightforward computerization of the design procedure of Design Manual-Part I. Six different computer design options are provided which permit complete flexibility for the design and optimization of the forced-cooled system. Four of the design options allow for the selection of alternative independent and dependent design variables and two design options provide for the system optimization based on specified optimization criteria.
ACKNOWLEDGEMENTS

This research work was supported by the Consolidated Edison Company of New York.

The cooperation of Mr. Michael D. Buckweitz of the Consolidated Edison Company is gratefully acknowledged.
PART III

FORCED-COOLED UNDERGROUND PIPE-TYPE CABLE

SYSTEM COMPUTER PROGRAM DESIGN MANUAL

1. INTRODUCTION

Although the Design Manual - Part I provides the complete analytical information required for the design of a forced cooled pipe-type cable system, it was recognized that typical system design optimization techniques necessitate the analysis of numerous design alternatives. Therefore, a forced-cooled system design computer program was created in order to expedite the optimization of the forced-cooled system design.

The computer program is primarily a straightforward computerization of the design analysis procedure of Design Manual - Part I; in order to perform a coolant loop design analysis it utilizes all of the relationships and correlations which appear in the written design manual, including the quasi-steady coolant loop energy balance (Section 5.1.2 - Part I) which is tedious to use manually. In order to provide adequate design flexibility, six different program design-options are offered; four options permit the selection of alternative groups of independent (input) and dependent (output) variables for the system analysis, and two design-options optimize the forced-cooled system design for a specified optimization criterion. Table 1.1 lists the independent and dependent variables for each design option and identifies the analysis options and optimization design-options.
### TABLE 1.1
FORCED-COOLED CABLE SYSTEM DESIGN-OPTIONS - INPUT & OUTPUT VARIABLES

<table>
<thead>
<tr>
<th>DESIGN-OPTION</th>
<th>PRIMARY INDEPENDENT VARIABLES</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| 1             | - system cable ampacity rating*  
                - system average cable ampacity**  
                - number of system coolant loops  
                - heat exchanger outlet temperature per loop  
                - length of each coolant loop  
                - total system axial length | - heat exchanger inlet temperature per loop  
                - oil flow rate per loop  
                - loop dynamic pressure loss  
                - loop cooling power  
                - loop pumping power | This is a straightforward design analysis program. Details are provided in Chapter 3.  
*** See note below. |

| 2             | - system cable ampacity rating  
                - system average cable ampacity  
                - heat exchanger outlet temperature (same for all loops)  
                - total system axial length | - optimum number of coolant loops  
                - length of each coolant loop  
                - oil flow rate per loop  
                - heat exchanger inlet temperature per loop  
                - loop dynamic pressure loss  
                - loop cooling power  
                - loop pumping power | This design-option optimizes system design for a minimum number of system coolant loops. Details are provided in Chapter 4.  
*** See note below. |

* peak operational ampacity  
** average daily cable ampacity used to calculate cable energy loss  
*** each option also requires the specification of certain design constraints and other system variables - refer to the General Program input section and to the pertinent design-option chapter.
<table>
<thead>
<tr>
<th>DESIGN-OPTION</th>
<th>PRIMARY INDEPENDENT VARIABLES</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
<th>COMMENTS</th>
</tr>
</thead>
</table>
| 3             | - system cable ampacity rating  
                - system average cable ampacity  
                - number of coolant loops  
                - oil flow rate per loop  
                - loop length per loop | - heat exchanger inlet temperature per loop  
                - heat exchanger outlet temperature per loop  
                - loop dynamic pressure loss  
                - loop cooling power  
                - loop pumping power | This is a straightforward design analysis program. Details are provided in Chapter 5.  
*** See note on first page of Table. |
| 4             | - loop heat exchanger inlet temperature  
                - loop heat exchanger outlet temperature  
                - loop length | - forced-cooled cable ampacity  
                - loop oil flow rate  
                - loop dynamic pressure loss  
                - loop cooling power  
                - loop pumping power | This analysis program applies to a single loop of a forced-cooled system.  
*** See note on first page of Table. |
| 5             | - loop heat exchanger outlet temperature  
                - loop length  
                - minimum cable line pressure  
                - maximum cable line pressure  
                - maximum discharge line pressure  
                - even number loop or odd numbered loop | - forced-cooled cable ampacity  
                - loop oil flow rate  
                - loop dynamic pressure loss  
                - loop cooling power  
                - loop pumping power | This design analysis program applies to a single loop of a forced-cooled system.  
*** See note on first page of Table. |
### TABLE 1.1 (CONT'D.)

<table>
<thead>
<tr>
<th>DESIGN OPTION</th>
<th>PRIMARY INDEPENDENT VARIABLES</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>- number of system coolant loops&lt;br&gt;- total system axial length&lt;br&gt;- heat exchanger outlet temperature (same for all loops)</td>
<td>- maximum permitted forced-cooled cable ampacity&lt;br&gt;- loop length per loop&lt;br&gt;- loop dynamic pressure loss&lt;br&gt;- heat exchanger inlet temperature per loop&lt;br&gt;- loop cooling power&lt;br&gt;- loop pumping power</td>
<td>This design-option optimizes the forced-cooled cable ampacity for a specified number of system coolant loops. *** See note on first page of Table.</td>
</tr>
</tbody>
</table>
1.1 Description of the Forced-Cooled Underground Transmission System Used by the Computer Program

The type of forced-cooled underground pipe-type transmission system to which the computer program applies is described in detail in Chapter 2 of the Design Manual - Part I. (This chapter should be read before proceeding further.) It must be noted that the computer program always assumes an identical oil circulation strategy for each coolant loop; the chilled oil leaving the heat exchanger at temperature TCOLD, enters the sending pipe (return pipe) to be further cooled or heated depending upon the relative temperature of the surrounding soil. Inside the cable pipe the oil is heated by the cables and returns to the heat exchanger at temperature THOT, which is the highest temperature in the system. A schematic drawing of a typical four loop system is shown in Figure 1.1.

1.2 Computer Design Manual Presentation Format

The computer program can be considered as consisting of a main control program or "General Program" and six mini-programs which constitute the forced-cooled system design-options. The General Program (as it will now be designated) consists of those parts of the computer program which control and/or assist the utilization of the program options. This refers to the following:

1) the General Program Data Input Section which reads into the program the forced-cooled system data utilized by all design-options,
Figure 1.1 A schematic drawing of a four-loop pipe-type underground transmission system.
2) the General Program Output Section which provides a generalized output format for all design options,
3) the computer program error messages, and
4) the computer program design subroutines.

The computer program design manual is laid out such that Chapter 2 examines the different aspects of the General Program and provides the associated computer documentation (user instructions). Each of the following chapters (3-8) fully explain and document each of the forced-cooled system design-options, respectively.

2. The General Program

A flow chart of the General Program is presented in Figure 2.1 (the blocks shown with heavy borders). A brief explanation of the four main parts of the General Program is provided in Section 2.1. Complete computer documentation (user instructions and additional information) is presented in Section 2.2.

2.1 Explanation of the Main Parts of the General Program

2.1.1 General Program Input Section

The General Program data input section is located in the front of the computer program (following the variable array dimension statements). The purpose of this section is to input into the program the forced-cooled system design variables and constraints which are required by all computer design-options (should one or more of these variables not be required by a particular option, the documentation section for that option will inform the user of that fact and provide further instructions). User instructions for the input section are found in Section 2.2.1.
Figure 2.1 Computer Program Flow Chart.
2.1.2 **Computer Program Design Subroutines**

The three primary design subroutines constitute a straightforward computerization of the design steps of Design Manual - Part I (Chapter 5). These subroutines are utilized by all design-options and provide a specific aspect of a coolant loop design analysis. As shown in Figure 2.1, the design option provides certain input to a design subroutine and the subroutine returns the output (of the analysis) to the design-option. Table 2.1 lists the main design subroutines and explains their function.

**TABLE 2.1**

**PRIMARY DESIGN SUBROUTINES**

<table>
<thead>
<tr>
<th>Subroutine Name</th>
<th>Function</th>
</tr>
</thead>
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<tr>
<td>ENBAL2</td>
<td>Provides the coolant loop energy balance between the heat dissipated by the cables and the heat absorbed by the oil and the surrounding soil environment (see Section 5.1 of Design Manual - Part I).</td>
</tr>
<tr>
<td>HEATTR</td>
<td>Calculates the cable conductor-to-oil temperature drop for a specified cable ampacity and voltage (see Section 5.2 of Design Manual - Part I).</td>
</tr>
<tr>
<td>PRDROP</td>
<td>Calculates the pressure-flow losses for a coolant loop of a forced-cooled pipe-type cable system (see Section 5.3 of Design Manual - Part I).</td>
</tr>
</tbody>
</table>

Other smaller subroutines also exist which aid the utilization of the design options. References to these subroutines may be made during the explanation of the individual design-options; any explanation required will be provided at that time.
2.1.3 Computer Program Error Messages

The computer program generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program (parameter range limits of design correlations are exceeded) or when specified design constraints are exceeded. Certain error messages apply to all design-options while others only apply to some of the options. In some cases the error causes the program to terminate.

These error messages are detailed in Section 2.2.4 and information is also provided which will aid the user in understanding the causes of a specific error.

2.1.4 General Program Output Section

The General Program Output Section provides a generalized output format for all computer design-options. This is provided, not only to reduce the number of output statements required by the computer program, but also to remove any confusion which may result from introducing different output formats for each of the design options.

The General Program output consists of the following:

1. Printout of General Program Input Variables,

2. Printout of the design-option input variables, and

3. Printout of the design analysis results.

Section 2.2.2 fully details the General Program Output Section.
2.2 General Program Computer Documentation

2.2.1 General Program Input Variables

The input variables used in the computer program by all of the design-options are listed in Table 2.2 along with a brief description of each variable. Table 2.2 also separates these variables into like groups such as those associated with pipe-cable geometry. The General Program input variables are the first to be inputted into the computer program. These variables are inputted only once for each group of problems to be solved.

The forced-cooled system oil properties are introduced into the program as discrete sets of temperature-property values. The values of DNTY(I), SPECHT(I), and VSCTY(I) are associated with the corresponding temperature values of TEMPD(I), TEMPSH(I), and TEMPV(I), respectively. The number of these sets of values specified is permitted to differ for each property type by specifying the number of density property values (NDPTS), number of specific heat values (NSHPTS), and number of viscosity values (NVPTS) which are to be inputted. However, the number of property values specified for any of the oil properties can never exceed the dimensioned value of the maximum number of oil property values expected to be needed, NPVALM (see Section 2.2.3 on array dimensions). (The oil thermal conductivity and the coefficient of thermal expansion are permitted only one input value each due to their relatively constant nature over the temperature range within which the forced-cooled system typically operates.) This method of property specification is utilized in order to
provide for the flexibility of modelling the forced-cooled system with any type of oil desired and without the restriction of specifying the same number of values for each property (which will not be called for in typical cases) and without the need to curve-fit nonlinear data. The computer program contains a subroutine (PTYINT) which accurately interpolates between known property values for an unknown value when given any specified oil temperature. Since the particular method applied utilizes all of the property values (of one property type) in the interpolation scheme, the greater the number of values specified (for a given property type), the greater will be the accuracy of the resultant property value. It is therefore recommended that at least 15 to 20 temperature-property value sets be specified for properties which exhibit a nonlinear temperature-property value relationship (typically only viscosity). The data sets should be distributed uniformly throughout the entire expected temperature range of the oil. Properties which exhibit a linear relationship with temperature (typically both specific heat and density) require (as a minimum) only the specification of the property values at the extremes of temperature (THOT and TCOLD) encountered by the oil. Also, the order in which the data sets are inputted is not important.

The design variables which are categorized under the title of pipe-cable geometry are shown in Figures 1, 2, 3, 5 and 6 of Design Manual Part I. Notice that the skid wire angle or helix angle (shown in Figure 6) is defined as the angle that the skid wire forms with a circumferential ring about the cable. Also be careful to note that the skid
wire spacing, PITCH, (shown in Figure 6) is defined as the axial spacing between adjacent or repeated skid wire loops, regardless if there is one skid wire start, two starts, or more in place. Also, as shown in Figure 3, the cable outside diameter, DCABLE, corresponds to the outside diameter and does not include the skid wire height.

Should it be desired to compute the total dielectric loss per unit length, WD, rather than specify it directly, the following expression can be used,

$$ WD = \frac{0.00276 \ E^2 \ \varepsilon / \varepsilon_0 \ \cos \phi}{\log(2DCABLE-DCOND)/DCABLE} $$

(2.1)

where

WD - dielectric loss per conductor foot per cable at 60 cycles (w/ft)
E - line to line voltage (kilovolts)
\varepsilon - relative dielectric constant (farads/meter)
\varepsilon_0 - dielectric constant of free space (8.85 \times 10^{-2} f/meter)
DCABLE - cable outside diameter (in)
DCOND - cable conductor diameter (in)

Due to the flowing oil, the temperatures of the cable conductor vary along the length of the system. Therefore, the conductor electrical resistance also changes (decreasing from the cold to the hot end of the loop) which results in nonuniform heat generation along the length of the cable. The computer program is not capable of dealing with this phenomenon.
and simply requires the input of a single conductor DC resistance value (RDC). For a conservative design, it is recommended that the electrical resistance corresponding to the maximum temperature that the cable experiences be utilized.

Under the category of system thermal characteristics, the computer program requires as part of its input selected output from Koci's "Transient Heat Conduction in the Soil" computer program [4]*. The values of $F_{11}$, $F_{12}$, $F_{22}$, $Q_{1A}$, and $Q_{2A}$ (which correspond to Koci's nomenclature as $F_{11}$, $F_{12}$, $F_{22}$, $Q_{1a}$, and $Q_{2a}$) taken from Koci's output, are utilized in the quasi-steady coolant loop energy balance. $F_{11}$, $F_{12}$, $F_{22}$, $Q_{1A}$, and $Q_{2A}$ should correspond to the set of values which minimize the soil heat transfer during the course of the year (namely during summertime operation). This results in a conservatively designed system which is capable of operating safely when the system forced-cooling requirements are maximized. The set of values obtained from Koci's program apply only to a double forced-cooled circuit as described in [4]. It must be noted that the selected set of values of $F_{11}$, $F_{12}$, $F_{22}$, $Q_{1A}$, and $Q_{2A}$ are determined for the following conditions:

1) specified system geometric configurations, i.e. pipe spacing, pipe depth, trench size, etc.,

2) specified system geographic location, i.e. New York, New York, and

3) specified time of year, i.e. day 220.

*The reference numbers provided in the computer design manual correspond to the references listed in Design Manual Part I.
If any of these conditions are altered, a new set of values must be determined from the "Transient Heat Conduction in the Soil" computer program.

Under the category of system design constraints, the cable temperature constraint corresponds to that temperature which causes cable failure (typically the maximum temperature that the paper insulation will tolerate) or some value below this critical temperature which takes into account a factor of safety. The minimum oil pressure constraint corresponds to the pressure at which the circulating oil will lose its dielectric properties or some pressure above this critical pressure which takes into account a factor of safety. The maximum cable and return line pressure constraints typically correspond to the manufacturer's recommended maximum allowable pipe pressures (which typically includes a factor of safety). The maximum allowable pump differential pressure is also based on manufacturer's recommendations.

The forced-cooled system elevation profile consists of the input of discrete length-height data sets, respectively PLTH(I) and PEL(I), which describe the elevation of various critical profile points along the cable system with respect to the system datum point. The system datum point is defined to be that end of the cable line where the operational head-tank is located. Each specified height of PEL(I) corresponds to a specified length of PLTH(I). The distance values corresponding to PLTH(I) are always measured from the datum point to the selected profile point. That end of the system at which the operational head tank is located (the system datum point) is defined in terms of
length and height to be $\text{PLT}^{(1)} = 0.0$ and $\text{PEL}^{(1)} = 0.0$, respectively, and must always be inputted as such. The remaining length-height data sets, which are required to describe the cable system contour, are numbered sequentially while moving away from the datum point. The system contour thus consists of a series of line segments which can be made as large or as small as desired when attempting to model level terrain, mountain, or valley crossings. The opposite end of the system, where typically the non-operational head tank is located, must assume the final values of $\text{PLT}^{(I)}$ and $\text{PEL}^{(I)}$. (It must be observed that the total number of system elevation profile points must not exceed the maximum number of system profile elevation points expected to be needed, $\text{NPPTSM}$ - see Section 2.2.3 on array dimensions.) An example of the use of the system elevation profile is provided in Figure 2.2. In this figure, the choice of the profile points is shown along with the respective values of $\text{PLT}^{(I)}$ and $\text{PEL}^{(I)}$.

Temperature and pressure profiles are produced by the computer program for each system coolant loop analyzed. The number of points for which the pressure is to be calculated (at equally spaced intervals) corresponds to the variable, $\text{NLPPTS}$ (number of loop pressure points). The value of $\text{NLPPTS}$ selected must never exceed the maximum number of loop pressure profile points expected to be needed, $\text{NLPPTM}$ (see Section 2.2.3 on array dimensions). Likewise the number of points for which the temperature is to be calculated (at equally spaced intervals) corresponds to the variable, $\text{NLTPTS}$ (number of loop temperature points). The value of $\text{NLTPTS}$ selected must never exceed the maximum number of loop temperature
SYSTEM ELEVATION PROFILE MODEL

- DESIGNATES PROFILE POINT

NUMBER OF PROFILE ELEVATION POINTS (NPPTS) = 8

Figure 2.2 Forced-Cooled System Elevation Profile Point Example.
profile points expected to be needed, NLTPTM (see Section 2.2.3 on array dimensions). Both NLPPTS and NLTPTS include the loop end-points in their values.

Minor pressure losses in valves on fittings, located in the return line of each coolant loop, are accounted for by evaluating the length, $L_e$, of the same diameter pipe which produces the same pressure drop as the fitting at a particular Reynolds number. The equivalent lengths of return line valves and fittings can be determined from Table 2 of Design Manual Part I. The sum of these separate equivalent lengths, $L_{THEQ}$, is inputted into the computer program so that the correct pump head and end of loop pressures can be calculated. It is assumed that all loops will be subject to similar minor pressure losses - thus the use of only one value of the equivalent length.

2.2.2 General Program Output

All design-options utilize the General Program Output Section to implement data printout. The general input data is printed out under the title GENERAL PROGRAM INPUT DATA. This information is printed only once for the group of problems being solved (since it is applicable to each problem). (The user should always check these values to make certain that no errors exist.) The input information and results for each computer problem are then printed out sequentially.

The design-option input data (for the respective problem) is printed out under the title DESIGN-OPTION__ -- PRINTOUT OF INPUT DATA. (The user should always check these values to make certain that no errors exist.) The analysis results (for the respective problem) are
TABLE 2.2
GENERAL INPUT VARIABLES FOR ALL DESIGN OPTIONS OF THE COMPUTER PROGRAM

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimensions ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(oil properties)</td>
<td></td>
</tr>
<tr>
<td>NDPTS</td>
<td>the number of data point values utilized to describe the density-temperature property relationship of the circulating oil (dimensionless)</td>
</tr>
<tr>
<td>DNTY(I)</td>
<td>the density values of the circulating oil (lbm/ft³)</td>
</tr>
<tr>
<td>TEMPD(I)</td>
<td>the temperature values which correspond to the respective density values of the circulating oil (°F)</td>
</tr>
<tr>
<td>NSHPTS</td>
<td>the number of data point values utilized to describe the specific heat-temperature property relationship of the circulating oil (dimensionless)</td>
</tr>
<tr>
<td>SPECHT(I)</td>
<td>the specific heat values of the circulating oil (BTU/lbm°F)</td>
</tr>
<tr>
<td>TEMPSH(I)</td>
<td>the temperature values which correspond to the respective specific heat values of the circulating oil (°F)</td>
</tr>
<tr>
<td>NVPTS(I)</td>
<td>the number of data point values utilized to describe the viscosity-temperature property relationship of the circulating oil (dimensionless)</td>
</tr>
<tr>
<td>VSCTY(I)</td>
<td>the viscosity values of the circulating oil (CP)</td>
</tr>
<tr>
<td>TEMPV(I)</td>
<td>the temperature values which correspond to the respective specific heat values of the circulating oil (°F)</td>
</tr>
<tr>
<td>KOIL</td>
<td>the thermal conductivity of the circulating oil (BTU/hr ft°F)</td>
</tr>
<tr>
<td>COTHEX</td>
<td>the coefficient of thermal expansion of the circulating oil (l/°F)</td>
</tr>
</tbody>
</table>
TABLE 2.2 (CONT'D.)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimensions ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pipe-cable geometry)</td>
<td></td>
</tr>
<tr>
<td>DPIPE</td>
<td>inside diameter of the cable-line pipe (in)</td>
</tr>
<tr>
<td>DRPIPE</td>
<td>inside diameter of the return line (discharge line) pipe (in)</td>
</tr>
<tr>
<td>SWH</td>
<td>cable skid wire height (diameter) (in)</td>
</tr>
<tr>
<td>PITCH</td>
<td>axial spacing between adjacent skid wire loops (in)</td>
</tr>
<tr>
<td>TAPTH</td>
<td>cable metallic tape thickness (in)</td>
</tr>
<tr>
<td>SWANG</td>
<td>skid wire helix angle (degrees)</td>
</tr>
<tr>
<td>DCOND</td>
<td>cable conductor diameter (insulation inside diameter) (in)</td>
</tr>
<tr>
<td>DCABLE</td>
<td>cable outside diameter, excluding skid wire (insulation outside diameter) (in)</td>
</tr>
<tr>
<td>(electrical system characteristics)</td>
<td></td>
</tr>
<tr>
<td>RDC</td>
<td>conductor DC electrical resistance (ohms)</td>
</tr>
<tr>
<td>WD</td>
<td>the total dielectric loss per unit length per cable (w/ft)</td>
</tr>
<tr>
<td>YC</td>
<td>percent increase of the AC/DC resistance ratio of the cable due to skin and proximity effects (dimensionless)</td>
</tr>
<tr>
<td>YS</td>
<td>percent increase of AC/DC resistance ratio due to induced current in the cable sheath (dimensionless)</td>
</tr>
<tr>
<td>YP</td>
<td>percent increase of the AC/DC resistance ratio due to induced current in the pipe (dimensionless)</td>
</tr>
<tr>
<td>(system thermal characteristics)</td>
<td></td>
</tr>
<tr>
<td>$K_{tape}$</td>
<td>cable metallic tape thermal conductivity (BTU/hr ft°F)</td>
</tr>
<tr>
<td>$F11,F12,F22$</td>
<td>factors which describe the steady state heat transfer relationship between the cable line, return line and soil for a selected time of the year (BUT/hr ft°F)</td>
</tr>
</tbody>
</table>
### TABLE 2.2 (CONT'D.)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimensions (___)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1A, Q2A</td>
<td>heat transfer values which take into account the dynamic heat transfer effects from the cable and return lines to the soil (BTU/hr ft) (system design constraints)</td>
</tr>
<tr>
<td>TCABMX</td>
<td>the maximum permitted cable temperature (°F)</td>
</tr>
<tr>
<td>PMIN</td>
<td>the minimum allowable oil pressure (psia)</td>
</tr>
<tr>
<td>PMAXCL</td>
<td>the maximum allowable cable line oil pressure (psia)</td>
</tr>
<tr>
<td>PMAXRL</td>
<td>the maximum allowable return line oil pressure (psia)</td>
</tr>
<tr>
<td>PHDMAX</td>
<td>the maximum allowable pump head (differential pressure) (psia)</td>
</tr>
<tr>
<td>PPHMAX</td>
<td>the maximum allowable pothead pressure (psia) (system elevation profile)</td>
</tr>
<tr>
<td>NPPTS</td>
<td>the number of data point values utilized to describe the elevation profile of the system (dimensionless)</td>
</tr>
<tr>
<td>PLTH(I)</td>
<td>the axial distance from the beginning of the system which places a specific profile point (Ft)</td>
</tr>
<tr>
<td>PEL (I)</td>
<td>the height of the system profile point above or below the system datum point (the operational head tank) which corresponds with the respective axial distance (Ft) (additional thermal and hydraulic input information)</td>
</tr>
<tr>
<td>NLPPTS</td>
<td>the number of coolant loop points at which the pressure is to be determined for use in establishing the loop pressure profile (dimensionless)</td>
</tr>
</tbody>
</table>
TABLE 2.2. (CONT'D.)

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimensions (___)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLTPTS</td>
<td>the number of coolant loop points at which the temperature is to be determined for use in establishing the loop temperature profile (dimensionless)</td>
</tr>
<tr>
<td>LTHEQ</td>
<td>the sum of the equivalent lengths of return line valves and fittings (ft)</td>
</tr>
<tr>
<td>DPHE</td>
<td>the heat exchanger pressure drop (psi)</td>
</tr>
</tbody>
</table>
### TABLE 2.3

GENERAL OUTPUT INFORMATION FOR ALL DESIGN OPTIONS OF THE COMPUTER PROGRAM

<table>
<thead>
<tr>
<th>HYDRAULIC INFORMATION FOR EACH COOLANT LOOP</th>
<th>THERMAL INFORMATION FOR EACH COOLANT LOOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>loop axial length</td>
<td>forced-cooled cable ampacity - peak value</td>
</tr>
<tr>
<td>loop flow rate</td>
<td>forced-cooled cable ampacity-average value</td>
</tr>
<tr>
<td>cable-line dynamic pressure loss/ft</td>
<td>total system energy losses</td>
</tr>
<tr>
<td>cable-line dynamic pressure loss</td>
<td>heat exchanger inlet temperature</td>
</tr>
<tr>
<td>return-line dynamic pressure loss/ft</td>
<td>heat exchanger outlet temperature</td>
</tr>
<tr>
<td>return-line dynamic pressure loss</td>
<td>total heat exchanger cooling power</td>
</tr>
<tr>
<td>pump inlet pressure</td>
<td>loop temperature profile</td>
</tr>
<tr>
<td>pump outlet pressure</td>
<td></td>
</tr>
<tr>
<td>loop pumping power</td>
<td></td>
</tr>
<tr>
<td>system head tank pressure</td>
<td></td>
</tr>
<tr>
<td>elevation profile point pressures</td>
<td></td>
</tr>
<tr>
<td>loop pressure profile</td>
<td></td>
</tr>
</tbody>
</table>
printed out next. All design-options utilize an identical format for
the printout of results (exceptions are noted) and, for clarity, the
output is divided into two groups: HYDRAULIC INFORMATION AND THERMAL
INFORMATION. Table 2.3 lists this output information in the same order
in which it appears in the program output.

2.2.3 General Program Array Dimensions

A number of subscripted variables, or arrays are used in the
computer program. Those variables which utilize the same dimension size
have been organized into six separate groups which are dimensioned
separately by their own dimension statement. These groups are presented
below, together with the variables which determine their dimension size
and their value in the present program.

a) DIMENSION STATEMENT 1

    DIMENSION LLTH(MAXLPS), THOT(MAXLPS), TCOLD(MAXLPS),
    1 LOOPEL(MAXLPS+1), PRESCL(MAXLPS+1), PRESRL(MAXLPS), DPLCL(MAXLPS),
    2 DPLRL(MAXLPS), SDP(MAXLPS), PWRPMP(MAXLPS), PWRREF(MAXLPS),
    3 PDIFHC(MAXLPS), PDIFHR(MAXLPS), PDIFLO(MAXLPS), NPC(MAXLPS),
    4 NPR(MAXLPS), NPCLO(MAXLPS), DPLULC(MAXLPS), DPLULR(MAXLPS),
    5 SPRESS(MAXLPS+1), DPEL(MAXLPS), XFL(MAXLPS+1), FLOWRT(MAXLPS)

    MAXLPS = the maximum number of coolant loops
    expected to be analyzed

    Present value of MAXLPS = 30

b) DIMENSION STATEMENT 2

    DIMENSION DNTY(NPVALM), VSCTY(NPVALM), SPECHT(NPVALM),
    1 TEMPD(NPVALM), TEMPSH(NPVALM), TEMPV(NPVALM), F1(NPVALM),
2 XP(NPVALM), F(NPVALM)

NPVALM = the maximum number of oil property values expected to be needed

Present value of NPVALM = 20

c) DIMENSION STATEMENT 3

DIMENSION PR(NPPTSM), PC(NPPTSM), XDIST(NPPTSM),
1 PLTH(NPPTSM), PEL(NPPTSM), PDIFFC(NPPTSM+1), PDIFFR(NPPTSM+1),
2 PDIFFL(NPPTSM+1), HTDN(NPPTSM), HTDP(NPPTSM)

NPPTSM = the maximum number of system profile elevation points expected to be used

Present value of NPPTSM = 50

d) DIMENSION STATEMENT 4

DIMENSION PRR(NLPPTM), PRC(NLPPTM), XPDIST(NLPPTM)

NLPPTM = the maximum number of loop pressure profile points expected to be used

Present value of NLPPTM = 50

e) DIMENSION STATEMENT 5

DIMENSION TR(NLTPTM), TC(NLTPTM), XTDIST(NLTPTM)

NLTPTM = the maximum number of loop temperature profile points expected to be used.

Present value of NLTPTM = 50

f) DIMENSION STATEMENT 6

DIMENSION FLRT(40), ICHNG(40), KCHNG(40), LL(40), IFCD(40)

The dimension of these variables is fixed.
The statements which assign the values to MAXLPS, NPVALM, NPPTSM, NLPPTM, NLTPTM are listed just after the five dimension statements in the computer program. If new dimensions are assigned to one or more of the five groups, then the value(s) of the dimensioned variable(s) must also be changed. This is required because the computer program utilizes execution-time dimensioning of subprograms.

The dimensions are presently set at values which are suitable for typical designs. If dimensions are increased, the required computer memory storage space will increase (present storage space requirements are discussed in Appendix A). The size of the increase depends upon the user's selection of the new dimension values; the user should make certain that the storage space of the computer facility is not exceeded.

2.2.4 Computer Program Error Messages

The computer program generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program (parameter range limits of design correlations are exceeded) or when specified design constraints are exceeded. If a program error occurs, the error message first specifies the number code of the error (see below) and then the entire message is printed out. All program error messages are listed below along with the pertinent information regarding the error (some errors are self-explanatory). Some of the errors are associated with only one design option, some correspond to a number of design options, while others can be associated with all of the options. Each design-option documentation section lists those errors which apply specifically to that design-option and further information regarding the errors is supplied if necessary.
1:**ERROR 1**
PARAMETER DCABLE/DPIPE(= ) IS OUTSIDE
THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM
PRESSURE-DROP CORRELATION 0.3 < DCABLE/DPIPE < 0.45.

The range of application of the parameter DCABLE/DPIPE is provided in the error message. The user is referred to Design Manual - Part I - Chapter 5 - STEPC (design analysis procedure) for more information. The error applies to all design-options. This error terminates the program.

2:**ERROR 2**
PARAMETER SWH/DCABLE (= ) IS OUTSIDE
THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM
PRESSURE-DROP CORRELATION 0.005 < SWH/DCABLE < 0.04.

Refer to Design Manual - Part I - Chapter 5 - STEPC for more information. The error applies to all design-options. The error terminates the program.

3:**ERROR 3**
PARAMETER PITCH/SWH(= ) IS OUTSIDE THE
LIMITS OF THE PIPE-TYPE CABLE SYSTEM
PRESSURE-DROP CORRELATION 10.0 < PITCH/SWH < 40.0.

Refer to Design Manual - Part I - Chapter 5 - STEPC for more information. The error applies to all design-options. The error terminates the program.

4:**ERROR 4**
PARAMETER SWANG(= ) IS OUTSIDE
THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM
PRESSURE-DROP CORRELATION 0.0 < SWANG < 60.0.
Refer to Design Manual - Part I - Chapter 5 - STEPC for more information. The error applies to all design-options. The error terminates the program.

5:**ERROR 5**
NUMBER OF SYSTEM LOOPS = . FORCED-COoled SYSTEM is INCORRECTLY BEING DESIGN FOR AN ODD NUMBER OF COOLANT LOOPS. INPUT A NEW VALUE OF NLOOPS.

The design manual will not accept a forced-cooled system design which utilizes an odd number of loops. This error applies to design-options 1, 3, and 6. The error terminates the program.

6:**ERROR 6**
THE VALUE OF THE PARAMETER INOND(= ) IS OUTSIDE THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM HEAT TRANSFER CORRELATION. THE RESULTS OF THE ANALYSIS ARE NOT VALID FOR AN AMPACITY VALUE EQUAL TO ____ AMPS. 0.35<INOND<12.0.

INOND is a parameter which is generated internally in the program. The parameter is defined as follows:

\[ \text{INOND} = (1.0 + \text{YC}) \times \text{RDC} \times \text{IFC} \times \text{IFC} / \text{WD} \]

The permitted range of the parameter is provided in the error message. This parameter is important to the proper utilization of the pipe-type cable system heat transfer correlation. Further Details can be found in the Design Manual - Part I - Appendix D-2. The error applies to all design-options. The error terminates the program (except when specified otherwise).
7: **ERROR 7**
THE REQUIRED OPERATIONAL HEAD-TANK PRESSURE
(= ) EXCEEDS THE SPECIFIED PRESSURE
LIMIT OF EITHER THE POTHEAD OR CABLE
LINE. CHECK ELEVATION PROFILE INPUT DATA.
PROGRAM IS TERMINATED.

This error applies to design-options 1, 2, 3, and 6.

8: **ERROR 8**
THE PRESSURE (= ) AT THE LOW PRESSURE
END OF LOOP EXCEEDS THE POTHEAD
PRESSURE. THE SYSTEM DESIGN MUST BE
MODIFIED.

This error applies to design-options 1, 2, 3, and 6. The
error does not terminate the program.

9: **ERROR 9**
THE HOT TEMPERATURE (= ) OF LOOPNO____
IS LOWER IN VALUE THAN THE SPECIFIED
COLD TEMPERATURE. LOWER THE VALUE OF
THE COLD TEMPERATURE OR DECREASE THE
SYSTEM AMPACITY. PROGRAM IS TERMINATED.

This error occurs when the specified peak ampacity, IFC, yields
an insulation temperature drop large enough such that the maximum permitted
oil temperature falls below the specified heat exchanger outlet temperature.
This error applies to design-options 1 and 2.

10: **ERROR 10**
THE OIL FLOW RATE IS LESS THAN 5 GAL/MIN
IN LOOP NO____. INCREASE THE VALUE OF
THE COLD TEMPERATURE. PROGRAM IS TERMINATED.
TCOLD = ___ °F. THOT = _____ °F.

This error occurs when the loop differential temperature
(THOT-TCOLD) is so large (and the loop length is so small) as to yield
a very low loop flow rate (the program will not permit flow rates less than 5 gal/min). The error applies to design options 1, 2, 4, 5, and 6. The error terminates the computer program.

11:**ERROR 11**
THE MAXIMUM ALLOWABLE PUMP HEAD HAS BEEN EXCEEDED IN LOOP NUMBER ___. THE PRESENT VALUE OF THE PUMP DIFFERENTIAL PRESSURE IS ___ PSI.

This error does not terminate the computer program. The error applies to design options 1 and 3.

12:**ERROR 12**
THE PRESSURE AT ELEVATION PROFILE POINT NO ___ IN LOOP NO ___ EXCEEDS THE MAXIMUM CABLE LINE PRESSURE PERMITTED BY ____ PSI. THE LOOP FLOW RATE OR LOOP LENGTH MUST BE MODIFIED.

This error does not terminate the computer program. The error applies to design options 1, 3, and 5.

13:**ERROR 13**
THE PRESSURE AT ELEVATION PROFILE POINT NO ___ IN LOOP NO ___ EXCEEDS THE MAXIMUM RETURN LINE PRESSURE PERMITTED BY ____ PSI. THE LOOP FLOW RATE OR LOOP LENGTH MUST BE MODIFIED.

This error does not terminate the computer program. The error applies to design options 1, 3, and 5.

14:**ERROR 14**
THE PRESSURE AT ELEVATION PROFILE POINT NO ___ IN LOOP NO ___ IS BELOW THE MINIMUM CABLE LINE PRESSURE PERMITTED BY ____ PSI. THE LOOP FLOW RATE OR LOOP LENGTH MUST BE MODIFIED.
This error does not terminate the computer program. The error applies to design options 1, 3, and 5.

15: **ERROR 15**

THE FLOW RATE (= ) REQUIRED TO SATISFY TCOLD (= ) AND THOT (= ) EXCEEDS A VALUE EQUAL TO GAL/MIN. THE COMPUTER PROGRAM CANNOT INCREASE THIS VALUE FURTHER. THE VALUE OF THE LOOP LENGTH IS EQUAL TO ____.

This error does not terminate the program. The error occurs because the flow rate required to produce a desired heat exchanger temperature drop, for the specified loop length, is too large for the program to calculate (the limit on the number of iterations performed in subroutine ENBAL2 has been exceeded). Apparently the hot and cold loop temperatures are very close in value and/or the loop length is very sizeable.

The error applies to design-options 1, 2, 4, 5, and 6.

16: **ERROR 16**

THE VALUE OF THE CABLE LINE TEMPERATURE (= ) IS OUTSIDE THE TEMPERATURE RANGE OF THE INPUTTED OIL PROPERTY DATA. THE COMPUTER PROGRAM WILL USE THE PROPERTY VALUES WHICH COINCIDE WITH THE CLOSEST TEMPERATURE RANGE CONSTRAINT VALUE.

This error will occur when the computer program attempts to work with oil temperature values which are outside the oil temperature range of the inputted oil property values (typically only the values of the oil viscosity are miscalculated under these circumstances). This can happen, for example, when a very high system cable ampacity is desired which subsequently results in a very low, hot oil temperature.
(required in order to maintain the cable below its maximum temperature constraint). The user must make certain that the inputted oil properties (especially the viscosity data) cover a wide range of values (beyond the minimum or maximum temperatures expected).

17:**ERROR 17**
NEITHER THE SPECIFIED CABLE LINE PRESSURE (= )
NOR THE SPECIFIED RETURN LINE PRESSURE (= )
CAN BE ACHIEVED. THE AMPACITY REQUIRED EXCEEDS
THAT VALUE OF THE AMPACITY (= ) WHICH YIELDS
THE SPECIFIED MAXIMUM PERMISSIBLE HEAT EXCHANGER
TEMPERATURE DROP (= ).

This error applies to design-options 5 and 6.

2.2.5 **Data Card Assembly for General Program Input Variables**

Instructions for assembling data cards for the general input variables are listed in Table 2.4. While most of this table is self-explanatory, a few additional remarks are offered below.

Attention is called to those variables which employ the I-format for their input. It is necessary that all these entries be right-justified to their respective columns.

The asterisk which is printed next to some of the card numbers in Table 4 indicates that more than one card may be required to input the particular variable array. If this is the case, the individual values are entered sequentially across each data card, with each value occupying ten columns. When all the values of a particular variable have been specified, the next variable begins on a new data card. (If more than one data card is specified for one of the variables so marked, the
### TABLE 2.4
DATA CARD ASSEMBLY FOR GENERAL PROGRAM

INPUT VARIABLES (SEE TABLE 2.2 FOR DESCRIPTION AND DIMENSION OF VARIABLES)

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*Indicates that more than one card may be necessary

**See Table 2.3 for variable dimensions
card numbering scheme no longer applies. However, the order of the variables remains unchanged.

2.2.6 Example Problems - General Input Data

This part provides the general input data which is used for the specified example problem presented in each design-option documentation section (there will be six example problems - one for each design option). The data used refers to an existing self-cooled cable system which is to be converted into a forced-cooled system. The complete set of this general input data for this problem is listed in Table 2.5.

A number of observations are made about the data used in this problem. A low viscosity polybutene oil is selected for use in the system. Cards 8 and 9 which list the viscosity-temperature data for this oil contain only 8 data sets. Typically a greater number of data sets should be used (as pointed out previously) but only 8 were used here so as to preserve the card numbering system of Table 2.4.

The soil heat transfer data of card 13 was obtained from Koci's "Transient Heat Conduction in the Soil" computer program. The values obtained correspond to the late summer months (DAY 220) when soil heat transfer is minimized.

The gear pumps proposed for use in the forced-cooled system have a pump pressure rating of approximately 450 psi.

Minor losses in the return line will not be taken into consideration and therefore the value of LthEQ is set equal to zero. The heat exchanger pressure drop has been set equal to 20 psi.
# TABLE 2.5

**GENERAL INPUT DATA USED FOR PROBLEM-OPTION DESIGN EXAMPLE PROBLEMS**

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3. DESIGN-OPTION 1

A detailed explanation of the analysis procedure utilized by Design-Option 1 (D.O.1) is presented in Section 3.1. Computer documentation (user instructions) is provided in Section 3.2.

3.1 Analysis Procedure of Design-Option 1

Design-Option 1 provides a thermal and hydraulic analysis for each coolant loop of a forced-cooled pipe-type cable system, taking into account the hydraulic interaction between coolant loops. Using the specified General Program input data (Section 2.2.1), the D.O.1 thermal analysis computes, for a given cable ampacity (peak and average values), axial loop length, and heat exchanger outlet temperature, the heat exchanger inlet temperature, oil flow rate, and the axial temperature distribution of the oil in the pipes. The D.O.1 hydraulic analysis uses the oil flow rate to calculate the loop dynamic pressure losses and the absolute loop pressure profile (loop-loop interaction is accounted for).

The independent variables, dependent variables, and system design constraints associated with D.O.1 are presented in Table 3.1 and simplified flow chart describing the analysis procedure is shown in Figure 3.1. The analysis begins with the input of the General Program variables (and constraints) and the D.O.1 input variables. Loop Number 1 (the loop adjacent to the operational head tank) of the forced-cooled underground transmission system is analyzed first (L00P0=1) and the other system loops are analyzed sequentially.
TABLE 3.1

DESIGN-OPTION 1 - INDEPENDENT AND DEPENDENT VARIABLES
AND DESIGN CONSTRAINTS

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<td>-system daily average cable ampacity</td>
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PRIMARY DESIGN CONSTRAINTS

- maximum permitted cable temperature
- minimum permitted oil pressure
- maximum permitted cable line oil pressure
- maximum permitted return line oil pressure
- maximum allowable pump head
- maximum allowable pothead pressure

*Design-Option 1 input data

**Specified as part of General Program Input data (see Table 2.2)
READ GENERAL PROGRAM INPUT DATA
READ DESIGN-OPTION 1 INPUT DATA
LOOPNO = 0
LOOPNO = LOOPNO + 1
INITIALIZE VALUE OF CABLE LINE OUTLET OIL TEMPERATURE, THOT
CALCULATE THE AVERAGE LOOP OIL TEMPERATURE AND CORRESPONDING AVERAGE OIL PROPERTIES (SUBROUTINE PTYINT)
CALCULATE THE LOOP OIL FLOW RATE, Q, USING THE LOOP ENERGY BALANCE (SUBROUTINE ENBAL2)
CALCULATE THE OIL PROPERTIES AT THE CABLE LINE OUTLET POINT
CALCULATE THE MAXIMUM PERMITTED OIL TEMPERATURE, TOILMX, BY CALCULATING THE CABLE CONDUCTOR-TO-OIL TEMPERATURE (SUBROUTINE HEATTR)
IS THOT = TOILMX?
NO
YES
CALCULATE AVERAGE OIL PROPERTIES FOR CABLE AND RETURN LINE, RESPECTIVELY
CALCULATE LOOP PRESSURE FLOW LOSSES AND LOOP PRESSURE PROFILE (SUBROUTINE PRDROP)
IS LOOPNO > NLOOPS?
NO
YES
END

Figure 3.1: Design Option 1-Flow Chart.
The loop thermal analysis consists of permitting the outlet cable line oil temperature (heat exchanger inlet temperature-THOT) to achieve its maximum permissible value, TOILMX, while simultaneously selecting an oil flow rate which satisfies the loop energy balance. The minimum cable line oil temperature is based on the maximum permitted cable temperature and the calculation of the conductor-to-oil temperature drop from the cable heat transfer correlation (Design Manual Part I - Section 5.2) for a peak cable ampacity. The loop energy balance is based upon Equations 3.6 as presented in Section 5.1 of Design Manual Part I and utilizes cable energy losses based on the daily average cable ampacity.

An iterative analysis is necessary since the cable heat transfer correlation is slightly dependent on the oil flow rate as calculated in the loop energy balance. Also, iteration is necessary because the oil properties used in the procedure are based on the average loop oil temperature, which is initially unknown, and whose value keeps changing until the cable heat transfer correlation and the energy balance are simultaneously satisfied. As shown in Figure 3.1, the iterative procedure begins by selecting an initial value of THOT. This value and the value of the heat exchanger outlet temperature (specified in D.O.1 input) are used to calculate an average loop temperature for which the average values of the oil properties (density and specific heat) are determined. The values are an input to the loop energy balance (subroutine ENBAL2), which calculates the oil flow rate needed to produce the present values of the heat exchanger inlet and outlet temperatures. The value
of the oil flow rate is then used in the cable heat transfer correlation (subroutine HEATTR) to calculate the value of TOILMX. If the calculated value of TOILMX differs from the chosen value of THOT, the analysis is repeated by setting the value of THOT equal to the value of TOILMX. The iteration ends when the value of the heat exchanger inlet temperature, THOT, is equal to the value of the maximum permitted oil temperature, TOILMX. The loop temperature profile is then calculated.

The loop hydraulic analysis follows and consists of using the value of the oil flow rate (determined above) to calculate the loop dynamic pressure drop (subroutine PRDROP). The loop static pressure profile is then utilized to calculate the loop absolute pressure profile.

This entire analysis is repeated for every loop in the forced-cooled system. The General Program output format is used to print out the analysis results.

3.2 Design Option 1 - Computer Documentation

3.2.1 Input Variables for Design-Option 1

The input variables used in Design-Option 1 are listed in Table 3.2 along with a brief description of each variable.

The forced-cooled system ampacity rating refers to the peak current to which the system is subjected. The computer program utilizes this current to determine the upper limit on the oil temperature which prevents the cable temperature from exceeding its maximum value.

The cable amperage does not typically stay constant at one value but fluctuates over some range. Therefore the amount of heat
### TABLE 3.2
INPUT VARIABLES FOR DESIGN-OPTION 1

<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>DESCRIPTION AND DIMENSION( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>1 - variable which &quot;informs&quot; the computer program that Design-Option 1 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem 1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted) (dimensionless)</td>
</tr>
<tr>
<td>IFC</td>
<td>forced-cooled system ampacity rating (the peak ampacity to which the system is subjected) (amps)</td>
</tr>
<tr>
<td>IFCAVG</td>
<td>the average cable ampacity which used to calculate pipe-to-soil heat transfer (amps)</td>
</tr>
<tr>
<td>FLT</td>
<td>the total forced-cooled system axial length (ft)</td>
</tr>
<tr>
<td>TCOLD(I)</td>
<td>the specified heat exchanger outlet temperatures (the cold temperatures) for each coolant loop (°F)</td>
</tr>
<tr>
<td>NLOOPS</td>
<td>the number of system coolant loops (dimensionless)</td>
</tr>
<tr>
<td>LLTH(I)</td>
<td>the axial length of each system coolant loop (ft)</td>
</tr>
</tbody>
</table>
dissipated by the cables is less than the amount that is calculated when using the value of IFC. Consequently, an average current value, IFCAVG, is used to calculate the cable heat generation for use in the loop energy balance. A conservative design sets the value of IFC equal to the value of IFCAVG.

The loop heat exchanger cold temperature, TCOLD(I) must never be specified so that it lies outside of the range of the oil properties as specified in the general program input section. The user must also be careful not to specify a cold temperature which is below the freezing point of the oil or one which prevents the oil from being pumped.

The axial loop length refers to the axial length of either the discharge line or cable line but not to their combined length. This also applies to the value of the total system axial length.

3.2.2 Output for Design-Option 1

After the general program input data is printed out, the input data associated with Design-Option 1 is printed out under the title PRINTOUT OF INPUT DATA.

Design-Option 1 utilizes the input information in order to calculate the oil flow rate and heat exchanger inlet temperature for each coolant loop. All design information is printed out in the General Program output format as described in Table 2.3. All of the output is self-explanatory.
3.2.3 **Array Dimensions**

The number of system coolant loops analyzed in Design-Option 1 can never exceed the value of MAXLPS, the array dimension value of all subscripted variables whose subscript value depends on the loop number (i.e. $LLTH(1) = \text{loop length of loop number 1}$). Refer to Section 2.2.3 for details.

3.2.4 **Error Messages for Design-Option 1**

Design-Option 1 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are exceeded. Those computer program error messages which apply to D.0.1 are listed below. Any additional information which is pertinent to the application of a given error to the design-option is provided.

a) Errors 1 - 9

b) Error 10

This error occurs in design-option 1 when the loop differential temperature ($THOT-TCOLD$) is so large (and the loop length is so small) as to yield a very low value of the loop oil flow rate (the computer program is unable to calculate oil flow rate values below 5 gal/min). Check the value of the IFC inputted and/or check the value of TCOLD inputted for the particular loop. also, make certain that the correct value of the loop length has been inputted.

c) Errors 10 - 14

d) Error 15
If this error occurs in Design-Option 1, the loop flow rate required to produce the desired heat exchanger temperatures drop (THOT-TCOLD), for the specified loop length, is too large for the program to calculate. Check the value of IFC inputted to make sure it isn't too large and/or check the value of TCOLD inputted for the particular loop and lower the value if necessary. Also, make certain that the loop length is not unreasonably large.

e) Error 16

3.2.5 Data Card Assembly for Design-Option 1

Instructions for assembling data cards for Design Option 1 are listed in Table 3.3. While most of this table is self-explanatory, a few additional remarks are offered below.

The card numbering sequence continues directly from the General Program input cards.

It is necessary that the variable using the I-format be right-adjusted in the column field. Also, the asterisk which is printed next to cards 21 and 22 indicates that more than one card may be required to input the variable array (eight variables are used for LLth(I) and TCOLD(I) as an example only).

3.2.6 Design-Option 1 - Example Problem

This section illustrates the solution of a particular forced-cooled system design problem utilizing computer Design-Option 1. An existing self-cooled cable system is to be converted into a forced-cooled system. A route survey indicates that a maximum of five locations exist
<table>
<thead>
<tr>
<th>CARD(s)</th>
<th>COLUMN(s)</th>
<th>VARIABLE**</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>NUPROB</td>
<td>I10</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>IFC</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>IFCAVG</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>FLT</td>
<td>F10.3</td>
</tr>
<tr>
<td>21</td>
<td>1-10</td>
<td>NLOOPS</td>
<td>I10</td>
</tr>
<tr>
<td>22*</td>
<td>1-10</td>
<td>LLTH(1)</td>
<td>F10.3</td>
</tr>
<tr>
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<td>10-20</td>
<td>LLTH(2)</td>
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<tr>
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<td>20-30</td>
<td>LLTH(3)</td>
<td>-</td>
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<tr>
<td></td>
<td>30-40</td>
<td>LLTH(4)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>LLTH(5)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>LLTH(6)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>LLTH(7)</td>
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</tr>
<tr>
<td></td>
<td>70-80</td>
<td>LLTH(8)</td>
<td>-</td>
</tr>
<tr>
<td>23*</td>
<td>-</td>
<td>TCOLD(I)</td>
<td>-</td>
</tr>
</tbody>
</table>

* Indicates that more than one data card may be necessary

** See Table 3.2 for variable dimensions
for the pumping-refrigeration stations. The route topography and station locations are shown in Figure 3.2. Thus, five pumping stations indicates that the system can utilize a maximum of eight coolant loops.

One design proposes to utilize all eight loops in order to increase the ampacity of the original system from 800 amps (peak) to 1400 amps (peak). (An average current of 1250 amps is to be used in order to calculate cable heat dissipation.) A rough preliminary analysis utilizing the Design Manual - Part I indicates a maximum permitted oil temperature of approximately 125°F. Based on this analysis it is decided to set all loop cold temperatures (TCOLD(I)) to a value of 110°F. Problem - Option 1 is now used to determine the actual loop hot temperatures and the loop flow rates. The general program input for this problem has been listed in Table 2.5.

The complete set of input data for Design-Option 1 is listed in Table 3.4. The computer program output is listed in Table 3.5.
### TABLE 3.4

**INPUT DATA USED FOR DESIGN-OPTION 1 EXAMPLE PROBLEM**

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMN(s)</th>
<th>DATA</th>
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<tr>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>1400.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>1250.0</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>51000.0</td>
</tr>
<tr>
<td>21</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>22</td>
<td>1-10</td>
<td>8500.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
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<td>95.0</td>
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<td></td>
<td>30-40</td>
<td>95.0</td>
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<tr>
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<td>40-50</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>95.0</td>
</tr>
</tbody>
</table>
### TABLE 3.5
**GENERAL PROGRAM INPUT DATA**

---TABULATION OF OIL PROPERTIES---

<table>
<thead>
<tr>
<th>TEMPD (F)</th>
<th>DENSITY (LBM/CUFT)</th>
<th>TEMPSH (F)</th>
<th>SPEC.HT. (BTU/LBM F)</th>
<th>TEMPV (F)</th>
<th>VISCOSITY (CP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.00</td>
<td>52.210</td>
<td>50.00</td>
<td>0.464</td>
<td>50.00</td>
<td>84.000</td>
</tr>
<tr>
<td>149.00</td>
<td>50.000</td>
<td>212.00</td>
<td>0.572</td>
<td>59.00</td>
<td>60.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>68.00</td>
<td>44.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>95.00</td>
<td>20.000</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>113.00</td>
<td>13.200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>131.00</td>
<td>9.300</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>149.00</td>
<td>6.800</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>167.00</td>
<td>5.400</td>
</tr>
</tbody>
</table>

OIL THERMAL CONDUCTIVITY (BTU/HR-FT F) ......... 0.1153
OIL COEFFICIENT OF THERMAL EXPANSION (1/F) ....... 0.3900E-03

---PIPE-TYPE CABLE GEOMETRY---

| INSIDE DIAMETER OF CABLE PIPE (IN) .......... | 10.250 |
| INSIDE DIAMETER OF RETURN PIPE (IN) ......... | 5.000  |
| SKID WIRE HEIGHT (IN) ..................... | 0.100  |
| AXIAL SPACING BETWEEN ADJACENT SKID WIRE LOOPS (IN) | 1.500  |
| CABLE METALLIC TAPE THICKNESS (IN) .......... | 0.905  |
| SKID WIRE HELIX ANGLE (DEGREES) ............. | 14.540 |
| CABLE CONDUCTOR DIAMETER (IN) ............. | 1.631  |
| INSULATION OUTSIDE DIAMETER(EXCLUDING SKID WIRE)(IN). | 3.681  |

---SYSTEM ELECTRICAL CHARACTERISTICS---

| CONDUCTOR DC ELECTRICAL RESISTANCE (OHMS) .......... | 0.643E-05 |
| TOTAL DIELECTRIC LOSS PER CONDUCTOR FOOT PER CABLE (WATTS/FT) .......... | 2.680 |
| YC-INCREMENT IN AC/DC RESISTANCE RATIO AT CONDUCTOR (DIMENSIONLESS) ... | 0.130 |
| YS-INCREMENT IN AC/DC RESISTANCE RATIO ........... |        |
### Table 3.5 (Cont'd.)

<table>
<thead>
<tr>
<th>AT SHEATH (DIMENSIONLESS)</th>
<th>0.050</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT PIPE (DIMENSIONLESS)</td>
<td>0.480</td>
</tr>
</tbody>
</table>

---

**--System Thermal Characteristics--**

<table>
<thead>
<tr>
<th>Cable Tape Thermal Conductivity (BTU/HR-FT F)</th>
<th>220.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>F11 (BTU/HR-FT F)</td>
<td>1.576</td>
</tr>
<tr>
<td>F12 (BTU/HR-FT F)</td>
<td>-0.931</td>
</tr>
<tr>
<td>F22 (BTU/HR-FT F)</td>
<td>1.843</td>
</tr>
<tr>
<td>Q1A (BTU/HR-FT)</td>
<td>-52.430</td>
</tr>
<tr>
<td>Q2A (BTU/HR-FT)</td>
<td>-87.500</td>
</tr>
</tbody>
</table>

---

**--System Design Constraints--**

| Maximum Permitted Cable Temperature (F)       | 185.00  |
| Minimum Allowable Oil Pressure (PSI)          | 150.00  |
| Maximum Allowable Cable Line Oil Pressure (PSI) | 600.00  |
| Maximum Allowable Return Line Oil Pressure (PSI) | 800.00  |
| Maximum Allowable Pump Head (PSI)             | 450.00  |
| Maximum Permitted Pothead Pressure (PSI)      | 400.00  |

---

**--System Elevation Profile--**

<table>
<thead>
<tr>
<th>Profile Point</th>
<th>Distance (FT)</th>
<th>Height (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>5000.00</td>
<td>0.00</td>
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<tr>
<td>3</td>
<td>10000.00</td>
<td>50.00</td>
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<tr>
<td>4</td>
<td>20000.00</td>
<td>50.00</td>
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<td>5</td>
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<td>-100.00</td>
</tr>
<tr>
<td>7</td>
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</tr>
<tr>
<td>8</td>
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</table>

---

**--Other Input Information--**
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLPTS - Number of Loop Pressure Profile Points</td>
<td>15</td>
</tr>
<tr>
<td>NLTPTS - Number of Loop Temperature Profile Points</td>
<td>11</td>
</tr>
<tr>
<td>LLTHEQ - Sum of Return Line Equivalent Lengths</td>
<td>0.00</td>
</tr>
<tr>
<td>Heat Exchanger Pressure Drop (PSI)</td>
<td>20.00</td>
</tr>
</tbody>
</table>
**COMPUTER PROBLEM NUMBER 1**

**DESIGN-OPTION 1**

---PRINTOUT OF INPUT DATA---

| FORCED-COOLED SYSTEM AMPLITUDE RATING (AMPS) | 1400.00 |
| AVERAGE CABLE AMPLITUDE (AMPS) | 1250.00 |
| TOTAL SYSTEM AXIAL LENGTH (FT) | 51000.00 |
| NUMBER OF SYSTEM COOLANT LOOPS (DIMENSIONLESS) | 6 |

<table>
<thead>
<tr>
<th>LOOP NUMBER</th>
<th>LOOP LENGTH (FT)</th>
<th>COLD TEMPERATURE (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8500.00</td>
<td>95.00</td>
</tr>
<tr>
<td>2</td>
<td>8500.00</td>
<td>95.00</td>
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<td>8500.00</td>
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</tr>
<tr>
<td>6</td>
<td>8500.00</td>
<td>95.00</td>
</tr>
</tbody>
</table>

---LOOP HYDRAULIC INFORMATION---

| LOOP AXIAL LENGTH (FT) | 8500.00 |
| LOOP FLOW RATE (GAL/MIN) | 266.41 |
| CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.564E-02 |
| CABLE LINE DYNAMIC PRESSURE LOSS (PSI) | 47.92 |
| RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.869E-02 |
| RETURN LINE DYNAMIC PRESSURE LOSS (PSI) | 73.89 |
| PUMP INLET PRESSURE (PSI) | 147.77 |
| PUMP OUTLET PRESSURE (PSI) | 289.58 |
| LOOP PUMPING POWER (WATTS) | 16396.01 |
| SYSTEM HEAD TANK PRESSURE (PSI) | 167.77 |

ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS

LOCATED WITHIN LOOP NUMBER 1 (INCLUDING LOOP END POINT PRESSURES).
### TABLE 3.5 (CONT'D.)

<table>
<thead>
<tr>
<th>AXIAL DISTANCE (FT)</th>
<th>CABLE LINE (PSI)</th>
<th>RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>167.77</td>
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### LOOP PRESSURE PROFILE 15-POINTS

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<tr>
<th>LOOP</th>
<th>AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE</th>
<th>CABLE LINE (PSI)</th>
<th>RETURN LINE (PSI)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.00</td>
<td>167.77</td>
<td>289.58</td>
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<td>607.14</td>
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--- LOOP THERMAL INFORMATION ---

- **SYSTEM FORCED-COoled PEAK AMPACITY RATING (AMPS)**: 1400.000
- **AVERAGE FORCED-COoled AMPACITY (AMPS)**: 1250.000
- **TOTAL SYSTEM ENERGY LOSS (WATTS/FT)**: 58.07

- **HEAT EXCHANGER INLET TEMPERATURE (F)**: 124.91
  - **(MAXIMUM PERMITTED OIL TEMPERATURE)**
- **HEAT EXCHANGER OUTLET TEMPERATURE (F)**: 95.00
- **TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS)**: 0.442E 06

### LOOP TEMPERATURE PROFILE 11-POINTS

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### LOOP HYDRAULIC INFORMATION

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| ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS |
| LOCATED WITHIN LOOP NUMBER 2 (INCLUDING LOOP END POINT PRESSURES) |

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### LOOP PRESSURE PROFILE 15-POINTS

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#### LOOP TEMPERATURE PROFILE 11-POINTS

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---SYSTEM LOOP NUMBER 3---

---LOOP HYDRAULIC INFORMATION---

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<td>Return Line Dynamic Pressure Loss/FT (PSI/FT)</td>
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Absolute Pressures at Elevation Profile Points located within Loop Number 3 (including Loop End Point Pressures).

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### TABLE 3.5 (CONT’D.)

#### LOOP PRESSURE PROFILE 15-POINTS

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#### LOOP THERMAL INFORMATION

- HEAT EXCHANGER INLET TEMPERATURE (F) ................. 124.91
- (MAXIMUM PERMITTED OIL TEMPERATURE)
- HEAT EXCHANGER OUTLET TEMPERATURE (F) ................. 95.00
- TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) ........ 0.442E 06

#### LOOP TEMPERATURE PROFILE 11-POINTS

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SYSTEM LOOP NUMBER 4

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#### LOOP HYDRAULIC INFORMATION
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ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 4 (INCLUDING LOOP END POINT PRESSURES).

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LOOP PRESSURE PROFILE 15-POINTS

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--LOOP THERMAL INFORMATION--

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LOOP TEMPERATURE PROFILE 11-POINTS
TABLE 3.5 (CONT'D.)

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SYSTEM LOOP NUMBER 5

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<td>PUMP OUTLET PRESSURE (PSI)</td>
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ABSOLUTE Pressures at elevation profile points located within loop number 5 (including loop end point pressures).

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LOOP PRESSURE PROFILE 15-POINTS

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|                         | 325.12             |
|                         | 319.84             |
|                         | 314.56             |
|                         | 309.28             |
|                         | 304.01             |
TABLE 3.5 (CONT'D.)

| 3035.71 | 220.42 | 298.73 |
| 3642.86 | 223.85 | 293.45 |
| 4250.00 | 227.27 | 288.17 |
| 4857.14 | 230.59 | 282.90 |
| 5464.28 | 234.12 | 277.62 |
| 6071.42 | 237.34 | 272.14 |
| 6678.56 | 239.04 | 265.13 |
| 7285.70 | 240.75 | 258.13 |
| 7892.84 | 242.46 | 251.13 |
| 8499.98 | 244.17 | 244.12 |

--LOOP THERMAL INFORMATION--

- Heat Exchanger Inlet Temperature (F): 124.91 (Maximum permitted oil temperature)
- Heat Exchanger Outlet Temperature (F): 95.00
- Total Heat Exchanger Cooling Capacity (Watts): 0.442E+06

LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
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<tbody>
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SYSTEM LOOP NUMBER 6

***

--LOOP HYDRAULIC INFORMATION--

- Loop Axial Length (FT): 8500.00
- Loop Flow Rate (gal/min): 266.41
- Cable Line Dynamic Pressure Loss/FT (psi/ft): 0.564E-02
- Cable Line Dynamic Pressure Loss (psi): 47.92
- Return Line Dynamic Pressure Loss/FT (psi/ft): 0.869E-02
- Return Line Dynamic Pressure Loss (psi): 73.89
- Pump Inlet Pressure (psi): 147.77
- Pump Outlet Pressure (psi): 289.58
- Loop Pumping Power (Watts): 16396.34

Absolute Pressures at Elevation Profile Points located within Loop Number 6 (including Loop End Point Pressures).
### Table 3.5 (Cont'd.)

<table>
<thead>
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<th>AXIAL DISTANCE (FT)</th>
<th>CABLE LINE (PSI)</th>
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### Loop Pressure Profile 15-Points

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<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
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<td>7892.84</td>
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<tr>
<td>3499.98</td>
<td>167.96</td>
<td>289.58</td>
</tr>
</tbody>
</table>

---Loop Thermal Information---

- Heat Exchanger Inlet Temperature (F) ......................... 124.91
- (Maximum Permitted Oil Temperature)
- Heat Exchanger Outlet Temperature (F) ......................... 95.00
- Total Heat Exchanger Cooling Capacity (Watts) ........... 0.442E 06

### Loop Temperature Profile 11-Points

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE CABLE LINE (FT)</th>
<th>RETURN LINE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>95.00</td>
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<tr>
<td>850.00</td>
<td>122.48</td>
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<td>8500.00</td>
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4. DESIGN-OPTION 2

Computer program Design-Option 2 (D.O.2) is a forced-cooled underground transmission system design optimization procedure. The optimization criterion upon which the analysis is based is discussed in Section 4.1. A detailed explanation of the entire computer analysis is presented in Section 4.2 and the computer documentation (user instructions) for D.O.2 is provided in Section 4.3.

4.1 The Optimization Criterion Used by Design-Option 2

The optimization criterion used by Design-Option 2 states that a forced-cooled underground transmission system of specified cable ampacity (and of specified total length) is to be designed utilizing a minimum number of coolant loops (all independent and dependent variables and design constraints for D.O.2 are discussed in Section 4.2). Each coolant loop is designed for a maximum permitted length; a cable line length is selected such that, when the loop energy balance (Section 5.1 of Design Manual I) and the cable heat transfer correlation (Section 5.2 of Design Manual I) are simultaneously satisfied, the resulting loop oil flow rate maximizes the loop dynamic pressure drop. Since the pressure drop cannot be increased, neither can the loop length be increased.

This design approach is based upon recognition of the absolute pressure constraints which exist for the forced-cooled pipe-type cable system. These constraints are as follows:

1) The maximum permitted return pipe (discharge pipe) pressure, $P_{\text{MAXRL}}$ (specified by user),
2) the maximum permitted cable pipe pressure, $P_{\text{MAXCL}}$ (specified by user),

3) the minimum permitted cable line pressure, $P_{\text{MIN}}$, which typically corresponds to the pressure at which the circulating oil loses its insulation characteristics (specified by user), and

4) the minimum permitted pump inlet pressure which corresponds to the pump cavitation pressure (15 psia). (Since the cable line minimum pressure is approximately an order of magnitude larger than this value, and since the heat exchanger pressure drop is at most 40-50 psi, this constraint is ignored.)

Each coolant loop is designed so that the loop oil flow rate produces a pressure profile which varies in value from the maximum permitted pump outlet pressure, $P_{\text{HIGH}}$ (see point number 3 in Figure 4.1) to the minimum permitted cable line pressure, $P_{\text{LOW}}$ (see point number 1 in Figure 4.1). Determination of the values of $P_{\text{HIGH}}$ and $P_{\text{LOW}}$, which do not necessarily correspond to the respective values of $P_{\text{MAXRL}}$ and $P_{\text{MIN}}$, is important to the ultimate results of the optimization technique.

The values of $P_{\text{HIGH}}$ and $P_{\text{LOW}}$ will be equal to the respective values of $P_{\text{MAXRL}}$ and $P_{\text{MIN}}$ if the entire forced-cooled system is constructed on level terrain. (If the value of $P_{\text{RHCL}}$ - point number 4 in Figure 4.1 - exceeds the value of $P_{\text{MAXCL}}$ for this loop hydraulic operation, then $P_{\text{RHCL}}$ is set equal to $P_{\text{MAXCL}}$ and the value of $P_{\text{HIGH}}$ assumes some pressure below the value of $P_{\text{MAXRL}}$.) In such a case, it is assured that all internal loop
Figure 4.1 A Schematic Drawing of a Single Coolant Loop.
pressures will always be within these pressure constraints and all optimized loop lengths will be of equal size. However, it is more typical that hills and valleys will also make-up the terrain profile and, consequently, the existence of elevation differences in the forced-cooled system will produce hydrostatic head variations. Under these circumstances, even though the loop end point pressures are still equal to the pressure constraints, it may be possible for the internal loop pressures (in one or more loops) to fall outside of the pressure constraints due to the hydrostatic head increase or decrease. Thus, alternative values of $P_{HIGH}$ and $P_{LOW}$ must be determined which will always maintain all system pressures within design pressure constraints. The manner of selecting the value of $P_{LOW}$ is examined first in Section 4.1.1 and that of $P_{HIGH}$ in Section 4.1.2.

4.1.1 Selection of the Coolant Loop Minimum Cable Line Pressure

Figure 4.2 depicts a conventional four loop forced-cooled system design as recommended by Koci [4] (the profile of the terrain over which the system is constructed is also shown). This system utilizes a head tank at both ends of the cable line (two-end head tank arrangement); the system is designed utilizing one head tank as a single pressure control while the other provides redundancy. The design pressure of the operational head tank is selected so that all cable line static pressures are maintained at or above the value of $P_{MIN}$. The pressure at the other end of the cable line (point 4-1 in Figure 4.2) is allowed to freely vary according to the conditions existing in the system. Typically, if the operational head-tank malfunctions, the redundant head
Figure 4.2 Typical Four Loop Forced-Cooled System and Corresponding Elevation Profile.
tank will assume that pressure which existed at point 4-1 during normal operating conditions.

In order to determine the most conservative, and therefore the safest, value of PLOW, the forced-cooled system must be examined during both normal and off-design operating conditions. Appendix B (Section B.1) does just this and shows that, in general, the value of PLOW should correspond to the system static pressure which exists (at the particular system point under study) when the system is inoperative. In order to prove this criterion the loop-loop hydraulic interaction is examined during the worst off-design operating conditions. Assume that the pumps in loops #3 and #4 (of the system shown in Figure 4.2) fail simultaneously. Under such circumstances the static pressures existing in each cable line segment of these loops are determined by the pressure which exists at point 2-1 in loop #2. This pressure value is PLOW in loop #2 and, besides maintaining acceptable operating pressures in loops #1 and #2 above the constraint value, it must maintain the static pressures in loops #3 and #4 at or above the value of PMIN. Based on the terrain profile, since all parts of loops #3 and #4 are below point 2-1, the value of PLOW can be set equal to the value of PMIN (operating conditions in loops #1 and #2 are ignored - see Appendix B).

However, it is also recognized that head tank #2 may be in operation (due to a malfunction of head tank #1). If this is the case and, for example loops #1 and #2 lost oil circulation (due to simultaneous pump failure), the pressure at point 3-1 (same as point 2-1) determines the absolute pressures in these loops. Since this pressure corresponds to
PLOW in loop #3, its value must correspond to that pressure which maintains the static pressures in loops #1 and #2 at or above PMIN. Based on the terrain profile shown, since all parts of loops #1 and #2 are above point 3-1, and since point 3-1 is on the same elevation as head tank #1, the value of PLOW must be set equal to the design pressure value of head tank #1 (which is higher in value than PMIN). This pressure value also corresponds to the static pressure which exists at point 3-1 when the entire system is inoperative (and the head tank pressure is adjusted so that the highest elevation point in the system has a pressure just above PMIN.) For this case, if PLOW is chosen any lower than its static value and if the adjoining loops are inoperative, the pressures in the inoperative loops will be lower than the full static situation and a pressure value below that of PMIN will occur at the highest elevation.

Thus since the latter case results in a more conservative value of PLOW, the value of PLOW is set equal to the static pressure at point 3-1. (As is shown, the selected value of PLOW depends upon the entire system elevation profile and is, therefore, considered a system characteristic rather than a loop characteristic - even though a different value must be selected for each loop.) In the case of the two-end head tank arrangement, it is always more conservative to utilize the system static pressure (which exists at the point under study) for the value of PLOW. If this value is used, coolant loop pressures are always assured of being maintained above PMIN during normal and abnormal coolant loop operation (see Appendix B - Section B.1). The computer program takes this
design approach for selection of the value of PLOW. (It must also be pointed out that, even if both head tanks are placed at one end of the system, the conservative value of PLOW corresponds to the system static pressure, where PMIN is reached at the highest system elevation.)

4.1.2 Selection of the Pump Outlet Pressure

The manner of selection of the pump outlet pressure depends upon whether the coolant loop is an even-numbered or odd-numbered loop as counted from the end of the system containing the operational head tank. Part A, below, discusses the odd-numbered loop and part B discusses the even numbered coolant loop.

A. Odd-Numbered Coolant Loop

In the case of an odd-numbered coolant loop, the pressure at point 1 in Figure 4.1 is defined as the loop reference pressure and is fixed in value (operational head tank is to the left). All other loop pressures are calculated based on the value of the reference pressure (PLOW). The computer program initially finds the coolant loop length (and corresponding oil flow rate) which establishes the value of the pump outlet pressure, PHIGH, equal to the value of PMAXRL, however, if under these operating conditions, the value of the pressure at the cable line inlet point, PCL (point 4 in Figure 4.1), exceeds a certain calculated pressure value, PRHCL, then the program readjusts the loop length so as to set the pressure at point 4 equal to the value of PRHCL. (The value of PHIGH thus assumes some value less than PMAXRL.) The value of PRHCL is selected so that under all normal and abnormal operating
conditions, all cable line pressures remain below PMAXCL. The manner in which PRHCL is chosen is discussed in Part A.1 below, in conjunction with Appendix B, Section B.2. The return line pressure profile is ignored in this analysis.

After the preceding analysis takes place, the computer program examines the return line pressure profile. Even though the return line end-of-loop pressures must be within constraint values, it is possible that internal pressures within the return line exceed PMAXRL due to a hydrostatic pressure change in the loop. If this is the case, the value of PHIGH is being maintained at too high a level and therefore the program readjusts (shortens) the loop length so as to eliminate any over-pressures in the return line. Thus, the value of PHIGH is again set at a new value and the pressure value of PCL will assume a value less than the selected value of PRHCL. This entire procedure is discussed in Appendix B, Section B.3.

Finally, the computer program checks to see if the maximum permitted pump pressure head has been exceeded. If not, the loop length and all pressure values remain the same. If the maximum pump head is exceeded, the computer program again shortens the loop length and the values of PHIGH and PCL decrease in value.

A.1 Selection of the Value of PRHCL

The value of PRHCL is selected so that during normal as well as off-design operating conditions all cable line pressures remain below PMAXCL. Appendix B (Section B.2) analyzes coolant loop operation and shows that only static conditions need be considered when calculating PRHCL.
Also, the following example problem shows that the entire system pressure profile must be examined when choosing PRHCL.

In order to determine a safe value of PRHCL, the loop-loop hydraulic interaction is examined during the worst off-design operating conditions. As an example of such conditions, assume that the pumps in loops #2 and #3 and #4 of the system shown in Figure 4.3 fail simultaneously. Under such circumstances the static pressures existing in each cable line segment of these loops are determined by the pressure which exists at point 1-4 in loop #1. Since this pressure value corresponds to PRHCL in loop #1, its value must correspond to that pressure value which maintains the static pressures at or below the value of PMAXCL. Based on the terrain profile shown, since all parts of loops #2, #3, and #4 are above point 1-4, the value of PRHCL can be set equal to the value of PMAXCL.

However, it is also recognized that head tank #2 may be in operation (due to a malfunction of head tank #1). If this is the case and, for example, loop #1 lost oil circulation, the pressure at point 2-4 (same as point 1-4) determines the absolute pressures in loop #1. Since this pressure corresponds to PRHCL in loop #2, its value must correspond to that pressure which maintains the static pressures at or below PMAXCL. Based on the terrain profile shown, since all points in loop #1 are below point 2-4, the value of PRHCL must be set at a value lower than PMAXCL (PRHCL is equal, in this case, to the value of PMAXCL minus the pressure differential in loop #1 due to the difference in the height of its end points).
Figure 4.3 Typical Four Loop Forced-Cooled System and Corresponding Elevation Profile.
Thus, since the latter case results in a more conservative value of PRHCL, PRHCL assumes this value. Based on this example and Section B.2 of Appendix B, it is always more conservative to use a value of PRHCL which maintains all cable line static pressures (in all loops) at or below the value of PMAXCL. (Since the selected value of PRHCL at a particular point depends upon the entire system elevation profile, it is considered a system characteristic value rather than a loop characteristic value.) The computer program takes this design approach.

B. Even-Numbered Coolant Loop

In the case of an even-numbered coolant loop, the pressure at point 4 in Figure 4.4 is defined as the loop reference pressure and is fixed in value - it must correspond to the pressure value at point 4 in the previous odd-numbered loop (operational head tank is to the left). All other loop pressures are calculated based on the value of the reference pressure, PCL (see part A). The computer program initially finds that loop length which utilizes an oil flow rate that results in establishing the value of the pump outlet pressure, PHIGH, equal to the value of PMAXRL. However, if under these operating conditions, the value of the pressure at the cable line outlet point (point 1 in Figure 4.4) is beneath the value of PLOW (see Section 4.1.1 for the calculation of PLOW), then the program readjusts the loop length so as to set the pressure at point 1 equal to the value of PLOW. (The value of PHIGH thus assumes some value less than PMAXRL.) Thus all cable line absolute pressures are assured of remaining within design constraints for both normal and off-design operating conditions.
Figure 4.4 Even-Numbered Coolant Loop
After the preceding analysis takes place, the computer program examines the return line pressure profile. Even though the return line end-of-loop pressures must be within constraint values, it is possible that internal pressures within the return line exceed $P_{\text{MAXRL}}$ due to a hydrostatic pressure change in the loop. If this is the case, the value of $PHIGH$ is being maintained at too high a level and therefore the program readjusts (shortens) the loop length so as to eliminate any over-pressures in the return line. Thus the value of $PHIGH$ is set at a new value and the pressure value at point 1 will assume a value above the selected value of $P_{\text{LOW}}$. This entire procedure is discussed in Appendix B, Section B.4.

Finally, the computer program checks to see if the maximum permitted pump pressure head has been exceeded. If not, the loop length and all pressure values remain the same. If the maximum pump head is exceeded, the computer program again shortens the loop length and the value of $PHIGH$ decreases and the pressure at point 1 increases.

4.2 Analysis Procedure of Design-Option 2

The Design-Option 2 optimization procedure provides a thermal and hydraulic analysis for each coolant loop of a forced-cooled pipe-type cable system, taking into account the hydraulic interaction between coolant loops. Using the specified General Program input data (Section 2.2.1), the D.O.2 analysis computes, for a given cable ampacity (peak and average values), heat exchanger outlet temperature (same for all loops) and total system axial length, the optimum number (minimum number) of system coolant loops required (see Section 4.1), length of each coolant loop...
(maximum loop length), oil flow rate, heat exchanger inlet temperature, the axial temperature distribution of the oil in the pipes, the loop dynamic pressure loss and the absolute loop pressure profile (with loop-loop interaction being accounted for).

The independent and dependent variables and design constraints associated with D.O.2 are presented in Table 4.1 and a simplified flow chart describing the analysis procedure is shown in Figure 4.5. The analysis begins with the input of the General Program variables (and constraints) and the D.O.2 input variables. Loop number 1 (the loop adjacent to the operational head-tank) of the forced-cooled system is analyzed first and the other system loops are analyzed sequentially.

An iterative analysis is necessary since that loop length must be found which simultaneously satisfies the cable heat transfer correlation and the loop energy balance to produce a flow rate which maximizes the loop pressure loss and consequently, the loop axial length. The analysis initializes the value of the loop length, L, after which a thermal and hydraulic analysis identical to that utilized in Design-Option 1 is used to determine the cable line maximum temperature, the oil flow rate, and the dynamic pressure loss (see Chapter 3, Section 3.1).

The computer program then checks to see if the loop pressure drop is maximized (see discussion in Section 4.1). If not, the coolant loop length is changed accordingly, and the analysis is repeated until the loop pressure drop and, therefore, loop length are maximized. Once the loop analysis is complete, the next loop design is initialized utilizing
### TABLE 4.1

DESIGN-OPTION 2 INDEPENDENT AND DEPENDENT VARIABLES AND DESIGN CONSTRAINTS

<table>
<thead>
<tr>
<th>PRIMARY INDEPENDENT VARIABLES*</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
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<tr>
<td>- system peak cable ampacity rating</td>
<td>- optimum number of coolant loops</td>
</tr>
<tr>
<td>- system daily average cable ampacity</td>
<td>(minimum number of loops of</td>
</tr>
<tr>
<td>- heat exchanger outlet temperature</td>
<td>maximum possible loop length)</td>
</tr>
<tr>
<td>(same for all loops)</td>
<td>- length of each coolant loop</td>
</tr>
<tr>
<td>- total system axial length</td>
<td>- oil flow rate per loop</td>
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<td>- heat exchanger inlet temperature</td>
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<tr>
<td></td>
<td>per loop</td>
</tr>
<tr>
<td></td>
<td>- loop dynamic pressure loss</td>
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<tr>
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<td>- loop cooling power</td>
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<td>- loop pumping power</td>
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<th>PRIMARY DESIGN CONSTRAINTS**</th>
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<td>- maximum permissible cable temperature</td>
</tr>
<tr>
<td>- maximum permissible cable line pressure</td>
</tr>
<tr>
<td>- maximum permissible return line pressure</td>
</tr>
<tr>
<td>- minimum permissible oil pressure</td>
</tr>
<tr>
<td>- maximum allowable pump head</td>
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<tr>
<td>- maximum allowable pothead pressure</td>
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* Design-Option 2 input data

** Specified as part of General Program input data (see Table 2.2)
INITIALIZE VALUE OF CABLE LINE OUTLET OIL TEMPERATURE, THOT
CALCULATE THE AVERAGE LOOP OIL TEMPERATURE AND CORRESPONDING AVERAGE OIL PROPERTIES (SUBROUTINE PTYINT)
CALCULATE LOOP OIL FLOW RATE, Q, USING THE LOOP ENERGY BALANCE (SUBROUTINE ENBAL2)
CALCULATE OIL PROPERTIES AT CABLE LINE OUTLET POINT
CALCULATE THE MAXIMUM PERMITTED OIL TEMPERATURE, TOILMX, BY CALCULATING THE CABLE CONDUCTOR-TO-OIL TEMPERATURE DROP (SUBROUTINE HEATTR)

\[ L_n = L_{n-1} + \Delta L \]

IS THOT = TOILMX?

\[ \text{NO} \quad \text{THOT} = \text{TOILMX} \quad \text{YES} \]

CALCULATE LOOP PRESSURE FLOW LOSSES AND LOOP PRESSURE PROFILE (SUBROUTINE PRDROP)

\[ \sum L_n \geq L_{\text{TOTAL}} \]

\[ \text{NO} \quad \text{YES} \]

Figure 4.5: Design-Option 2-Flow Chart
Figure 4.5 Continuation of Design-Option 2 Flow Chart.
the length of the previous loop. This part of the system design optimization is complete when the accumulated sum of the loop lengths equals or exceeds the specified total system length.

In the next part of the analysis the computer program checks the final number of optimum-length loops. If an even number of loops results and the accumulated length of the optimum system is equal to the specified system length, then the system analysis is complete for the optimum design. However, should an even number of loops result with their accumulated length extending beyond the specified system length, the computer program shortens the final loop length so as to meet the total system length requirement. The program then checks if the final loop length is greater in size than the minimum permissible loop length, LLTHMN, as specified by the user. If so, a thermal and hydraulic analysis is performed on this final loop and the system analysis ends. If not, the program keeps the same number of coolant loops, but makes all coolant loops of equal length. The design analysis procedure of Design-Option 1 is then used to perform the thermal and hydraulic analysis on all system loops.

If an odd number of loops results, the computer program always adds an additional loop to the system and makes all coolant loops of equal length. The analysis procedure of Design-Option 1 is then used to perform the thermal and hydraulic analysis on all system loops. The General Program output is used to output the results.
4.3 Design-Option 2 - Computer Documentation

4.3.1 Input Variables for Design-Option 2

The input variables used in Design-Option 2 are listed in Table 4.2 along with a brief description of each variable.

The comments which refer to IFC and IFCAVG and FLT in Section 3.2.1 also apply here.

Only one heat exchanger outlet temperature (cold temperature) is specified in Design-Option 2. All coolant loops utilize this temperature. The comments which refer to the cold temperature in Section 3.2.1 also apply here.

4.3.2 Output for Design Option 2

After the General Program input data is printed out, the input data associated with Design-Option 2 is printed out under the title DESIGN-OPTION 2 - PRINTOUT OF INPUT DATA.

The results of the computer analysis are printed out under the title DESIGN-OPTION 2----RESULTS. Design-Option 2 utilizes the input information in order to calculate the number of required coolant loops, the length of each coolant loop, maximum permitted oil temperature per loop, and the loop flow rates. All design information is printed out in the General Program output format as described in Table 2. All of the output is self-explanatory.

4.3.3 Error Messages for Design-Option 2

Design-Option 2 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are
TABLE 4.2

INPUT VARIABLES FOR DESIGN-OPTION 2

<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>DESCRIPTION and DIMENSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>2 - variable which &quot;informs&quot; the computer program that Design-Option 2 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem</td>
</tr>
<tr>
<td></td>
<td>1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted (dimensionless)</td>
</tr>
<tr>
<td>IFC</td>
<td>Forced-cooled system ampacity rating (the peak ampacity to which the system is subjected) (AMPS)</td>
</tr>
<tr>
<td>IFCAVG</td>
<td>the average cable ampacity which is used to calculate pipe-to-soil heat transfer (AMPS)</td>
</tr>
<tr>
<td>FLT</td>
<td>the total forced-cooled system axial length (ft)</td>
</tr>
<tr>
<td>TOILMN</td>
<td>the specified heat exchanger outlet temperature for all coolant loops (°F)</td>
</tr>
<tr>
<td>LLTHMN</td>
<td>the minimum axial length of a coolant loop (ft)</td>
</tr>
</tbody>
</table>
exceeded. These computer program error messages which apply to
Design-Option 2 are listed below. Any additional information which
is pertinent to the application of a given error to the design-option
is provided.

a) Errors 1-4
b) Errors 6-10
c) Error 15

This error should typically be ignored for Design-Option 2
since the computer program will right itself. If the error occurs a
number of times in succession, the specified value of the cold temperature
(TOILMN) should be examined.

d) Error 16

4.3.4 Data Card Assembly for Design-Option 2

Instructions for assembling data cards for Design-Option 2
are listed in Table 4.3 below.

<table>
<thead>
<tr>
<th>CARD(s)</th>
<th>COLUMN(s)</th>
<th>VARIABLE</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>NUPROB</td>
<td>I10</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>IFC</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>IFCAVG</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>FLT</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>TOILMN</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>LLTHMN</td>
<td>F10.3</td>
</tr>
</tbody>
</table>
4.3.5 Design-Option 2 - Example Problem

This section illustrates the solution of a particular forced-cooled system design problem utilizing computer Design-Option 2. Design-Option 2 is to be used to determine the minimum number of flow loops which can be utilized for the conversion of the self-cooled cable system described in the Design-Option 1 example problem.

The peak cable ampacity (IFC) of the system is to be 1400 amps with an average ampacity (IFCAVG) of 1250 amps. The cold temperature of the loops is to be 95°F. These same values are also used in the example problem of Design-Option 1.

The complete set of Option 2 input data for the example problem is listed in Table 4.4 below. The General Program input data remains unchanged (see Section 2.2.6). The card numbering sequence continues from the General input data.

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMNS</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>1400.0</td>
</tr>
<tr>
<td>20</td>
<td>10-20</td>
<td>1250.0</td>
</tr>
<tr>
<td>20</td>
<td>20-30</td>
<td>51,000.0</td>
</tr>
<tr>
<td>20</td>
<td>30-40</td>
<td>95.0</td>
</tr>
<tr>
<td>20</td>
<td>40-50</td>
<td>5000.0</td>
</tr>
</tbody>
</table>

The computer program output is listed in Table 4.5 (compare with the output of the Design-Option 1 example problem).
### TABLE 4.5

**COMPUTER PROBLEM NUMBER 1**

**DESIGN-OPTION 2**

--PRINTOUT OF INPUT DATA--

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FORCED-COOLED SYSTEM AMPACITY RATING (AMPS)</td>
<td>1400.00</td>
</tr>
<tr>
<td>AVERAGE CABLE AMPACITY (AMPS)</td>
<td>1250.00</td>
</tr>
<tr>
<td>TOTAL SYSTEM AXIAL LENGTH (FT)</td>
<td>51000.00</td>
</tr>
<tr>
<td>HEAT EXCHANGER OUTLET TEMPERATURE (ALL LOOPS) (F)</td>
<td>95.00</td>
</tr>
<tr>
<td>MINIMUM AXIAL LOOP LENGTH (FT)</td>
<td>5000.00</td>
</tr>
</tbody>
</table>

**DESIGN-OPTION 2---RESULTS**

**SYSTEM LOOP NUMBER 1**

---LOOP HYDRAULIC INFORMATION---

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOOP AXIAL LENGTH (FT)</td>
<td>13375.00</td>
</tr>
<tr>
<td>LOOP FLOW RATE (GAL/MIN)</td>
<td>418.75</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.130E-01</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>173.22</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.192E-01</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>256.60</td>
</tr>
<tr>
<td>PUMP INLET PRESSURE (PSI)</td>
<td>147.77</td>
</tr>
<tr>
<td>LOOP PUMPING POWER (WATTS)</td>
<td>597.59</td>
</tr>
<tr>
<td>SYSTEM HEAD TANK PRESSURE (PSI)</td>
<td>81749.19</td>
</tr>
</tbody>
</table>

ABSOLUTE Pressures at Elevation Profile Points located within Loop Number 1 (Including Loop End Point Pressures).

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CABLE LINE (PSI)</td>
</tr>
<tr>
<td>0.00</td>
<td>167.77</td>
</tr>
<tr>
<td>5000.00</td>
<td>232.53</td>
</tr>
<tr>
<td>10000.00</td>
<td>279.52</td>
</tr>
<tr>
<td>13375.00</td>
<td>323.22</td>
</tr>
</tbody>
</table>

LOOP PRESSURE PROFILE 15-POINTS
TABLE 4.5 (CONT'D.)

<table>
<thead>
<tr>
<th>(FT)</th>
<th>(PSI)</th>
<th>(PSI)</th>
<th>355.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>167.77</td>
<td>597.59</td>
<td></td>
</tr>
<tr>
<td>955.36</td>
<td>180.14</td>
<td>579.26</td>
<td></td>
</tr>
<tr>
<td>1910.71</td>
<td>192.52</td>
<td>560.93</td>
<td></td>
</tr>
<tr>
<td>2866.07</td>
<td>204.89</td>
<td>542.61</td>
<td></td>
</tr>
<tr>
<td>3821.43</td>
<td>217.26</td>
<td>524.28</td>
<td></td>
</tr>
<tr>
<td>4776.78</td>
<td>229.64</td>
<td>505.95</td>
<td></td>
</tr>
<tr>
<td>5732.14</td>
<td>239.42</td>
<td>485.02</td>
<td></td>
</tr>
<tr>
<td>6687.49</td>
<td>248.42</td>
<td>463.29</td>
<td></td>
</tr>
<tr>
<td>7642.85</td>
<td>257.42</td>
<td>441.57</td>
<td></td>
</tr>
<tr>
<td>8598.20</td>
<td>266.42</td>
<td>419.85</td>
<td></td>
</tr>
<tr>
<td>9553.56</td>
<td>275.42</td>
<td>398.12</td>
<td></td>
</tr>
<tr>
<td>10508.91</td>
<td>286.21</td>
<td>378.21</td>
<td></td>
</tr>
<tr>
<td>11464.27</td>
<td>298.59</td>
<td>359.88</td>
<td></td>
</tr>
<tr>
<td>12419.63</td>
<td>310.96</td>
<td>341.55</td>
<td></td>
</tr>
<tr>
<td>13374.98</td>
<td>323.33</td>
<td>323.22</td>
<td></td>
</tr>
</tbody>
</table>

--LOOP THERMAL INFORMATION--

SYSTEM FORCED-COOLED PEAK AMPACITY RATING (AMPS) .... 1400.000
AVERAGE FORCED-COOLED AMPACITY (AMPS) ................. 1250.000
TOTAL SYSTEM ENERGY LOSS (WATTS/FT) .................. 58.07

HEAT EXCHANGER INLET TEMPERATURE (F) ................. 124.91
(MAXIMUM PERMITTED OIL TEMPERATURE)
HEAT EXCHANGER OUTLET TEMPERATURE (F) ................. 95.00
TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) ...... 0.695E 06

LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>CABLE LINE TEMPERATURE (F)</th>
<th>RETURN LINE TEMPERATURE (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>95.00</td>
</tr>
<tr>
<td>1337.50</td>
<td>122.48</td>
<td>95.41</td>
</tr>
<tr>
<td>2675.00</td>
<td>119.98</td>
<td>95.81</td>
</tr>
<tr>
<td>4012.50</td>
<td>117.41</td>
<td>96.17</td>
</tr>
<tr>
<td>5350.00</td>
<td>114.76</td>
<td>96.47</td>
</tr>
<tr>
<td>6687.50</td>
<td>112.04</td>
<td>96.73</td>
</tr>
<tr>
<td>8025.00</td>
<td>109.24</td>
<td>96.93</td>
</tr>
<tr>
<td>9362.50</td>
<td>106.36</td>
<td>97.08</td>
</tr>
<tr>
<td>10700.00</td>
<td>103.40</td>
<td>97.18</td>
</tr>
<tr>
<td>12037.50</td>
<td>100.36</td>
<td>97.24</td>
</tr>
<tr>
<td>13375.00</td>
<td>97.24</td>
<td>97.24</td>
</tr>
</tbody>
</table>

***

SYSTEM LOOP NUMBER 2
***

--LOOP HYDRAULIC INFORMATION--

LOOP AXIAL LENGTH (FT) .................................... 13375.00
LOOP FLOW RATE (GAL/MIN) ................................ 418.75
### TABLE 4.5 (CONT'D.)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.130E-01</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>173.22</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.192E-01</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>256.60</td>
</tr>
<tr>
<td>PUMP INLET PRESSURE (PSI)</td>
<td>183.32</td>
</tr>
<tr>
<td>PUMP OUTLET PRESSURE (PSI)</td>
<td>633.14</td>
</tr>
<tr>
<td>LOOP PUMPING POWER (WATTS)</td>
<td>81749.19</td>
</tr>
</tbody>
</table>

**ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 2 (INCLUDING LOOP END POINT PRESSURES).**

<table>
<thead>
<tr>
<th>System</th>
<th>Absolute Pressure</th>
<th>Cable Line</th>
<th>Return Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Distance (FT)</td>
<td>(PSI)</td>
<td>(PSI)</td>
<td>(PSI)</td>
</tr>
<tr>
<td>13375.00</td>
<td>323.22</td>
<td>323.22</td>
<td></td>
</tr>
<tr>
<td>20000.00</td>
<td>237.43</td>
<td>450.33</td>
<td></td>
</tr>
<tr>
<td>25000.00</td>
<td>225.96</td>
<td>599.54</td>
<td></td>
</tr>
<tr>
<td>26750.00</td>
<td>203.32</td>
<td>633.14</td>
<td></td>
</tr>
</tbody>
</table>

**LOOP PRESSURE PROFILE 15-POINTS**

<table>
<thead>
<tr>
<th>Loop</th>
<th>Absolute Pressure</th>
<th>Cable Line</th>
<th>Return Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Distance (FT)</td>
<td>(PSI)</td>
<td>(PSI)</td>
<td>(PSI)</td>
</tr>
<tr>
<td>0.00</td>
<td>323.22</td>
<td>323.22</td>
<td></td>
</tr>
<tr>
<td>955.36</td>
<td>310.85</td>
<td>341.55</td>
<td></td>
</tr>
<tr>
<td>1910.71</td>
<td>298.47</td>
<td>359.88</td>
<td></td>
</tr>
<tr>
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<td>286.10</td>
<td>378.21</td>
<td></td>
</tr>
<tr>
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<td>273.73</td>
<td>396.53</td>
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</tr>
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<td>248.98</td>
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<td></td>
</tr>
<tr>
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<td>237.27</td>
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</tr>
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<td>480.70</td>
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</tr>
<tr>
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<td>215.35</td>
<td>519.22</td>
<td></td>
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<tr>
<td>9553.56</td>
<td>204.27</td>
<td>558.73</td>
<td></td>
</tr>
<tr>
<td>10508.91</td>
<td>193.27</td>
<td>598.25</td>
<td></td>
</tr>
<tr>
<td>11464.27</td>
<td>182.27</td>
<td>638.76</td>
<td></td>
</tr>
<tr>
<td>12419.63</td>
<td>171.35</td>
<td>679.21</td>
<td></td>
</tr>
<tr>
<td>13374.98</td>
<td>160.97</td>
<td>719.14</td>
<td></td>
</tr>
</tbody>
</table>

--- LOOP THERMAL INFORMATION ---

| HEAT EXCHANGER INLET TEMPERATURE (F) | 124.91 |
| HEAT EXCHANGER OUTLET TEMPERATURE (F) | 95.00 |
| TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) | 0.695E 06 |

**LOOP TEMPERATURE PROFILE 11-POINTS**
<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE CABLE LINE (FT)</th>
<th>TEMPERATURE RETURN LINE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>95.00</td>
</tr>
<tr>
<td>1337.50</td>
<td>122.48</td>
<td>95.41</td>
</tr>
<tr>
<td>2675.00</td>
<td>119.98</td>
<td>95.81</td>
</tr>
<tr>
<td>4012.50</td>
<td>117.41</td>
<td>96.17</td>
</tr>
<tr>
<td>5350.00</td>
<td>114.76</td>
<td>96.47</td>
</tr>
<tr>
<td>6687.50</td>
<td>112.04</td>
<td>96.73</td>
</tr>
<tr>
<td>8025.00</td>
<td>109.24</td>
<td>96.93</td>
</tr>
<tr>
<td>9362.50</td>
<td>106.36</td>
<td>97.08</td>
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<tr>
<td>10700.00</td>
<td>103.40</td>
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<td>97.24</td>
</tr>
<tr>
<td>13375.00</td>
<td>97.24</td>
<td>97.24</td>
</tr>
</tbody>
</table>

*** SYSTEM LOOP NUMBER 3 ***

---LOOP HYDRAULIC INFORMATION---

<table>
<thead>
<tr>
<th>LOOP AXIAL LENGTH (FT)</th>
<th>13390.63</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOOP FLOW RATE (GAL/MIN)</td>
<td>418.75</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.130E-01</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>173.43</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.192E-01</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>256.85</td>
</tr>
<tr>
<td>PUMP INLET PRESSURE (PSI)</td>
<td>183.32</td>
</tr>
<tr>
<td>PUMP OUTLET PRESSURE (PSI)</td>
<td>633.60</td>
</tr>
<tr>
<td>LOOP PUMPING POWER (WATTS)</td>
<td>91833.00</td>
</tr>
</tbody>
</table>

ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 3 (INCLUDING LOOP END POINT PRESSURES).

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26750.00</td>
<td>203.32</td>
<td>633.60</td>
</tr>
<tr>
<td>40000.00</td>
<td>374.90</td>
<td>379.42</td>
</tr>
<tr>
<td>46140.63</td>
<td>376.34</td>
<td>376.34</td>
</tr>
</tbody>
</table>

LOOP PRESSURE PROFILE 15-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>203.32</td>
<td>633.60</td>
</tr>
<tr>
<td>956.47</td>
<td>215.70</td>
<td>615.25</td>
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<td>560.21</td>
</tr>
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</table>
### TABLE 4.5 (CONT'D.)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
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<td>4782.36</td>
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<td>523.52</td>
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<td>290.03</td>
<td>505.17</td>
</tr>
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<td>450.13</td>
</tr>
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<td>351.97</td>
<td>413.44</td>
</tr>
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<td>12434.14</td>
<td>364.36</td>
<td>395.09</td>
</tr>
<tr>
<td>13390.62</td>
<td>376.35</td>
<td>376.34</td>
</tr>
</tbody>
</table>

**--LOOP THERMAL INFORMATION--**

**HEAT EXCHANGER INLET TEMPERATURE (F)....** 124.91 (MAXIMUM PERMITTED OIL TEMPERATURE)

**HEAT EXCHANGER OUTLET TEMPERATURE (F)....** 95.00

**TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS).....** 0.695E 06

### LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>CABLE LINE RETURN LINE TEMP (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
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<tr>
<td>1339.06</td>
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<tr>
<td>2678.13</td>
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<td>13390.63</td>
<td>97.21</td>
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</table>

**SYSTEM LOOP NUMBER 4**

**---LOOP HYDRAULIC INFORMATION---**

| LOOP AXIAL LENGTH (FT) | 10859.38 |
| LOOP FLOW RATE (GAL/MIN) | 340.63 |
| CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.884E-02 |
| CABLE LINE DYNAMIC PRESSURE LOSS (PSI) | 95.96 |
| RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.134E-01 |
| RETURN LINE DYNAMIC PRESSURE LOSS (PSI) | 145.10 |
| PUMP INLET PRESSURE (PSI) | 225.24 |
| PUMP OUTLET PRESSURE (PSI) | 486.30 |
| LOOP PUMPING POWER (WATTS) | 38592.29 |

**ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 4 (INCLUDING LOOP END POINT Pressures).**

**SYSTEM ABSOLUTE PRESSURE**
### TABLE 4.5 (CONT'D.)

<table>
<thead>
<tr>
<th>AXIAL DISTANCE (FT)</th>
<th>CABLE LINE (PSI)</th>
<th>RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40140.63</td>
<td>376.34</td>
<td>376.34</td>
</tr>
<tr>
<td>45000.00</td>
<td>319.57</td>
<td>427.44</td>
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<tr>
<td>51000.00</td>
<td>245.24</td>
<td>486.30</td>
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</tbody>
</table>

### LCOP PRESSURE PROFILE 15-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>CABLE LINE ABSOLUTE PRESSURE (PSI)</th>
<th>RETURN LINE ABSOLUTE PRESSURE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>376.34</td>
<td>376.34</td>
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<tr>
<td>775.67</td>
<td>367.30</td>
<td>384.50</td>
</tr>
<tr>
<td>1551.34</td>
<td>358.25</td>
<td>392.66</td>
</tr>
<tr>
<td>2327.01</td>
<td>349.21</td>
<td>400.82</td>
</tr>
<tr>
<td>3102.68</td>
<td>340.16</td>
<td>408.98</td>
</tr>
<tr>
<td>3878.35</td>
<td>331.12</td>
<td>417.14</td>
</tr>
<tr>
<td>4654.02</td>
<td>322.07</td>
<td>425.30</td>
</tr>
<tr>
<td>5429.68</td>
<td>312.62</td>
<td>433.05</td>
</tr>
<tr>
<td>6205.35</td>
<td>303.03</td>
<td>440.66</td>
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<tr>
<td>6981.02</td>
<td>293.44</td>
<td>448.26</td>
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<tr>
<td>7756.69</td>
<td>283.84</td>
<td>455.87</td>
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<tr>
<td>8532.36</td>
<td>274.25</td>
<td>463.48</td>
</tr>
<tr>
<td>9308.02</td>
<td>264.66</td>
<td>471.09</td>
</tr>
<tr>
<td>10083.69</td>
<td>255.06</td>
<td>478.69</td>
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<tr>
<td>10859.36</td>
<td>245.47</td>
<td>486.30</td>
</tr>
</tbody>
</table>

---LOOP THERMAL INFORMATION---

- **Heat Exchanger Inlet Temperature (F)**: 124.91 (Maximum Permitted Oil Temperature)
- **Heat Exchanger Outlet Temperature (F)**: 95.00
- **Total Heat Exchanger Cooling Capacity (Watts)**: 0.565E+06

### LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>CABLE LINE TEMPERATURE (FT)</th>
<th>RETURN LINE TEMPERATURE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>95.00</td>
</tr>
<tr>
<td>1095.94</td>
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<td>95.47</td>
</tr>
<tr>
<td>2171.88</td>
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<td>95.88</td>
</tr>
<tr>
<td>3257.81</td>
<td>117.42</td>
<td>96.23</td>
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<tr>
<td>4343.75</td>
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<td>112.06</td>
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<tr>
<td>10859.38</td>
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</tbody>
</table>
5. DESIGN-OPTION 3

A detailed explanation of the analysis procedure utilized by Design-Option 3 (D.O.3) is presented in Section 5.1. Computer documentation (user instructions) is provided in Section 5.2.

5.1 Analysis Procedure of Design-Option 3

Design-Option 3 provides a thermal and hydraulic analysis for each coolant loop of a forced-cooled pipe-type cable system, taking into account the hydraulic interaction between coolant loops. Using the specified General Program input data (Section 2.2.1), the D.O.3 thermal analysis computes, for a given cable ampacity (peak and average values), axial loop length, and oil flow rate, the heat exchanger inlet and outlet temperatures and the axial temperature distribution of the oil in the pipes. The D.O.1 hydraulic analysis uses the oil flow rate to calculate the loop dynamic pressure losses and the absolute loop pressure profile (with loop-loop interaction being accounted for).

The independent and dependent variables and design constraints associated with D.O.3 are presented in Table 5.1 and a simplified flow chart describing the forced-cooled system analysis procedure is shown in Figure 5.1. The analysis begins with the input of the General Program variables (and constraints) and the D.O.3 input variables. Loop number 1 (the loop adjacent to the operational head tank) of the forced-cooled underground transmission system is analyzed first (LOOPNO=1) and the other system loops are analyzed sequentially.

Initially, the value of the heat exchanger inlet temperature (cable line outlet temperature), THOT, and the heat exchanger outlet
### TABLE 5.1  
**DESIGN-OPTION 3 - INDEPENDENT AND DEPENDENT VARIABLES AND DESIGN CONSTRAINTS**

<table>
<thead>
<tr>
<th>PRIMARY INDEPENDENT VARIABLES</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>- system peak cable ampacity rating</td>
<td>- heat exchanger inlet temperature per loop</td>
</tr>
<tr>
<td>- system daily average cable ampacity</td>
<td>- heat exchanger outlet temperature per loop</td>
</tr>
<tr>
<td>- number of coolant loops</td>
<td>- loop dynamic pressure loss</td>
</tr>
<tr>
<td>- oil flow rate per loop</td>
<td>- loop cooling power</td>
</tr>
<tr>
<td>- loop length per loop</td>
<td>- loop pumping power</td>
</tr>
</tbody>
</table>

**PRIMARY DESIGN CONSTRAINTS**

- maximum permitted cable temperature  
- minimum permitted oil pressure  
- maximum permitted cable line oil pressure  
- maximum permitted return line oil pressure  
- maximum allowable pump head  
- maximum allowable pothead pressure

*Design-Option 1 input data

**Specified as part of General Program input data (see Table 2.2)*
READ GENERAL PROGRAM INPUT DATA

READ DESIGN-OPTION 3 INPUT DATA

LOOPNO = 0

LOOPNO = LOOPNO + 1

INITIALIZE VALUE OF CABLE LINE OUTLET OIL TEMPERATURE, THOT

CALCULATE OIL PROPERTIES AT CABLE LINE OUTLET POINT

THOT = TOILMX

CALCULATE THE MAXIMUM PERMITTED OIL TEMPERATURE, TOILMX, BY CALCULATING THE CABLE CONDUCTOR-TO-OIL TEMPERATURE DROP (SUBROUTINE HEATTR)

IS THOT - TOILMX?

CALCULATE THE LOOP COLD TEMPERATURE, TCOLD, USING THE LOOP ENERGY BALANCE (SUBROUTINE ENBAL2)

CALCULATE AVERAGE OIL PROPERTIES FOR CABLE AND RETURN LINE, RESPECTIVELY

CALCULATE LOOP PRESSURE FLOW LOSSES AND LOOP PRESSURE PROFILE (SUBROUTINE PHDROP)

NO

IS LOOPNO > NLOOPS?

YES END

NLOOPS - specified number of coolant loops

Figure 5.1: Design-Option 3-Flow Chart
temperature, TCOLD, are unknown. The value of THOT is calculated first. This is accomplished by permitting THOT to attain its maximum permissible value, TOILMX. Since the required oil properties (specific heat and density) are initially unknown, an initial value of THOT is selected and the oil properties are calculated. The specified values of the cable ampacity, oil flow rate, and cable geometry, as well as the calculated values of the oil properties are then utilized by the cable heat transfer correlation (see Section 5.2 - Design Manual I) in order to determine the cable conductor-to-oil temperature drop, THETA. This value is used in conjunction with the value of the maximum permitted cable temperature, TCABMX, in order to determine the value of TOILMX (TOILMX = TCABMX-THETA). If the calculated value of TOILMX differs from the chosen value of THOT, the analysis is repeated by setting the value of THOT equal to the value of TOILMX. The iteration ends when the value of the heat exchanger inlet temperature, THOT, is equal to the value of the maximum permitted oil temperature, TOILMX.

The coolant loop energy balance (see Section 5.1 - Design Manual I) uses the calculated value of THOT, as well as the values of the average daily cable losses (calculated from the average daily ampacity), the loop oil flow rate, and the soil heat transfer characteristics to calculate the value of TCOLD. The entire loop temperature profile is also calculated.

The loop hydraulic analysis follows and consists of using the value of the oil flow rate to calculate the loop dynamic pressure drop (see Section 5.3 - Design Manual Part I). The loop static pressure profile
is then utilized to calculate the loop absolute pressure profile.

This entire analysis is repeated for every loop in the forced-cooled system. The General Program output format is used to printout the analysis results.

5.2 Design-Option 3 - Computer Documentation

5.2.1 Input Variables for Design-Option 3

The input variables used in Design-Option 3 are listed in Table 5.2 along with a brief description of each variable.

The comments which refer to IFC, IFCAVG, and FLT in Section 3.2.1 also apply here.

5.2.2 Output for Design-Option 3

After the General Program input data is printed out, the input data associated with Design-Option 3 is printed out under the title DESIGN-OPTION 2 - PRINTOUT OF INPUT DATA.

The results of the computer analysis are printed out under the title DESIGN-OPTION 3----RESULTS. Option 3 utilizes the input information in order to calculate for each loop the maximum permitted oil temperature and the heat exchanger outlet temperature. All design information is printed out in the General Program Output format as described in Table 2.3. All of the output is self-explanatory.

5.2.3 Array Dimensions

The number of system coolant loops analyzed in Design-Option 3 can never exceed the value of MAXLPS, the array dimension value of all subscripted variables whose subscript value depends on the loop number (i.e. LLTH(1) = loop length of loop number 1). Refer to Section 2.2.3 for details.
### TABLE 5.2
**INPUT VARIABLES FOR DESIGN-OPTION 3**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimension ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>3 - variable which &quot;informs&quot; the computer program that Design-Option 3 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem</td>
</tr>
<tr>
<td></td>
<td>1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted (dimensionless)</td>
</tr>
<tr>
<td>IFC</td>
<td>forced-cooled system ampacity rating (peak ampacity to which the system is subjected) (Amps)</td>
</tr>
<tr>
<td>IFCAVG</td>
<td>the average cable ampacity which is used to calculate pipe-to-soil heat transfer (Amps)</td>
</tr>
<tr>
<td>FLT</td>
<td>the total forced-cooled system axial length (ft)</td>
</tr>
<tr>
<td>NLOOPS</td>
<td>number of system coolant loops (dimensionless)</td>
</tr>
<tr>
<td>LLTH(I)</td>
<td>the axial length of each system coolant loop (ft)</td>
</tr>
<tr>
<td>FLOWRT(I)</td>
<td>the specified oil flow rate for each coolant loop (gal/min)</td>
</tr>
</tbody>
</table>
5.2.4 Error Messages for Design-Option 3

Design-Option 3 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are exceeded. Those computer program error messages which apply to Design-Option 3 are listed below. Any additional information which is pertinent to the application of a given error to the design-option is provided.

a) Errors 1-8
b) Errors 11-14
c) Error 16

5.2.5 Data Card Assembly for Design-Option 3

Instructions for assembling data cards for Design-Option 3 are listed in Table 5.3. While most of this table is self-explanatory, a few additional remarks are offered below.

The card numbering sequence continues directly from the General Program input cards.

It is necessary that the variables using the I-format be right-adjusted in the column field. Also, the asterisk which is printed next to cards 21 and 22 indicates that more than one card may be required to input the variable array (eight variables are used for LLTH(I) and FLRT(I) as an example only).

5.2.6 Design-Option 3 - Example Problem

This section illustrates the solution of a particular forced-cooled system design problem utilizing computer Design-Option 3. Design-Option 3 is to be used to determine the required heat exchanger inlet and
## Table 5.3

### Data Card Assembly for Design-Option 3

<table>
<thead>
<tr>
<th>CARD(s)</th>
<th>COLUMN(s)</th>
<th>VARIABLE**</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
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<td>I10</td>
</tr>
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<td>20</td>
<td>1-10</td>
<td>IFC</td>
<td>F10.3</td>
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<td>10-20</td>
<td>IFCAVG</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>FLT</td>
<td>F10.3</td>
</tr>
<tr>
<td>21</td>
<td>1-10</td>
<td>NLOOPS</td>
<td>I10</td>
</tr>
<tr>
<td>22*</td>
<td>1-10</td>
<td>LLTH(1)</td>
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<td>10-20</td>
<td>LLTH(2)</td>
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<td>20-30</td>
<td>LLTH(3)</td>
<td>-</td>
</tr>
<tr>
<td></td>
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<td>70-80</td>
<td>LLTH(8)</td>
<td>-</td>
</tr>
<tr>
<td>23*</td>
<td>-</td>
<td>FLOWRT(I)</td>
<td>-</td>
</tr>
</tbody>
</table>

* Indicates that more than one data card may be necessary.

** See Table 5.2 for variable dimensions.
### TABLE 5.4

**INPUT DATA USED FOR DESIGN-OPTION 3 EXAMPLE PROBLEM**

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMNS</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>20</td>
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<td>1400.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>1250.0</td>
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<td></td>
<td>20-30</td>
<td>51000.0</td>
</tr>
<tr>
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<td>10</td>
<td>6</td>
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<td></td>
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<td>200.0</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>300.0</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>400.0</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>500.0</td>
</tr>
</tbody>
</table>
outlet temperatures of each loop for a proposed forced-cooled system design conversion of the existing self-cooled cable system discussed in Section 2.2.6. All design information of the General Program Output is also printed.

The complete set of Option 3 input data for the example problem is listed in Table 5.4. The General Program input data remains unchanged (see Section 2.2.6). The card numbering sequence continues from the General Program input cards.

The computer program output is listed in Table 5.5.
**CONTROL PROGRAM NUMBER 1**

---PRINTOUT OF INPUT DATA---

FORCED-COOLED SYSTEM AMPACITY RATING (AMPS) .......... 1400.000
AVERAGE CABLE AMPACITY (AMPS) ........................................ 1250.000
TOTAL SYSTEM AXIAL LENGTH (FT) .................................. 51000.000
NUMBER OF SYSTEM COOLANT LOOPS (DIMENSIONLESS) ....... 6

<table>
<thead>
<tr>
<th>LOOP NUMBER</th>
<th>LOOP LENGTH (FT)</th>
<th>FLOW RATE (GPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8500.00</td>
<td>150.00</td>
</tr>
<tr>
<td>2</td>
<td>8500.00</td>
<td>200.00</td>
</tr>
<tr>
<td>3</td>
<td>8500.00</td>
<td>300.00</td>
</tr>
<tr>
<td>4</td>
<td>8500.00</td>
<td>350.00</td>
</tr>
<tr>
<td>5</td>
<td>8500.00</td>
<td>400.00</td>
</tr>
<tr>
<td>6</td>
<td>8500.00</td>
<td>500.00</td>
</tr>
</tbody>
</table>

**DESIGN-OPTION 3---RESULTS**

---LOOP HYDRAULIC INFORMATION---

<table>
<thead>
<tr>
<th>LOOP AXIAL LENGTH (FT)</th>
<th>LOOP FLOW RATE (GAL/IN)</th>
<th>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</th>
<th>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</th>
<th>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</th>
<th>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</th>
<th>PUMP INLET PRESSURE (PSI)</th>
<th>PUMP OUTLET PRESSURE (PSI)</th>
<th>LOOP PUMPING POWER (WATTS)</th>
<th>SYSTEM HEAD TANK PRESSURE (PSI)</th>
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</thead>
<tbody>
<tr>
<td>8500.00</td>
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<td>0.379E-02</td>
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<td>167.96</td>
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ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 1 (INCLUDING LOOP END POINT PRESSURES).
### Table 5.5 (Cont'd.)

<table>
<thead>
<tr>
<th>AXIAL DISTANCE (FT)</th>
<th>CABLE LINE PRESSURE (PSI)</th>
<th>RETURN LINF PRESSURE (PSI)</th>
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<tbody>
<tr>
<td>0.00</td>
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<tr>
<td>5000.00</td>
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</tr>
<tr>
<td>8500.00</td>
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<td>175.12</td>
</tr>
</tbody>
</table>

### Loop Pressure Profile 15-Points

<table>
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<tr>
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<th>AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINF (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00</td>
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<td></td>
<td>1821.43</td>
<td>172.19</td>
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<td>179.61</td>
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<tr>
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<td>8499.98</td>
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</table>

---Loop Thermal Information---

- System Forced-Cooled Peak Ampacity Rating (AMPS) .... 1400.000
- Average Forced-Cooled Ampacity (AMPS) .................. 1250.000
- Total System Energy Loss (Watts/FT) .................... 58.07

- Heat Exchanger Inlet Temperature (F) .................... 124.91
  (Maximum Permitted Oil Temperature)
- Heat Exchanger Outlet Temperature (F) ................... 64.37
- Total Heat Exchanger Cooling Capacity (Watts) ......... 0.507E 06

### Loop Temperature Profile 11-Points

<table>
<thead>
<tr>
<th>LOOP</th>
<th>AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE CABLE LINE (FT)</th>
<th>TEMPERATURE RETURN LINF (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>124.91</td>
<td>64.37</td>
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<tr>
<td></td>
<td>850.00</td>
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TABLE 5.5 (CONT'D.)

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<td>78.39</td>
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SYSTEM LOOP NUMBER 2

--- LOOP HYDRAULIC INFORMATION ---

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<td>LOOP AXIAL LENGTH (FT)</td>
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<tr>
<td>LOOP FLOW RATE (GAL/MIN)</td>
<td>200.00</td>
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<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.361E-02</td>
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<td>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</td>
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</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.569E-02</td>
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<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>48.33</td>
</tr>
<tr>
<td>PUMP INLET PRESSURE (PSI)</td>
<td>119.14</td>
</tr>
<tr>
<td>PUMP OUTLET PRESSURE (PSI)</td>
<td>218.18</td>
</tr>
<tr>
<td>LOOP PUMPING POWER (WATTS)</td>
<td>8596.54</td>
</tr>
</tbody>
</table>

ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 2 (INCLUDING LOOP END POINTS)

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>175.12</td>
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<tr>
<td>10000.00</td>
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</tr>
<tr>
<td>17000.00</td>
<td>139.14</td>
<td>218.18</td>
</tr>
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</table>

**ERROR**

THE CABLE LINE PRESSURE AT THE OUTLET POINT (= 139.144 ) IS BELOW THE MINIMUM PERMITTED CABLE LINE PRESSURE.

LOOP PRESSURE PROFILE 15-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
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<td>175.12</td>
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<tr>
<td>607.14</td>
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<td>2428.57</td>
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<tr>
<td>3035.71</td>
<td>158.85</td>
<td>187.03</td>
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<tr>
<td>3642.86</td>
<td>156.66</td>
<td>190.48</td>
</tr>
<tr>
<td>4250.00</td>
<td>154.46</td>
<td>193.94</td>
</tr>
<tr>
<td>4857.14</td>
<td>152.27</td>
<td>197.39</td>
</tr>
<tr>
<td>5464.28</td>
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### TABLE 5.5 (CONT'D.)

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<th>Value</th>
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<td>207.75</td>
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<td>7285.70</td>
<td>143.50</td>
<td>211.20</td>
</tr>
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<td>7892.84</td>
<td>141.31</td>
<td>214.65</td>
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<td>8499.98</td>
<td>139.11</td>
<td>218.10</td>
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</tbody>
</table>

--- LOOP THERMAL INFORMATION ---

- HEAT EXCHANGER INLET TEMPERATURE (F)          124.91
- HEAT EXCHANGER OUTLET TEMPERATURE (F)          82.62
- TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS)  0.471E06

**LOOP TEMPERATURE PROFILE 11-POINTS**

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE</th>
<th>TEMP</th>
<th>RETURN LINE</th>
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</thead>
<tbody>
<tr>
<td>0.00</td>
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<tr>
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</tr>
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</tr>
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<td>87.64</td>
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<td>5950.00</td>
<td>101.24</td>
<td>88.12</td>
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</tr>
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<td>88.50</td>
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<td>88.98</td>
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</tbody>
</table>

--- LOOP HYDRAULIC INFORMATION ---

- LOOP AXIAL LENGTH (FT)          8500.00
- LOOP FLOW RATE (CAL/MIN)        300.00
- CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)  0.680E-02
- CABLE LINE DYNAMIC PRESSURE LOSS (PSI)       57.84
- RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)  0.105E-01
- RETURN LINE DYNAMIC PRESSURE LOSS (PSI)       89.02
- PUMP INLET PRESSURE (PSI)            119.14
- PUMP OUTLET PRESSURE (PSI)            286.00
- LOOP PUMPING POWER (WATTS)           21724.74

**ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 3 INCLUDING LOOP END POINT PRESSURES.**

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE</th>
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<tbody>
<tr>
<td></td>
<td>CABLE LINE (PSI)</td>
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<tr>
<td></td>
<td>RETURN LINE (PSI)</td>
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</table>
Table 5.5 (Cont'd.)

<table>
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<tr>
<th>Axial Distance (ft)</th>
<th>Absolute Pressure Cable Line (PSI)</th>
<th>Absolute Pressure Return Line (PSI)</th>
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</thead>
<tbody>
<tr>
<td>0.00</td>
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<td>147.41</td>
<td>273.28</td>
</tr>
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<td>1821.43</td>
<td>151.54</td>
<td>266.93</td>
</tr>
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<td>2428.57</td>
<td>155.67</td>
<td>260.57</td>
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<td>3035.71</td>
<td>160.18</td>
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<td>3642.86</td>
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<td>170.30</td>
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<td>6678.56</td>
<td>188.73</td>
<td>255.23</td>
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<td>7285.70</td>
<td>193.48</td>
<td>255.34</td>
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<td>255.44</td>
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<td>255.51</td>
</tr>
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</table>

**Error**

The cable line pressure at the outlet point (139.144) is below the minimum permitted cable line pressure.

--- Loop Temperature Profile 11-Points ---

<table>
<thead>
<tr>
<th>Axial Distance (ft)</th>
<th>Temperature Cable Line (F)</th>
<th>Temperature Return Line (F)</th>
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</thead>
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<tr>
<td>0.00</td>
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<td>850.00</td>
<td>122.70</td>
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</tr>
<tr>
<td>1700.00</td>
<td>120.44</td>
<td>99.45</td>
</tr>
<tr>
<td>2550.00</td>
<td>118.12</td>
<td>99.68</td>
</tr>
<tr>
<td>3400.00</td>
<td>115.74</td>
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<td>100.01</td>
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### TABLE 5.5 (CONT'D.)

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<th>System Loop Number 4</th>
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<td><strong>AXIAL LENGTH (FT)</strong></td>
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<tr>
<td><strong>FLOW RATE (GAL/MIN)</strong></td>
</tr>
<tr>
<td><strong>CABLE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</strong></td>
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<tr>
<td><strong>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</strong></td>
</tr>
<tr>
<td><strong>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</strong></td>
</tr>
<tr>
<td><strong>PUMP INLET PRESSURE (PSI)</strong></td>
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<tr>
<td><strong>PUMP OUTLET PRESSURE (PSI)</strong></td>
</tr>
<tr>
<td><strong>LOOP PUMPING POWER (WATTS)</strong></td>
</tr>
</tbody>
</table>

---

**LOOP HYDRAULIC INFORMATION**

- **Loop Axial Length (FT):** 8500.00
- **Loop Flow Rate (GAL/MIN):** 350.00
- **Cable Line Dynamic Pressure Loss/FT (PSI/FT):** 0.918E-02
- **Cable Line Dynamic Pressure Loss (PSI):** 78.05
- **Return Line Dynamic Pressure Loss/FT (PSI/FT):** 0.134E-01
- **Return Line Dynamic Pressure Loss (PSI):** 113.99
- **Pump Inlet Pressure (PSI):** 152.22
- **Pump Outlet Pressure (PSI):** 364.26
- **Loop Pumping Power (WATTS):** 32208.84

**Absolute Pressures at Elevation Profile Points Located Within Loop Number 4 (Including Loop End Point Pressures):**

<table>
<thead>
<tr>
<th>System Axial Distance (FT)</th>
<th>Absolute Pressure Cable Line (PSI)</th>
<th>Absolute Pressure Return Line (PSI)</th>
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</thead>
<tbody>
<tr>
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<td>250.33</td>
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<td>34000.00</td>
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</table>

**Loop Pressure Profile 15-Points**

<table>
<thead>
<tr>
<th>Loop Axial Distance (FT)</th>
<th>Absolute Pressure Cable Line (PSI)</th>
<th>Absolute Pressure Return Line (PSI)</th>
</tr>
</thead>
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<td>0.00</td>
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<td>250.33</td>
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<tr>
<td>607.14</td>
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</tr>
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<td>194.58</td>
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<td>6678.56</td>
<td>189.00</td>
<td>339.89</td>
</tr>
<tr>
<td>7285.70</td>
<td>183.43</td>
<td>348.03</td>
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TABLE 5.5 (CONT'D.)

--LOOP THERMAL INFORMATION--

<table>
<thead>
<tr>
<th>HEAT EXCHANGER INLET TEMPERATURE (F)</th>
<th>124.91</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MAXIMUM PERMITTED OIL TEMPERATURE)</td>
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<tr>
<td>HEAT EXCHANGER OUTLET TEMPERATURE (F)</td>
<td>103.15</td>
</tr>
<tr>
<td>TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS)</td>
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</table>

LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE CABLE LINE (FT)</th>
<th>RETURN LINE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>103.15</td>
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<td>850.00</td>
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<tr>
<td>5100.00</td>
<td>112.63</td>
<td>103.72</td>
</tr>
<tr>
<td>5950.00</td>
<td>110.43</td>
<td>103.72</td>
</tr>
<tr>
<td>6800.00</td>
<td>108.19</td>
<td>103.69</td>
</tr>
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<td>7650.00</td>
<td>105.90</td>
<td>103.64</td>
</tr>
<tr>
<td>8500.00</td>
<td>103.57</td>
<td>103.57</td>
</tr>
</tbody>
</table>

***
SYSTEM LOOP NUMBER 5
***

--LOOP HYDRAULIC INFORMATION--

<table>
<thead>
<tr>
<th>LOOP AXIAL LENGTH (FT)</th>
<th>8500.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOOP FLOW RATE (GAL/MIN)</td>
<td>400.00</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.117E-01</td>
</tr>
<tr>
<td>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>99.46</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</td>
<td>0.167E-01</td>
</tr>
<tr>
<td>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</td>
<td>141.61</td>
</tr>
<tr>
<td>PUMP INLET PRESSURE (PSI)</td>
<td>152.22</td>
</tr>
<tr>
<td>PUMP OUTLET PRESSURE (PSI)</td>
<td>413.29</td>
</tr>
<tr>
<td>LOOP PUMPING POWER (WATTS)</td>
<td>45321.59</td>
</tr>
</tbody>
</table>

ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 5 (INCLUDING LOOP END POINT PRESSURES).

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34000.00</td>
<td>172.22</td>
<td>413.29</td>
</tr>
<tr>
<td>42000.00</td>
<td>242.37</td>
<td>313.27</td>
</tr>
<tr>
<td>42500.00</td>
<td>264.56</td>
<td>264.56</td>
</tr>
</tbody>
</table>

LOOP PRESSURE PROFILE 15-POINTS
<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE (PSI)</th>
<th>CABLE LINE</th>
<th>RETURN LINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>172.22</td>
<td>413.29</td>
<td></td>
</tr>
<tr>
<td>607.14</td>
<td>179.33</td>
<td>403.18</td>
<td></td>
</tr>
<tr>
<td>1214.29</td>
<td>186.43</td>
<td>393.06</td>
<td></td>
</tr>
<tr>
<td>1821.43</td>
<td>193.54</td>
<td>382.95</td>
<td></td>
</tr>
<tr>
<td>2428.57</td>
<td>200.64</td>
<td>372.83</td>
<td></td>
</tr>
<tr>
<td>3035.71</td>
<td>207.74</td>
<td>362.72</td>
<td></td>
</tr>
<tr>
<td>3642.86</td>
<td>214.85</td>
<td>352.60</td>
<td></td>
</tr>
<tr>
<td>4250.00</td>
<td>221.95</td>
<td>342.49</td>
<td></td>
</tr>
<tr>
<td>4857.14</td>
<td>229.06</td>
<td>332.37</td>
<td></td>
</tr>
<tr>
<td>5464.28</td>
<td>236.16</td>
<td>322.26</td>
<td></td>
</tr>
<tr>
<td>6071.42</td>
<td>243.07</td>
<td>311.94</td>
<td></td>
</tr>
<tr>
<td>6678.56</td>
<td>248.46</td>
<td>300.11</td>
<td></td>
</tr>
<tr>
<td>7285.70</td>
<td>253.85</td>
<td>288.27</td>
<td></td>
</tr>
<tr>
<td>7892.84</td>
<td>259.24</td>
<td>276.44</td>
<td></td>
</tr>
<tr>
<td>8499.98</td>
<td>264.64</td>
<td>264.61</td>
<td></td>
</tr>
</tbody>
</table>

--LOOP THERMAL INFORMATION--

HEAT EXCHANGER INLET TEMPERATURE (F) .......... 124.91
(MAXIMUM PERMITTED OIL TEMPERATURE)

HEAT EXCHANGER OUTLET TEMPERATURE (F) .......... 106.22

TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) .. 0.414E 06

LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>CABLE LINE TEMPERATURE (FT)</th>
<th>RETURN LINE TEMPERATURE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>124.91</td>
<td>106.22</td>
</tr>
<tr>
<td>850.00</td>
<td>123.18</td>
<td>106.30</td>
</tr>
<tr>
<td>1700.00</td>
<td>121.42</td>
<td>106.36</td>
</tr>
<tr>
<td>2550.00</td>
<td>119.62</td>
<td>106.40</td>
</tr>
<tr>
<td>3400.00</td>
<td>117.80</td>
<td>106.42</td>
</tr>
<tr>
<td>4250.00</td>
<td>115.94</td>
<td>106.43</td>
</tr>
<tr>
<td>5100.00</td>
<td>114.05</td>
<td>106.41</td>
</tr>
<tr>
<td>5950.00</td>
<td>112.12</td>
<td>106.37</td>
</tr>
<tr>
<td>6800.00</td>
<td>110.16</td>
<td>106.31</td>
</tr>
<tr>
<td>7650.00</td>
<td>108.17</td>
<td>106.24</td>
</tr>
<tr>
<td>8500.00</td>
<td>106.14</td>
<td>106.14</td>
</tr>
</tbody>
</table>

***

SYST EEM LOOP NUMBER 6.

***

--LOOP HYDRAULIC INFORMATION--

LOOP AXIAL LENGTH (FT) ........................................ 8500.00

LOOP FLOW RATE (GAL/MIN) ....................................... 500.00

CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) ............ 0.176E-01
TABLE 5.5 (CONT'D.)

<table>
<thead>
<tr>
<th>Cable Line Dynamic Pressure Loss (PSI)</th>
<th>149.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Line Dynamic Pressure Loss/FT (PSI/FT)</td>
<td>0.240E-01</td>
</tr>
<tr>
<td>Return Line Dynamic Pressure Loss (PSI)</td>
<td>204.36</td>
</tr>
<tr>
<td>Pump Inlet Pressure (PSI)</td>
<td>66.88</td>
</tr>
<tr>
<td>Pump Outlet Pressure (PSI)</td>
<td>440.60</td>
</tr>
<tr>
<td>Loop Pumping Power (Watts)</td>
<td>81097.25</td>
</tr>
</tbody>
</table>

Absolute Pressures at Elevation Profile Points located within Loop Number 6 (including Loop End Point Pressures).

<table>
<thead>
<tr>
<th>System AXIAL DISTANCE (FT)</th>
<th>Cable Line ABSOLUTE PRESSURE (PSI)</th>
<th>Return Line ABSOLUTE PRESSURE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42500.00</td>
<td>264.56</td>
<td>264.56</td>
</tr>
<tr>
<td>45000.00</td>
<td>213.50</td>
<td>317.54</td>
</tr>
<tr>
<td>51000.00</td>
<td>86.88</td>
<td>440.60</td>
</tr>
</tbody>
</table>

**ERROR**
The cable line pressure at the outlet point (= 86.885 ) is below the minimum permitted cable line pressure.

Loop Pressure Profile 15-Points

<table>
<thead>
<tr>
<th>Loop AXIAL DISTANCE (FT)</th>
<th>Cable Line ABSOLUTE PRESSURE (PSI)</th>
<th>Return Line ABSOLUTE PRESSURE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>264.56</td>
<td>264.56</td>
</tr>
<tr>
<td>607.14</td>
<td>257.18</td>
<td>277.44</td>
</tr>
<tr>
<td>1214.29</td>
<td>239.81</td>
<td>290.32</td>
</tr>
<tr>
<td>1821.43</td>
<td>227.43</td>
<td>303.21</td>
</tr>
<tr>
<td>2428.57</td>
<td>215.05</td>
<td>316.09</td>
</tr>
<tr>
<td>3035.71</td>
<td>202.29</td>
<td>328.59</td>
</tr>
<tr>
<td>3642.86</td>
<td>189.49</td>
<td>341.04</td>
</tr>
<tr>
<td>4250.00</td>
<td>176.68</td>
<td>353.49</td>
</tr>
<tr>
<td>4857.14</td>
<td>163.88</td>
<td>365.94</td>
</tr>
<tr>
<td>5464.28</td>
<td>151.07</td>
<td>378.40</td>
</tr>
<tr>
<td>5071.42</td>
<td>138.26</td>
<td>390.85</td>
</tr>
<tr>
<td>5678.56</td>
<td>125.46</td>
<td>403.30</td>
</tr>
<tr>
<td>6285.70</td>
<td>112.65</td>
<td>415.75</td>
</tr>
<tr>
<td>6892.84</td>
<td>99.85</td>
<td>428.20</td>
</tr>
<tr>
<td>8499.98</td>
<td>87.04</td>
<td>440.66</td>
</tr>
</tbody>
</table>

--Loop Thermal Information--

<table>
<thead>
<tr>
<th>Heat Exchanger Inlet Temperature (F)</th>
<th>124.91</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Permitted Oil Temperature</td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger Outlet Temperature (F)</td>
<td>110.36</td>
</tr>
<tr>
<td>Total Heat Exchanger Cooling Capacity (Watts)</td>
<td>0.402E 06</td>
</tr>
<tr>
<td>LOOP AXIAL DISTANCE (FT)</td>
<td>TEMPERATURE</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.00</td>
<td>124.91</td>
</tr>
<tr>
<td>850.00</td>
<td>123.49</td>
</tr>
<tr>
<td>1700.00</td>
<td>122.05</td>
</tr>
<tr>
<td>2550.00</td>
<td>120.59</td>
</tr>
<tr>
<td>3400.00</td>
<td>119.12</td>
</tr>
<tr>
<td>4250.00</td>
<td>117.62</td>
</tr>
<tr>
<td>5100.00</td>
<td>116.10</td>
</tr>
<tr>
<td>5950.00</td>
<td>114.56</td>
</tr>
<tr>
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<td>112.99</td>
</tr>
<tr>
<td>7650.00</td>
<td>111.41</td>
</tr>
<tr>
<td>8500.00</td>
<td>109.80</td>
</tr>
</tbody>
</table>
6. DESIGN-OPTION 4

A detailed explanation of the analysis procedure utilized by Design-Option 4 (D.O.4) is presented in Section 6.1. Computer documentation (user instructions) is provided in Section 6.2.

6.1 Analysis Procedure of Design-Option 4

Design-Option 4 provides a thermal and hydraulic analysis for a single coolant loop of a forced-cooled pipe-type cable system. Using the specified General Program input data (Section 2.2.1), the D.O.4 thermal analysis computes, for given heat exchanger inlet and outlet temperatures and the axial loop length, the required cable ampacity value (peak and average values), the oil flow rate, and the axial temperature distribution of the oil in the pipes. The D.O.4 hydraulic analysis uses the oil flow rate to calculate the loop dynamic pressure losses.

The independent and dependent variables and design constraints associated with D.O.4 are presented in Table 6.1 and a simplified flow chart describing the coolant loop analysis procedure is shown in Figure 6.1. The analysis of D.O.4 applies only to a single coolant loop of a forced-cooled system. The goal of D.O.4 is to calculate the cable ampacity value which yields a coolant loop operation that produces the specified heat exchanger inlet and outlet temperatures. The analysis begins with the input of the General Program variables (the values of which will already be in the computer memory if this is not the first design problem examined) and the D.O.4 input variables.

In the design-options of the previous chapters, the heat exchanger inlet temperature (cable line outlet temperature), THOT, is
TABLE 6.1
DESIGN-OPTION 4 INDEPENDENT AND DEPENDENT VARIABLES
AND DESIGN CONSTRAINTS

<table>
<thead>
<tr>
<th>PRIMARY INDEPENDENT VARIABLES*</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>- loop heat exchanger inlet temperature</td>
<td>- forced-cooled peak cable ampacity rating</td>
</tr>
<tr>
<td>- loop heat exchanger outlet temperature</td>
<td>- loop oil flow rate</td>
</tr>
<tr>
<td>- axial loop length</td>
<td>- loop dynamic pressure loss</td>
</tr>
<tr>
<td>- ampacity factor</td>
<td></td>
</tr>
</tbody>
</table>

PRIMARY DESIGN CONSTRAINTS**

- maximum permitted cable temperature

* Design-Option 4 input data

** Specified as part of General Program input data (see Table 2.2)
FIGURE 6.1: Design Option-4-Flow Chart
(conservatively) permitted to attain the maximum permissible value, TOILMX, in accordance with the value of the cable ampacity. In this case, however, the cable ampacity must be selected so that that value of TOILMX coincides with the specified value of THOT. Simultaneously, the resultant cable energy losses produced by the selected ampacity must produce an oil flow rate which satisfies the requirements of the heat exchanger inlet and outlet temperatures. An iterative procedure is therefore required to perform the loop analysis.

Initially, a value of the peak cable ampacity is selected. This value and the specified ampacity factor, AMPFAC, (ratio of the average cable ampacity and the peak ampacity) are used to calculate the average daily cable ampacity (IFCAVG=IFC*AMPFAC) which in turn is used to calculate the average cable energy losses. The Loop Energy Balance (see Section 5.1 - Design Manual Part I) then uses the calculated energy losses, the heat exchanger temperatures, and the soil heat transfer characteristics to calculate the required value of the oil flow rate. The cable heat transfer correlation (see Section 5.2 - Design Manual Part I) subsequently uses the value of the peak ampacity, the oil flow rate, the cable geometry, and the calculated values of the oil properties to determine the cable conductor-to-oil temperature drop, THETA. This value is used in conjunction with the value of the maximum permitted cable temperature, TCABMX, to calculate the value of TOILMX (TOILMX=TCABMX-THETA). If the calculated value of TOILMX differs from the specified value of THOT, a new value of the cable peak ampacity is selected, accordingly, and the analysis is repeated. The iteration ends
when an ampacity value is found that produces a maximum permitted oil temperature, TOILMX, equal to the specified value of THOT. The loop temperature profile is then calculated using the resultant oil flow rate. The loop dynamic pressure drop is also calculated (see Section 5.3 - Design Manual Part I). The General Program output format is used to printout the analysis results (output of the loop hydraulic information is modified).

6.2 Design-Option 4 - Computer Documentation

6.2.1 input Variables for Design-Option 4

The input variables used in Design-Option 4 are listed in Table 6.2 along with a brief description of each variable.

The axial coolant loop length, XLTH, refers to the axial length of either the discharge line or cable line (they both have the same value) but not their combined length.

The input of the ampacity factor value, AMPFAC, allows for the flexibility of selecting that ampacity (which is some percentage of the peak cable ampacity) which is used for the calculation of the cable energy losses. Use of the peak value for calculation of cable losses (AMPFAC=1.0) always results in a conservative estimate of the maximum possible loop ampacity.

The values of TOILMX and TOILMN must always remain within the temperature range of the oil property data. Also, the value of TOILMX must never exceed the maximum permitted cable temperature (as specified in the General Program input section.)
### TABLE 6.2
**INPUT VARIABLES FOR DESIGN-OPTION 4**

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description and Dimension ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>4 - variable which &quot;informs&quot; the computer program that Design-Option 4 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem</td>
</tr>
<tr>
<td></td>
<td>1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted (dimensionless)</td>
</tr>
<tr>
<td>TOILMN</td>
<td>the specified heat exchanger outlet temperature for the coolant loop under study (°F)</td>
</tr>
<tr>
<td>TOILMX</td>
<td>the specified heat exchanger inlet temperature for the coolant loop under study (°F)</td>
</tr>
<tr>
<td>XLTH</td>
<td>the axial length of the coolant loop (ft)</td>
</tr>
<tr>
<td>AMPFAC</td>
<td>the ampacity factor - the desired (or expected) ratio of the average cable ampacity and the (calculated) peak cable ampacity (used in order to accurately model cable energy losses) (dimensionless)</td>
</tr>
</tbody>
</table>
Design-Option 4 does not utilize the elevation profile input data. Therefore, any values or no values of PLTH(I) and PEL(I) can be inputted.

6.2.2 Output for Design-Option 4

After the General Program input data is printed out, the input data associated with Design-Option 4 is printed out under the title DESIGN-OPTION 4 - PRINTOUT OF INPUT DATA.

The results of the computer analysis are printed out under the title DESIGN-OPTION 4----RESULTS. Option 4 utilizes the input information to calculate, for the loop under study, the maximum permitted ampacity as well as the average loop ampacity (based on AMPFAC) and the loop temperature profile. The output is self-explanatory.

6.2.3 Error Messages for Design-Option 4

Design-Option 4 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are exceeded. Those computer program error messages which apply to Design-Option 4 are listed below. Any additional information which is pertinent to the application of a given error to the design-option is provided.

a) Errors 1-4
b) Error 6

This error may occur during the loop analysis even though the final result is O.K. Therefore, it is suggested that the value of INOND be calculated by hand (for the final resultant ampacity) if Error 6 is
printed. If INOND is within its limiting values, then the output is valid.

c) Error 10

Design-Option 4 calculates a cable ampacity which maintains the hot oil temperature at the specified value of TOILMX. If, when using this ampacity value, a value of the flow rate does not exist which will produce the specified heat exchanger outlet temperature (flow rate is too low) then Error 10 is printed out. If it is still desired to maintain the same loop length, then either the cold temperature must be increased or the hot temperature must be decreased.

d) Error 15

Design-Option 4 calculates a cable ampacity which maintains the hot oil temperature at the specified value of TOILMX. If, when using this ampacity value, the value of the flow rate, which is required to produce the heat exchanger outlet temperature (TOILMN), is so large as to be incalculable (program exceeds maximum permitted number of iterations), then Error 15 is printed out. If it is still desired to maintain the same loop length, then either the cold temperature must be decreased or the hot temperature must be increased.

e) Error 16

6.2.4 Data Card Assembly for Design-Option 4

Instructions for assembling the data cards for Design-Option 4 are listed in Table 6.3. The card numbering sequence continues directly from the General Program input cards. It is necessary that the variables using the I-Format be right-adjusted in the column field.
TABLE 6.3
DATA CARD ASSEMBLY FOR DESIGN-OPTION 4

<table>
<thead>
<tr>
<th>Card</th>
<th>Column(s)</th>
<th>Variable **</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td>10-20</td>
<td>NUPROB</td>
<td>I10</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>TOILMN</td>
<td>F10.3</td>
</tr>
<tr>
<td>10-20</td>
<td>TOILMX</td>
<td>F10.3</td>
<td></td>
</tr>
<tr>
<td>20-30</td>
<td>XLTH</td>
<td>F10.3</td>
<td></td>
</tr>
<tr>
<td>30-40</td>
<td>AMPFAC</td>
<td>F10.3</td>
<td></td>
</tr>
</tbody>
</table>

** See Table 6.2 for variable dimensions.

6.2.5 Design-Option 4 - Example Problem

This section illustrates the solution of a particular forced cooled system design problem utilizing computer program Design-Option 4. Design-Option 4 is to be used to determine the cable ampacity value that can be attained for the system analyzed in Section 3.2.5 if the values of the heat exchanger inlet and outlet temperatures for loop number 1 are set equal to the values listed in Table 6.4.

The complete set of Option 4 input data for the example problem is listed in Table 6.4. The General Program input data remains unchanged (see Section 2.2.6). The computer program output is listed in Table 6.5 (compare with the output of Design-Option 1 example problem).
TABLE 6.4

INPUT DATA FOR DESIGN-OPTION 4

EXAMPLE PROBLEM

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMNS</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>95.0</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>115.0</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>8500.0</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>0.89</td>
</tr>
</tbody>
</table>
**Design-Option 4**

--- Printout of Input Data ---

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Exchanger Outlet Temperature (F)</td>
<td>95.000</td>
</tr>
<tr>
<td>Heat Exchanger Inlet Temperature (F)</td>
<td>115.000</td>
</tr>
<tr>
<td>Axial Length of Coolant Loop (FT)</td>
<td>8500.000</td>
</tr>
<tr>
<td>Ampacity Factor (Dimensionless)</td>
<td>0.890</td>
</tr>
</tbody>
</table>

**Design-Option 4---Results**

--- Loop Hydraulic Information ---

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Oil Flow Rate (GPM)</td>
<td>475.000</td>
</tr>
<tr>
<td>Cable Line Dynamic Pressure Loss/FT (PSI/FT)</td>
<td>0.167E-01</td>
</tr>
<tr>
<td>Return Line Dynamic Pressure Loss/FT (PSI/FT)</td>
<td>0.240E-01</td>
</tr>
</tbody>
</table>

--- Loop Thermal Information ---

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Forced-Cooled Peak Ampacity Rating (AMPS)</td>
<td>1522.136</td>
</tr>
<tr>
<td>Average Forced-Cooled Ampacity (AMPS)</td>
<td>1354.701</td>
</tr>
<tr>
<td>Total System Energy Loss (Watts/FT)</td>
<td>66.81</td>
</tr>
<tr>
<td>Heat Exchanger Inlet Temperature (F)</td>
<td>115.000</td>
</tr>
<tr>
<td>(Maximum Permitted Oil Temperature)</td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger Outlet Temperature (F)</td>
<td>95.000</td>
</tr>
<tr>
<td>Total Heat Exchanger Cooling Capacity (Watts)</td>
<td>0.575E 06</td>
</tr>
</tbody>
</table>

**Loop Temperature Profile 11-Points**

<table>
<thead>
<tr>
<th>Axial Distance (FT)</th>
<th>Cable Line Temperature (FT)</th>
<th>Return Line Temperature (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>115.00</td>
<td>95.00</td>
</tr>
<tr>
<td>850.00</td>
<td>113.22</td>
<td>95.18</td>
</tr>
<tr>
<td>1700.00</td>
<td>111.41</td>
<td>95.34</td>
</tr>
<tr>
<td>2550.00</td>
<td>109.58</td>
<td>95.47</td>
</tr>
<tr>
<td>3400.00</td>
<td>107.72</td>
<td>95.59</td>
</tr>
<tr>
<td>4250.00</td>
<td>105.82</td>
<td>95.69</td>
</tr>
<tr>
<td>5100.00</td>
<td>103.90</td>
<td>95.77</td>
</tr>
<tr>
<td>5950.00</td>
<td>101.95</td>
<td>95.84</td>
</tr>
<tr>
<td>6800.00</td>
<td>99.96</td>
<td>95.91</td>
</tr>
<tr>
<td>7650.00</td>
<td>97.96</td>
<td>95.92</td>
</tr>
<tr>
<td>8500.00</td>
<td>95.92</td>
<td></td>
</tr>
</tbody>
</table>
7. **DESIGN-OPTION 5**

A detailed explanation of the analysis procedure utilized by Design-Option 5 (D.O.5) is presented in Section 7.1. Computer documentation (user instructions) is provided in Section 7.2.

7.1 **Analysis Procedure of Design-Option 5**

The independent and dependent variables and the design constraints associated with D.O.5 are presented in Table 7.1 and a simplified flow chart describing the coolant loop analysis procedure is shown in Figure 7.1. The analysis of D.O.5 applies only to a single coolant loop of a forced-cooled system. The goal of D.O.5 is to calculate the peak cable ampacity value which yields a coolant loop hydraulic operation that produces a specified loop pressure profile (pressure values are specified by the user for points 1, 3, and 4 in Figure 7.2). If the exact values of all specified pressures are impossible to produce (for any oil flow rate), the design analysis utilizes the specified loop pressures as constraint values and designs a loop which optimizes the pressure profile for these constraints. In this regard, it is important to note that the loop pressure profile calculations depend upon specification as to whether an even or odd numbered system loop is under study.

7.1.1 **Odd-Numbered Coolant Loop**

If an odd-numbered coolant loop (1,3,5, etc. - counting from the operational head tank) of a forced-cooled system is under study, the specified value of the minimum cable line pressure, PCLOW (point 1 in Figure 7.2) is used as the loop reference pressure (and is fixed in
TABLE 7.1

DESIGN-OPTION 5 INDEPENDENT AND DEPENDENT VARIABLES
AND DESIGN CONSTRAINTS

<table>
<thead>
<tr>
<th>PRIMARY INDEPENDENT VARIABLES*</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>- loop heat exchanger outlet temperature</td>
<td>- forced-cooled peak cable ampacity rating</td>
</tr>
<tr>
<td>- loop length</td>
<td>- forced-cooled peak cable ampacity rating</td>
</tr>
<tr>
<td>- minimum cable line pressure</td>
<td>- loop oil flow rate</td>
</tr>
<tr>
<td>- maximum cable line pressure</td>
<td>- loop dynamic pressure loss</td>
</tr>
<tr>
<td>- maximum discharge line pressure</td>
<td>- loop cooling power</td>
</tr>
<tr>
<td>- even-numbered loop or odd-numbered coolant loop</td>
<td>- loop pumping power</td>
</tr>
<tr>
<td>- ampacity factor</td>
<td></td>
</tr>
</tbody>
</table>

PRIMARY DESIGN CONSTRAINTS**

- maximum permitted cable temperature

* Design-Option 5 input data

** Specified as part of General Program input data (see Table 2.2)
CALCULATE THE AVERAGE LOOP OIL TEMPERATURE AND CORRESPONDING AVERAGE OIL PROPERTIES (SUBROUTINE PTYINT)

CALCULATE LOOP OIL FLOW RATE, Q, USING THE LOOP ENERGY BALANCE (SUBROUTINE ENBAL2)

CALCULATE THE MAXIMUM PERMITTED OIL TEMPERATURE, TOILMX, BY CALCULATING THE CABLE CONDUCTOR-TO-OIL TEMPERATURE DROP (SUBROUTINE HEATTR)

CALCULATE AVERAGE OIL PROPERTIES FOR CABLE AND RETURN LINES, RESPECTIVELY

CALCULATE LOOP PRESSURE-FLOW LOSSES (SUBROUTINE PRODROP)

IFCn = IFCn-1 + ΔIFC

IFCn = IFCn-1 - ΔIFC

IS THOT = TOILMX? NO

THOT = TOILMX

N=N+1

ΔP LOOP = ΔP

END

Figure 7.1: Design Option-5-Flow Chart
Figure 7.2 A Schematic Drawing of an Odd-Numbered Coolant Loop.
value). Calculation of all other loop absolute pressures are based on this pressure value. A cable ampacity value is initially found which yields an oil flow rate that produces a pump outlet pressure (point 3 in Figure 7.2) equal in value to the specified maximum discharge line pressure, PRHIGH. If the value of PRHIGH can be produced which maintains the value of the cable line inlet pressure, PCHIGH (point 4 in Figure 7.2), at or below its specified value, the analysis is halted. However, if the calculated value of PCHIGH exceeds its specified value, a new value of the ampacity is selected which yields a loop oil flow rate that produces the specified value of PCHIGH. Subsequently, the value of the pump outlet pressure will take on a value which is below PRHIGH.

7.1.2 Even-Numbered Coolant Loop

If an even-numbered coolant loop (2, 4, 6, etc. - counting from the operational head tank) of a forced-cooled system is under study, the specified value of the maximum cable line pressure (point 4 in Figure 7.3) is used as the loop reference pressure (and is fixed in value). Calculation of all other absolute pressures are based on this pressure value. A cable ampacity value is initially found which yields an oil flow rate that produces a pump outlet pressure (point 3 in Figure 7.3) equal in value to the specified maximum discharge line pressure, PRHIGH. If the value of PRHIGH can be produced which maintains the value of the cable line outlet pressure (point 1 in Figure 7.3), PCLOW, at or above its specified value, the analysis is halted. However, if the calculated value of PCLOW is below its specified value, a new value of the ampacity is selected which yields a loop oil flow rate that
Figure 7.3 A Schematic Drawing of an Even-Numbered Coolant Loop.
produces the specified value of PCLOW. Subsequently, the value of the pump outlet pressure will take on a value which is below PRHIGH.

7.1.3 Design Procedure

Initially, a value of the peak cable ampacity is selected. This value and the specified ampacity factor, AMPFAC (ratio of the average cable ampacity and the peak ampacity) are used to calculate the average daily cable ampacity (IFCAVG = IFC×AMPFAC) which in turn is used to calculate the average cable energy losses. An iterative procedure is then required to perform the loop thermal analysis. This procedure is identical to the loop thermal analysis discussed in Chapter 3, Section 3.1 for Design-Option 1 (the loop thermal analysis is included in the flow chart of Figure 7.1).

The loop hydraulic analysis follows and consists of using the value of the oil flow rate (determined from the thermal analysis) to calculate the loop dynamic pressure drop (subroutine PRDROP). The loop static pressure profile is then utilized to calculate the loop absolute pressure profile. If the pressure profile meets the specified requirements (according to the discussions of Sections 7.1.1 and 7.1.2), the analysis ends. If design requirements are not met, a new value of the cable ampacity is selected, accordingly, and the entire procedure is repeated. The analysis continues until the loop pressure profile requirements are satisfied.
7.2 DESIGN-OPTION 5 - COMPUTER DOCUMENTATION

7.2.1 Input Variables for Design-Option 5

The input variables used in Design-Option 5 are listed in Table 7.2 along with a brief description of each variable. Comments concerning these variables are provided below.

The specified value of TOILMN must always remain within the temperature range of the oil property data.

The axial coolant loop length, XLTH, refers to the axial length of either the discharge line or cable line (both have the same value) but not their combined length.

If an odd-numbered coolant loop (1, 3, 5, etc.) of a forced-cooled system is being analyzed, the value of the minimum cable line pressure (PCLOW) specified is used as the loop reference pressure, and is fixed in value. All other loop absolute pressures are based on this pressure value. If the value of PRHIGH can be produced while maintaining the value of RCHIGH at or below its specified value, then the analysis is halted. However, if the (calculated) value of PCHIGH exceeds its specified value, the loop is redesigned, to produce the specified value of PCHIGH and PRHIGH will have a (calculated) value below that value specified.

If an even numbered coolant loop (2, 4, 6, etc.) of a forced-cooled system is being analyzed, the value of the maximum cable line pressure (PCHIGH) specified is used as the loop reference pressure (and is fixed in value). All other loop absolute pressures are based on this value. If the value of PRHIGH can be produced while maintaining the value
<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>DESCRIPTION and DIMENSION ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>5 - variable which &quot;informs&quot; the computer program that Design-Option 5 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem</td>
</tr>
<tr>
<td></td>
<td>1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted (dimensionless)</td>
</tr>
<tr>
<td>TOILMN</td>
<td>the specified heat exchanger outlet temperature for the coolant loop under study (°F)</td>
</tr>
<tr>
<td>XLTH</td>
<td>the axial length of the coolant loop (ft)</td>
</tr>
<tr>
<td>PCLOW</td>
<td>the desired minimum cable line pressure value (psi)</td>
</tr>
<tr>
<td>PCHIGH</td>
<td>the desired maximum cable line pressure value (psi)</td>
</tr>
<tr>
<td>PRHIGH</td>
<td>the desired maximum return line pressure value (psi)</td>
</tr>
<tr>
<td>DTHE</td>
<td>the minimum permissible heat exchanger temperature drop (°F)</td>
</tr>
<tr>
<td>EVODD</td>
<td>variable specifying an even or odd numbered loop (dimensionless)</td>
</tr>
<tr>
<td>AMPFAC</td>
<td>the ampacity factor - the desired (or expected) ratio of the average cable ampacity and the (calculated) peak cable ampacity (used in order to accurately model cable energy losses) (dimensionless)</td>
</tr>
</tbody>
</table>
of PCLOW at or above its specified value the analysis is halted. However, if the (calculated) value of PCLOW is below its specified value, the loop is redesigned to produce the specified value of PCLOW and PRHIGH will have a (calculated) value below that value specified.

The value of DTHE must be specified in order to prevent the computer program from choosing an ampacity which yields a value of THOT, less than the value of TCOLD (TOILMN). Also, other reasons may exist which necessitate the specification of a minimum value of the heat exchanger temperature drop. If the program cannot design the system without violating this constraint value, an error message is printed and the program stops.

The input of the ampacity factor value, AMPFAC, allows for the flexibility of selecting that ampacity (which is some percentage of the peak cable ampacity) which is used for the calculation of the cable energy losses. Use of the peak ampacity value for calculation of cable losses (AMPFAC=1.0) always results in a conservative estimate of the maximum possible loop ampacity.

Design-Option 5 utilizes the elevation profile input data of the general program for the single loop under study. The values of PEL(1) and PLTH(1) are associated with the same end of the loop as is the reference pressure (PCLOW for odd loops and PCHIGH for even loops). The other values of PEL(I) and PLTH(I) are numbered sequentially as the values move toward the opposite end of the loop. The final values, PEL(XLTH) and PLTH(XLTH), correspond to the values of the opposite end of the loop (PLTH(XLTH)-PLTH(1)=XLTH).
7.2.2 Output for Design-Option 5

After the general program input data is printed out, the input data associated with Design-Option 5 is printed out under the title DESIGN-OPTION 5 - PRINTOUT OF INPUT DATA.

The results of the computer analysis are printed out under the title DESIGN-OPTION 5 - RESULTS. OPTION 5 utilizes the input information to calculate, for the loop under study, the maximum permitted ampacity, as well as the average loop ampacity (based on AMPFAC), the loop pressure profile, and the loop temperature profile. The General Program output format is used which is self-explanatory.

7.2.3 Error Messages for Design-Option 5

DESIGN-OPTION 5 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are exceeded. Those computer program error messages which apply to Design-Option 5 are listed below. Any additional information, which is pertinent to the application of a given error to the design-option, is provided.

a) Errors 1-4

b) Error 6

This error may occur during the loop analysis even though the final result is okay. Therefore, if Error 6 is printed, it is suggested that the value of INOND be calculated by hand (for the resultant ampacity value). If INOND is within the range of its limiting values, then the output is valid.
c) Error 12-14

d) Error 10

Design-Option 5 attempts to determine the cable ampacity which yields a flow rate that produces the desired cable line and/or return line pressure(s). However if during this procedure the program selects an ampacity value for which no flow rate exists that will produce the necessary heat exchanger temperature drop (based on TOILMN and the calculated value of the maximum oil temperature), then Error 10 is printed. Typically, this occurs when the specified cable line and/or return line differential pressures are very small and the loop length is also very short.

e) Error 15

Typically this error occurs when the specified cable-line and/or return line differential pressures are very large and the loop length is very short.

f) Error 16

f) Error 17

The computer program cannot increase the ampacity high enough so that the desired pressures can be achieved. This typically happens if DTHE is specified to be too large or if the loop pressure drop required is excessively large for the specified loop length.

7.2.4 Data Card Assembly for Design-Option 5

Instructions for assembling the data cards for Design-Option 5 are listed in Table 7.3. The card numbering sequence continues directly from the General Program input cards. It is necessary that variables using the I-format be right-adjusted in the column field.
### TABLE 7.3

DATA CARD ASSEMBLY FOR DESIGN-OPTION 5

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMN(s)</th>
<th>VARIABLE**</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>NUPROB</td>
<td>I10</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>TOILMN</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>XLTH</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>PCLOW</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>PCHIGH</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>PRHIGH</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>DTHE</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>AMPFAC</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>1-10</td>
<td>EVODD</td>
<td>F10.1</td>
</tr>
</tbody>
</table>

**See Table 7.2 for variable dimensions**
7.2.5 Design-Option 5 - Example Problem

This section illustrates the solution of a particular forced-cooled system design problem utilizing computer program Design-Option 5. Design-Option 5 is to be used to determine the cable ampacity value that can be attained for the system analyzed in Section 3.2.5 if the loop pressure profile of loop number 1 is altered. The complete set of Option 5 input data for the example problem is listed in Table 7.4. The General Program input data remains unchanged (see Section 2.2.6). The computer program output is listed in Table 7.5 (compare with the output of the Design-Option 1 example problem).
## TABLE 7.4

**INPUT DATA USED FOR DESIGN-OPTION 5**

**EXAMPLE PROBLEM**

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMNS</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>95.0</td>
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<tr>
<td></td>
<td>10-20</td>
<td>8500.0</td>
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<tr>
<td></td>
<td>20-30</td>
<td>167.77</td>
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<tr>
<td></td>
<td>30-40</td>
<td>300.0</td>
</tr>
<tr>
<td></td>
<td>40-50</td>
<td>600.0</td>
</tr>
<tr>
<td></td>
<td>50-60</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>60-70</td>
<td>0.89</td>
</tr>
</tbody>
</table>
**DESIGN-OPTION 5**

**PRINTOUT OF INPUT DATA**

**HEAT EXCHANGER OUTLET TEMPERATURE (F)**: 95.000

**AXIAL LENGTH OF COOLANT LOOP (FT)**: 8500.000

**MINIMUM CABLE LINE PRESSURE (PSI)**: 167.770

**MAXIMUM CABLE LINE PRESSURE (PSI)**: 300.000

**MAXIMUM DISCHARGE LINE PRESSURE (PSI)**: 600.000

**MINIMUM PERMISSIBLE HEAT EXCHANGER TEMPERATURE DROP (F)**: 5.000

**AMPACITY FACTOR (DIMENSIONLESS)**: 0.890

**Obsd-NUMBERED COOLANT LOOP UNDER STUDY**

**DESIGN-OPTION 5----RESULTS**

**SYSTEM LOOP NUMBER 1**

---LOOP HYDRAULIC INFORMATION---

**LOOP AXIAL LENGTH (FT)**: 8500.00

**LOOP FLOW RATE (GAL/MIN)**: 477.34

**CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)**: 0.170E-01

**CABLE LINE DYNAMIC PRESSURE LOSS (PSI)**: 144.69

**RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)**: 0.243E-01

**RETURN LINE DYNAMIC PRESSURE LOSS (PSI)**: 206.13

**PUMP INLET PRESSURE (PSI)**: 147.77

**PUMP OUTLET PRESSURE (PSI)**: 518.59

**LOOP PUMPING POWER (WATTS)**: 76822.06

**ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS**

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE</th>
<th>RETURN LIN(\text{E}) (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>167.77</td>
<td>518.59</td>
</tr>
<tr>
<td>5000.00</td>
<td>252.88</td>
<td>397.34</td>
</tr>
<tr>
<td>8500.00</td>
<td>297.35</td>
<td>297.35</td>
</tr>
</tbody>
</table>

**LOOP PRESSURE PROFILE 15-POINTS**
## Table 7.5 (Cont'd.)

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE RETURN LINN (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>167.77</td>
</tr>
<tr>
<td>607.14</td>
<td>178.11</td>
</tr>
<tr>
<td>1214.29</td>
<td>188.44</td>
</tr>
<tr>
<td>1821.43</td>
<td>198.78</td>
</tr>
<tr>
<td>2428.57</td>
<td>209.11</td>
</tr>
<tr>
<td>3035.71</td>
<td>219.45</td>
</tr>
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<td>4857.14</td>
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</tr>
<tr>
<td>5464.28</td>
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<td>7892.84</td>
<td>289.67</td>
</tr>
<tr>
<td>8499.98</td>
<td>297.39</td>
</tr>
</tbody>
</table>

### Loop Thermal Information

- **System Forced-Cooled Peak Ampacity Rating (Amps):** 1580.469
- **Average Forced-Cooled Ampacity (Amps):** 1406.617
- **Total System Energy Loss (Watts/FT):** 71.40

- **Heat Exchanger Inlet Temperature (F):** 109.98
- **Heat Exchanger Outlet Temperature (F):** 95.00
- **Total Heat Exchanger Cooling Capacity (Watts):** 0.398E 06

### Loop Temperature Profile 11-Points

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE CABLE LINE RETURN LINN (FT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>109.98</td>
</tr>
<tr>
<td>850.00</td>
<td>108.64</td>
</tr>
<tr>
<td>1700.00</td>
<td>107.29</td>
</tr>
<tr>
<td>2550.00</td>
<td>105.92</td>
</tr>
<tr>
<td>3400.00</td>
<td>104.52</td>
</tr>
<tr>
<td>4250.00</td>
<td>103.11</td>
</tr>
<tr>
<td>5100.00</td>
<td>101.67</td>
</tr>
<tr>
<td>5950.00</td>
<td>100.21</td>
</tr>
<tr>
<td>6800.00</td>
<td>98.73</td>
</tr>
<tr>
<td>7650.00</td>
<td>97.23</td>
</tr>
<tr>
<td>8500.00</td>
<td>95.70</td>
</tr>
</tbody>
</table>
8. DESIGN-OPTION 6

Computer program Design-Option 6 (D.O.6) is a forced-cooled underground transmission system design optimization procedure. The optimization criterion upon which the analysis is based is discussed in Section 8.1. A detailed explanation of the entire computer analysis is presented in Section 8.2 and the computer documentation (user instructions) for D.O.6 is provided in Section 8.3.

8.1 The Optimization Criterion Used by Design-Option 6

The optimization criterion used by Design-Option 6 states that a forced-cooled underground transmission system (of specified total length) consisting of a specified number of coolant loops is to be designed utilizing the maximum permissible cable ampacity. (The length of each coolant loop is not required.) In order to accomplish this task, the design optimization method of Design-Option 2 (Chapter 4) is utilized to determine the cable ampacity value which yields a forced-cooled system design corresponding to the specified number of coolant loops and of the specified total length. Since D.O.2 optimizes for the minimum permissible number of loops per specified cable ampacity and total system length, the value of the cable ampacity is increased until the number of calculated loops just exceeds the number of coolant loops specified in D.O.6; hence the ampacity is maximized.

8.2 Analysis Procedure of Design-Option 6

The Design-Option 6 optimization procedure provides a thermal and hydraulic analysis for each coolant loop of a forced-cooled pipe-type cable system, taking into account the hydraulic interaction between coolant
loops. Using the specified General Program input data (Section 2.2.1), the D.O.6 analysis computes, for a given number of coolant loops, heat exchanger outlet temperature (same for all loops) and total system axial length, the maximum permitted forced-cooled cable ampacity, loop length for each loop, the heat exchanger inlet temperature for each loop, the loop oil flow rate, the axial temperature distribution of the oil in the pipes, the loop dynamic pressure loss and the absolute loop pressure profile (with loop-loop interaction being accounted for).

The independent and dependent variables and the design constraints associated with D.O.6 are presented in Table 8.1 and a simplified flow chart describing the analysis procedure is shown in Figure 8.1. The analysis begins with the input of the General Program variables (the values of which will already be in the computer memory if this is not the first design problem examined) and the D.O.6 input variables.

Initially, a value of the peak cable ampacity is selected. This value and the specified ampacity factor, AMPFAC (ratio of the average cable ampacity and the peak cable ampacity) are used to calculate the average daily cable ampacity (IFCAVG=IFC×AMPFAC). Both of these values are then used as input to Design-Option 2 (along with all other system parameters). Design-Option 2 yields a forced-cooled system design utilizing the minimum number of coolant loops (for the specified total system length). If this optimum number of loops does not correspond to the specified number of system coolant loops, a new value of the peak cable ampacity is selected and the entire procedure is repeated. The cable ampacity is continually increased until the optimum number of coolant
**TABLE 8.1**

DESIGN-OPTION 6 INDEPENDENT AND DEPENDENT VARIABLES AND DESIGN CONSTRAINTS

<table>
<thead>
<tr>
<th>PRIMARY INDEPENDENT VARIABLES*</th>
<th>PRIMARY DEPENDENT VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of system coolant loops</td>
<td>maximum permitted forced-cooled cable ampacity</td>
</tr>
<tr>
<td>total system axial length</td>
<td>loop length per loop</td>
</tr>
<tr>
<td>heat exchanger outlet temperature</td>
<td>oil flow rate per loop</td>
</tr>
<tr>
<td>(same for all loops)</td>
<td>heat exchanger inlet temperature per loop</td>
</tr>
<tr>
<td>ampacity factor</td>
<td>loop dynamic pressure loss</td>
</tr>
<tr>
<td></td>
<td>loop cooling power</td>
</tr>
<tr>
<td></td>
<td>loop pumping power</td>
</tr>
</tbody>
</table>

**PRIMARY DESIGN CONSTRAINTS**

- maximum permitted cable temperature
- minimum permitted oil pressure
- maximum permitted cable line pressure
- maximum permitted return line pressure
- maximum allowable pump head
- maximum allowable pothead pressure

*Design-Option 2 input data

** Specified as part of General Program input data (see Table 2.2)
NLOOPS - Specified number of coolant loops

IFCₙ - Peak cable ampacity

AMPFAC - Ampacity ratio

ΔIFC - Incremental value of ampacity

Figure 8.1 Design-Option 6 Flow Chart.
loops (for a specified total system length), as determined in D.O.2, just exceeds that number of coolant loops specified in D.O.6. The ampacity is then decreased in small increments until the calculated number of loops again equals the specified number. Thus the ampacity is maximized and the iterative analysis ends.

8.3 Design-Option 6 - Computer Documentation

8.3.1 Input Variables for Design-Option 6

The input variables used in Design-Option 6 are listed in Table 8.2 along with a brief description of each variable. Comments concerning these variables are provided below.

The specified value of TOILMN must always remain within the temperature range of the oil property data.

The total system axial length, FLT, refers to the total axial length of the cable line. It does not refer to the combined lengths of the cable line and return line.

The input of the ampacity factor value, AMPFAC, allows for the flexibility of selecting that ampacity (some percentage of the peak cable ampacity) which is used for the calculation of the cable energy losses. Use of the peak ampacity value for the calculation of cable losses (AMPFAC=1.0) always results in a conservative estimate of the maximum possible loop ampacity.

The value of DTHE must be specified in order to prevent the computer program from choosing an ampacity which yields a value of THOT less than the value of TCOLD (TOILMN). Also, other reasons may exist which necessitate the specification of a minimum value of the heat
### TABLE 8.2
**INPUT VARIABLES FOR DESIGN-OPTION 6**

<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>DESCRIPTION AND DIMENSION ( )</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPROB</td>
<td>6-variable which &quot;informs&quot; the computer program that Design-Option 6 is being used (dimensionless)</td>
</tr>
<tr>
<td>NUPROB</td>
<td>0 - denotes that no new problems follow the present problem</td>
</tr>
<tr>
<td></td>
<td>1 - denotes that a new problem follows the present problem (prevents termination of the program and allows a new data set to be inputted (dimensionless)</td>
</tr>
<tr>
<td>TOILMN</td>
<td>the specified heat exchanger outlet temperature for the coolant loop under study (°F)</td>
</tr>
<tr>
<td>FLT</td>
<td>the total forced-cooled system axial length (ft)</td>
</tr>
<tr>
<td>AMPFAC</td>
<td>the ampacity factor - the desired (or expected) ratio of the average cable ampacity and the (calculated) peak cable ampacity (used in order to accurately model cable energy losses (dimensionless)</td>
</tr>
<tr>
<td>DTHE</td>
<td>the minimum permissible heat exchanger temperature drop (°F)</td>
</tr>
<tr>
<td>NLOOPS</td>
<td>the desired number of system coolant loops (dimensionless)</td>
</tr>
</tbody>
</table>
exchanger temperature drop. If the program cannot design the system without violating this constraint value, an error message is printed and the program stops.

8.3.2 Output for Design-Option 6

After the General Program input data is printed out, the input data associated with Design-Option 5 is printed out under the title DESIGN-OPTION 5 - PRINTOUT OF INPUT DATA.

The results of the computer analysis are printed out under the title Design-Option 5----RESULTS. Option 6 utilizes the input information to calculate the maximum permitted cable ampacity as well as the average loop ampacity (based on AMPFAC) and the loop pressure profile, loop temperature profile, and loop length for each system coolant loop. The General Program output format is used which is self-explanatory.

8.3.3 Array Dimensions

The number of system coolant loops analyzed in Design-Option 6 can never exceed the value of MAXLPS, the array dimension value of all subscripted variables whose subscript value depends on the loop number (i.e. LLTH(1) = loop length of loop number 1 - used in the program). Refer to Section 2.2.3 for details.

8.3.4 Error Messages for Design-Option 6

Design-Option 6 generates error messages when certain design parameters (created from the input variables) fall outside the range capabilities of the program or when specified design constraints are exceeded. Those computer program error messages which apply to Design-
Option 6 are listed below. Any additional information, which is pertinent to the application of a given error to the design-option, is provided.

a) Errors 1-5
b) Error 6

This error may occur during the system analysis even though the final result is okay. Therefore, if Error 6 is printed, it is suggested that the value of INOND be calculated by hand (for the resultant ampacity value). If INOND is within the range of its limiting value, then the output is valid.

c) Errors 7-8
d) Error 10

This error occurs in Design-Option 6, typically, because the desired number of coolant loops is too small. A small number of system loops produces large loop lengths which require low values of flow rate in order to meet pressure drop constraints. Design-Option 6 subsequently selects a low ampacity value in order to maximize the loop temperature drop and minimize the loop flow rate. However, if a flow rate cannot be found which maintains loop pressures within specified constraints, then Error 10 is printed and the program is terminated.

e) Error 15

This error typically occurs in Design-Option 6 when a very large number of coolant loops is desired. A large number of system loops produces small loop lengths which require high values of flow rate in order to meet specified pressure drop constraints. Subsequently, a high
Ampacity value is selected in order to minimize the loop temperature drop and maximize the flow rate. If the specified value of DTHE is small, it is possible (although improbable) that the program cannot find an ampacity which produces the necessary flow rate.

f) Errors 16-17

8.3.5 Data Card Assembly for Design-Option 6

Instructions for assembling the data cards for Design-Option 6 are listed in Table 8.3. The card numbering sequence continues directly from the General Program input cards. It is necessary that variables using the I-format be right-adjusted in the column field.

8.3.6 Example Problem for Design-Option 6

This section illustrates the solution of a particular forced-cooled system design problem utilizing computer program Design-Option 6. Design-Option 6 is to be used to determine the maximum cable ampacity value that can be attained for the system analyzed in Section 3.2.5. The same number of coolant loops is specified as is the same ampacity factor. The complete set of Option 6 input data is listed in Table 8.4. The General Program input data remains unchanged (see Section 2.2.6). The computer program output is listed in Table 8.5 (compare with the output of the Design-Option 1 example problem).
### Table 8.3

**Data Card Assembly for Design-Option 6**

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMN(s)</th>
<th>VARIABLE**</th>
<th>FORMAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>1-10</td>
<td>IPROB</td>
<td>I10</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>NUPROB</td>
<td>I10</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td>TOILMN</td>
<td>F10.3</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>FLT</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>AMPFAC</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>DTHE</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>1-10</td>
<td>NLOOPS</td>
<td>I10</td>
</tr>
</tbody>
</table>

**See Table 8.2 for variable dimensions**
### TABLE 8.4
INPUT DATA FOR DESIGN-OPTION 6 EXAMPLE PROBLEM

<table>
<thead>
<tr>
<th>CARD</th>
<th>COLUMN(s)</th>
<th>DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>1-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>51000.0</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>5.0</td>
</tr>
<tr>
<td>21</td>
<td>10</td>
<td>6</td>
</tr>
</tbody>
</table>
TABLE 8.5
COMPUTER PROBLEM NUMBER 1
****************************************

**DESIGN-OPTION 6**
--PRINTOUT OF INPUT DATA--

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Exchanger Outlet Temperature (F)</td>
<td>95.000</td>
</tr>
<tr>
<td>Total System Axial Length (FT)</td>
<td>51000.000</td>
</tr>
<tr>
<td>Ampacity Factor (Dimensionless)</td>
<td>0.890</td>
</tr>
<tr>
<td>Minimum Permissible Heat Exchanger Temperature Drop (F)</td>
<td>5.000</td>
</tr>
</tbody>
</table>

**DESIGN-OPTION 6----RESULTS**

--LOOP HYDRAULIC INFORMATION--

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop Axial Length (FT)</td>
<td>8515.63</td>
</tr>
<tr>
<td>Loop Flow Rate (GAL/MIN)</td>
<td>534.38</td>
</tr>
<tr>
<td>Cable Line Dynamic Pressure Loss/FT (PSI/FT)</td>
<td>0.208E-01</td>
</tr>
<tr>
<td>Cable Line Dynamic Pressure Loss (PSI)</td>
<td>177.54</td>
</tr>
<tr>
<td>Return Line Dynamic Pressure Loss/FT (PSI/FT)</td>
<td>0.295E-01</td>
</tr>
<tr>
<td>Return Line Dynamic Pressure Loss (PSI)</td>
<td>251.46</td>
</tr>
<tr>
<td>Pump Inlet Pressure (PSI)</td>
<td>147.78</td>
</tr>
<tr>
<td>Pump Outlet Pressure (PSI)</td>
<td>596.78</td>
</tr>
<tr>
<td>Loop Pumping Power (Watts)</td>
<td>104133.06</td>
</tr>
<tr>
<td>System Head Tank Pressure (PSI)</td>
<td>167.78</td>
</tr>
</tbody>
</table>

Absolute Pressures at Elevation Profile Points Located Within Loop Number 1 (Including Loop End Point Pressures).

<table>
<thead>
<tr>
<th>System Axial Distance (FT)</th>
<th>Absolute Pressure Cable Line (PSI)</th>
<th>Absolute Pressure Return Line (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>167.78</td>
<td>596.78</td>
</tr>
<tr>
<td>5000.00</td>
<td>272.02</td>
<td>449.14</td>
</tr>
<tr>
<td>8515.63</td>
<td>332.82</td>
<td>332.82</td>
</tr>
</tbody>
</table>

Loop Pressure Profile 15-Points
### TABLE 8.5 (CONT'D.)

<table>
<thead>
<tr>
<th>(FT)</th>
<th>(PSI)</th>
<th>(PSI)</th>
<th>420</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>167.78</td>
<td>596.78</td>
<td></td>
</tr>
<tr>
<td>608.26</td>
<td>180.46</td>
<td>578.82</td>
<td></td>
</tr>
<tr>
<td>1216.52</td>
<td>193.14</td>
<td>560.86</td>
<td></td>
</tr>
<tr>
<td>1824.78</td>
<td>205.82</td>
<td>542.90</td>
<td></td>
</tr>
<tr>
<td>2433.04</td>
<td>218.50</td>
<td>524.94</td>
<td></td>
</tr>
<tr>
<td>3041.29</td>
<td>231.19</td>
<td>506.98</td>
<td></td>
</tr>
<tr>
<td>3649.55</td>
<td>243.87</td>
<td>489.01</td>
<td></td>
</tr>
<tr>
<td>4257.81</td>
<td>256.55</td>
<td>471.05</td>
<td></td>
</tr>
<tr>
<td>4866.07</td>
<td>269.23</td>
<td>453.09</td>
<td></td>
</tr>
<tr>
<td>5474.32</td>
<td>280.23</td>
<td>433.44</td>
<td></td>
</tr>
<tr>
<td>6082.58</td>
<td>290.76</td>
<td>413.32</td>
<td></td>
</tr>
<tr>
<td>6690.84</td>
<td>301.29</td>
<td>393.20</td>
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</tr>
<tr>
<td>7299.10</td>
<td>311.81</td>
<td>373.07</td>
<td></td>
</tr>
<tr>
<td>7907.36</td>
<td>322.34</td>
<td>352.95</td>
<td></td>
</tr>
<tr>
<td>8515.61</td>
<td>332.87</td>
<td>332.82</td>
<td></td>
</tr>
</tbody>
</table>

### --LOOP THERMAL INFORMATION--

| SYSTEM FORCED-COOLED PEAK AMPACITY RATING (AMPS) | 1542.188 |
| AVERAGE FORCED-COOLED AMPACITY (AMPS) | 1372.547 |
| TOTAL SYSTEM ENERGY LOSS (WATTS/FT) | 68.36 |
| HEAT EXCHANGER INLET TEMPERATURE (F) | 113.29 |
| (MAXIMUM PERMITTED OIL TEMPERATURE) | |
| HEAT EXCHANGER OUTLET TEMPERATURE (F) | 95.00 |
| TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) | 0.544E 06 |

### LOOP TEMPERATURE PROFILE 11-POINTS

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CABLE LINE</td>
</tr>
<tr>
<td></td>
<td>(FT)</td>
</tr>
<tr>
<td>0.00</td>
<td>113.29</td>
</tr>
<tr>
<td>851.56</td>
<td>111.65</td>
</tr>
<tr>
<td>1703.13</td>
<td>109.97</td>
</tr>
<tr>
<td>2554.69</td>
<td>108.28</td>
</tr>
<tr>
<td>3406.25</td>
<td>106.56</td>
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<td>4257.81</td>
<td>104.82</td>
</tr>
<tr>
<td>5109.38</td>
<td>103.05</td>
</tr>
<tr>
<td>5960.94</td>
<td>101.26</td>
</tr>
<tr>
<td>6812.50</td>
<td>99.45</td>
</tr>
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<td>7664.06</td>
<td>97.61</td>
</tr>
<tr>
<td>8515.63</td>
<td>95.74</td>
</tr>
</tbody>
</table>

### ***

SYSTEM LOOP NUMBER 2

### ---LOOP HYDRAULIC INFORMATION---

<table>
<thead>
<tr>
<th>LOOP AXIAL LENGTH (FT)</th>
<th>8453.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCG: FLOW RATE (GAL/MIN)</td>
<td>531.25</td>
</tr>
</tbody>
</table>
TABLE 8.5 (CONT'D.)

<table>
<thead>
<tr>
<th></th>
<th>CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</th>
<th>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</th>
<th>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</th>
<th>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</th>
<th>PUMP INLET PRESSURE (PSI)</th>
<th>PUMP OUTLET PRESSURE (PSI)</th>
<th>LOOP PUMPING POWER (WATTS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.206E-01</td>
<td>174.34</td>
<td>0.292E-01</td>
<td>247.14</td>
<td>133.21</td>
<td>574.68</td>
<td>101787.19</td>
</tr>
</tbody>
</table>

**ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 2 (INCLUDING LOOP END POINT PRESSURES).**

<table>
<thead>
<tr>
<th>SYSTEM AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8515.63</td>
<td>332.82</td>
<td>332.82</td>
</tr>
<tr>
<td>10000.00</td>
<td>296.94</td>
<td>370.95</td>
</tr>
<tr>
<td>16968.75</td>
<td>153.21</td>
<td>574.68</td>
</tr>
</tbody>
</table>

**LOOP PRESSURE PROFILE 15-POINTS**

<table>
<thead>
<tr>
<th>LOOP AXIAL DISTANCE (FT)</th>
<th>ABSOLUTE PRESSURE CABLE LINE (PSI)</th>
<th>ABSOLUTE PRESSURE RETURN LINE (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>332.82</td>
<td>332.82</td>
</tr>
<tr>
<td>603.79</td>
<td>318.23</td>
<td>348.33</td>
</tr>
<tr>
<td>1207.59</td>
<td>303.64</td>
<td>363.83</td>
</tr>
<tr>
<td>1811.38</td>
<td>290.21</td>
<td>380.50</td>
</tr>
<tr>
<td>2415.18</td>
<td>277.75</td>
<td>398.15</td>
</tr>
<tr>
<td>3018.97</td>
<td>265.30</td>
<td>415.81</td>
</tr>
<tr>
<td>3622.77</td>
<td>252.85</td>
<td>433.46</td>
</tr>
<tr>
<td>4226.56</td>
<td>240.40</td>
<td>451.11</td>
</tr>
<tr>
<td>4830.35</td>
<td>227.94</td>
<td>468.76</td>
</tr>
<tr>
<td>5434.14</td>
<td>215.49</td>
<td>486.42</td>
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<td>6037.94</td>
<td>203.04</td>
<td>504.07</td>
</tr>
<tr>
<td>6641.73</td>
<td>190.58</td>
<td>521.72</td>
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<td>7245.52</td>
<td>178.13</td>
<td>539.37</td>
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<tr>
<td>7849.32</td>
<td>165.68</td>
<td>557.03</td>
</tr>
<tr>
<td>8453.11</td>
<td>153.23</td>
<td>574.68</td>
</tr>
</tbody>
</table>

**--LOOP THERMAL INFORMATION--**

| HEAT EXCHANGER INLET TEMPERATURE (F) | 113.29 |
| MAXIMUM PERMITTED OIL TEMPERATURE |
| HEAT EXCHANGER OUTLET TEMPERATURE (F) | 95.00 |
| TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) | 0.541E 06 |

**LOOP TEMPERATURE PROFILE 11-POINTS**

<table>
<thead>
<tr>
<th>LOOP TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
</tr>
</tbody>
</table>
### TABLE 8.5 (CONT'D.)

<table>
<thead>
<tr>
<th>AXIAL DISTANCE (FT)</th>
<th>CABLE LINE (FT)</th>
<th>RETURN LINE (FT)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>95.00</td>
</tr>
<tr>
<td>845.31</td>
<td>111.65</td>
<td>95.16</td>
</tr>
<tr>
<td>1690.63</td>
<td>109.98</td>
<td>95.29</td>
</tr>
<tr>
<td>2535.94</td>
<td>108.28</td>
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<td>3381.25</td>
<td>106.57</td>
<td>95.50</td>
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<tr>
<td>4226.56</td>
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<tr>
<td>5071.87</td>
<td>103.06</td>
<td>95.65</td>
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**SYSTEM LOOP NUMBER 3**

---

**LOOP HYDRAULIC INFORMATION**

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**LOOP PRESSURE PROFILE 15-POINTS**

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TABLE 8.5 (CONT'D.)

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--LOOP THERMAL INFORMATION--

HEAT EXCHANGER INLET TEMPERATURE (F) .................. 113.29
(MAXIMUM PERMITTED OIL TEMPERATURE)
HEAT EXCHANGER OUTLET TEMPERATURE (F) ................. 95.00
TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) ........ 0.542E 06

LOOP TEMPERATURE PROFILE 11-POINTS

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***

SYSTEM LOOP NUMBER 4

***

--LOOP HYDRAULIC INFORMATION--

| LOOP AXIAL LENGTH (FT) .................. | 8484.37 |
| LOOP FLOW RATE (GAL/Min) ................ | 532.81  |
| CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.207E-01 |
| CABLE LINE DYNAMIC PRESSURE LOSS (PSI) ....... | 175.92  |
| RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) | 0.294E-01 |
| RETURN LINE DYNAMIC PRESSURE LOSS (PSI) ....... | 249.29  |
| PUMP INLET PRESSURE (PSI) ................ | 186.54  |
| PUMP OUTLET PRESSURE (PSI) ............... | 631.75  |
| LOOP PUMPING POWER (WATTS) .............. | 102951.50 |

ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS
LOCATED WITHIN LOOP NUMBER 4 (INCLUDING LOOP END POINT PRESSURES).

SYSTEM
ABSOLUTE PRESSURE
### Table 8.5 (Cont'd.)

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### Loop Pressure Profile 15-Points

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### Loop Thermal Information

- **Heat Exchanger Inlet Temperature (F)**: 113.29 (Maximum Permitted Oil Temperature)
- **Heat Exchanger Outlet Temperature (F)**: 95.00
- **Total Heat Exchanger Cooling Capacity (Watts)**: 0.542E 06

### Loop Temperature Profile 11-Points

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### LOOP HYDRAULIC INFORMATION

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<td><strong>LOOP FLOW RATE (GAL/MIN)</strong></td>
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<td><strong>CABLE LINE DYNAMIC PRESSURE LOSS (PSI)</strong></td>
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<td><strong>RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT)</strong></td>
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<td><strong>RETURN LINE DYNAMIC PRESSURE LOSS (PSI)</strong></td>
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<td><strong>LOOP PUMPING POWER (WATTS)</strong></td>
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Absolute pressures at elevation profile points located within Loop Number 5 (including loop end point pressures).

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--- LOOP PRESSURE PROFILE 15-POINTS ---

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--- LOOP THERMAL INFORMATION ---

Heat Exchanger Inlet Temperature (F) | 113.29
TABLE 8.5 (CONT'D.)

(HALF MAXIMUM PERMITTED OIL TEMPERATURE)

\textbf{HEAT EXCHANGER OUTLET TEMPERATURE (F)} \quad 95.00

\textbf{TOTAL HEAT EXCHANGER COOLING CAPACITY (Watts)} \quad 0.545E 06

\textbf{LOOP TEMPERATURE PROFILE 11-POINTS}

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<tr>
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<th>CABLE LINE TEMPERATURE (F)</th>
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--- LOOP HYDRAULIC INFORMATION ---

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<tr>
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ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS LOCATED WITHIN LOOP NUMBER 6 (INCLUDING LOOP END POINT PRESSURES).

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--- LOOP PRESSURE PROFILE 15-POINTS ---

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**--LOOP THERMAL INFORMATION--**

| HEAT EXCHANGER INLET TEMPERATURE (F) | 113.29 |
| MAXIMUM PERMITTED OIL TEMPERATURE    |       |
| HEAT EXCHANGER OUTLET TEMPERATURE (F) | 95.00  |
| TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) | 0.545E06 |

**LOOP TEMPERATURE PROFILE 11-POINTS**

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APPENDIX A: A SOURCE LISTING OF "THE FORCED-COOLED UNDERGROUND PIPE-TYPE TRANSMISSION SYSTEM DESIGN ANALYSIS" COMPUTER PROGRAM

The computer code has been written in a standard FORTRAN IV computer language. The program version listed requires 80,000 bytes of storage space. Design-options 1 and 3 have typical run times of less than two minutes when analyzing a six-loop forced-cooled system. Design-options 2 and 6 have typical run times of approximately four to five minutes for analysis of a six loop system. Run time for these four options is dependent upon the number of coolant loops analyzed. Design-options 4 and 5 have typical run times of under one minute.

To use the code on a machine different from the one for which it was written, it may be necessary to change the values of the NW and NR integer variables appearing near the beginning of the main program (after the Dimension statements). They refer, respectively, to the device numbers of the printer and the reader.

User instructions for each computer program design-option are contained in the respective design-option chapters of the computer program design manual.
REAL IF,IFCAGV,LLTH,KOIL,KTAPE,NL,INOND,LOPEL,LLTHMN,
*LL, LHI, LLO, IFC, IFCG, IFCG, IFCG, IFCG, IFCG, IFCG,
DIMENSION LLTH(30),THOT(30),TCOLD(30),
1LOPEL(31),PRESCL(31),PRESRL(30),DPLCL(30),
2DPLRL(30),SDP(30),PWRPM(30),PWRREF(30),
3PDIFHC(30),PDIFHR(30),PDIFLO(30),NPC(30),
4NPR(30),NPCLO(30),DPLULC(30),DPLULR(30),
5SPRESS(31),DPEL(30),XFL(31),FLOWRT(30)
DIMENSION DNTY(20),VSCTY(20),SPECHT(20),
1TEMPD(20),TEMPSH(20),TEPV(20),F1(20),
2XP(20),F(20)
DIMENSION PR(50),PC(50),XDIST(50),
1PLTH(51),PEL(51),PDIFFC(51),PDIFFR(51),
2PDIFFL(51),HTDN(50),HTDP(50)
DIMENSION PR(50),PRC(50),XPDIST(50)
DIMENSION TR(50),TC(50),XTDIST(50)
DIMENSION FLRT(40),ICHNG(40),KCHNG(40),LL(40),IFCD(40)
MAXLPS=30
NPVALM=20
NPPTSM=50
NLPTM=50
NLPTM=50
MAXLP1=MAXLPS+1
NPPTS1=NPPTSM+1
NW=5
NR=8
ERR1=0.0
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ERR2=0.0
ERR3=0.0
ERR4=0.0
ERR5=0.0
ERR6=0.0

C GENERAL PROGRAM INPUT DATA
MPR=0

C OIL PROPERTIES
READ(NP,01)NDPTS
READ(NP,02)(DNTY(I),I=1,NDPTS)
READ(NP,02)(TEMPD(I),I=1,NDPTS)
READ(NP,01)NSHPTS
READ(NP,02)(SPECHT(I),I=1,NSHPTS)
READ(NP,02)(TEMPSH(I),I=1,NSHPTS)
READ(NP,01)NVPTS
READ(NP,02)(VSCTY(I),I=1,NVPTS)
READ(NP,02)(TEMPV(I),I=1,NVPTS)
READ(NP,03)KOIL,COTHEX

01 FORMAT(10)
02 FORMAT(6F10.4)
03 FORMAT(F10.4,E10.4)

C PIPE-TYPE CABLE GEOMETRY
READ(NP,04)SWH,PITCH,TAPTH,SWANG,DPIPE,DPRIPE,DCOND,DCABLE

04 FORMAT(6F10.3)

C SYSTEM ELECTRICAL CHARACTERISTICS
READ(NP,05)RDC,WD,YC,YS,YP

05 FORMAT(E10.3,4F10.3)

C SYSTEM THERMAL CHARACTERISTICS
READ(NP,06)KTAPE,F11,F12,F22,Q1A,Q2A

06 FORMAT(6F10.3)
C SYSTEM OPERATING CONSTRAINTS
READ(NR,07)TCABMX,PMIN,PMAXCL,PMAXRL,PHDMAX,PPHMAX
07 FORMAT(6F10.2)
C SYSTEM ELEVATION PROFILE
READ(NR,09)NPPTS
09 FORMAT(I10)
READ(NR,10)(PLTH(I),I=1,NPPTS)
READ(NR,10)(PEL(I),I=1,NPPTS)
10 FORMAT(8F10.2)
C ADDITIONAL THERMAL AND HYDRAULIC INPUT INFORMATION
READ(NR,08)NLPPTS,NLTPTS,LTHEQ,DPHE
08 FORMAT(2I0,2F10.2)
C DESIGNATE PROBLEM-OPTION AND INDICATE IF ANOTHER PROBLEM FOLLOWS
11 READ(NR,12)IPROB,NUPROB
12 FORMAT(2I10)
NUPR=NUPR+1
C SYSTEM PROBLEM OPTIONS--INPUT SPECIFIED
C OPERATIONAL VARIABLES
IF(IPROB.EQ.1)GO TO 13
IF(IPROB.EQ.2)GO TO 16
IF(IPROB.EQ.3)GO TO 18
IF(IPROB.EQ.4)GO TO 22
IF(IPROB.EQ.5)GO TO 60
IF(IPROB.EQ.6)GO TO 24
C PROBLEM-OPTION-1--INPUT VARIABLES
13 READ(NR,14)IFC,IFCAVG,FLT
14 FORMAT(3F10.3)
READ(NR,01)NLOOPS
READ(NR,15)(LLTH(I),I=1,NLOOPS)
READ(NR,15)(TCOLD(I),I=1,NLOOPS)
FORMAT(8F10.3)
GO TO 27

C PROBLEM OPTION-2---INPUT VARIABLES
READ(NR,17)IFC,IFCAG,FLT,TOILMN,LLTHMN
FORMAT(5F10.3)
GO TO 28

C PROBLEM OPTION-3---INPUT VARIABLES
READ(NR,19)IFC,IFCAVG,FLT
FORMAT(3F10.3)
READ(NR,01)NLOOPS
READ(NR,20)(LLTH(I),I=1,NLOOPS)
FORMAT(8F10.3)
READ(NR,21)(FLOWRT(I),I=1,NLOOPS)
FORMAT(8F10.3)
GO TO 27

C PROBLEM OPTION-4---INPUT VARIABLES
READ(NR,23)TOILMN,TOILMX,XLTH,AMPFAC
FORMAT(4F10.3)
GO TO 28

C PROBLEM OPTION-5---INPUT VARIABLES
READ(NR,61)TOILMN,XLTH,PCLOW,PCHIGH,PRHIGH,DTHF,AMPFAC
FORMAT(7F10.3)
READ(NR,62)EVODD
FORMAT(F10.1)
GO TO 28

C PROBLEM OPTION 6---INPUT VARIABLES
READ(NR,25)TOILMN,FLT,AMPFAC,DTHF
25 FORMAT(4F10.3)
   READ(NR,26)NLOOPS
26 FORMAT(I10)
   GO TO 28
C
C CHECK ON PROGRAM PARAMETER LIMITS AND CONSTRAINTS
C CHECK FOR AN EVEN NUMBER OF SYSTEM COOLANT LOOPS
   IF(NLOOPS.EQ.1)GO TO 28
27 IF(IPROB.EQ.2.0R.IPROB.EQ.4.OR.IPROB.EQ.5)GO TO 28
   CALL EVORD(NLOOPS,EVODD)
   IF(EVODD.EQ.1.0)GO TO 28
   GO TO 34
C
C PRESSURE DROP CORRELATION LIMITS
28 IF(DCABLE/DPIPE.LT.0.3.0R.DCABLE/DPIPE.GT.0.45)GO TO 36
29 IF(SWH/DCABLE.LT.0.005.0R.SWH/DCABLE.GT.0.04)GO TO 38
30 IF(PITCH/SWH.LT.10.0.OR.PITCH/SWH.GT.40.0)GO TO 40
31 IF(SWANG.LT.0.0.OR.SWANG.GT.60.0)GO TO 42
32 IF(IPROB.GE.4)GO TO 46
C
C PIPE-TYPE CABLE SYSTEM HEAT TRANSFER CORRELATION LIMITS
   INOND=(1.0+YC)*RDC*IFC*IFC/WD
   IF(INOND.LT.0.35.OR.INOND.GT.12.0)GO TO 44
33 IF(ERR1.EQ.1.0.OR.ERR2.EQ.1.0.OR.ERR3.EQ.1.0.OR.ERR4
   *.EQ.1.0.OR.ERR5.EQ.1.0.OR.ERR6.EQ.1.0)GO TO 10000
   GO TO 46
C
C ERROR STATEMENTS
34 ERR1=1.0
   WRITE(NW,35)NLOOPS
35 FORMAT(18X,
      ***ERROR 5***"/20X,
         **NUMBER OF SYSTEM LOOPS =',I3,' FORCED-COOLER"/20X,
         **SYSTEM IS INCORRECTLY BEING DESIGNED FOR AN"/20X,
* ODD NUMBER OF COOLANT LOOPS. INPUT A NEW VALUE OF NLOOPS. */
GO TO 28

36 ERR2=1.0
RDODP=DCABLE/DPIPE
WRITE(NW,37)RDODP
37 FORMAT(18X,
***ERROR 1***/20X,
*PARAMETER DCABLE/DPIPE (=',F8.3,' ) IS OUTSIDE'/20X,
*THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM'/20X,
*PRESSURE-DROP CORRELATION. 0.3 <DCABLE/DPIPE< 0.45.'//)
GO TO 29

38 ERR3=1.0
RSWDC=SWH/DCABLE
WRITE(NW,39)RSWDC
39 FORMAT(18X,
***ERROR 2***/20X,
*PARAMETER SWH/DCABLE (=',F8.3,' ) IS OUTSIDE'/20X,
*THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM'/20X,
*PRESSURE-DROP CORRELATION. 0.005 <SWH/DCABLE< 0.04.'//)
GO TO 30

40 ERR4=1.0
RPISWH=PITCH/SWH
WRITE(NW,41)RPISWH
41 FORMAT(18X,
***ERROR 3***/20X,
*PARAMETER PITCH/SWH (=',F8.3,' ) IS OUTSIDE THE'/20X,
*LIMITS OF THE PIPE-TYPE CABLE SYSTEM'/20X,
*PRESSURE-DROP CORRELATION. 10.0 <PITCH/SWH< 40.0.'//)
GO TO 31

42 ERR5=1.0
WRITE(NW,43)SWANG
43 FORMAT(18X,
***ERROR 4***/20X,
*PARAMETER SWANG ('F8.3,' ) IS OUTSIDE'/20X,
* 'THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM'/20X,
* 'PRESSURE-DROP CORRELATION. 0.0 <SWANG<60.0.'//)
GO TO 32
44 ERR6=1.0
WRITE(NW,45)INOND,IFC
45 FORMAT(18X,
**ERROR 6**'/20X,
*THE VALUE OF THE PARAMETER INOND ('F8.3,' )'/20X,
*IS OUTSIDE THE LIMITS OF THE PIPE-TYPE CABLE SYSTEM'/20X,
*HEAT TRANSFER CORRELATION. THE RESULTS OF THE ANALYSIS'/20X,
*ARE NOT VALID FOR AN AMPACITY VALUE EQUAL TO ',F8.3,' AMPS.'/20X,
*0.35 <INOND< 12.0'//)
GO TO 33
C
C EVALUATE REQUIRED SYSTEM PARAMETERS
46 PWETC=3.1416*(DPIPE+3.0*DCABLE)
PETR=3.1416*DRPIPE
AFLOWC=3.1416*(DPIPE**2-3.0*DCABLE**2)/4.0
AFLOWR=3.1416*DRPIPE**2/4.0
TEMBIG=TEPV(1)
DO 48 I=2,NVPTS
IF(TEMBIG-TEPV(I))47,48,48
47 TEMBIG=TEPV(I)
48 CONTINUE
TEMSM=TEPV(1)
DO 50 I=2,NVPTS
IF(TEPV(I)-TEMSM)49,50,50
49 TEMSM=TEPV(I)
50 CONTINUE
IF(IPROB.EQ.1)GO TO 100
IF(IPROB.EQ.2)GO TO 200
IF(IPROB.EQ.3)GO TO 300
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IF(IPROB.EQ.4)GO TO 400
IF(IPROB.EQ.5)GO TO 500
IF(IPROB.EQ.6)GO TO 600

C PROBLEM OPTION 1
C CALCULATE CABLE ENERGY LOSSES
100 CALL CLOSS(IFC,IFCAVG,RDC,YC,YS,YP,WD,W,WC)

LOOPNO=0
10010 LOOPNO=LOOPNO+1
XLTH=LLTH(LOOPNO)
TOILMN=TCOLD(LOOPNO)

C SATISFY ENERGY BALANCE AND PIPE-TYPE CABLE HEAT TRANSFER
C CORRELATION IN ORDER TO MAXIMIZE HEAT EXCHANGER INLET
C TEMPERATURE.

ICNT1=1
C INITIALIZE VALUE OF TOILMX
NBYPAS=1
CALL HEATTR(DCOND,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC,
*YS,TC,BMX,PWET,AFLOW,FLRATE,IFC,TOILMX,COTHEX,RNC,RAYN,IPROB,
*DNTY,SPECHT,VSCTY,TEMPD,TEMPH,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
*DTY,SPHT,VTY,FILMC,CONV,TAPE,THETA,NBYPAS,F1,XP,NPVALM)
NBYPAS=0
ISKIP1=0
IF(TOILMX.GT.TOILMN)GO TO 101

10011 WRITE(NW,972)TOILMX,LOOPNO
GO TO 10000
101 TOIL=TOILMX
IF(ICNT1.GT.50)GO TO 10000

C CALCULATE OIL FLOW RATE
TDIST=0.0
CALL ENBAL2(FLRATE,TOILMN,TOILMX,XLTH,W,F11,F12,F22,Q1A,
*Q2A,DNTY,SPECHT,VSCTY,TEMPD,TEMPH,TEMPV,NDPTS,NSHPTS,NVPTS,
*TAVG,DTY,SPHT,VTY,TOILCR,TC,TH,XTDIST,XL1,XL2,A1,A2,
*B1,B2,C1,C2,X3,ISKIP1,ISKIP2,NBYPAS1,LOOPNO,IPROB,TDIST,
*F1,XP,F,NPVALM,NLTPTM,NLTPTS)
IF(TDIST.NE.100.0)GO TO 10012
WRITE(NW,973)LOOPNO,TOILMN,TOILMX
GO TO 10000
10012 IF(TDIST.NE.200.0)GO TO 10013
WRITE(NW,975)FLRATE,TOILMX,TOILMY
10013 ICNT1=ICNT1+1
TAVG=TOILMX
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,P,NPVALM)
RNC=(FLRATE*DTY)/(VTY*PWETC*6.271E-3)
CALL HEATTR(DCOND,DCABLE,DPIPE,TAPTH,KOIL,WD,KTAPF,RDC,YC,
*YS,TCABMX,PWET,AFLOW,FLRATE,IFC,TOILMX,COHEX,RNC,RAYN,IPRB,
*DTY,SPHT,VTY,FILMC,CONV,TCAPE,TETR,NBYPAS,F,F1,XP,NPVALM)
IF(TOILMX.LE.TOILMN)GO TO 10011
IF(ABS(TOIL-TOILMX).LE.0.25)GO TO 107
ISKIP1=1
GO TO 101
C CALCULATE TEMPERATURE DISTRIBUTION
102 FLRT(LOOPNO)=FLRATE
ISKIP2=1
TDIST=1.0
CALL ENBAL2(FLRATE,TOILMN,TOILMX,XLTH,W,F11,F12,F22,Q1A,
*C2A,DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,NVPTS,
*TAVG,DTY,SPHT,VTY,TOILCR,TC,TR,XTDIST,XL1,XL2,A1,A2,
*31,B2,C1,C2,X3,ISKIP1,ISKIP2,NBYES1,LOOPNO,IPRB,TDIST,
*F1,XP,F,NPVALM,NLTPTM,NLTPTS)
ISKIP1=0
ISKIP2=0
THOT(LOOPNO)=TOILMX
TCOLD(LOOPNO)=TOILMN
PWRRF(LoopNO)=2.35*DTY*SPHT*FLRATE*(TOILMX-TOILMN)
TAVG = (TOILMN + TOILCR) / 2.0
CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)

CALL PTINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS,
* NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, MPVALM)
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PRESRL(LOOPNO) = PRESCL(LOOPNO+1) + DPLRL(LOOPNO) - DPEL(LOOPNO)
PINLET = ABS(PRESCL(LOOPNO) - DPHE)
GO TO 105

104 PRESCL(LOOPNO+1) = PRESCL(LOOPNO) - DPLCL(LOOPNO) + DPEL(LOOPNO)
PRESRL(LOOPNO) = PRESCL(LOOPNO) + DPLRL(LOOPNO) + DPEL(LOOPNO)
PINLET = ABS(PRESCL(LOOPNO+1) - DPHE)

C CALCULATE REQUIRED LOOP PUMP POWER
105 DPPUMP = PRESRL(LOOPNO) - PINLET
PWRPMP(LOOPNO) = 0.434 * DPPUMP * FLRATE

C DETERMINE LOOP PRESSURE PROFILE AND CHECK INTERIOR LOOP POINTS FOR EXCESSIVE PRESSURES
CALL PRDIST(PRESCL, PRESRL, NPPTS, SPRESS, DPLULC, * DPLULR, PLTH, XFL, LOOPNO, IMEMRY, PEL, PC, PR, XDIST, * PDIFHC, PDIFHR, PDIFLO, NPC, NPR, NPCLC, K, DTY, PMAXCL, * PMAXR, PMIN, FLT, PDIFFFC, PDIFFFR, PDIFFLL, NPPTSM, NPPTS1, MAXLPS, MAXLP1)

CALL PPCALC(NPPTS, LOOPNO, XLTH, NLPT, PRESCL, NPPTS, * PRESRL, * LOOPNO, XFL, PLTH, PEL, LOOP, DTU, DTU, DPLULC, DPLULR, PRC, PRR, * XDIST, NLPT, MAXLPS, MAXLP1, NPPTS)
GO TO 900

C DESIGN OPTION 2
C CALCULATE CABLE ENERGY LOSSES
200 CALL CLOSS(IFC, IFCAVG, RD, YC, YS, YP, W, W, WC)

LOOPNO = 0
IFIX1 = 0
IFIX2 = 0
IFIX4 = 0
ISARA = 0
IPCS = 0

201 LOOPNO = LOOPNO + 1
DELL = 5000.0
IF (LOOPNO .GT. 1) DELL = 1000.0
IFIX3 = 0
KCHNG(1) = 1
IC=1
JAY1=0
JAY3=0

C INITIALIZE VALUE OF LOOP AXIAL LENGTH
IF(LOOPNO.GT.1)GO TO 202
IF(TPROB.EQ.6)GO TO 203
LLTH(LOOPNO)=15000.0
GO TO 203

202 LLTH(LOOPNO)=LLTH(LOOPNO-1)
203 LL(1)=LLTH(LOOPNO)

C SATISFY LOOP ENERGY BALANCE AND PIPE-TYPE CABLE
C HEAT TRANSFER CORRELATION IN ORDER TO MAXIMIZE HEAT
C EXCHANGER INLET TEMPERATURE.
C INITIALIZE TOILMX

NBYPAS=1
CALL HEATTR(DCOND,DCABLE,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC, *YS,TX,BMX,PF,EFLR,IFC,TOILMX,COTHX,RENC,RAYN,IPROB, *DNY,SYCMT,TEMPPD,TEMPPH,TEMPPV,NDSPTS,NMSPTS,NVPTS,TAVG, *DNY,SPTH,VTY,FILMC,CCONV,CTAPE,THEGA,NBYPAS,F,F1,XP,NPVALM)

NBYPAS=0
ISKIP1=0
IF(TOILMX.GT.TOILMN)GO TO 204

20400 WRITE(NW,1972)TOILMX,LOOPNO
TOIL=TOILMX
XLTH=LL(IC)
LLTH(LOOPNO)=LL(IC)

C CALCULATE OIL FLOW RATE
TDIST=0.0

CALL ENBALT2(FLRAT,TOILMN,TOILMX,XLTH,\n,F11,F12,F22,Q1A, *Q2A,DNTY,SYCMT,TEMPPD,TEMPPH,TEMPPV,NDSPTS,NMSPTS,NVPTS, *TAVG,DNY,SPTH,VTY,TOILCP,TC,TR,TDIST,XL1,XL2,A1,A2, *B1,B2,C1,C2,X3,ISKIP1,ISKIP2,NBYPAS,LOOPNO,IPROB,TDIST,
*F1,XP,F,NPVALM,NLPTM,NLTPS)
   IF(TDIST.NE.100.0)GO TO 20101
   WRITE(NW,973)LOOPNO,TOILMN,TOILMX
   GO TO 10000
20101 IF(TDIST.NE.200.0)GO TO 20102
   WRITE(NW,975)FLRATE,TOILMN,TOILMX
20102 TAVG=TOILMX
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
   *NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,YP,NPVALM)
   RNC=(FLRATE*DTY)/(VTY*PWETC*6.271E-3)
   CALL HEATTR(DCOND,DCA,EP,TAPTH,OLMT,KR,KT,P,EW4,TY,PP,SC,VTY,SS,
   *YS,TCABMX,PWET,AFLOW,FLRATE,IFC,TOILMX,COHEX,NC,RAH,RIN,IPR,H,
   *DTY,SPHT,VTY,FILMC,CCONV,CTAPE,THETA,NBYPAS,F,F1,XP,NPVALM)
   IF(TOILMX.LE.TOILMN)GO TO 20100
   IF(ABS(TOIL-TOILMX).LE.0.25)GO TO 205
   ISKIPI=1
   GO TO 204
205 FLRT(LOOPNO)=FLRATE
C CALCULATE LOOP PRESSURE PROFILE-MAXIMIZ PRESSURE DROP
206 IC=IC+1
   IF(LL(IC-1).EQ.0.0)GO TO 10000
   IF(ISARA.EQ.1.OR.ISARA.EQ.2)GO TO 20600
   IF(LL(IC-1).EQ.5000.0)DELLL=500.0
20600 IF(IC.GT.50)GO TO 10000
C CALCULATE AVERAGE OIL PROPERTIES FOR CAPLE LINE AND RETURN LINE
   TAVG=(TOILMX+TOILCR)/2.0
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
   *NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,YP,NPVALM)
   DTYC=DTY
   VTYC=VTY
   TAVG=(TOILMN+TOILCR)/2.0
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F1,YP,NPVALM)
DTYR=DTY
VTYP=VTY
IF(LOOPNO.GT.1)GO TO 207
C CALCULATE SYSTEM HEAD-TANK PRESSURE
CALL PHTDET(PEL,NPPTS,DTY,PMTNPHT,NPPTSM)
PRESCL(1)=PHT
IF(PHT.LT.PPHMAX.AND.PHT.LT.PMAXCL)GO TO 207
WRITE(NW,970)PHT
GO TO 10001
207 CALL PRDROP(DCABLE,DPIPE,SWH,PITCH,SWANG,DTYC,VTYC,DTYR,VTYR,
*PWETC,PWETR,AFLOWC,AFLOWR,FLRATE,FFSTD,FFC,FFR,RNC,RNR,
*IPFOR,DPLULC,DPLULR,LOOPNO,MAXLPS)
DPLCL(LOOPNO)=DPLULC(LOOPNO)*XLTH
DPLRL(LOOPNO)=DPLULR(LOOPNO)*(XLTH+LTHEQ)
C CALCULATE LOOP STATIC PRESSURES
CALL STPPG(DTY,LOOPNO,FLT,NPPTS,PLTH,PEL,LLTH,LOOPEL,XFL,
*SPRESS,DPEL,SDP,NPPTSM,MXLPS,MAXLP1)
CALL EVOROD(LOOPNO,EVODD)
IF(EVODD.EQ.1.0)GO TO 208
PRESCL(LOOPNO+1)=PRESCL(LOOPNO)+DPLCL(LOOPNO)+DPEL(LOOPNO)
PRESRL(LOOPNO)=PRESCL(LOOPNO+1)+DPLRL(LOOPNO)-DPEL(LOOPNO)
PINLET=ABS(PRESCL(LOOPNO)-DPHE)
GO TO 2008
208 PRESCL(LOOPNO+1)=PRESCL(LOOPNO)-DPLCL(LOOPNO)+DPEL(LOOPNO)
PRESRL(LOOPNO)=PRESCL(LOOPNO)+DPLRL(LOOPNO)+DPEL(LOOPNO)
PINLET=ABS(PRESCL(LOOPNO+1)-DPHE)
2008 DPPUMP=PRESRL(LOOPNO)-PINLET
IF(IFIX3.EQ.1)GO TO 2280
IF(ISARA.EQ.1)GO TO 2290
IF(ISARA.EQ.2)GO TO 252
CALL LOOKBY(XFL,LOOPEL,PEL,HTDNEG,HTDPOS,NPPTS,
*LOOPNO,PLTH,IPCS,HTDN,HTDP,NPPTSM,MAYLP1)
IF(EVODD.EQ.1.0)GO TO 209
STPRD=6.944E-3*DTY*HTDPOS
PRHCL=PMAACL-STPRD
GO TO 209
STPRD=6.944E-3*DTY*HTDNEG
PRLCL=PMIN+STPRD
209 IF(EVODD.EQ.1.0)GO TO 210
  C CHECK PRESSURE AT LOOP END POINTS
209 IF(EVODD.EQ.1.0)GO TO 210
  C ODD NUMBERED LOOP
    IF(IFIX1.EQ.1)IFIX2=1
    IF(IFIX2.NE.1)GO TO 211
    IFIX1=0
    IF(ABS(PRESCL(LOOPNO+1)-PRHCL).LE.5.0)GO TO 227
    GO TO 212
    C EVEN NUMBERED LOOP
210 IF(IFIX2.EQ.1)IFIX1=1
    IF(IFIX1.NE.1)GO TO 211
    IFIX2=0
    IF(ABS(PRESCL(LOOPNO+1)-PRLCL).LE.5.0)GO TO 227
    GO TO 212
    IF(ABS(PRESRL(LOOPNO)-PMAXR).LE.5.0)GO TO 227
211 IF(JAY1.EQ.1)GO TO 221
212 IF(JAY1.EQ.1)GO TO 221
213 IF(IFIX2.NE.1)GO TO 214
214 IF(IFIX1.NE.1)GO TO 215
215 IF(ABS(PRESRL(LOOPNO)-PMAXR).LE.5.0)GO TO 227
216 LL(IC)=LL(IC-1)+DELLL
    KCHNG(IC)=2
218 LL(IC)=LL(IC-1)-DELLL
KCHNG(IC)=4
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 219
GO TO 204
219 IF(KCHNG(IC).EQ.4)GO TO 220
LLHIGH=LL(IC-2)
LLLOW=LL(IC-1)
JAY1=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
220 LLHIGH=LL(IC-1)
LLLOW=LL(IC-2)
JAY1=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
221 IF(IFIX1.NE.1)GO TO 222
IF(PRESCL(LOOPNO+1)-PRLCL)226,225,224
222 IF(IFIX2.NE.1)GO TO 223
IF(PRESCL(LOOPNO+1)-PRHCL)224,225,226
223 IF(PRESRL(LOOPNO)-PMAXRL)224,225,226
224 LLLOW=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
225 GO TO 227
226 LLHIGH=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
227 LTH(LOOPNO)=XLTH
FLRT(LOOPNO)=FLRATE
THOT(LOOPNO)=TOILMX
TCOLD(LOOPNO)=TOILMN
C CHECK CABLE LINE PPRESSURE FOR CONSTRAINT SATISFACTION
IF(EVODD.EQ.1.0)GO TO 228
IF((PRESCL(LOOPNO+1)-PRHCL).GT.5.0)GO TO 2270
IF((PRESRL(LOOPNO)-PMAXRL).GT.5.0)GO TO 2271
IF((PRESCL(LOOPNO+1)-PRLCL).LE.5.0)GO TO 229
IF((PRESRL(LOOPNO)-PMAXRL).LE.5.0)GO TO 229

2270 IFIX2=1
IFIX4=0
GO TO 2272

2271 IFIX4=1
IFIX2=0
GO TO 2272

2272 JAY1=0
KCHNG(IC-1)=1
IF(IFIX2.EQ.1)GO TO 213
IF(IFIX4.EQ.1)GO TO 213
GO TO 229

228 IF((PRLCL-PRESCL(LOOPNO+1)).GT.5.0)GO TO 2273
IF((PRESRL(LOOPNO)-PRLCL).GT.5.0)GO TO 2274
IF((PRESCL(LOOPNO+1)-PRLCL).LE.5.0)GO TO 229
IF((PRESRL(LOOPNO)-PMAXRL).LE.5.0)GO TO 229

2273 IFIX1=1
IFIX4=0
GO TO 2275

2274 IFIX4=1
IFIX1=0
GO TO 2275

2275 JAY1=0
KCHNG(IC-1)=1
IF(IFIX1.EQ.1)GO TO 213
IF(IFIX4.EQ.1)GO TO 213

229 CALL PPDIST(PRESCL,PRESRL,NPPTS,SPRESS,DPLULC,
* DPLULR,PLTH,XFL,LOOPNO,IMEMRY,PEL,PC,PR,XDIST,
* PDIFHC,PDIFHR,PDIFLO,NPC,NPR,NPCLO,K,DTY,PMAXCL,
* PMAXRL,PMIN,FLT,PDIFFC,PDIFFR,PDIFFL,NPPTSM,NPPTS1,MAXLPS,MAXLP1)
IF(PDIFHR(LOOPNO).EQ.0.0)GO TO 263
IJKL=NPR(LOOPNO)
SDPP=-6.944E-3*DTYR*PEL(IJKL)

2290 IF(EVODD.EQ.1.0) GO TO 250
YDIST=XFL(LOOPNO+1)-PLTH(IJKL)
YDIST1=ABS(XFL(LOOPNO)-PLTH(IJKL))
SDIF=SDPP-SPRESS(LOOPNO+1)
POPP=PRESCL(LOOPNO+1)+DPLULR(LOOPNO)*YDIST+SDIF
GO TO 251

250 SDIF=SDPP-SPRESS(LOOPNO)
YDIST=PLTH(IJKL)-XFL(LOOPNO)
YDIST1=YDIST
POPP=PRESCL(LOOPNO)+DPLULR(LOOPNO)*YDIST+SDIF

251 IF(ISARA.EQ.1) GO TO 252
IC=1
LL(IC)=LLTH(LOOPNO)
DELLL=YDIST/4.0
KCHNG(IC)=1
ISARA=1
IC=IC+1
GO TO 2521

252 IF(ISARA.EQ.2) GO TO 2521
IF(ABS(POPP-PMAXRL).LE.5.0) GO TO 262
GO TO 2522

2521 IF(ABS(FRESRL(LOOPNO)-PMAXRL).LE.5.0) GO TO 262
2522 IF(JAY4.EQ.1) GO TO 258
IF(ISARA.EQ.2) GO TO 2523
IF(POPP-PMAXRL.253,254,255
2523 IF(PRESRL(LOOPNO)-PMAXRL.253,254,255
253 LL(IC)=LL(IC-1)+DELLL
KCHNG(IC)=2
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2) GO TO 256
GO TO 204

254 GO TO 262
255 LL(IC)=LL(IC-1)-DELLL
IF(LL(IC).LT.YDIST1)ISARA=2
IF(ABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 256
GO TO 204
256 IF(KCHNG(IC).EQ.4)GO TO 257
LLHIGH=LL(IC-2)
LLLOW=LL(IC-1)
JAY4=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
257 LLHIGH=LL(IC-1)
LLLOW=LL(IC-2)
JAY4=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
258 IF(ISARA.EQ.2)GO TO 2580
IF(POPP-PMAXRL)259,260,261
2580 IF(PRESRL(LOOPNO)-PMAXRL)259,260,261
259 LLLOW=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
260 GO TO 262
261 LLHIGH=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204
262 LLTH(LOOPNO)=XLTH
FLRT(LOOPNO)=FLRATE
THOT(LOOPNO)=TOILMX
TCOLD(LOOPNO)=TOILMN
C CHECK IF MAXIMUM ALLOWABLE PUMP HEAD IS EXCEEDED
263 IF(DPPUMP.LE.PHDMAX)GO TO 230
IC=1
LL(1)=LLTH(LOOPNO)
DELLL=2000.0
KCHNG(IC)=1
IFIX3=1
IC=IC+1

2280 IF(ABS(DPPUMP-PHDMAX).LE.5.0)GO TO 230
IF(JAY3.EQ.1)GO TO 2286
IF(DPPUMP-PHDMAX)2281,2282,2283

2281 LL(IC)=LL(IC-1)+DELLL
KCHNG(IC)=2
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 2284
GO TO 204

2282 GO TO 230

2283 LL(IC)=LL(IC-1)-DELLL
KCHNG(IC)=4
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 2284
GO TO 204

2284 IF(KCHNG(IC).EQ.4)GO TO 2285
LLHIGH=LL(IC-2)
LLLOW=LL(IC-1)
JAY3=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204

2285 LLHIGH=LL(IC-1)
LLLOW=LL(IC-2)
JAY3=1
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204

2286 IF(DPPUMP-PHDMAX)2287,2288,2289

2287 LLLOW=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204

2288 GO TO 230

2289 LLHIGH=LL(IC-1)
LL(IC)=(LLHIGH+LLLOW)/2.0
GO TO 204

230 LLTH(LOOPNO)=XLTH
FLRT(LOOPNO)=FLRATE
THOT(LOOPNO)=TOILMX
TCOLD(LOOPNO)=TOILMN
IF(IPROB.NE.6)GO TO 231
IF(LOOPNO.LT.NLOOPS)GO TO 201
GO TO 602

231 IF(XFL(LOOPNO+1).GT.FLT)GO TO 232
GO TO 201

232 NLOOPS=LOOPNO
CALL ENDCMK(NLOOPS,XFL,FLT,LLTH,LLTHMN,LOOPNO,
*IPROB,NEND1,MAXLPS,MAXLP1)
TCOLD(NLOOPS)=TOILMN
GO TO 100

C DESIGN OPTION 3
C CALCULATE CABLE ENERGY LOSSES
300 CALL CLOSS(IFC,IFCAVG,RDC,YC,YS,YP,WP,W,WC)
ICNT3=0
LOOPNO=0

3003 LOOPNO=LOOPNO+1
FLRATE=FLOWRT(LOOPNO)
XLTH=LLTH(LOOPNO)

C CALCULATE CABLE LINE MAXIMUM OIL TEMPERATURE
NBPAS=1
CALL HEATTR(DCOND,DCABLE,DPIPE,TAPTH,KCIL,WD,KTAPE,RDC,YC,
*YS,TCAEBX,PWET,AFLOW,FRATE,IFC,TOILMX,COHEX,RNC,RAYN,IPROB,
*DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
*DTY,SHPT,VTY,FILMC,CONV,CTAPE,THETA,NBPAS,F,P1,XP,NPVALM)
NBPAS=0

301 TOIL=TOILMX
ICNT3=ICNT3+1
IF(ICNT3.GT.50)GO TO 10000
TAVG=TOIL
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XPNPVALM)
RNC=(FLRATE*DTY)/(VTY*PWETC*6.271E-3)
CALL HEATT(DCOND,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC,
*YS,TCABMX,PWET,AFLOW,FLRATE,IFC,TOILMX,COTHEX,RNC,RAYN,IPROB,
*DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
*DTY,SPHT,VTY,FILMC,CONVM,CTAPE,THETA,NBYPAS,F,F1,XPNPVALM)
IF(ABS(TOIL-TOILMX).LE.0.2)GO TO 302
GO TO 301
C CALCULATE HEAT EXCHANGER EXIT TEMPERATURE-TOILMN-AS A FUNCTION
C OF TIME OF YEAR
302 NBYP1=0
THOT(LOOPNO)=TOILMX
ISKIPI=0
ISKIP2=0
TDIST=1.0
CALL ENBAL2(FLRATE,TOILMN,TOILMX,XLT"W,F11,F12,Q1A,
*Q2A,DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,NVPTS,
*TAVG,DTY,SPHT,VTY,TOILCR,TC,TB,XTDIST,XL1,XL2,A1,A2,
*B1,B2,C1,C2,X3,ISKIPI,ISKIP2,NBYP1,LOOPNO,IPROB,TDIST,
*F1,XPNPVALM,WHPTM,NLPTM)
ISKIPI=0
ISKIP2=0
TDIST=0.0
IF(TOILMN.GE.TEMSN)GO TO 321
WRITE(NW,978)LOOPNO,TOILMN
978 FORMAT(1HO,19X,'**ERROR 18**/22X,
*A PROBLEM EXISTS IN LOOP NO.',13,'. THE SPECIFIED'/22X,
'OIL FLOW RATE YIELDS A HEAT EXCHANGER OUTLET TEMPERATURE'/22X,
'(=',F8.2,' ) WHICH IS OUTSIDE THE TEMPERATURE'/22X,
'RANGE OF THE OIL PROPERTY DATA. INCREASE THE FLOW RATE'/22X,
'OR DECREASE THE LOOP LENGTH./')
321 TCOLD(LOOPNO)=TOILMN
FWRREF(LOOPNO)=2.35*DTY*SPHT*FLRATE*(TOILMX-TOILMN)
TAVG=(TOILMX+TOILMN)/2.0
IF(TAVG.GT.TEMSM.AND.TAVG.LT.TEMBIG)GO TO 310
WRITE(NW,976)TAVG
C
CALCULATE AVERAGE OIL PROPERTIES FOR CABLE LINE AND RETURN LINE
310
TAVG=(TOILMX+TOILCR)/2.0
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,YP,NPVALM)
DTYC=DTY
VTYC=VTY
TAVG=(TOILMN+TOILCR)/2.0
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,YP,NPVALM)
DTYR=DTY
VTYR=VTY
IF(LOOPNO.GT.1)GO TO 303
C
CALCULATE SYSTEM HEAD-TANK PRESSURE
CALL PHTDET(PEL,NPPTS,DTY,PMIN,PHT,NPPTSM)
PRESCL(1)=PHT
IF(PHT.LT.PPHMAX.AND.PHT.LT.PMAXCL)GO TO 303
WRITE(NW,970)PHT
GO TO 10001
C
CALCULATE LOOP PRESSURE PROFILE
303
CALL PRDROP(DCAELE,DPIPE,SW,SWH,PITCH,SWANG,DTY,DTYC,VTYC,DTYR,VTYR, *PWETC,PWETR,AFLOWC,AFLOWR,FLRATE,FFSTDC,FFCCR,RNC,RNR,*IPROB,DPLULC,DPLULR,LOOPNO,MEXLPS)
DPLCL(LOOPNO)=DPLULC(LOOPNO)*XLTH
DPLRL(LOOPNO)=DPLULR(LOOPNO)*(XLTH+LTHEQ)
C
CALCULATE STATIC OIL PRESSURES
CALL STPPG(DTY,LOOPNO,FLT,NPPTS,PLTH,PEL,LLTH,LOOPEL,XFL,*SPRESS,DPGL,SDP,NPPTSM,MAXLPS,MEXLP1)
CALL EVOROD(LOOPNO,EVODD)
IF(EVODD.EQ.1.0)GO TO 304
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PRESCL(LOOPNO+1) = PRESCL(LOOPNO) + DPLCL(LOOPNO) + DPEL(LOOPNO)
PRESRL(LOOPNO) = PRESCL(LOOPNO+1) + DPLRL(LOOPNO) - DPEL(LOOPNO)
PINLET = ABS(PRESCL(LOOPNO) - DPHE)
GO TO 305

304 PRESCL(LOOPNO+1) = PRESCL(LOOPNO) - DPLCL(LOOPNO) + DPEL(LOOPNO)
PRESRL(LOOPNO) = PRESCL(LOOPNO) + DPLRL(LOOPNO) + DPEL(LOOPNO)
PINLET = ABS(PRESCL(LOOPNO+1) - DPHE)
C CALCULATE REQUIRED LOOP PUMP POWER
305 DPPUMP = PRESRL(LOOPNO) - PINLET
PWRPMP(LOOPNO) = 0.434 * DPPUMP * FLRATE
C DETERMINE LOOP PRESSURE PROFILE AND CHECK INTERIOR LOOP
C POINTS FOR EXCESSIVE PRESSURES
CALL PRDIST(PRESCL, PRESRL, NPPTS, SPRESS, DPLULC, * DPLULR, PLTH, XFL, LOOPNO, IMEMRY, PEL, PC, PR, XDIST, * PDFHC, PDFHRE, PDFICO, NPC, NPEL, K, DTLY, PMAXCL, * PMAXRL, PMIN, FLT, PDFICF, PDFIFR, PDFIFL, NPPTSM, NPPTST1, MAXLPS, MAXLP1)
CALL PPGCALC(NPPTS, LOOPNO, XFLTH, NPPTS, PRESCL, PRESRL, LOOPNO, XFL, PLTH, PEL, LDOPEL, DTLY, DPLULC, DPLULR, PRC, PRR, * XPDIST, NLPPTM, MAXLPS, MAXLP1, NPPTSM)
GO TO 900
C PROBLEM-OPTION 4
400 IC4 = 1
AVGFAC = AMPFAC
JAY4 = 1
LOOPNO = 1
NLOOPS = 1
TOILMS = TOILMX
C INITIALIZE VALUE OF FORCED COOLED CURRENT
TAVG = (TOILMX + TOILMN) / 2.0
CALL PTYINT(DTLY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS, * NSHPTS, NPPTS, TAVG, DTLY, SPHT, VTY, F, F1, XP, NPVALM)
NBYPAS = 1
CALL HEATTR(DCOND, DCABLE, DPIPE, TAPTH, KOIL, WD, KTAPE, RDC, YC,
USER=BROWN  311 24594  JOINT COMPUTER FACILITY, MIT

*YS, TCA, P, AFLOW, FRLA, IFC, TOILM, COTH, RNC, RAYN, IPRB, 0794
*DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS, NVPTS, TAVG, 0795
*DNTY, SPHT, VTY, FILMC, CCNV, CTPE, THETA, NBPAS, F, F1, XP, HPVALM) 0796
$NBYPAS=0 0797
IFCD(1)=IFC 0798
C CALCULATE REQUIRED FLOW RATE 0799
$ISKIP1=0 0800
ISKIF2=0 0801
TDIST=0.0 0802
401 IC4=IC4+1 0803
IF(IDC4.GT.50) GO TO 10000 0804
IFCAVG=IFCD(IC4-1) 0805
IFC=IFCD(IC4-1) 0806
C CHECK PIPE-TYPE CABLE SYSTEM HEAT TRANSFER 0807
C CORRELATION LIMITS 0808
INOND=(1.0+YC)*RDC*IFC*IFC/WD 0809
IF((INOND.GE.0.35.AND.INOND.LE.12.0))GO TO 412 0810
WRITE(NW,45)INOND,IFC 0811
412 CALL CLOSS(IFC,IFCAVG,PDC,YC,YS,YP,WD,W,W,C) 0812
CALL ENBAL2(FRLA,TOILMN,TOILMX,XLTH,W,F11,F12,F22,Q1A, 0813
*Q2A,DNTY,SPECHT,VSCTY,TEMPP,TEMPSH,TEMPV,NDPTS,NVPTS,TAVG, 0814
*TAVG,DNTY,SPHT,VTY,TOILCR,TC,TR,XDIST,SL1,SL2,SL,A1,A2, 0815
*B1,B2,C1,C2,X3,ISKIP1,ISKIP2,NBPAS,LOOPNO,IPROB,TDIST, 0816
*F1,XP,F,HPVALM,NLPTM,NLPTP) 0817
ISKIP1=1 0818
IF(TDIST.NE.100.0)GO TO 40100 0819
WRITE(NW,973)LOOPNO,TOILMN,TOILMX 0820
GO TO 10000 0821
40100 IF(TDIST.NE.200.0)GO TO 40101 0822
WRITE(NW,975)FRLA,TOILMN,TOILMX 0823
C CHECK IF MAXIMUM OIL TEMPERATURE EQUALS SPECIFIED VALUE 0824
40101 TAVG=TOILMN 0825
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPP,TEMPSH,TEMPV,NDPTS, 0826
RNC=(FLRATE*DTY)/(VTY*PWET*6.271E-3)

CALL HEATTR(DCOND,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,IC,
*YS,TCABMX,PWET,AFLOW,FLRATE,IROY,TOILMX,COTHEX,RNC,RAYN,IPROB,
*DTY,SPHT,VTY,FILMC,CCONV,CTAPE,THETA,NBYPAS,F,F1,XP,NPVALM)

IF(ABS(TOILMS-TOILMX).LE.0.25)GO TO 411

IF(JAY4.EQ.1)GO TO 407

402 IFCD(IC4)=IFCD(IC4-1)+50.0
ICHNG(IC4)=2
IF(IABS(ICHNG(IC4)-ICHNG(IC4-1)) .EQ. 2) GO TO 405
GO TO 401

403 GO TO 411

404 IFCD(IC4)=IFCD(IC4-1)-50.0
ICHNG(IC4)=4
IF(IABS(ICHNG(IC4)-ICHNG(IC4-1)) .EQ. 2) GO TO 405
GO TO 401

405 IF(ICHNG(IC4) .EQ. 4) GO TO 406
IHIGH=IFCD(IC4-2)
ILOW=IFCD(IC4-1)
JAY4=1
IFCD(IC4)=(IHIGH+ILOW)/2.0
IF(AABS(IFCD(IC4)-IFCD(IC4-1)) .LE. 1.0) GO TO 411
GO TO 401

406 IHIGH=IFCD(IC4-1)
ILOW=IFCD(IC4-2)
JAY4=1
IFCD(IC4)=(IHIGH+ILOW)/2.0
IF(AABS(IFCD(IC4)-IFCD(IC4-1)) .LE. 1.0) GO TO 411
GO TO 401

407 IF(TOILMS-TOILMX)408,409,410

408 ILow=IFCD(IC4-1)
IFCD(IC4)=(IHIGH+ILOW)/2.0
IF(ABS(IFCD(IC4)-IFCD(IC4-1)).LE.1.0)GO TO 411
GO TO 401
409 GO TO 411
410 IHIGH=IFCD(IC4-1)
IFCD(IC4)=(IHIGH+ILOW)/2.0
IF(ABS(IFCD(IC4)-IFCD(IC4-1)).LE.1.0)GO TO 411
GO TO 401
411 IFC=IFCD(IC4-1)
PWRREF(LOOPNO)=2.35*DTY*SPHT*FLRATE*(TOILMX-TOILMN)
C CALCULATE LOOP TEMPERATURE DISTRIBUTION
ISKIP1=1
ISKIP2=1
TDIST=1.0
CALL ENDAL2(FLRATE,TOILMN,TOILMX,XLTH,W,F11,F12,F22,Q1A,
*Q2A,DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TFMPV,NDPTS,NVPTS,
*TAVG,DTY,SPHT,VTY,TOILCR,TC,TR,XDIST,XL1,XL2,A1,A2,
*B1,B2,C1,C2,X3,ISKIP1,ISKIP2,NBYP51,LOOPNO,IPROB,TDIST,
*F1,XP,F,NPVALM,NLTPTM,NLTPTS)
TAYG=(TOILMX+TOILMN)/2.0
IF(TAVG.GT.TEMSM.AND.TAVG.LT.TEMBIG)GO TO 40102
WRITE(NW,976)TAVG
40102 ISKIP1=0
ISKIP2=0
TDIST=0.0
C CALCULATE AVERAGE OIL PROPERTIES FOR CABLE LINE AND RETURN LINE
TAVG=(TOILMX+TOILCR)/2.0
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XP,NPVALM)
DTYC=DTY
VTYC=VTY
TAVG=(TOILMN+TOILCR)/2.0
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
C PROBLEM-OPTION 5
C CALCULATE THE MAXIMUM FORCED-COOLED CURRENT PERMITTED
C BASED ON THE SELECTED HEAT EXCHANGER OUTLET TEMPERATURE.
500 TOILMX=TOILMN+DTHE
NBYPAS=2
CALL HEATTRP(DCOND,DCABLE,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC,
*YS,TCAOBX,PWET,AFLOW,FLRAT,IFC,TOILMX,COTHX,RNC,RAYN,IPROB,
*DNTY,SPCET,VSCTY,TEMPD,TEMPH,TFMPV,NDPTS,NHPTS,NVPTS,TAVG,
*NPVALM)
IFCMAX=IFC
C INITIALIZE VALUE OF FORCED COOLED CURRENT
IFC=1200.0
IFCAVG=IFC*AVGFAC
CALL CLOSS(IFC,IFCAVG,PDC,YC,YS,YP,W,W,W)
C CALCULATE VALUE OF CABLE ENERGY LOSSES
ICOR=0
DELIFC=100.0
IFIX1=0
IFIX2=0
LOOPNO=1
IFCD(1)=IFC
KCHNG(1)=1
USER=BROWN  311 24594  JOINT COMPUTER FACILITY, MIT

IC=1
JAY1=0
JAY3=0

C SATISFY LOOP ENERGY BALANCE AND PIPE-TYPE CABLE
C HEAT TRANSFER CORRELATION IN ORDER TO MAXIMIZE
C HEAT EXCHANGER INLET TEMPERATURE
C INITIALIZE TOILMX

NBYPAS=1
CALL HEATTR(DCOND,DCABLE,DPipe,TAPE,KOIL,WD,KTAPE,RDC,YC,
*YS,TCABMX,PWET,AFlow,FLRATE,IFC,TOILMX,COTHEX,RNC,RAYN,IPROB,
*SNTY,Specht,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
*DTY,SPHT,VTY,FILMC,CCONV,CTAPE,THETA,NBYPAS,F,F1,XP,NPVALM)

NBYPAS=0
ISKIP1=0

501  IFC=IFCD(IC)
IFCAVG=IFC*AVGFAC
C CHECK PIPE-TYPE CABLE SYSTEM HEAT TRANSFER
C CORRELATION LIMITS
INOND=(1.0+YC)*RDC*IFC*IFC/WD
IF(INOND.GE.0.35.AND.INOND.LE.12.0)GO TO 50003
WRITE(NW,45)INOND,IFC

50003 CALL CLOSS(IFC,IFCAVG,RDC,YC,YS,YP,WD,W,WC)

50001 TOIL=TOILMX
C CALCULATE OIL FLOW RATE
TDIST=0.0
IFCAVG=IFCD(IC)*AVGFAC
CALL ENBAL2(FRATE,TOILMN,TOILMX,XLTu,W,F11,F12,F22,Q1A,
*Q2A,DTNY,Specht,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,NVPTS,
*TAVG,DTY,SPHT,VTY,TOILCR,TC,TR,XTDIST,XL1,XL2,A1,A2,
*B1,B2,C1,C2,X3,ISKIP1,ISKIP2,NBYPAS1,TOOPNO,IPROB,TDIST,
*F1,F2,MPVALM,NLTPTM,NLTPTS)
IF(TDIST.NE.100.0)GO TO 50004
WRITE(NW,973)LOOPNO,TOILMN,TOILMX
GO TO 10000

50004 IF(TDIST.NE.200.0)GO TO 50005
WRITE(NW,975)FLRATE,TOTLMN,TOILMX

50005 TAVG=TOILMX
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,
   *NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XP,NPVALM)
   RNC=(FLRATE*DTY)/(VTY*PWETC*6.271E-3)
   CALL HEATTR(DCOND,DCABLE,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC,
   *YS,TCABMX,PWET,AFLOW,FLRATE,IFC,TOILMX,COTHEX,RNC,RATN,IPROB,
   *DNTY,SPECHT,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
   *DTY,SPHT,VTY,FILMC,CONV,TAPE,THETA,NBYPAS,F,F1,XP,NPVALM)
   IF(ABS(TOIL-TOILMX).LE.0.25)GO TO 50002
   ISKI?1=1
   GO TO 50001

C CALCULATE LOOP PRESSURE PROFILE

50002 IC=IC+1
   IF(IC.GT.50)GO TO 10000
   C CALCULATE AVERAGE OIL PROPERTIES FOR CABLE LINE AND RETURN LINE.
   TAVG=(TOILMX+TOILCR)/2.0
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,
   *NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XP,NPVALM)
   DTYC=DTY
   VTYC=VTY
   TAVG=(TOILMN+TOILCR)/2.0
   CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSh,TEMPV,NDPTS,
   *NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XP,NPVALM)
   DTYR=DTY
   VTYR=VTY
   CALL PRDROP(DCABLE,DPIPE,SWH,PITCH,SWANG,DTYC,VTYC,DTYR,VTYR,
   *PWETC,PWETR,AFLOW,AFLOWR,FLRATE,FFSTDC,FFC,FFR,RNC,RNR,
   *IPROF,DFLULC,DFLULR,LOOPNO,MAXLPS)
   DPLCL(LOOPNO)=DFLULC(LOOPNO)*XLTH
   DPLRL(LOOPNO)=DFLULR(LOOPNO)*XLTH
C CALCULATE LOOP STATIC PressURES

FLT = XLTH

LLTH(LOOPNO) = XLTH

CALL STPPG(DTY, LOOPNO, FLT, NPPTS, PLTH, PEL, LLTH, LOOPEL, XFL, *SPRESS, DPEL, SDP, NPPTS, MAXLPS, MAXLP1)

IF (EVODD.EQ.1.0) GO TO 502

IF (EVODD.EQ.1.0) GO TO 502

PRESCL(LOOPNO) = PCLOW

PRESCL(LOOPNO+1) = PRESCL(LOOPNO) + DPLCL(LOOPNO) + DPEL(LOOPNO)

PRESRL(LOOPNO) = PRESCL(LOOPNO) + DPLRL(LOOPNO) - DPEL(LOOPNO)

PINLET = A3S (PRESCL(LOOPNO) - DPHE)

GO TO 503

502 PRESCL(LOOPNO) = PCHIGH

PRESCL(LOOPNO+1) = PRESCL(LOOPNO) - DPLCL(LOOPNO) + DPEL(LOOPNO)

PRESRL(LOOPNO) = PRESCL(LOOPNO) + DPLRL(LOOPNO) + DPEL(LOOPNO)

PINLET = A3S (PRESCL(LOOPNO+1) - DPHE)

GO TO 503

503 DPPUMP = PRESRL(LOOPNO) - PINLET

IF (IFIX3.EQ.1) GO TO 526

IF (IFIX3.EQ.1) GO TO 526

PRHCL = PCHIGH

GO TO 505

504 PRLCL = PCLOW

C CHECK PRESSURE AT LOOP END POINTS

IF (EVODD.EQ.1.0) GO TO 506

C ODD-NUMBERED LOOP

IF (IFIX2.NE.1) GO TO 507

IF (ABS(PRESCL(LOOPNO+1) - PRHCL).LF.5.0) GO TO 523

GO TO 508

C EVEN-NUMBERED LOOP

IF (IFIX1.NE.1) GO TO 507

IF (ABS(PRESCL(LOOPNO+1) - PRLCL).LE.5.0) GO TO 523

GO TO 508

507 IF (ABS(PRESRL(LOOPNO) - PRHIGH).LE.5.0) GO TO 523

508 IF (JAY1.EQ.1) GO TO 517
IF(IFIX2.NE.1)GO TO 510
IF(PRESCL(LOOPNO+1)-PRHCL)512,513,514
IF(IFIX1.NE.1)GO TO 511
IF(PRESCL(LOOPNO+1)-PRLCL)514,513,512
IF(PRESRL(LOOPNO)-PRHIGH)512,513,514
IFCD(IC)=IFCD(IC-1)+DELIFC
IF(ICOR1.EQ.1)GO TO 50014
IF(IFCD(IC).GT.IFCMAX)GO TO 50012
GO TO 50013
IF(IFCD(IC)=IFCMAX
TCOR1=1
IF(IFIX1.EQ.1)GO TO 50021
IF(IFIX2.EQ.1)GO TO 50016
GO TO 50013
ICOR1=0
IFC=IFCMAX
GO TO 50023
WRITE(NW,977)PCHIGH,PRHIGH,IFCMAX,DTHF
977 FORMAT(1HO,19X,***ERROR 17***/22X,
*NEITHER THE SPECIFIED CABLE LINE PRESSURE (=',F8.2,' )'/22X,
*NOR THE SPECIFIED RETURN LINE PRESSURE (=',F8.2,' )'/22X,
*CAN BE ACHIEVED. THE AMPACITY REQUIRED EXCEEDS'/22X,
*THAT VALUE OF THE AMPACITY (=',F10.2,' ) WHICH YIELDS'/22X,
*THE SPECIFIED MAXIMUM PERMISSIBLE TEMP DROP EXCHANGER'/22X,
*TEMPERATURE DROP (=',F8.2,').'/)
IFC=IFCMAX
GO TO 525
50021 WRITE(NW,977)PCLOW,PRHIGH,IFCMAX,DTHF
IFC=IFCMAX
GO TO 525
KCHNG(IC)=2
IF(TARS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 515
GO TO 501
GO TO 523

IF(COR1=0)

KCHNG(IC)=4

IF(KCHNG(IC).EQ.4)GO TO 516

IHIGH=IFCD(IC-1)

ILOW=IFCD(IC-2)

IFABS(IFCD(IC)-IFCD(IC-1)).LE.1.0)GO TO 523

JAY1=1

IFCD(IC)=(IHIGH+ILOW)/2.0

GO TO 501

IF(IFIX1.NE.1)GO TO 518

IF(PRESCL(LOOPNO+1)-PRLCL)522,521,520

IF(IFIX2.NE.1)GO TO 519

IF(PRESCL(LOOPNO+1)-PRHCL)520,521,522

IF(PRESRL(LOOPNO)-PRHIGH)520,521,522

ILOW=IFCD(IC-1)

IFCD(IC)=(IHIGH+ILOW)/2.0

GO TO 501

IF(IFIX1.NE.1)GO TO 518

IF(PRESCL(LOOPNO+1)-PRLCL)522,521,520

IF(IFIX2.NE.1)GO TO 519

IF(PRESCL(LOOPNO+1)-PRHCL)520,521,522

IF(PRESRL(LOOPNO)-PRHIGH)520,521,522

ILOW=IFCD(IC-1)

IFCD(IC)=(IHIGH+ILOW)/2.0

GO TO 501

C CHECK CABLE LINE PRESSURE FOR CONSTRAINT SATISFACTION
IF(EVODD.EQ.1.0)GO TO 524
IF(PRESCL(LOOPNO+1).GT.PRHCL)IFIX2=1
IF(ABS(PRESCL(LOOPNO+1)-PRHCL).LE.5.0)GO TO 525
JAY1=0
KCHNG(IC-1)=1
IF(IFIX2.EQ.1)GO TO 509
GO TO 525
IF(PRESCL(LOOPNO+1).LT.PRLCL)IFIX1=1
IF(ABS(PRESCL(LOOPNO+1)-PRLCL).LE.5.0)GO TO 525
JAY1=3
KCHNG(IC-1)=1
IF(IFIX1.EQ.1)GO TO 509
C CHECK IF MAXIMUM ALLOWABLE PUMP HEAD IS EXCEEDED
525 IFCD(IC-1)
IF(DPPUMP.LE.PHDMAX)GO TO 537
IC=1
IFCD(1)=IFC
DELIFC=20.0
KCHNG(IC)=1
IFIX3=1
IC=IC+1
526 IF(ABS(DPPUMP-PHDMAX).LE.5.0)GO TO 536
IF(JAY3.EQ.1)GO TO 532
IF(DPPUMP-PHDMAX)=527,528,529
527 IFCD(IC)=IFCD(IC-1)+DELIFC
KCHNG(IC)=2
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 530
GO TO 501
528 GO TO 536
529 IFCD(IC)=IFCD(IC-1)-DELIFC
KCHNG(IC)=4
IF(IABS(KCHNG(IC)-KCHNG(IC-1)).EQ.2)GO TO 530
GO TO 501
IF(KCHNG(IC).EQ.4)GO TO 531
IHIGH=IFCD(IC-2)
ILOW=IFCD(IC-1)
IF(ABS(IFCD(IC)-IFCD(IC-1)).LE.1.0)GO TO 536
JAY3=1
IFCD(IC)=(IHIGH+ILOW)/2.0
GO TO 501

IHIGH=IFCD(IC-1)
ILOW=IFCD(IC-2)
IF(ABS(IFCD(IC)-IFCD(IC-1)).LE.1.0)GO TO 536
JAY3=1
IFCD(IC)=(IHIGH+ILOW)/2.0
GO TO 501

IF(DPPUMP-PHDMAX).LT.533,534,535
ILOW=IFCD(IC-1)
IFCD(IC)=(IHIGH+ILOW)/2.0
GO TO 501
GO TO 536

IFCD(IC)=(IHIGH+ILOW)/2.0
GO TO 501

WRITE(NW,50036)PHDMAX

FORMAT(1H1,'THE AMPERAGE HAS BEEN SELECTED SO AS TO', * YIELD THE MAXIMUM PERMITTED PUMP HFAD = ',F10.3)

C CALCULATE LOOP TEMPERATURE DISTRIBUTION
TDIST=1.0
ISKIP1=1
ISKIP2=1
CALL ENBAL2(FLRATE,TOILMN,TOILMX,XLTH,W,F11,F12,F22,Q1A,*Q2A,DNTY,SPECHT,VSTCY,TEMPD,TEMPSH,TEMPV,NDPTS,NVPTS,*TAVG,DTY,SPHT,VTY,TOILCR,TC,TR,XTDIST,XL1,XL2,A1,A2,
C DETERMINE LOOP PRESSURE PROFILE AND CHECK INTERIOR LOOP
C POINTS FOR EXCESSIVE PressURES

540  CALL  P*DIST(PRESCL,PRESRL,NPPTS,SPRESS,DPLULC,
*DPULR,PLTH,XFL,LOOPNO,IMEMRY,PEL,PC,PR,XDIST,
*PDIFHC,PDIFHR,PDFLO,NPC,NPC0,K,DTY,PMAXCL,
*PMAXR,PMIN,FLT,PDIFFC,PDIFFR,PDIFFL,NPPTS1,MAXLPS,MAXLP1)

PWRP*P(LOOPNO)=0.434*DPPUMP*FLRATE

IF(EVODD.EQ.1.0)GO TO 538

CALL  PPCALC(NPPTS,LOOPNO,XLTH,NLPPTS,PRESCL,PRESRL,
*LOOPNO,XFL,PLTH,PEL,LOOPEL,DTYC,DTYR,DPLULC,DPLULR,PRC,PRR,
*XPDIST,NLPPTM,MAXLPS,MAXLP1,NPPTS1)  
GO TO 539

538  LOOPNO=2

CALL  PPCALC(NPPTS,LOOPNO,XLTH,NLPPTS,PRESCL,PRESRL,
*LOOPNO,XFL,PLTH,PEL,LOOPEL,DTYC,DTYR,DPLULC,DPLULR,PRC,PRR,
*XPDIST,NLPPTM,MAXLPS,MAXLP1,NPPTS1)

GO TO 539

539  GO TO 900

C PROBLEM OPTION 6
C CALCULATE PRELIMINARY VALUE OF FORCED-COOLED CURRENT

600  XLTH=FLT/FLOAT(NLOOPS)

AVGFAC=AMPFAC

IPCS=3

DIFIFIC=50.0
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TAVG=TOILMN
CALL PHYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F1,YP,NPVALM)
CALL PHETDET(PEL,NPPTS,DTY,PMIN,PHT,NPPTSM)
PCLOW=PHT
LLTH(1)=XLTH
LOOPNO=1
CALL STPPG(DTY,LOOPNO,FLT,NPPTS,PLTH,PEL,LLTH,LOOPEL,XFL,
*SPRESS,DPEL,SDP,NPPTSM,MALPS,MALP1)
CALL LOOKBY(XFL,LOOPEL,PEL,HDTNeg,HDTPOS,NPPTS,
*LOOPNO,PLTH,IPCS,HDTN,HDTD,NPPTSM,MALP1)
STPRD=6.944E-3*DTY*HDTPOS
PCHIGH=PMAXCL-STPRD
FBHIGH=PMAXRL
EVOD=0.0
GO TO 500

601 IC6=1
IFCD(1)=IFC
IFCAVG=IFC*AMPFAC
ICHNG(1)=1
JAY6=0
GO TO 500

602 IC6=IC6+1
IF(IC6.GT.50)GO TO 612
IF((IFCMAX-IFC).LE.50.0)DIFIFC=10.0
C CHECK PIPE-TYPE CABLE SYSTEM HEAT TRANSFER
C CORRELATION LIMITS
INOND=(1.0+YC)*RDC*IFC*IFC/WD
IF(INOND.GE.0.35.AND.INOND.LE.12.0)GO TO 60001
WRITE(NW,45)INOND,IFC

60001 IF(ABS(XFL(NLLOOPS+1)-FLT).LE.100.0)GO TO 512
IF(JAY6.EQ.1)GO TO 608
IF(XFL(NLLOOPS+1)-FLT603,604,605
IFCD(IC6)=IFCD(IC6-1)-DIFIFC
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
ICHNG(IC6)=2
IF(IABS(ICHNG(IC6)-ICHNG(IC6-1)).EQ.2)GO TO 606
GO TO 200

IFCD(IC6)=IFCD(IC6-1)+DIFIFC
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
IF(IFC.LE.IFCMAX)GO TO 615
IFC=IFCMAX
IFCAVG=IFC*AVGFAC
WRITE(NW,379)IFC,IFCMAX

979 FORMAT(1HO,19X,'**ERROR 19**'/22X,
*THE CALCULATED AMPACITY (=',F8.2,' ) EXCEEDS THE MAXIMUM'/22X,
**PERMISSIBLE AMPACITY (=',F8.2,' ) BASED ON THE SPECIFIED'/22X,
**VALUE OF THE MINIMUM HEAT EXCHANGER TEMPERATURE DROP.'/)
GO TO 100

ICHNG(IC6)=4
IF(IABS(ICHNG(IC6)-ICHNG(IC6-1)).EQ.4)GO TO 606
GO TO 200

IF(ICHNG(IC6).EQ.4)GO TO 607
IHIGH=IFCD(IC6-1)
ILOW=IFCD(IC6-2)
JAY6=1
IFCD(IC6)=(IHIGH+ILOW)/2.0
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
IF(ABS(IFCD(IC6)-IFCD(IC6-1)).LE.1.0)GO TO 612

GO TO 200

IHIGH=IFCD(IC6-2)
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ILOW=IFCD(IC6-1)
IFCD(IC6)=(IHIGH+ILLOW)/2.0
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
IF(ABS(IFCD(IC6)-IFCD(IC6-1)).LE.1.0)GO TO 612
JAY6=1
GO TO 200

608 IF(XFL(NLOOPS+1)-FLT)=609,610,611
609 IHIGH=IFCD(IC6-1)
IFCD(IC6)=(IHIGH+ILLOW)/2.0
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
IF(ABS(IFCD(IC6)-IFCD(IC6-1)).LE.1.0)GO TO 612
GO TO 200
610 GO TO 612
611 ILOW=IFCD(IC6-1)
IFCD(IC6)=(IHIGH+ILLOW)/2.0
IFC=IFCD(IC6)
IFCAVG=IFC*AVGFAC
IF(ABS(IFCD(IC6)-IFCD(IC6-1)).LE.1.0)GO TO 612
GO TO 200
612 IFC=IFCD(IC6-1)
IFCAVG=IFC*AVGFAC
GO TO 100
900 IF(NUPR.GT.1)GO TO 929
IF(LOOPNO.GT.1)GO TO 929
WRITE(NW,901)
901 FORMAT(1H1,33X,'GENERAL PROGRAM INPUT DATA'/33X,
'*'***************'/30X,
'*-TABULATION OF OIL PROPERTIES--'/21X,
'TEMPFD',4X,'DENSITY',5X,'TEMPSH',3X,'SPEC.HT.',
'5X','TEMPV',4X,'VISCOSITY'/22X,
'*(F)',4X,'(LBM/CUFT)',5X,'(F)',3X,'(FTU/LBM F)',
467.
IF(NDPTS.GE.FVPTS.AND.NDPTS.GE.NSHPTS)GO TO 902
IF(NYPTS.GE.NDPTS.AND.NVPTS.GE.NSHPTS)GO TO 903
JP=NSHPTS
GO TO 904
902 NP=NDPTS
GO TO 904
903 NP=NVPTS
904 DO 918 I=1,NP
IF(I.GT.NOPTS.AND.I.GT.NSHPTS)GO TO 906
IF(I.GT.NOPTS.AND.I.GT.NVPTS)GO TO 908
IF(I.GT.NOPTS.AND.I.GT.NSHPTS)GO TO 910
IF(I.GT.NOPTS)GO TO 912
IF(I.GT.NOPTS)GO TO 914
IP(I.GT.NSHPTS)GO TO 916
WRITE(NW,905)TEMPD(I),DNTY(I),TEMPSH(I),SPECHT(I),
*TFMPV(I),VSCTY(I)
905 FORMAT(20X,F7.2,4X,F6.3,5X,F6.2,3X,F6.3,6X,F6.2,3X,F7.3/) GO TO 918
906 WRITE(NW,907)TEMPV(I),VSCTY(I)
907 FORMAT(63X,F6.2,3X,F7.3/) GO TO 918
908 WRITE(NW,909)TEMPSH(I),SPECHT(I)
909 FORMAT(42X,F6.2,3X,F6.3/) GO TO 918
910 WRITE(NW,911)TEMPD(I),DNTY(I)
911 FORMAT(20X,F7.2,4X,F6.3/) GO TO 918
912 WRITE(NW,913)TEMPSH(I),SPECHT(I),TEMPV(I),VSCTY(I)
913 FORMAT(42X,F6.2,3X,F6.3,6X,F6.2,3X,F7.3/) GO TO 918
914 WRITE(NW,915)TEMPD(I),DNTY(I),TEMPSH(I),SPECHT(I)
915 FORMAT(20X,F7.2,4X,F6.3,5X,F6.2,3X,F6.3/)
GO TO 918

916 WRITE(NW,917)TEMPD(I),DNTY(I),TEMPY(I),VSCTY(I)
917 FORMAT(20X,F7.2,4X,F6.3,26X,F6.2,3X,F7.3/)
918 CONTINUE
919 WRITE(NW,919)KOIL,COTH
920 FORMAT(/20X,'OIL THERMAL CONDUCTIVITY (RTU/HR-FT F)........
*OIL COEFFICIENT OF THERMAL EXPANSION (1/F)...........
WRITE(NW,920)
921 FORMAT(34X,'--PIPE-TYPE CABLE GEOMETRY--'//)
922 FORMAT(34X,'--SYSTEM ELECTRICAL CHARACTERISTICS--'//'20X,
**INSIDE DIAMETER OF CABLE PIPE (IN) ......................',F10.3/20X,
**INSIDE DIAMETER OF RETURN PIPE (IN) ....................',F10.3/20X,
**SKID WIRE HEIGHT (IN) .................................',F10.3/20X,
**AXIAL SPACING BETWEEN ADJACENT SKID WIRE LOOPS (IN)  ',F10.3/20X,
**CABLE METALLIC TAPE THICKNESS (IN) .....................',F10.3/20X,
**SKID WIRE HELIX ANGLE (DEGREES) ........................',F10.3/20X,
**CABLE CONDUCTOR DIAMETER (IN) ..........................',F10.3/20X,
**INSULATION OUTSIDE DIAMETER(EXCLUDING SKID WIRE)(IN) ',F10.3///)
923 FORMAT(34X,'--SYSTEM THERMAL CHARACTERISTICS--'///20X,
**CONDUCTOR DC ELECTRICAL RESISTANCE (OHMS) ..............',E10.3/20X,
**TOTAL DIELECTRIC LOSS PER CONDUCTOR FOOT'/20X, 
** PER CABLE (WATTS/FT) .................',F10.3/20X,
**YC-INCREMENT IN AC/DC RESISTANCE RATIO'/20X, 
** AT CONDUCTOR (DIMENSIONLESS) ....',F10.3/20X,
**YS-INCREMENT IN AC/DC RESISTANCE RATIO'/20X, 
** AT SHEATH (DIMENSIONLESS) ....',F10.3/20X,
**YP-INCREMENT IN AC/DC RESISTANCE RATIO'/20X, 
** AT PIPE (DIMENSIONLESS) ....',F10.3///)
924 FORMAT(34X,'--TOTAL RESPONSE MEASUREMENTS--'///20X,
**AC/DC RATIO AT LINE END',E10.3/20X,
**AC/DC RATIO AT CONDUCTOR',E10.3/20X,
**AC/DC RATIO AT SKID WIRE LOOP',E10.3/20X,
**AC/DC RATIO AT BURIAL LOOP',E10.3/20X,
**AC/DC RATIO AT RETURN LOOP',E10.3/20X,
**AC/DC RATIO AT FACE',E10.3/20X,
**AC/DC RATIO AT END',E10.3/20X,
**AC/DC RATIO AT SITE',E10.3/20X,
**AC/DC RATIO AT SYSTEM',E10.3/20X,
**AC/DC RATIO AT COND',E10.3/20X,
**AC/DC RATIO AT SHEATH',E10.3/20X,
**AC/DC RATIO AT PIPE',E10.3/20X,
**AC/DC RATIO AT ALUMINUM',E10.3/20X,
**AC/DC RATIO AT COPPER',E10.3/20X,
**AC/DC RATIO AT CONDUCTOR MEASUREMENTS',E10.3///)
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**CABLE TAPE THERMAL CONDUCTIVITY (BTU/HR-FT F) .........',F10.3/20X,
**F11 (BTU/HR-FT F) .....................................',F10.3/20X,
**F12 (BTU/HR-FT F) .....................................',F10.3/20X,
**F22 (BTU/HR-FT F) .....................................',F10.3/20X,
**Q1A (BTU/HR-FT) .......................................',F10.3/20X,
**Q2A (BTU/HR-FT) .......................................',F10.3/////

WRITE(NW,924)TCABMX,PMIN,PMAXCL,PMAXRL,PHDMAX,PPHMAX

924 FORMAT(34X,'--SYSTEM DESIGN CONSTRAINTS--'///2OX,
**MAXIMUM PERMITTED CABLE TEMPERATURE (F) ...............',F10.2/20X,
**MINIMUM ALLOWABLE OIL PRESSURE (PSI) ..................',F10.2/20X,
**MAXIMUM ALLOWABLE CABLE LINE OIL PRESSURE (PSI) .......',F10.2/20X,
**MAXIMUM ALLOWABLE RETURN LINE OIL PRESSURE (PSI) .......',F10.2/20X,
**MAXIMUM ALLOWABLE PUM HEAD (PSI) ......................',F10.2/20X,
**MAXIMUM PERMITTED POTHEAD PRESSURE (PSI) ............',F10.2/////

WRITE(NW,925)

925 FORMAT(34X,'--SYSTEM ELEVATION PROFILE--'///2OX,
**PROFILE POINT',10X,'DISTANCE(FT)',10X,'HEIGHT(FT)'/)
   DO 927 I=1,NPPTS
   WRITE(NW,926)I,PLTH(I),PEL(I)
926 FORMAT(1HO,25X,I2,16X,F10.2,9X,F10.2)
   CONTINUE
   WRITE(NW,928)NLPPTS,NLTPTS,LTHEQ,DPHF
928 FORMAT(1HO,34X,'--OTHER INPUT INFORMATION--'///20X,
**NLPPTS-NUMBER OF LOOP PRESSURE PROFILE'/20X,
**POINTS (DIMENSIONLESS) ............',I10/20X,
**NLTPTS-NUMBER OF LOOP TEMPERATURE PROFILE'/20X,
**POINTS (DIMENSIONLESS) ............',I10/20X,
**LTHEQ-SUM OF RETURN LINE EQUIVALENT LENGTHS'/20X,
**PER LOOP (FT) .......',F10.2/20X,
**HEAT EXCHANGER PRESSURE DROP (PSI) ......................',F10.2/////<
**18X, '************'**

929 IF(IPROB.EQ.1)GO TO 1000
IF(IPROB.EQ.2)GO TO 2000
IF(IPROB.EQ.3)GO TO 3000
IF(IPROB.EQ.4)GO TO 4000
IF(IPROB.EQ.5)GO TO 5000
IF(IPROB.EQ.6)GO TO 6000

C GENERAL PROGRAM OUTPUT STATEMENTS

930 WRITE(NW,931)LOOPNO
931 FORMAT(51X,***'/32X,'SYSTEM LOOP NUMBER',I3/51X,***'/30X,
*'-LOOP HYDRAULIC INFORMATION--'/)
WRITE(NW,932)XLTH,FLRATE,DPLULC(LOOPNO),DPLCL(LOOPNO),
*DPLULR(LOOPNO),DPLRL(LOOPNO),PINLET,PRESRL(LOOPNO),PWRPMP(LOOPNO)
932 FORMAT(20X,
*"LOOP AXIAL LENGTH (FT) "'F10.2/20X,
*"LOOP FLOW RATE (GAL/MIN) "'F10.2/20X,
*"CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) "'E10.3/20X,
*"CABLE LINE DYNAMIC PRESSURE LOSS (PSI) "'F10.2/20X,
*"RETURN LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) "'E10.3/20X,
*"RETURN LINE DYNAMIC PRESSURE LOSS (PSI) "'F10.2/20X,
*"PUMP INLET PRESSURE (PSI) "'F10.2/20X,
*"PUMP OUTLET PRESSURE (PSI) "'F10.2/20X,
*"LOOP PUMPING POWER (WATTS) "'F10.2//)

IF(IPROB.EQ.5)GO TO 934
IF(LOOPNO.GT.1)GO TO 934
WRITE(NW,933)PHT
933 FORMAT(20X,
*"SYSTEM HEAD TANK PRESSURE (PSI) "'F10.2//)

934 WRITE(NW,935)LOOPNO
935 FORMAT(25X,'ABSOLUTE PRESSURES AT ELEVATION PROFILE POINTS'/25X,
*"LOCATED WITHIN LOOP NUMBER',I2,'(INCLUDING LOOP END POINT'/25X,
*"PRESSURES).")
WRITE(NW,936)
936 FORMAT(1HO,24X,'SYSTEM',16X,'ABSOLUTE PRESSURE'/20X,
*"AXIAL DISTANCE',8X,'CABLE LINE',5X,'RETURN LINE'/24X,
*'(FT)',15X,'(PSI)',10X,'(PSI)'/
DO 938 I=1,K
WRITE(NW,937)XDIST(I),PC(I),PR(I)
937 FORMAT(22X,F9.2,12X,F7.2,8X,F7.2)
938 CONTINUE
IF(EVDDD.EQ.1.0)GO TO 963
IF(PRESCL(LOOPNO+1).LE.PMAXCL)GO TO 961
WRITE(NW,960)PRESCL(LOOPNO+1)
960 FORMAT(1H0,19X,**ERROR**/22X,
*THE CABLE LINE PRESSURE AT THE INLET POINT (=',F10.3,')/22X,
*EXCEEDS THE MAXIMUM PERMITTED CABLE LINE PRESSURE.*/)
961 IF(PRESCL(LOOPNO).GE.PMIN)GO TO 965
WRITE(NW,962)PRESCL(LOOPNO)
962 FORMAT(1H0,19X,**ERROR**/22X,
*THE CABLE LINE PRESSURE AT THE OUTLET POINT (=',F10.3,')/22X,
*IS BELOW THE MINIMUM PERMITTED CABLE LINE PRESSURE.*/
GO TO 965
963 IF(PRESCL(LOOPNO).LE.PMAXCL)GO TO 964
WRITE(NW,960)PRESCL(LOOPNO)
964 IF(PRESCL(LOOPNO+1).GE.PMIN)GO TO 965
WRITE(NW,962)PRESCL(LOOPNO+1)
965 IF(PRESEL(LOOPNO).LE.PMAXRL)GO TO 967
WRITE(NW,966)PRESRL(LOOPNO)
966 FORMAT(1H0,19X,**ERROR**/22X,
*THE RETURN LINE PRESSURE AT THE PUMP OUTLET POINT'/22X,
*('=',F10.3,' ) EXCEEDS THE MAXIMUM PERMITTED RETURN LINE '/22X,
*PRESSURE.*/
967 IF(PDIFHC(LOOPNO).GT.0.0)GO TO 939
GO TO 941
939 WRITE(NW,940)NPC(LOOPNO),LOOPNO,PDIFFC(LOOPNO)
940 FORMAT(1H0,19X,**ERROR**/22X,
*THE PRESSURE AT ELEVATION PROFILE POINT NO',I3,'/22X,
*IN LOOP NO',I3,' EXCEEDS THE MAXIMUM'/22X,
**CABLE LINE PRESSURE PERMITTED BY',F10.3,' PSI. '/22X,**
* THE LOOP FLOW RATE OR LOOP LENGTH MUST BE MODIFIED.'*/

941 IF(PDIFHR(LOOPNO).GT.0.0)GO TO 942
   GO TO 944
942 WRITE(NW,943)NPR(LOOPNO),LOOPNO,PDIFHR(LOOPNO)
943 FORMAT(1HO,19X,'**ERROR 13**,13/22X,**THE PRESSURE AT ELEVATION PROFILE POINT NO',I3/22X,**IN LOOP NO','I3,' EXCEEDS THE MAXIMUM RETURN LINE'/22X,**PRESSURE PERMITTED BY',F10.3,' PSI. THE LOOP FLOW'/22X,**RATE OR LOOP LENGTH MUST BE MODIFIED.'*/

944 IF(PDIFLO(LOOPNO).GT.0.0)GO TO 945
   GO TO 947
945 WRITE(NW,946)NPCLO(LOOPNO),LOOPNO,PDIFLO(LOOPNO)
946 FORMAT(1HO,19X,'**ERROR 14**,14/22X,**THE PRESSURE AT ELEVATION PROFILE POINT NO',I3/22X,**IN LOOP NO','I3,' IS BELOW THE MINIMUM CABLE'/22X,**LINE PRESSURE PERMITTED BY',F10.3,' PSI. THE'/22X,**LOOP FLOW RATE OR LOOP LENGTH MUST BE MODIFIED.'*/

947 IF(IPROB.EQ.5)GO TO 9470
   IF(LOOPNO.LT.NLOOPS)GO TO 9470
   IF(PRESCL(NLOOPS+1).LT.PPHMAX)GO TO 9470
   WRITE(NW,971)PRESCL(NLOOPS+1),NLOOPS
   WRITE(NW,948)NLPPTS
9471 WRITE(NW,949)XPDIS(I),PRC(I),PRR(I)
949 FORMAT(22X,F9.2,12X,F7.2,8X,F7.2)
950 CONTINUE
WRITE(NW,952)
FORMAT('(/30X,'--LOOP THERMAL INFORMATION--'/)
IF(LOOPNO.GT.1)GO TO 954
WRITE(NW,953)IFC,IFCAVG,W
FORMAT(20X,'**SYSTEM FORCED-COOLED PEAK AMPACITY RATING (AMPS) ...',F10.3/20X,
**'AVERAGE FORCED-COOLED AMPACITY (AMPS) .............',F10.3/20X,
**'TOTAL SYSTEM ENERGY LOSS (WATTS/FT) .............',F10.2/)
WRITE(NW,955)TOILMX,TOILMN,PWRREF(LOOPNO),NLTPTS
FORMAT(20Y,
**'HEAT EXCHANGER INLET TEMPERATURE (F) ..................',F10.2/20X,
**'(MAXIMUM PERMITTED OIL TEMPERATURE)'/20X,
**'HEAT EXCHANGER OUTLET TEMPERATURE (F) ..............',F10.2/20X,
**'TOTAL HEAT EXCHANGER COOLING CAPACITY (WATTS) ......',E10.3///,
**'LOGP TEMPERATURE PROFILE',I4,'-POINTS'/26X,
**'LOOP',21X,'TEMPERATURE'/20X,'AXIAL DISTANCE',8X,
**'CABLE LINE',5X,'RETURN LINE'/24X,'(FT)',16X,'(FT)',12X,'(FT)'/)
DO 957 I=1,NLTPTS
WRITE(NW,956)XTDIST(I),TC(I),TR(I)
FORMAT(22X,F9.2,12X,F7.2,8X,F7.2)
CONTINUE
IF(IPROE.EQ.4.OR.IPROB.EQ.5)GO TO 10000
IF(LOOPNO.EQ.NLOOPS)GO TO 10000
IF(I9PROB.EQ.1.OR.I9PROB.EQ.2.OR.I9PROB.EQ.6)GO TO 10010
IF(9PROB.EQ.3)GO TO 30003
FORMAT(1HO,19X,'**ERROR 7**'/22X,
**'THE REQUIRED OPERATIONAL HEAD TANK PRESSURE'/22X,
**('=',F8.2,' ) EXCEEDS THE SPECIFIED PRESSURE'/22X,
**'LIMIT OF EITHER THE POTHEAD OR CABLE LINE.'/22X,
**'CHECK ELEVATION PROFILE INPUT DATA.'/22X,
**'PROGRAM IS TERMINATED.'/
FORMAT(1HO,19X,'**ERROR 8**'/22X,
**'THE PRESSURE (=',F8.2,' ) AT THE LOW PRESSURE'/22X,
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**END OF LOOP NO',I3,' EXCEEDS THE POTEAD'/22X,
**PRESSURE. THE SYSTEM DESIGN MUST BE MODIFIED.'/)

972 FORMAT(1HO,19X, '*ERROR 9**'/22X,
*THE HOT TEMPERATURE (=',F8.2,' ) OF LOOP NO ',I3/22X,
**IS LOWER IN VALUE THAN THE SPECIFIED'/22X,
**COLD TEMPERATURE. LOWER THE VALUE OF'/22X,
**THE COLD TEMPERATURE OR DECREASE THE'/22X,
**SYSTEM AMPLCITY. PROGRAM IS TERMINATED.'/)

973 FORMAT(1HO,19X, '*ERROR 10**'/22X,
*THE OIL FLOW RATE IS LESS THAN 5 GAL/MIN'/22X,
**IN LOOP NO',I3,'. INCREASE THE VALUF OF'/22X,
**THE COLD TEMPERATURE. PROGRAM IS TERMINATED.'/22X,
**TCOLD= ',F8.2,' F. THOT= ',F8.2,' F./)

974 FORMAT(1HO,19X, '*ERROR 11**'/22X,
*THE MAXIMUM ALLOWABLE PUMP HEAD HAS'/22X,
**BEEN EXCEEDED IN LOOP NUMBER',I3,'. THE'/22X,
**PRESENT VALUE OF THE PUMP DIFFERENTIAL'/22X,
**PRESSURE IS',F8.2,' PSI.'/)

975 FORMAT(1HO,19X, '*ERROR 15**'/22X,
*THE FLOW RATE (=',F8.2,' ) REQUIRED TO SATISFY'/22X,
**TCOLD (=',F8.2,' ) AND THOT (=',F8.2,' ) EXCEEDS A'/22X,
**VALUE EQUAL TO',F8.2,' GAL/MIN. THE COMPUTER PROGRAM'/22X,
**CANNOT INCREASE THIS VALUE FURTHER. THE'/22X,
**VALUE OF THE LOOP LENGTH IS EQUAL TO',F10.2,' .'/)

976 FORMAT(1HO,19X, '*ERROR 16**'/22X,
*THE VALUE OF THE CABLE LINE TEMPERATURE'/22X,
**(=',F8.2,' ) IS OUTSIDE THE TEMPERATURE'/22X,
**RANGE OF THE INPUTTED OIL PROPERTY'/22X,
**DATA. THE COMPUTER PROGRAM WILL USE'/22X,
**THE PROPERTY VALUES WHICH COINCIDE WITH'/22X,
**THE CLOSEST TEMPERATURE RANGE CONSTRAINT VALUE.'/)

C OUTPUT FOR DESIGN-OPTION 1
1003 IF(LOOPNO.GT.1)GO TO 930
```
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WRITE(NW,1001)NUPR
1001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
      '*********************************************************************/39X,
      '***DESIGN-OPTION 1***/34X,
      '*--PRINTOUT OF INPUT DATA--***/)
WRITE(NW,1002)IFC,IFCAVG,FLT,NLOOPS
1002 FORMAT(20X,
      '*FORCED-COOL SYSTEM CAPACITY RATING (AMPS) ************',F10.3/20X,
      '*AVERAGE CABLE CAPACITY (AMPS) ************',F10.3/20X,
      '*TOTAL SYSTEM AXIAL LENGTH (FT) ************',F10.3/20X,
      '*NUMBER OF SYSTEM COOLANT LOOPS (DIMENSIONLESS) ************',I2//25X,
      '*LOOP NUMBER',10X,'LOOP LENGTH',10X,'COLD TEMPERATURE'/50X,
      '*FT',20X,'(F)'/)
DO 1004 I=1,NLOOPS
1004 CONTINUE
WRITE(NW,1005)
1005 FORMAT(18X,'****************************************************',
      '*********************************************************************/,
      '*1H0.31X,'***DESIGN-OPTION 1----RESULTS***/)
GO TO 930
C OUTPUT FOR DESIGN-OPTION 2
2000 IF(LOOPNO.GT.1)GO TO 930
WRITE(NW,2001)NUPR
2001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
      '*********************************************************************/39X,
      '***DESIGN-OPTION 2***/34X,
      '*--PRINTOUT OF INPUT DATA--***/)
WRITE(NW,2002)IFC,IFCAVG,FLT,TOILMN,LLTHMN
2002 FORMAT(20X,
      '*FORCED-COOL SYSTEM CAPACITY RATING (AMPS) ************',F10.3/20X,
      '*AVERAGE CABLE CAPACITY (AMPS) ************',F10.3/20X,
```
**DESIGN-OPTION 2----RESULTS**

GO TO 930

C OUTPUT FOR DESIGN-OPTION 3

3000 IF(LOOPNO.GT.1) GO TO 930

WRITE(NW,3001)NUPR

3001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
******************************//39X,
**DESIGN-OPTION 3***/34X,'--PRINTOUT OF INPUT DATA--'//)

WRITE(NW,3002)IFC,IFCAVG,FLT,NLOOPS

3002 FORMAT(20X,*FORCED-COOLED SYSTEM AMPACITY RATING (AMPS) ..............',F10.3/20X,
* AVERAGE CABLE AMPACITY (AMPS) ..................................',F10.3/20X,
* TOTAL SYSTEM AXIAL LENGTH (FT) ..................................',F10.3/20X,
* NUMBER OF SYSTEM COOLANT LOOPS (DIMENSIONLESS) .......',I2//25X,
* LOOP NUMBER',10X,'LOOP LENGTH',13X,'FLOW RATE'/50X,
**(FT)',19X,'(SPM)/'

DO 3004 I=1,NLOOPS

WRITE(NW,3003)I,LLTH(I),FLOWRT(I)

3003 FORMAT(28X,I2,17X,F8.2,14X,F8.2/) 

3004 CONTINUE

WRITE(NW,3005)

3005 FORMAT(18X,**DESIGN-OPTION 3----RESULTS**/) 

GO TO 930

C OUTPUT FOR DESIGN-OPTION 4

4000 WRITE(NW,4001)NUPR
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4001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
      '*****************************/39X,
      '***DESIGN-OPTION 4***/34X,
      '*--PRINTOUT OF INPUT DATA--'//)
      WRITE(NW,4002)TOILMN,TOILMX,XLTH,AMPFAC

4002 FORMAT(20X,
      '*HEAT EXCHANGER OUTLET TEMPERATURE (F) ...................',F10.3/20X,
      '*HEAT EXCHANGER INLET TEMPERATURE (F) ...................',F10.3/20X,
      '*AXIAL LENGTH OF COOLANT LOOP (FT) .....................',F10.3/20X,
      '*AMPACITY FACTOR (DIMENSIONLESS) ......................',F10.3/18X,
      '*****************************/39X,
      '***DESIGN-OPTION 4----RESULTS**'//)
      WRITE(NW,4003)FLRATE,DPLULC(LOOPNO),DPLULR(LOOPNO)

4003 FORMAT(30X,'--LOOP HYDRAULIC INFORMATION--'//20X,
      '*LOOP OIL FLOW RATE (GPM) .....................................',F10.3/20X,
      '*CABLE LINE DYNAMIC PRESSURE LOSS/FT (PSI/FT) ...........',E10.3//)
      GO TO 951

C OUTPUT FOR DESIGN-OPTION 5
5000 IF(LOOPNO.GT.1)GO TO 930
      WRITE(NW,5001)NUPR

5001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
      '*****************************/39X,
      '***DESIGN-OPTION 5***/34X,'--PRINTOUT OF INPUT DATA--'//)
      WRITE(NW,5002)TOILMN,XLTH,PCLOW,PCHIGH,PRHIGH,DTHE,AMPFAC

5002 FORMAT(20X,
      '*HEAT EXCHANGER OUTLET TEMPERATURE (F) ...................',F10.3/20X,
      '*AXIAL LENGTH OF COOLANT LOOP (FT) .....................',F10.3/20X,
      '*MINIMUM CABLE LINE PRESSURE (PSI) .....................',F10.3/20X,
      '*MAXIMUM CABLE LINE PRESSURE (PSI) .....................',F10.3/20X,
      '*MAXIMUM DISCHARGE LINE PRESSURE (PSI) ...................',F10.3/20X,
      '*MINIMUM PERMISSIBLE HEAT EXCHANGER'//20X,
* 'TEMPERATURE DROP (F) ................................. ',F10.3/20X,
* 'AMPCACITY FACTOR (DIMENSIONLESS) ...................... ',F10.3/
IF(EVODD.EQ.0.0)GO TO 5004
WRITE(NW,5003)
5003 FORMAT(20X,'EVEN-NUMBERED COOLANT LOOP UNDER STUDY'/)
GO TO 5006
5004 WRITE(NW,5005)
5005 FORMAT(20X,'ODD-NUMBERED COOLANT LOOP UNDER STUDY'/)
5006 WRITE(NW,5007)
5007 FORMAT(18X, 'DESIGN-OPTION 5----RESULTS**'*/)
GO TO 930

C OUTPUT FOR DESIGN-OPTION 6
6000 IF(LOOPNO.GT.1)GO TO 930
WRITE(NW,6001)NUPR
6001 FORMAT(1H1,33X,'COMPUTER PROBLEM NUMBER',I3/33X,
'****************************************************'/39X,
'**DESIGN-OPTION 6**'/34X,'--PRINTOUT OF INPUT DATA--'*/)
WRITE(NW,6002)TOILMN,FLT,AMPFAC,DTHE
6002 FORMAT(20X,
'HEAT EXCHANGER OUTLET TEMPERATURE (F) .................... ',F10.3/20X,
'TOTAL SYSTEM AXIAL LENGTH (FT) .......................... ',F10.3/20X,
'AMPCACITY FACTOR (DIMENSIONLESS) ...................... ',F10.3/20X,
'MINIMUM PERMISSIBLE HEAT EXCHANGER'/20X,
'TEMPERATURE DROP (F) ................................... ',F10.3/
WRITE(NW,6003)
6003 FORMAT(18X, '****************************************************',
'****************************************************'/
'**DESIGN-OPTION 6----RESULTS**'*/)
GO TO 930
10000 IF(NUPROB.EQ.1)GO TO 11
10001 STOP
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END

PROGRAM *MAIN* HAS NO ERRORS
SUBROUTINE CLOSS(IFC, IFCAVG, RDC, YC, YS, YP, WD, W, WC)
REAL TFC, IFCAVG
W = 3.0 * (IFCAVG ** 2 * RDC * (1.0 + YC + YS + YP) + WD)
WC = IFC ** 2 * RDC * (1.0 + YC) + WD
RETURN
END

PROGRAM CLOSS HAS NO ERRORS
SUBROUTINE EVOROD(LOOPNO, EVODD)
C THIS SUBROUTINE DETERMINES WHETHER AN INTEGER IS EVEN OR ODD
ODCHK=FLOAT(LOOPNO)/2.
IEVCHK=LOOPNO/2
IF((ODCHK-FLOAT(IEVCHK)).GT.0.0) GO TO 1
C EVODD=1.0 FOR AN EVEN NUMBER
EVODD=1.0
GO TO 2
C EVODD=0.0 FOR AN ODD NUMBER
1 EVODD=0.0
2 RETURN
END

PROGRAM EVOROD HAS NO ERRORS
SUBROUTINE ENBAL2(FLRATE, TOILMN, TOILMX, XLTH, W, F1, F2, Q1A, *Q2A, DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS, NVPTS, *TAVG, DTY, SPHT, VTY, TOILCR, TC, TR, XTDIST, XL1, XL2, A1, A2, *B1, B2, C1, C2, X3, ISKIP1, ISKIP2, NYPTS1, LOOPNO, IPRB, TDIST, *F1, XP, F, NPVALM, NTPTM, NLTP, DNTY(NPVALM), SPECHT(NPVALM), VSCTY(NPVALM), F1(NPVALM), *XP(NPVALM), TEMPD(NPVALM), TEMPSH(NPVALM), TEMPV(NPVALM), 2TC(NLTP, TR(NLTP), XTDIST(NLTP), FLRT(40), ICHNG(40), F(NPVALM))
QC=3.413*W
IF(ISKIP1.EQ.1)GO TO 100
C CALCULATE PIPE-SOIL-PIPE STATIC HEAT TRANSFER CONSTANTEX1=F12*F12-F11*F22
X2=SQRT(F11*F11+F22*F22+2.*F11*F22-4.*F12*F12)
A11=F11/X1
A12=F12/X1
A22=F22/X1
YL1=(F11-F22+X2)/2.
XL2=(F11-F22-X2)/2.
A1=-A22*(QG-Q1A)-A12*Q2A
A2=A12*(QG-Q1A)+A11*Q2A
100 IF(IPROB.EQ.1)GO TO 1
IF(IPROB.EQ.2)GO TO 1
IF(IPROB.EQ.3)GO TO 13
IF(IPROB.EQ.4)GO TO 1
IF(IPROB.EQ.5)GO TO 1
C PROBLEM-OPTION 1
C CALCULATE FLRATF GIVEN THE LOOP LENGTH AND OIL TEMPERATURE DROP
TAVG=(TOILMN+TOILMX)/2.0
CALL PTYINT(DNTY, SPECHT, VSCTY, TEMPD, TEMPSH, TEMPV, NDPTS, *NSHPTS, NVPTS, TAVG, DTY, SPHT, VTY, F, F1, XP, NPVALM)
IF(ISKIP2.EQ.1)GO TO 16
JAY=0
ICHNG(1)=1
IC=1
DELFR=50.0
FLRT(1)=500.0
IF(ISKP1.EQ.1)FLRT(1)=FLRATE
IF(LOOPNO.GT.1)FLRT(1)=FLRATE
2 IC=IC+1
IF(IC.GT.40)GO TO 21
FLRATE=FLRT(IC-1)
IF(FLRT(IC-1).LE.0.0)GO TO 19
X3= XLTH/DTY/SPHT/FLRATE/0.134/60.0
XL1B=(F11+F12-XL1)/F12*EXP(XL1*X3)
XL2B=(F11+F12-XL2)/F12*EXP(XL2*X3)
P1=((YL2B-1.)*A1+A2-XL2B*TOILMX)/(XL1P-XL2B)
P2=(XL1-F11)/F12*B1
C1=TOILMX-A1-B1
C2=(XL2-F11)/F12*C1
TOILM=A2+B2+C2
IF(ABS(TOILM-TOILMN).LE.0.05)GO TO 12
IF(JAY.EQ.1)GO TO 8
IF(TOILM-TOILMN).LT.3,4,5
GO TO 12
FLRT(IC)=FLRT(IC-1)+DELFR
ICHNG(IC)=2
IF(IABS(ICHNG(IC)-ICHNG(IC-1)).EQ.2)GO TO 6
GO TO 2
4 GO TO 12
5 FLRT(IC)=FLRT(IC-1)-DELFR
ICHNG(IC)=4
IF(IABS(ICHNG(IC)-ICHNG(IC-1)).EQ.2)GO TO 6
GO TO 2
6 IF(ICHNG(IC).EQ.4)GO TO 7
FRHIGH=FLRT(IC-2)
FRLOW=FLRT(IC-1)
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JAY=1
FLRT(IC)=(FRHIGH+FRLow)/2.0
GO TO 2
7 FRHIGH=FLRT(IC-1)
FRLow=FLRT(IC-2)
JAY=1
FLRT(IC)=(FRHigh+FRLow)/2.0
GO TO 2
8 IF(TOILM-TOILMN)9,10,11
9 FRLow=FLRT(IC-1)
FLRT(IC)=(FRHigh+FRLow)/2.0
GO TO 2
10 GO TO 12
11 FRHigh=FLRT(IC-1)
FLRT(IC)=(FRHigh+FRLow)/2.0
GO TO 2
12 FLRATE=FLRT(IC-1)
TOILCR=A1+B1*EXP(XL1*X3)+C1*EXP(XL2*X3)
IF(TDIST.EQ.1.0)GO TO 16
GO TO 18
C PROBLEM-OPTION 3-ENERGY BALANCE BETWEEN PIPES AND SOIL
C CALCULATE TOILMN GIVEN THE FLOW RATE AND LOOP LENGTH
13 IF(NPYPs1.EQ.1)GO TO 14
TOILMN=50.0
IC=1
14 TOILM=TOILMN
IC=IC+1
IF(IC.GT.50)GO TO 18
TAVG=(TOILMX+TOILMN)/2.0
CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPSH,TEMPV,NDPTS,
*NSPPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,VF,NPVALM)
X3=XLTH/DTY/SPHT/FLRATE/0.134/60.0
XL1B=(F11+F12-XL1)/F12*EXP(XL1*X3)
XL2B=(F11+F12-XL2)/F12*EXP(XL2*X3)
R1=((XL2B-1.0)*A1+A2-XL2B*TOILMX)/(XL1B-XL2B)
B2=(XL1-F11)/F12*B1
C1=TOILMX-A1-B1
C2=(XL2-F11)/F12*C1
TOILMN=A2+B2+C2
IF(ABS(TOILMN-TOILM).LE.0.5)GO TO 15
GO TO 14
15 IF(TDIST.EQ.1.0)GO TO 16
GO TO 18
C LOOP TEMPERATURE DISTRIBUTION
16 DZ=XLTH/FLOAT(NLTPTS-1)
Z=0.0
TC(1)=TOILMX
TR(1)=TOILMN
XTDIST(1)=0.0
DO 17 L=2,NLTPTS
Z=Z+DZ
XX=Z/DTY/SPHT/FLRATE/0.134/60.0
TC(L)=A1+B1*EXP(XL1*XX)+C1*EXP(XL2*XX)
XTDIST(L)=Z
17 CONTINUE
TOILCR=TR(NLTPTS)
GO TO 18
19 TDIST=100.0
GO TO 18
21 TDIST=200.0
18 RETURN
END

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PROGRAM ENBAL2 HAS NO ERRORS
SUBROUTINE ENDCHECK(NLOOPS,XFL,FLT,LLTH,LLTHMN,LOOPNO,
  *IPROB,NEND1,MAXLPS,MAXLP1)
REAL LLTH,LLTHMN
DIMENSION XFL(MAXLP1),LLTH(MAXLPS)

C PROBLEM-2--END OF LINE LENGTH COMPATABILITY
NEND1=0

C DETERMINE IF NO OF LOOPS IS EVEN OR ODD
CALL EVOROD(LOOPNO,EVODD)
IF(EVODD.EQ.1)GO TO 2

C ODD NUMBER OF LOOPS-TOTAL LENGTH GREATER THAN THE LINE LENGTH
NLOOPS=NLOOPS+1
PL=FLT/FLOAT(NLOOPS)
DO 1 I=1,NLOOPS
  LLTH(I)=PL
1 CONTINUE
NEND1=1
GO TO 5

2 IF((FLT-XFL(NLOOPS)).GT.LLTHMN)GO TO 4
PL=FLT/FLOAT(NLOOPS)
DO 3 I=1,NLOOPS
  LLTH(I)=PL
3 CONTINUE
NEND1=1
GO TO 5

4 LLTH(NLOOPS)=FLT-XFL(NLOOPS)
LOOPNO=NLOOPS
NEND1=1
GO TO 5

5 RETURN
END

PROGRAM ENDCHECK HAS NO ERRORS
SUBROUTINE LOOKBY(XFL, LOOPEL, PEL, HTDNEG, HTDPOS, NPPTS,
  *LOOPNO, PLTH, IPCS, HTDN, HTDP, NPPTSM, MAXLP1)

REAL LOOPEL

DIMENSION PLTH(NPPTSM), XFL(MAXLP1), LOOPEL(MAXLP1),
  HTDN(NPPTSM), HTDP(NPPTSM), PEL(NPPTSM)

IF(IPCS.EQ.0)GO TO 3

II=NPPTS-1

DO 2 L=1,II

KL=L+1

IF(PLTH(L+1)-XFL(LOOPNO+1))2,2,1

1 CONTINUE

2 KKK=0

LLL=0

IF(IPCS.EQ.0)KL=1

DO 5 M=KL,NPPTS

HTDIFF=LOOPEL(LOOPNO+1)-PEL(M)

IF(HTDIFF.GE.0.0)GO TO 4

KKK=KKK+1

HTDNEG=HTDN(KKK)

GO TO 5

3 KKK=KKK+1

HTDNEG=HTDN(KKK)

HTDN(KKK)=0.0

LLL=LLL+1

HTDP(LLL)=HTDIFF

GO TO 5

4 CONTINUE

HTDNEG=HTDN(KKK)

HTDPOS=HTDP(KKK)

DO 7 I=1,KKK

IF(HTDNEG-HTDN(I))6,7,7

5 CONTINUE

DO 9 I=1,LLL
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IF(HTDPOS-HTDP(I))8,9,9
  9  HTDPOS=HTDP(I)
  9  CONTINUE
RETURN
END

PROGRAM LOOKEY HAS NO ERRORS
SUBROUTINE PHTDET(PEL,NPPTS,DTY,PMIN,PHT,NPPTSM)  
DIMENSION PEL(NPPTSM)  
C FIND MAXIMUM POSITIVE HEIGHT OF ALL PROFILE POINTS  
NBIG=2  
PELBIG=PEL(2)  
DO 2 K=3,NPPTS  
IF(PELBIG-PEL(K))1,2,2  
1 PELBIG=PEL(K)  
NBIG=K  
2 CONTINUE  
SDPP=6.944E-3*DTY*PELBIG  
PHT=PMIN+SDPP  
RETURN  
END  

PROGRAM PHTDET HAS NO ERRORS
SUBROUTINE PDIST(PRESCL,PRESRL,NPPTS,SPRESS,DPLULC,
*DPLULR,FLT,XFL,LOOPNO,IMEMRY,PEL,PC,PR,XDIST,
*PDIFHC,PDIFHR,PDIFLO,NPC,NPR,NPCLO,K,DTY,PMAXCL,
*PMAXRL,PMIN,FLT,PDIFFC,PDIFFR,PDIFFL,NPPTSM,NPPTS1,MAXLPS,MAXLP1)
DIMENSION PRESCL(MAXLP1),PRESRL(MAXLP1),SPRESS(MAXLP1),
1PLTH(NPPTS1),XFL(MAXLP1),PR(NPPTSM),PC(NPPTSM),XDIST(NPPTSM),
2PDIFHC(MAXLPS),PDIFHR(MAXLPS),PDIFLO(MAXLPS),NPC(MAXLPS),
3NPTR(MAXLPS),NPCLO(MAXLPS),DPLULC(MAXLPS),DPLULR(MAXLPS),
4PDIFFC(NPPTSM),PDIFFR(NPPTSM),PDIFFL(NPPTSM),PEL(NPPTSM)

\( k = 1 \)
\( \text{PC}(k) = \text{PRESCL}(\text{LOOPNO}) \)
\( \text{XDIST}(k) = \text{XFL}(\text{LOOPNO}) \)
\( \text{CALL EVOROD(LOOPNO,EVODD)} \)
\( \text{IF(EVODD.EQ.1.0)GO TO 1} \)
\( \text{PR}(k) = \text{PRESRL}(\text{LOOPNO}) \)
\( \text{GO TO 2} \)
\( 1 \)
\( \text{PR}(k) = \text{PRESCL}(\text{LOOPNO}) \)
\( \text{IF(LOOPNO.GT.1)GO TO 3} \)
\( \text{IMEMRY}=? \)
\( 2 \)
\( \text{IFMEMY}=? \)
\( \text{NPPTS2}=\text{NPPTS}+1 \)
\( \text{DO 10} \)
\( \text{J}=\text{IREM},\text{NPPTS2} \)
\( \text{IF(XFL(LOOPNO+1).GT.FLT)PLTH(NPPTS2)=XFL(LOOPNO+1)} \)
\( \text{IF(XFL(LOOPNO+1).GT.FLT)PEL(NPPTS2)=PEL(NPPTS)} \)
\( \text{PDIFFC}(J)=0.0 \)
\( \text{PDIFFR}(J)=0.0 \)
\( \text{PDIFFL}(J)=0.0 \)
\( k=k+1 \)
\( \text{SDPP}=-6.94E-3*\text{DTY}^{*}\text{PEL}(J) \)
\( \text{IF(PLTH(J)-XFL(LOOPNO+1))4,6,6} \)
\( \text{IF(EVODD.EQ.1.0) GO TO 5} \)
\( \text{DPELPP}=\text{SDPP}-\text{SPRESS}(\text{LOOPNO}+1) \)
\( \text{DPLFPC}\text{DPLULC}(\text{LOOPNO})*(XFL(\text{LOOPNO}+1)-\text{PLTH}(J)) \)

\( 3 \)

\( 4 \)
DPLPPR=DPLULR(LOOPNO)*(XFL(LOOPNO+1)-PLTH(J))  
PRPPTC=PRESCL(LOOPNO+1)-DPLPPC+DPELPP  
PRPPTR=PRESCL(LOOPNO+1)+DPLPPR+DPELPP  
PC(K)=PRPPTC  
PR(K)=PRPPTR  
XDIST(K)=PLTH(J)  
GO TO 9  

5  
DPELPP=SDPP-SPRESS(LOOPNO)  
DPLPPC=DPLULC(LOOPNO)*(PLTH(J)-XFL(LOOPNO))  
DPLPPR=DPLULR(LOOPNO)*(PLTH(J)-XFL(LOOPNO))  
PRPPTC=PRESCL(LOOPNO)-DPLPPC+DPELPP  
PRPPTR=PRESCL(LOOPNO)+DPLPPR+DPELPP  
PC(K)=PRPPTC  
PR(K)=PRPPTR  
XDIST(K)=PLTH(J)  
GO TO 9  

6  
PC(K)=PRESCL(LOOPNO+1)  
XDIST(K)=XFL(LOOPNO+1)  
IF(EVODD.EQ.1.0)GO TO 7  
PR(K)=PRESCL(LOOPNO+1)  
GO TO 8  

7  
PR(K)=PRESRL(LOOPNO)  

8  
IMEMRY=J  
GO TO 11  

9  
IF(PRPPTR .GT. PMAXRL)PDIFFR(J)=PRPPTR - PMAXRL  
IF(PRPPTR .LT. PMIN)PDIFFL(J)=PMIN-PRPPTR  
CONTINUE  

10  
PDIFHC(LOOPNO)=PDIFFC(IREM)  
NPC(LOOPNO)=IREM  
PDIFHR(LOOPNO)=PDIFFR(IREM)  
NPR(LOOPNO)=IREM  
PDIFLO(LOOPNO)=PDIFFL(IREM)
NPCLO(LOOPNO) = IFEM
JREM = IREM + 1
JMEMRY = IMEMRY
DO 17 I = JREM, JMEMRY
12 IF (PDIFHC(LOOPNO) - PDIFFC(I)) 12, 13, 13
12 PDIFHC(LOOPNO) = PDIFFC(I)
NPC(LOOPNO) = I
13 IF (PDIFHR(LOOPNO) - PDIFFR(I)) 14, 15, 15
14 PDIFHR(LOOPNO) = PDIFFR(I)
NPR(LOOPNO) = I
15 IF (PDIFLO(LOOPNO) - PDIFFL(I)) 16, 17, 17
16 PDIFLO(LOOPNO) = PDIFFL(I)
NPCLO(LOOPNO) = I
CONTINUE
RETURN
END

PROGRAM PRDIST HAS NO ERRORS
SUBROUTINE PRDROP(DCABLE, DPIPE, SWH, PITCH, SWANG, DTYC, VTYC, DTYR, 
* VTYR, PWETC, PWETR, AFLWNC, AFLWFR, FLRATE, FFSTDC, FFC, FFR, RNC, RNR, 
* IPROB, DPLULC, DPLULR, LOOPNO, MAXLPS)
DIMENSION DPLULC(MAXLPS), DPLULR(MAXLPS)

C CABLE LINE PRESSURE DROP CALCULATIONS
C CALCULATE REYNOLDS NUMBER AND DETERMINE FLOW REGIME
RNC=(FLRATE*DTYC)/(VTYC*PWETC*6.271E-3)
IF(RNC.LE.460.0)GO TO 1
IF(RNC.LT.2790.0)GO TO 2
IF(RNC.LE.17000.0)GO TO 3
GO TO 4

1  FFSTDC=10.468/(RNC**0.9506) 12
GO TO 5
2  FFSTDC=0.2308*(RNC**(-0.3294)) 14
GO TO 6
3  FFSTDC=0.0566*(RNC**(-0.1491)) 16
GO TO 6
4  FFSTDC=0.0132
GO TO 6
5  FFC=FFSTDC*(3.581-6.5*DCABLE/DPIPE)
GO TO 9
6  IF(SWANG.LE.15.0)GOTO 7
CSWANG=1.135-0.00876*SWANG
GO TO 8
7  CSWANG=1.0
8  FFC=FFSTDC*15.894*(SWH/DCABLE)**0.387*(PITCH/SWH)**(-0.373)*(2.725**DCABLE/DPIPE-0.099)*CSWANG
9  DPLULC(LOOPNO)=1.3394E-4*FFC*DTYC*PWETC*FLRATE**2/AFLOWC**3
C RETURN LINE PRESSURE DROP CALCULATION
C CALCULATE REYNOLDS NUMBER AND DETERMINE FLOW REGIME
RNR=(FLRATE*DTYR)/(VTYR*PWETR*6.271E-3)
IF(RNR.LT.1187.0)FFR=16.0/RNR
IF(RNR.GT.1187.0.AND.RNR.LT.51094.0)FFR=0.0791/RNR**0.25
IF(RNR*.GT.*51094*.0)FFR=0.046/RNR**0.20
QPLULR(LOOPNO)=1.3394F-4*FFR*DTYR*PWTR*FLRATE**2/
*AFLOWR**3
RETURN
END

PROGRAM PRDROP HAS NO ERRORS
SUBROUTINE HEATTR(DCOND,DCABLE,DPIPE,TAPTH,KOIL,WD,KTAPE,RDC,YC, 01
*YS,TCABMX,PFET,AFLOW,FLRATE,IFC,TOILMX,COTHEX,RNC,RAYN,IPROB,
*DNTY,SPECHT,VSCTY,TEMPD,TEMPH,TEMPV,NDPTS,NSHPTS,NVPTS,TAVG,
*DTY,SPHT,VTY,FILMC,CONV,CTAPE,THETA,NBYPAS,F,F1,XP,NPVALM)
REAL KOIL,KTAPE,IFC,NU
DIMENSION DNTY(NPVALM),SPECHT(NPVALM),VSCTY(NPVALM),F(NPVALM),
1F1(NPVALM),XP(NPVALM),TEMPD(NPVALM),TEMPH(NPVALM),TEMPV(NPVALM)
ICT=1
C CALCULATE HEAT TRANSFER CORRELATION CONVECTION CORRECTION FACTOR
09 IF(NBYPAS.EQ.2)GO TO 11
10 IF(IPROB.EQ.4)GO TO 11
11 WCABLE=3.413*IFC**2*RDC*(1.0+YC+YS)+WD
12 WC=(1.0+YC)*RDC*IFC**2
13 ITGO=1
14 IF(NBYPAS.EQ.3)GO TO 1
15 IF(NBYPAS.EQ.2)GO TO 7
16 IF(NBYPAS.EQ.1)GO TO 4
17 IF(RNC.GT.460.0)GO TO 4
18 CLAMINAR FLOW--NATURAL CONVECTION DOMINATES
19 C INITIALIZE CABLE SURFACE-TO-OIL TEMPERATURE DROP
20 ITGO=0
21 NBYPAS=3
22 GO TO 7
23 ITGO=1
24 DTSTO=5.0
25 2 TEMAN=TOILMX+(DTSTO/2.0)
26 ICT=ICT+1
27 IF(ICT.GT.30)GO TO 12
28 TAVG=TEMAN
29 CALL PTYINT(DNTY,SPECHT,VSCTY,TEMPD,TEMPH,TEMPV,NDPTS,
*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,XP,NPVALM)
30 RAYN=9.979E4*COTHEX*DTSTO*DCABLE**3*DNTY**2*SPHT/VTY/KOIL
31 NU=EXP(0.22*(ALOG(RAYN)-16.118)+2.944)
FILMC = 12.0 \times \nu \times \frac{KOIL}{DCABLE}

C SUBSTITUTE FILMC INTO CABLE-TO-OIL ENERGY BALANCE

DTST01 = 12.0 \times \frac{WCABLE}{FILMC}/3.1416/DCABLE

IF(A3S(DTST01-DTST0).LE.0.10)GO TO 3

DTSTO=DTST01

GO TO 2

3 \chi^p = 12.0 \times \frac{KOIL}{FILMC}/DCABLE/ALOG(DCABLE/DCOND)

CCONV=0.578*W^2*(-0.120)

GO TO 5

4 C CALCULATE HEAT TRANSFER CORRELATION TAPF CORRECTION FACTOR

5 \chi T = TAPF*\chi^P*ALOG(DCABLE/DCOND)/KOIL/DCABLE

IF(XT.GT.1.0)GO TO 6

CTAPE=0.988*XT**0.056

GO TO 8

6 CTAPE=0.945*XT**0.136

GO TO 8

7 CCONV=1.0

CTAPE=1.0

IF(NRYPAS.EQ.2)GO TO 9

8 IF(IPROP.EQ.4)GO TO 9

\chi T = ((WC/WD/CCONV/CTAPE)+0.53)\times WD*ALOG(DCABLE/DCOND)/1.764/KOIL

TOILMI=TCABMX-\chi T

IF(NRYPAS.EQ.1)GO TO 10

IF(NRYPAS.EQ.3)GO TO 13

IF(RNC.GT.460.O)GO TO 10

13 IF(ITGO.EQ.0)GO TO 10

IF(A3S(TOILMX-TOILMI).LE.0.2)GO TO 10

TOILMX=TOILMI

GO TO 2

9 \chi T = TCABMX-TOILMX

IFC=SQRT((1.764*KOIL*\chi T/WD/ALOG(DCABLE/DCOND)-0.53)**CCONV*CTAPE*WD/(1.0+YC)/RDC)

GO TO 2
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GO TO 12
10  TOILMX=TOILMI
   IF(ITGO.EQ.0)GO TO 1
12  RETURN
   END

PROGRAM HEATTR HAS NO ERRORS
SUBROUTINE PPCALC(NPPTS, LOOPNO, XLT, NLPPTS, PRESCL, PRESRL, * LOOPNO, XFL, PLTH, PEL, LOOPFL, DTYC, DTYP, DPLULC, DPLULR, PRC, PRR, * XPDIST, NLPPTM, MAXLPS, MAXLP1, NPPTSM)
REAL LOOPTL
DIMENSION PRC(NLPPTM), PRR(NLPPTM), XPDIST(NLPPTM), PRESCL(MAXLPS), * PRESRL(MAXLPS), XFL(MAXLP1), PLTH(NPPTFM), PEL(NPPTSM), * LOOPEL(MAXLP1), DPLULC(MAXLPS), DPLULR(MAXLPS)

C LOOP PRESSURE DISTRIBUTION

IREM=1
II=NPPTS-1
CALL EWOROD(LOOPNO, EVODD)
XPDIST(1)=0.0
DZ=XLT/FLOAT(NLPPTS-1)
Z=0.0
PRC(1)=PRESCL(LOOPNO)
PRR=PRESRL(LOOPNO)
IF(EVODD.EQ.1.0)GO TO 7
GO TO 2
1
PRR(1)=PRESCL(LOOPNO)
GO TO 2
2
DO 9 L=2,NLPPTS
Z=Z+DZ
ZP=XFL(LOOPNO)+Z
XPDIST(L)=Z
DO 5 J=IREM,II
IF(ZP-PLTH(J+1))3,4,5
3
ZEL=((ZP-PLTH(J))*(PEL(J+1)-PEL(J))/(PLTH(J+1)-PLTH(J))+PEL(J)
GO TO 6
4
ZEL=PEL(J+1)
GO TO 6
5
CONTINUE
6
DZEL=ZEL-LOOPEL(LOOPNO)
IF(EVODD.EQ.1.0)GO TO 7
DPEL = -6.944E-3 * DTYC * DZEL
PRC(L) = PR + DPEL + DPLULC(LOOPNO) * Z
DPEL = -6.944E-3 * DTYR * DZEL
PRR(L) = PRR(1) + DPEL - DPLULR(LOOPNO) * Z
GO TO 8

7  DPEL = -6.944E-3 * DTYC * DZEL
PRC(L) = PR + DPEL - DPLULC(LOOPNO) * Z
DPEL = -6.944E-3 * DTYR * DZEL
PRR(L) = PR + DPEL + DPLULR(LOOPNO) * Z

8  IREM = J
9  CONTINUE
10  RETURN
11  END

PROGRAM PPCALC HAS NO ERRORS
SUBROUTINE PTYINT(DNTY,SPECHT,VSCTYT,'EMPD,TEMPSH,TEMPV,NDPTS, 01*NSHPTS,NVPTS,TAVG,DTY,SPHT,VTY,F,F1,YP,NPVALf) 02
DIMENSION DNTY(NPVALM),SPECHT(NPVALM),VSCTYT(NPVALM),F(NPVALM), 03
1F1(NPVALM),XP(NPVALM),TEMPD(NPVALM),TEMPSH(NPVALM),TEMPV(NPVALM) 04
TEMBIG=TEMPV(1) 05
DO 22 I=2,NVPTS 06
IF(TEMBIG-TEMPV(I))21,22,22 07
21 TEMBIG=TEMPV(I) 08
22 CONTINUE 09
IF(TAVG.LT.TEMBIG)GO TO 23 10
TAVG=TEMBIG 11
23 TEMSM=TEMPV(1) 12
DO 25 I=2,NVPTS 13
IF(TEMPV(I)-TEMSM)24,25,25 14
24 TEMSM=TEMPV(I) 15
25 CONTINUE 16
IF(TAVG.GT.TEMSM)GO TO 26 17
TAVG=TEMSM 18
26 IF(NDPTS.EQ.1)GO TO 4 19
DO 1 I=1,NDPTS 20
XP(I)=TEMPD(I)-TAVG 21
1 F(I)=DNTY(I) 22
DO 3 I=2,NDPTS 23
DO J=I,NDPTS 24
2 F1(J)=(F(I-1)*XP(J)-F(J)*XP(I-1))/(TEMPD(J)-TEMPD(I-1)) 25
DO3 J=I,NDPTS 26
3 F(J)=F1(J) 27
DTY=F(NDPTS) 28
GO TO 5 29
4 DTY=DNTY(1) 30
IF(NSHPTS.EQ.1)GO TO 9 31
DO6 I=1,NSHPTS 32
XP(I)=TEMPSH(I)-TAVG 33
PROGRAM PTYINT HAS NO ERRORS
SUBROUTINE STPPG(DTY, LOOPNO, FLT, NPPTS, PLTH, PEL, LLTH, LOOPEL, XFL, SPRESS, DPFL, SDP, NPPTS*, MAXLPS, MAXLP1)

REAL LLTH, LOOPEL

DIMENSION PLTH(NPPTS*), PEL(NPPTS*), LLTH(MAXLPS), LOOPEL(MAXLP1),
XFL(MAXLP1), SPRESS(MAXLP1), DPFL(MAXLPS), SDP(MAXLPS)

XFL(1)=0.0
II=NPPTS-1
PLTH(1)=0.0
PEL(1)=0.0
LOOPEL(1)=0.0
DO 3 J=1,II
XFL(LOOPNO+1)=LLTH(LOOPNO)+XFL(LOOPNO)
IF(XFL(LOOPNO+1)-PLTH(J+1))1,2,3

1 LOOPEL(LOOPNO+1)=((XFL(LOOPNO+1)-PLTH(J))*(PEL(J+1)-PEL(J))/PLTH
*(J+1)-PLTH(J)))*PEL(J)
GO TO 4

2 LOOPFL(LOOPNO)=PEL(J+1)
GO TO 4

3 IF(XFL(LOOPNO+1).GT.FLT) LOOPFL(LOOPNO+1)=NPPTS

4 SDP(LOOPNO)=-6.944E-3*DTY*LOOPEL(LOOPNO+1)
SPRESS(1)=0.0
SPRESS(LOOPNO+1)=SDP(LOOPNO)
SPEL(LOOPNO)=SPRESS(LOOPNO+1)-(SPRESS(LOOPNO)
RETURN
END

PROGRAM STPPG HAS NO ERRORS
APPENDIX B

SELECTION OF THE VALUES
OF PLOW AND PHIGH FOR DESIGN-OPTION 2

B.1 Selection of PLOW (two-end head tank system)

The example discussed in Section 4.1.1 shows that during the worst off-design operating conditions the most conservative value of PLOW is equal to the system static pressure (at the point of interest) which exists when the entire system is inoperative. Before it can be concluded that this value is truly the most conservative, the system absolute pressure profile must be examined during normal operating conditions (to make certain that internal loop pressures are maintained within design constraints). For this purpose, both even and odd numbered loops of a forced-cooled system (counting from the end containing the operational head tank) are examined and a conservative approach is taken in that only the system loops containing the highest hills and lowest valleys are examined (otherwise, the rest of the system profile would also have to be considered when selecting the value of PLOW). The purpose of this analysis will be to determine that value of PLOW which is the most conservative (and therefore the safest) for the system design.

B.1.1 Odd-Numbered Loop Containing a Hill

Figure B.1 shows the elevation profile of an odd-numbered loop (operational head tank is to the left) and the direction of the oil circulation in the cable line; only the cable line is examined because low
pressure values are of no concern in the return pipe. The value of PCL (the maximum cable line pressure) is also of no concern in this analysis. Points a and b are the highest elevation profile points in the forced-cooled system. The pressure at point N-1 is the reference pressure for this coolant loop (all other loop absolute pressures depend on this value).

![Diagram of coolant loop elevation profile with points a and b highlighted.](image)

Figure B.1 Odd-Numbered Coolant Loop Elevation Profile - Hill.

When the entire system is inoperative, the value of PLOW must be set equal to the pressure that maintains all loop static pressures above the value of PMIN (no other system points must be considered since this loop contains the highest elevation points). Therefore the value of PLOW is equal to the following:

\[ PLOW = PMIN + \Delta P_{EL} \]  

(B.1)
where $\Delta P_{EL}$ is equal to the hydrostatic pressure change between point N-1 and point a (highest elevation point). In this case, the value of PLOW must also equal the static pressure which exists at point N-1 when the system is inoperative (system static pressures maintained by head tank pressure).

During normal operating conditions the pressure at point a, for example, will be equal to the following:

$$P_a = PLOW - \Delta P_{EL} + \Delta P_f$$  \hspace{1cm} (B.2)

where $\Delta P_f$ is the frictional pressure loss which results from the circulating oil. (The value of $\Delta P_f$ is added to PLOW because movement from point N-1 to point a is counter to the direction of the oil flow. The value of $\Delta P_{EL}$ is subtracted from PLOW because point a is higher in elevation than point N-1.) If the value of PLOW is equal to the system static pressure, the quantity ($PLOW - \Delta P_{EL}$) will be equal to PMIN and therefore, the pressure at point a (call this pressure $P_{a1}$) will always be maintained above the value of PMIN since $\Delta P_f$ is always added to the value of PLOW. (A similar argument can also be used to show that this is also the case at point b and at all loop points.)

The value of PLOW can be lowered (below the static value) so that during normal operating conditions the pressure at point a (call this value $P_{a2}$) is below the value of $P_{a1}$. However, if oil circulation is discontinued in this loop (due to pump failure) while all loops to the left are still operating, the resulting static pressure at point a will fall below the value of PMIN. Thus, the lowest value PLOW can attain in this
particular case, is the system static pressure (at point N-1). The static case will always provide the most conservative value of PLOW during normal and abnormal operating conditions.

**B.1.2 Odd-Numbered Loop Containing a Valley**

Figure B.2 shows the elevation profile of an odd-numbered loop (operational head tank to the left) and the direction of the oil circulation in the cable line (again the return line is ignored). The value of PCL is, again, of no concern in the analysis. Points a and b are the lowest elevation profile points in the forced-cooled system. Point N-1 is the loop reference point.

![Figure B.2 Odd-Numbered Coolant Loop Elevation Profile-Valley](image)

During normal loop operation, both the hydrostatic pressure change and the frictional pressure loss are added to the value of PLOW when calculating the loop pressure profile. Since all elevation points
are lower than point N-1 (the reference point), the loop pressures will always be maintained above the value of PLOW. Consequently, only the static case is of importance in calculating PLOW. As was discussed in Section 4.1.1 and B.1.1 the conservative value of PLOW corresponds to the static pressure which exists at point N-1.

**B.1.3 Even-Numbered Loop Containing a Hill**

Figure B.3 shows the elevation profile of an even-numbered loop (operational head tank to the left) and the direction of the oil circulation in the cable line (again the return line is ignored). Although the value of PCL constitutes the reference pressure for the loop, its value is of no importance to this analysis. Points a and b are the highest elevation points in the forced-cooled system.

![Figure B.3 Even-Numbered Coolant Loop Elevation Profile-Hill](image)

A value of PLOW must be selected which maintains all loop pressures above PMIN. Rather than calculate the loop pressure profile
utilizing the value of PCL, a value of PLOW is selected and will be used to calculate the loop pressures. The pressure at point b, for example, is calculated as follows (for normal operating conditions):

\[ P_b = PLOW - \Delta P_{EL} + \Delta P_f \]  

(B.3)

where \( \Delta P_f \) is the frictional pressure loss which results from the circulating oil. If the value of PLOW is set equal to the static pressure which exists at point N-1 when the system is inoperative (PLOW=PMIN+\( \Delta P_{EL} \)), the pressure at point b (and all other loop pressures) will always be maintained above the value of PMIN since \( \Delta P_f \) is always added to the value of PLOW. Based on the discussion in B.1.1 and Section 4.1.1, the system static pressure at the point of interest (point N-1) represents the most conservative selection of PLOW.

**B.1.4 Even-Numbered Loop Containing a Valley**

The proof that the static conditions represent the most conservative case for selecting PLOW follows the same reasoning that is used in Section B.1.2.

**B.2 Selection of PRHCL**

The example discussed in Section 4.1.2 shows that during the worst off-design operating conditions the most conservative value of PRHCL is chosen so as to maintain the pressures in inoperative loops below the value of PMAXCL. Before it can be concluded that this value is truly the most conservative, the system absolute pressure profile must be examined during normal operating conditions (to make certain that
internal loop pressures are maintained within design constraints). For this purpose, both even and odd numbered loops of a forced-cooled system (counting from the end containing the operational head tank) are examined and a conservative approach is taken in that only the system loops containing the highest hills and lowest valleys are analyzed (otherwise, the rest of the system profile would have to be considered when selecting the value of PRHCL) the purpose of this analysis will be to determine that value of PRHCL which is the most conservative (and therefore the safest) for the system design.

B.2.1 Even-Numbered Loop Containing a Hill

Figure B.4 shows the elevation profile of an even-numbered loop (operational head tank is to left) and the direction of the oil circulation in the cable line; only the cable line is examined. Points a and b are the highest elevation profile points in the forced-cooled system. The pressure at point N-4 is the reference pressure for the coolant loop (all other loop absolute pressures depend on this value). The value of PLOW is set equal to the system static pressure at point N-1.

If this loop is inoperative (due to pump failure), but the result of the system to the left of this loop is operating, the value of PRHCL must correspond to the pressure that maintains all loop static pressures below the value of PMAXCL (other system points to the right of point N-1 must also be considered, but it will be assumed here that no other point is lower than point N-4). Therefore, the value of PRHCL is equal to the maximum permitted cable line pressure:

\[ \text{PRHCL} = \text{PMAXCL} \]  

(B.4)
During normal operating conditions the pressure at point a, for example, will be equal to the following:

$$p_a = PRHCL - \Delta P_{EL} - \Delta P_f$$  \hspace{1cm} (B.5)

where \( \Delta P_f \) is the frictional pressure loss which results from the circulating oil. (The value of \( \Delta P_f \) is subtracted from PRHCL because movement from point N-4 to point a is in the same direction of the oil flow. The value of \( \Delta P_{EL} \) added to PRHCL because point a is higher in elevation than point N-1.) If the value of PRHCL is set equal to the value calculated in Equation B.4, the pressure at point a (and all other points) will always be maintained below the value of PMAXCL because both the frictional pressure drop and the hydrostatic pressure drop are subtracted from PRHCL to calculate the pressure at another point.
The value of PRHCL can be set at a higher pressure value (higher than calculated in B.4) which will still maintain all loop pressures within constraints during normal operation; however, if circulation stops, the loop static pressures will exceed PMAXCL. Thus a conservative design rule is to always select PRHCL for static conditions.

### B.2.2 Even-Numbered Loop Containing a Valley

Figure B.5 shows the elevation profile of an even-numbered loop (operational head tank to left) and the direction of the oil circulation in the cable line; only the cable line is considered. Points a and b are the lowest elevation profile points in the forced-cooled system. The pressure at point N-4 is the reference pressure for the coolant loop (all other loop absolute pressures depend on this value). The value of PLOW is set equal to the system static pressure at point N-1.

![Figure B.5 Even-Numbered Loop Elevation Profile - Valley.](image-url)
If this loop is inoperative (due to pump failure), but the rest of the system to the left of this loop is operating, the value of PRHCL must correspond to the pressure that maintains all loop static pressures below the value of PMAXCL (other system points need not be considered since points a and b are the lowest elevations in the system). Therefore, the value of PRHCL is equal to the following:

$$PRHCL = PMAXCL - \Delta P_{EL}$$  \hspace{1cm} (B.6)

where $\Delta P_{EL}$ is equal to the hydrostatic pressure change between point N-4 and point a (lowest elevation point).

During normal operating conditions the pressure at point a, for example, will be equal to the following:

$$P_a = PRHCL + \Delta P_{EL} - \Delta P_f$$

where $\Delta P_f$ is the frictional pressure loss which results from the circulating oil. If the value of PRHCL is set equal to the value calculated in Equation B.5, the pressure at point a ($P_a^1 = PMAXCL - \Delta P_f$) will always be maintained below the value of PMAXCL because the frictional pressure drop is subtracted from PRHCL. (A similar argument can also be used to show that this is also the case at point b and at all loop points.) The value of PRHCL can be increased above the value calculated in Equation B.6 so that during normal operating conditions the pressure at point a (call this value $P_{a2}$) is above the value of $P_a^1$ (but still within the
constraint value); however, if circulation is discontinued in this loop (due to pump failure), while all loops to the left are still operating, the resulting static pressure at point a will exceed PMAXCL. Thus, the highest value PRHCL can attain, in this particular case, is calculated for static conditions.

Similar arguments can be applied to the odd-numbered coolant loop as is done in Section B.2.1 and B.2.2. The conclusion drawn is the same.

B.3 Calculation of PHIGH - Even-Numbered Loop

The selection of the proper values of PLOW and PRHCL assure that the pressures in the cable line of the system will always be maintained within design constraints. However, after these values have been determined, pressures within the return line may still exceed PMAXRL due to hydrostatic pressure change in the loop (and even though the return line end pressures remain within constraints). Figure B.6 presents an example of why this can happen; the return line elevation profile of an even-numbered coolant loop is shown (counting from the operational head tank which is to the left) along with the direction of the oil circulation. The

![Figure B.6 Return Line Elevation Profile - Even-Numbered Loop.](image-url)
value of PRHCL is the loop reference pressure. Point a will be considered as the lowest elevation point in the entire forced-cooled system. Therefore, the value of PRHCL is as follows:

\[
PRHCL = P_{\text{MAXCL}} - \Delta P_{\text{EL}} \tag{B.7}
\]

where \( \Delta P_{\text{EL}} \) is equal to the hydrostatic pressure change between point a (lowest elevation) and point N-4.

The value of the pressure at point a, for example, will be:

\[
P_a = PRHCL + \Delta P_{\text{EL}} + \Delta P_{f,N-4\rightarrow a} \tag{B.8}
\]

\[
= P_{\text{MAXCL}} + \Delta P_{f,N-4\rightarrow a}
\]

and the value of \( P_a \) must be less than PMAXRL.

\[
P_a = P_{\text{MAXCL}} + \Delta P_{f,N-1\rightarrow a} < P_{\text{MAXRL}}
\]

\[
\therefore \Delta P_{f,N-1\rightarrow a} < (P_{\text{MAXRL}} - P_{\text{MAXCL}})
\]

If \( \Delta P_{f,N-4\rightarrow a} \) exceeds the quantity \((P_{\text{MAXRL}} - P_{\text{MAXCL}})\), then the pressure at point a will exceed its pressure limit. If this is the case, is it still possible for PHIGH to be less in value than PMAXRL? The value of PHIGH is calculated from the value of \( P_a \) as:

\[
PHIGH = P_a - \Delta P_{\text{EL}} + \Delta P_{f,a\rightarrow N-1} \tag{B.9}
\]
If $P_a$ exceeds PMAXRL the value of $P_{EL}$ will have to exceed $\Delta P_{f,a} N-1$ by the same amount if the pressure at point N-4 is to be equal to PMAXRL. Consequently, given the right elevation profile, the pressure at point a can exceed PMAXRL while the pressure at point N-1 is below PMAXRL. An actual example of this occurrence is presented in Figure B.7; although the loop elevation profile is contrived, the thermal and hydraulic data is correct.

As is shown the pressure at point a exceeds the return line pressure constraint by over 30 psi, while the pressure at point N-1 remains below PMAXRL. Under these circumstances the computer program will shorten the coolant loop length until the pressure at point a (the highest pressure in the loop) equals the value of PMAXRL. If this cannot be accomplished, the program makes the axial length shorter than the distance from point N-4 to point a until the value of the end point return line pressure is equal to PMAXRL.

**B.4 Calculation of PHIGH - Odd-Numbered Loop**

The discussion presented in Section B.3 for an even-numbered loop also applies for an odd-numbered loop. The only differences which exist are that the return line arrangement is reversed (see Figure B.8) and therefore points N-1 and N-4 should be interchanged (i.e. Equation B.8 should read - for the odd-numbered loop - $P_a = PRHCL + \Delta P_{EL} + \Delta P_{D,N-4+a}$). The computer program performs the same procedure to alleviate any over-pressures in the return line.
PRESSURE CONSTRAINTS

P_{MAXCL} = 600 \text{ psi}
P_{MAXRL} = 750 \text{ psi}

THERMAL INFORMATION

THOT = 124.91 °F
TCOLD = 110.0 °F
Q = 504 \text{ gal/min}
\rho = 50 \text{ lbm/ft}^2

HYDRAULIC INFORMATION

5" return line
\left( \frac{\Delta P}{L} \right)_r = 2.45 \times 10^{-2} \text{ psi/ft}

\Delta P_{EL} = 6.944 \times 10^{-3} \times 50 \times 200 = 69.4 \text{ psi}
\Delta P_{f,N-4\rightarrow a} = 2.45 \times 10^{-2} \text{ psi/ft} \times 7500 \text{ ft} = 183.75 \text{ psi}
\Delta P_{f,a\rightarrow N-1} = 2.45 \times 10^{-2} \text{ psi/ft} \times 1250 \text{ ft} = 30.6 \text{ psi}

P_a = PRHCL + \Delta P_{EL} + \Delta P_{f,N-4\rightarrow a} = 783.75
P_{N-1} = P_a - \Delta P_{EL} + \Delta P_{f,a\rightarrow N-1} = 744.95

Figure B.7: Return Line Elevation Profile and Pressure Profile Calculation